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Maps, laws and planning policy: Working with biophysical and spatial uncertainty in the case of sea level rise

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ABSTRACT

Rapid sea level rise over the 21st century threatens coastal settlements and populations worldwide. Significant land-use policy reform will be needed to mitigate exposure to hazards in the coastal zone. Sea-level rise maps that indicate areas that are potentially prone to future inundation are a valuable tool for policymakers and decision makers. However, errors, assumptions, and uncertainties inherent in spatial data are not often explicitly recognised or communicated. In 2011, the state of Queensland, Australia, published a series of 'state of the art' sea-level rise maps as part of its coastal planning regime. This article uses the Queensland coastal planning regime as a case study to explore how errors, uncertainties and variability in physical, geographical and biological processes in the coastal zone pose challenges for policy makers. Analysis of the case study shows that the use of spatial data in sea-level rise policy formulation is complicated by the need to: (1) acknowledge and communicate uncertainties in existing and projected rates of rise; (2) engage in site-specific mapping based upon best available scientific information; (3) incorporate probabilities of extreme weather events; (4) resolve whether coastal engineering solutions should be included in mapping; (5) ensure that mapping includes areas required for future ecosystem migration; (6) manage discretion in planning and policy decision-making processes; (7) create flexible policies which can be updated in line with scientific developments; and (8) balance the need for consistency with the ability to apply developments in science and technology. Scientists working with spatial data and governments

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developing and implementing coastal planning policies can recognise, communicate, and seek to overcome uncertainty by addressing these factors.

1. Introduction

Maps today are central to the world of government and public policy. New Geographical Information Systems ('GIS') and digital mapping technologies allow a previously unimaginable amount of social and environmental information to be linked to a geographic location with unprecedented clarity. New computer developments also advance the ability to analyse relationships among different kinds of data. This ''legibility'' is one of the central distinctions between the premodern and modern state: ''The premodern state was, in many crucial respects, partially blind; it knew precious little about its subjects, their wealth, their landholdings and yields, their location, their very identity. It lacked anything like a detailed ''map'' of its terrain and its people. It lacked, for the most part, a measure, a metric, that would allow it to ''translate'' what it knew into a common standard necessary for a synoptic view'' (Scott, 1998, p. 2).

Modern policymakers, communities and media commentators by contrast find the simple graphic portrayal of complex information extremely powerful in understanding and making decisions. Yet, while the scope of mapping capabilities is expanding, problems remain. These problems include: operational effectiveness of satellite imagery, privacy issues, evidential use in courts and by regulatory bodies, data transfer issues, use for broader public communication, competing local knowledges, use by environment and land use advocates, and issues with scientific uncertainty (Purdy, 1999; Robbins, 2003; McCusker and Weiner, 2003). One of the most difficult aspects of all of these is *scientific uncertainty*. Whereas scientists are used to working with uncertainty and complexity, the general public, environment and land use advocates and policy makers are often more inclined to seek certainty and often deterministic solutions (Bradshaw and Borchers, 2000; Waite et al., 2009; Bebbington, 2012). The problem of uncertainty is nowhere more challenging than in the case of sea level rise (SLR).

Global sea-levels rose by approximately 20 cm over the 20th century, and the rate of rise is likely to accelerate throughout the 21st century due to global warming (Nicholls and Cazenave, 2010). Human settlements have traditionally favoured the most hazardous areas within the coastal zone, with at least 600 million people living less than 10 m above current sea-level (McGranahan et al., 2007). Consequently, calls for changes to land-use policies to incorporate SLR impacts are increasingly common (e.g. IPCC, 2007; Revell et al., 2011), and data to inform these policies are increasingly needed (e.g. Tribbia and Moser, 2008; Hunt and Watkiss, 2011).

This article discusses and analyses the challenges of using spatial data projecting SLR in land-use planning for new developments. To illustrate the planning and policy challenges associated with SLR we draw on a case study from Queensland, Australia. The paper proceeds as follows. First, we provide an overview of the biophysical and spatial uncertainties in SLR policy. This includes uncertainties in sea-level observations and forecasts, SLR modelling techniques and the potential impacts of SLR on coastal systems. We then analyse how a real-world planning case has sought to respond to these uncertainties. The State Government of Queensland, Australia, was one of the first jurisdictions to incorporate mapping methods into their coastal plan and therefore provided an ideal case study. Analysis reveals that while the Queensland Coastal Plan provided certainty for stakeholders by integrating mapping into land-use planning, the high degree of uncertainty associated with the factors outlined below continues to influence how sea-level rise is understood to impact the population and infrastructure of coastal areas, and warrants further consideration by scientists and policymakers. From this analysis we distill 8 general principles and recommendations for scientists and policymakers working with biophysical and spatial uncertainty in the case of SLR.

2. Biophysical and spatial uncertainties in SLR policy

There is general agreement that the massive global impact of SLR on coastal populations can be mitigated and/or adapted to through effective land-use planning. Maps of 'at-risk' areas can be identified from analysis of spatial data and used as a tool for stakeholders to better understand potential impacts, create better planning policies, and undertake other associated decision-making processes.

Maps of SLR can vary from simple 'bathtub' models which indicate locations of inundation based on present topography, through to more realistic inundation scenarios incorporating responses of vegetation and the shoreline to rising seas. Furthermore, SLR mapping can be integrated with more general coastal hazard models, which may indicate locations prone to storm surge or river flooding. SLR maps can also reduce uncertainty by delivering science to policy-makers in an accessible format. Evidence-based spatial data can also minimise poor decisions by providing a consistent basis for decision-making (Tribbia and Moser, 2008).

This is dependent, however, on appropriate supporting information on the methods of production and accuracy, and how effectively uncertainties have been dealt with. In the case of SLR, there are a number of uncertainties critical to policy and plan development. These include uncertainties in sea-level observations and forecasts, uncertainties in SLR modelling techniques, and uncertainties relating to the potential impacts of SLR on coastal systems. These are outlined in detail below.

2.1. Uncertainties relating to existing observations and future estimates under different scenarios

The first set of uncertainties relates to existing SLR observations and future SLR estimates under different climate scenarios. Quantifying rates of SLR is contingent on accurate measurements of past and present sea-level height, which is complicated as sea-level typically varies more over a tidal cycle than the long-term average has changed over the past century. New technologies such as satellite altimetry allow for high precision estimates of global sea-level, but in most locations the lack of a continuous record of accurate historical data compounds uncertainty (Church et al., 2011).

Projections of future sea-level height are generated using models incorporating potential future CO_2 emissions and warming scenarios. The Intergovernmental Panel on Climate Change 4th Assessment Report (AR4, IPCC, 2007) projected a global rise of 59 cm based on 'business-as-usual' emission scenarios, with the majority of this projection based on ocean thermal expansion. Only relatively small contributions from melting glaciers and the Greenland and Antarctic ice sheets were included, primarily due to a lack of scientific evidence and consensus concerning the role of ice sheet dynamics, but an often overlooked contribution of an additional 20 cm (resulting in an overall estimate of 79 cm) was considered possible due to melting. The newly released IPCC 5th Assessment Report (AR5, Church et al., 2013) reported the magnitude of SLR by 2100 is likely to be 0.52–0.98 m, with a rate during 2081–2100 of 8–16 mm yr^{-1}. These figures incorporated a larger contribution from melting ice-sheets, due to the improved understanding of ice sheet dynamics since AR4.

Projected rates of SLR are also spatially heterogeneous; there is considerable uncertainty involved in downscaling global predictions to local areas (Spada et al., 2013). Local relative sea-level is further influenced by seasonal and inter-annual climatic factors such as the El Niño Southern Oscillation and by geological factors such as subsidence of land due to tectonic activity (Ballu et al., 2011) and sediment compaction (Syvitski et al., 2009). Thus, there are a number of uncertainties to consider, relating to existing SLR observations and future SLR estimates under different climate scenarios.

2.2. Uncertainty relating to the models used to predict risk

The second set of uncertainties relates to the models that are used to predict risk. As discussed earlier, SLR maps are often prepared using the simple 'bathtub' approach, whereby areas lower in elevation than a particular sea-level scenario are assumed to be inundated. The bathtub approach has been widely used for SLR mapping, particularly with the advent of highly precise digital elevation models (DEMs). However, this approach assumes a static rise in sea level and ignores the dynamics of coastal environments and geomorphic feedbacks such as erosion/accretion cycles. In addition, even precise DEMs have inherent vertical errors which vary with terrain characteristics. For example, errors over substrates such as coastal wetlands and mangroves can be higher than over sandy beaches (Schmid et al., 2011). These models therefore create an additional layer of uncertainty relating to the prediction of risk.

2.3. Uncertainty about impacts on coastal geomorphology

The third set of uncertainties relates to impacts on coastal geomorphology. Densely populated coastal systems such as low lying deltas, estuaries or sandy barriers are dynamic environments where sediment redistribution and shoreline position are continuously adjusting to environmental conditions. Modelling long-term (>10 years) coastal evolution is complex due to feedbacks and dependencies on antecedent conditions (Cowell and Thom, 1994).

The response of coastal systems to changing boundary conditions including rising sea-levels, increased storminess or modified rates of sediment supply will greatly vary in space and time based on local conditions (Fitzgerald et al., 2008). For example, there is clear evidence that the eastern coast of Australia will be subject to fewer but larger storms and associated larger waves, which will influence the distribution and magnitude of local beach erosion (Dowdy et al., 2014). Further, changes in the rate of natural sediment supply or human-induced sediment compaction have resulted in increased coastal vulnerability. The chronic erosion of the Yangtze River delta has been linked to the reduced sediment yield as a result of the Three Gorges Dam (Yang et al., 2011). Syvitski et al. (2009) estimated that 85% of deltas, supporting around half a billion people, have experienced severe flooding during the last decade and that at least a 50% increase in flooding can be expected under current SLR forecasts (also see Hettiarachchi et al., 2014). Accurately measuring such processes and constraining decadal to centennial trends have remained elusive and require improved techniques (Kolker et al., 2011).

The evolution of coastlines can be approximated using numerical models. For example, long-term models used to predict shoreline erosion due to sea level rise are commonly based on a deterministic equilibrium profile concept known as the 'Bruun rule', which essentially predicts a landward and upward displacement of the cross-shore profile in response to SLR (Bruun, 1962). Simplistically, for every 1 m of SLR, there will be 100 m of shoreline recession. However, this simplification has been repeatedly criticised, particularly for environments other than wave-dominated sandy beaches (Cooper and Pilkey, 2004; Ranasinghe et al., 2012). Thus, there are also uncertainties about the impacts of SLR on coastal geomorphology.

2.4. Uncertainty about impacts on coastal ecosystem dynamics

The fourth set of uncertainties relates to impacts on coastal ecosystem dynamics. SLR impacts not only on property, but also on important coastal ecosystems, including saltmarshes and mangroves. These ecosystems are located near sea-level due to their particular tolerance to complete or periodic inundation by seawater, and provide important ecosystem services, including protection from coastal erosion (Barbier et al., 2011). However, these ecosystems are under threat from a range of different human-related pressures. For example, over 65% of seagrasses and wetland habitats in estuaries and coastal seas have been destroyed by human activities (Lotze et al., 2006). Increases in sea-level are predicted to cause loss of coastal wetlands globally by 5–20% by 2080 (Nicholls, 2004), although rates of loss will be region specific (Saunders et al., 2013).

In order to predict the future distribution and extent of coastal habitats we must be able to produce accurate maps of their present day distribution. Large scale mapping is typically conducted using remote sensing. The reliability of mapping techniques using remote sensing is habitat specific. For instance, mangroves can be mapped from remote sensing with higher reliability than submerged habitats such as seagrass. For submerged habitats, there is uncertainty in the mapped extent of habitats even when the most state of the art techniques are applied, due temporal variability in the opacity of water (Roelfsema et al., 2013; Leon and Woodroffe, 2013).

The response of coastal ecosystems to sea-level rise will depend in part on their capacity to accrete materials vertically. Coastal ecosystems have some ability to 'keep pace' with rising sea-levels by trapping organic and sedimentary material, thereby maintaining vertical position relative to the sea surface. This capability, however, is limited to regions of particular environmental conditions (Kirwan et al., 2010). In many cases the continued existence of coastal ecosystems will be dependent on their inland migration with rising sea-levels, which in turn will depend on the suitability of other environmental factors. For instance, the vertical accretion of coral reefs to keep pace with sea-level rise could be severely compromised under global conditions of warming temperatures and acidification (Hoegh-Guldberg et al., 2007). Local factors will also influence the accretion and migration capabilities of coastal ecosystems (Lovelock et al., 2011; Hamylton et al., 2013, 2014). Where development prevents the inland migration of coastal ecosystems, their abundance will decline. This process is referred to as 'coastal squeeze', and may require protection of undeveloped land in regions inland of inundated areas so that ecosystems can migrate without obstruction (Shoo et al., 2014). Uncertainties relating to impacts on coastal ecosystem dynamics are therefore also a feature of SLR mapping and policymaking.

2.5. *Uncertainty about the impact of extreme weather events*

The fifth set of uncertainties relates to the impact of extreme weather events. Sea-level extremes are driven by a combination of changes in global and regional sea-level trends (e.g. ENSO cycles), and local weather events such as storms and tropical cyclones (Walsh et al., 2012). Ideally, SLR maps should be comprehensive, and illustrate areas projected to be subject to both permanent and temporary sea-level and storm inundation, and erosion. The frequency of 'extreme' events may change considerably as current 100-year water levels might become decadal events, impacting on the ability of coastal communities to recover (Tebaldi et al., 2012).

Changes in the frequency of flooding events should be included in planning policies and decisions (Walsh et al., 2004). Unfortunately, the ability to determine future trends in the frequency and magnitude of storms and cyclones due to warmer climates remains limited (although there tends to be general consensus amongst climate models that tropical cyclones will decrease in frequency and storm intensity will increase in magnitude, Walsh et al., 2012). The impact of extreme weather events therefore creates an additional layer of uncertainty.

2.6. *Uncertainty about the impact of coastal defence structures*

The final set of uncertainties relates to the impact of coastal defence structures. Options for defending against actions of the sea include construction of sea walls, levees and beach nourishment (Caldwell and Segall, 2007). Defence against inundation by the sea is costly and fraught with challenges, as demonstrated in cities located in subsiding regions, such as New Orleans, Amsterdam, and Venice (Jelgersma, 1996). Defences are more appropriate for chronic threats than for acute stresses, such as cyclones or hurricanes, and are generally only cost-effective where there is high population density (Tornqvist and Meffert, 2008). There is also uncertainty around the potential impacts of using coastal protection in the future (i.e. a seawall might protect the coast in some cases, and enhance erosion in others), and there is also potential for legal liability if a defence structure fails. If a government chooses to install, or allow private installation of a defence structure, policymakers need to decide how these features are factored into broader mapping and decision-making processes. Further, policymakers implementing mapping in one region may need to consider the possibility that defence structures will be implemented in another region, impacting on erosion further down the coast. Thus uncertainty about the impact and future construction of coastal defence structures creates another layer of complexity.

In summary, there are a number of uncertainties and complexities in planning for SLR. These include uncertainties relating to sea-level observations and forecasts, SLR modelling techniques, and the potential impacts of SLR, extreme weather and human responses on coastal systems. These present specific challenges and opportunities for effectively addressing SLR in policy and planning. To analyse the planning and policy opportunities and challenges associated with these uncertainties we now draw on a case study from Queensland, Australia.

3. Case study – spatial data and coastal planning in Queensland, Australia

The State of Queensland, in Australia, is geographically large, with an area nearly three times the size of Texas, bounded by an extensive coastline (see Fig. 1). The state is particularly vulnerable to the impacts of climate change, with up to 56,900 residential buildings at risk of inundation from a 1.1 m SLR. Additionally, natural assets like open sandy beaches and sand cays on the Great Barrier Reef ecological and tourism hotspot are highly vulnerable to shoreline erosion associated with SLR. Taking SLR into account in development decision-making in Queensland is therefore critical (Australian Government Department of Climate Change, 2009).

In 2011, the Queensland State Government released detailed coastal hazard maps indicating regions of potential

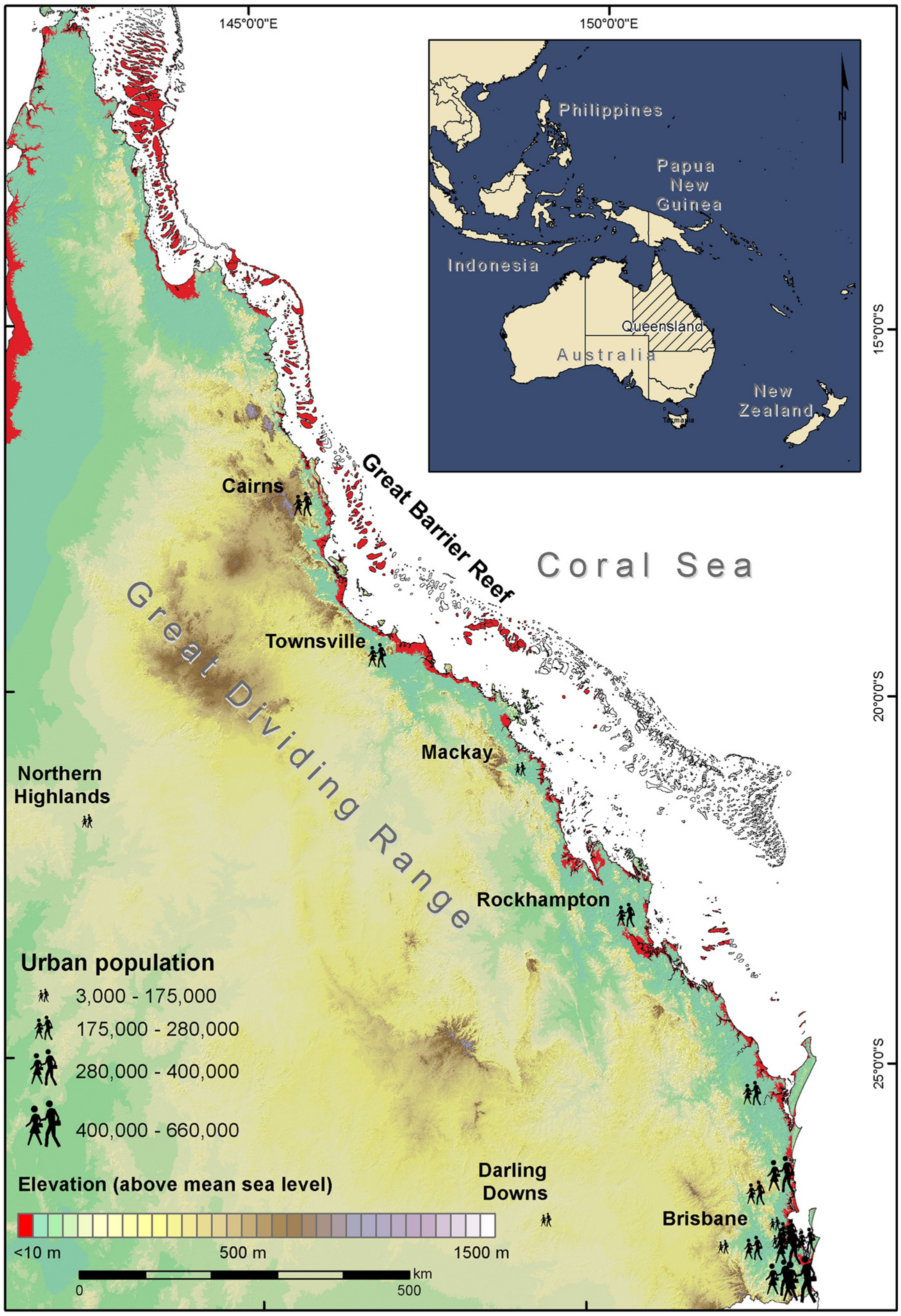

Fig. 1 – Map of Queensland, Australia.

inundation and erosion risk from storm surge and SLR by 2100. The Queensland Coastal Plan (QCP) then came into force on 3 February 2012, following five years of development and consultation (Queensland Government, 2012a)[1]. The QCP was developed under the State's general planning framework, which is underpinned by the precautionary principle (*Sustainable Planning Act* 2009). The QCP incorporated a planning policy and SLR mapping for local governments to take into account at the strategic planning and decision-making stages for development in 'coastal hazard areas'. Coastal hazard areas were defined as areas subject to permanent or temporary inundation, or erosion-prone areas. These areas were mapped using high-precision LiDAR-derived elevation data of Queensland's coastline, and were represented on a coastal hazard map (see Fig. 2a and b). The QCP required climate change to be factored into this mapping, accounting for a SLR factor of 0.8 m and 10% increase in cyclone intensity by 2100. Areas prone to erosion were assessed based on various risks like projected SLR, short-term storm-induced erosion and long-term beach-specific erosion trends. The QCP maps were then linked to a development assessment code which regulated development

[1] The QCP took effect on 3 February 2012 but is under review at the time of writing due to a change of government in Queensland.

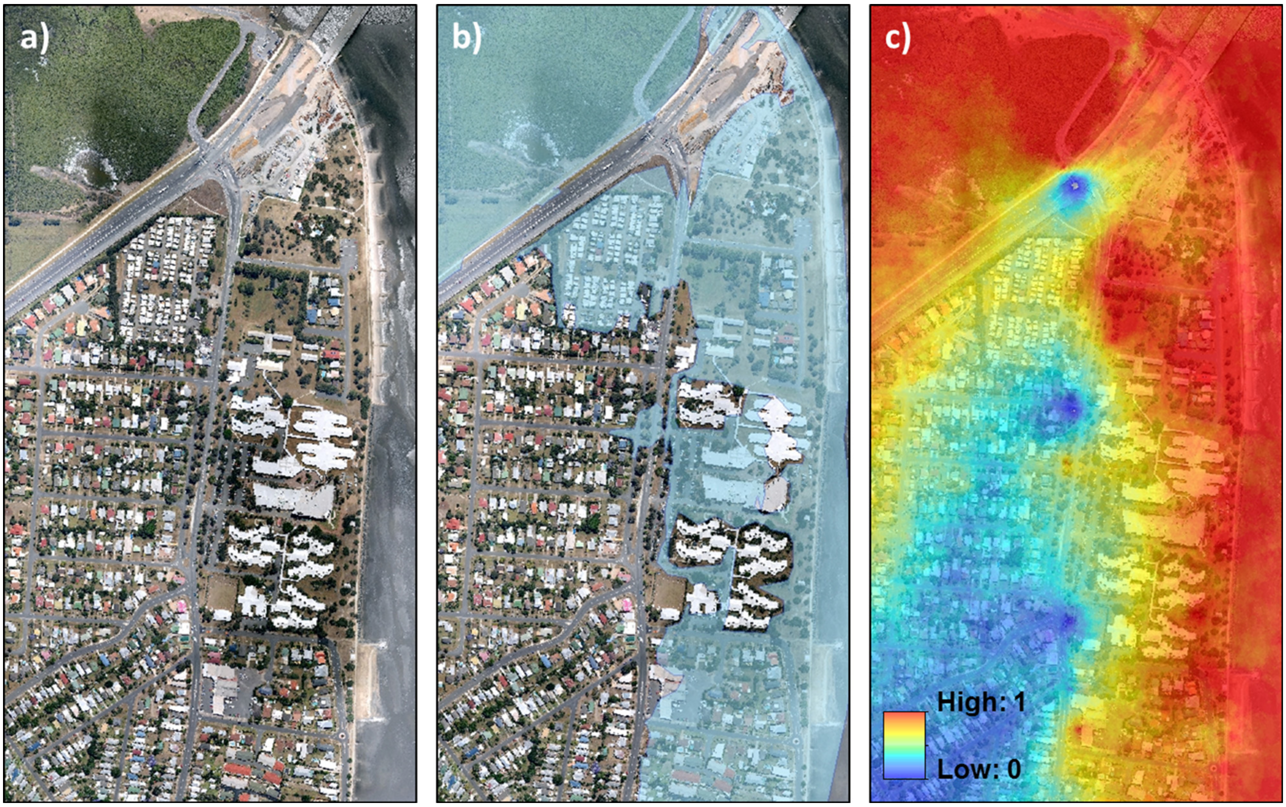

Fig. 2 – (a) Example of a coastal suburb in South East Queensland, (b) conventional inundation mapping for a storm surge scenario based on a high-resolution digital elevation model and bathtub approach, and (c) probability map for the same scenario.

in erosion prone and coastal hazard areas. As such, these maps were an integral underpinning of development decision-making in coastal areas.

As Queensland was the first Australian state to incorporate mapping methods into its coastal plan (Office of Climate Change, 2011), this provided an ideal case study to analyse how to effectively address the uncertainties inherent in spatial data in SLR policies. We analysed the QCP with an explicit focus on how the Plan dealt with the uncertainties outlined in Section 2. These included uncertainties relating to sea-level observations and forecasts, SLR modelling techniques and the potential impacts of SLR on coastal systems as identified earlier. Our team comprised experts in geography and GIS, environment and planning law, policy and management, and coastal and marine ecology. The QCP case study revealed how errors, uncertainties and variability in physical, geographical and biological processes in the coastal zone pose both challenges and opportunities for policy making. These are now discussed.

3.1. *Addressing uncertainties relating to existing observations and future estimates under different scenarios: the QCP*

As discussed in Section 2, there are a number of uncertainties relating to existing observations of sea-level, and estimates of the future rate of SLR under different emission scenarios. Our analysis of the QCP revealed a projected SLR of 0.8 m by 2100, but support for local governments to explore higher projections at a local scale. Additionally, the methodology underpinning the QCP maps was set to be reviewed within six months of the release of a new IPCC assessment report (Queensland Government, 2012a). While this is positive, mapping in both Queensland and in other jurisdictions could be carried out for a range of scenarios, allowing for potential impacts of melting ice sheets and local variations. This would have a stronger impact on future development. Given the long lifespan of new developments, this would also allow coastal planners to balance uncertainty with the need for confidence in investments.

3.2. *Addressing uncertainty relating to the models used to predict risk: the QCP*

Section 2 of this paper also discussed uncertainties relating to the elevation models used to predict risk of inundation. We found that the QCP maps were based on a high-resolution (1 m spatial resolution) coastal digital elevation model derived from state-of-the-art LiDAR technology with a nominal vertical accuracy of 0.15 m. This is sufficient to confidently model minimum inundation scenarios in the order of 0.5 m (Gesch, 2009), but uncertainty will still vary over different land covers (Zandbergen, 2011). Moreover, the use of LiDAR has many caveats for coastal applications (Xhardé et al., 2011), and even though LiDAR was acquired in Queensland at low-tidal stages to maximise above-water land coverage, the lack of near-shore bathymetric data limited the calculation of important parameters to determine erosion-prone and storm-tide inundation areas.

There are a number of ways in which SLR mapping can be improved by incorporating, acknowledging and communicating the uncertainties in elevation datasets. Governments could, for example, model error propagation by using probabilistic approaches such as geostatistical simulation (Hengl et al., 2010). Fig. 2 shows a commonly used bathtub inundation map for a 1.5 m storm surge scenario (Fig. 2b) and a probability map (Fig. 2c) for the same scenario derived from multiple equiprobable DEM realizations. This map (Fig. 2c) effectively conveys the degree of uncertainty in an intuitive, spatially-explicit way.

Where possible, governments can also undertake site-specific mapping to determine local vulnerability to SLR. We found that the QCP allows for landholders to override the SLR maps by providing more precise local or property-scale surveys, which does expose a weakness in the provision of state-wide spatial data to underpin decision-making. However, until there are further technological advances in acquiring spatial data at a large scale, such as seamless coastal elevation, other jurisdictions may also need to use similar methods in their coastal planning instruments to allow landholders to introduce more accurate, site-specific information.

3.3. *Addressing uncertainty about impacts on coastal geomorphology: the QCP*

Uncertainties relating to impacts on coastal geomorphology are also important. As discussed in Section 2, long-term models used to predict shoreline erosion due to sea level rise are commonly based on a deterministic equilibrium profile concept known as the 'Bruun rule', which essentially predicts a landward and upward displacement of the cross-shore profile in response to SLR (Bruun, 1962). In Queensland, we found that the application of the Bruun rule to assess erosion due to SLR was based on physical assumptions that did not necessarily apply to most of the coast. Even though this was acknowledged in the QCP, the uncertainties of applying this model to tide-dominated coasts were not explicitly incorporated in the mapping. We suggest that a solution to the application of the Brunn rule to the Queensland coast could be modification of the model to deal with different beach morphologies such as coral reef environments (Cowell and Kench, 2001) or completely departing from the Bruun model (Ranasinghe et al., 2012). Additionally, a probabilistic framework to determine erosion (Callaghan et al., 2009) could be more suitable to manage and communicate uncertainties.

3.4. *Addressing uncertainty about impacts on coastal ecosystem dynamics: the QCP*

As discussed earlier, planning for SLR also involves uncertainties about impacts on coastal ecosystem dynamics. In Queensland, large losses of ecological systems in coastal areas have already been reported over recent decades. We found that the QCP protected coastal ecosystems in their present locations through a requirement that development in coastal hazard areas is designed to maintain or enhance coastal ecosystems and natural features such as mangroves and coastal wetlands, qualified by an exception where changes to these features cannot be avoided (Queensland Government, 2012a). The QCP also required a default buffer zone of 100 m for some mangrove forests (Queensland Government, 2012a), but this zone has been criticised as needing more direct links to accepted coastal ecosystem migration modelling tools and predicted rates of SLR (Shoo et al., 2014).

Given the inevitability of 'coastal squeeze' (Gilman et al., 2008), there is a need to consider greater protection of existing mangroves and marshes, as well as areas demarcated for future migration. Importantly, we found that while the QCP does protect existing coastal ecosystems, it does not adequately provide for the future extent of coastal ecosystems. This is a key weakness that needs to be addressed in Queensland and in other jurisdictions. Current mapping and modelling programmes can identify areas which are suitable for ecosystems of conservation concern in the future, and buffer zones could be based on these areas. For example, to protect mangroves, where reasonable, laws could protect current forests, and provide for migration up to a certain elevation (e.g. 0.8 m above SLR). Governments could undertake studies on the economic feasibility of increasing buffer zones in this manner.

3.5. *Addressing uncertainty about the impact of extreme weather events: the QCP*

Section 2 of this paper also detailed the uncertainties in relation to the impact of extreme weather events. We found that the QCP hazard maps identified properties predicted to be at risk from gradual SLR, storm surge inundation and short-term erosion due to cyclones. The hazard maps incorporated current hazard areas, as well as hazards forecast through to 2100 due to a 0.8 m rise in sea-level and an increase in cyclone intensity by 10% (relative to maximum potential intensity). Affected areas were projected based on typical storm conditions and empirical or theoretical techniques to estimate horizontal recession. However, while these maps attempted to provide for an increase in the frequency of events, coastal hazards are highly variable in space and time and their impacts vary with underlying coastal geomorphology and location specific characteristics (e.g. leading to shifts in velocities of winds or currents).

We suggest that where such spatial data is used in planning, there needs to be an acknowledgement that local trends in the frequency and magnitude of events due to climate change cannot yet be determined accurately, and mapping may need to be updated as evidence improves. It is important that adaptation decisions are not delayed until the science is refined (Ranger and Niehorster, 2012), and coastal hazards maps can address this by explicitly incorporating the variability of coastal hazards and associated uncertainties in potential future impacts. For example, this could be achieved using reliability maps indicating areas projected to be inundated, and the level of certainty underpinning that projection (see Fig. 2c). Research has already shown that even slow rates of local SLR will exacerbate flooding in regions already vulnerable to storm surges, such as Cairns in northern Queensland (McInnes et al., 2003).

3.6. *Addressing uncertainty about the impact of coastal defence structures: the QCP*

Finally, uncertainties about the impacts of coastal defence structures also need to be resolved. We found that the QCP maps did not incorporate information on existing defence structures, as there was no comprehensive data on their existence. This meant that in Queensland, development was allowed where risks could be avoided because of existing coastal protection works, but the existence of coastal protection works were not reflected in hazard mapping. If seawalls were then damaged or failed during storms, exposure to a coastal hazard without notification was likely (Queensland Government, 2012b), along with the corresponding threat of legal liability. We recommend that where a jurisdiction chooses to allow the construction of coastal defence works, mapping, monitoring, and maintenance should be required to retain the integrity of coastal defence works and to better incorporate the coastal defence structure into broader decision-making.

3.7. *Summarising uncertainty and the QCP*

Analysis of the case study shows that the use of spatial data in sea-level rise policy formulation is complicated by the need to acknowledge and communicate uncertainties in existing and projected rates of rise. There is also a need to engage in site-specific mapping based upon best available scientific information, and incorporate probabilities of extreme weather events. Analysis also revealed that policymakers need to resolve whether coastal engineering solutions should be included in mapping, and ensure that mapping includes areas required for future ecosystem migration. Some of these warrant further discussion.

On the issue of scientific uncertainty, the QCP attempted to strike a balance by allowing some amendments to be made quickly, in response to changes in science. For example, the mapping methodology was to be updated if a new IPCC report is released (Queensland Government, 2012b). (More major amendments required public consultation processes, including, for example, amendments to maps to set aside areas for ecosystem migration).

On the issue of local uncertainty, policy-makers were in the difficult position of needing to implement a balance suited to local conditions, allowing for quick consideration of scientific developments, whilst acknowledging the need for public consultation on matters impacting on private property rights. The need for localised solutions which reflect the latest science but are underpinned by a strong policy framework is a challenging one.

On the issue of administrative and stakeholder uncertainty, the QCP maps were linked to a development assessment code which regulated development in erosion prone and coastal hazard areas. The code placed different levels of restriction on development based on the degree of hazard, and whether the area was classified as urban or non-urban. The code was less stringent in relation to development in lower-risk areas, and urban areas. This reflected a key theme of the QCP: its focus on intensifying development in areas already at risk, whilst avoiding exposing new localities to risks.

In the Queensland administrative context, the link between the QCP and development restrictions removed scope for discretion, promoted consistency, and reduced the possibility of different decisions being reached in relation to properties subject to similar degrees of risk. Although complete certainty is impossible to achieve for the reasons outlined in this paper, the QCP provided some assurance to landholders and prospective purchasers, in that they could consult a map to obtain a reasonably accurate indication of whether development would be allowed. However, some flexibility was retained as the QCP allowed for more detailed local strategies to be adopted (Queensland Government, 2012a). These strategies were required to address the impacts of climate change and SLR, but also to allow for discretion and consideration of local variations.

In summary, it is difficult to distill general principles for policy-makers globally, as any approach must be tailored to a jurisdiction's legal system. However, the QCP represents a useful model due to its blend of top-down prescription, allowance for specific, local-level initiatives, and consideration of new scientific developments. Nevertheless, there is room for SLR maps to incorporate more comprehensive impacts of inundation on coastal systems, such as responses in coastal geomorphology and the role of ecosystem dynamics, local impacts of extreme weather events, and interactions with coastal defence structures (e.g. seawalls). Although the QCP mapping provided certainty for stakeholders by integrating mapping into land-use planning, the high degree of uncertainty associated with the factors outlined above continues to influence how sea-level rise is understood to impact the population and infrastructure of coastal areas, and warrants further consideration.

4. Discussion

Incorporating the science surrounding SLR into planning laws and policies is challenging. There is often a substantial time lapse between technological and scientific advances being made, and incorporation into these planning laws and policies. The gap between climate science and related policy is also difficult to bridge (e.g. Glasser, 1995; Lemos and Morehouse, 2005), and developing appropriate adaptation policies related to climate change symptoms like SLR are exacerbated by other influencing factors such as territorial scale (e.g. Nicholls and Mimura, 1998; Adger et al., 2005) and population growth (Nicholls and Tol, 2006; Abel et al., 2011).

Uncertainty is a difficult factor to incorporate, and the need for confidence in investments must be balanced with flexibility to allow for adjustments to be made as a response to improved knowledge and insights (Klein and Nicholls, 1999). This requires a trade-off between acknowledging the uncertainty in spatial data and updating datasets according to scientific advancements to allow for better decisions, or mandating set periodic reviews to engender confidence in future policy implementation and economic investments. However, review periods will likely not match the timing of new research within the field, and errors in maps can be 'locked-in' for extended amounts of time and lead to undesired consequences on coastal ecosystems and development (e.g. Pressey et al., 2013).

The extent to which uncertainty is effectively communicated and managed is likely to influence public support for adaptation (Keys et al., 2014). Effective communication of uncertainty surrounding sea-level impacts should increase the speed at which decisions involving SLR maps can be improved by facilitating stakeholder buy-in to decisions based on up-to-date science. However to date, the dynamism of spatial data and associated uncertainty is rarely represented in maps, although we have argued there are increasingly the tools to do so (see Fig. 2c; also Davis and Keller, 1997; Wilson, 2010).

Integration of spatial data into decision-making processes can also reduce administrative and stakeholder discretion. Completely removing discretion is unrealistic, but unfettered discretion can allow for manipulation of laws, and arbitrariness leading to uncertainty, unpredictability, and insecurity (Forsyth, 1999; Morrison, 2014). On the other hand, reducing administrative discretion may also prevent decision-makers from using new developments in science to make better-informed decisions.

In a coastal planning context, it has been suggested that a top-down approach with strong leadership can result in more responsible decisions (Vasey-Ellis, 2009; Schmidt and Morrison, 2012), and linking maps to restrictions or prohibitions on development can encourage this. This prescriptive approach also means that stakeholders can clearly see the criteria on which decisions will be based. However, there needs to be a balance between the use of flexible approaches, whilst limiting discretion to do nothing or deviate from the main goals, and governments should explore prescribing consistent overall principles, with flexibility to apply them locally (Craig, 2010).

From this overall analysis it is possible to distill 8 principles for scientists and policymakers working with biophysical and spatial uncertainty in the case of SLR. We recommend that scientists and policymakers can and should: (1) acknowledge and communicate uncertainty in existing spatial data and modelling; (2) engage in site-specific mapping; (3) incorporate extreme weather events using a probabilistic approach; (4) assess whether features of the built environment will be included in mapping; (5) ensure that mapping includes areas required for future ecosystem migration; (6) reduce discretion in planning and policy decision-making processes; (7) create flexible policies which can be updated in line with scientific developments; and (8) balance the need for consistent approaches with the ability of decision-makers to apply the latest developments in science and technology. Whilst it is impossible to prescribe a universal approach to addressing coastal hazards for use in all local jurisdictions due to place-specific physical, governance and legal conditions, these principles can provide a useful starting point for relevant policymakers.

5. Conclusion

Complexity and uncertainty are hallmarks of land use policy and planning. Some SLR commentators argue that the requisite information and certainty fall short of scientific standards for decision making; others argue that science is not the issue and that political indecisiveness is the problem. While the need to overcome uncertainty and complexity is a perennial problem in public policy and administration, the digital revolution and advances in GIS have radically transformed the way governments and communities can understand and decide. Yet there has been little attention paid to what the remaining biophysical and spatial uncertainties means for governments and communities seeking to understand and respond to SLR. These include uncertainties in sea-level observations and forecasts, SLR modelling techniques, and the potential impacts SLR on coastal systems. These inherent uncertainties in spatial data and modelling *must* be balanced with the need for stakeholders to have some assurance as to the development potential of land (Lehman, 2013). Developing effective land-use planning policy for new development in areas projected to be at risk from SLR thus presents an enormous challenge.

This paper has used the Queensland Coastal Plan as a case to analyse how to effectively address the biophysical and spatial uncertainties and complexities inherent in SLR policies. Whilst it is impossible to prescribe a universal approach to addressing coastal hazards for use in all local jurisdictions due to place-specific physical, governance and legal conditions, we have developed 8 principles as a useful starting point for relevant policymakers. It is important to acknowledge here that these recommendations are more relevant to new developments, and decision-makers must also address the more challenging issue of existing developments. In the case of both retrospective and future developments, we conclude that localised solutions *must* be underpinned by a strong legal policy framework which is responsive to new scientific developments (Bell and Morrison, forthcoming). We also assert (following Bradshaw and Borchers, 2000, and Lawrence et al., 2013) that SLR policy and planning is most effective if scientific uncertainty is incorporated into a rigorous decision-theoretic framework as *knowledge*, not ignorance.

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