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Extreme sea-level rise and adaptation options for coastal resort cities: A qualitative assessment from the Gold Coast, Australia

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ABSTRACT

The Gold Coast, Australia is a coastal resort city whose urban environment has evolved through a series of human interventions on the natural shoreline. Such cities rely on a perceived high quality environment which in turn is reliant on continuing maintenance (e.g. beach nourishment, inlet dredging, drainage). Climate change consequently holds particular challenges for coastal resort cities. Sea-level rise impacts are likely to be manifest in increased frequency of flooding and beach erosion episodes. Here we consider adaptation options for the city under various future sea-level rise (SLR) scenarios at the high end of current predictions for the next century (+1 m, +2 m and +5 m) with the proviso that the beach and waterways must be preserved to enable the city to continue to exist as a resort.

We conclude that pre-planned adaptation would probably enable the city to survive SLR of 1 m. An unplanned response to the same SLR would likely be characterised by periodic crises, growing uncertainty and public unease and would have marginal chances of success. For a 2 m SLR we contend that even with an adaptation plan in place, the scale of measures required would severely stretch the city's resources. Under a 5 m SLR over the next century we do not believe that any amount of planning would enable the city to survive as a coastal resort.

Any adaptation to SLR would involve increased cost to maintain the artificial coastal environment. Adaptation options are particularly constrained by the widespread development around the waterways of the back-barrier area. Unlike other coastal cities, resorts depend on a public perception of a high quality environment. Maintaining this perception under SLR imposes particular adaptation constraints on resort cities.

1. Introduction

Adaptation to climate change (Easterling et al., 2004; Adger et al., 2009) requires an appraisal of future climate change scenarios and the development of strategies and plans to modify current practices so as to enable future human co-existence with changed environmental conditions. In this paper we distinguish between *planned* and *unplanned* adaptation. Planned adaptation involves *deliberate* and proactive forward planning, taking account of likely or possible environmental changes and developing pre-emptive actions to address the likely changes. Walsh et al. (2004) discussed the incorporation of sea-level rise projections into urban planning in Australia, which would constitute planned adaptation. In contrast, unplanned adaptation is entirely reactive and management decisions evolve as circumstances change. The style of adaptation at any given location is contingent on several parameters that collectively define the adaptive capacity of the system under consideration (e.g. Levina and Tirpak, 2006).

Adaptation is bedevilled with problems, many of which relate to uncertainties in future climate scenarios. However, because many human response actions have a long lead-in time, planning has to proceed on the basis of current information about likely future climate (see for example, Lonsdale et al., 2008; Fankhauser, 1994). A fundamental principle of proactive adaptation planning is acknowledgement that information on future climate may change as scientific investigations progress (UKCP, 2009).

In this paper we consider the adaptation issues on the coastlines of heavily developed, coastal resort cities, taking the Gold Coast of Australia as an example (Fig. 1). On developed or anthropic coasts (Cooper and Alonso, 2004), human activities dominate over natural processes in shaping the coastline and thus the adaptive capacity of the system to future changes in boundary conditions is contingent

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Fig. 1. The beachfront at Surfers Paradise showing the density of high-rise development along the coast. The beach is maintained by a sand nourishment programme.

on the adaptive capacity of the socio-economic system in which it occurs. The adaptive capacity (resilience) of natural coasts, in contrast, is solely dependent on environmental parameters (sediment supply, accommodation space, surrounding topography etc) and a lack of human interference therein.

The adaptive capacity of human systems, depend on several system, sector, and location specific characteristics (Yohe and Tol, 2002), including:

1. The range of available technological options for adaptation,
2. The availability of resources and their distribution across the population,
3. The structure of critical institutions, the derivative allocation of decision-making authority, and the decision criteria that would be employed,
4. The stock of human capital including education and personal security,
5. The stock of social capital including the definition of property rights,
6. The system's access to risk spreading processes (e.g. insurance systems),
7. The ability of decision-makers to manage information, the processes by which these decision-makers determine which information is credible, and the credibility of the decision-makers, themselves, and
8. The public's perceived attribution of the source of stress and the significance of exposure to its local manifestations

In the modern 'risk society' where the social production of wealth goes hand in hand with the social production of risks (Beck, 1992), there is a need to build adaptive capacity (Gunderson and Holling, 2002). An essential ingredient of such capacity is a continued dialogue on possible futures (Dryzek, 1987). This requires that exercises in "what-if?" scenarios be conducted so that potential weaknesses in operating systems might be identified. In the spirit of contributing to this dialogue, we consider the adaptations necessary to maintain the existing values (natural and social) and system functioning (natural and social) of the Gold Coast, Australia under a range of sea-level rise conditions that are currently regarded as being at the high end of the possibility spectrum for changes over the next century.

We consider three scenarios involving sea-level rise of 1, 2 and 5 m, and discuss the nature and scale of adaptations necessary to maintain the existing system functions of a tourism city with a heavily adapted coast. The effects of extreme sea-level rise (5 m in the next century) have previously been considered for a few parts of the world (e.g. Tol et al., 2006; UKCP, 2009), but not for tourism cities. Al such analyses involve substantial simplification because of data limitations and uncertainty regarding the likely adaptation options. On the Gold Coast (as with most similar cities), adaptation options are constrained by the need to maintain certain essential elements without which the city loses its *raison d'être*. By keeping this goal in mind, future adaptation options can be restricted to only those that attempt to satisfy this precondition. Such an approach minimises the socio-cultural influences on adaptation that are believed change with time (Adger et al., 2008). Knowing the target condition for the resort city enables us to determine the sea-level rise conditions under which it becomes impossible to meet these preconditions: such a condition would thus represent a limit to adaptation. To our knowledge this is the first study in which the adaptation options have been assessed specifically for a coastal resort city.

2. Coastal resort cities

Highly developed resorts exist in many coastal locations, but particularly in the subtropical and warm temperate zones where most owe their existence to increased wealth and mobility of people who wish to use these areas for vacations. This process of tourism-driven urbanization, was defined by Mullins (1991 p. 188) as "… the process whereby urban areas, particularly large cities, are specially developed for the production, sale, and consumption of goods and services providing pleasure".

A key attractor in most of the world's examples of resort cities has been the presence of an adjacent beach for the recreational opportunities and aesthetic values that it affords. Well known examples include Benidorm and Torremolinos (Spain), Cannes (France), West Palm Beach, Florida, (USA) Atlantic City, New Jersey (USA), Myrtle Beach, South Carolina (USA), Virginia Beach, Virginia (USA), Cancun (Mexico) and the most rapidly developed of all coastal resort cities, Dubai (United Arab Emirates). These coasts have in common high population density, often with a strongly seasonal component, highly concentrated multi-storey development and high real estate values.

For the most part, the coastal sedimentary systems have been heavily altered by humans and in the majority of cases, the beach is maintained only by regular beach nourishment operations. In the recent phases of their development, each of these sites has been developed particularly with tourism in mind and they share the following characteristics of "tourism cities" as described by Lawton (2005):

a) the economic dominance of tourism;
b) an image focused on hedonistic beach resort tourism;
c) spatial distinctiveness; and
d) rapid population growth

3. Study site physical characteristics

The Gold Coast (Fig. 2) coastal environment comprises a series of sandy barrier beaches backed by extensive lagoonal and floodplain areas (Chapman, 1981). Both the barriers and back-barrier areas are heavily developed (Fig. 3). The sand barriers developed under a south to north longshore drift system which terminates in three barrier islands (South and North Stradbroke Islands and Moreton Island) in Moreton Bay. The study area considered in this paper comprises the region from the Tweed River mouth northward to

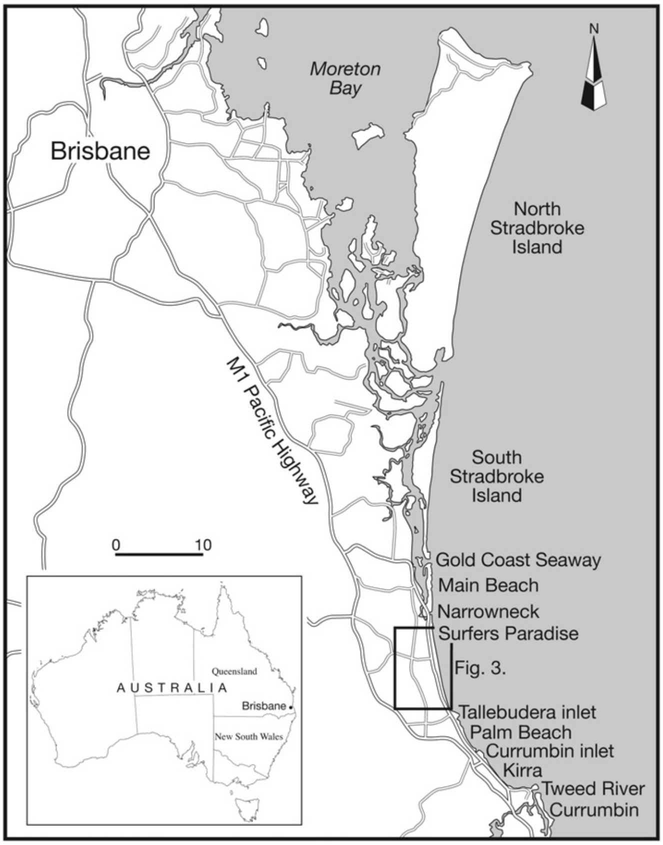

Fig. 2. Location of the Gold Coast, Australia.

Fig. 3. High density residential development around the back-barrier waterways (Image from Google Earth).

the Gold Coast Seaway (Fig. 2). The sandy beach is characterised by shore-parallel nearshore bars that migrate on and offshore and which are the focus of longshore drift (Van Enckevort et al., 2004). The sandy intertidal beach is generally steep and is backed by a vegetated dune (Castelle et al., 2007). Net longshore drift rates were estimated at 500,000 m^3/year to the north (Delft Hydraulics, 1970). The barrier beach is 54 km long from Tweed River to the Northern end of South Stradbroke Island. In this paper we are concerned with the 30 km shoreline between Tweed River and the Gold Coast Seaway.

The entire littoral system has been extensively modified since development of the area began in the 1960s, and particularly in response to the storm year of record in 1967 (McGrath, 1967; Delft Hydraulics, 1970). The incremental construction of a coastal defence structure began after that storm to provide a backstop beyond which shoreline erosion would not be permitted. It is known as the 'A-line' and consists of a rock-armoured core over which an artificial sand dune is emplaced. Infrastructure is not normally placed seaward of the A-line (although there are exceptions). The artificial dune crest of the A-line is maintained at a height estimated to withstand a 1:100 year storm (Delft Hydraulics, 1970). The A-Line seawall protection is a requirement of any new development along the shore, however, a number of properties particularly in Palm Beach do not yet have this wall in place (Gold Coast Planning Scheme Policies, 2003, 2005; GCCC land development guidelines SS16).

The littoral system is regulated by Gold Coast City Council (GCCC). The beach is maintained by artificial nourishment at a width determined to be able to withstand erosion during a 1:50 year storm (Delft Hydraulics, 1970), although recent observations (Castelle et al., 2007, 2008) suggest that current sand volumes may not be able to cope with similar storms at certain locations on the Gold Coast. The beach volume is maintained by artificial sand bypassing around jetties on the Tweed River in the south (updrift) side of the littoral cell). The amount of sand transported by the Tweed River Entrance Sand Bypassing Project to the southern Gold Coast beaches varies each year (Shannon Hunt, pers comm.). Average quantities vary between 400,000 and 700,000 m^3. Each of the tidal inlets has been stabilized by jetty construction and is artificially maintained (Fig. 4). GCCC dredges Currumbin and Tallebudgera Creek inlets each year and deposits this sand on the downdrift side of the inlet on southern Palm Beach (Castelle et al., 2007) and southern Burleigh Beach, respectively (Fig. 1). Quantities vary but average about 40,000 m^3 per year from each creek (Shannon Hunt, pers. comm.). Any sand that is excavated from development sites within 500 m of the A-Line is required to be placed on the open beaches after screening. This introduces a further 40,000 m^3 of sand to the active profile each year on average. The sand collected in any *ad hoc* dredging undertaken by State agencies is also added to the beach. This does not happen annually and the quantities are usually small ($<$40,000 m^3 per year). In addition, periodic individual beach nourishments are occasionally undertaken in response to specific erosion events. Other shoreline management structures include two rock groynes constructed on Palm Beach in an attempt to trap sand on areas prone to periodic erosion and two at Kirra. An artificial surfing reef at Narrowneck was also intended to have a coastal protection function (Jackson et al., 2007).

On top of the A-line defences is an artificial sand dune that adds an extra measure of protection against flooding. The elevation prescribed (4.9 m AHD) is based on protection against a 1:100 year event. Standards Australia (AS 4997-2005; their Table 5.4) suggest that "residential developments" of "high property value", having a working life of at least 100 years, should be designed for a 1 in 2000 (i.e. 0.05%) annual exceedance event.

Fig. 4. The tidal inlets of the Gold Coast. A. Gold Coast Seaway, B. Tallebudgera Inlet and C. Currumbin Creek. (Images from Google Earth). All inlets have been stabilized by jetty construction and are routinely dredged.

Construction of the A-line defences is the responsibility of property owners immediately landward. Since the regulations were brought in 1981 they have applied to all new building and redevelopments. The GCCC is responsible for the A-line where civic amenities or public land abuts the beach. To date, almost all of the Gold Coast has an A-line defence constructed to the specified standard. The rock core is seldom visible, being covered with an artificial sand dune, except when exposed after storms.

The barrier system is intensively developed. Original one storey houses have been progressively replaced with high-rise as coastal land availability decreased and land values increased. Residential buildings up to 80 storeys now line much of the Gold Coast beachfront area (Fig. 1). Several stretches still contain low-rise structures (Fig. 5) that on current trends will ultimately be converted to high-rise. Some areas are, however, restricted in the development of high-rise. For example, a height restriction in the Nobby and Mermaid Beach areas (Fig. 3) does not allow for construction of any building over 3 storeys.

Fig. 5. While much of the coast is characterised by high-rise development, there are both individual occurrences and stretches of low-rise structures.

The lagoon margins and islands including former tidal deltas have been subject to intensive residential development and a number of canal estates have been constructed around new channels dredged from the floodplain and filled ground in the lagoon (Figs. 3and 6). The shoreline length of the Gold Coast lagoonal area is approximately 500 km (www.ozcoasts.gov.au/). Much of the lagoonal shoreline is natural vegetation while other sections contain flood defences of variable style and quality (Fig. 7), all of which are constructed and maintained by the property owner. Much of this development and associated infrastructure experiences periodic flooding from increased river discharge and flood risk maps (Natural flood management areas) are published by Gold Coast City Council [http://www.goldcoast.qld.gov.au/gcplanningscheme_0803/maps/overlay_maps/OM_17.pdf]. The current exposure to flood risk does not impede the overall operation of activities in the Gold Coast and must therefore currently be viewed as posing an acceptable risk by the community.

The major episodic events to which the area is subject are (i) marine storms whose main impacts are beach erosion, property damage and flooding, and (ii) extreme rainfall events which cause flooding in the waterways. Current building regulations have been informed by past extreme events and the Disaster Management Plan (GCCC, 2010) contains a co-ordinated approach to floods, storms and other potential risks.

4. Gold coast as a coastal resort city

The Gold Coast originated as a seaside resort in the 1890s when the Queensland Governor built a holiday home there. Its initial growth in low-rise hotels through the early 20th century was followed in the 1960s and 1970s by the construction of the first high-rise apartment blocks. The Gold Coast airport opened in 1981 and the region quickly became Australia's best known family holiday destination. By the 1980s almost all vacant land within 10 km of the coast had been developed. More recently development has continued on reclaimed land within the lagoon and on its margins and low-rise is being replaced by high-rise development. The population of the Gold Coast increased from 110,900 in 1976 (ABS, 1986) to 497,848 in 2008 (ABS, 2008) and is projected to reach

Fig. 6. Oblique aerial view of dense low-rise development around lagoon shoreline.

Fig. 7. Various forms of shoreline on the lagoon margins. A, B, Natural shorelines comprising sand and mangroves. C. Quays and revetments, D. Rock armour, E, F. Revetments.

900,000 by 2030. It is currently the sixth largest city in Australia. Tourists make up a sizeable proportion of the population at any given time. On average the city receives almost 29,000 visitors per day, 92 per cent of whom are Australian. The remaining 8% are mainly from Japan, New Zealand, Asia and China (GCCC, 2006). Visitors to Gold Coast City spend an average of Aus$4 billion each year and the city's tourism sector employed almost 18,500 people in 2006 (GCCC, 2006). The beach is central to the city's appeal as a tourist destination (Rabould and Lazarow, 2009), while its waterways play a secondary role.

The community and corporate attitude of the Gold Coast is confident and forward-looking. Gold Coast City Council literature abounds with statements of confidence and its officials likewise portray a strongly confident image. Such an attitude has important implications for adaptation to climate change. In some ways that on the Gold Coast mirrors the Dutch attitude of human dominance over nature and that a technical solution can be found to 'water management issues' (Olsthoorn et al., 2008). A community visioning exercise (Bold New Future) undertaken by GCCC (2009) to identify community perceptions of the future noted "The Gold Coast economy, while multi-faceted, is largely underpinned by the construction and tourism industries. However, to increase the resilience of the Gold Coast economy, diversification and expansion is occurring around key industries such as marine, education, environment, creative, food, information technology, sport and health and medical." Adapting to climate change is a central challenge identified in the City Council's future visioning (GCCC, 2009, p. 10).

The "Bold New Future" document (GCCC, 2009) identified several goals for the City's beaches as follows:

- Concentration on the environmental aspects of the beaches;
- Protection, maintenance and retention of the beaches – allowing for continued access, usage and experiences of the beaches by all users;
- Limiting high density, high-rise developments along the beach/foreshore;
- The provision of access, amenities, facilities and infrastructure all contributing to the usage and experience of beaches; and
- Importance of beaches for the lifestyle and image of the city.

The following statement derived from the visioning exercise identifies maintenance of the beach as a key priority: "Defined by our spectacular beaches, hinterland ranges, forests and waterways, the Gold Coast is an outstanding city which celebrates nature and connects distinct communities with the common goal of sustainability, choice and well being for all."

5. Methods

Our approach is based upon some basic assumptions regarding the future functioning of the Gold Coast. The city exists as a high quality urban coastal environment, based upon its sand beach and back-barrier waterways. The city's future is thus reliant on (i) maintaining the beach resource, (ii) enabling access to waterways and between the waterways and the ocean, (iii) at a minimum, maintaining a similar level of protection of property against flooding in the future as currently exists. Future adaptation strategies involving retreat from the coast are not likely to be considered in this densely urbanized area.

In this paper we considered these criteria to be the minimum that would have to be achieved to enable the Gold Coast to continue to exist as a coastal resort city. They therefore set a useful target condition for any adaptation scenario. We considered the actions necessary in order to meet these conditions in the context of their financial cost and operational constraints for a series of future sea-level scenarios. These scenarios range form the high end of current Australian planning guidance (+1 m sea-level) to the worst case scenario as currently envisaged (+5 m sea-level).

The main resources involved in adapting the physical coast to meet these criteria (enhanced sea defences, additional beach sand volume and drainage modifications) were analysed taking account of projected population changes (which are predicated on maintaining the existing environmental conditions).

The analysis is based on our own accumulated experience of coastal management, informed by observations of current practice and discussions with local authority officials. The approach is necessarily qualitative and impressionistic as are all such assessments (e.g. Olsthoorn et al., 2008; Nicholls et al., 2008; Dawson et al., 2005; Lonsdale et al., 2008) but they serve to illustrate the issues that must be considered in adaptation planning by (i) focussing attention on the likely manifestations of climate change on the natural and human environment and (ii) highlighting the policy and practice implications of adapting.

6. Future climate and sea-level scenarios

6.1. Future Sea levels

There is much uncertainty around projections of future climate change and the implications for future sea level (Nicholls, 2004). The uncertainties begin with future emissions scenarios, and extend to the way in which these will affect global temperatures. The outworking of these increased temperatures on global sea level introduces further uncertainty in relation to the influence on both thermal expansion of the oceans and the contribution of meltwater (see the discussion by Rahmstorf, 2010).

Hunter (2009, 2010) undertook analyses of sea-level extremes for the Brisbane region under the influence of tropical cyclones. The Australian Department of Climate Change (DCC, 2009) provides an assessment of the risk associated with future climate and sea-level change for the Australian coast associated with a 1.1 m sea-level rise during the next century. This was regarded as a mid-point estimate based on data presented at the 2009 Climate Change conference that had recently concluded in Copenhagen (DCC, 2009), and which had identified sea-level rise estimates in the next century of 75–190 cm relative to 1990, with a mid-range estimate of 110–120 cm. DCC (2009, p. 28) noted that "there is growing consensus in the science community that sea-level rise at the upper end of the IPCC (2007) estimates is plausible by the end of this century, and that a rise of more than 1.0 m and as high as 1.5 m cannot be ruled out" (Steffen, 2009). This was consistent with a growing scientific opinion that climate change might be at the severe end of the projected spectrum (Solomon et al., 2009). Sea-level rise greater than 2 m is currently considered to be barely within the bounds of possibility (Pfeffer et al., 2008) (and the most extreme scenarios of sea-level change in the next century are based on the possible, but unlikely collapse of the west Antarctic Ice sheet which could cause global sea levels to rise by 5–6 m (Nicholls et al., 2008). The fact that recent sea-level trends have been reported to exhibit rates of increase consistent with the trajectory for the high end sea-level rise as reported in Rahmstorf et al. (2007) also influenced this choice of sea-level scenario.

In order to test adaptive capacity under a range of sea-level rise scenarios it was decided to consider three future scenarios in this paper for sea-level rise in the next 100 years at the upper end of the possibility spectrum. These are as follows:

1. Sea-level rise of 1 m (broadly similar to the 1.1 m in the risk assessment of DCC, 2009)

2. Sea-level rise of 2 m (similar to the 190 cm upper limit estimate reported at Copenhagen in 2009; Pfeffer et al., 2008)
3. Sea-level rise of 5 m (the value used in other studies of the potential impacts of the West Antarctic Ice sheet).

It has been estimated that between 4000 and 8000 residential buildings on the Gold Coast are at risk of inundation from a 1.1 m sea-level rise (DCC, 2009). DCC (2009) estimates that 2300 residential buildings are located within 50 m of sandy coast and 4750 within 110 m. Most of these residential buildings are multi-storey and multi-unit blocks. A 5 m rise in sea level (Fig. 8) would flood most of the existing developed area. At present the GCCC budget for coastal and shoreline engineering is $3 M out of a current income of $700 M (approximately 0.4%).

6.2. Additional risk factors

It is widely acknowledged that extreme water levels, rather than slow changes in average water level, pose the biggest challenges for the coastal zone and human habitation there. Several factors in addition to global sea-level rise potentially influence the occurrence of extreme water levels under changing climate conditions. Variations in the East Australia current could enhance local sea-level rise by a few (<10) cm (DCC, 2009). Indeed McInnes et al. (2009) show this occurs in 2 climate models by the end of the 21st century. This is, however, beyond the level of sensitivity adopted in this paper. Changes in wave climate could also potentially cause an additional risk if enhanced circulation modifies the future wind field (McInnes et al., 2011). Information on the likely impacts on the east Australian coast are, however, limited. Hemer et al. (2010) noted an increase in wave heights on the south coast of Australia and DCC (2009) noted “Climate change may slightly increase mean wave climates (both wave height and wave energy) in many regions, in line with slight increases projected in mean wind speed. Variability may also increase with greater variations in air pressure. The dynamic regional analysis required to estimate possible changes in wave direction has not been undertaken for Australia”.

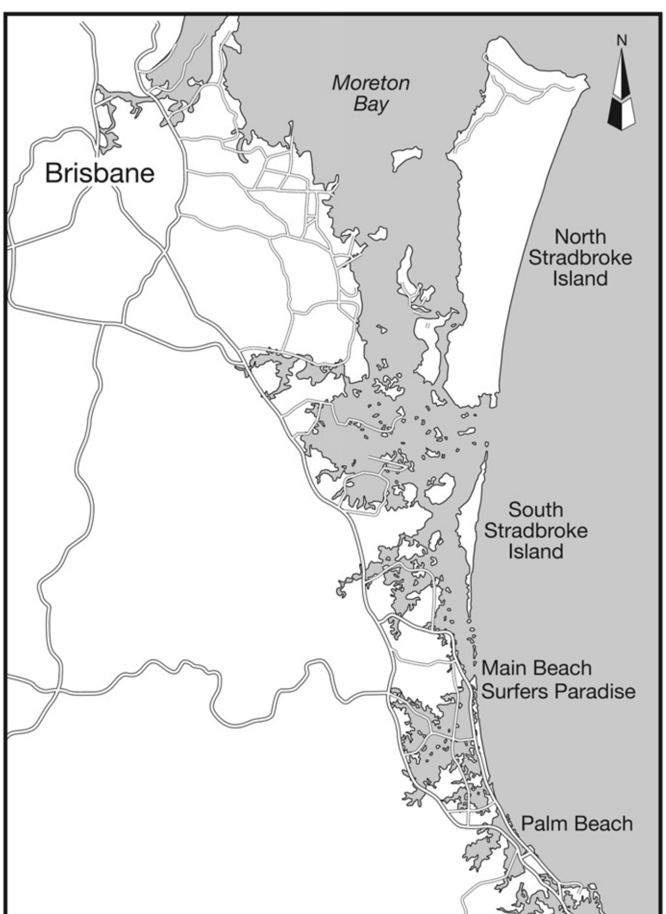

Fig. 8. Area likely to be flooded under a 5 m rise in sea level (left), taking no account of barrier migration.

Wave climate in Australia at decadal timescales is also strongly correlated with the Southern Oscillation Index (Allen and Callaghan, 1999) whose behaviour under future climate scenarios is highly uncertain. In any case the use of the word ‘slight’ to describe changes in the wind and wave fields prompts us to disregard such changes in our scenario-building exercise.

The study area is within the zone of periodic tropical cyclones and east coast lows of mid latitude origin (Harper, 1998, 1999; McInnes et al., 2002). The potential exists for enhanced frequency of low pressure weather systems including tropical cyclones on the east Australian coast under future climate conditions. McInnes et al. (2009) modelled an example of each that caused elevated sea levels over the Gold Coast and Broadwater. The few studies of projected changes in wind using climate models (e.g. McInnes et al., 2007) further suggest that “winds associated with tropical cyclones and mid-latitude lows may increase (DCC, 2009, p. 28). There is also literature that suggests more intense east coast lows occur when the EAC is warmer (Lynch, 1987; McInnes et al., 1992). There is, however, considerable variation in opinion between the several studies of contribution of future cyclone activity to extreme water levels in Queensland (Church et al., 2006). In any case, the influence on extreme water level elevations in those studies ranges from zero to a few decimetres.

It was speculated (DCC, 2009, p. 28) that changes in the East Australian Current “could possibly drive an intensification of east coast lows and extreme wave conditions, such as happened in 1950, 1967 and 1974”. Although any increase in the frequency of such events would have a serious impact on the future coast, there is currently no means of incorporating it into the scenarios being tested.

A final factor that might influence future water level extremes is freshwater discharge both from rivers and urban runoff. Warmer temperatures may make small-scale convective systems in coastal regions more active, producing micro-bursts of locally high winds and intense rainfall (DCC, 2009). McInnes et al. (2002) modelled the sea levels over the Gold Coast region for the 1974 event incorporating runoff, surge, tides and wave setup. Reported in their findings are that ‘A simulation of this event with present day bathymetry at the Seaway produced sea levels that were 0.3–0.4 m lower than the simulation with 1974 bathymetry highlighting the effectiveness of deepened Seaway channel to reduce the impact of severe runoff events in the Broadwater.’ Most of the inflowing rivers are dammed but periodic flooding does occur at present. Increased freshwater discharge does require that drainage be suitable and in the context of any projected sea-level rise, storm water drains and urban wastewater drains may need to be adjusted.

To conclude, there are several additional factors that could exacerbate future extreme water levels. However, because of the uncertainty associated with them and the already extreme values being employed, we chose not to include them in the scenarios considered here. Instead our scenarios of 1, 2 and 5 m sea-level rise make the assumption that at each of these mean sea levels, other factors that contribute to extreme water levels remain as they are at present, i.e. an extreme event at contemporary mean sea level would be regarded as happening on top of the projected rises in mean sea level.

7. Adaptation considerations

Based on the assumptions above, to maintain the current level of protection from flooding at future sea levels will mean increasing the elevation of defences (beach profile, A-Line defences and back-barrier revetments) by an amount equal to the sea-level rise. In this regard there are distinctly two styles of development on the Gold coast that must be considered. The beachfront is dominated by high-rise multiple units while around the lagoon are low-rise, often single family units. Each of these areas present different challenges for adaptation and are considered separately below. The response of the insurance industry will be highly influential in any adaptation scenario as would the role of city, state and federal authorities. Non-intervention would likely lead to a decline in property value and prompt a movement away from risk zones whereas intervention, as in the United States FEMA program (Burby, 2001), would promote continued occupation of high-risk areas (Bagstad et al., 2007).

7.1. Beach and beachfront

The beach is the *sine qua non* for the Gold Coast. Without its beach, the Gold Coast would lose its essential, defining characteristic. Under rising sea levels and without additional sediment input, beaches tend to move landward and upward (Woodroffe, 2002). On the SE Australian coast, however, there was a brief period towards the close of the Holocene transgression when an abundance of sand on the shelf caused shorelines to advance seaward even during periods of rising sea level (Thom, 1978; Roy and Thom, 1981). This sediment surplus condition now seems to have passed and the coast in the study area has been essentially stable and in dynamic equilibrium before human interference in the longshore drift system caused the onset of erosion (Chapman, 1981). This led in turn to installation of the current sand bypassing systems.

Since the beach and dune is now backed by dense high-rise development and cannot be permitted to move landwards, maintenance of the beach in the face of future sea-level rise will require the beach profile to be augmented by the addition of sand from external sources. The amount of sand to be added will have to be sufficient to cause a vertical increase in elevation equal to the amount of future sea-level rise. Since the beach profile also extends offshore, in order to maintain equilibrium with the ambient wave field, the entire beach profile would have to be augmented by the same vertical amount.

Determining the offshore extent of the beach profile is fraught with difficulties because of the temporal variability in depth to which wave action reaches – it is much greater during storms that average conditions. Fortunately the Gold Coast City Council has a record of beach profile changes in both the emerged and submerged part of the beach that extend back over 40 years. An analysis of this 40 year dataset for a section of the Gold Coast off Palm Beach (Adair, 1998) revealed that significant volume changes occurred month on month out to about 600 m offshore, beyond which bathymetric change was quite limited. This sets the approximate seaward limit of the active beach, but it is well known that significant sediment transfers often take place beyond this often-termed 'depth of closure', particularly during storms (e.g. Cooper and Pilkey, 2004).

At the landward limit of the beach, the crest of the artificial dune would have to be raised by an amount equal to the future sea-level rise if it is to provide a level of protection similar to that afforded by present conditions. This would mean an increase in its horizontal footprint to maintain its stability and, since development to landward prevents expansion in that direction, the extended footprint would have to extend onto the beach. The beach in its current managed width, is believed to provide protection to a 1:50 yr storm event (Warren Day, pers. comm., 2010). On the assumption of no future change in wave climate alongside future sea-level rise, the beach profile shape could remain the same as at present but would have to be raised by an amount equal to sea-level rise to maintain the beach.

For each of the three future sea-level scenarios the approximate additional volume of sand required to maintain the beach profile is given in Table 1. This is *in addition* to the volume transported in longshore drift annually (500,000 m^3) and which is believed to be accommodated by the existing sand bypassing schemes. There is limited development on the northernmost 20 km section of the beach on South Stradbroke Island. It is likely that efforts would not be made to maintain this stretch of beach as it is not backed by intensive development. It would inevitably migrate landward under rising sea level. Its abandonment would, however, pose problems for the sand bypassing scheme because as the spit moved landward it could become detached from the existing intake of the sand bypass works. Certainly some additional expenditure on physical infrastructure would be required if the bypassing system was to be maintained. The same would be true at the updrift end of the system at Tweed Heads where a retreat of the shoreline south of the river mouth would be expected. Adjustments to the sand bypassing infrastructure would be required to follow the anticipated coastal retreat if sand bypassing was to continue. The timetable for both is likely within the existing management plans for capital replacement and therefore not entirely an additional adaptation cost.

On the remaining 30 km of sand beach that is backed by intensive development, if the projected increases in volume were to be achieved, substantial volumes of sand (additional to those currently bypassed in the longshore drift system) would have to be added to the beach from external sources. If added at a constant rate each year, the additional volume required over the next century ranges from 180 to 900 $\times$ 10^3 m^3. At current prices, this equates to an expenditure of between $11 million and $54 million per year (depending on the amount of sea-level rise) based on the current price of $60/m^3 for sand placed and spread (Rawlinsons, 2009).

The raising of the artificial dune and the rock bund at its core would require additional material and capital expenditure, (estimates varying between $30 million to $150 million over the century). The costs of such work are currently borne by the city council where public facilities are on the foreshore. Elsewhere, it is the responsibility of private property owners and, like the present system could only be brought in through regulations applicable to new buildings and redevelopment. This would take some time to implement and in the meantime, there would be weak stretches in the sea defences, as exists at present. At present, a renewal period

Table 1
Additional sand volume required to maintain beach for various sea-level rise scenarios. Total volumes, averaged annual amounts over the next century and approximate costs (in Australian Dollars) are presented. In reality, the annual volumes to be emplaced would likely be skewed towards later years as the problems of erosion became more evident.

	Sea level rise scenario (m)		
Length of beach = 30 km	1	2	5
Total Additional Sand Volume (m^3)	18,000,000	36,000,000	90,000,000
Additional volume /year over 100 years	180,000	360,000	900,000
Annual cost (1 m^3 sand = $60)	10,800,000	21,600,000	54,000,000

of about 20–30 years applies to low-rise buildings (Warren Day, pers. comm., 2010). The city's evolving policy on high-rise development on the beachfront will ultimately influence this rebuilding interval.

Several additional factors relevant to the beach as sea-level rises derive from impacts on the water table if seaward drainage (storm water in particular, but also septic tanks) outlets and associated infrastructure have to be raised. Basements and underground facilities would be at risk of damage from groundwater. The scale of infrastructure at risk is likely to be significant and is likely to place additional pressure over and above normal replacement costs.

The landward margin of the sand barrier on which the beachfront properties rest is a low energy lagoonal shoreline that would also have to be defended under any sea-level rise scenario to protect the buildings on the beachfront. It is subject to the same considerations as those applied to the lagoon and waterways below.

7.2. Lagoon and waterways

This low-lying floodplain area landward of the beach is flanked by intensive developments of single and multi-unit developments. These are mainly residential but are interspersed with commercial and municipal developments and associated infrastructure. The area is currently subject to a flood risk principally from freshwater discharge but influenced by tidal level. Several access roads to and from the beachfront passes through these areas (Fig. 2); it can also be accessed by road from the south along the line of the beach.

The style of development in the waterfront areas comprises units with direct water access via natural channels or canals (Figs. 3and 6). The waterfront units are fronted by a variety of shorelines ranging from natural mangroves, to gently sloping, landscaped ground to revetments, bunds and rock armour. Low revetments are often close to the dwelling since land values are at a premium. The typical ground elevation in waterfront developments is about 2 m above mean high tide level and periodic flooding does occur in the lowest lying areas after extreme rainfall events. The revetments are installed by private developers but municipal regulations require that they be designed by a suitably qualified engineer. There is no specific elevation requirement for these defences. Maintenance is the responsibility of property owners although the city council maintains the drainage and navigation channels by periodic dredging. Sediment yielded by dredging is often dumped against the revetments to enhance their stability.

A rise in sea level would increase the frequency of flooding and increase its spatial extent (e.g. Fig. 8). The 500 km-long lagoonal shoreline on the Gold Coast is intensively developed. To raise the flood defences by 1, 2 or 5 m presents many engineering challenges, not least regarding their stability. In addition, the defence of property on the lagoon side would require a concerted effort by all owners if it was to be effective; these revetments would have to be raised around the entire perimeter of the lagoonal waterbody.

The bridges and roads which provide access to the beachfront, would have to be raised in the event of sea-level rise, as would all bridges that cross waterways when water levels threatened their existence. In addition, increased saline intrusion would necessitate their reconstruction with salt-tolerant concrete. Storm water drains would have to be raised to remain effective at higher sea level. The timescale of the changes envisaged (<100 years) is within the design lifetime of many types of infrastructure and these are therefore likely to replaced within the routine operation of city council management activities. In the adaptation options discussed below, therefore, we focus on the major infrastructural issues associated with maintenance and defence of coastal property, infrastructure and, in particular, the continued existence of the beach.

8. Future adaptation scenarios

For each of the potential 2100 sea-level rise scenarios the likely outcomes of both planned and unplanned adaptation are considered. In the unplanned scenarios, the adaptation is based on how the effects of sea-level rise would be manifest in the lives of Gold Coast residents and visitors (flooding, erosion, and their practical implications) and what the responses of residents and the city council might be. In the planned scenarios, we consider what steps might be taken in a proactive adaptation strategy adopted *in advance of* sea-level rise happening.

8.1. 1 m sea-level rise

8.1.1. Ad hoc adaptation

Under a 1 m sea-level rise extreme water level, recurrence plots for Brisbane suggest that the current 1:100 year high water level would be reached every year (John Hunter, pers comm., 2010). Since the current A-line is designed for a 1:100 year event, this means that the entire area would be extremely vulnerable to flooding and without systematic enhancement would be flooded semi-annually. Without concerted efforts to provide additional sand, the beach would narrow and erosion events that strip the covering dune sand from the A-line defences would be very frequent, perhaps even annual occurrences. Persistent erosion events like those that currently happen due to localised sand paucity on the beaches (Fig. 9), would probably prompt frequent sediment inputs to the beach additional to those supplied by the routine sand bypassing scheme. If undertaken sufficiently rapidly, this might enable gradual changes in the beach profile that would enable it to survive under a 1 m sea-level rise, but the under the current operational system some stretches of coast (particularly Palm Beach and Currumbin) remain in a sand-poor and vulnerable position for months after storm-induced erosion (Sano et al., 2011) (Fig. 9).

Palm Beach is recognised as a particularly erosion-prone section of the Gold Coast beachfront. After a storm in May 2009, the beach remained in a severely eroded condition for almost a year (Fig. 10), with the A-line core exposed by removal of the covering sand and

Fig. 9. Active dune erosion at main beach adjacent to a narrow section of beach prompted by local sediment scarcity (March 2010).

Fig. 10. A-line defences exposed by erosion of covering dune sand and adjacent beach during a storm in May 2009. Photo taken in March 2010.

much of the beach volume (Strauss et al., 2011; Splinter et al., 2011). The current beach protection strategy of the city council involves the following planned steps:

- emplacement of an aboulder seawall construction
- Initial nourishment from offshore and/or Tweed River Entrance
- Construction of three offshore submerged reefs
- Maintenance nourishment from Currumbin Creek (http://coastalmanagement.com.au/projects/PBBPS/scheme%20of%20works.pdf)

These short-term measures would not be sufficient to cope with future sea-level rise but the situation is probably indicative of what would occur with increasing regularity under an *ad hoc* response. This situation suggests that if a succession of storms occurred in close proximity, it is unlikely that remedial works could be carried out between storms to prevent the A-line being breached, and major marine flooding would doubtless ensue. The additional sand volume required to maintain the current beach profile volume for a 1 m sea-level rise (15 million m^3) is in the same order of magnitude of all known local sand sources (Shannon Hunt, pers comm., 2010). The chances are low that an *ad hoc*, reactive approach to augmenting the sand volume could be carried out efficiently enough to maintain the beach against a 1 m sea-level rise over a century timescale.

The sand bypassing scheme would be expected to continue to operate at the historical rate to maintain the longshore drift. Anticipated retreat of the shoreline in the updrift sand source area south of the Tweed River, would not pose immediate problems for the sand bypassing scheme source area as that stretch of coast has prograded historically since the jetties were constructed and the accumulated sand has not yet been dispersed. Once a new equilibrium shoreline position was reached, sand pumping could continue at current rates. The landward movement of the bypassing intake works might, however, have to be considered as the existing system nears the end of its design life. It is likely that increased erosion and beach narrowing would precipitate a periodic increase in sand pumping rates in excess of the volume arriving in the source area. This would inevitably mean an onset of erosion in northern New South Wales and precipitate inter-state dialogue on the issue.

The increased frequency of extreme water levels under sea-level rise would be bound to cause a reappraisal of the elevation of the A-line defences. The lead-in time for replacement of this line under the current regulations would mean that stretches of the coast would remain vulnerable to flooding for considerable periods. This could be avoided by a change in conditions for requiring property owners to raise their A-line defences.

In the lagoon, the increased frequency of flooding would likely lead to individual attempts to build or enhance flood defences around properties and would certainly precipitate council action to protect roads and other infrastructure. The scale of these adaptations would likely vary according to the individual's resources and attitudes and might lead to modifications to the building regulations for bayside development. In many instances, however, there is little space available on existing plots to enable flood defences to be built. The only options for these properties would be either to abandon them, or parts of them, or advance into the water to enable sufficient space to be created for foundations for flood defences. This would have knock-on effects for navigation and water circulation. In many new developments GCCC requests that flood storage be provided on site in basement car parks to ameliorate the effects of flooding. In either case a substantial financial burden would accrue to property owners, making the desirability of a Gold Coast waterfront property diminish somewhat. Access roads would be flooded regularly and these would have to be raised or defended at public expense. The costs of infrastructural improvements and beach maintenance would become an important recurrent item on council budgets and begin to become a major expenditure for the individual property owner. If storm water drains became inefficient, retrofitting would likely take place on a case by case basis as the problems were identified.

Although the necessary material is probably available and the financing (tax base) is probably adequate to cope with the costs of the necessary adaptations described above, we think the chances of success are only marginal for a purely reactive mode of adaptation to cope with a 1 m sea-level rise. The sequence of rapid erosional and flooding events with little time between for repairs and recovery, coupled with unplanned and erratic demands for major finances, and a growing awareness of the hazards and costs of living with them (flood defences, increased insurance premiums, clean-up costs etc) would likely end in failure of such efforts and an ultimate abandonment of the area.

8.1.2. Planned adaptation

A planned approach to a 1 m sea-level rise would necessarily envisage the periodic injection of additional sand to the beaches throughout the next century to maintain the beach profile as sea-level rose. It would identify sand sources and cost their excavation and emplacement into recurrent council budgets. A model of sustained beach volume maintenance along the lines of the Dutch dynamic shoreline preservation strategy (De Ruig, 1998) might be implemented. In such a strategy, the volume of sand on the beach is routinely monitored and when the volume falls below a certain threshold, additional sand is added. A similar procedure is followed at several beaches in southern England (Mason, 2009). The anticipated sea-level rise would be preceded by a phased increase in elevation of the A-line defences brought about by a change in building regulations, enabling the defences to be raised in advance of the risk.

On the bayside, new regulations for building elevations would be implemented for new build and redevelopments such that base levels were raised and appropriate flood protection became part of the scheme. Appropriate changes to materials would be prescribed to accommodate increased flood risk. Certain areas might be re-zoned as not suitable for development. A programme to raise, demolish or defend existing structures (roads, houses, infrastructure) that are at risk of flooding would be implemented over several decades to allow a phased adaptation so as to minimize damage and risk. A financing scheme for this planned adaptation would be developed. Any drainage works being repaired or replaced would take account of projected rises in sea level.

Properties that currently have limited space for flood defence would be identified, enabling owners of private property to make informed decisions regarding their future investment plans. It might also influence their actions in terms of making political representations. For public infrastructure, a planned system of protection works could be put in place to minimize exposure to increased flood risk. As buildings came to the end of their life, new design criteria would apply to rebuilding works. The rise in groundwater levels would be addressed by changes in building codes, provision for pumping of water, raising ground levels artificially, or some combination of these approaches. A planned adaptation would reduce the risk for insurance companies and therefore enable premiums to be maintained at affordable levels.

With a proactive, planned approach to adaptation, it seems likely that essentially the same urban footprint could be maintained under a sea-level rise of 1 m, although the increased cost would likely require a higher property tax.

8.2. 2 m sea-level rise

8.2.1. Ad hoc adaptation

A 2 m rise in sea level over the next century would cause a marked increase in erosion events and storm damage on Gold coast beaches that would probably require periodic injections of additional sand from external sources. The volumes of sand required would test the abilities of the local authority to source and transport the required amount in an appropriate period of time to prevent damage to or destruction of property. The costs involved too might stretch available budgets. Flooding in the bayside areas would become very frequent and the ability of some property owners to construct the necessary flood defences would probably be exceeded. This would lead to some properties and even neighbourhoods experiencing urban decay. There would be a large and unanticipated demand on public finances to construct flood defences to protect infrastructure, but the scale of the changes required would likely exceed the capacity of society to respond, leading to abandonment of the area as a resort city.

8.2.2. Planned adaptation

A planned approach would see the staged acquisition of additional beach sand and costed into budgets. However, the sand volumes required to maintain the beach volume would be doubled as would the required elevation rise of the A-Line. This would be difficult to maintain by simply waiting for new development to keep pace and would require some legislative stimulus to encourage private property owners to comply. This would involve periodic elevation increases in the A-line defences and dune crest heights. New building codes would likely require an increase in the base level of construction works to take account of forthcoming changes.

Landuse planning might involve an assessment that not all of the bayside shoreline are could be defended and perhaps a drawing back to more straight sections of shoreline that could be defended would occur. The long waterfrontage that flanks the complex shorelines of canal estates, would likely be considered unfeasible to protect and we envisage that either the canals would be filled in to reduce the length of shoreline needed to be defended, or the canal systems would be enclosed by lock gates, thus requiring only the external margins of the estates to be defended. Ground floor units of new developments on the beach might be planned as car parks or commercial units because their view would be obscured by sea defences. The need for infrastructural changes would likely exceed contemporary replacement rates for civic infrastructure such as roads and bridges, placing additional and unanticipated demands on financial resources. Storm water drainage would have to be replaced by a pumped scheme to remove storm water from the low-lying areas inside the dyked zone as significant areas of the enclosed zone would be below sea level.

The rapidity of the changes in such a scenario is beyond current visioning exercises and would require plans to be put in place before the impacts became a reality. This would likely encounter difficulty in gaining political buy-in at an early stage to generate development and agreement of an appropriate plan. Several additional factors make successful planned adaptation under this scenario an unlikely proposition. They include the availability of sand, the dramatic increase in flooding risk, additional costs that would inevitably impact on other services, the availability of cheaper alternative living locations and a host of unpredictable social and psychological influences that reduce the desirability of living in a hazardous coastal location (e.g. Donner and Rodríguez, 2008). In short, we doubt that even a panned adaptation strategy could cope with a 2 m rise in sea level by 2100.

8.3. 5 m sea-level rise

8.3.1. Ad hoc adaptation

A 5 m rise in sea level over the next century would be accompanied by dramatic rates of coastal erosion with insufficient time between erosion events for artificial replenishment to be effective. The amount of sand required to enable the beach profile to adjust would not be able to be sourced in sufficient time from local sources and would have major cost implications. The inability of private property owners to withstand the repeated erosional damage and pay for ongoing repairs would lead inevitably to demands on the local council to take responsibility. Insurance cover for beachfront properties would be impacted (see, for example, Sydney Morning Herald, 2009). An inability to artificially maintain the beach is inevitable under such circumstances and without the beach, one of the main elements of the Gold Coast's existence as a resort city would be gone.

In the lagoon increased frequency of flooding of property and infrastructure would likely also have insurance implications and increased demands for public intervention in defences. The costs of defence would become prohibitive, whether borne by public or private individuals and many would be technically impossible. The remaining buildings would be blighted by association as accommodation is abandoned or not maintained. This would cause the demise of the resort.

8.3.2. Planned adaptation

In addition to the actions already discussed for lesser sea-level rise, continued occupation of the region under a 5 m sea-level rise would necessitate major engineering intervention. A planned and phased introduction of additional sand to the beach would be required with sources identified and acquisition costs built into council budgets. The A-line defences would have to be progressively raised in a phased and managed replacement scheme that would have to involve existing buildings as well as new build schemes. Recognition of the scale of the problem would inevitably lead to the conclusion that every part of the lagoonal shoreline could not be protected against catastrophic flooding and so only a major engineering intervention could be envisaged. This would have to involve building levees on the inflowing rivers, and either installing lock gates on surrounding lagoonal areas, or infilling them. With the volume of sediment required to maintain the beach probably exhausting all available sediment reserves, impoundment by lock gates seems the most likely option. All drainage would have to be via pumped systems to discharge storm water and rainwater and enhanced disaster management measure would have to be put in place for the community living below sea-level surrounded by dykes. The details would no doubt be the subject of major feasibility studies, but as noted in the Thames 2100 study (Lonsdale et al., 2008) the long lead-in time for the design and financing of such structures means they need to be planned far in advance of certainty of impacts.

To seal the system, a dyke would likely have to be constructed from South Stradbroke Island to a high point on the mainland (Fig. 2) to exclude water from Moreton Bay entering the system. The cost of such massive interventions would be enormous and would likely place such a high tax burden on the local populace that appeals would be made to higher levels of governance for assistance. Given the problems that would be being faced elsewhere the chances of success might be marginal.

Abandonment might well be the preferred (indeed only viable) option under such a scenario. If phased in, this could be done in an orderly way enabling some properties to be maintained for a period of time. It would require careful infrastructural planning to enable access and services to property on higher ground. Land on other coastal sites would be cheaper to maintain and build upon and the tax levy required for maintenance would likely be so high as to make the environment economically unsustainable. There is not a shortage of coastal land in Australia and clinging to an expensive and increasingly dangerous section of coastline under such a circumstance seems to be an unlikely proposition.

9. Discussion

The evolving literature on adaptation to future sea-level rise typically considers the high-level, strategic issues that shape the policies of national governments and international organisations (see Nicholls et al., 2007; Hoozemans et al., 1993; Nicholls and Tol, 2006; Titus et al., 1991; and volumes edited by Adger et al., 2009 and Nicholls and Leatherman, 1995). A few assessments consider the practical implications of sea-level rise for major cities (e.g. Lonsdale et al., 2008; Woodroffe et al., 2006). We have highlighted some of the practical considerations that specifically characterise large coastal resort cities. In contrast to large ports and centres of commerce, the future viability of resort cities depends upon provision of certain recreational amenities (principally their beaches) and the maintenance of a particular quality of living environment that makes such areas attractive to residents and visitors.

The scenarios discussed above give a qualitative impression of the nature of adaptation measures based on the need to maintain the beach as a recreational resource and enable residents to continue living with a socially acceptable level of risk from flooding. The scale of changes necessary to maintain a habitable environment suggest that adapting to the lowest scenario considered (1 m sea-level rise over the next century) *may* be possible if carefully planned and if steps are taken in advance of actual need, but it will place an added financial burden on taxpayers as the coast is increasingly brought under human influence. In the context of an unplanned response, it appears unlikely that management structures could cope with the scale of changes envisaged for a 1 m rise in sea level; the frequency of erosion and flooding would likely stretch the ability of agencies to cope but more importantly might degrade the living environment such that it fell below the threshold deemed acceptable for residents and visitors.

Approaches to adaptation are influenced by many factors including the prevailing social view (Adger et al., 2008) but decisions regarding adaptation planning are made in the political arena. Our contention that a planned adaptation to a 1 m sea-level rise has the potential to succeed is based largely on the technical and financial resources available, but is also influenced by the fact that national climate change policy in Australia is considering a 1 m sea-level rise (DCC, 2009), thus making it likely that it will enter the national, state and municipal political arena. Predictions of higher sea-level rise are subject to much uncertainty. This is likely to keep such scenarios outside serious political debate and thereby preclude the development of adaptation plans sufficiently early to enable the requisite procedures in design, consultation and financing to be undertaken.

Adaptation to 2 m of sea-level rise or greater therefore seems unlikely to be able to provide a safe living environment even if planned, given the increased flood and erosion risk and this and higher future sea levels would likely result in eventual abandonment of the entire area.

Maintaining the beach with its adjacent high-rise development is at least technically possible if adequate sand resources can be found to nourish the entire shoreface. From a cost and practicality perspective, the numbers of units per length of shoreline may well be an important factor in guiding defence options. If the density of units on the beachfront is sufficient to generate the revenue for defence of the beachfront, the simplest option is to just defend that area. Any such decision would of course depend upon the prevailing political situation.

The weakest point in any adaptation strategy on the Gold Coast is the extensive residential areas around the lagoon and waterways. The large areal extent of one and two-storey developments in this marginal location mean that it is unlikely to be economically viable to maintain it under 2 and 5 m sea-level rise scenarios. Potential future abandonment of the waterside development poses many additional problems and urban blight is likely to occur if units are simply flooded and abandoned. This would be inconsistent with the contemporary image of the area and would likely deter other residents and potential residents.

The position of resort cities with the indulgence thereby implied is likely to be precarious in national and state-level adaptation planning. In contrast to the Netherlands, where the entire country is imperilled by sea-level rise, or commercial cities on which national or regional economies depend, resort cities are likely to receive a lower priority ranking in terms of national approaches to adaptation, particularly under extremes of future change. The global economic downturn, for example, has led to the postponement of major tourism-related developments in Dubai (Cooper and McKenna, 2009). The tourism component of several major coastal cities have also seen serious decline in the last century including the Costa do Sul in Maputo (Mozambique) Ilha do Cabo, Luanda (Angola) and the Durban beachfront (South Africa). While these cities declined for socio-economic reasons other than climate change, they show that when circumstances dictate even densely developed, high-rise beach resorts decline. The decline of Atlantic City, New Jersey was only reversed by a change in tourism product from beach-related activities to gambling (Gladstone, 1998).

Coastal resort cities might be regarded as a societal indulgence and as such, are likely to have a lower priority than coastal centres of commerce and trade when it comes to adaptation to sea-level rise. An attractive environment including a beach and waterways is central to their existence. As cities they can take advantage of shared resources in adapting and thus have a higher adaptive capacity than areas with scattered coastal development, or coastal areas with a low socio-economic status. Their main strength is in the ability to adapt proactively through the powers of their local governments. These do require proactive political thinking which is hampered by the uncertainty around the rate and scale of future climate and sea-level rise projections. However, coastal resort cities face additional constraints to ports and commercial cities. The latter, not being reliant on maintaining a particular atmosphere or attractive facilities, can adopt more blunt approaches such as simply raising hard defences, while resort cities must seek to maintain the beach and waterways in a state that is attractive to tourists. This is a major challenge to coastal resort cities worldwide.

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