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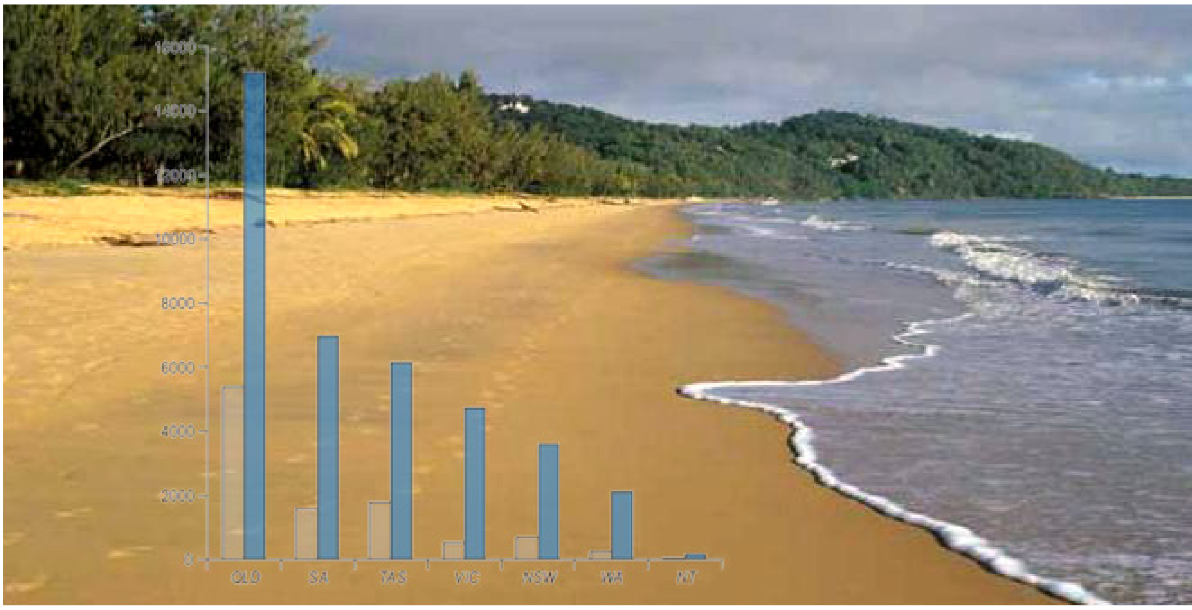

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R. Cechet, M. Hazelwood, D. Skene, C. Griffin, M. Dunford, L. Power, S. Canterford, K. Nadimpalli, P. Taylor, M. Woolf and H. Anderson

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GEOSCIENCE AUSTRALIA
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by

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Front Cover: Number of residential buildings (by State) located within 55 and 110 metres of 'soft' coastlines.

Back Cover: Potential inundation by 2100 for Sandy Point (Victoria) which is a small coastal community situated at the entrance of a narrow peninsula that fronts both Waratah Bay and Shallow Inlet with its adjacent wetlands. The simulation considers a 1.1 metre sea level rise (SLR) by 2100, a 1 in 100 year "current climate" storm surge event and zones of potential instability (ZPI's) equivalent in width to 50 and 100 times the SLR.

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Executive Summary

An assessment of the potential impacts of climate change on coastal communities has been undertaken in collaboration with the Department of Climate Change and Energy Efficiency (DCCEE). This first-pass national assessment includes an evaluation of the exposure of infrastructure (residential and commercial buildings, as well as roads and rail) to sea-level rise (SLR), storm surge and coastal recession. Some of the information contained in this report was included in the Department of Climate Change (now Department of Climate Change and Energy Efficiency) report, "Climate Change Risks to Australia's Coast", published in November 2009 (DCC, 2009).

This report examines the influence of climate change on coastal vulnerability to inundation and erosion under a future climate scenario associated with 1.1m sea-level rise for 2100. An understanding of the quantity and replacement value of infrastructure at risk has been determined given current and projected future population. To undertake this study, Geoscience Australia (GA) has engaged experts from around the nation to assist with the design and development of two nationally consistent databases describing Australia's infrastructure assets and the coastal geomorphology. Geoscience Australia's *National EXposure Information System* (*NEXIS)* provides the necessary exposure information for risk assessments by supplying nationally consistent exposure information categorised into residential, business (commercial and industrial), institutions and transport infrastructure exposure (road; highways, local roads and unsealed roads; rail, ports and airports). *Smartline* is a National Coastal Landform and Stability Map, providing vital nationally consistent information used to identify potential zones of shoreline instability.

Information from *Smartline* and NEXIS was combined to assess the number of buildings at risk from coastal erosion within dynamic coastlines, where coastal recession may occur from the projected sea-level rise. Nationally, nearly 39,000 residential buildings are located within 110 metres of potentially erodible shorelines, with nearly 40% of those buildings located in Queensland. There was no consideration in this study of any existing, planned or future protective structures associated with the buildings at risk.

Assessment of vulnerability to inundation requires an accurate understanding of coastal elevation as water associated with flooding over land will move to lower lying areas where accessible. The Digital Elevation Model (DEM), which represents the height above sea-level for each grid cell in a national map, was derived from SPOT *High Resolution Stereoscopic Reference3D* (SPOT-HRS) satellite imagery.

In addition to *Smartline,* the core data sets for the inundation and recession assessment were:

- *Sea-level rise* (SLR) estimated as a maximum of 1.1 metres for 2100, based on adjusted predictions for the IPCC AR4 A1F1 scenario.
- Observed *"current climate" Mean High Water Level*
- *"Current climate" Storm tide* estimated from models (1 in 100 year events) using observations from tide gauges, global tide data and wind models.

The assessment methodology involved the mapping of areas of coastal inundation utilising the above data inputs and the SPOT-HRS derived DEM. The number of residential and commercial buildings located within the extents of the predicted inundation and their value (utilising NEXIS), were provided as well as the lengths of road and rail infrastructure and their values. Building counts/values and road/rail lengths/values were assessed at local government area for a lower and upper end estimate of vulnerability.

When the coastal recession regions are convolved with the coastal inundation regions to produce a combined region (area), this can be used to determine the zone that is vulnerable to the combined impacts of potential inundation and erosion. Viewed nationally, this zone includes between 187,000 and 274,000 residential buildings at a combined replacement value up to $72 billion, between 5,800 and 8,600 commercial buildings up to $58-81 billion, and between 27,000 and 35,000km of roads and rail across the states and Northern Territory with a joint replacement value of over $220 billion.

The analysis also considered the impact that future population growth may have on national levels of risk from sea level rise. The Australian Bureau of Statistics (ABS 2009) predicts that Australia's population could increase to between 33.7 and 62.2 million people by 2101. It is likely that a large percentage of this increased population will live in the coastal zone. When the ABS population projections are used to assess the potential vulnerability to inundation in terms of future, rather than current structures, this indicates that between 271,000 to 399,900 residential buildings could be at risk. For the more extreme population projections, the population increase has a larger impact on the vulnerability to inundation than sea-level rise, in relative terms. The changes in the distribution of the projected population in 2101 means that Queensland would have the largest number of residential buildings vulnerable to inundation. In southeast Queensland, and in fact all along the eastern seaboard, adaptation to rising sea-level should and is becoming a priority for local councils.

This study provides an assessment of the potential future implications of inundation and recession due to climate change induced sea-level rise for Australia’s coastal zone, with a particular focus on coastal infrastructure and settlements. More information on the study including a break-up of results for each State, by LGA, with regards to the residential, commercial and road/rail vulnerability is also provided. The results of this study will inform the Australian Government’s consideration of national priorities for adaptation to reduce climate change risk in the coastal zone.

In summary, key outputs of this study include:

- an initial assessment of the implications of climate change for nationally significant aspects of Australia’s coastal regions (national overview and for key regions);
- identification of national priority regions to inform effective adaptation policy responses in the coastal zone (utilising a national standard for comparison);
- provision of key elements of a nationally coordinated approach to assessing climate vulnerability and risk in the coastal zone;
- identification and initial remediation of shortfalls in coastal adaptation research.

In collaboration with state and local governments and private industry, this assessment will provide information for application to policy decisions for, inter alia, land use, building codes, emergency management and insurance applications. As well, it provides a baseline against which future climate impact assessments can be compared.

1. Introduction

1.1 BACKGROUND

Rising sea-level is increasing the vulnerability of Australia's coasts. Australia's coastal zone contains major cities, and supports agriculture, fisheries, tourism, wetlands, estuaries, mangroves and other coastal vegetation, coral reefs, heritage areas and threatened species or habitats. Sea-level around Australia has risen some 13cm since 1820, with 7cm of that rise since 1950 (Helman *et al.*, 2010). The 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) estimated a global sea level rise between 18 and 59cm by 2100, though this could be an underestimate as it did not include consideration of the ice sheet dynamics in Greenland and Antarctica (Pfeffer *et al.*, 2008). Many recent studies have extended the upper limit of sea level projections for 2100 to more than 1.8 meters above 1990 levels, although lower values are more likely (e.g. Pfeffer *et al.*, 2008; Rahmstorf, 2010; Nicholls and Cazenave, 2010). While there remains considerable uncertainty around the exact level of sea level rise, the scientific consensus is that sea level is likely to continue rising past 2100.

Australia's major cities will all be affected by rising sea-level, tides and storms into the future. Perth, Adelaide, Melbourne, Sydney, Brisbane and Darwin all contain low-lying areas and critically important commercial precincts, infrastructure, and very large numbers of residential properties. In 2008, researchers told a federal enquiry (CoA, 2009) that Australia's coastline is especially vulnerable, and sea-level rise is already tracking above IPCC global projections. This echoed the sentiments expressed in the National Climate Change Adaptation Framework (NCCAF, 2007). Adaptation to sea-level rise includes engineering solutions (barrages and weirs), coastal modification (erosion control measures) or even re-location of communities.

Much of Australia's residential and commercial infrastructure located near the coast was originally built surrounding the port facility, being the focal point of activity within the community. Most of the road and rail dates from the early 20th century, and was built around the need for reliable harbour access both from the sea and the land. Ongoing development of the coastal zone has added to the number and value of assets in areas that potentially are vulnerable to inundation. Since World War II many coastal settlements have changed from 'weekenders' and 'family beach holiday villages' to permanent settlements. The Gold Coast for example, has grown into the sixth largest urban area in Australia. The Sunshine Coast in Queensland and Central and Mid-North Coasts in New South Wales are also developing rapidly. Coastal councils managing these growing regions have not always had the resources to plan and manage the growth that has occurred to ensure communities are resilient to the hazards that threaten them. Newcomers to these rapidly growing coastal areas may not have experienced the physical or economic impacts of major coastal storms that occur on a multi-decadal time scale, and are potentially less aware of the risks from sea-level rise and intense mid-latitude storms (such as East-Coast Lows) and tropical cyclones.

More than 80% of Australians live within the coastal zone, with an estimated 6% of Australian addresses (approximately 700,000) within 3km of the shoreline, and in areas less than 5m above mean sea-level (Chen & McAneney, 2006). A significant number of Australia's ports, harbours and airports are at risk. The coastline also contains a number of vulnerable environments of national or global significance. Rising sea-level has the potential to result in damage to assets and loss of biodiversity.

Recent research (CSIRO, 2007) has shown that:

- Concentrations of greenhouse gases are on the rise; including an unexpected increase in methane.
- Carbon sinks, which remove considerable amounts of anthropogenic carbon dioxide, are becoming less efficient.
- Sea-level is rising at or just outside the upper envelope predicted by IPCC.
- Southern Ocean acidity has increased, while salinity has decreased.
- Regardless of efforts to stabilise greenhouse gas emissions, sea-level rise will continue for centuries.
- Rainfall in southern Australia has declined over a 30-year period, caused by changes in climate systems (synoptic circulation) over the region.

These observations indicate increasing vulnerability of Australia's coastal settlements associated with a changing climate.

Coastal adaptive capacity is defined as the coastal system's ability to adapt in order to accommodate climatic changes or to increase the range of variability with which the system can cope (IPCC, 2007). The concept of adaptive capacity has assumed greater prominence partly as it enables researchers and policymakers to account for the multiple stressors in which climate adaptation measures must be implemented. In the coastal zone, defining and establishing a resilient community, as well as enhancing both resilience and adaptive capacity, are crucial for increasing disaster preparedness and prevention, disaster recovery and coastal adaptation to climate change (Klein *et al.*, 2003).

In an attempt to address and quantify these issues, a study has been undertaken by Geoscience Australia in collaboration with the Australian Government Department of Climate Change and Energy Efficiency to assess the risk to coastal communities from climate related hazards. This first-pass national assessment includes an evaluation of the potential impacts of sea-level rise (SLR), storm surge and coastal recession on infrastructure (residential, commercial and light industrial buildings, as well as roads and rail).

The results in this report detail the vulnerability to coastal inundation under a future climate scenario for the end of the 21st century. It includes results of the number and "replacement value" of infrastructure at risk. The report is structured into seven sections plus three appendices:

Section 1	Background and project objectives as well as the datasets derived and commissioned for this study.
Section 2	Overview of the methodology
Section 3	Outcomes of the coastal inundation and recession determination, with the results aggregated to local government area (LGA) and State level.
Section 4	Discussion on the limits of both the data and the methodology.
Section 5	Conclusions for the study.
Section 6	Discussion regarding "Future Work" on a national approach to assessing coastal vulnerability to inundation.

Three Appendices complete the report detailing the modelling methodology and reporting the results by State.

1.2 PROJECT RATIONALE AND OBJECTIVES

Adaptation, the third pillar of the Australian Government's response to climate change, recognises that, whatever policy decisions are made today, some degree of climate change is inevitable. Adapting to or managing the risks associated with climate change will be essential.

Australia's extensive sandy low-lying coastal zone areas are particularly vulnerable, and the capacity to adapt to changes in those zones will be of critical importance to the communities living there. This study provides an assessment of the future implications of climate change for Australia's coastal zone. The report therefore forms a significant output from the Australian Governments investment in understanding and providing information that can be utilised for adaptation.

The assessment of potential impact from coastal inundation follows an impact/risk assessment process which consists of the following key steps:

- Determine the hazard: physical effects due to sea-level rise, storm surge, and coastal erosion were considered for a future climate scenario. Footprints of the extent of the potential hazard were determined by various modelling techniques for the different hazards.
- Identify what's at risk: the residential and commercial properties, as well as the key infrastructure (roads, rail, ports, and airports) that may be exposed to the hazard were assessed. The hazard footprints determined from the modelling were integrated with the NEXIS spatial database to quantify the exposure to the hazard.
- Estimate the impact: the number and value of residential and commercial properties, and the key infrastructure potentially at risk were quantified.

The assessment considers the following hazards:

- coastal instability (erosion and recession) due to sea-level rise;
- inundation due to sea-level rise combined with the maximum high spring tides, or the 1 in 100 year storm surge (including tide) where data was available;
- the combined effects of coastal instability and inundation due to sea-level rise on top of a maximum high spring tide (or the 1 in 100 year storm surge and tide where data was available).

Most importantly, this report will inform the Australian Government's consideration of national priorities for adaptation to reduce climate change risk in the coastal zone. This assessment will provide:

- an initial assessment of the implications of climate change for nationally significant aspects of Australia's coastal regions (national overview and for key regions);
- identification of national priority regions to inform effective adaptation policy responses in the coastal zone (utilising a national standard for comparison);
- provision of key elements of a nationally coordinated approach to assessing climate vulnerability and risk in the coastal zone; and
- identification and initial remediation of shortfalls in coastal adaptation research.

Since the release of the IPCC Fourth Assessment in 2007, a considerable body of new data and observation has been assembled, and in 2009 a major climate conference was convened in Copenhagen by the International Alliance of Research Universities. The Synthesis Report of the Conference made a number of significant points, summed up as: 'faster change and more serious risks', and one over-riding message: "key climate indicators are already moving beyond the patterns of natural variability within which contemporary society and economy have developed and thrived." This has increased the urgency of the type of information provided in this report. Some of the results of this assessment (residential buildings; inundation or coastal recession only) were released as part of the Department of Climate Change (now Department of Climate Change and Energy Efficiency) report, "Climate Change Risks to Australia's Coast", published in November 2009 (DCC, 2009). Other results of this report were published in the "Climate Change Risks to Coastal Buildings and Infrastructure; a supplement to the first pass national assessment" (2011).

An understanding of coastal vulnerability and risk is derived from a number of factors, including: the frequency and intensity of the hazard(s); community exposure and the relationship with stressors; vulnerability related to socio-economic factors; impacts that result from the interaction of those components; and the capacity of communities, particularly vulnerable groups, to plan, prepare, respond and recover from these impacts. These factors and the resulting impacts from hazard events are often complex and poorly understood, but such complexity and uncertainty is not an excuse for inaction. Acknowledging its limitations, this assessment of potential impact of coastal inundation has been undertaken using the best information available, in order to contribute to a better understanding of the risk to coastal areas on a national scale, and to allow prioritisation of areas that will require more detailed and comprehensive assessment.

In collaboration with state and local governments and private industry, this assessment will provide information for application to policy decisions for, inter alia, land use planning, building codes, emergency management and insurance applications.

1.3 OUR APPROACH

Adapting to climate change and coastal variation will be a major challenge for communities and governments in the 21st century. One of the first requirements for meeting this challenge is the acquisition of accurate knowledge of the coast and its properties as well as knowledge of the infrastructure located therein (i.e. comprehensive national datasets of underpinning information).

Australia's federated system of state/territory and local governance has meant that often essential information is obtained using different measurement techniques and schema and it is also often stored using different systems. Geoscience Australia has undertaken the task of collating infrastructure data from local and state governments, scientific institutions, and the private sector. Most of this vital information was collected and stored to meet different needs, at different scales, and without reference to other parts of the country. Recognising these historical constraints, the narrow focus of much of the work in coastal science in Australia, as well as that in the documentation regarding infrastructure exposure and vulnerability, Geoscience Australia has engaged experts from around the nation to assist with the design and development of two nationally consistent databases.

1. The National EXposure Information System (NEXIS) describes Australia's infrastructure assets (residential, commercial and industrial structures, as well as institutions and infrastructure).
2. The National Coastal Landform and Stability Map, *Smartline*, describes the geomorphology of the shoreline.

In addition to these two fundamental datasets, the Australian Government, through the Department of Climate Change and Energy Efficiency, purchased a mid-resolution digital elevation model (DEM), derived from SPOT-HRS satellite imagery. This provides nationally consistent coastal elevation for the assessment of vulnerability to inundation.

1.3.1 National EXposure Information System (NEXIS)

In 2002 COAG announced a commitment to establish "a nationally consistent system of data collection, research and analysis to ensure a sound knowledge base on natural disasters and disaster mitigation" (COAG, 2002). In 2004 Geoscience Australia commenced work to develop the National Exposure Information System (NEXIS), which was significantly accelerated to support the needs of national climate change risk analysis, for example to support the Garnaut Review.

Geoscience Australia collects, collates, manages and provides exposure information, through the NEXIS database, to assess multi-hazard impacts (Nadimpalli *et al.*, 2007). Exposure information available includes population demographics, income demographics, age of the buildings, number and type (construction) of residential, commercial, and industrial buildings. Infrastructure associated with the transport sector such as (roads, railway, tunnels, bridges, airports, sea ports) is also available. NEXIS enhancement is a continuing program. Future sectors to be included in NEXIS are Energy, Communication, Water and Waste. Exposure information will also cover institutions including Education, Health, Emergency services, Government, Recreation, and Cultural buildings in future.

NEXIS draws upon publically available reference datasets to identify or statistically derive (where information is not available) the spatial location of features and associated exposure information. Figure 1.1 shows a graphical interpretation of how the fundamental datasets are accessed by NEXIS-applications to produce exposure outputs. Figure 1.2 provides an example of the NEXIS classification of buildings for the Gold Coast region between Palm Beach and Tugun.

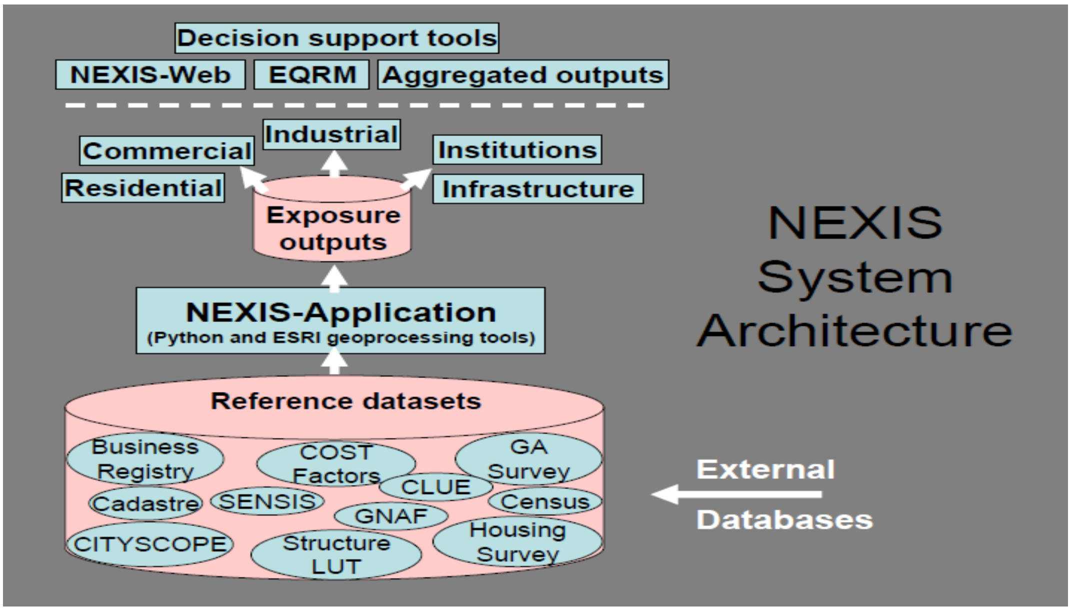


Figure 1.1: *NEXIS System Architecture depicting how fundamental datasets are accessed by NEXIS-applications to produce exposure outputs.*

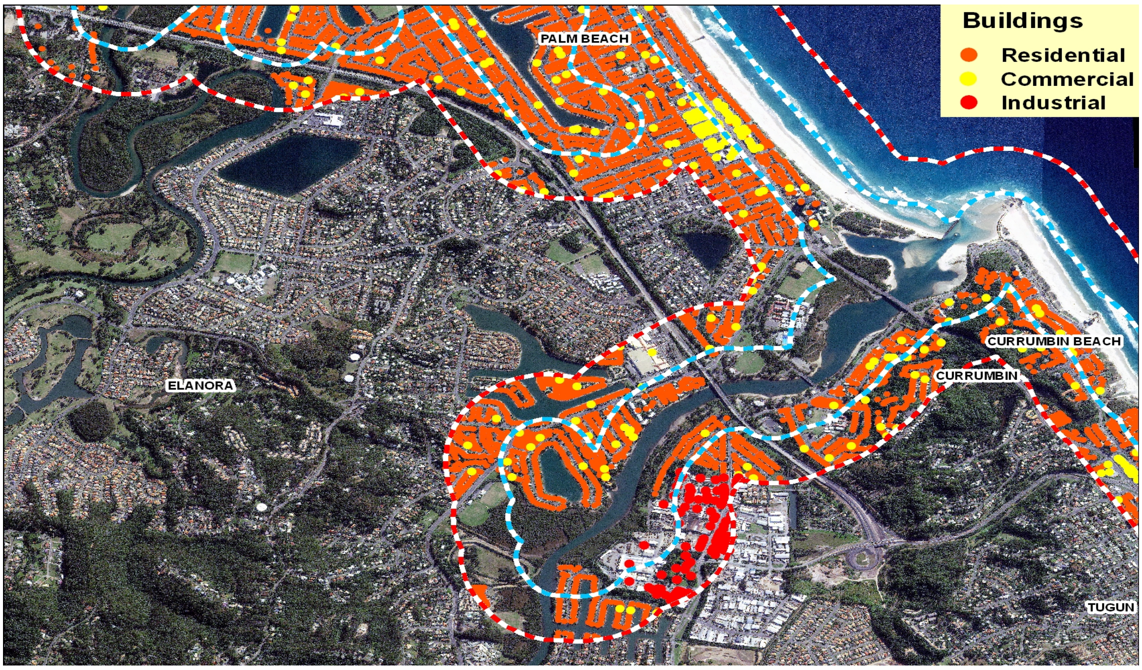


Figure 1.2: *NEXIS classification of buildings (residential, commercial and industrial) for the Gold Coast region between Palm Beach and Tugun. Buildings within a 500 metre buffer of the coastline and estuary are highlighted.*

NEXIS is an essential dataset for assessing socio-economic impacts on communities. National datasets including the Australian Bureau of Statistics (ABS) Census information provide demographic information aggregated at Census Collection District (CD) level (Census 2006). The spatial location is derived from Geocoded National Address File (GNAF) and structural details are gathered from local, state or national building specific or survey data. Building age was derived from historical census datasets. Building replacement value is calculated to replace the same size building, of the same construction type, at current construction prices (2008). Residential contents value is calculated as a percentage of the replacement value by income classification.

NEXIS residential buildings exposure was validated against the Tasmanian Valuer Generals database of 2007 (data primarily maintained for taxation purposes by local government). In residential suburban areas the number of buildings recorded in this data is more than 90% accurate. Roof and wall type information is credible when considering large sample areas; however replacement values for Hobart city were overestimated by up to ninety five percent. NEXIS exposure value was calculated using an estimated replacement value for a building of the same size using current (2008) standards.

The business component of NEXIS is divided into:

- commercial in Central Business Districts (CBD)
- commercial – non CBD
- industrial buildings.

ABS Meshblock categories classify the use of the building. The building location was derived from the Cityscope database in Central Business Districts (CBD) areas and GNAF for the non CBD areas. Cityscope provides information about the size, number of stories, refurbishment and usage. The replacement value for commercial and industrial buildings is calculated using an algorithm similar to that utilised for residential buildings, however the contents, stock inventories and plant (means of production) are not included in the business component.

NEXIS provides nationally consistent exposure information to support risk assessments of buildings, people and infrastructure. Information is managed at the building or feature level that can then be aggregated to meet individual hazard boundaries, local, regional or national impact analyses.

1.3.2 Smartline (National Coastal Landform and Stability Map)

One of the expected impacts from climate change is the potential for accelerated erosion of the coastal zone due to rising sea-level around Australia. In order to get some indication of the potential for accelerated erosion it is necessary to understand the geomorphology of the Australian coastline. In regions where the coastline is unconsolidated or 'soft' (e.g. sandy beaches), there is an increased potential for accelerated erosion. In contrast, where the coastline is 'hard' (e.g. rocky cliffs), erosion may not be a significant issue. To undertake a national assessment of the extent of the Australian coastline that may be susceptible to increased rates of erosion, a national coastal landform dataset was assembled. With funding provided by the DCCEE, and managed by Geoscience Australia, a team of specialists from the University of Tasmania (UTAS) were engaged to develop a national *Smartline* dataset.

Smartline was derived from existing geomorphic, geological and physical data, available in a variety of formats, classifications and scales. Building on formats developed for coastal mapping in Tasmania, the data has been captured in a Geographic Information System (GIS) polyline format, and reclassified using a descriptive fabric- and form-based classification system. The digital polyline map represents a proxy of the national coastline and is tagged with multiple attributes describing the types of landforms adjacent to the coastline. The polyline mapping achieves a high degree of detail in the along-shore direction; being segmented wherever any significant change in any of the mapped attributes occurs.

Smartline presents this information in the form of a single polyline map representing the coastline (typically the High Water Mark), which is then segmented wherever the coastal landform types change. The coastal characteristics recorded refer not only to those at the precise location of the line itself, but to a coastal zone nominally extending up 500m inland and offshore of the HWM itself. Each distinctive segment is tagged or assigned with multiple attribute fields (data records) describing the landform types at that segment of the coast. The line can be divided into long or short segments representing different coastal landforms, allowing the *Smartline* to record variations in coastal type to a high degree of detail. Figure 1.3 provides a graphical interpretation of four *Smartline* segments, detailing the geology, backshore and intertidal zones. Figure 1.4 shows landforms of the coastal zone region described in terms of landform types found in three shore-parallel tidally-defined zones (subtidal, intertidal and backshore). Figure 1.5 shows the four basic geomorphic attribute fields for *Smartline* for an example section of coastline. Figure 1.6 shows a map of the coastal cliffs of Australia identified by *Smartline*.

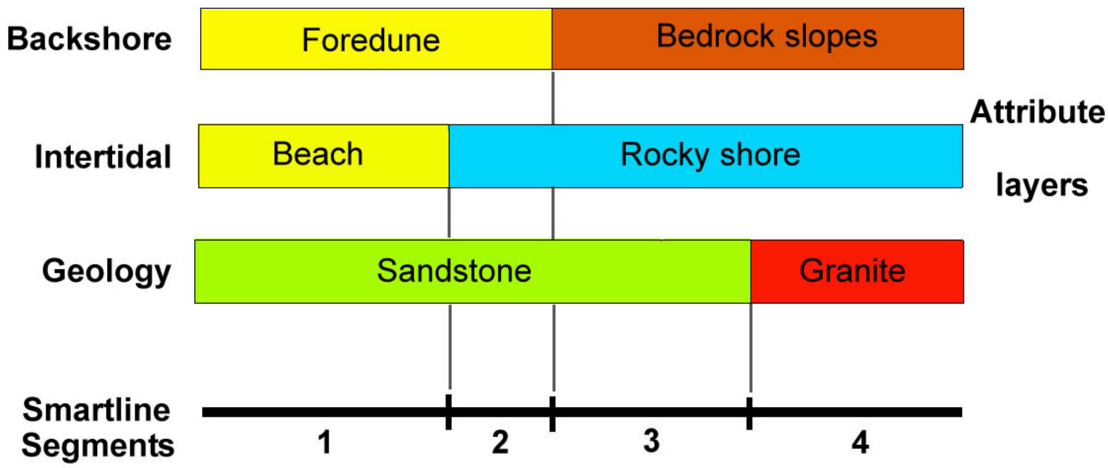


Figure 1.3: *Smartline is segmented wherever any one or more coastal attributes change, thereby allowing the full alongshore extent of all attributes to be recorded.*

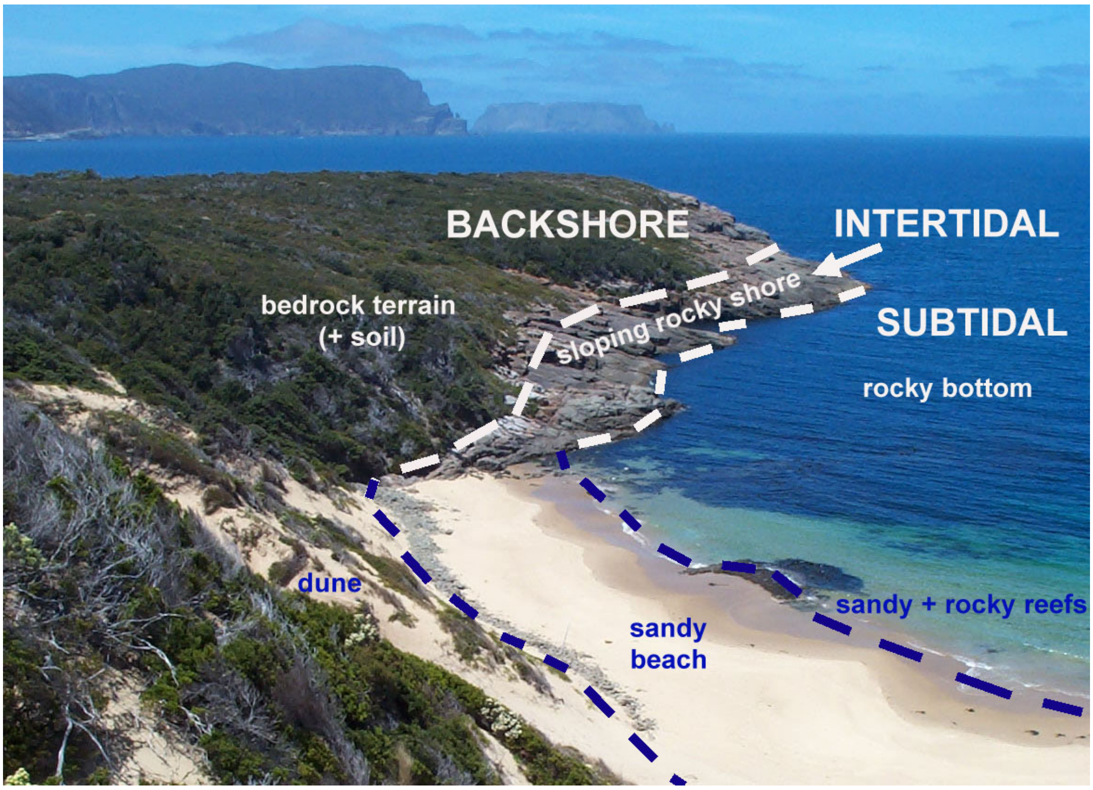


Figure 1.4: *Landforms of the coastal zone are described in terms of landform types found in three shore-parallel tidally-defined zones as indicated in this figure. Landforms within each of these zones are described using two descriptive attribute fields plus another field describing the overall zone profile or slope.*

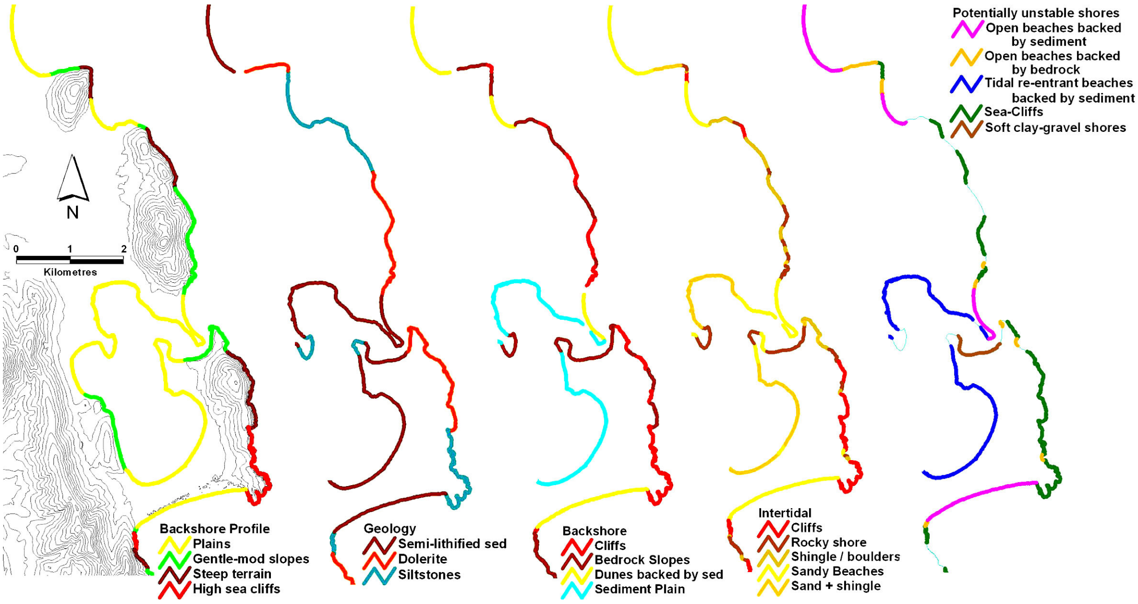


Figure 1.5: *Example showing the four basic geomorphic attribute fields of the Smartline.*

Figure 1.6: *Coastal cliffs of Australia identified by Smartline.*

Smartline is an appropriate map format for many coast-related purposes, but there are some applications for which polygon or topographic mapping is required. For example, whilst *Smartline* can indicate potentially flood-prone coastal segments (via the Backshore profile attribute – see below), a contour map or DEM is necessary to map the actual areas likely to be inundated.

Smartline captures the enormous diversity of Australian coastal landforms within a simple descriptive geomorphic classification that has been applied uniformly to the entire Australian coast. The data from which *Smartline* is constructed comprised over 200 pre-existing maps and datasets, many compiled at different times, at different scales for different purposes, and using different classification systems. Pertinent landform data has been imported into *Smartline* from all these sources, and reclassified into a single nationally-consistent classification. Thus the *Smartline* map represents the first national dataset to provide coastal landform information in a consistent format for the entire national coast, and at a level of detail sufficiently good that features down to 50 metres or less in size (such as small pocket beaches or short cliff-lines) can be individually distinguished. For more information on *Smartline* visit the OzCoasts website (www.ozcoasts.gov.au).

1.3.3 National coastal digital elevation model (DEM)

An accurate understanding of coastal elevation is required to identify areas vulnerable to inundation. The Digital Elevation Model (DEM), which represents the height above sea-level for each grid cell in a national map, was a key dataset for the nationally consistent assessment of potential coastal inundation.

Digital Elevation Models (DEMs) have become widely used in the last 20 years. They provide a 3D representation of the landscape and its features in terms of their elevation values. DEMs are essential for a range of purposes, including environmental and geophysical modelling. DEMs are also directly compatible with remotely sensed data sources and are able to represent complex terrain. Two national coastal DEMs are currently available for use around the Australian coastline: the SPOT High Resolution Stereoscopic Reference3D DEM (SPOT HRS); and the 3 second Shuttle Radar Topographic Mission (SRTM) DEM.

Elevation data and modelling options were assessed by the Australian Spatial Information Council and the Cooperative Research Centre for Spatial Information (CRCSI). The Australian Government decided to invest in a mid resolution DEM covering the entire coast, derived from SPOT High Resolution Stereoscopic (SPOT HRS) Reference3D satellite imagery. Limited regional comparisons with high resolution LiDAR (Light Detection and Ranging) elevation data (around 10 to 15cm vertical accuracy and a horizontal resolution of the order of 1 to 2m) indicated that the SPOT DEM generally provided an adequate representation of the shape of coastal elevation, even if individual height points were not accurate. The SPOT data was assessed as fit-for-purpose for a whole of continent 'first-pass' national analysis as relative patterns of inundation were able to be obtained. This study utilised the SPOT HRS DEM for the entire Australian coast apart from small areas on Cape York and a small part of the Northern Territory. Where coverage of the SPOT HRS DEM was not available, the Shuttle Radar Terrestrial Mission (SRTM) DEM was substituted.

The SPOT HRS DEM is a coastal-only DEM which was commissioned by the then Department of Climate Change. The Reference3D geo-referenced tiles each cover one square degree in area. Individual grid cells cover one arc second in the Australian latitude range (approximately 30m horizontal resolution) and have a vertical height resolution of 1 m, with an absolute elevation accuracy (mean height error) of approximately 6m. The SRTM DEM covers the whole of the Australian continent, with one arc second grid cell size (approximately 30m horizontal resolution) with a height resolution of 1m, and a mean height error of 1.8m. The horizontal and height resolution are similar to the SPOT HRS DEM.

Both of the national coastal DEM systems (SPOT HRS & SRTM) have limitations, which must be taken into account when interpreting the results. For example, readings from an area of dense vegetation may be influenced by the vegetation cover, while the height of any urban DEM will be affected by the buildings in the area. Thus, heights measured in cities will represent average building heights, rather than the height of the ground on which the buildings sit.

Since this study, the Australian Government, with funding through the Department of Climate Change and Energy Efficiency, has invested in the development of the National Elevation Data Framework (NEDF) to support improved elevation data and products. The aim of NEDF is to optimise investment in existing and future data collections and provide access to digital elevation data and derived products to a range of users. Data will be accessible through an 'all of Government' license for public good purposes through a dedicated web portal managed by Geoscience Australia[1].

[1] http://www.ga.gov.au/topographic-mapping/digital-elevation-data.html for more information

2. Methodology

The methodology was designed to determine the location of the areas most susceptible to coastal inundation and recession associated with sea-level rise. The outcomes will enable an understanding of the national levels of exposure to some of the risks associated with climate change. Through identifying regional levels of risk it will allow adaptation resources to be focused more efficiently on priority areas. It is also intended to build the national capability for recession and inundation modelling, both in method development and operationally.

The specific aim of this work is to model Australia's shoreline to identify the areas of land potentially at risk from recession and/or inundated by sea water using sea-level rise projections and where available 1 in 100 year storm tide level predictions for the "current climate". Where storm tide level predictions are not available, the maximum tidal range is considered.

This assessment has been designed as a "first-pass" approach to the problem of locating areas where recession and inundation of the coastline by the sea may occur on a national scale. It is conservative in that it errs on the side of caution and uses projections from "high emissions" scenarios and also "high-end" sea-level rise projections, providing worst case scenarios to inform risk management planning. It uses a simple model, considering only a few of the contributing factors. It does not aim to provide the precise location of the national shoreline in 2100. More comprehensive studies for high risk areas will be required at the local scale.

This section first briefly describes the key input datasets required to undertake this "first pass' assessment of coastal vulnerability. Secondly, it describes methodologies for determining spatial extent of potential future coastal inundation and recession due to inundation by SLR and storm surge events. Thirdly, it outlines the population projections used to determine the future impacts on residential coastal exposure. Lastly, it describes the methodology for determining the exposure of Australia's coastal infrastructure to the identified slow-onset natural hazard associated with climate change.

2.1 INPUT DATASETS

The choice regarding projections and thresholds was undertaken by DCCEE in consultation with the major science providers, Geoscience Australia (GA), CSIRO, and the National Tidal Centre (located at the Bureau of Meteorology). Sea-level rise estimates reflected the upper threshold of possible future sea-level, in line with the risk-management focus of the study.

The major inputs and data providers for the national coastal inundation modelling include:

- Mid resolution digital elevation models (DEM) – SPOT Image and Geoscience Australia
- Sea-level rise estimates – based on the IPCC's Fourth Assessment Report (IPCC, 2007) and more recent research
- Standard modelled mean high tide heights – National Tidal Centre, Bureau of Meteorology
- "Storm Tide" modelling in Tasmania, Victoria and NSW – (CSIRO, McInnes)
- Datum – Australian Height Datum 1971 (AHD71)

This section summarises the inputs to the modelling process and subsequent vulnerability analysis. Further detail relating to these input datasets are in Appendix 1.

2.1.1 Digital elevation model (DEM)

Two digital elevation models were available for use around the Australian coastline – the Shuttle Radar Terrestrial Mission (STRM) 3 second DEM, and the SPOT High Resolution Stereoscopic (SPOT HRS) Reference 3D DEM.

SPOT DEM

The SPOT HRS DEM consists of a mosaic of geocell tiles covering one square degree, with individual grid cell coverage of one arc second in the Australian latitude range and a height resolution of 1 metre. The geographic coordinate system is WGS84 and vertical datum is EGM96 (Appendix 1 contains important discussion of datum choice and its implications). Absolute elevation accuracy for flat and rolling (i.e. slopes of less than or equal to 20%) has 90% confidence interval of 10m with respect to the EGM96 datum, which equates 1m ± 6.08m.

The SPOT HRS DEM did not cover the entire Australian coastline within the timeframe of the project; a small area of the Cape York in Queensland was not included. Where the SPOT HRS DEM was not available the SRTM DEM was substituted.

SRTM-3 v.2

The SRTM DEM covers the whole Australian continent with 3 arc second grid size and has a height resolution of 1 metre. Standard deviation of the SRTM height error over the Australian region is quoted as 3.5 metres (Rodrigues *et al.*, 2005) with the corresponding 90% level being 6.0 metres and mean height error of ±1.8m. Coordinates are geographic, using WGS84.

2.1.2 Sea-level rise (SLR) projections

The IPCC Fourth Assessment Report (AR4; IPCC 2007) models a number of potential greenhouse gas (GHG) emission scenarios. The scenarios reflect a range of possible trends in global economic growth and resultant projections of climate change. The A1FI scenario in the IPCC AR4 report results in the highest growth in GHG emissions and the greatest increase in sea-level. Current observations of sea-level rise indicate it is tracking near the upper end of the IPCC model projections (Woodworth et al., 2009; Church and White, 2011).

Since the publication of the IPCC AR4 report, there has been more research that seeks to better quantify the upper end of sea level rise projections. The Antarctic and Climate Ecosystems (ACE) Cooperative Research Centre published a position analysis on climate change, sea-level rise and extreme events (Church et al., 2008) that summarises the more recent research since the IPCC's Fourth Assessment Report as well as sea level rise modelling and its areas of uncertainties. It concludes that it is reasonable to assume higher projections are plausible.

The scenarios defined by the Department of Climate Change and Energy Efficiency for this project were:

- A "Present day" or "Current climate" scenario, with no sea level rise in the modelling.
- A "2100 scenario" assuming a "high end" sea-level rise of 1.1m.

In addition, the methodology included a "2030 scenario", assuming a sea-level rise of 0.146m, as predicted by the IPCC AR4 (IPCC, 2007). However, the resolution of the digital elevation models available for this study was insufficient to allow modelling inundation under this scenario. The results for the 2030 scenario are therefore not included in this report.

2.1.3 "Storm Tide" modelling in Tasmania, Victoria and NSW

Storm tide surface modelling was undertaken along the temperate shores of Australia with 2D and 3D hydrodynamic models that receive inputs from observed measurements at tide gauges and global tide and wind models. The methods are explained in detail in a series of CSIRO papers, including McInnes *et al.* (2009), and summarised for this report in Appendix 1.

Hydrodynamic modelling in this study was undertaken using the depth integrated storm surge model GCOM2D (Hubbert and McInnes, 1999). Storm surge event probabilities were estimated by simulating a population of storm surge events identified from a selection of suitably long tide gauge records. The pre-selection of extreme events in the observational records was to circumvent the need to continuously simulate sea-level data over the entire length of the record but rather to simulate only the extreme events that would ultimately contribute to the estimation of storm surge return periods, thereby minimising computational requirements. This approach assumes that the scale of the meteorological disturbance is of sufficiently large spatial scale to produce a sea-level response that will be captured on the tide gauge network that has been used. As discussed in McInnes *et al.* (2009, Appendix 1) this is a reasonable assumption for the mid-latitude regions of Australia. It would not be a suitable approach for the tropical regions of Australia where the main driver of storm surges are the small scale and relatively short-lived tropical cyclones whose impact may not be recorded by the relatively sparse tide gauge network. For these regions, a method such as described in McInnes *et al.*, (2003) would be more suitable. Preliminary storm tide surface data associated with 1 in 100 year return periods was obtained for Victoria, Tasmania and NSW.

2.1.4 Standard modelled mean high tide heights – National Tidal Centre, BOM

Where storm tide surfaces were not available the standard National Tidal Centre (NTC) modelled high water surface was used. The standard tidal range modelled data was obtained from the National Tidal Centre in the form of a five minute resolution grid of points extending from longitude 111º to 116º East and from latitude 9º to 45º South. This model represents tidal amplitudes in metres between Mean Sea-level and Indian Spring Low Water multiplied by two to give an estimate of the complete tidal range. It includes the four main tidal constituents, M2, S2, O1 and K1, and was calculated as:

Tidal amplitude = (M2 + S2 + O1 + K1) amplitudes x 2

Error estimates associated with individual tidal components for 80 tide gauge locations were also obtained from the National Tidal Centre. Calculation of error associated with the model is complex and takes into account phase shifts in the individual tidal components. An average estimate of height error in the tidal range model for 80 tide gauge locations was calculated as 0.155 metres.

Table 2.1 summarises the tide data used in this study.

Table 2.1: Summary of the tide values used in this study to model the 2100 scenario hazard. The modelled inundation is driven by sea-level rise and the storm tide or tidal range, depending on the location.

	2100 Hazard
Storm tide	Current climate data for NSW, Victoria and Tasmania (CSIRO, 2009).
Tidal range (spring)	Current climate data for Queensland, Northern Territory, Western & South Australia (NTC, 2009)

2.1.5 Datum – Australian Height Datum 1971 (AHD71)

There are a number of challenging issues associated with selecting an optimum vertical datum for the inundation modelling work. While the key input of the DEM's were supplied in the vertical datum of EGM96, the rest of the data, and, indeed, the preferred vertical datum, is the Australian Height Datum 1971 (AHD71). AHD71 is preferred as, despite some drawbacks detailed below, it is designed to be 0m at the measured mean sea-level and is tied to actual sea-level observations collected at a large network of tide stations around Australia.

2.2 COASTAL INUNDATION

The purpose of modelling coastal inundation is to determine a spatially indicative representation of land potentially inundated by the sea using the projections for sea-level rise and modelled storm tide projections considering the spatial resolution and accuracy of the available datasets at the national scale. For a more detailed explanation of the Inundation Modelling Methodology, see Appendix 1.

The "bathtub" method, adapted from Eastman (1993), was utilised for the inundation assessment. It is essentially a passive model that assumes a calm sea surface, and extends the sea-level towards the shoreline until it encounters land at the same elevation as the sea surface. The method combines sea-level components, including estimates of sea-level rise, tidal range and storm surge (where available) with a digital elevation model (DEM) to calculate a spatial grid over the areas of interest showing the locations likely to be inundated given the model settings and constraints. The approach taken is considered to be useful because it is a simple, fast method that indicates locations with the potential for inundation with a level of spatial resolution that can, if used carefully and with other lines of evidence, assist with prioritising further activity.

The methodology shows the regions (areas) likely to be inundated given the model settings and constraints (Figure 2.1). The likelihood of the position of future shorelines is limited to what is known about the errors in the data inputs. The method does not account for the complexity of the full range of interacting factors and forces that actually occur on the shoreline such as erosion (soil types), wave climate, wind, freshwater flooding or event timing and clustering.

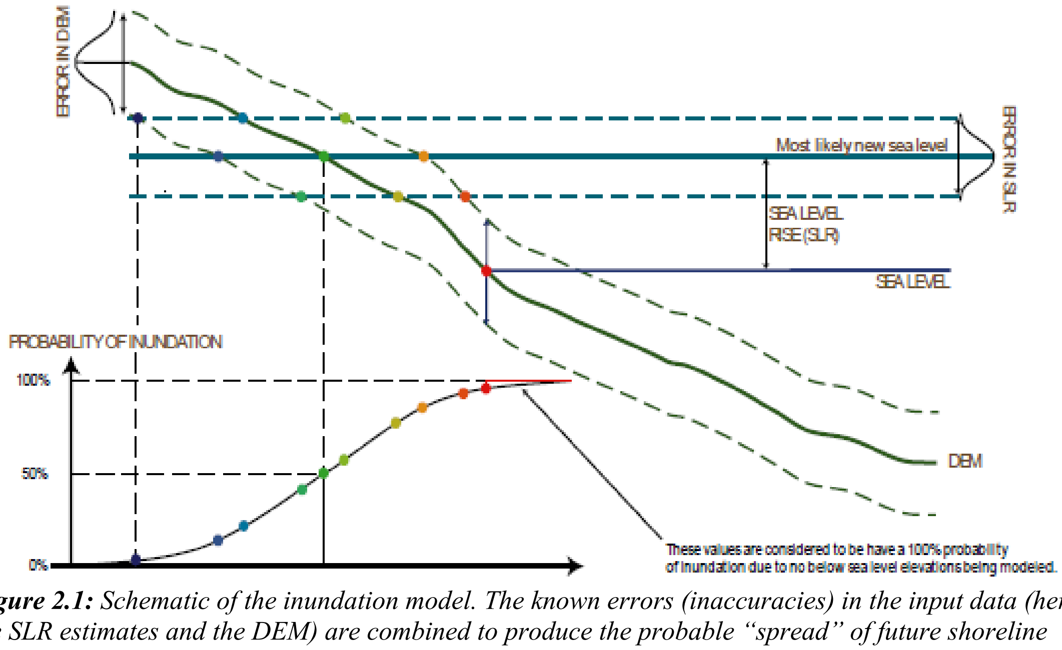


Figure 2.1: *Schematic of the inundation model. The known errors (inaccuracies) in the input data (here, the SLR estimates and the DEM) are combined to produce the probable "spread" of future shoreline positions. These probabilities are then, in effect, "mapped" back onto the DEM.*

To determine the extent of coastal inundation, the potential sea-level rise in each scenario was combined with the maximum predicted tidal height, and, where data was available, the 1 in 100 year predicted storm surge height. These three components were assessed around the coast approximately every 10km and combined to provide a potential high water level. This predicted high water level was then projected onto the SPOT DEM of the coastal topography to estimate areas that might be inundated under each scenario/projection.

The output is a grid representing the probability of a resultant shoreline position based on the input. A new shoreline position can then be drawn at a selected probability level, and be used to identify areas that are vulnerable to inundation.

2.3 COASTAL RECESSION

Smartline has been used to assess the entire national coastline to determine which sections of coast are 'soft' and therefore potentially unstable and prone to recession due to sea-level rise, and those which are hard and therefore more resistant to coastal recession. *Smartline* was used to classify the coasts into "Stability Classes", each characterised by particular landform types with potential to physically respond to sea-level rise and other coastal processes in distinctive ways (including differing styles of erosion, accretion or stability). The stability classes identify coasts that may be susceptible to various distinctive styles of instability. However, the stability classes do not attempt to predict the degree of instability or rate of change likely to affect particular shores. Coastal Landform Stability Classes have been defined on the basis of fundamental characteristics which would affect their response to coastal processes including sea-level rise:

- Fabric – What the landform is made of (ranging from hard to soft rock to unlithified sediments of varying grain sizes) – this defines the broad stability classes.
- Form - Basic distinctions ranging from flat through sloping to vertical or cliff landforms play a major role in determining how coastal landforms respond to change-driving mechanisms such as waves.
- Coastal setting - This is considered to be a major factor controlling coastal stability for soft-sediment stability themes. This refers to whether the shoreline is located on the open coast or within an inlet, and is important in defining a first-order distinction in the types of sediment transport processes to which a shoreline will be exposed.
- Geomorphic Setting - For areas of soft-sediment stability this is the basic factor determining whether or not a shore has the potential to recede significant distances in response to coastal erosion.

The analysis of *Smartline* has determined that approximately 63% of the Australian coast is classed as either sandy or muddy. The remainder is composed of 'soft' rock or "hard" rock shores. Approximately 47% of sandy and muddy shores are backed by soft sediments (as opposed to bedrock) and are therefore potentially mobile. This encompasses shores which are both uninhabited by human structures and those in more built-up areas where migration of "soft" shorelines will generate planning and management issues for local and regional communities. Sandy shores make up 30% of the "free-moving", unimpeded shores while 17% are muddy shores. The identification of potentially mobile shores is significant for the determination of the "zones of potential instability", and also for the implementation of successful coastal planning and climate change adaptation.

2.3.1 Shoreline - Determination of "Zones of Potential Instability" (ZPI)

The definition of 'Zones of Potential Instability' was adopted after the assumption that shorelines would universally retreat in the face of climate change (i.e. shoreline "recession") was strongly challenged at an expert workshop held in Sydney (December 2008). The coastal geomorphology experts at the meeting considered that some types of shores could advance under these scenarios, though they could not be consistently identified. In the light of these discussions, it was considered prudent not to attempt to model shoreline recession. Rather, it was considered preferable to create "zones of potential instability" (ZPI) under a "worst case" assumption of recession for all shoreline types.

The designation of a zone of instability was based on the area in which the shoreline may be located depending on the shoreline response to the climate forcing under the given scenarios. To estimate the potential area, a multiplication factor was applied to the projected sea-level in areas of the coast classified as unstable. The zones of potential instability are created for each shoreline stability class identified by the *Smartline* as being potentially unstable due to erosion under a scenario combining sea-level rise and climate forcing. To represent the uncertainty and variation in the potential areas that could be affected in unstable zones, a minimum and a maximum multiplication factor were applied. These were 50 times (minimum) and 100 times (maximum) the sea-level rise. These multiplication factors are drawn from the literature including that referring to the Bruun Rule (e.g. Bird 1993, p.56; Zhang *et al.* 2004). The ZPI scenario sea-level rise estimates are as listed below (Table 2.2).

Table 2.2: Input distances for each zone of potential instability ZPI per scenario for 1.1m of SLR.

	Distance	**Scenario name**
ZPI min (50 x SLR)	55 m	2100min
ZPI max (100 x SLR)	110 m	2100max

The relationship between measured 'soft-rock' recession rates over the last century from a number of stable and subsiding coasts around the world (based on Sunamura 1992) with relative sea-level rise for the same sites revealed a wide range of shoreline recession multiplication factors varying between <1 x SLR to 600 x SLR (Appendix 2). These wide variations in recession rates fully overlap with average recession factors reported from sandy coasts (Zhang *et al.* 2004) and are probably related to wide variations in local site-specific factors affecting erosion. Hence it was considered that the widely-cited "average" Bruun Rule recession factors for sandy coasts, namely 50-100 x SLR, are likely to be valid "average" recession factors for other erodible substrates, including soft rock..

Thus, for each scenario all segments classified as being sensitive to recession were receded by a single distance regardless of stability category. The reason for this is that the rates of recession due to sea-level rise are similar for all the stability classes, that is, whether a shoreline is sand or soft rock it is assumed to recede a similar distance over the time frames in this study. Segments classified as being recession insensitive were not processed.

NOTE: There are significant limitations in the use of the SLR multiplication factor to produce a recession of the shoreline because numerous local coastal process factors can override the general application of the Bruun Rule.

The actual movement of the shoreline is dependent on a great many variables including, but not limited to the:

- local sediment budget
- local sea-level rise
- actual exposure to the erosive power of the waves, whether swell or fetch generated
- vegetation integrity on or near the shoreline and
- actual physical geological and geomorphologic structures underlying and immediately behind the shoreline.

Therefore, the actual boundaries of the ZPI may not necessarily align with a future erosion event.

The results are produced by "buffering" the sensitive parts of the coast by the defined distances. ZPI's are produced for the entire *Smartline* where the stability class has been calculated, identifying locations that may be at risk of becoming unstable due to erosion in the face of sea-level rise through time. These results are then imported into geographic information systems (GIS) to assist with identifying infrastructure that could be facing impacts from climate change related erosion hazards.

2.4 IDENTIFYING COMBINED INUNDATION AND INSTABILITY RISK AREAS

The combination of the zones of potential instability (ZPI) with the modelled areas of inundation was done in a way that supported a rapid national level identification of the areas of the coast most likely to be impacted by the climate change hazards of erosion and inundation for the defined scenarios (Figure 2.2). The areas identified were named Rapid Assessment Impact Zones (RAIZ). A detailed methodology for the creation of the RAIZ footprints can be found in Appendix 2.

It is important to note that all of the contributing models and data sets and the method of combination to produce these RAIZ footprints are highly simplified versions of reality and include many untested assumptions. The assumptions are likely to cause both over- and under estimates in the results. For example, wind and wave effects were not considered in the modelling of storm tide inundation, meaning the area is likely to be underestimated. At the same time, the impact of tidal attenuation was also not included when identifying inundation adjacent to estuaries and rivers, which would overestimate the inundated area. Despite these inaccuracies, the method has the benefit of providing a relatively fast, cost-effective national-scale approach for identifying regional locations where further investigation is needed.

NOTE: *Limitations on the Rapid Assessment Impact Zones (RAIZ)*

RAIZ are the product of many different data sets of mixed resolution around Australia. Where possible and practical, data sets have been used that are consistent across the study area, such as the SPOT DEM; however, inconsistencies are inevitable. The RAIZ should be considered as indicating vicinities within or nearby which there is a potential for impacts caused by the climate change hazards of inundation and/or erosion. The boundaries of a RAIZ are the most uncertain part and they should not be used for detailed planning purposes.

RAIZ are only valid in locations where valid ZPI and inundation input layers have been calculated. Offshore islands outside the extent of the input SPOT DEM were not sampled in the inundation modelling (and also not included in the ZPI output). This includes, for example, Christmas Island, Macquarie Island, Torres Strait islands and Ashmore reef. Many smaller islands were included in the inundation modelling but not in the ZPI modelling.

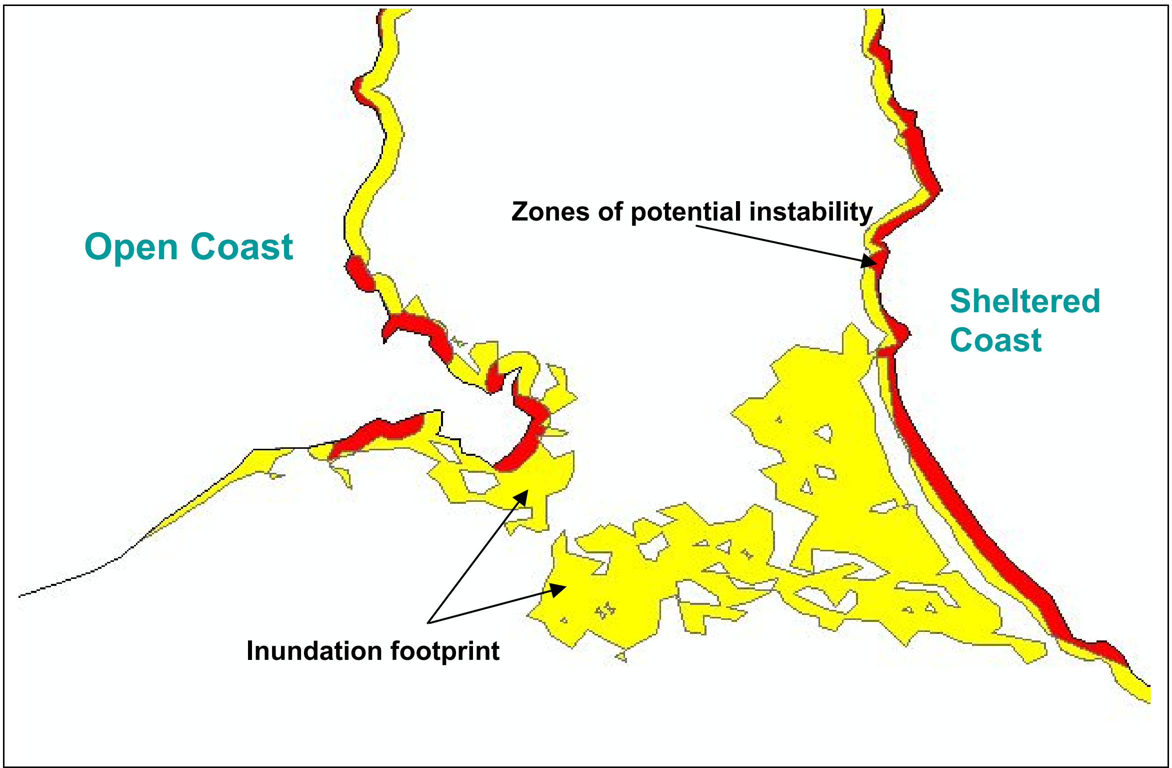


Figure 2.2: *The final RAIZ combined output footprint symbolised with the two levels of evidence: red for "more evidence" and yellow for "some evidence". The exact meaning of these evidence levels is given in Appendix 2.*

2.5 POPULATION PROJECTIONS

The population projections utilised for this study were released by the Australian Bureau of Statistics (ABS) on 14 June 2006 and cover the period 2004 to 2101 for Australia (ABS 2006). A more disaggregated treatment covering the states and the capital city/balance of state population projections were presented by the ABS only for the period 2004 to 2054.

The projections illustrate the growth and change in population under certain assumptions about fertility, mortality, internal migration and net overseas migration. Compared to Series B, Series A assumes higher levels of fertility, life expectancy, and migration while Series C assumes lower levels. As a result, Series A results in larger projected populations and Series C results in lower populations (Figure 2.3). These projections are not predictions or forecasts and are used to simply illustrate the growth and change in population that would occur under certain assumptions (fertility, mortality, internal migration and net overseas migration).

Series B and C projections reach a state of natural decrease, in which deaths outnumber births, during the projection period. In Series B net overseas migration compensates for natural decrease, and Australia's population continues to increase throughout the projection period. By contrast, in Series C overseas migration fails to compensate for natural decrease, and Australia's population declines from 2049. The approach adopted for this study was to project the state metropolitan and non-metropolitan growth in population out to 2054 according to the state based projections. Beyond that, the Australia wide projections were used to carry forward the 2054 state metropolitan and non-metropolitan populations. This captures the differentials of state and territory growth in the capital cities and the rural areas through to 2054 and underpins the drift to the north and the coastal regions.

In Series B, Queensland is projected to experience the largest increase in population between 2004 and 2051, increasing by 3.0 million people (77%) to reach 6.9 million people. Queensland replaces Victoria as Australia's second most populous state in 2041. Western Australia is projected to increase by 1.2 million people (60%) to reach a population of 3.2 million people in 2051. The Northern Territory's population is projected to increase by 150,200 people between 2004 and 2051, to 350,000 people. Although a smaller absolute increase than those projected for the larger states, this is a significant increase (75%, second only to Queensland's projected increase of 77%) relative to the Northern Territory's 2004 population of just under 200,000 people.

The projected movement and growth in population in Queensland and Northern Australia underscores the increases in exposure that could occur through the period to 2101.

Under these 2006 projections the total population in Australia is projected to rise from current levels of 21 million to around 44 million by 2100 under *Series A* assumptions, or as low as 23 million under *Series C* assumptions. Updates to the population projections have revised these numbers upward (ABS 2009) to reflect a higher rate of increase than had originally been estimated. The results in this report do not take these revised figures into account, and will therefore underestimate to some extent the potential impact of coastal vulnerability on future exposure.

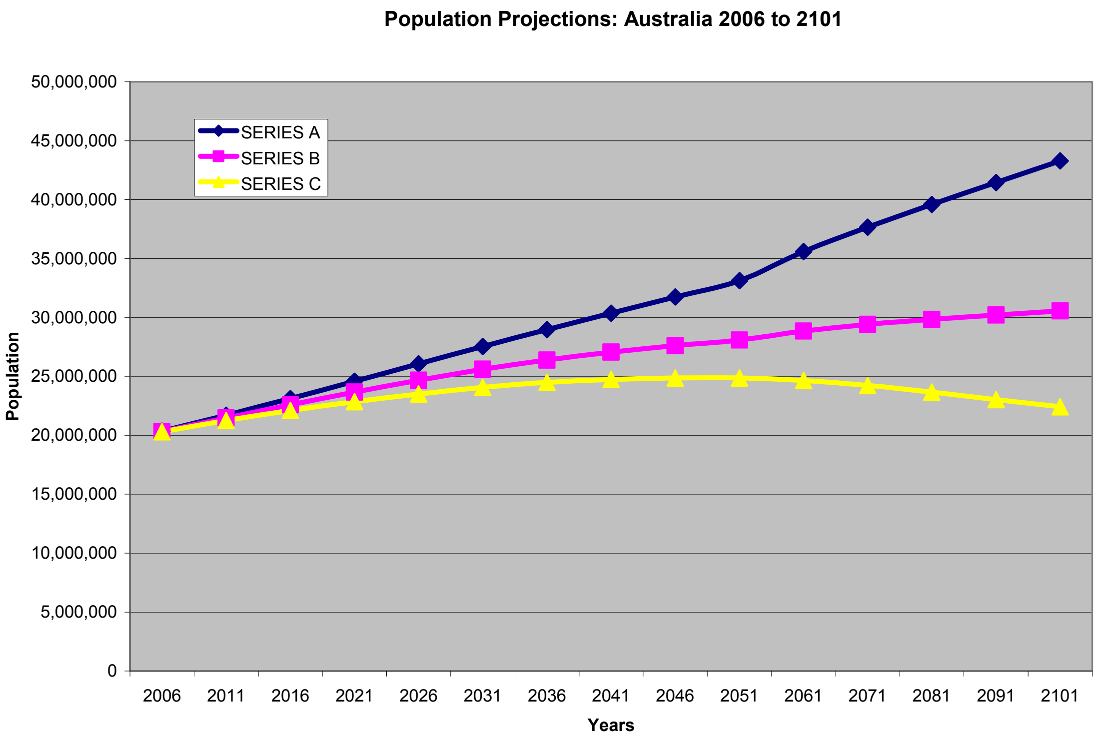


Figure 2.3: *Australian Bureau of Statistics Series A, B & C population projections (2006) illustrating the growth and change in population under certain assumptions about fertility, mortality, internal migration and net overseas migration.*

2.5.1 Impact of population projections on Australia's coastal exposure

It is predicted that a large percentage of the increase in Australia's population will live in the coastal zone (the current trend). Along the eastern seaboard in particular, our coastline is developed for residential use and is heavily populated. Increased population will put greater pressure on the coastal zone, and this gives particular urgency to the need for adaptation to rising sea-level.

Research has been carried out by Geoscience Australia and others investigating levels of occupancy, housing construction methods, and household income, with a view to compiling a nationwide measure of the cost of replacement of assets. Existing databases (e.g. CityScope) for commercial and business buildings in the main urban centres have been supplemented by Geoscience Australia surveys. This study used the ABS Series A, B & C population projections to illustrate the change in exposure with respect to residential structures. Projections of residential infrastructure exposure (within NEXIS) have maintained the current ratio of people to buildings within each statistical local area (1000+ coastal regions in Australia). In addition, for the period post-2056, the ratio of local to national change has been maintained in order to maintain the 2056 local trend (for each series) up to the end of the 21st century. The current ratio of people to buildings has been gradually reducing over the past four decades; it was maintained at current levels in an effort to offset the trend of increasing medium density (multi-storey) developments that have a lower vulnerability to inundation.

2.6 INTEGRATION WITH NEXIS

The RAIZ and ZPI's for the entire nation were integrated with NEXIS to determine the infrastructure exposed in each local government area (LGA). This integration was undertaken in the ArcGIS 9.3 environment utilising simple spatial queries to determine the number and value of coastal infrastructure potentially vulnerable to the combined impacts of SLR and coastal recession. The total number of residential and commercial buildings within each LGA that fall within the RAIZ for each scenario has been determined and is reported (Figure 2.4). The total length of road and rail in each LGA within each RAIZ has also been determined and reported. In addition, the approximate replacement value of the residential and commercial properties, and the road and rail at risk is also reported. These values have been based on average replacement values per state or LGA (where available).

Due to the limitations of the datasets and the techniques applied, it is only appropriate to provide results of areas and infrastructure at risk that have been aggregated to the LGA level (i.e. determining the actual locations and for that matter inundation level for specific structures is not appropriate). Population projections, originally covering SLA regions, were reprojected to LGA regions within ArcGIS.

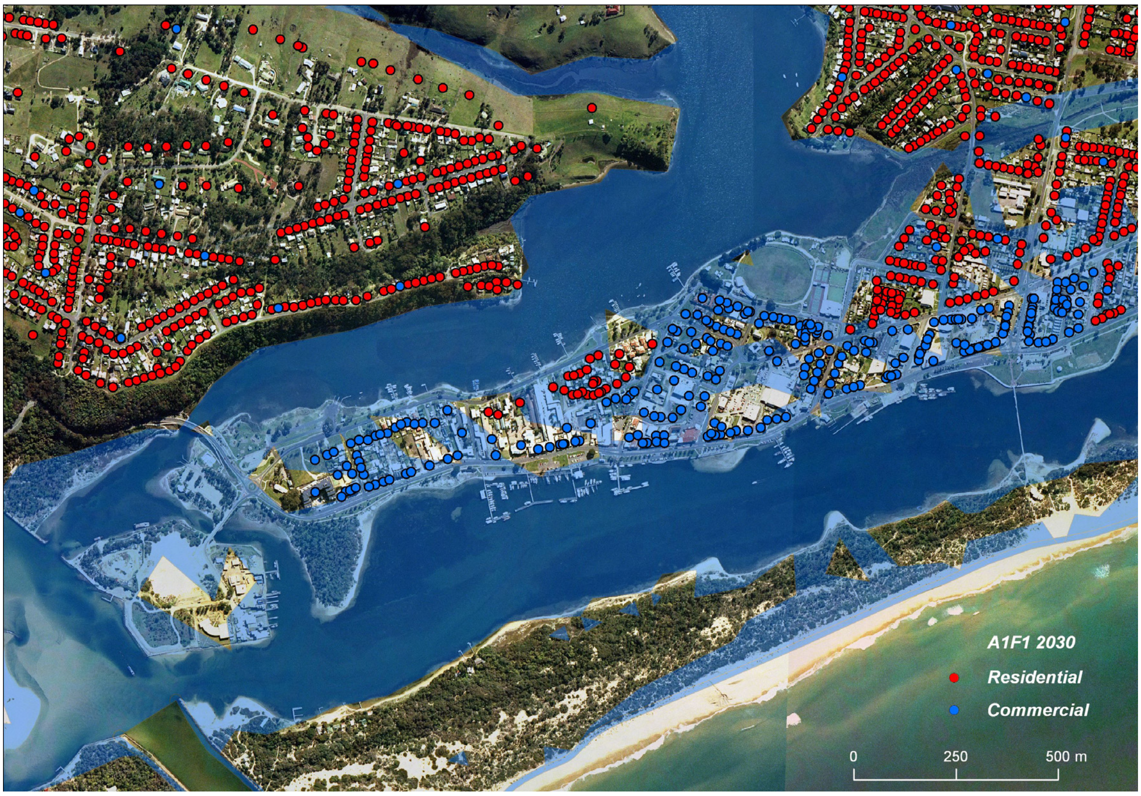


Figure 2.4: *Example of NEXIS database being integrated with the RAIZ for the 2030 climate scenario (Lakes Entrance, Victoria).*

2.7 VALIDATION

Initial methodology assumed a 50% probability as the basis for the inundation footprints. The 50% probability inundation results derived from the mid-resolution SPOT DEM were validated against high-resolution LiDAR, sourced from the Department of Sustainability and Environment (DSE) for the Victorian coastline. High resolution elevation data (LiDAR) typically has a vertical error value in the range of +/-10-30cm, compared with the vertical error value associated with the SPOT DEM of +/- 6m. The raw LiDAR data was supplied to the University of Tasmania (UTAS) in order for them undertake the same inundation modelling (Appendix 1) as for the SPOT DEM data.

As with the inundations footprints derived from the mid-resolution SPOT DEM, a series of 50% probability inundation footprints were derived from the LiDAR DEM for current climate (using storm surge only), and 2100 (high end = 1.1m SLR). Rapid Assessment Impact Zones (RAIZ) were produced by combining the Victorian LiDAR inundation (50% probability grid) modelling results with the existing Zones of Potential Instability (ZPI) derived from the Smartline using the same method as for the SPOT based RAIZs. Using the same methodology, the LiDAR 2100 minimum and 2100 maximum footprints were generated by applying the 55m and 110m buffers respectively.

The new LiDAR derived RAIZ footprints were integrated with the NEXIS database in order to determine the number of residential buildings at potentially risk from inundation under selected climate scenarios using the high resolution LiDAR DEM along the Victorian coastline. Table 2.3 details the numbers of residential buildings at risk from inundation in the Victorian coastal LGAs, enabling a comparative sensitivity analysis to be undertaking between the two sets of modelling results.

Table 2.3: Comparison of the number of buildings potentially risk from combined impacts inundation and recession under the SPOT 50% and the LiDAR 50% probability RAIZ footprints.

	SPOT 50%			LiDAR 50%		
LGA NAME	Current Climate	2100 min	2100 max	Current Climate	2100 min	2100 max
Kingston	0	12	358	34	6125	6459
Port Phillip	1	8	260	16	3568	3755
Greater Geelong	10	90	775	383	3240	3599
Frankston	0	6	163	19	2015	2172
Hobsons Bay	0	142	284	13	1818	1840
Mornington Peninsula	4	90	1143	117	756	1765
Queenscliffe	0	7	123	459	1159	1248
E. Gippsland	453	699	699	180	1163	1163
Bayside	0	46	618	2	65	629
Glenelg	12	38	93	0	55	111

As the data illustrates, at the 50% probability level, the SPOT inundation footprint was found to have underestimated the area potentially inundated by over an order of magnitude when compared to the LiDAR 50% inundation footprint (Figure 2.5). For example, the LGA of Kingston had approximately 360 buildings at risk using the SPOT hazard footprint compared with over 6400 buildings using the LiDAR hazard footprint, a 17 fold increase in the buildings potentially at risk from the combined inundation and recession by 2100. For all 10 LGAs reported above, there was a total of over 38,400 residential buildings potentially at risk from inundation using the LiDAR hazard footprint compared with approximately 4,500 residential buildings using the SPOT 50% hazard footprint.

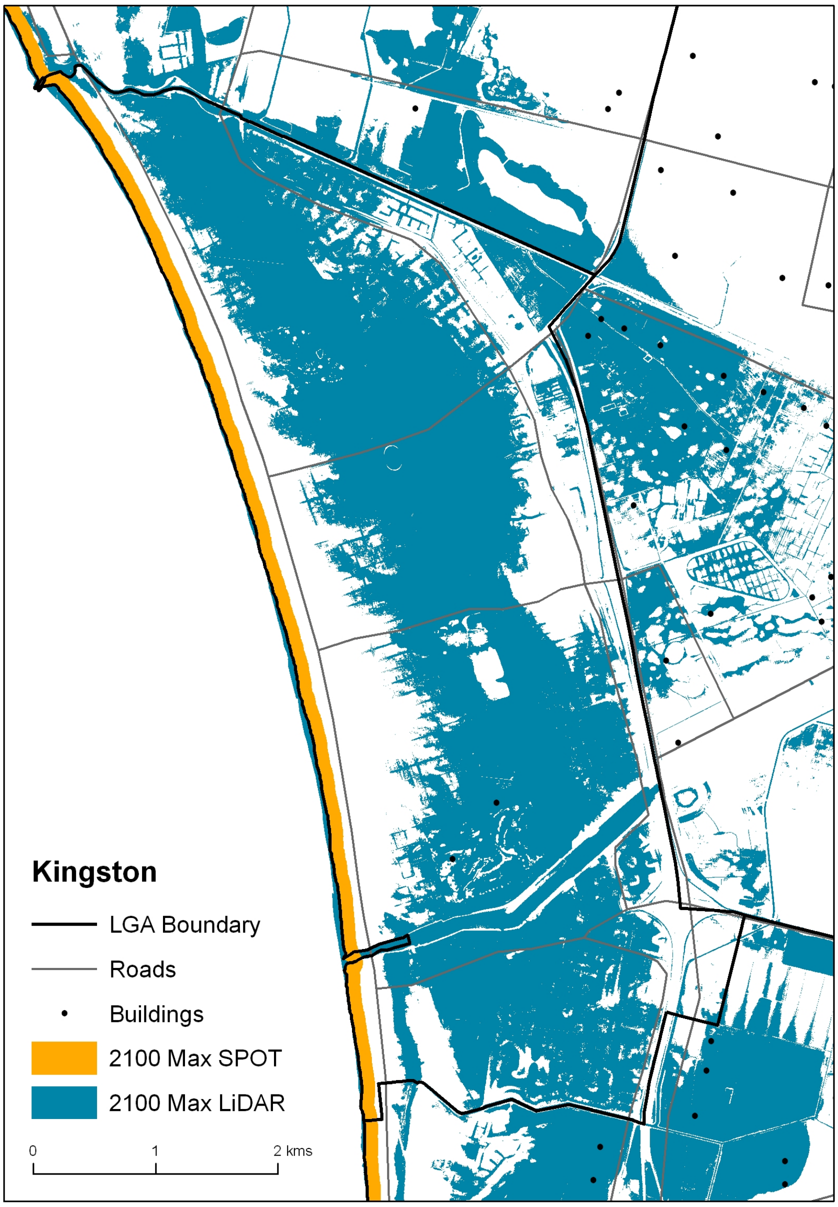


Figure 2.5: *Comparison of the extent of area potentially at risk from inundation by the SPOT (2100 Max SPOT) & LiDAR 50% probability RAIZ footprint (2100 Max LiDAR).*

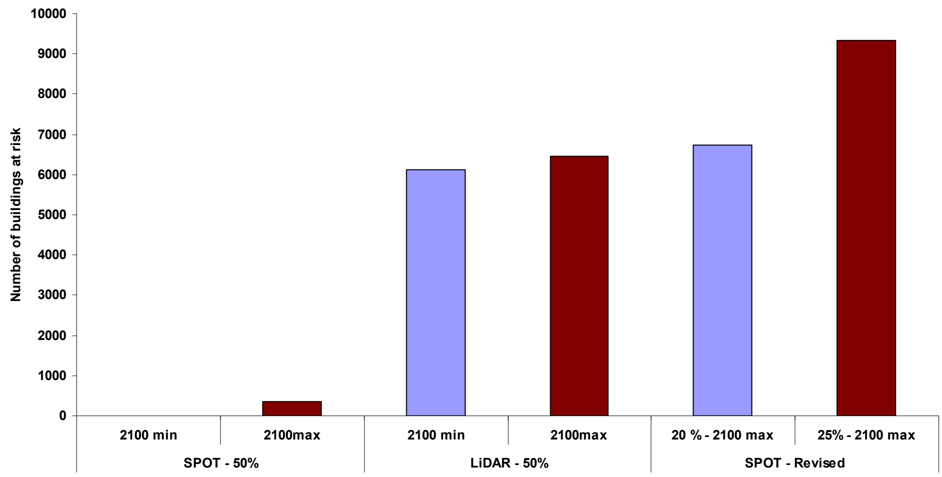
In order to generate a range of options to compare with the LiDAR 50%, inundation footprints were generated by the Spatial Data Team at the DCCEE from the SPOT HSR DEM, based on 15%, 20% and 25% probability of inundation respectively. These were integrated with the existing Zones of Potential Instability footprints. The new RAIZ footprints were subsequently integrated with the NEXIS database in order to determine the number of residential buildings at risk from inundation under the 2100 climate scenario along the Victorian coastline. Table 2.4 details the numbers of residential buildings potentially at risk from combined impacts of inundation and recession in the Victorian coastal LGAs. This enabled a comparative sensitivity analysis to be undertaking between the three sets of modelling results. Based on the comparison of the data from Table 2.4, it was decided to carry out a reassessment of the vulnerability using both the 20% and 25% probability SPOT DEM RAIZ footprints to represent a lower and upper bound of vulnerability. Figure 2.6 shows the improved match between results based on the revised 20-25% SPOT footprint and the 50% LiDAR, compared to the original 50% SPOT footprints.

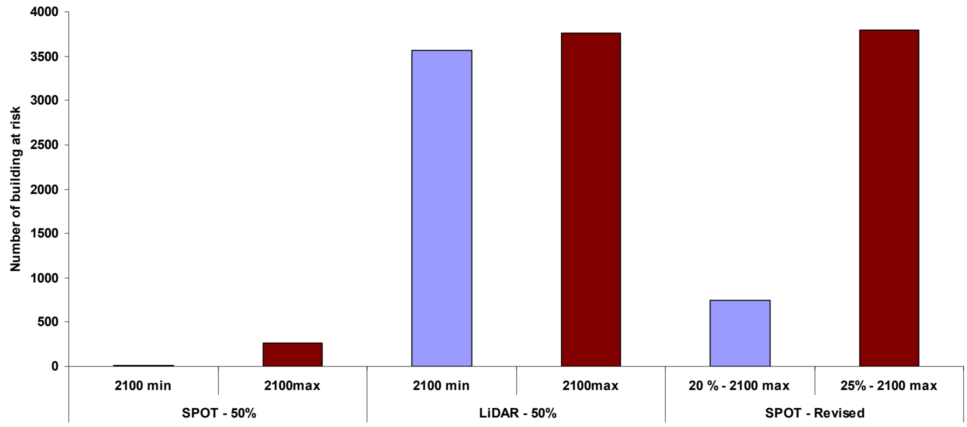
The analyses reported in Chapter 3 and Appendix 3 are based on the bias corrected footprints. For these results, the initial SPOT 50% 2100 minimum and 2100 maximum estimates are replaced by the following two estimates:

- 2100 lower; representing the combination of the SPOT 25% probability inundation and maximum ZPI extent (110m buffer), and
- 2100 upper; representing the combination of the SPOT 20% probability inundation footprint and maximum ZPI extent (110m buffer).

Table 2.4: Comparison of the number of buildings potentially at risk from the combined impact of inundation and recession under the SPOT 50%, the LiDAR 50%, and the revised SPOT 20 & 25% probability RAIZ footprints.

	SPOT - 50%		*LiDAR - 50%*		*SPOT – revised* 25%	20%
LGA NAME	2100 min	2100 max	2100 min	2100 max	2100 lower*	2100 upper *
Kingston	12	358	6125	6459	6728	9325
Port Phillip	8	260	3568	3755	748	3799
Greater Geelong	90	775	3240	3599	4951	7022
Frankston	6	163	2015	2172	1610	3335
Hobsons Bay	142	284	1818	1840	4601	7533
Mornington Peninsula	90	1143	756	1765	1411	1697
Queenscliffe	7	123	1159	1248	220	797
E. Gippsland	699	699	1163	1163	2568	2878
Bayside	46	618	65	629	621	641
Glenelg	38	93	55	111	206	314





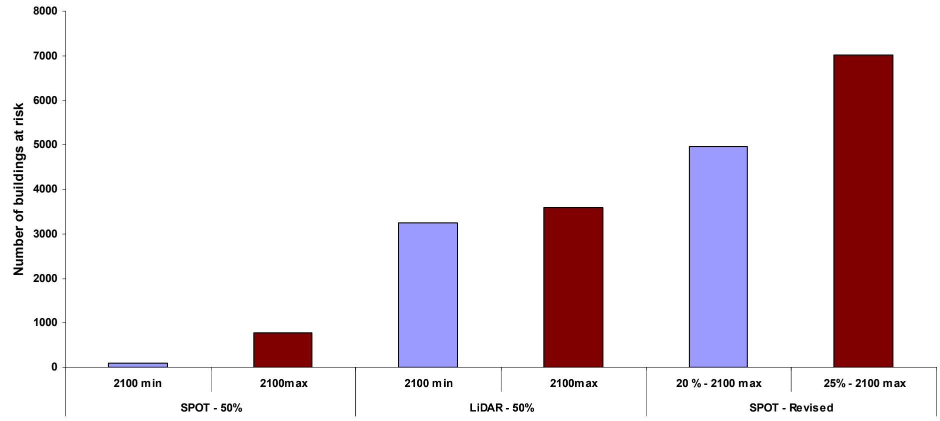


Figure 2.6: *Comparison of the number of residential buildings potentially at risk from the combined impacts of inundation and recession for SPOT 50%,, the LiDAR 50%) and the revised SPOT 20 & 25% footprints (maximum 110m buffer applied) for the most vulnerable three Victorian LGAs; Kingston (A), Port Phillip (B) and Greater Geelong (C).*

3. Results

The results presented in this chapter are based on the 2100 lower and 2100 upper estimates, derived from the 25% and 20% probability SPOT DEM RAIZ footprints, respectively. This chapter provides a national overview of the potential risk to residential and commercial buildings, and rail and road infrastructure. A set of results by State can be found in Appendix 3.

3.1 RISK TO RESIDENTIAL BUILDINGS

Australia faces significant risk to residential buildings under both the upper and lower 2100 estimates (Figure 3.1). Nationally the total residential risk ranges from 187,000 to 274,000 buildings from the combined impact of inundation and recession. Queensland and New South Wales contain the highest values, with between approximately 44,000 to 68,000 residential buildings potentially risk from the combined impacts of inundation (sea-level rise and storm surge inundation) and recession by 2100. The total replacement cost for residential buildings at risk in Australia by 2100 is between $51 billion and $72 billion (Figure 3.2). This upper limit includes $63 billion at risk from just inundation. Queensland and New South Wales have the highest replacement value with between $14 billion and 20 billion dollars, followed Victoria and then South Australia, Western Australia and Tasmania. Table 3.1 shows the vulnerability of residential infrastructure (by State) considering the combined inundation and recession impacts.

Figure 3.1: *Lower and upper estimates of the number of residential buildings by state potentially at risk from the combined impact of inundation and recession by 2100.*

Figure 3.2: *Lower and upper estimated replacement value of existing residential buildings potentially at risk from the combined impact of inundation and recession by 2100.*

Table 3.1: Number and replacement value of residential buildings potentially vulnerable to inundation, recession and combined inundation and recession for all states. The values consider a sea-level rise of 1.1 metres by 2100 and a rise in sea-level from a 1 in 100 year return period storm surge event (for New South Wales, Victoria and Tasmania) and the spring high-water tide for all other states. Values are based on the "upper end estimate" (20% probability footprint and the 110m ZPI buffer) estimate.

STATE	*"Inundation" only*		*"Recession" only (Zone of Potential Instability)*		*Combined Inundation + Recession (Zone of Potential Instability)*	
	Number	Value ($bil)	Number	Value ($bil)	Number	Value ($bil)
New South Wales	62,400	18.7	3,600	1.3	65,200	19.8
Northern Territory	180	0.06	190	0.08	400	0.1
Queensland	56,900	16	15,200	5.8	67,700	20.5
South Australia	43,000	7.4	7,000	1.3	47,800	8.3
Tasmania	11,600	3.3	6,100	1.8	14,900	4.3
Victoria	44,700	10.3	4,700	1.5	48,000	11.4
Western Australia	28,900	7.7	2,100	o.6	30,000	8.0
AUSTRALIA	**247,600**	**63.0**	**38,900**	**12.3**	**274,000**	**72.4**

Queensland contains five of the top ten LGAs most at risk from sea-level rise in Australia (Figure 3.3). The Moreton Bay LGA in Queensland contains the greatest risk from combined inundation and recession to residential buildings for the 2100 upper estimate with approximately 15,000 buildings at risk. This is followed by the Charles Sturt (SA), Gold Coast (QLD), Port Adelaide (SA), Kingston (TAS), Mackay (QLD), Busselton (WA), Hobsons Bay (VIC) and Fraser Coast (QLD) and Bundaberg (QLD).

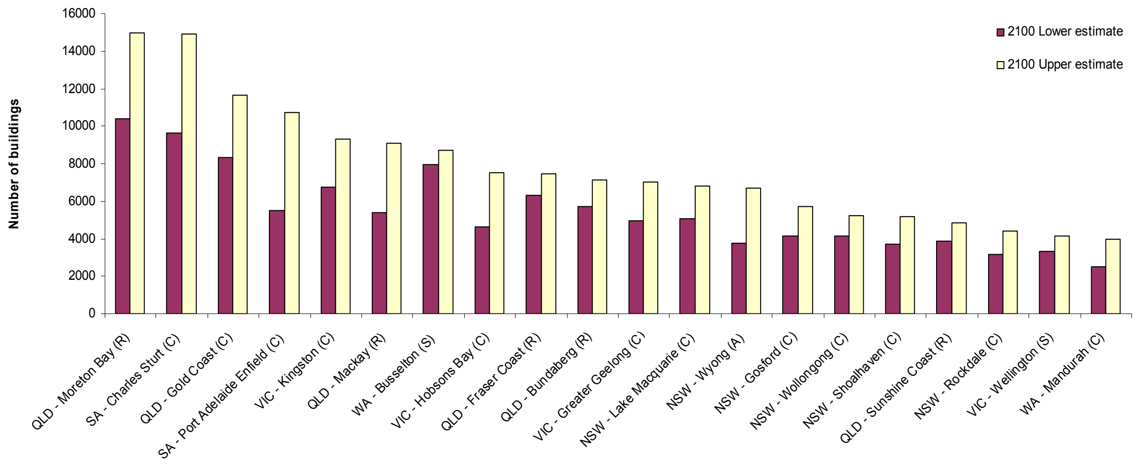


Figure 3.3: *The top twenty LGAs with the greatest risk from combined inundation and recession to residential buildings nationally for the 2100 upper and lower estimates.*

3.2 Risk to commercial buildings

Nationally, between 5,800 and 8,600 commercial buildings are at risk from the combined impact of inundation and recession by 2100 with a replacement value of approximately $58 billion to $81 billion dollars. The number of commercial buildings potentially vulnerable represents between 15,560 and 22,000 individual business, as multiple businesses can operate from a single building. WA and Victoria have approximately same number of commercial buildings at risk, between 1,500 and 2,000 buildings (Figure 3.4). Whilst SA does not have the largest number of commercial buildings at risk, between 900 and 1500, the replacement value of these buildings is between $22 billion and $27 billion, more than any other state (Figure 3.5). This is due to the area of potential inundation being concentrated around the Port Adelaide and Enfield CBD's.

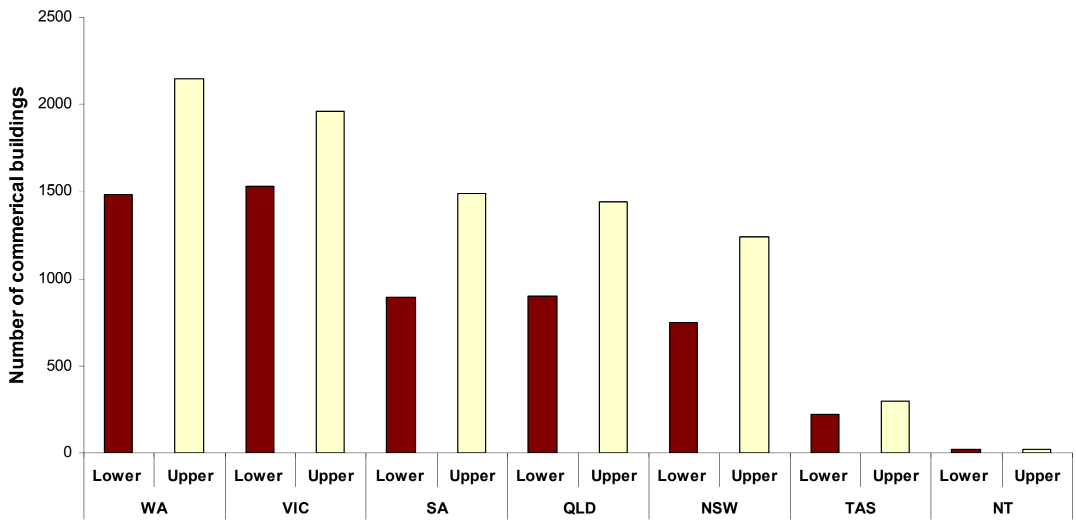


Figure 3.4: *Lower and upper estimates for the number of commercial at risk from the combined impact of inundation and recession by 2100.*

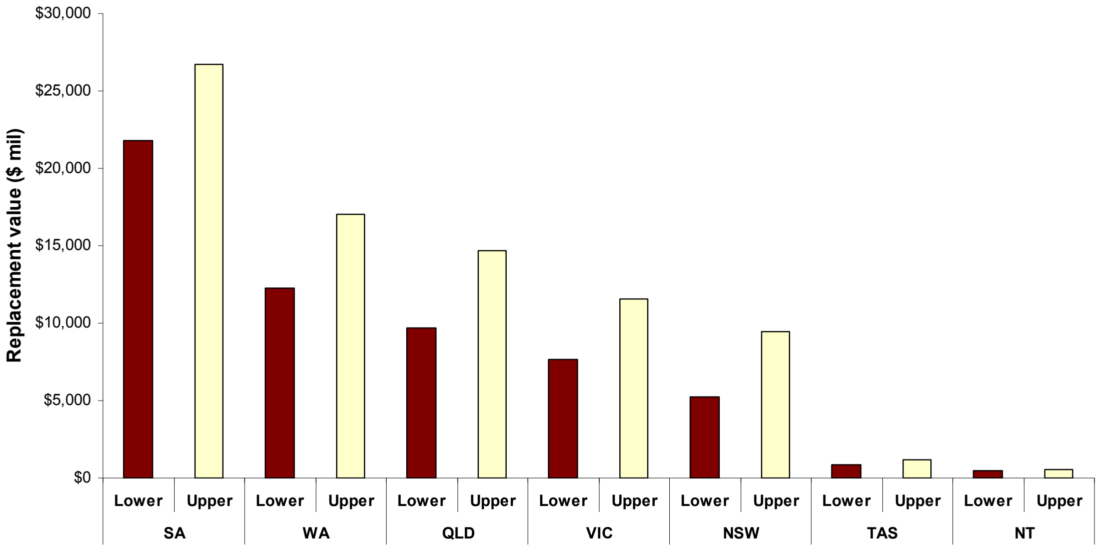


Figure 3.5: *Lower and upper estimates of the replacement value of existing commercial buildings at risk from the combined impact of inundation and recession by 2100.*

3.3 Risk to road and rail infrastructure

Nationally, between 26,000 and 33,000km of roads, consisting of freeway (1,100 to 1,500km), main roads (10,000 to 13,000km) and un-sealed roads (15,000 to 18,000km) are potentially at risk from the combined impact of inundation and recession by 2100 (Figure 3.6). This roadway has a total replacement value of between $46-60 billion. The majority of the risk occurs on unsealed roads and tracks and main roads. Western Australia has the greatest length of roadway at risk, with between 7,500 and 9,100kms in total.

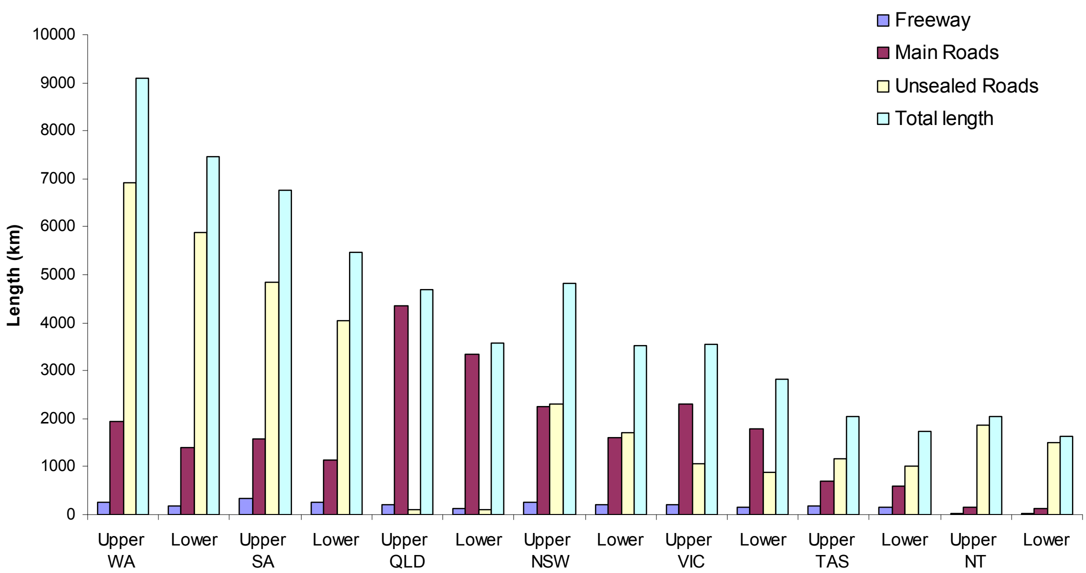


Figure 3.6: *Lower and upper estimates of the length of road infrastructure at risk from the combined impact of inundation and recession by 2100.*

Queensland has the greatest replacement value for existing road infrastructure at between $9.7 billion and $12.9 billion, due to the greater percentage of freeway and main roadway at risk. In comparison, in Western Australia the greatest exposure to risk is from unsealed roadway. All states, with exception of Tasmania and the North Territory, have an estimated replacement value of greater than $7 billion (Figure 3.7).

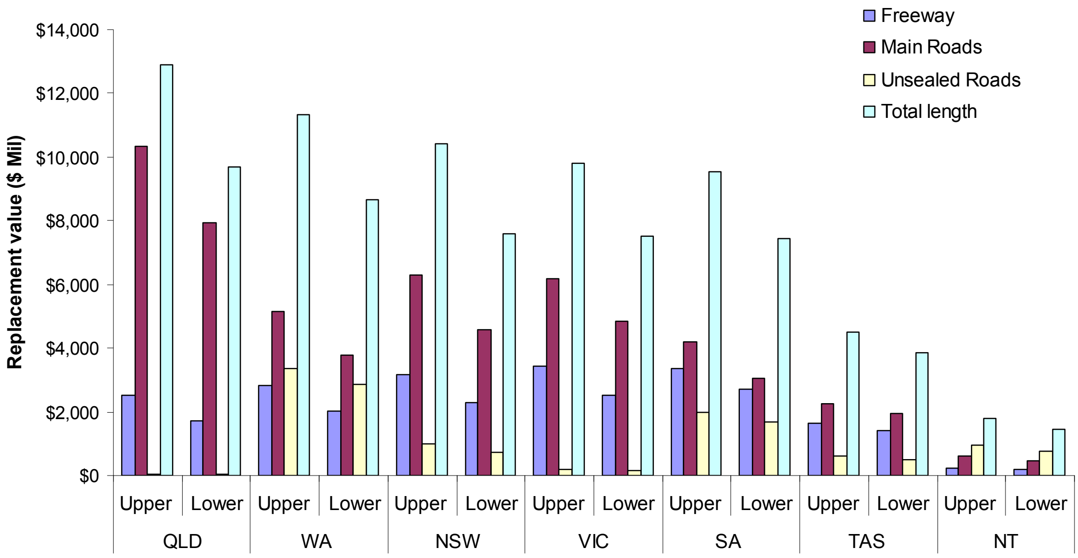


Figure 3.7: *Lower and upper estimated replacement value of existing road infrastructure at risk from the combined impact of inundation and recession by 2100.*

Nationally, between 1,200 and 1,500km of rail lines and tramways are potentially at risk from inundation and recession by 2100 (Figure 3.8), with a replacement value range of $4.9 billion and $6.4 billion (Figure 3.9). Queensland has the greatest length and highest estimated replacement value for rail and tramway infrastructure, followed by New South Wales, South Australia and Tasmania.

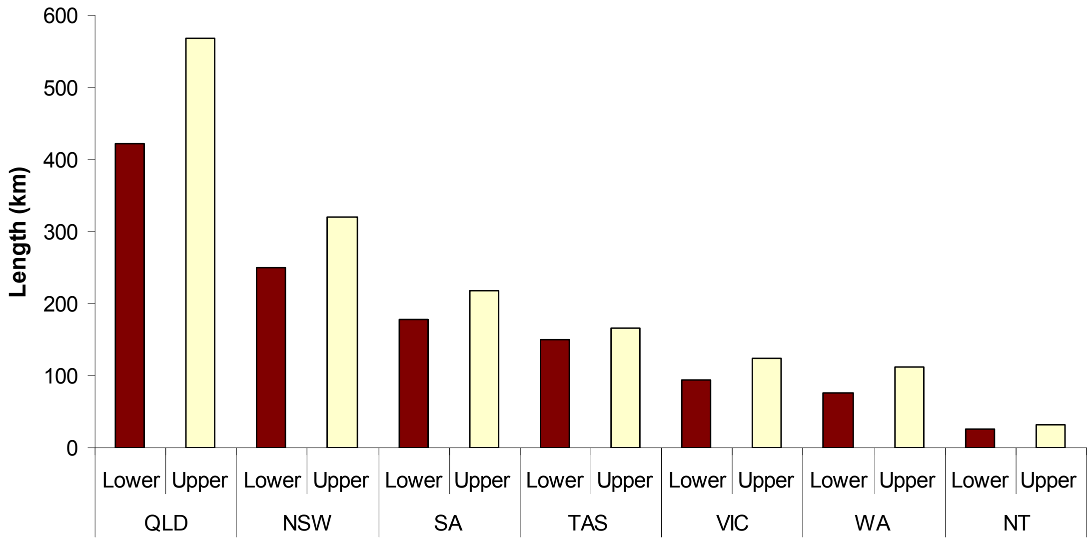


Figure 3.8: *Lower and upper estimated length of existing rail and tramway infrastructure at risk from the combined impact of inundation and recession by 2100.*

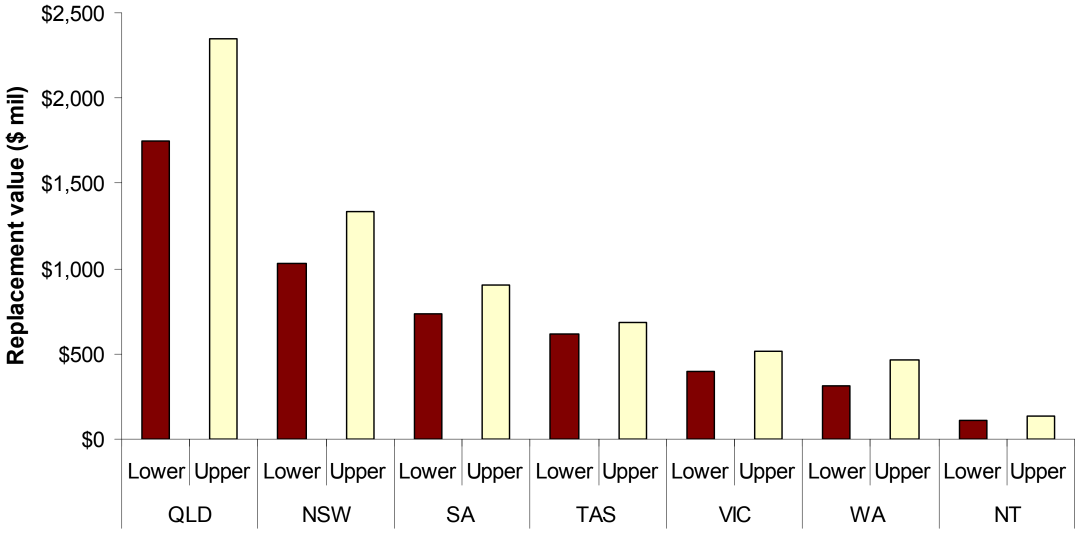


Figure 3.9: *Lower and upper estimated replacement value of existing rail and tramway infrastructure at risk from the combined impact of inundation and recession by 2100.*

3.4 Impact of population projections on risk to residential buildings

Under the Australian Bureau of Statistics population projections utilised for this study (ABS 2006), the total population in Australia is projected to rise from current levels of 21 million to around 43.5 million by 2100 under *Series A* assumptions, or to as little as 22.4 million under *Series C* assumptions. Since this analysis was conducted, further population projections have been released (ABS 2008). The new projections take into account the much higher than anticipated levels of Net Overseas Migration experienced in recent years and the increased total fertility rate which resulted in a record number of births over the last 5 years. The population under *Series A* is estimated to grow to over 62 million people in 2101, under *Series B* to 45 million and under *Series C* to nearly 34 million.

It is predicted that a large percentage of this increased population will live in the coastal zone, as is the current situation, especially if climatic predictions of higher inland temperatures are correct. Along the eastern seaboard in particular, the coastline is developed for residential use and is already heavily populated, and current building booms in areas such as south-east Queensland are further concentrating population in the coastal zone.

When the 2006 ABS population projections are used to assess the potential vulnerability to inundation and erosion in terms of future, rather than current structures, it indicates that an additional 271,000 to 399,900 residential buildings could be at risk. Figure 3.10 shows the number of vulnerable residential buildings with current population and the respective population projections. For the more extreme population projections, the population increase has a larger impact on the vulnerability to inundation than sea-level rise, in relative terms. The changes in the spatial distribution of the projected population in 2101 mean that Queensland would have the largest number of residential buildings vulnerable to inundation. Increased population concentrations will put greater pressure on the coastal zones, and underscores the need for early planning to manage future risks associated with sea-level rise.

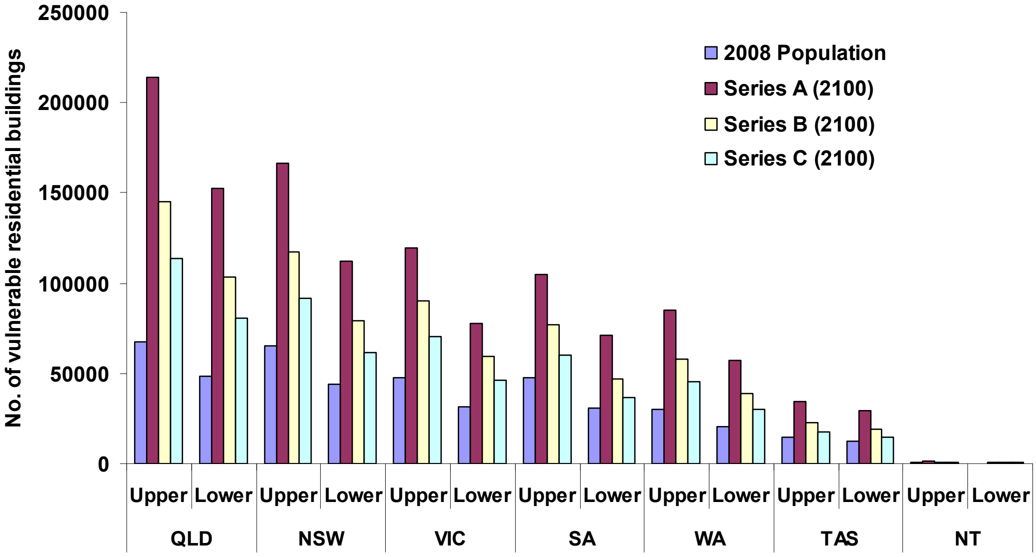


Figure 3.10: *Lower and upper estimate of the number of vulnerable residential buildings at risk from the combined effects of inundation and erosion for 2008 population and the ABS (2006) Series A, B & C population projections by 2100.*

4. Discussion

The purpose of this section is to summarise and discuss the implications of the results of this report, highlight the modification of the vulnerability assessment methodology, and finally to note some limitations of the current methodology and suggest potential improvements.

4.1 INFRASTRUCTURE VULNERABLE TO CLIMATE CHANGE

The results of the SPOT 20-25% inundation footprint analyses indicates that Australia faces significant risk to its coastal infrastructure from the combined impacts of inundation and recession (under both the upper and lower 2100 estimates). Nationally the total of current residential assets potentially at risk ranges from 187,000 to 274,000 buildings. Queensland and New South Wales contain the highest values, with between approximately 44,000 to 68,000 residential buildings potentially at risk from the combined impacts of inundation and recession by 2100. Similarly, the risk to commercial infrastructure nationally was found to be between 5,800 and 8,600 buildings by 2100 with a replacement value of approximately $58 billion to $81 billion dollars. Transport infrastructure is also at risk from inundation and recession by 2100, with between 26,000 and 33,000km of road, rail and tramway identified nationally. The upper end estimated of total replacement value of coastal infrastructure is greater than $220 billion (Figure 4.1).

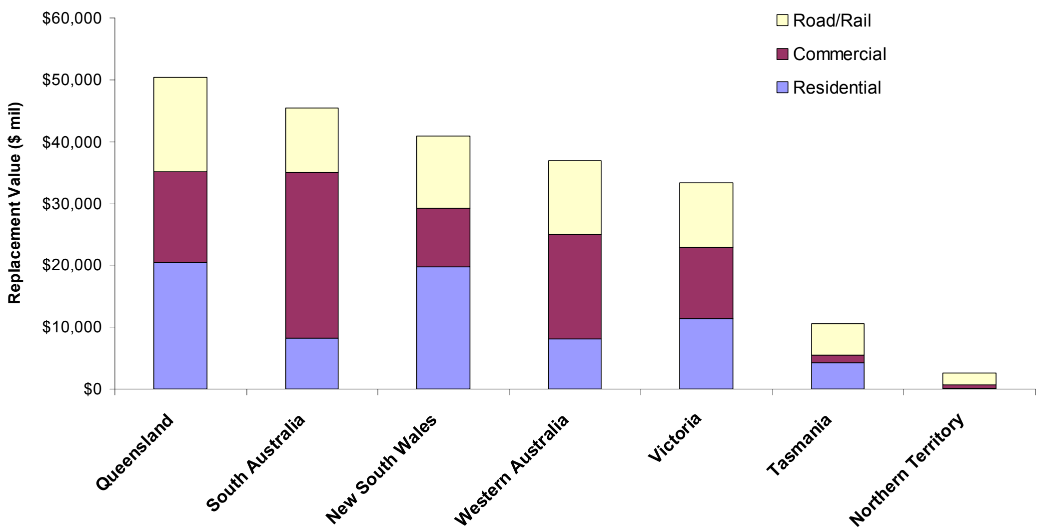


Figure 4.1: *The upper estimate of the replacement value ($ million) for residential, commercial and transport infrastructure at risk from the combined effects of inundation or recession by 2100.*

Queensland and New South Wales have the greatest risk, in terms of both quantity and replacement value, for residential buildings. Queensland has the largest replacement value of road/rail infrastructure at risk to inundation and recession. South Australia has the highest replacement value for commercial buildings.

4.2 COMPARISON OF SPOT 50% AND 20-25% ANALYSIS

The validation assessment (Section 2.7) indicates that the results of this study are sensitive to the probability assumption used for the inundation footprint. Despite this sensitivity, comparison of the analyses indicates there is also a robustness in the results. One objective of this study was to identify the regions, at the level of LGA, most at risk from the impacts of climate change. Spatially the distribution the risk was found to be concentrated on the east coast of Australia. Although the revised methodology increased the number of assets at risk, it did not significantly alter the spatial distribution of the most vulnerable areas (Figure 4.2). Eight of the LGAs in the top twenty from the SPOT 50% analysis for residential buildings were also included in the top twenty LGAs from the SPOT 20-25% analysis.

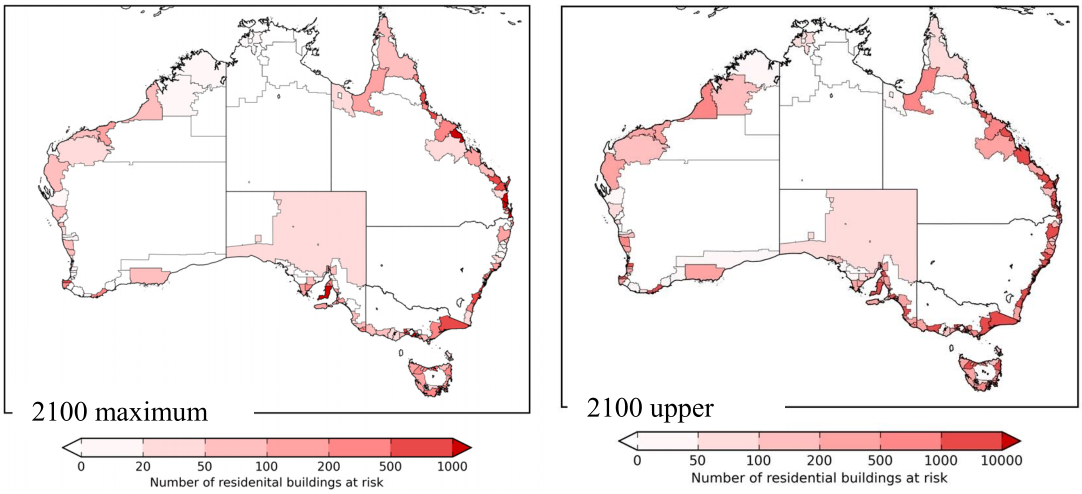


Figure 4.2: *Spatial distribution of residential buildings potentially at risk by LGA from inundation at 2100 using the SPOT 50% 2100 maximum (left) and SPOT 20-25% 2100 upper(right) the estimate.*

4.3 LIMITATIONS OF THE METHODOLOGY

It is important to understand the limitations of the methodology when interpreting the results. There is still only a partial ability to model the wide range of complex impacts from coastal inundation on communities. This study carried out a relatively limited assessment, in that it only considers vulnerability of coastal communities in terms of their exposed assets. In the course of undertaking this assessment, a number of areas were identified where further improvement in the methodology and underlying datasets are needed. Prior to undertaking this work, there were significant gaps in knowledge of what existed at the coast in terms of both geomorphology and infrastructure. This analysis has provided a significant improvement in national capability. Areas where further improvements can be made are identified below.

- *Smartline* – due to the timeframe of the project and inherent complexities of the Australian coastline, a number of key areas of vulnerability were not able to be incorporated into this dataset. For example, the *Smartline* does not include any of the smaller estuaries, intermittently closed and open coastal lakes and lagoons (ICOLLS) or drowned river valleys along the NSW coast. There were two reasons for this, 1) only the large systems have been adequately mapped and 2) there was insufficient time within the scope of this project to convert what data was available into the *Smartline* format.

- SPOT DEM – the SPOT DEM used in this study was only available in 1m elevation steps, which placed restrictions on the accuracy of the results. A higher resolution DEM would be far better for this type of study. Where that is not available, an alternative would be to modify the DEM from the integer steps of 1m to a floating point via the application of a spline function.

- Bathtub modelling – this is a simplified method for inundating the coast, that may over-estimate the extent of inundation within the coastal re-entrants as it doesn't consider the attenuation of the water depth as it moves inland. In addition it may also underestimate the increase in the extent of inundation due to the tidal prism in enclosed or semi-enclosed coastal lagoons and estuaries.

- Storm tide modelling – storm tide modelling was not available for the whole continent due to the time constraints of the project. Where it was not available tidal data was utilised. This tended to underestimate the potential vulnerability (inundation) to extreme events especially in the regions of the coastline impacted by tropical cyclones.

- The NEXIS database – NEXIS has evolved through obtaining data from a range of agencies, and this results in data of varying quality and with some gaps in characteristics. For example, floor height of buildings would be particularly useful for assessing vulnerability to inundation. In addition, the number and replacement value may have been underestimate in those regions/LGAs where the database has been derived from the statistical approach rather than from actual data. More validation is required, as only Tasmanian region was validated.

- Population projections – this assessment has been undertaken based on 2006 population data and population projections. Revised figures estimate that the population of Australia may be greater than 60 million by 2100 (ABS 2008). A significant proportion of that future population will be living and working near the coast if the current demographic trend continues. The impact of global warming on temperatures will be moderated near the coast by the oceans, and the greatest warming is expected in inland regions. This may add to the demographic trend "seachange".

5. Summary and Conclusions

The Australian Government has developed a three part response to climate change: helping to shape a global conclusion; reducing Australia's greenhouse gas emissions; and adapting to unavoidable climate change. The need to adapt to future climate risk recognizes that, whatever policy decisions are made today about reducing greenhouse gas emissions, some degree of climate change is now unavoidable.

This project has provided an assessment of the coastal infrastructure and settlements that may be exposed to impacts associated with sea level rise. It includes an evaluation of the exposure of infrastructure (residential and commercial buildings, as well as roads and rail) to sea-level rise (SLR), storm surge and coastal recession. This assessment examines the climate change influence on vulnerability to inundation under a future climate scenario and population projections for the end of the 21st century. The results of this work contribute significantly to an understanding of the national levels of risk and identification of the priority areas.

Information from two national spatial datasets, *Smartline* and NEXIS, was combined to assess the number of residential buildings at risk from coastal erosion on unstable coastlines, where coastal recession is likely due to the projected sea-level rise. *Smartline* has enabled the first national assessment of the extent of different landform types around Australia's coastline. Approximately 63% of the Australian coast is classed as either sandy or muddy. The remainder is composed of 'soft' rock or "hard" rock shores. Approximately 47% of sandy and muddy shores are backed by soft sediments (as opposed to bedrock) and are therefore potentially mobile. This is a significant statistic as it encompasses shores which are both unimpeded by human structures and those in more built-up areas where migration of "soft" shorelines will generate planning and management issues for local and regional communities. Sandy shores make up 30% of the "free-moving" unimpeded shores while 17% are muddy shores. The identification of potentially mobile shores is significant for the implementation of successful coastal planning and climate change adaptation.

Nationally, nearly 39,000 residential buildings are located within 110 metres of potentially erodible shorelines, with nearly 40% of those buildings located in Queensland. There was no consideration of any existing, planned or future protective structures associated with the buildings at risk, due to potentially erodible shorelines.

The assessment methodology also involved the mapping of areas of coastal inundation utilising the data inputs detailed and the SPOT DEM. The number of residential and commercial buildings located within inundation areas and their value (utilising NEXIS) were provided as well as the lengths of road and rail infrastructure and their values. Building counts/values and road/rail lengths/values were assessed at local government area for a lower and upper end estimate of vulnerability. Nationally, up to $63 billion (replacement value) of existing residential buildings are potentially at risk of inundation. This corresponds to between 157,000 and 247,000 residential buildings across the states and Northern Territory. Queensland and NSW have the largest vulnerability when considering both the value of the infrastructure and also the number of buildings affected. When the coastal recession regions are convolved with the coastal inundation regions to produce a combined region (area), this can be used to determine the effect of the combined impacts of inundation and erosion. Regionally, the results are similar to the inundation outcomes, with the upper estimate of national vulnerability to combined erosion and inundation impacts increasing up to 274,000 residential buildings and $72 billion (replacement value).

Under the Australian Bureau of Statistics population projections utilised for this study (ABS 2006), the total population in Australia is projected to rise from current levels of 21 million to around 43.5 million by 2100 under *Series A* assumptions, or to as little as 22.4 million under *Series C* assumptions. It is predicted that a large percentage of this increased population will live in the coastal zone, as is the current trend. Increased population will put greater pressure on the coastal zone, and underscores the need for early planning to manage future climate risks. The vulnerability from inundation and recession is significantly increased by the ABS Series A & B population projections. For Series A (highest population increase) the increase in population itself is a relatively more important driver for increased vulnerability than the increase from sea-level rise.

The results of this study indicate a substantial number of existing assets could be exposed to risks from rising sea levels. Early planning to manage the risks associated with sea level rise would be prudent. Projections of future sea levels under changing climate scenarios indicate that sea levels will increase over the coming centuries. In the context of an increasing future population located in the vulnerable coastal zones, it is important to consider strategies that can contribute to minimising an increasing vulnerability of settlements and infrastructure to coastal risks.

The results of this project will inform the Australian Government's consideration of national priorities for adaptation to reduce climate change risk in the coastal zone. The assessment of settlements and significant infrastructure potentially at risk to inundation in the coastal zone has:

- Provided an initial assessment of the implications of climate change for nationally significant aspects of Australia's coastal regions (national overview and for key regions).
- Identified national priority regions to support effective adaptation policy responses in the coastal zone
- Identified key elements of a nationally consistent approach to assessing climate vulnerability and risk in the coastal zone
- Located and begun the process of remedying shortfalls in research, as well as creating a national standard for comparison.

State and local governments and private industry can draw on this assessment as a source of information to underpin policy decisions for, inter alia, land use, building codes, emergency management and insurance applications.

6. Future Work

The objective of this section is to build on the lessons from this project and provide a strategic outline of the development of a national framework for undertaking further coastal vulnerability assessments. The framework will include a robust methodology and decision support toolkit (DST) that utilises some of the methodologies and the datasets/products created by this project to enable State and Local Government agencies to conduct more comprehensive assessments of the vulnerability of their coastal zone to climate change. This methodology will help build capability at the Local Government level that does not currently exist.

Development of a national framework is required that will provide access to relevant data/information, tools and guidance to both State and Local Governments to enable them to undertake informed local level coastal vulnerability assessments for planning and adaptation purposes. It will also provide a vulnerability assessment methodology that will enable data, models and tools to be utilised appropriately when studies are conducted. It will be built around the development of the National Coastal Zone Database and online portal, as recommended by the House of Representatives report (CoA, 2009), and will integrate, and further develop (where necessary) previous and current work funded by the DCCEE, and others in this area.

These products will assist State, Territory and coastal Local Governments to make decisions about which adaptation strategies, and planning and development controls will be appropriate for local conditions. It will also assist them in identifying data and knowledge gaps that may require further investigation or assistance.

Geoscience Australia is seeking a longer-term strategic partnership with DCCEE to develop the national framework, methodologies, publicly accessible online databases and outcomes for government and community coastal stakeholders in Australia. Geoscience Australia has also held discussions with other technical agencies, e.g., CSIRO Climate Adaptation Flagship personnel, to combine complementary technical capabilities to produce required national outcomes.

Geoscience Australia views these proposed activities as part of a broader, strategic national approach that will greatly increase the quality of available information for Australian coastal zone stakeholders potentially affected by climate change, and will reduce the uncertainties inherent in decision making associated with incomplete data or lack of knowledge. Specifically the proposed national framework will integrate the following existing products:

- The ‘First Pass’ datasets and outputs created for this project (including the Smartline)
- National Elevation Data Framework (LiDAR derived DEMs and extension of Urban DEM pilot)
- National Topographic Mapping
- Near-shore Bathymetric Datasets
- National Coastal Geomorphic Polygon Mapping
- National Exposure Information System (NEXIS)
- National Wind Risk Assessment
- The detailed coastal vulnerability modelling undertaken at Mandurah, WA
- Other relevant studies, undertaken by Federal, State and Local Government

Other products / datasets that should also be developed and integrated are:

- National Dataset of Wave Climates
- National Dataset of Storm Tide Levels (e.g. 1 in 100 year design storm)
- National Dataset of Sediment Budgets (e.g. from Shoreface Translation Modelling)
- National Dataset of Riverine Flood Maps
- Spatially-enabled web based inventory of coastal assessments

Additionally there are a range of modelling / assessment tools that are required to support this framework which should also be developed (where required) and integrated, including:

- Storm Tide Modelling
- Severe Wind Modelling
- Flood Modelling
- Sediment Transport Modelling

A methodology or guidelines document should also be developed to enable stakeholders to seek the best and most appropriate advice and to provide benchmarking for risk assessment work to be done in a consistent and technically robust and defensible manner.

Framework outline:

The proposed national framework aims to provide a mechanism to allow robust and informed coastal vulnerability assessments to be undertaken at the appropriate scale, using the best available information and methodologies. The specific requirements of each assessment will vary depending on the needs of the local government, and the quality of the local information available, but the framework will be scalable and flexible to accommodate this.

The framework proposed uses a Whole of Government (WoG) collaborative approach, with engagement and consultation across all three tiers of government, as well as relevant researchers where required. The approach can utilise team interaction and multiple cycles of data collection followed by data review/analysis. The methodology would accommodate a rapid assessment phase (2 to 3 months) if required, and importantly the framework should enable a quick assessment of the quality of the information available, so that any limitations of such a rapid assessment are identified. Equally, if a more thorough assessment is needed, the same framework can be applied, and any data/knowledge gaps for such an assessment will be quickly identified.

By using a systems approach, consideration of all aspects of the local situation quickly moves toward the definition of a model that identifies and focuses on the most important elements and their relationship to each other.

Importantly, this methodology will be scalable; i.e. where the information is detailed the output will directly be able to assist in the selection of an appropriate adaptation response (e.g. planned retreat). However, where the quality and coverage of the data is coarser or less accurate, a ‘Second Pass’ vulnerability of the LGAs coastline to recession/impact will be required, then enabling LGAs to make informed planning decisions or identify areas for further detailed study.

It is envisaged that the key steps below would form the basis of the methodology:

1. Consultation and stakeholder engagement to determine the requirements of the assessment.

2. Collation of existing datasets into a nationally consistent data framework for the LGA
   - *Smartline* & Coastal Geomorphology
   - Elevation data – LiDAR, or best available from the National Elevation Data Frameworks (NEDF), UDEM Portal
   - Data from regional (State) or local studies – through collaboration with state and local government stakeholders. Emphasis here is to discover additional information from the state and local level studies.

3. Conduct historical shoreline analysis to identify (where possible) trends in local shoreline behaviour under known rates of sea-level rise. There has been significant literature published recently demonstrating the utility of undertaking detailed historical shoreline analysis (Frazer *et al.*, 2009; Genz *et al.*, 2009; Romine *et al.*, 2009; Ruggiero and List 2009) using the following datasets to identify environmental and anthropogenic forcing at local scales;
   - Historical aerial photography (digitised and ortho-rectified) from federal, state and local collections
   - Cadastral data, including early surveys and maps
   - Digitising shoreline (using suitable proxy) through time

4. Mapping and quantification of coastal development through examination of the change in temporal and spatial extent using local data (development plans and cadastral data) specifically to locate coastal development that may have impacted/exacerbated potential vulnerability. Projections of coastal development based on spatially-enabled ABS and other data will increase knowledge of future exposure and vulnerability

5. Data Analysis - modelling future shoreline behaviour using appropriate scenarios and modelling tools
   - Nationally agreed SLR projections / scenarios (note that these could still vary at regional or State level) and storm surge data where available
   - Local geology and geomorphology data
   - Local wave climate data
   - Coastal and estuarine response to climate change
   - Coastal and riverine inundation modelling
   - Models: Commercially available products (MIKE, Delft3D, GCOM2D, MMUSURGE, TUFLOW), University of Sydney's Shoreline Translation Model, ANUGA (Open source).

6. Infrastructure Exposure Assessment
   - Inclusion of LGA specific building data where available into NEXIS
   - Overlay the data in Step 5 with NEXIS to determine potential vulnerability of LGA property and infrastructure.

7. Creation of outputs – To be confirmed through stakeholder engagement. However, it is expected that these will include;
    - Vulnerability and Hazard map(s) identifying areas of the LGA potentially at risk (from inundation/recession) under nationally consistent SLR scenarios
    - Datasets for inclusion in the National Database
    - Inventory of exposed populations and exposure for present day and future projections, and valuations of those assets.

Geoscience Australia is strategically and technically well placed to partner with DCCEE to develop this Framework, and National Coastal Zone Database / portal. Specifically, Geoscience Australia has the following:

- an existing capability and responsibilities in the development, management and provision of scalable, national datasets such as the National Topographic Maps;
- contribution to the development, and hosting of the National Elevation Data Framework and Urban DEM Portal;
- contribution to the development and hosting of the OzCoasts Web Portal;
- ongoing work being conducted under the National Coastal Vulnerability Assessment for the DCCEE, including the geomorphic polygon mapping and the detailed coastal vulnerability and risk assessment;
- preparation, and hosting, of the National Flood Studies Database that is an inventory of riverine flood studies undertaken across the country;
- extensive experience in stakeholder engagement and management with Emergency Managers to achieve similar outcomes to those sought here (i.e. Geoscience Australia led development and agreement on the National Risk Assessment Framework for sudden onset natural hazards as a part of the COAG Natural Disasters reforms).
- Geoscience Australia also has established excellent relationships with State Governments through the National Topographic Mapping project.

7. References

ABS 2006. Australian Bureau of Statistics (ABS) Population Projections, Australia, 2004 to 2101. Reissue 14/06/2006. http://www.abs.gov.au/Ausstats/abs@.nsf/mf/3222.0

ABS 2008. Australian Bureau of Statistics (ABS) Population Projections, Australia, 2006 to 2101. Released 04/09/2008. Available at http://www.abs.gov.au/Ausstats/abs@.nsf/mf/3222.0

Bird E.C.F. 1993. Submerging Coasts: The effects of a Rising Sea-level on Coastal Environments. Wiley and Sons, Chichester. Pp 184.

Chen, K. and McAneney, K.J.,2006. High-resolution estimates of Australian coastal population. *Geophysical Research Letters*, 33, L16601, doi:10.1029/2006GL026981.

Census 2006. Census of population and housing. Australian Bureau of Statistics, Available at: http://www.abs.gov.au/websitedbs/d3310114.nsf/51c9a3d36edfd0dfca256acb00118404/b9504d79bc140d7eca25715e0027d788!OpenDocument

Church, J.A., N.J. White, T. Aarup, W.S. Wilson, P.L. Woodworth, C.M. Domingues, J.R. Hunter & K. Lambeck 2008. Understanding global sea levels: past, present and future. *Sustainability Science*, Special Feature: Original Article, doi:10.1007/s11625-008-0042-4.

Church, J. A. and N.J. White 2011. Sea-level rise from the late 19th to the early 21st Century. *Surveys in Geophysics*, 32, 585-602, doi:10.1007/s10712-011-9119-1

CoA, 2009. Managing our coastal zone in a changing climate: the time to act is now, Parliamentary Inquiry into climate change and environmental impacts on coastal communities, House of Representatives Standing Committee on Climate Change, Water, Environment and the Arts, October 2009. http://www.aph.gov.au/house/committee/ccwea/coastalzone/report.htm

COAG. 2002. Natural Disasters in Australia: Reforming mitigation, relief and recovery arrangements, Council of Australian Governments, Available at http://www.ag.gov.au/www/emaweb/emaweb.nsf/Page/Publications_ProgramPublications_CouncilofAustralianGovernments_COAGReportonNaturalDisastersinAustralia

CSIRO, 2007. Climate change in Australia. http://climatechangeinaustralia.com.au/

DCC 2009. Climate Change Risks to Australia's Coast: A first pass National Assessment, Published by the Federal Department of Climate Change, November 2009. http://www.climatechange.gov.au/en/publications/coastline/climate-change-risks-to-australias-coasts.aspx

Frazer, L. N., Genz, A. S. and Fletcher, C. H., 2009. Towards Parsimony in Shoreline Change Prediction (I): Basis Function Methods. *Journal of Coastal Research*, 25(2), 366-379.

Genz, A. S., Frazer, L. N. and Fletcher, C. H., 2009. Towards Parsimony in Shoreline Change Prediction (II): Applying Basis Function Methods to Real and Synthetic Data. *Journal of Coastal Research*, 25(2), 380-692.

Helman, P., Thomalla, F. and Metusela, C. 2010. Historical Case Studies – 'Storm Tides', Griffith Centre for Coastal Management Research Report No, 105.1

Hubbert, G. D., and McInnes, K. L. 1999. A storm surge inundation model for coastal planning and impact studies. *Journal of Coastal Research*, 15, 168-185.

IPCC 2007. Climate Change 2007. Climate Change Impacts, Adaptation and Vulnerability, Summary for Policy Makers, April 6, 2007.

Klein, R.J.T., Nicholls, R.J. and Thomalla, F. 2003. Resilience to natural hazards: How useful is this concept?'.*Environmental Hazards*, 5:35-45.

McInnes, K.L., K.J.E. Walsh, G. D. Hubbert and T. Beer, 2003: Impact of Sea-level Rise and Storm Surges on a Coastal Community. *Natural Hazards,* 30(2), 187-207.

McInnes, K.L., Macadam, I., Hubbert, G.D. and O'Grady, J.G. 2009. A Modeling Approach for Estimating the Frequency of Sea-level Extremes and the Impact of Climate Change in Southeast Australia. *Natural Hazards*. 51, 115-137, doi:10.1007/s11069-009-9383-2.

Nadimpalli, K. Edwards, M. and Mullaly, D. 2007. National Exposure Information System (NEXIS) for Australia: Risk Assessment Opportunities (MODSIM 2007; International Congress on Modelling and Simulation. Oxley, L. and Kulasiri, D. (Eds)) 1674-1680

NCCAF 2007. National Climate Change Adaptation Framework, http://www.coag.gov.au/coag_meeting_outcomes/2007-04-13/docs/national_climate_change_adaption_framework.pdf

Nicholls, R.J. and Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. *Science*, 328, 1517-1519

Pfeffer, W.T., Harper, J. T. and O'Neel, S. 2008. Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise. *Science*, Vol. 321. no. 5894, pp. 1340–1343

Rahmstorf, S. 2010. A new view on sea level rise. *Nature reports,* Vol. 4. pp. 44-45

Romine, B. M., Fletcher, C. H., Frazer, L. N., Genz, A. S., Barbee, M. M. and Lim, S-C., 2009. Historical Shoreline Change, Southeast Oahu, Hawaii; Applying Polynomial Models to Calculate Shoreline Change Rates. *Journal of Coastal Research*, 25(2), 1236-1253.

Ruggiero, P. and List, J, H., 2009. Improving Accuracy and Statistical Reliability to Shoreline Position and Change Rate Estimates. *Journal of Coastal Research*, 25(5), 1069-1081.

Woodworth, P.L., N.J. White, S. Jevrejeva, S. J. Holgate, J. A. Church, and W. R. Gehrels 2009. Evidence for the accelerations of sea level on multi-decade and century timescales. *International Journal of Climatology*, 29, 777-789, doi:10.1002/joc.1771.

Zhang, K., B. C. Douglas, and S.P. Leatherman. 2004. Global Warming and Coastal Erosion. *Climatic Change,* 64: 41-58.

APPENDIX 1.

Sub-project Report - Coastal Inundation Modelling

29th May 2009

Dr RE Mount and Dr MJ Lacey

Spatial Sciences Group,
School of Geography and Environmental Studies,
University of Tasmania

UTAS

Executive Summary

- This work takes a **conservative approach** to address the problem of determining where inundation of the Australian coastline by the sea may occur in a small set of climate change scenarios for 2030 and 2100.
    - It is conservative in that it errs on the side of caution and uses the IPCC's "high emissions" scenarios when setting the contributing inputs to the modelling including **sea level rise** due to oceanic warming and **storm tide levels** due to increased wind strengths.
    - It is also conservative because it is a **simple model** of only a few of the contributing factors to inundation of the shoreline. The "bathtub" method used here is essentially a passive model and assumes a calm sea surface. It doesn't account for the complexity of the full range of interacting factors and forces that actually occur on the shoreline such as erosion, soil types, wave climate, wind, event timing or freshwater flooding.
- The approach taken is **considered to be useful** because it is a simple, fast method that indicates locations with the potential for inundation with a degree of spatial resolution that can, if used judiciously and with other lines of evidence, assist with prioritising further activity.
- The **major data sources** include:
    - Digital elevation models – SPOT Image
    - Storm Tide modelling in Temperate Australia – Kathy McInnes, CSIRO
    - Modelled high water – National Tidal Centre, BOM
    - Sea level rise estimates – John Hunter, CSIRO/ACE CRC
- **Improvements** to the work can most usefully be made by:
    - Upgrading the accuracy of the Australian vertical height datum (currently AHD71)
    - Using higher resolution and more accurate digital elevation models (e.g. Lidar)
    - Extending the storm tide modelling around the coast
    - Confirming the accuracy of the National Tidal Centre's Highest Astronomic Tide (HAT) modelling for Australia
    - Modelling a tidal attenuation coefficient for estuaries using the OzEstuaries database

Project aim and purpose

The aim of this modelling is to provide spatially explicit indicative representations of land potentially inundated by the sea using projections for sea level rise for the year 2030 from the IPCC scenario A1FI (IPCC 2001; 2007), predicted sea levels for 2100 sourced from the Atmosphere and Climate Ecosystems (ACE) CRC (Church *et al.* 2008; Hunter 2009) and modelled storm tide predictions (McInnes *et al.* 2009; Appendix 1.2). It includes consideration of the spatial resolution and accuracy of the available data sets at the national scale.

It is intended to be used as an input, along with the Smartline geomorphic sensitivity classes and their derived "zones of potential instability" sub-project outputs, to modelling work by Geoscience Australia that will assist in prioritising activities that will contribute to Australia's response to coastal impacts caused by climate change. This work is being conducted under the Australian Coastal Vulnerability project and is sponsored by the Australian Government's Department of Climate Change.

Project Limitations

It is unusual to discuss limitations so early in a report; however, given the acute interest in this work it is considered important to highlight the limitations of this inundation modelling so that any users are under no illusions about the characteristics of the data and information produced by this work.

This subproject's inundation modelling uses the "bathtub" inundation method (Eastman, 1993). In this approach, sea level components (including sea level rise estimates, tidal range and storm surge) together with their associated error estimates, are combined with a digital elevation model (DEM) to calculate a spatial grid over the area of interest showing the locations likely to be inundated given the model settings and constraints. The positions of possible future shorelines were extracted from the grid model.

It is important to note that the result **does not show the "probability of inundation" per se** but is actually showing a "spread" of estimated shoreline positions with a probability limited to that derived from the combination of errors propagated from the inputs. It is designed to give the most likely position of a new shoreline but that likelihood is limited to what is known about the errors in the data inputs.

Note also that not all variables relevant to the accurate modelling and prediction of new shoreline positions are currently available for all the locations of interest around the coast, that is, there are limitations on the available data inputs at the national scale. For example, there is no consideration of the complex interactions between erosion, coastal recession and inundation. The "bathtub" method is essentially a passive model and assumes a calm sea surface. It is useful because it is a simple, fast method that indicates locations with the potential for inundation and can, if used judiciously and with other lines of evidence, assist with prioritising further activity.

Definitions

A1FI	The IPCC's "high emission" scenario
AR4	IPCC Fourth Assessment Report (IPCC 2007)
DCC	Department of Climate Change, Australian Government
DEM	digital elevation model, a surface representing the surface heights of the land
GA	Geoscience Australia
IPCC	Intergovernmental Panel on Climate Change
Lidar	light direction and ranging
Radar	radio direction and ranging
SLR	sea level rise
SPOT	Spot Image: a supplier of satellite imagery and derived products including DEMs
SRTM	Shuttle Radar Terrestrial Mission
Storm Tide	A combination of the tidal component plus any raised sea level due to wind set up or reduced air pressure. It is what is measured at tide gauges during a storm event.
TAR	IPCC Third Assessment Report (IPCC 2001)

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Colin Woodroffe, Wollongong University

Chris Sharples, Chris Watson, and Tore Pedersen Spatial Sciences Group, School of Geography and Environmental Studies, University of Tasmania

Method

The project's inundation modelling used the "bathtub" inundation method (Eastman, 1993). The "bathtub" method is essentially a passive model and assumes a calm sea surface.

In summary, sea level components, including estimates of sea level rise, tidal range and storm surge (where available), together with their associated error estimates, were combined with a digital elevation model (DEM) to calculate a spatial grid over the area of interest showing the locations likely to be inundated given the model settings and constraints. The positions of possible future shorelines were then extracted from the grid model.

It is important to note that the result does not show the "probability of inundation" per se but is actually showing a "spread" of estimated shoreline positions with a probability limited to that derived from the combination of errors propagated from the inputs. It is designed to give the most likely position of a new shoreline but that likelihood is limited to what is known about the errors in the data inputs.

Importantly, not all variables relevant to the accurate modelling and prediction of new shoreline positions are available for all the locations of interest around the coast, that is, there are limitations on the available data inputs especially at the national scale. For example, there is no consideration of the complex interactions between erosion, coastal recession and inundation.

Figure A1.1 illustrates with a schematic diagram how the inundation estimates are calculated for a DEM and a single input, here SLR. When adding in the storm and tide inputs the heights are simply summed with the SLR and the combined error calculated to estimate the likely sea level.

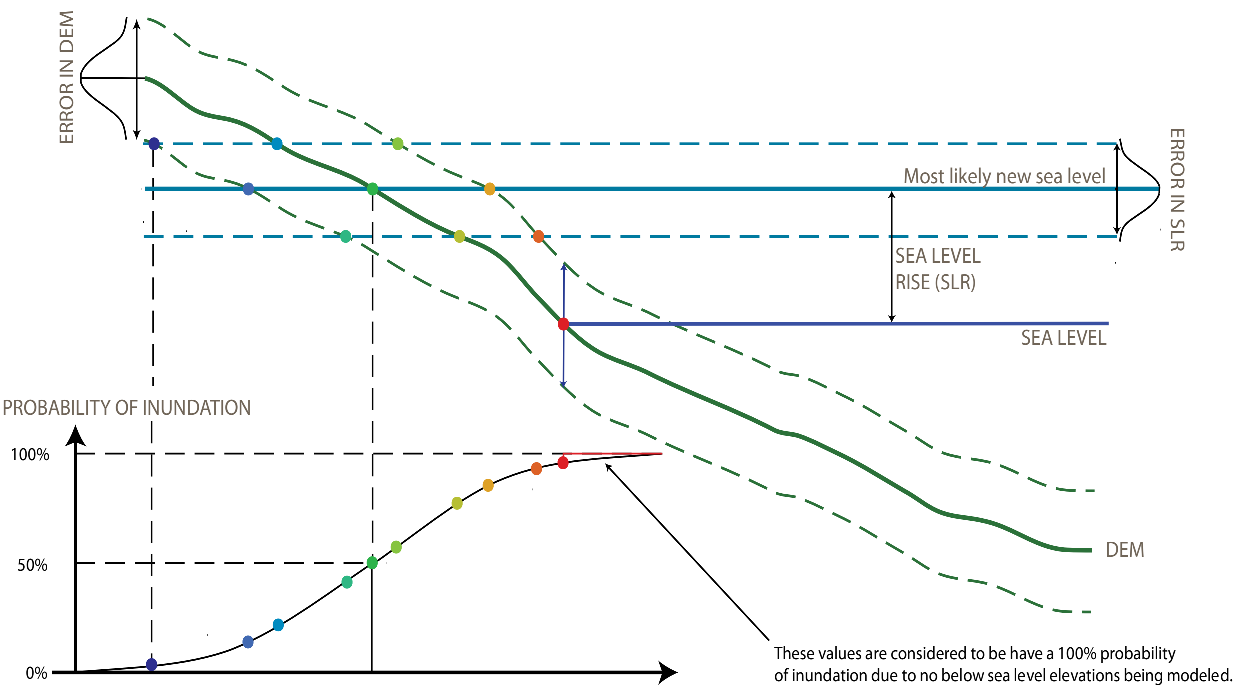


Figure A1.1. Schematic of the inundation model. The known errors (inaccuracies) in the input data (here, the SLR estimates and the DEM) are combined to produce the probable "spread" of future shoreline positions. These probabilities are, in effect, "mapped" back onto the DEM.

The starting inputs include:

- A DEM in which height error is estimated and assumed to be normally distributed
- The initial sea level, which is a function of the height datum of the DEM,
- Tide and storm surge estimates including error estimates, and
- Sea level rise components together with their respective height errors.

The output is a grid representing the probability of a resultant shoreline position based on the inputs. A shoreline can then be drawn at a selected probability level (here, 50%).

There are a number of potential sets of inputs to the bathtub model. Firstly, as documented in detail in this report, the inundation may be modelled as the sum of individually modelled components including tidal range, sea level rise and storm surge estimates. These can be separately entered into the model along with their individual RMS error estimates. The first two estimates are available, with acknowledged limitations, for the entire Australian coast though storm surge estimates are not.

Alternative forms of the inputs were considered. Firstly, using a method that is designed to include all of the sea level constituents together, John Hunter has estimated extreme sea level probabilities from empirical measurements of the actual sea levels obtained via observations for at least 30 years at tide stations around Australia and explicitly including sea level rise estimates (Hunter 2009). While the value of this approach is acknowledged, there are complex problems encountered when attempting to extrapolate the exceedences around the coastline between the tide stations. Unfortunately, it was, therefore, not possible to use the results in this work.

Secondly, an alternative to separately estimated tidal range and storm surge levels has been under development in Australia by CSIRO (e.g., McInnes *et al.* 2009). The approach estimates combined storm and tide levels, i.e. "storm tide", for current and future scenarios with 2D and 3D hydrodynamic models based on a combination of inputs including extreme tide gauge observations, and global wind and astronomical tide models (McInnes *et al.* 2009; Appendix A1.2). The results of the storm tide modelling were only available for Victoria, Tasmania and NSW within the timeframe of this subproject. Where available they were used and in their absence the standard mean high tide estimates sourced from the National Tidal Facility, BOM were used as a proxy. This was considered the next best option as it gives a consistent nationwide approach.

Combination of errors

The combined error of the inputs is the square root of the sum of squared standard deviations of the individual sea level components and of the DEM.

$$\sigma_z = \sqrt{\left(\sigma_x{}^2 + \sigma_y{}^2\right)}$$

Formula for combining RMS errors

Inundation model inputs

The following sections describe in detail the inputs to the modelling process. A number of issues are highlighted and the approaches taken to address those issues are presented.

DEM

Two digital elevation models were available for use around the Australian coastline within the timeframe of this project – the Shuttle Radar Terrestrial Mission (SRTM) DEM, which has been recently updated to a new version, and the very recently created SPOT Reference3D DEM, which was commissioned by the DCC.

SPOT DEM

The Reference3D geocell tiles each cover one square degree. Individual grid cells cover one arc second in the Australian latitude range and have a height resolution of 1 metre. Coordinates are geographic, using WGS84. Vertical datum is EGM96 (please see the important discussion in the "Datum Choice" section).

Absolute elevation accuracy for flat and rolling terrain (slopes of less than or equal to 20%) has a 90% confidence interval of 10 metres with respect to EGM96 (SPOT IMAGE, 2007). This translates to a standard deviation of 6.08 metres.

A series of quality control masks are used in producing the SPOT DEM including a water mask that was produced by "manual delineation" of maritime water bodies including, we understand, using "fair sheets" from the RANH. The process also included "flattening of the DEM to a constant level" within maritime water bodies and the "raising of negative Z areas near coastlines". As this boundary is of critical interest to the project, further clarification of the accuracy of these methods is warranted. Further, given that the method uses optical stereo pairs to generate the DEM, there may be consistent errors where the DEM is created over the top of vegetation canopies. This could be particularly problematic in mangrove dominated areas and could be leading to 2-3 m "cliffs" in these areas.

Not all the Australian coastline was expected to be covered by SPOT DEM tiles within the timeline of this project; however, the entire coast was delivered apart from a small area on Cape York. Where the SPOT DEM was not available for parts of the coast, the SRTM DEM was substituted. Conveniently, SPOT and SRTM grid cells are aligned so that 9 SPOT grid cells fit within a SRTM grid cell.

SRTM-3 v2

The SRTM DEM covers of the whole of the Australian continent with three arc second grid cell size and has a height resolution of 1 metre. Standard deviation of the SRTM height error over the Australian region is quoted as 3.5 metres (Rodrigues et al., 2005) with the corresponding 90% level being 6.0 metres and mean height error of $\pm$1.8m. Coordinates are geographic, using WGS84. The following are extracts from Rodrigues et al., 2005:

"For the SRTM mission, the EGM96, the TOPEX mean sea surface, together with a tidal model tuned for coastal accuracy, were used to generate ocean ground-truth surfaces."

"SRTM did not always map the true ground surface. Instead it measured an effective height determined by the phase of the complex vector sum of all the returned signals from within the pixel being imaged. If the pixel contained bare ground, the phase reflected the height of the surface. If the ground was covered with vegetation, the return was influenced by the vegetation height, structure, and density."

"…..the height of any urban SRTM pixel will be affected by the buildings within that pixel. Thus, heights measured in cities will represent average building sizes, rather than the height of the ground on which the buildings sit."

These limitations must be taken into account when interpreting the results produced when the STRM DEM is an input. For example, land surface heights in areas of mangroves are likely to over-estimated by the SRTM DEM leading to a reduced likelihood of modelled inundation. Secondly, the difference (separation) between the EGM96 ellipsoid and the Australian Height Datum (AHD71) needs to be considered and accounted for – this issue is addressed in detail below in the "Datum Choice" section.

Sea Level Rise (SLR)

Two scenario dates are used for SLR in this modelling; 2030 and 2100. Both were identified by the DCC and confirmed by Geoscience Australia for use.

Firstly, for 2030, SLR estimates is based on the A1FI scenario (IPCC 2007) which forecasts a rise of 0.146 m relative to 1980-1999. This scenario is at the higher end of the AR4 projections and assumes ongoing high emissions.

Secondly, for 2100, a "high end" estimate of 1.1. m SLR was sourced from the Antarctic and Climate Ecosystems (ACE) CRC group including John Church and John Hunter.

No SLR error estimates were included in the inundation model as these SLR values were taken to be scenario "givens" rather than estimates. That is, the modelling was completed as if there definitely was 0.146 m and 1.1 m of SLR for 2030 and 2100 respectively.

Storm tide

Storm tide surface modelling is proceeding along the temperate shores of Australia with 2D and 3D hydrodynamic models that receive inputs from observed measurements at tide gauges and global tide and wind models. The methods are explained in detail in a series of CSIRO papers, including McInnes *et al.* (2009), and summarised for this report in Appendix A1.2.

Preliminary storm tide surface data associated with 1 in 100 year return periods was obtained from Kathy McInnes for Victoria, Tasmania and NSW.

Estimates of error values to use with storm tide data were obtained from similar tidal modelling by John Hunter (pers. comm.) involving some of the same data inputs. RMS error values for his modelled tidal maxima for Point Lonsdale for the years 2000, 2030 and 2070 are 0.10, 0.10 and 0.13 metres respectively. For 2100 the error estimate for 2070 was used.

Tidal range

Where storm tide surfaces were not available the standard NTC modelled high water surface was used. The standard tidal range modelled data was obtained from the National Tidal Centre (NTC) in the form of a five minute resolution grid of points extending from longitude 111º to 116º East and from latitude 9º to 45º South. This model represents tidal amplitudes in metres between Mean Sea Level and Indian Spring Low Water multiplied by two to give an estimate of the complete tidal range. It includes the four main tidal constituents, M2, S2, O1 and K1, and was calculated as:

Tidal amplitude = (M2 + S2 + O1 + K1) amplitudes * 2

Error estimates associated with individual tidal components for 80 tide gauge locations were also obtained from the National Tidal Centre. Calculation of error associated with the model is complex and takes into account phase shifts in the individual tidal components.

An average estimate of height error in the tidal range model for 80 tide gauge locations was calculated as 0.155 metres. This was calculated as the square root of the sum of squared mean errors of the individual tidal constituents used in the model.

Note that a second tide range model of Lowest and Highest Astronomic Tide heights (LAT and HAT) was obtained from the NTC. This model includes LAT and HAT computations based on NTC Australian region tidal model inclusive of eight major tidal constituents: M2, S2, O1, K1, P1, Q1, N2 and K2. The model was created following a request from this project.

A comparison was made by NTC between the modelled data with LAT HAT observations at 100 ports (inclusive of up to 112 tidal constituents). The general trend shows the model (8 constituents) captures on average around 87% of observed (112 constituents) LAT/HAT variability. Unfortunately, the modelled HAT heights were in some places lower than the high tide modelled with only four constituents (see Figure A1.2). This means there is some doubt raised over both tidal models and, given that doubt, it was considered prudent to use the standard tidal range model.

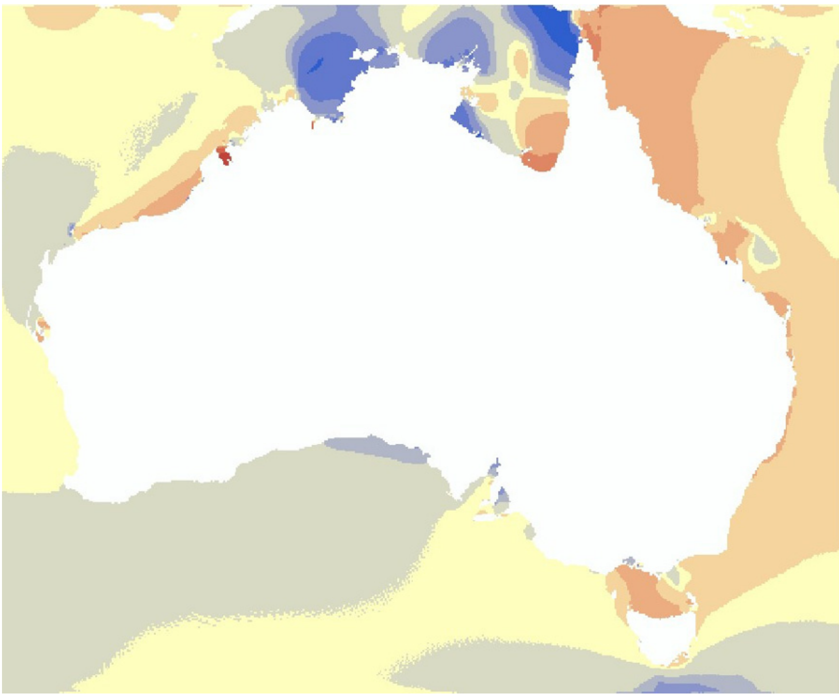


Figure A1.2. Differences between the modelled HAT and the high water level in the standard NTC tidal range model. Note that the red areas indicate where HAT is above the standard high water and blue areas indicate it is below.

The NTC have identified that possible future efforts to improve the eight constituent model include:

1. Devise a grid of Sa and Ssa (12-month and 6-month sea level cycles), perhaps by way of surface fitting to observations, and include these in computations
2. Include another 15 or so related constituents to the 8 modelled by way of equilibrium tidal relationships.

Datum choice

There are a number of challenging issues associated with selecting an optimum vertical datum for the inundation modelling work. While the key input of the DEMs were supplied in the vertical datum of EGM96, the rest of the data, and, indeed, the preferred vertical datum, is the Australian Height Datum 1971 (AHD71). AHD71 is preferred as, despite some drawbacks detailed below, it is designed to be 0 m at the measured mean sea level and is tied to actual sea level observations collected at a large network of tide stations around Australia.

It became apparent that there were significant but unquantified differences between the two datums, and their respective estimated surfaces, and, following discussions with the Geodesy Group at Geoscience Australia, they modelled the difference as a "correction surface" for the purposes of this project (see Appendix A1.3.1 for details). The differences are indeed significant, particularly in the north of Australia, where EGM96 height values ranged up to 1 m higher than the AHD71 height values at the same location (i.e. 2 m EGM96 = 1 m AHD71). The correction surface itself highlights problems and inaccuracies within AHD71 and these problems are considered a significant issue for any further inundation work in Australia.

The correction surface, and its associated error estimates, was incorporated in to the inundation modelling as simply another layer needed to determine extreme sea levels.

The following are some definitions and comments about some of the relevant factors in the choice of datum

Datum Definitions and comments

AHD71
Australian Height Datum (AHD71) is the current official standard Australian height reference (ICSM, 2006). It is based on a limited set of mean sea level measurements for the epoch 1966 to 1968 for thirty Australian tide gauges. For Tasmania it is based on mean sea level at Burnie and Hobart tide gauges in 1972. For a number of reasons including suboptimal location of some tide gauges, limited period of the reference sea level determination and non-inclusion of sea level topography AHD is an approximation of mean sea level.

AUSGeoid98
AUSGeoid98 is the latest of a series of Australian national geoid models and is a modelled equipotential surface for the Australian continent (ICSM, 2006). It closely approximates but does not coincide exactly with mean sea level. There is a north-south gradation of almost a metre in the difference between this geoid and the Australian Height Datum (AHD71).

EGM96
The EGM96 ellipsoid is the height datum used by both the SPOT and SRTM DEMS.

WGS84/GRS80
The ellipsoid used by GPS and other satellite navigation systems

Mean Sea Level
For a tidal station Mean Sea Level is the mean over a period of time of the hourly heights at that station (ICSM, 2007).

Mean High Water
The average of all high waters over a period of time (ICSM, 2007).

Implementation

Geoprocessing preparation

Model inputs were prepared as per the previous section using generic ArcGIS 9.3 (ESRI 2008) tools.

DEMs

A choice was made to process all the DEM data using the same grid cell size and coordinate system as the SPOT DEM. Where used the SRTM DEM was re-sampled to the same cell size as the SPOT DEM which effectively meant increasing the number of cells by nine. Both DEMs were projected into in GDA94 for processing.

SLR

A separate grid was calculated for each sea level rise scenario using ArcToolbox. These grids consisted of a single floating point value. Grids were calculated with the same raster settings and extent as the DEM to be used in the analysis.

Storm Tide and Tidal Range

Modelled storm tide and tidal range data consisted of two series of points. Storm tide had been calculated for points along portions of the coastline while the tidal range data existed as points around the whole Australian coast. The modelled points were all on the seaward side of the coastline and usually did not extend to the coast, especially in the vicinity of bays and estuaries. A method was required to extend these modelled values landward to overlap the DEMs.

Euclidean Allocation (ArcTools>EucAllocation) was the method used to create a grid for each of these datasets. Grid cell values were allocated according to the minimum Euclidean distance from the source data point using this method. Grids were calculated with the same raster settings and extent as the DEM to be used in the analysis. Additionally a coastal zone mask was applied so that values were calculated inland to the maximum of either 500 m or to the 20 m contour. The 20 m contour was used as it was calculated to be higher than the expected height of any modelled sea level rise taking into account error ranges. Figure A1.3 shows an example from the output Euclidean Allocation grid of the storm tide data for Victoria with the masking applied.

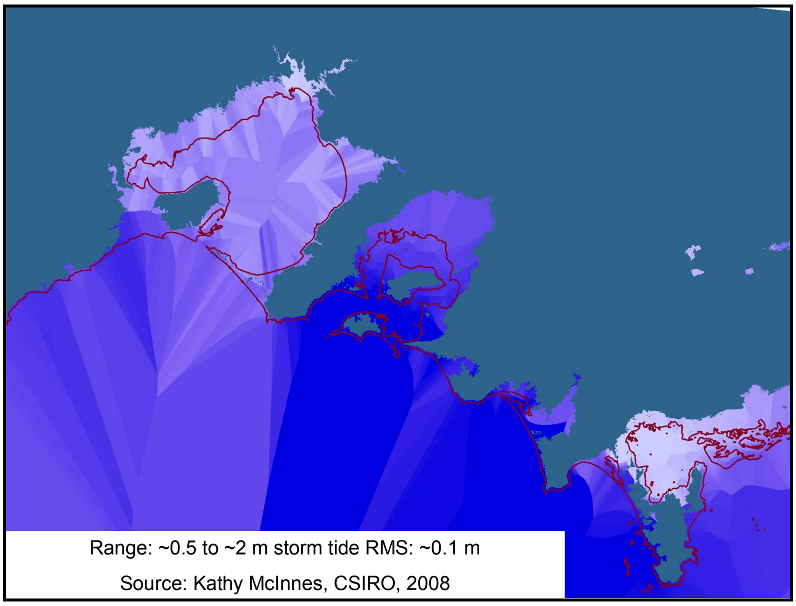
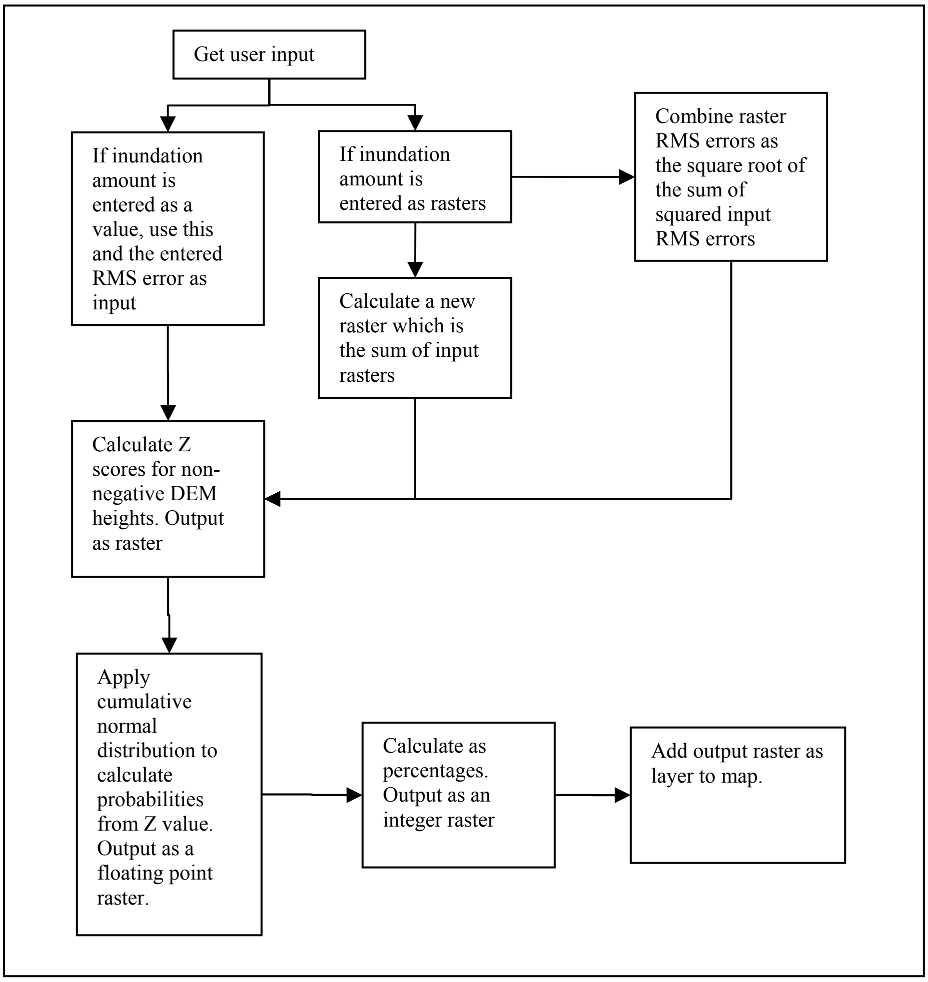


Figure A1.3. A portion of the Victorian coast showing the extent of the interpolated storm tide surface grid. While there are large artefacts visible in parts of this image, the surface is considered to adequately interpolate the modelled values along the shoreline for inundation modelling purposes.

Software and Scripting implementation

The inundation model is run as a tool within ArcMap. It was scripted in Visual Basic for Applications (VBA) as a module with an associated data entry form (Figure A1.4) which can be accessed via a toolbar button. Shown below is a diagrammatic representation of the steps in running the model. The script itself is included in Appendix A1.1.

Processing steps used by the inundation modelling tool



The cumulative normal distribution was approximated according to the following formula adapted from Knight (2006).

((0.5 - (((exp(- sqr([ZValue]) / 2)) / 2.5066282746) * (1 / (1 + (0.33267 * [ZValue]))) * (0.4361836 + (1 / (1 + (0.33267 * [ZValue]))) * (((1 / (1 + (0.33267 * [ZValue]))) * 0.937298) - 0.120167)))) + 0.5))

Figure A1.4 is the user input form, which is used to enter input the chosen data sets. With this form the user has a choice of whether to enter sea level rise values as text or as grids. For each input an associated RMS error can be entered. Entered values are processed by the model script.

Cell values in the output percentage grid show the probability that the coastline will be on or at a higher altitude than the cell position. A second tool can be applied to produce a polygon version depicting the projected coastline at a specific percentage probability selected by the user (e.g. 50%).

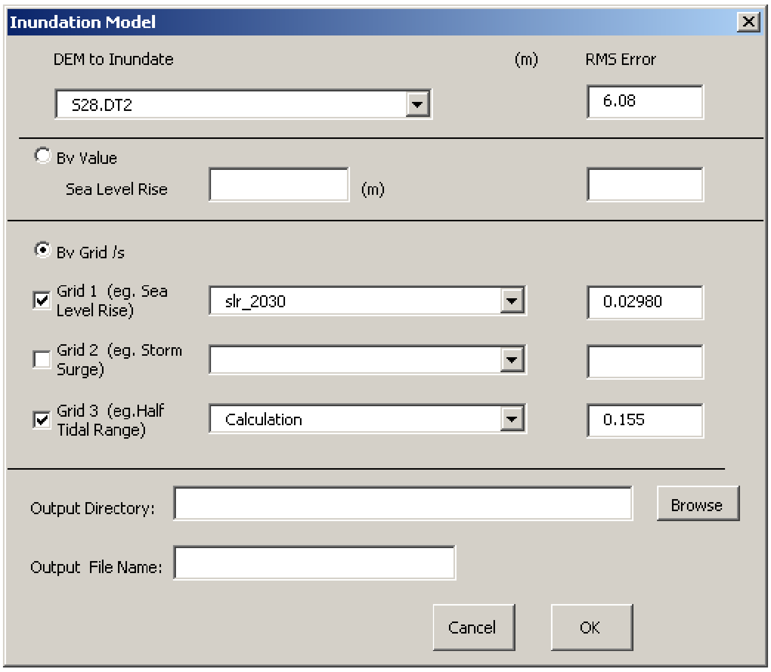


Figure A1.4. The data input form created for running the inundation modelling. The form calls VBA scripts.

The inundation script also logs a number of settings including date, start, end time and user input settings from the input form. These are logged to a csv file which is stored with the output raster.

Results

The following tables list the resulting output files and the inputs used to create them.

Queensland

Notes:	Inundation inputs used a combination of SPOT and SRTM DEMs. Most of the region was covered by SPOT except for part of Cape York. A shapefile (CapeYork_SRTM_only_mask.shp) is included with the combination outputs to show that region where SRTM was used in

Inundation modelling for Queensland with EGM96 to AHD71 correction applied

Scenario	**A1FI 2030**	**A1FI 2030**	**Highend 2100**	**Highend 2100**
Sea level rise (metres)	0.146	0.146	1.1	1.1
SLR RMS error	0	0	0	0
DEM	**SPOT**	**SRTM**	**SPOT**	**SRTM**
DEM RMS error	6.08	3.5	6.08	3.5
Tidal heights	Tidal Range (NTC)	Tidal Range (NTC)	Tidal Range (NTC)	Tidal Range (NTC)
Tidal heights RMS error	0.155	0.155	0.155	0.155
EGM96 to AHD71 correction applied	Yes	Yes	Yes	Yes
Separation layer RMS error	0.207	0.207	0.207	0.207
	North		**North**	
Probability grid output file name	**q1_146s_e**		**q1_1_1s_e**	
50% coastline shapefile name	**q1_146s_e_50.shp**		**q1_1_1s_e_50.shp**	
	Central		**Central**	
Probability grid output file name	**q2_146s_e**		**q2_1_1s_e**	
50% coastline shapefile name	**q2_146s_e_50.shp**		**q2_1_1s_e_50.shp**	
	South East		**South East**	
Probability grid output file name	**q3_146s_e**		**q3_1_1s_e**	
50% coastline shapefile name	**q3_146s_e_50.shp**		**q3_1_1s_e_50.shp**	
	Cape York (SPOT)		**Cape York (SPOT)**	
Probability grid output file name	**q4_146s_e**		**q4_1_1s_e**	
50% coastline shapefile name	**q4_146s_e_50.shp**		**q4_1_1s_e_50.shp**	
		Cape York (SRTM)		**Cape York (SRTM)**
Probability grid output file name		**q5_146r_e**		**q5_1_1r_e**
50% coastline shapefile name		**q5_146r_e_50.shp**		**q5_1_1r_e_50.shp**
Scenario	**A1FI 2030**		**Highend 2100**	
Whole state 50% coastline shapefile name	**Qld_146s_e_50_All.shp**		**Qld_1_1s_e_50_All.shp**	

NSW

Scenario	A1FI 2030	Highend 2100
Sea level rise (metres)	0.146	1.1
SLR RMS error	0	0
DEM	**SPOT**	**SPOT**
DEM RMS error	6.08	6.08
Tidal heights	Storm Tide (McInnes)	Storm Tide (McInnes)
Tidal heights RMS error	0.054	0.054
EGM96 to AHD71 correction applied	Yes	Yes
Separation layer RMS error	0.207	0.207
Probability grid output file name	**nsw_146s_e**	**nsw_1_1s_e**
50% coastline shapefile name	**nsw_146s_e_50.shp**	**nsw_1_1s_e_50.shp**

Tasmania

Notes:

SPOT DEM was used for all of Tasmania. Tide range was storm tide data from Kathy McInnes. An EGM96 to AHD71 correction was applied. This state was processed in one section. And a whole state 50% coastline shapefile was produced

Inundation modelling for Tasmania with EGM96 to AHD71 correction applied

Scenario	A1FI 2030	Highend 2100
Sea level rise (metres)	0.146	1.1
SLR RMS error	0	0
DEM	tas_spot	tas_spot
DEM RMS error	6.08	6.08
Tidal heights	Storm tide (McInnes)	Storm tide (McInnes)
Tidal heights RMS error	0.0825	0.0825
EGM96 to AHD71 correction applied	Yes	Yes
Separation layer RMS error	0.207	0.207
Whole state 50% coastline shapefile name	**tas_146s_e_50.shp**	**tas_1_1s_e_50.shp**

Victoria

Notes:	SPOT DEM was used for all of Victoria. Tide range was storm tide data from Kathy McInnes. An EGM96 to AHD71 correction was applied. This state was processed in two sections. Outputs for sections were later combined to produce whole state 50% coastline shapefiles.

Inundation modelling for Victoria with EGM96 to AHD71 correction applied

Scenario	A1FI 2030	Highend 2100
Sea level rise (metres)	0.146	1.1
SLR RMS error	0	0
DEM	SPOT	SPOT
DEM RMS error	6.08	6.08
Tidal heights	Storm tide (McInnes)	Storm tide (McInnes)
Tidal heights RMS error	0.0896	0.0896
EGM96 to AHD71 correction applied	Yes	Yes
Separation layer RMS error	0.207	0.207
	Eastern section	
Probability grid output file name	**v1_146s_e**	**v1_1_1s_e**
50% coastline shapefile name	**v1_146s_e_50.shp**	**v1_1_1s_e_50.shp**
	Western section	
Probability grid output file name	**v2_146s_e**	**v2_1_1s_e**
50% coastline shapefile name	**v2_146s_e.shp**	**v2_1_1s_e.shp**
	Whole state (combined sections)	
Whole state 50% coastline shapefile name	**SA_146s_e_50_All.shp**	**SA_1_1s_e_50_All.shp**

SA

Notes:	SPOT DEM was used for all of SA. Tide range data was from NTC. An EGM96 to AHD71 correction was applied. This state was processed in two sections. Outputs for sections were later combined to produce whole state 50% coastline shapefiles.

Inundation modelling for South Australia with EGM96 to AHD71 correction applied

Scenario	A1FI 2030	Highend 2100
Sea level rise (metres)	0.146	1.1
SLR RMS error	0	0
DEM	SPOT	SPOT
DEM RMS error	6.08	6.08
Tidal heights	Tidal Range (NTC)	Tidal Range (NTC)
Tidal heights RMS error	0.155	0.155
EGM96 to AHD71 correction applied	Yes	Yes
Separation layer RMS error	0.207	0.207
	Eastern section	
Probability grid output file name	**sv_1_1s_e**	**sv_146s_e**
50% coastline shapefile name	**sv_1_1s_e_50.shp**	**sv_146s_e_50.shp**
	Western section	
Probability grid output file name	**sa1_1_1s_e**	**sa1_146s_e**
50% coastline shapefile name	**sa1_1_1s_e.shp**	**sa1_146s_e.shp**
	Whole state (combined sections)	
Whole state 50% coastline shapefile name	**SA_1_1s_e_50_All.shp**	**SA_146s_e_50_All.shp**

WA

Scenario	**A1FI 2030**	**Highend 2100**
Sea level rise (metres)	0.146	1.1
SLR RMS error	0	0
DEM	**SPOT**	**SPOT**
DEM RMS error	6.08	6.08
Tidal heights	Tidal Range (NTC)	Tidal Range (NTC)
Tidal heights RMS error	0.155	0.155
EGM96 to AHD71 correction applied	Yes	Yes
Separation layer RMS error	0.207	0.207
	South	
Probability grid output file name	**wa1_146s_e**	**wa1_1_1s_e**
50% coastline shapefile name	**wa1_146s_e_50.shp**	**wa1_1_1s_e_50.shp**
	West	
Probability grid output file name	**wa2_146s_e**	**wa2_1_1s_e**
50% coastline shapefile name	**wa2_146s_e_50.shp**	**wa2_1_1s_e_50.shp**
	North-west	
Probability grid output file name	**wa3_146s_e**	**wa3_1_1s_e**
50% coastline shapefile name	**wa3_146s_e_50.shp**	**wa3_1_1s_e_50.shp**
	North	
Probability grid output file name	**wa4_146s_e**	**wa4_1_1s_e**
50% coastline shapefile name	**wa4_146s_e_50.shp**	**wa4_1_1s_e_50.shp**
	SPOT geocell S14E125	
Probability grid output file name	**wa4a_146s_e**	**wa4a_1_1s_e**
50% coastline shapefile name	**wa4a_146s_e_50.shp**	**wa4a_1_1s_e_50.shp**

NT

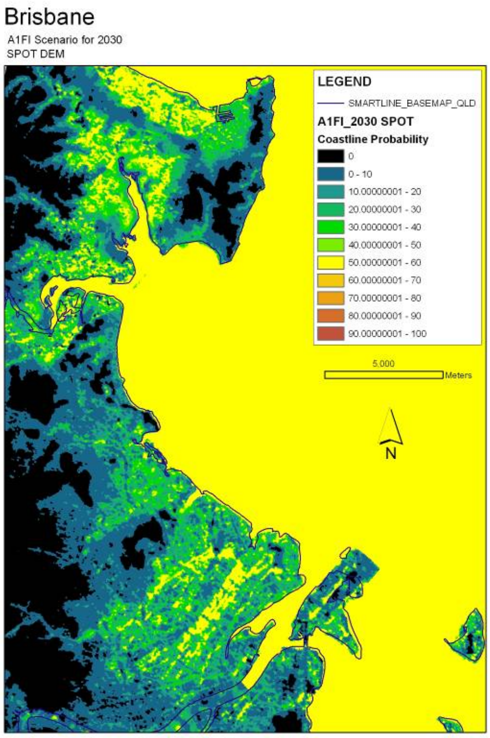
Notes:	Inundation inputs used a combination of SPOT and SRTM DEMs. Most of the region was covered by SPOT except for 3 geocells in the Arnhem Land region. A shapefile (NT_SRTM_only_mask.shp) is included with the combination outputs to show that region where SRTM was used in combination layers.

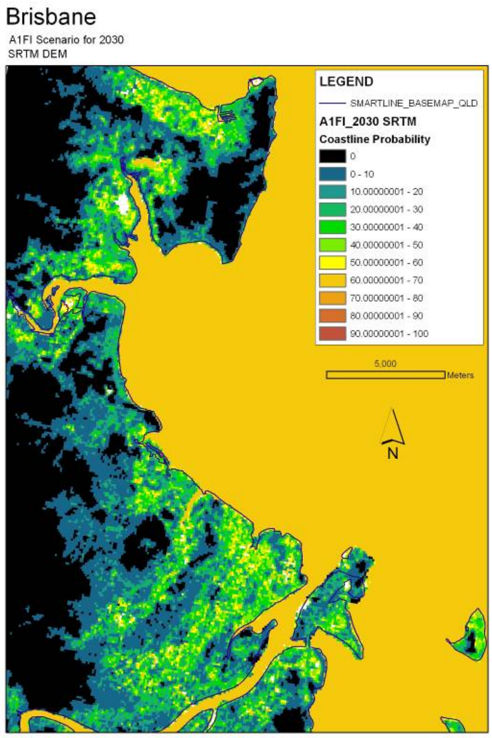
Inundation modelling for Northern Territory with EGM96 to AHD71 correction applied

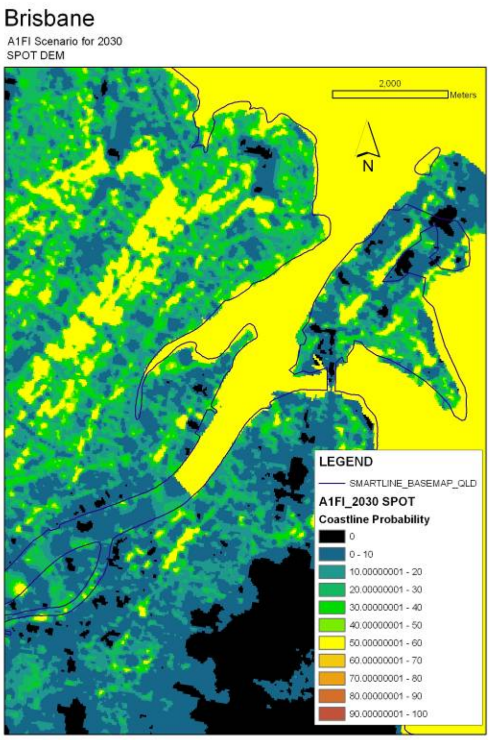
Scenario	A1FI 2030	Highend 2100	A1FI 2030	Highend 2100
Sea level rise (metres)	0.146	1.1	0.146	1.1
SLR RMS error	0	0	0	0
DEM	SPOT	SPOT	SRTM	SRTM
DEM RMS error	6.08	6.08	3.5	3.5
Tidal heights	Tidal Range (NTC)	Tidal Range (NTC)	Tidal Range (NTC)	Tidal Range (NTC)
Tidal heights RMS error	0.155	0.155	0.155	0.155
EGM96 to AHD71 correction applied	Yes	Yes	Yes	Yes
Separation layer RMS error	0.207	0.207	0.207	0.207
Probability grid output file name	**nt_146s_e**	**nt_1_1s_e**	**ntx_146r_e**	**ntx_1_1r_e**
50% coastline shapefile name	**nt_146s_e_50.shp**	**nt_1_1s_e_50.shp**	**ntx_146r_e_50.shp**	**ntx_1_1r_e_50.shp**

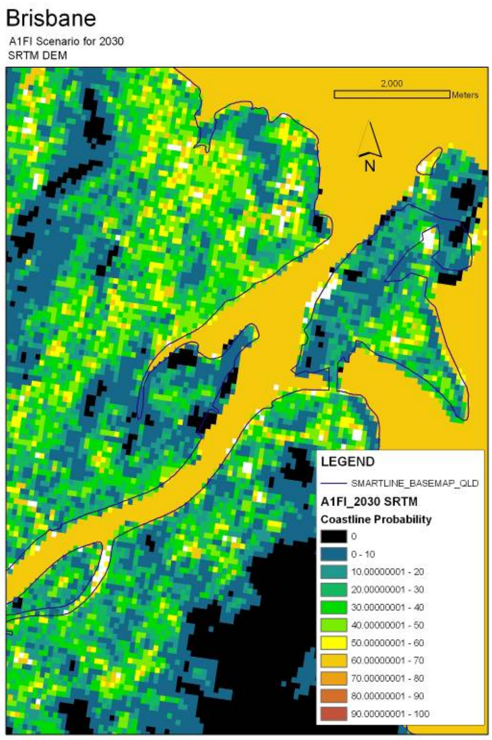
Minor Case Study

An informal comparison of the SPOT and SRTM DEMs around Brisbane airport









Notes:

- The SRTM DEM is more 'noisy'
- White cells in the SRTM output are where the DEM has negative values.
- Application of a water mask in the SPOT DEM has produced a stepping effect in rivers, estuaries and possibly parts of the coastline where the mask extends over the coast.
- Both DEMs appear to measure to the tops of trees, large buildings and other tall objects

References

Eastman, J.R., Kyem, P.A.K, Toledano, J., & Jin, W. (1993) GIS and decision making. Explorations in Geographic Information Systems Technology, Vol. 4. Geneva: United Nations Institute for Training and Research (UNITAR).

Church, J., J. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, M. Nhuan, D. Qin, and P. Woodworth (2001) Climate Change 2001: The Scientific Basis, Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Chapt. 11, pp. 639–693. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Hunter, J. (2009) Estimating sea-level extremes under conditions of uncertain sea-level rise. Climate Change (submitted)

IPCC (2001) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

SPOT IMAGE (2007) Reference3D product Description version 5.3 http://www.spotimage.fr/automne_modules_files/standard/public/p807_e66fdc8d9baeb629a19beb53be67339dReference3D_-_Product_description.pdf

Knight, William (2006) JavaScript program for the NORMAL DISTRIBUTION INTEGRAL, http://www.math.unb.ca/~knight/utility/normalj1.html , University of New Brunswick, (Last accessed 08/10/08)

Rodríguez, E., Morris, C.S., Belz, J.E.,. Chapin, E.C, Martin, J.M., Daffer, W., Hensley, S. (2005) An Assessment of the SRTM Topographic Products, Jet Propulsion Laboratory D-31639

ICSM, GDA technical Manual Version 2.3 (2006) http://www.icsm.gov.au/gda/gdatm/gdav2.3.pdf

Appendix A1.1 – Software scripts

Inundation modelling module 'F_modInundate'

```
Option Explicit

Dim pMxDoc As IMxDocument               'The current document
Dim pMap As IMap                        'The current Map
Dim nLayerCount As Integer              'The number of layers in the current map

'Function: InundateDEM
'Input: From Form
'Output: Raster With Probability values
'Description:
'Author: Luke Wallace
'Code modified by Michael Lacey, September 2008
'Date Created: 14th May 2008 ,Date Updated: ,Version: 0
'
'Called From: fRecessThis, Calls to: fGetPoint(2), fGetAlpha
Public Sub InundateDEM()
    Dim sSeaRise As String, dSeaRiseRMS As Double
    Dim dDemRMS As Double
    Dim dTotalRMS As Double
    Dim dSubRMS As Double
'added dSubVar  to substitute for square of dSubRMS (ML 16/9/08)
    Dim dSubVar As Double

    Dim pLayer As IRasterDataset
    Dim pRLayer As IRasterLayer
    Dim pInRaster As IRaster
    Dim pRiseRaster As IRaster

    Dim pAlgbOp As IMapAlgebraOp
    Dim sExp As String
    Dim pEnv As IRasterAnalysisEnvironment
    Dim pWS As IWorkspace
    Dim pWSF As IWorkspaceFactory

    Dim pOutRaster As IRaster
    Dim sOutputDir As String, sOutputName As String

    Dim i As Integer

    'log file number (ML270908)
    Dim LogFileNo
    LogFileNo = FreeFile
    'current date and time (ML270908)
    Dim CurTime, CurDate
    CurTime = Time
    CurDate = Date


    'Get the Map
    Set pMxDoc = ThisDocument
    Set pMap = pMxDoc.FocusMap

    'Prompt user for input
    frmInundate.Init
    If Not frmInundate.bContinue Then Exit Sub

    sOutputDir = frmInundate.txtOutdir
    sOutputName = frmInundate.txtOutName

    'open log file in output directory and log date and time (ML270908)
    Open sOutputDir + "\" + sOutputName + "_log.csv" For Append As #LogFileNo 'create log file
    Write #LogFileNo, "Inundation model run date:", CStr(CurDate)             'log date
    Write #LogFileNo, "Start time:", CStr(CurTime)                            'and time

    Set pAlgbOp = New RasterMapAlgebraOp
    Set pEnv = pAlgbOp
    Set pWSF = New RasterWorkspaceFactory
    Set pWS = pWSF.OpenFromFile(sOutputDir, 0)
    Set pEnv.OutWorkspace = pWS
```

```
    'Get the User Input
    If frmInundate.optValue.value Then
        sSeaRise = CStr(frmInundate.txtSLR)
        dSubRMS = frmInundate.txtSlrErrorNo
    Else
        Dim pSeaRiseRaster As IRaster
        Dim pStormRaster As IRaster
        Dim pTideRaster As IRaster
        dSubVar = 0   ' square of RMS error
        sExp = "0"
        'Here I need to add the three together then give the new one as the rise raster and
also need yto account for rms
        nLayerCount = pMap.LayerCount
        For i = 0 To pMap.LayerCount - 1
            If frmInundate.chkSLR And pMap.Layer(i).Name = frmInundate.cboSLR.value Then
                Set pRLayer = pMap.Layer(i)
                Set pSeaRiseRaster = pRLayer.Raster
                dSubVar = dSubVar + (frmInundate.txtSlrErrorNoGrid ^ 2)
                sExp = sExp + " + [SeaRise]"
                pAlgbOp.BindRaster pSeaRiseRaster, "SeaRise"
            End If

            If frmInundate.chkStorm And pMap.Layer(i).Name = frmInundate.cboStorm.value Then
                Set pRLayer = pMap.Layer(i)
                Set pStormRaster = pRLayer.Raster
                dSubVar = dSubVar + (frmInundate.txtStormError ^ 2)
                sExp = sExp + " + [StormRise]"
                pAlgbOp.BindRaster pStormRaster, "StormRise"
            End If

            If frmInundate.chkTide And pMap.Layer(i).Name = frmInundate.cboTide.value Then
                Set pRLayer = pMap.Layer(i)
                Set pTideRaster = pRLayer.Raster
                sExp = sExp + " + [TideRise]"
                pAlgbOp.BindRaster pTideRaster, "TideRise"
                dSubVar = dSubVar + (frmInundate.txtTideError ^ 2)
            End If

            dSubRMS = Sqr(dSubVar)
        Next i

        Set pRiseRaster = pAlgbOp.Execute(sExp)
        pAlgbOp.BindRaster pRiseRaster, "RiseRaster"
        sSeaRise = "[RiseRaster]"
    End If

    dSeaRiseRMS = dSubRMS
    dDemRMS = frmInundate.txtDemError

    'Get the input Raster
    nLayerCount = pMap.LayerCount
    For i = 0 To pMap.LayerCount - 1
        If pMap.Layer(i).Name = frmInundate.cboDEM.value Then
            Set pRLayer = pMap.Layer(i)
            Set pInRaster = pRLayer.Raster
            Exit For
        End If
    Next i

    'Calculate the total error as per
    dTotalRMS = Sqr((dDemRMS ^ 2) + (dSeaRiseRMS ^ 2))

    pAlgbOp.BindRaster pInRaster, "DEM"
'the following three lines have been quoted-out as they appear to apply an incorret name to
pRiseRaster (ML15/09/08)
'    If Not frmInundate.optValue.value Then
'        pAlgbOp.BindRaster pRiseRaster, frmInundate.cboSLR.value
'    End If

' Calculation of Z value
'test modification (ML 16/9/08)
'condition changed from >0 to >=0 (25/09/08)
    If frmInundate.optGrid.value Then
         sExp = "CON([DEM] >= 0, ABS([RiseRaster] - [DEM]) / " + CStr(dTotalRMS) + ")"
    End If
    If frmInundate.optValue.value Then
    sExp = "CON([DEM] >= 0, ABS(" + CStr(sSeaRise) + " - [DEM]) / " + CStr(dTotalRMS) + ")"
    'sExp = "CON([DEM] > 0, ABS([DEM] - " + CStr(sSeaRise) + ") / " + CStr(dTotalRMS) + ", -1)"
    End If
```

```
    Set pOutRaster = pAlgbOp.Execute(sExp)
    pAlgbOp.BindRaster pOutRaster, "ZValue"

'rewriting equations to calculate cumulative normal distribution instead of normal distribution
'old code applies normal distribution
'    sExp = "con([ZValue]  <  3.5, exp(- sqr([ZValue]) / 2) / sqrt(3.141 * 2), 0)"   'This line
applies the distribution function
'new code applies cumulative normal distribution (ML Sept'08)
'    sExp = "con([ZValue] < 3.6,1 - ((0.5 - (((exp( - sqr([ZValue]) / 2)) / 2.5066282746) * (1
/ (1 + (0.33267 * [ZValue]))) * (0.4361836 + (1 / (1 + (0.33267 * [ZValue]))) * (((1 / (1 +
(0.33267 * [ZValue]))) * 0.937298) - 0.120167)))) + 0.5), 0)"
'rewritten to produce output as percentage and integer (ML 30/09/08)
    sExp = "con([ZValue] < 3.6,Int( 100 * (1 - ((0.5 - (((exp( - sqr([ZValue]) / 2)) /
2.5066282746) * (1 / (1 + (0.33267 * [ZValue]))) * (0.4361836 + (1 / (1 + (0.33267 *
[ZValue]))) * (((1 / (1 + (0.33267 * [ZValue]))) * 0.937298) - 0.120167)))) + 0.5)) + 0.5), 0)"
    Set pOutRaster = pAlgbOp.Execute(sExp)
    pAlgbOp.BindRaster pOutRaster, "Prob1"
    pAlgbOp.BindRaster pInRaster, "DEM"

    pAlgbOp.UnbindRaster "ZValue"
 '   sExp = "con([DEM] < " + CStr(sSeaRise) + ", 1 - [Prob1],[Prob1])"
 'rewritten to work with percentages (ML 30/09/08)
    sExp = "con([DEM] < " + CStr(sSeaRise) + ", 100 - [Prob1],[Prob1])"
    Set pOutRaster = pAlgbOp.Execute(sExp)
    pAlgbOp.BindRaster pOutRaster, "ZValue"

    Dim pDataset As IDataset
    Dim prasterop As IRasterAnalysisProps

    Set prasterop = pOutRaster
    Set pDataset = prasterop.RasterDataset
        Set prasterop = Nothing
    Set pOutRaster = Nothing

    pDataset.Rename sOutputName

    Set pRLayer = New RasterLayer
    pRLayer.CreateFromDataset pDataset
    pMap.AddLayer pRLayer

    'log the file settings (ML270908)
    Write #LogFileNo, "Inundated DEM:", CStr(frmInundate.cboDEM)
    Write #LogFileNo, "DEM RMS error:", CStr(frmInundate.txtDemError)
    Write #LogFileNo, "SLR entered as text:", CStr(frmInundate.optValue)
    If frmInundate.optValue.value Then
        Write #LogFileNo, "SLR value:", CStr(frmInundate.txtSLR)
        Write #LogFileNo, "SLR RMS error:", CStr(frmInundate.txtSlrErrorNo)
    End If
    Write #LogFileNo, "SLR entered as grids:", CStr(frmInundate.optGrid)
    If frmInundate.optGrid.value Then
        Write #LogFileNo, "Grid 1 selected:", CStr(frmInundate.chkSLR)
        Write #LogFileNo, "Grid 1 name:", CStr(frmInundate.cboSLR)
        Write #LogFileNo, "Grid 1 RMS error:", CStr(frmInundate.txtSlrErrorNoGrid)
        Write #LogFileNo, "Grid 2 selected:", CStr(frmInundate.chkStorm)
        Write #LogFileNo, "Grid 2 name:", CStr(frmInundate.cboStorm)
        Write #LogFileNo, "Grid 2 RMS error:", CStr(frmInundate.txtStormError)
        Write #LogFileNo, "Grid 3 selected:", CStr(frmInundate.chkTide)
        Write #LogFileNo, "Grid 3 name:", CStr(frmInundate.cboTide)
        Write #LogFileNo, "Grid 3 RMS error:", CStr(frmInundate.txtTideError)
    End If
    Write #LogFileNo, "Output directory:", CStr(frmInundate.txtOutdir)
    Write #LogFileNo, "Output file name:", CStr(frmInundate.txtOutName)
    Write #LogFileNo, "End time:", CStr(Time)

    'close log file (ML270908)
    Close #LogFileNo

End Sub
```

Variables used in the script

`frmInundate.cboDEM`	DEM to inundate
`frmInundate.txtDemError`	RMS error in DEM
`frmInundate.optValue`	True if directly entering sea level rise values as text
`frmInundate.txtSLR`	Entered sea level rise value as text
`frmInundate.txtSlrErrorNo`	Entered sea level rise rms error
`frmInundate.optGrid`	True if entering sea level rise from grid cell values
`frmInundate.chkSLR`	Check box for selecting sea level rise grid
`frmInundate.cboSLR`	Name of sea level rise grid
`frmInundate.txtSlrErrorNoGrid`	RMS error in sea level rise grid
`frmInundate.chkStorm`	Check box for selecting storm rise grid
`frmInundate.cboStorm`	Name of storm rise grid
`frmInundate.txtStormError`	RMS error in storm rise grid
`frmInundate.chkTide`	Check box for selecting half tide range grid
`frmInundate.cboTide`	Name of half tide range grid
`frmInundate.txtTideError`	RMS error in half tide range grid
`frmInundate.txtOutdir`	Output directory
`frmInundate.txtOutName`	Output file name

Appendix A1.2 – CSIRO Storm Tide Modelling

Evaluation of storm tide surfaces associated with 1 in 100 year return periods
Author: Kathy McInnes, 2009

Extreme sea levels are comprised primarily of positive astronomical tides in conjunction with a storm surge caused by the severe winds and falling pressure associated with a severe weather event. The approach to evaluating return periods of the combination of the tide and the surge, the so-called 'storm tide' employed both hydrodynamic and extreme value statistical modelling techniques. The two components were modelled separately and combined using well established joint probability methods based upon Pugh and Vassie, (1980) and Tawn and Vassie (1989). The methodology for each is described below.

Storm surge

Hydrodynamic modelling in this study was undertaken using the depth integrated storm surge model GCOM2D (Hubbert and McInnes, 1999). Storm surge event probabilities were estimated by simulating a population of storm surge events identified from a selection of suitably long tide gauge records. The pre-selection of extreme events in the observational records was to circumvent the need to continuously simulate sea level data over the entire length of the record but rather to simulate only the extreme events that would ultimately contribute to the estimation of storm surge return periods, thereby minimising computational requirements. This approach assumes that the scale of the meteorological disturbance is of sufficiently large spatial scale to produce a sea level response that will be captured on the tide gauge network that has been used. As discussed in McInnes et al. (2009) this is a reasonable assumption for the mid-latitude regions of Australia. It would not be a suitable approach for the tropical regions of Australia where the main driver of storm surges are the small scale and relatively short-lived tropical cyclones whose impact may not be recorded by the relatively sparse tide gauge network. For these regions, a method such as described in McInnes et al., (2003) would be more suitable.

Prior to the event selection, hourly sea level data from the selected tide gauges were filtered using the method of Godin (1972) to obtain a time series of hourly sea level residuals, which closely represent the component of sea level variability due to meteorological forcing. Records of the maximum residual value occurring in each day were then derived for the tide gauges. A summary of the tide gauge records used to select extreme events is given in Table A1.1. These gauges were used to identify storm surges, owing to their length, completeness and distribution along the southern Australian coastline. Data gaps in these records were filled with data from alternative tide gauge records, which were selected on the basis of a high correlation with the key record being treated. Linear regression relationships were established between the key record and each of the alternative records and these were used to scale the data being used to fill data gaps prior to insertion into the key record. Hence systematic differences between the key record and alternative records were accounted for.

Table A1.2.1: Summary of the tide gauge records used for event selection in each state.

Station name	State	Approximate No. of years	Start date	End date	Threshold cm
Brisbane	QLD	20	1986	2005	21
Gold Coast	QLD	20	1986	2005	18
Coffs Harbour	NSW	20	1986	2005	19
Sydney	NSW	20	1986	2005	19
Batemans Bay	NSW	20	1986	2005	22
Lakes Entrance	VIC	37	1966	2003	14
Point Lonsdale	VIC	37	1966	2003	20
Portland	VIC	37	1966	2003	15
Georgetown	TAS	37	1966	2003	19
Hobart	TAS	37	1966	2003	22
Adelaide	SA	37	1966	2003	40
Esperance	WA	37	1967	2004	25
Freemantle	WA	37	1967	2004	28
Port Hedland	WA	37	1967	2004	16

A population of independent storm surge events suitable for extreme event analysis was identified from the complete key time series of residuals on a state-by-state basis. An event was defined as an episode during which daily maximum residual values exceeded a threshold, μ, above a background level. The value of μ that was used in each case was selected conservatively to yield a population of events that included all of the extreme events in the time series without being overly conservative such that multiple independent events were represented as single events. The selection of the threshold required knowledge of the typical meteorological drivers of extreme sea levels in the different regions and their associated time scales. These are described in McInnes and Hubbert (2001), McInnes et al., (2001) and McInnes and Hubbert, (2003) for the south and east coasts. The population also included many events that were not extreme. These had no impact on the results of the subsequent extreme value analysis since they were not used. For each state, events identified in different key time series used for that state that overlapped in time were regarded as a single event, the assumption being that they were the result of a single weather system propagating through the region.

For each state indicated in Table A1.2.1, the population of selected events was modelled with GCOM2D with atmospheric forcing only. The 10 m winds and mean sea level pressures required to force the hydrodynamic model were obtained from the US National Center for Environmental Prediction (NCEP) reanalyses (Kalnay et al., 1996). Wind fields were available on a 1.875°×1.875° global grid and mean sea level pressure fields were available on a 2.5°×2.5° global grid every 6 hours from 1958 onwards. The NCEP data were interpolated spatially to each of the GCOM2D grids. Modelling was carried out over a 5 km grid shown in Figure A1.2.1 for all states except Victoria for which modelling was also carried out at 1 km resolution as described in McInnes et al., (2009). At the termination of the simulation of each storm surge event, the maximum sea level attained at each model gridpoint throughout the simulation, hereafter referred to as the "storm surge height", and was stored for later analysis.

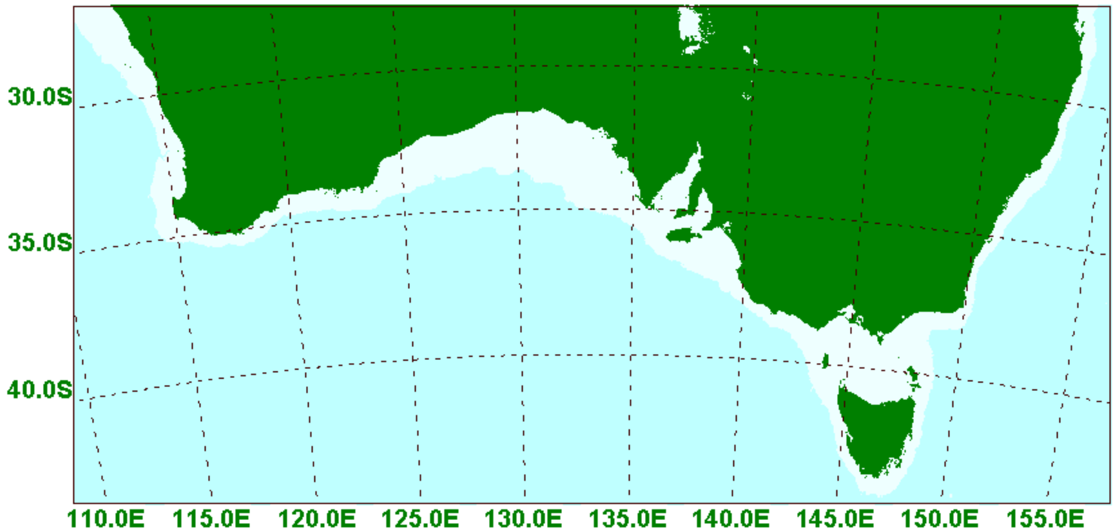


Figure A1.2.1: Region over which hydrodynamic modelling was undertaken on a 5 km resolution grid.

Since the population of storm surge events identified in the tide gauge records represents an interval of time that is shorter than the return period for which extreme sea level heights are being sought, extreme value statistical techniques were used to extrapolate from the data set to estimate probabilities for extreme storm surge heights with longer average recurrence intervals. Experimentation with different approaches (see McInnes et al., 2009) yielded the r-largest Generalized Extreme Value distribution (GEV) (see Coles, 2001), in which the highest 2 events to occur each year are fitted to the distribution, as being the most suitable method for use in this study.

Astronomical Tides

Astronomical tide constituents are available at the locations of tide gauges around Australia. However for the purposes of developing continuous surfaces of tide height, hydrodynamical modelling was used to generate tidal information on a grid comparable to that used for the storm surge modelling. The three-dimensional counterpart to GCOM2D (GCOM3D) was used for this purpose. GCOM3D (Hubbert 1993, 1999) calculates water currents in both the horizontal and vertical planes. This is important for representing tides accurately because seabed friction affects the vertical gradient of tidal currents and hence the phase and amplitude of tides at the coast.

Model simulations were carried out for several months using tidal heights from a global tidal model (Le Provost et al., 1995) as deep water boundary conditions. The time series of tide heights were then subjected to analysis at each model grid point to obtain an improved set of tidal phases and amplitudes. An iterative approach was adopted that involved running the model over several tidal cycles, calculating the root mean square errors of phase and amplitude of the modelled constituents at locations where tide gauge data existed and adjusting the boundary conditions until the RMS errors were minimised.

Frequency histograms for the tidal heights were then developed for the location of each grid point of the storm surge domain by running a tide model (Foreman, 1977) over a full astronomical (18.6 year) cycle using the derived tidal constituents.

Estimation of storm tide return periods

The common approach for combining the tidal distributions with those of storm surges is to assume independence between the tide and surge distributions. This is a reasonable assumption in cases where water depths are very much greater than the tidal range. Along much of the coastline under consideration in southern Australia this is a reasonable assumption. The approach, commonly referred to as the “joint probability” method (Pugh and Vassie, 1980), allows the convolution of the two probability distributions for tide and surge height (see also Tawn and Vassie, 1989). Formally this is written as

$$P(t) = \int_{-\infty}^{\infty} P_S(\tau) P_T(\tau - t) d\tau \qquad (1)$$

where P_S and P_T represent the probability distributions for surge and tide respectively. The convolution of two probability distributions is equivalent to the probability distribution of the sum of the two independent random variables. An equivalent (and in some respects simpler) approach to convolving the tide and surge distributions is to employ a Monte-Carlo approach to randomly sample a population of tide and surge values that are summed to develop a storm tide probability distribution. A practical advantage of combining the two distributions in this way rather than undertaking a more formal mathematical convolution of the two probability or frequency distributions is that the interval widths of the two distributions do not need to be identical. Total sea levels were estimated using the Monte-Carlo approach in which 200 sets of 1000 storm tides were sampled to enable the evaluation of both average storm tide height and 95% confidence limits. The sea level totals were ranked from largest to smallest and the return levels were calculated using $R = N / r$ where R is the return level, N is the number of random samples and r is the rank of the event.

The methodology used in this study is illustrated schematically in Figure A1.2.2 for the Victorian coast. This illustrates the spatial pattern of the estimated 1 in 100 year storm surge height over this region with the largest surges occurring within Western Port Bay. Also shown is the 99^{th} percentile tide height from the tide frequency histogram indicating that the highest tides occur in central Bass Strait. The 1 in 100 year storm tide surface reflects how the contributions from the tides and surge combine to produce the highest storm tides on the coastline between Western Port Bay and Wilson’s Promontory. On the other hand, in Port Phillip Bay, where the magnitude of the 1 in 100 year storm surge is similar to that on the adjacent Bass Strait coastline, the combination with tides (which are considerably attenuated within Port Phillip Bay) yields lower 1 in 100 year storm tides compared to the adjacent Bass Strait coastline. The storm tide values as represented in Figure A1.2.2 for the Victorian coastline, were then interpolated to a series of latitude and longitude coordinates which represent the Smartline, that has been generated for the National Coastal Vulnerability Assessment, which comprises a line of points around the coastline of Australia to which a range of coastal characteristics and attributes such as 1 in 100 year storm tide height can be assigned..

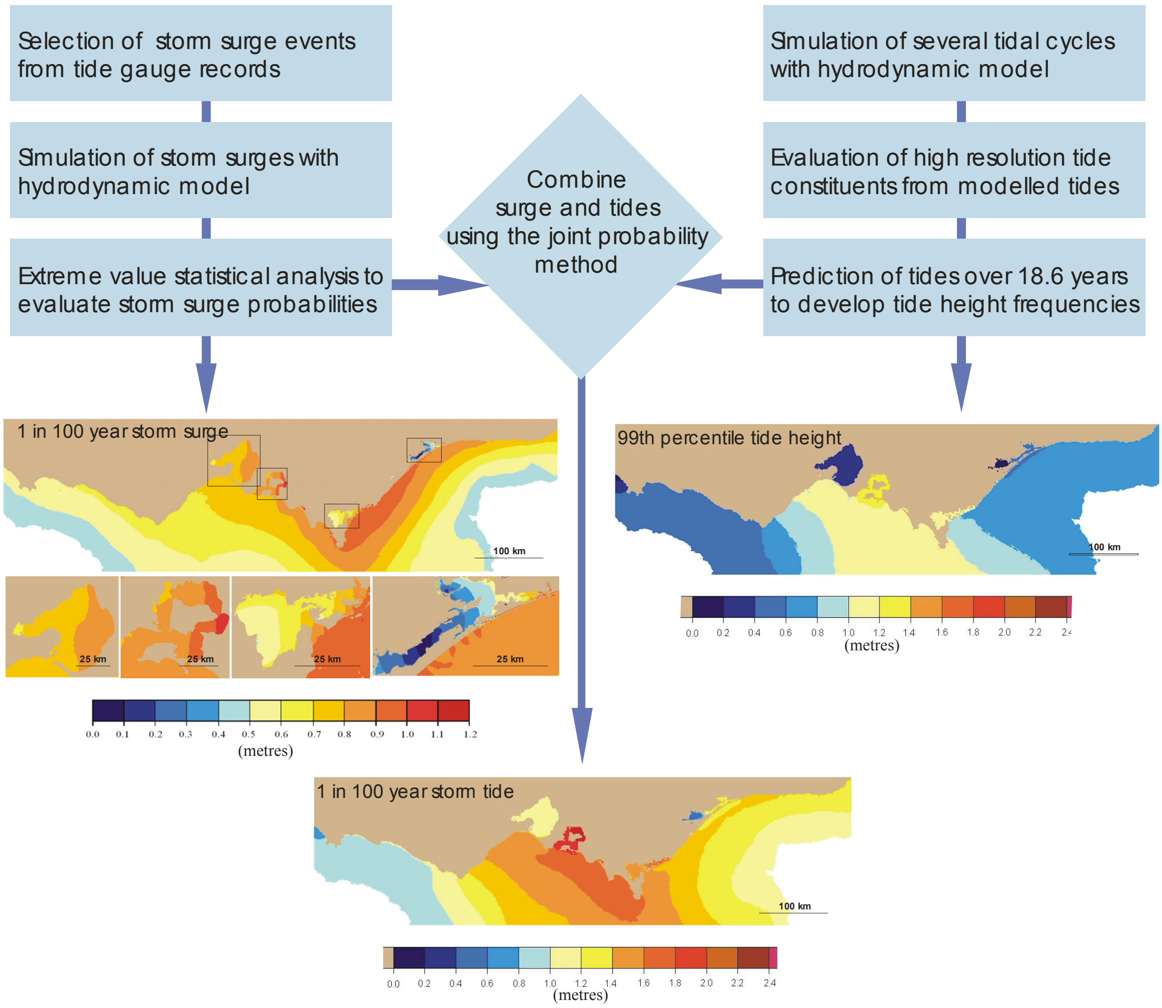


Figure A1.2.2: Schematic diagram illustrating the methodology used to evaluate storm tide return periods. The illustrations present examples of the spatial variation of the 1 in 100 year storm surge and storm tide surfaces and the 99th percentile tide height.

References

Foreman, G. G.: Manual for Tidal Heights Analysis and Prediction, Pacific Marine Science Report 77-10, Institute of Ocean Sciences, Victoria, Canada, 98pp., 1977.

Godin, G.: The Analysis of Tides. University of Toronto Press, Toronto, Canada, 1972.

Hubbert, G. D., and McInnes, K. L. 1999. A storm surge inundation model for coastal planning and impact studies, J. Coastal Res., 15, 168-185.

Hubbert, G.D. 1993: Modelling continental shelf flows along the New South Wales coast with a fully three dimensional ocean model. Proc. 11th Australasian Coastal and Ocean Engineering Conference, Townsville, Australia.

Hubbert, G.D. 1993: Oil spill trajectory modelling with a fully three dimensional ocean model. Proc. 11th Australasian Coastal and Ocean Engineering Conference, Townsville, Australia.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, B., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R., and Joseph, D.: The NCEP/NCAR 40-year reanalysis project, B. Am. Meteorol. Soc., 77, 437–471, 1996.

Le Provost, C. Bennet, A.F. and Cartwright D.E. 1995: Ocean tides for and from TOPEX/POSEIDON. Science 267; 639-642.

McInnes, K.L., Macadam, I., Hubbert, G.D. and O'Grady, J.G. 2009: A Modelling Approach for Estimating the Frequency of Sea Level Extremes and the Impact of Climate Change in Southeast Australia. Natural Hazards DOI 10.1007/s11069-009-9383-2

McInnes, K.L. and Hubbert, G.D. 2003: A numerical modeling study of storm surges in Bass Strait. Aust. Met. Mag. 52. 143-156.

McInnes, K.L., K.J.E. Walsh, G. D. Hubbert and T. Beer, 2003: Impact of Sea-level Rise and Storm Surges on a Coastal Community. Nat. Haz. 30(2) 187-207.
McInnes, K.L., D.J. Abbs, G. D. Hubbert and S. E. Oliver, 2002: A Numerical Modelling Study of Coastal Flooding. Meteorol. Atmos. Phys. 80, 217-233.
McInnes, K.L. and Hubbert, G.D. 2001: The impact of eastern Australian cut-off lows on coastal sea levels. *Meteorological Applications,* **8***,* 229-243.
Pugh, D. T., and Vassie, J. M.: Applications of the joint probability method for extreme sea level computations, P. I. Civil Eng. Part 2, 69, 959-975, 1980.
Tawn, J. A., and Vassie, J. M.: Extreme sea levels: the joint probabilities method revisited and revised, P. I. Civil Eng. Part 2, 87, 429-442, 1989.

Appendix A1.3 – EGM96-AHD71 Separation modelling

Author: Nicholas Brown, Geoscience Australia, 2009

Correction Surface between EGM96 and AHD71

```
This document refers to the production of a correction surface
between the Earth Geopotential Model 1996 and 336 AHD marks
collocated with ellipsoidal heights captured from GPS.

This correction surface is only for use by Richard Mount and his
team and is not to be distributed to other parties.

NOTE: The EGM96 geoid used for the purpose of this study is that
provided on the National Geospatial Intelligence Agency Website
(http://earth-
info.nga.mil/GandG/wgs84/gravitymod/egm96/intpt.html)

Two surfaces have been developed;
   1. GPS-geoid.0.100.100.xyz = 0.25 degree grid of offset values
      to be added to EGM96 to estimate AHD heights.

   2. draped.0.100.100.xyz = the geometric geoid which is the
      surface between the ellipsoid and AHD. Also has resolution
      of 0.25 degrees.

NOTE: The values 0.100 m and 100 km refer to the parameters used
to produce the surface. 0.100 m denotes the GPS / Levelling data
noise and 100 km denotes the optimal correlation length based on
empirical testing. This is explained in greater detail below.

--Surface developed by Nick Brown (Geoscience Australia)
--Software developed by Featherstone et al (Curtin University)
```

Background

By calculating the difference in height between the Australian Height Datum (AHD) and the geoid (Figure A1.3.1) at a number of positions around Australia, a correction surface was developed which can be draped over EGM96 to provide a geometric geoid for the nation. Using the geometric geoid, ellipsoidal heights can be converted to AHD heights as opposed to only being able to convert to heights above the geoid using geoid – ellipsoid separation values.

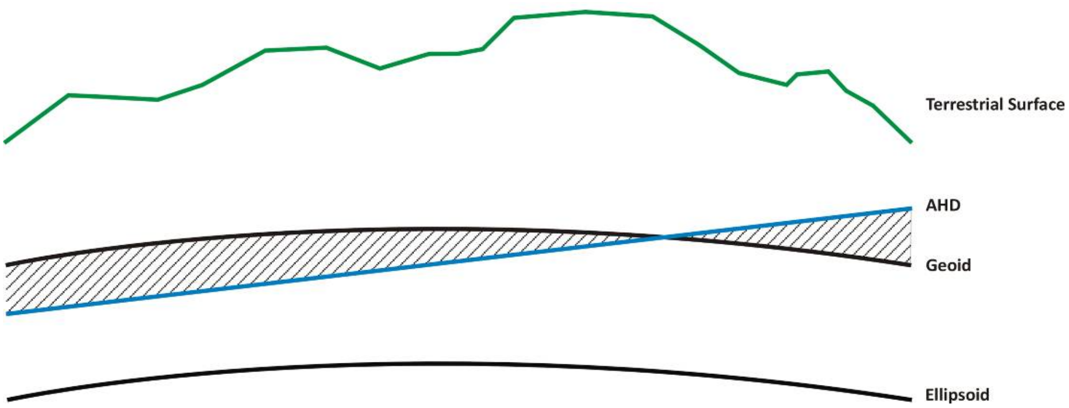


Figure A1.3.1: The offset between the AHD and Geoid.

The Cause of the Offset

The predominant cause of the offset between the AHD and the geoid is the differential heating of the oceans. The colder, denser water of the south has the same mass as water from the warmer north; however, the height of the northern waters is ~1 metre higher. A secondary cause of offsets between the geoid and AHD are blunders / errors in the AHD levelling network.

EGM96 Grid

There are many variations of EGM96 available. The model chosen is the one published on the National Geospatial Intelligence Agency Website (http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm96/intpt.html).

Using the provided Fortran script on the NGIA website, I extracted a 0.25 degree resolution grid of EGM96 for the whole of Australia.

NOTE: This was the highest resolution available.

The Correction Surface

At 336 points across the country, the following heights were known;

- Ellipsoidal Height (h) – *from GPS*
- AHD height (Hahd) – *from levelling*
- Geoid – Ellipsoidal Separation (Negm96) – *from EGM96*

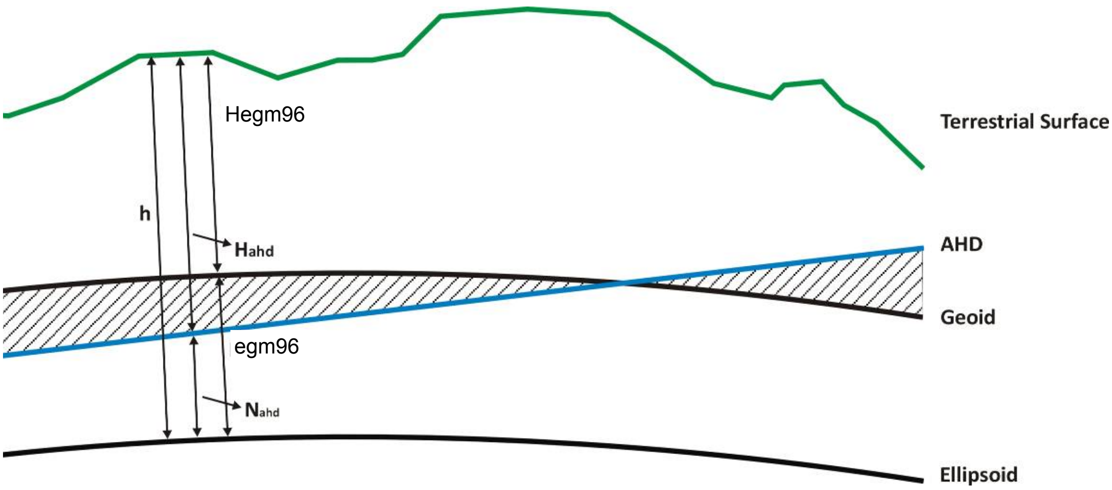


Figure A1.3.2: Diagram depicting h: ellipsoidal height, Hemg96: orthometric height above EGM96, Hahd: height above AHD, Negm96: geoid – ellipsoid separation, Nahd: geoid to AHD height.

As shown in Figure A1.3.2, by subtracting the AHD height from the ellipsoidal height at each of these collocated points, a derived AHD - Ellipsoid value (Nahd) was derived. Therefore at 336 points across the country we have the offset between the AHD and EGM96 (Nahd – Negm96).

Least Squares Collocation

The following is the procedure used to develop the correction surface between EGM96 and AHD71:

1. The EGM96 data is converted to a 0.25 degree regular grid. Given that this is the same resolution as that provided by NGIA, this is simply a formatting change.

2. The 336 GPS_level data points are averaged into a mesh with multiple points within 0.25 degrees of each other combined to yield one point. This reduces the number of points to 319.

3. Uses a bilinear interpolator to calculate the offset between the geoid and GPS_level data for each of the 319 points.

4. Produce a grid of the offsets between the geoid and AHD using collocation to give an offset value at 0.25 degree grid spacing.
   - The collocation software uses the 319 points to interpolate / extrapolate an offset at a 0.25 degree grid spacing across Australia.
   - The parameters used in the LSC solution are based on empirical testing (explained later).

5. Add the interpolated / extrapolated offsets of each grid cell to the original geoid grid to give a geometric geoid (***`draped.0.100.100.xyz`***). This is offset between the ellipsoid and AHD.

Basic Theory (from LSC User Manual – Curtin University)

Least Squares Collocation (LSC) is a statistical method used in physical geodesy for deriving parameters of the anomalous gravitational field (e.g. Moritz, 1980). The method utilises stochastic relationships among variables, in the form of a covariance function.

Let l be a set of observations, and s a set of unknown desired signals. The covariance matrix for l, and the cross-covariance matrix, are given by:

$$C_{ll} = \text{cov}(l,l) = \sigma_l^2$$
$$C_{sl} = \text{cov}(s,l)$$

The estimate of the signal s is given by :

$$\hat{s} = C_{sl} C_{ll}^{-1} l$$

If noise is considered so that the measurements l are composed of the measurement signal t and noise n,

$$l = t + n$$

then the estimate of the signal is given by:

$$\hat{s} = C_{st}(C_{tt} + C_{nn})^{-1} l$$

The covariance function C, in the programs used in this application is derived analytically. The covariance function is assumed to be both homogenous and isotropic, thus the spatial dependence between points can be described by a single distance parameter, referred to as the correlation length. LSC is conceptually the same as Kriging (e.g. Dermanis, 1984).

Calculating the Correction Surface

The LSC procedure incorporates a cross validation technique which removes one of the 336 points, calculates a correction surface from the remaining 335 points and then uses the omitted point to validate the model. This procedure is performed for each of the 336 points to somewhat independently check the accuracy of the derived surface.

Noise and Correlation Length

The parameters of the LSC Software are the correlation length and noise. The optimal parameters were calculated using empirical testing over a variety of distances and GPS / levelling data noise values. As the name suggests, the correlation length refers to how closely grid cells at a certain distance correlate with the central grid cell. The noise value on the other hand defines the expected uncertainty associated with the input Nahd values. Given that both GPS and levelling data is used to produce the Nahd values, the noise value is a combination of both.

Accuracy

Based on empirical testing, the optimal parameters to fit a surface for the available data were a correlation length of 100km and a noise value of 0.10m.

Using the LSC software, the RMS of the surface fit between the EGM96 geoid and available 336 Nahd data points is 0.207m.

Results

`GPS-geoid.0.100.100.xyz`

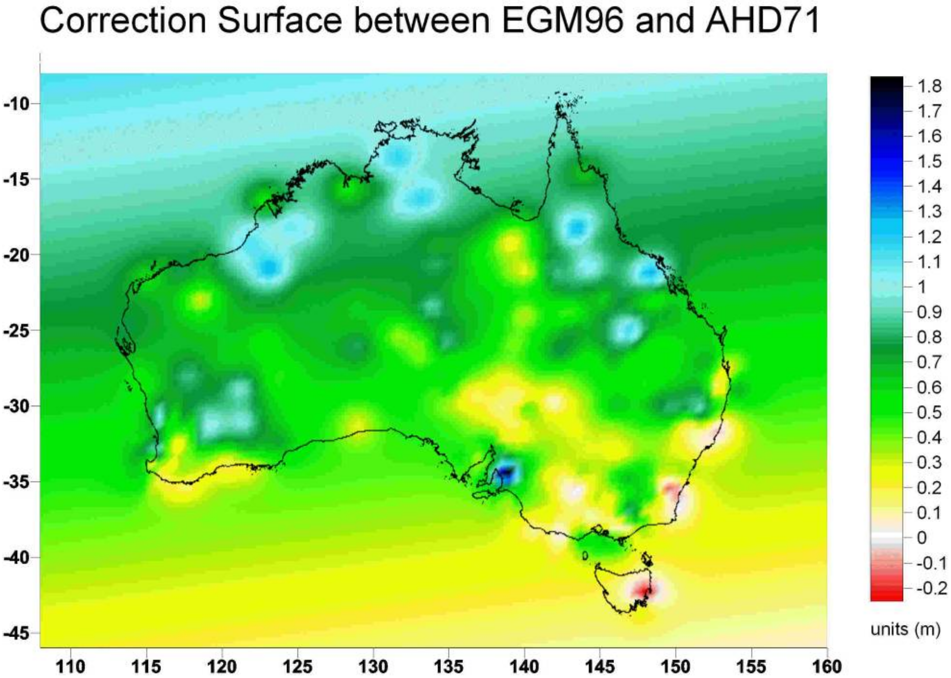


Figure A1.3.3: The offset between EGM96 and the AHD.

NOTE: Spikes in the model are caused by either geoid anomalies or AHD inaccuracies.

`draped.0.100.100.xyz`

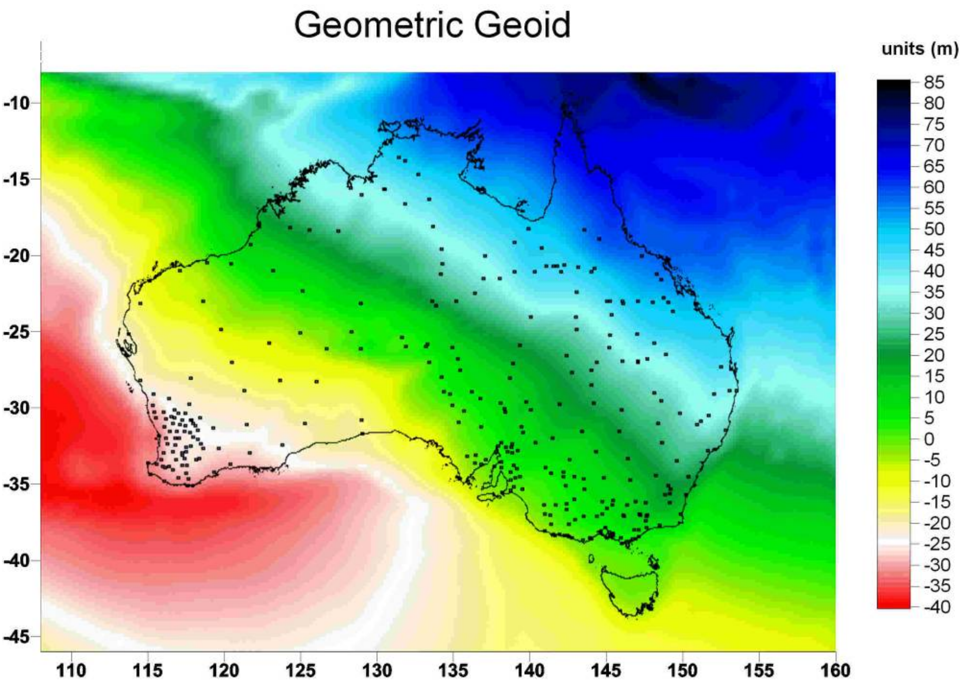


Figure A1.3.4: The geometric geoid.

Further Information

For further information on the topic, contact Nick Brown from Geoscience Australia on (02) 6249 9831 or email nicholas.brown@ga.gov.au

APPENDIX 2.

Rapid Assessment Impact Zones of the Australian coastline:

Combining modelled areas of potential inundation and potential instability

Sub-project Report

30th June 2009

Dr Michael Lacey and Dr Richard Mount

Spatial Sciences Group,
School of Geography and Environmental Studies,
University of Tasmania

Summary

- The combination of the zones of potential instability (ZPI) (i.e. outputs described in Part A of this report) with the modelled areas of inundation (i.e. outputs described in Mount and Lacey, 2009) has been done in a way that supports a rapid national level identification of the areas of the coast most likely to be impacted by the climate change hazards of erosion and inundation for defined 2030 and 2100 sea level rise scenarios.

- It is important to note that all of the contributing models and data sets and the method of combination to produce these areas are significantly simplified versions of reality and include many untested assumptions. This approach was still deemed reasonable given the available data sets and the urgency of the task in hand. The areas identified are called Rapid Assessment Impact Zones (RAIZ) in this report.

- RAIZ are the product of many different data sets of mixed resolution around Australia. Where ever possible and practical, data sets have been used that are consistent across the study area, such as the SPOT HRS DEM or the Smartline (Sharples et al., 2009); however, inconsistencies are inevitable.

- The RAIZ should be considered as indicating vicinities where there is a potential for impacts caused by the climate change hazards of inundation and/or erosion. These impacts could occur within or nearby the RAIZ. The boundaries are the most uncertain part of a RAIZ and they should not be used for detailed planning purposes.

- The method is a very simple additive model that produces a simple set of maps identifying areas with three levels of **evidence**, as follows,
    - **More Evidence**: Level 1 areas are where there are “more evidence” that they will be potentially subject to impact, potentially both inundation and erosion.
    - **Some Evidence**: Level 2 areas are where there is a “some evidence” that they will be potentially subject to impact, either inundation or erosion.
    - **Absence of evidence**: These are the locations where neither set of input layers occur. These areas should be regarded as having an “absence of evidence” with regard to inundation or erosion impacts.
- The value of this assessment is in its
    - rapidity
    - ability make use of the available data sets and
    - national coverage and consistency.

  It is intended to be used to assist broad regional and national assessments that will enable prioritising of activities and responses to climate change including where further more detailed investigations are needed and supporting mitigation and adaptation planning and activities.

Contents

Introduction

This report details the technical methods applied to produce two sets of spatially explicit data for the whole of the Australian coast:

Part A The **Zones of Potential Instability** (ZPI) using a simple model of erosion and recession based on the Smartline Sensitivity Classes (Sharples et al., 2009), and

Part B The combination of the coastal inundation modelling (see Mount and Lacey, 2009) with the ZPI modelling to produce nationally consistent **Rapid Assessment Impact Zones** (RAIZ) that are subject to impacts caused by the climate change hazards of inundation and erosion.

These data are intended for internal use by Geoscience Australia with the NEXIS database in the Human Infrastructure Vulnerability Modelling project.

Definitions

A1FI	The IPCC's "high emission" scenario
AR4	IPCC Fourth Assessment Report (IPCC 2007)
DCC	Department of Climate Change, Australian Government
DEM	digital elevation model, a surface representing the surface heights of the land
GA	Geoscience Australia
IPCC	Intergovernmental Panel on Climate Change
RAIZ	"Rapid Assessment Impact Zones" are areas are where there is at least some evidence that they will be potentially subject to impact from the climate change hazards of inundation and erosion
SLR	sea level rise
SPOT	Spot Image: a supplier of satellite imagery and derived products including DEMs
ZPI	"Zones of Potential Instability" are the areas within which the shore is modelled to be, should the shore retreat under the various given scenarios

Part A: Coastal Zones of Potential Instability (ZPI)

Introduction

The UTAS *National Shoreline Geomorphic and Stability Mapping Project* Principal Investigators and Steering Committee agreed to define areas that could potentially become unstable due to erosion under the climate change scenarios defined by the Department of Climate Change for a number of associated sub-projects. The three climate change scenarios defined are the:

A. "Present Day Scenario", where no sea level rise is incorporated into the modelling;

B. "2030 Scenario", where sea level rise is as predicted by the IPCC's fourth report (IPCC, 2008); and

C. "2100 Scenario", where a "high end" sea level rise prediction from the ACE CRC (as advised by the DCC and GA; Vellinga, 2008) is used.

The potentially unstable coastal areas are defined as the areas (zones) within which the shore is modelled to be, should the shore retreat under the various given scenarios. This definition was adopted after the assumption of universal shoreline retreat in the face of climate change was strongly challenged in an expert workshop held in Sydney in December, 2008. The coastal geomorphology experts at the meeting considered that some types of shores could advance, though these could not be consistently identified. In the light of these discussions, the Steering Committee and the project client agreed that it would be prudent not to attempt to model recession and estimate receded shorelines. Rather, it was considered preferable to model the zones of potential instability (ZPI) and clearly state the "worst case" assumption of recession for all shoreline types.

The ZPI are modelled for each type of shoreline sensitivity class defined by the Smartline created by the *National Shoreline Geomorphic and Stability Mapping Project* (Sharples et al., 2009).

Methods

Early efforts at modelling zones of potential instability used a tool scripted by Luke Wallace, UTAS in VBA to run in ArcMap 9.2 (ESRI, 2006). Although this earlier approach proved effective in trial runs there were technical problems with the software that could not be quickly resolved.

An alternative approach was adopted which was to build a model using Model Builder in ArcGIS 9.2 (ESRI, 2006). This approach proved efficient and had the flexibility to cope with varied inputs. Inputs for the model were the coastal Smartline with calculated geomorphic sensitivity classes and a polygon version of the coastline. A schematic representation of the steps in the model is shown in Figure A2. 1. The model applied a sequence of selection and buffering steps to smartline segments to define the zones of potential instability. Output was a polygon layer for each selected ZPI scenario.

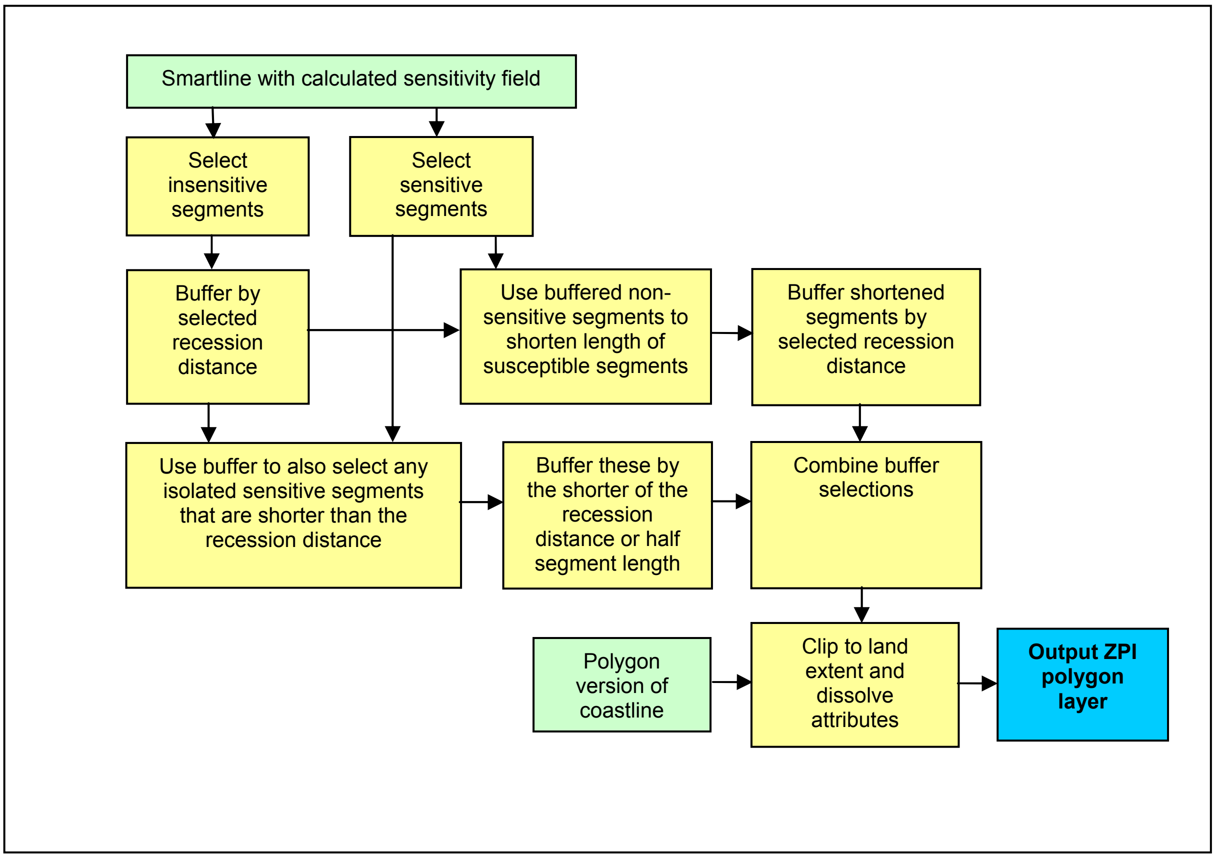


Figure A2. 1. Schematic representation of geoprocessing steps in calculating zones of potential instability (ZPI).

The ZPI scenarios were as listed in Table A2.1. For each scenario of projected sea level rise – 0.146 m by 2030 or 1.1 m by 2100 – a recession distance was calculated as either fifty times sea level rise ("min") or one hundred times sea level rise ("max"). These factors are drawn from the literature including that referring to the Brunn Rule (e.g. Bird, 1993, p.56; Zhang et al., 2004). A comparison of measured 'soft-rock' recession rates over the last century from a number of stable and subsiding coasts around the world (based on Sunamura, 1992, Appendix 2) with relative sea-level rise for the same sites, conducted by C. Sharples (pers. comm. 2009), revealed a wide range of shoreline recession factors varying between <1 x SLR to 600 x SLR.

Table A2.1. Distances modelled for each ZPI per scenario

Year	Sea level rise projection	ZPI min (50 x SLR)	ZPI max (100 x SLR)
2030	0.146 metre	7.3 metres	14.6 metres
2100	1.1 metre	55 metres	110 metres

These wide variations in recession rates fully overlap with average recession factors reported from sandy coasts (Zhang et al., 2004) and are probably related to wide variations in local site-specific factors affecting erosion. Hence it was considered that the widely-cited "average" Bruun Rule recession factors for sandy coasts, namely 50-100 x SLR, are likely to be as valid "average" recession factors for other erodible substrates, including soft rock, as could reasonably be derived by any other logic. Thus, for each scenario all segments classified as being sensitive to recession were receded by a single distance regardless of sensitivity category. The reason for this is that the rates of recession due to sea level rise are similar for all the sensitivity classes, that is, whether a shoreline is sand or soft rock it is assumed to recede a similar distance over the time frames in this study. Segments classified as being recession insensitive were not processed.

Sea Level Rise (SLR)

Two scenario dates are used for SLR in this modelling; 2030 and 2100. Both were identified by the DCC and confirmed by Geoscience Australia for use. Firstly, for 2030, SLR estimates is based on the A1FI scenario (IPCC 2007) which forecasts a rise of 0.146 m relative to 1980-1999. This scenario is at the higher end of the AR4 projections and assumes ongoing high emissions. Secondly, for 2100, a "high end" estimate of 1.1 m SLR was sourced from the Antarctic and Climate Ecosystems (ACE) CRC group including John Church and John Hunter and incorporates recent literature (e.g. Vellinga, 2008) and other observations made since the IPCC fourth report (IPCC 2007).

No SLR error estimates were included in the model as these SLR values were taken to be scenario "givens" rather than estimates. That is, the modelling was completed as if there definitely was 0.146 m and 1.1 m of SLR for 2030 and 2100 respectively.

Examples of Results

An example of the calculated zones of potential stability for a section of coastline is shown in Figure A2. 2. Recession buffers (yellow) are drawn inland of recession sensitive coastal segments (red) but not inland from coastal segments identified as recession insensitive (blue).

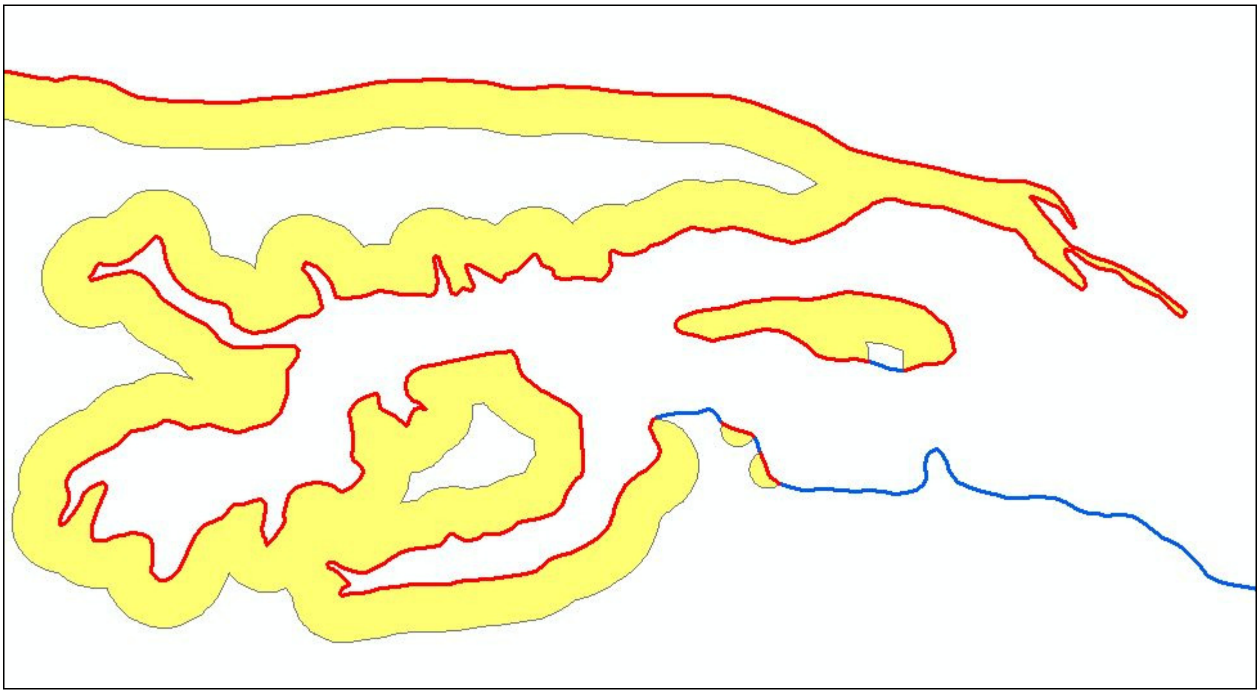


Figure A2. 2. Example of zones of potential instability (ZPI) (yellow) modelled inland from erosion sensitive shoreline segments are shown in red; insensitive shores in blue.

Figure A2. 3 shows the four ZPI scenarios (110 m, 55 m, 14.6 m and 7.3 m) superimposed on the same section of coastline.

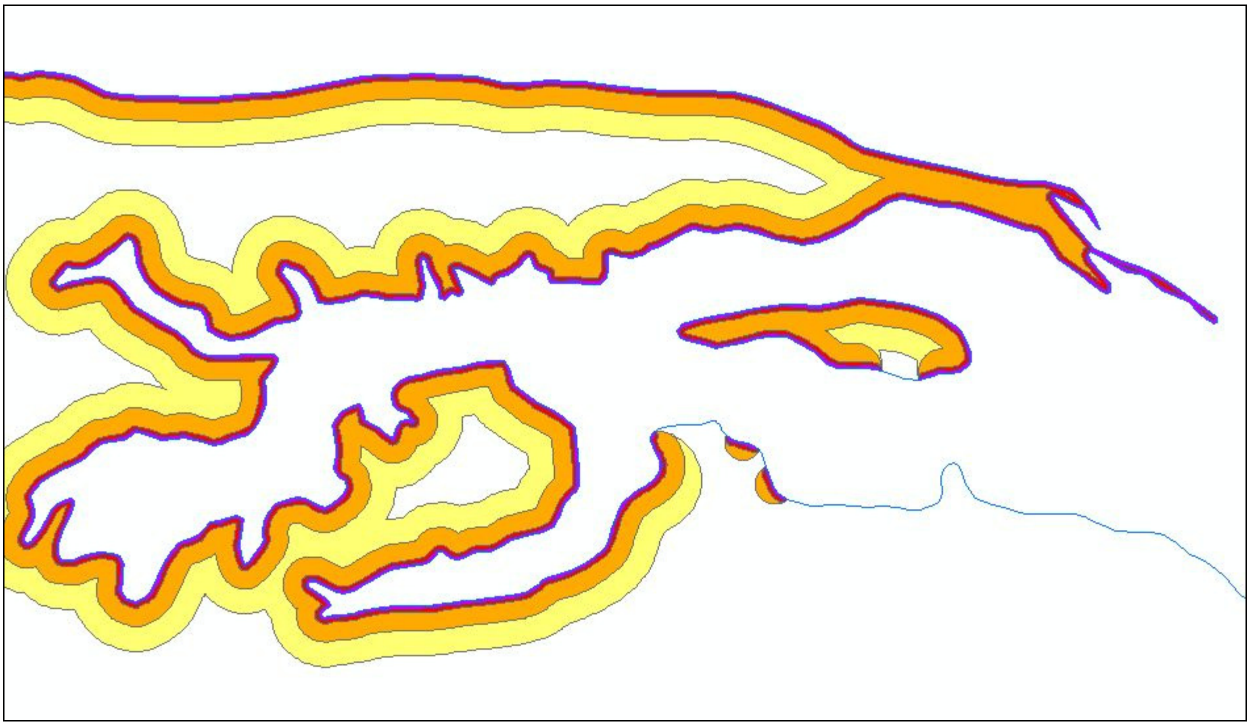


Figure A2. 3. All four ZPI scenarios displayed simultaneously. Yellow is 2100 max, orange is 2100 min, red is 2030 max and purple is 2030 min.

Four options that were implemented in the model with an effect on the outcome were:

- Use of rounded ends to recession buffers produced a natural looking outcome which is likely to be more representative of actual sea level rise outcomes in most cases than if buffers had been drawn with square ends (Figure A2. 4).
- The model included a mechanism by which the recession buffers when drawn did not 'overshoot' the ends of the recession sensitive segments (Figure A2. 4).
- Recession sensitive sections of coastline which were shorter in length than twice the selected recession distance were receded by no more than the lesser of the selected recession distance or half the segment length. For examples, see small buffers in Figure A2. 3 and the right hand buffer in Figure A2. 4.

Figure A2. 4. Note that the buffers are all curved at the ends and all finish exactly at the ends of the sensitive shore segments.

Limitations

- ZPI can only be determined for those sections of the coast represented in the Smartline and where sensitivity classes have been calculated. This excludes some areas such as small offshore islands and many riverine and estuarine areas.
- The ZPI locations depend on the accuracy of sensitivity class definitions and calculations. The sensitivity classes are derived from the complex mapping and exercise that produced the Smartline. This exercise compiled and translated hundreds of mapping sources into geomorphic classes, which, in turn, were classified into sensitivity classes. While much care was taken, there is scope for error in this process. This also means that if the map doesn't show a ZPI, it doesn't mean the shore will not erode.
- There are significant limitations in the use of the SLR multiplication factor within the modelling process to produce a lateral movement of the shoreline because numerous local coastal process factors can override the general application of the Bruun Rule.
- The actual movement of the shoreline is dependent on a great many variables including, but not limited to: the local sediment budget; the local sea level rise; actual exposure to the erosive power of the waves, whether swell or fetch generated; vegetation integrity on or near the shoreline; and the actual physical geological and geomorphological structures underlying and immediately behind the shoreline. The actual boundaries of the ZPI don't necessarily align with a future erosion event.

Part B: Coastal Rapid Assessment Impact Zones (RAIZ): Combining the ZPI and inundation modelling results

Introduction

The combination of the zones of potential instability (ZPI) (i.e. outputs described in Part A of this report) with the modelled areas of inundation (i.e. outputs described in Mount and Lacey, 2009) has been done in a way that supports a rapid national level identification of the areas of the coast most likely to be impacted by the climate change hazards of erosion and inundation for the defined 2030 and 2100 Scenarios. It is important to note that all of the contributing models and data sets and the method of combination to produce these areas are highly simplified versions of reality and include many untested assumptions. This approach was still deemed reasonable given the available data sets and the urgency of the task in hand. The areas identified are called Rapid Assessment Impact Zones (RAIZ) in this report.

The actual physical interactions between the processes modelled by the two input data sets are highly complex and include feedback loops. The method is a very simple additive model that produces a simple set of maps identifying areas with three levels of **evidence**, as follows,

1. **More Evidence**: Where both the input layers identify a potential impact (i.e. overlap or "agree"); there is more evidence that there will be an actual impact than for locations at Level 2 or 3. Level 1 areas are where there are "more evidence" that they will be potentially subject to impact, potentially both inundation and erosion.
2. **Some Evidence**: Where one or the other input layer identifies a potential impact; there is some evidence that there will be an actual impact than at locations at Level 3. Level 2 areas are where there is a "some evidence" that they will be potentially subject to impact, either inundation or erosion.
3. **Absence of evidence**: Even though the data holds some evidence of a lesser likelihood of impact outside the identified RAIZ, we strongly recommend discounting it. For example, it may be tempting to suggest that such areas are "safe" from impact. This analysis is definitely not designed to produce safe areas. These are the locations where neither set of input layers occur. These areas should be regarded as having an "absence of evidence" with regard to inundation or erosion impacts.

The relationship between these "levels of evidence" and estimates of impact "likelihood" is complex. It is suggested that if estimates of likelihood are required, for example for a risk assessment, then the evidence should be assessed with that outcome in mind.

The levels of evidence are deliberately broad categories and are relative to each other, not absolute. The constraints on the entire modelling process do not allow more precision or accuracy. The value in this sort of assessment is in its rapidity; in its ability make use of the available data sets and in its national coverage and consistency. It is intended to be used to assist broad regional and national assessments that will enable prioritising of activities and responses to climate change including where further more detailed investigations are needed and supporting mitigation and adaptation planning and activities.

Description of Inputs

Output polygon layers from ZPI modelling (Part A of this report) and from inundation modelling (Mount and Lacey, 2009) were the main inputs. Other inputs required for the combination model include the coastal Smartline (Sharples and Mount, 2009) and a polygon version of the Smartline. Outputs required were minimum (i.e. 50 x SLR) and maximum (i.e.

100 x SLR) extents for year 2100 and maximum (i.e. 100 x SLR) extent for year 2030 (see Table A2.1). The model inputs required to generate these outputs are as listed in Table A2.2.

Table A2.2 Specific inputs used in combination to produce the rapid assessment impact zones (RAIZ) for each scenario

RAIZ Output	Input ZPI layer	Input inundation layer
Year 2030 max extent	ZPI year 2030 max extent (i.e. 100 x SLR) polygon layer	Inundation 0.146 metre polygon layer
Year 2100 min extent	ZPI year 2100 min extent (i.e. 50 x SLR) polygon layer	Inundation 1.1 metre polygon layer
Year 2100 max extent	ZPI year 2100 max extent (i.e. 100 x SLR) polygon layer	Inundation 1.1 metre polygon layer

Methods

The input inundation layer is a polygon version of the most likely inundation extent produced from an inundation probability raster (please see Mount and Lacey (2009) for details). The raster based grid cell origin of this layer gives it an irregular blocky outline.

A schematic representation is shown in Figure A2. 5 of the steps taken to combine the ZPI and inundation model outputs to produce a layer identifying areas likely to be impacted by inundation and/or potential instability

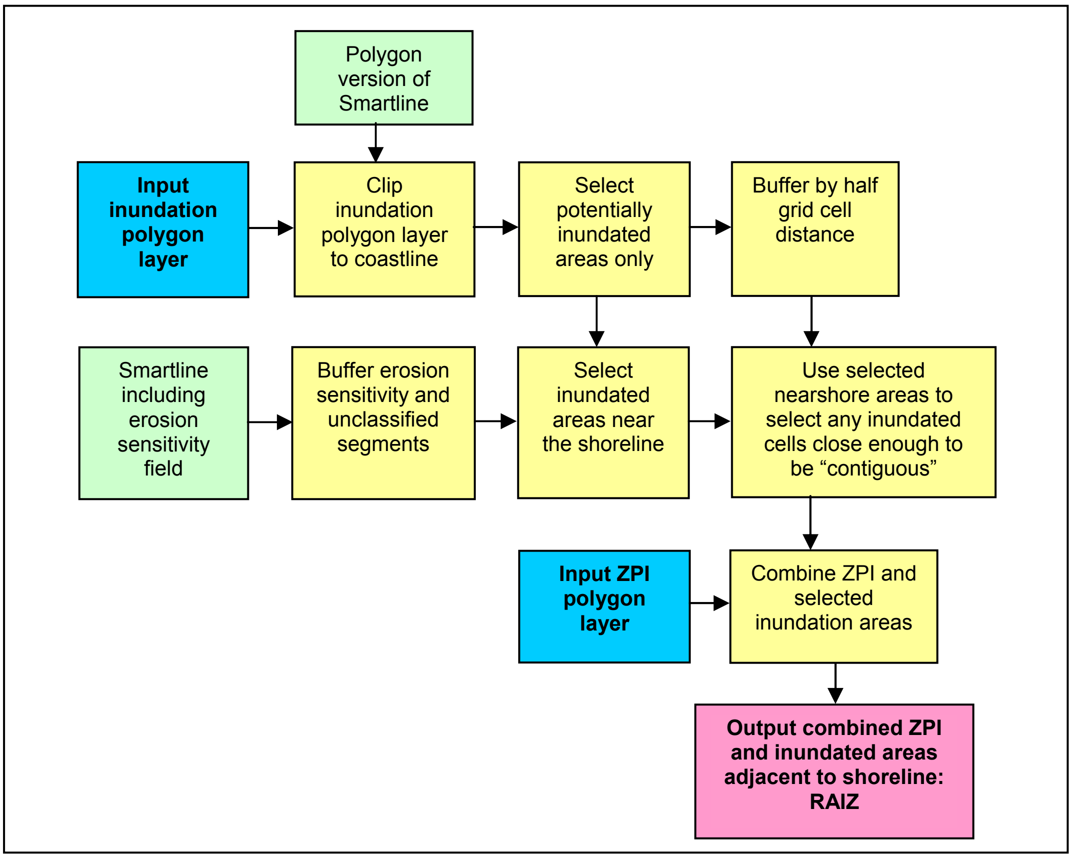


Figure A2. 5. Schematic representation of geoprocessing steps in calculating the Rapid Assessment Impact Zones (RAIZ)

Geoprocessing was conducted using a model constructed in ArcGIS 9.2 Model Builder (ESRI, 2006). A general outline of the model steps is shown in Figure A2. 5 and detailed below:

1) The input layer showing land that is unlikely to be inundated (Figure A2. 6) is clipped to the extent of the polygon version of the coastline and then, using an erase step, a polygon layer showing only the potentially inundated areas is created (Figure A2. 7), i.e. the reverse of the input layer.
2) Segments of the Smartline that are either classified as either potentially unstable or unclassified are buffered by 120 metres (See Appendix A2.1). This step creates a layer able to select potentially inundated areas within 120 m of the shore. This distance was chosen in an attempt to ensure potentially inundated areas in the immediate backshore area would be included, for example, low lying areas behind primary dunes. Selection of unclassified segments was intended to ensure selection of estuarine shores, where sensitivity classes had often not been calculated. This also meant the selection of a number of other unclassified parts of coastline, such as small offshore islands.
3) The output from Step 1 is buffered (and dissolved) by the equivalent of slightly more than half the distance to an adjoining grid cell (See Appendix A2.1). This step is intended to (eventually) ensure that cells that are separated by only one cell are grouped together for selection purposes. Even though they are separated, for the purposes of this project they are assumed to be part of a contiguous nearshore region that is as likely to be potentially inundated as those cells directly adjacent to the coast.
4) The buffer produced in Step 2 is used to select potentially inundated areas close to the coastline (See Appendix A2.1).
5) Selected inundated areas from Step 4 are used to select the buffered and dissolved regions from Step 3 (See Appendix A2.1).
6) Buffered regions selected in Step 5 are used to select the potentially inundated polygons they contain. This is the step where potentially inundated polygons away from the coastline and at a distance from any contiguous group of likely inundated polygons are excluded (and Appendix A2.1)
7) Areas selected in Step 6 are combined with ZPI polygons (Figure A2. 8) to produce a polygon layer showing potentially inundated and unstable areas i.e. the RAIZ (Figure A2. 10 and Figure A2. 11).

Examples of Results

Figure A2. 6. The input inundation layer showing remaining non-inundated land after low-lying regions identified as potentially inundated are excluded.

Figure A2. 7. Potentially inundated regions

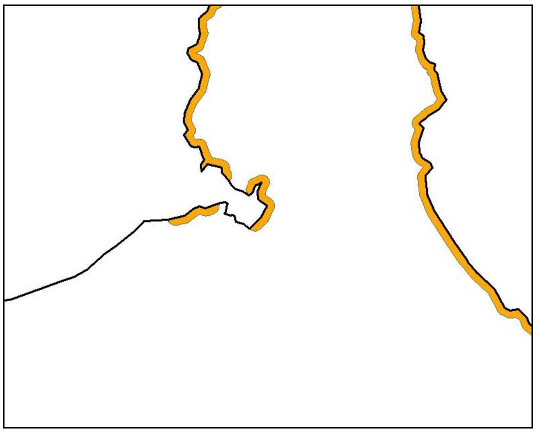


Figure A2. 8. ZPI (orange) from 2100 max scenario

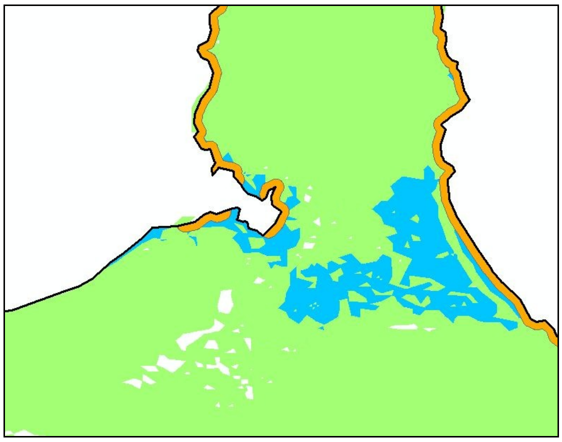


Figure A2. 9. ZPI (orange) and inundated (blue) regions.

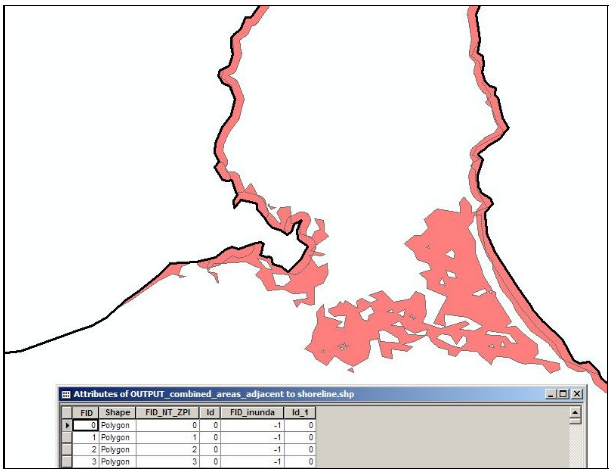


Figure A2. 10. The final RAIZ combined output showing also part of the layer attribute table. The origin of each output polygon (i.e. from inundation or from ZPI modelling) can be traced via the attribute table.

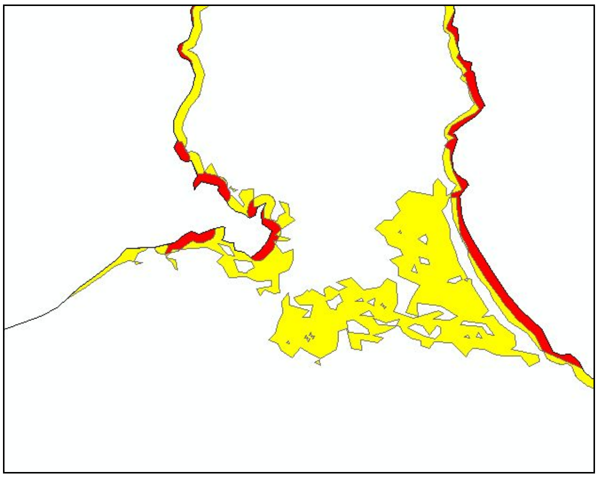


Figure A2. 11. The final RAIZ combined output symbolised with the two levels of evidence: red for "more evidence" and yellow for "some evidence".

Limitations

- RAIZ are the product of many different data sets of mixed resolution around Australia. Where ever possible and practical, data sets have been used that are consistent across the study area, such as the SPOT HRS DEM; however, inconsistencies are inevitable. The RAIZ should be considered as indicating vicinities within or nearby which there is a potential for impacts caused by the climate change hazards of inundation and/or erosion. The boundaries of a RAIZ are the most uncertain part and they should not be used for detailed planning purposes.
- The RAIZ are intended for internal use by Geoscience Australia.
- RAIZ are valid in locations where valid ZPI and inundation input layers have been calculated. Offshore islands outside the extent of the input SPOT HRS geocells were not sampled in the inundation modelling (and also not included in the ZPI output). This includes, for example, Christmas Island, Macquarie Island, Torres Strait islands and Ashmore reef. Many smaller islands were included in the inundation modelling but not in the ZPI modelling.

Conclusions and Suggestions

Further work - ZPI

- Improve the coverage of the Smartline Sensitivity classes to include the estuaries, lagoons, islands and other “unclassified” segments.
- Improved estimates of the erosive hazards to improve estimates of likely erosive recession factors
- A more accurate DEM would increase the accuracy of the slope classes in the Smartline

Further work - RAIZ

- To support a risk assessment process, estimate likelihoods associated with each level of evidence
- Test the separation distances for generating optimal “virtually contiguous” areas of inundation at the last stage of producing the RAIZ. One cell, as used here, may be too small a separation distance in some cases (See Appendix A2.1).
- It would be worth more rigorously checking the alignment of the two input data sets.
- More sophisticated interaction between the two inputs could improve the RAIZ. For example, interactively eroding a shoreline and then inundating it will produce different results to simply adding together the areas.

References

Bird E.C.F., (1993) Submerging Coasts: The effects of a Rising Sea Level on Coastal Environments. Wiley and Sons, Chichester. Pp 184

Church, J., J. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, M. Nhuan, D. Qin, and P. Woodworth (2001) Climate Change 2001: The Scientific Basis, Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Chapt. 11, pp. 639–693. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Church, J. & N.J. White, (2006) ‘A 20th century acceleration in global sea-level rise’, Geophysical Research Letters, vol. 33, L01602.

Church, John A., John R. Hunter, Kathleen McInnes and Neil J. White, (2006) Sea-level rise around the Australian coastline and the changing frequency of extreme events. Australian Meteorological Magazine, 55, 253-260.

ESRI (2006) ArcGIS Version 9.2. Redlands, CA: Environmental Systems Research Institute

Hunter, J. (2009) Estimating sea-level extremes under conditions of uncertain sea-level rise. Climate Change (submitted)

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Mount, R.E. and M.J. Lacey (2009) *Coastal Inundation Modelling Sub-project Report*. Internal Report to Geoscience Australia as part of the National Coastal Vulnerability of Australia (NCVA). Project sponsored by the Department of Climate Change.

Sharples, C.S. and R.E. Mount (2009) *National Shoreline Geomorphic and Stability Mapping Project - Final Report*. Report to Geoscience Australia as part of the National Coastal Vulnerability of Australia (NCVA). Project sponsored by the Department of Climate Change.

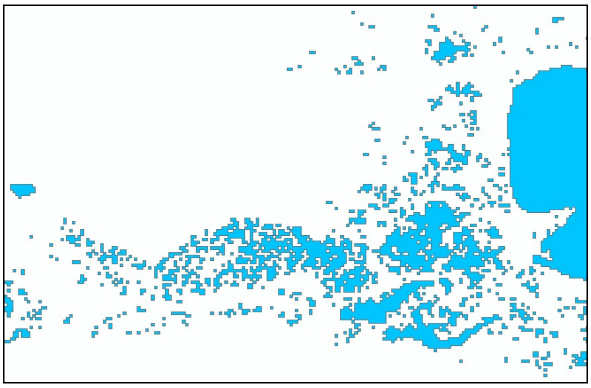
Sunamura, T., (1992) *Geomorphology of Rocky Coasts*. John Wiley and Sons, Chichester, 302 p.

Vellinga, Pier, (2008) *Exploring high end climate change scenarios for flood protection of the Netherlands*. International Scientific Assessment, 136pp.

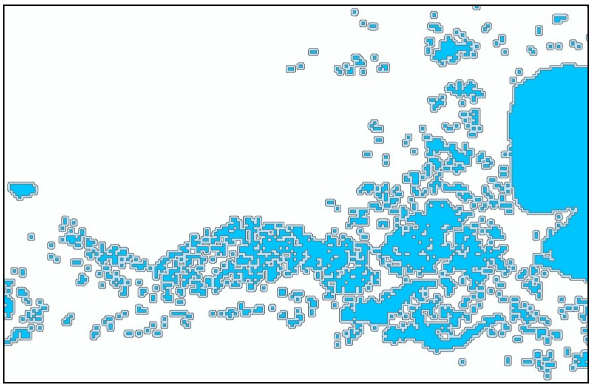
Zhang, K., B. C. Douglas, and S.P. Leatherman (2004). "Global Warming and Coastal Erosion." *Climatic Change* **64**: 41-58.

Appendix A2.1: Contiguous buffering technique

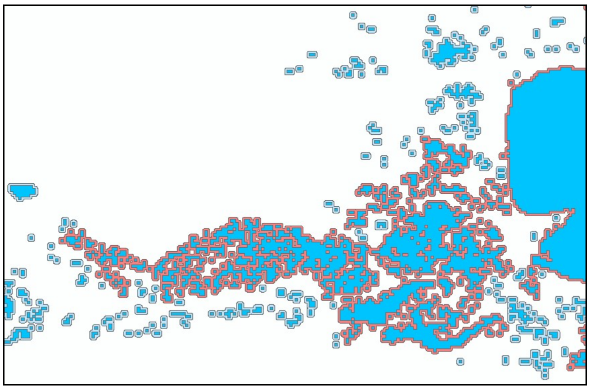
A buffering technique designed to include separate but nearby polygons into a "virtually contiguous" set of potentially inundated areas



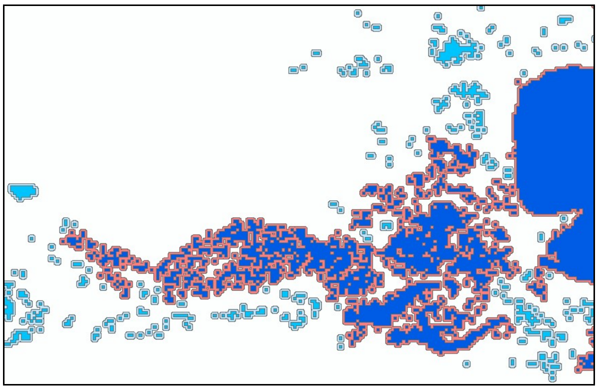
A) Starting with potentially inundated areas identified from inundation modelling



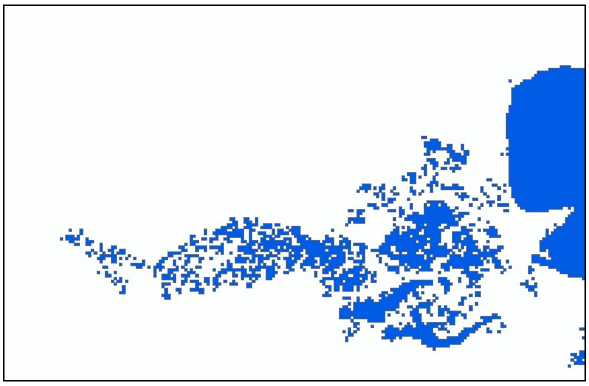
B) Buffer by half distance between grid cells to identify contiguous areas



C) Select buffered areas that intersect the coast



D) Use this buffer to select potentially inundated area and exclude areas isolated from the coast



E) Finally selected inundated areas near the coast

Appendix 3 Results – State overviews for the modified SPOT 25-25% RAIZ footprints

This section contains a summary of the results for residential buildings by State from the analysis of the 20 and 25% RAIZ footprints.

A3.1 New South Wales

New South Wales (NSW) has between 44,000 and 65,200 residential structures potentially at risk from the combined impacts of inundation and recession under both the upper and lower 2100 estimates. The LGA of Lake Macquarie contains the greatest risk to residential buildings with between 5,000 and 6,800 buildings potentially vulnerable by 2100, followed by the LGAs of Wyong and Gosford (Figure A3.1). These three LGAs and the LGAs of Wollongong, Shoalhaven, and Rockdale are included in the 20 most vulnerable LGAs nationally. The top ten LGAs in New South Wales account for more than 70% the total number of residential buildings vulnerable by 2100. The LGA of Lake Macquarie also has the highest replacement value for buildings at between $1.4 billion and $1.9 billion. Collectively, the total replacement value of residential buildings at risk by 2100 is in excess of $19.8 billion for the upper 2100 estimate, with the top ten LGAs accounting for over 70% of this value as well (Figure A3.2).

The results of this study indicate that NSW has between 1,300 and 2,200 commercial and light industrial buildings at risk by 2100, at a total value of between $5.9 billion and $10.5 billion. Compared to the residential exposure at risk, the commercial and industrial risk in NSW is more evenly distributed across the LGAs. The ten LGAs most at risk are shown in Figures A3.3 and A3.4. These represent around 50% of the number of commercial and light industrial buildings at risk in NSW. This corresponds to over 75% of the total replacement value of commercial buildings and over 50% of the light industrial buildings at risk in the state. Many of the ten most vulnerable LGAs in terms of the replacement value of commercial and light industrial exposure also rank among the most vulnerable in terms of the value of residential assets at risk: Wyong, Gosford, Wollongong, Shell Harbour and Rockdale.

The replacement value of road and rail networks exposed to potential inundation and erosion in New South Wales comprises more than $10 billion of road and over $1.3 billion of rail. The roads at risk are relatively evenly spread across the vulnerable LGAs, with the LGAs of Clarence Valley, Port Stephens, Shoalhaven, Greater Taree and Great Lakes containing the between 1,300 and 1,780km of the vulnerable roads in the state (Figure A3.5). However, Port Stephens, Wollongong, Clarence Valley, Tweed and Lake Macquarie contain the largest value of roads at risk in NSW, between $2.4 billion and $3.3 billion, which represents over 4.5% of the national value (Figure A3.6). NSW is the state with the largest length of rail at risk after Queensland (over $1.3 billion). The LGAs of Newcastle, Wollongong, Kiama and Shoalhaven have the highest replacement value of vulnerable rail, over 10% of the total value across the country.

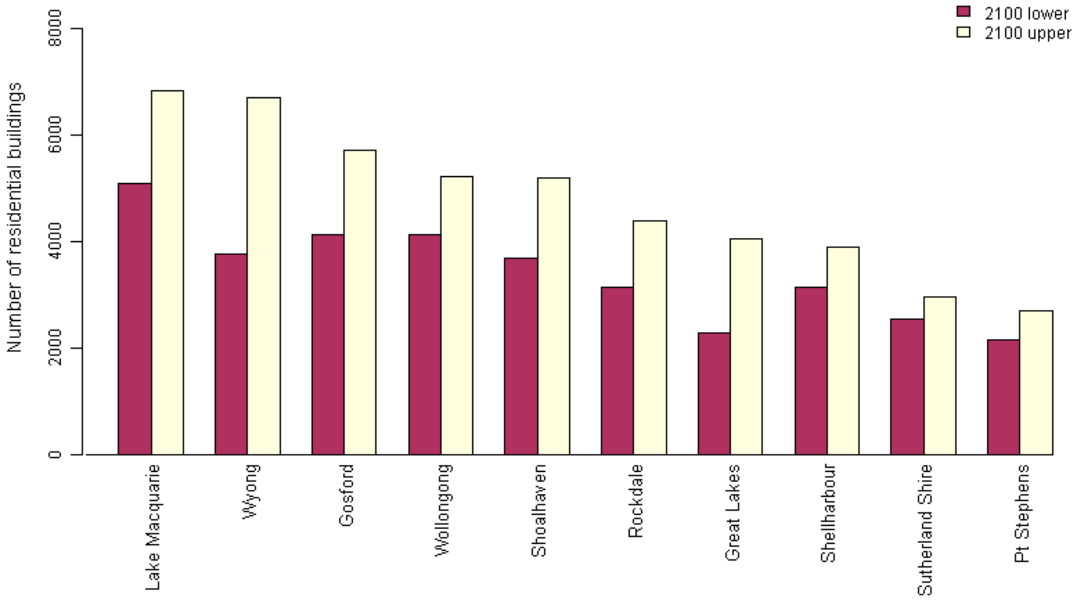


Figure A3.1: *Lower and upper estimated number of existing residential buildings in New South Wales potentially at risk from the combined impact of inundation and recession by 2100. LGAs most at risk are shown.*

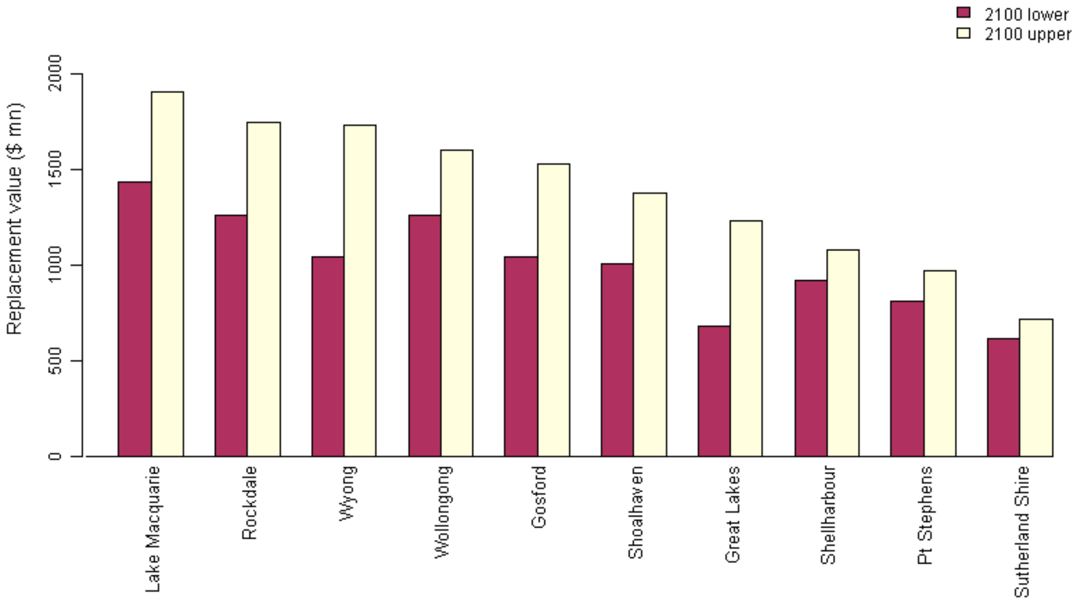


Figure A3.2: *Lower and upper estimated replacement value of existing residential buildings in New South Wales potentially at risk from the combined impact of inundation and recession by 2100. LGAs most at risk are shown.*

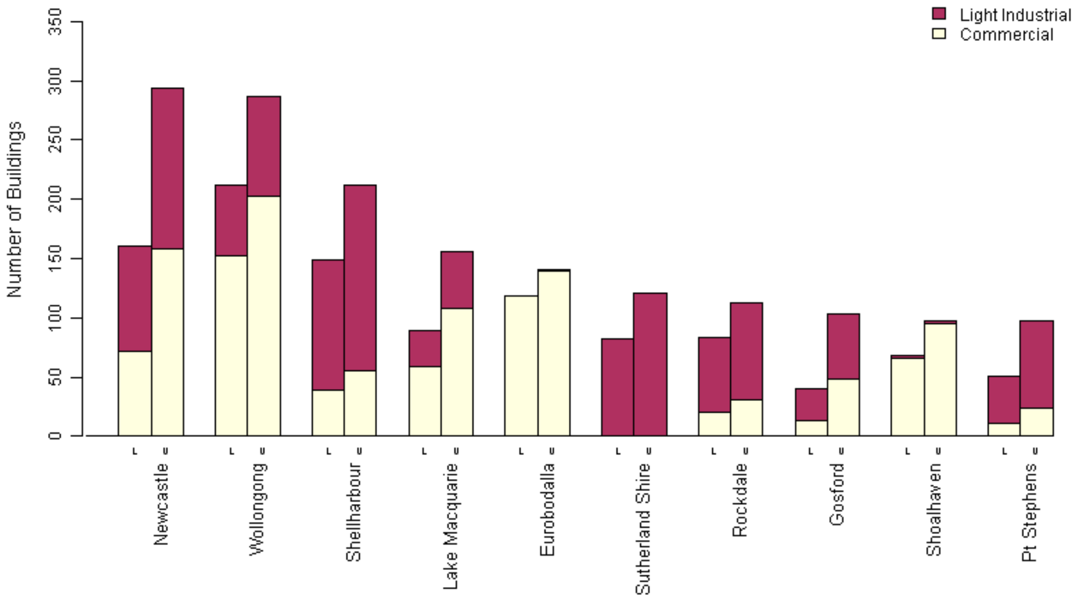


Figure A3.3: *Lower and upper estimated number of existing commercial and light industrial buildings in New South Wales potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

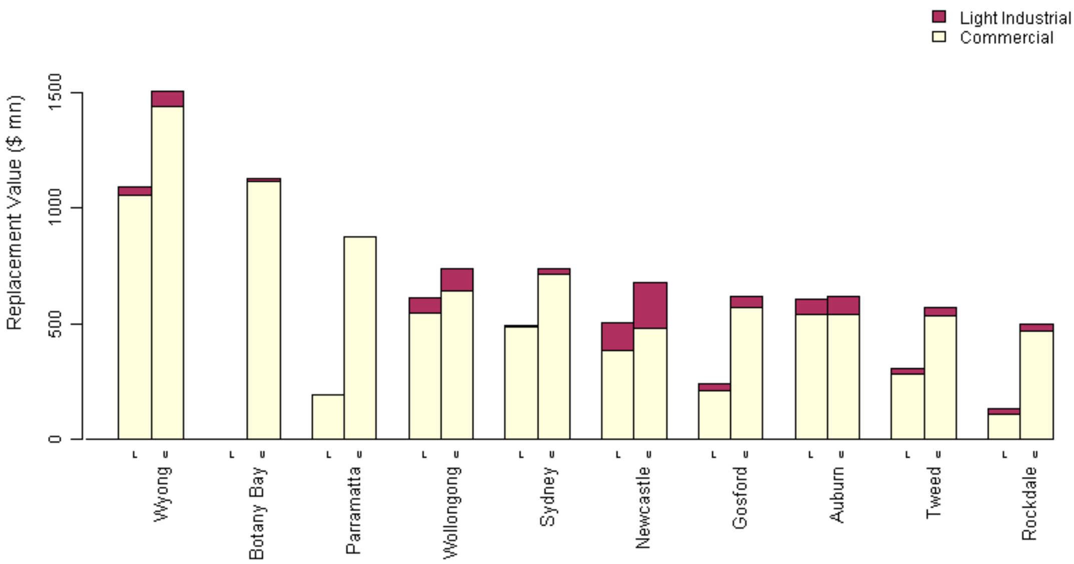


Figure A3.4: *Lower and upper estimated replacement value of existing commercial and light industrial buildings in New South Wales potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

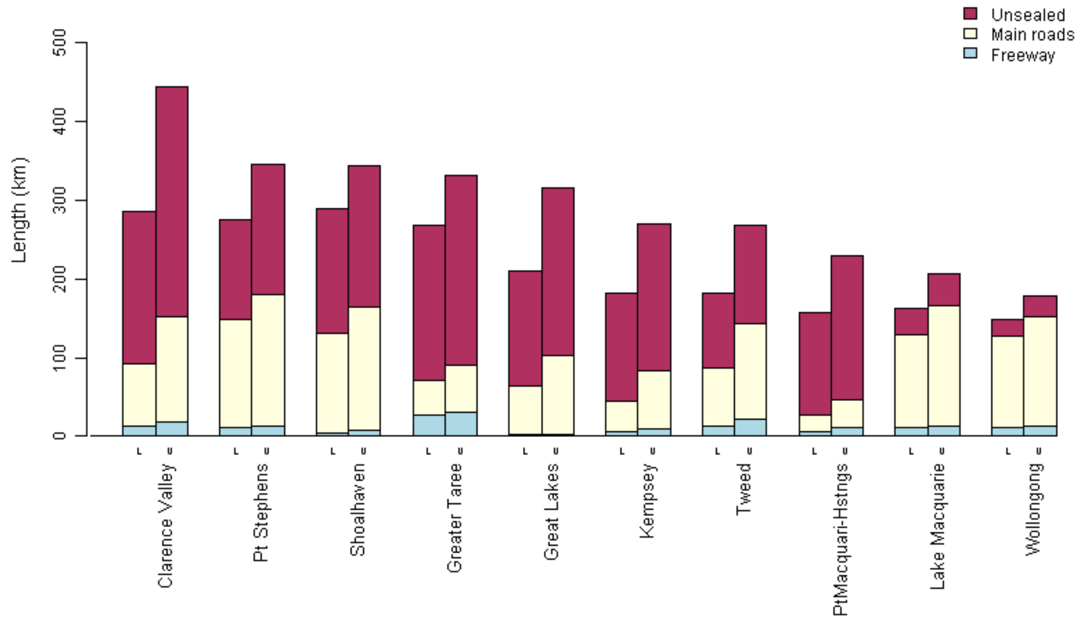


Figure A3.5: Lower and upper estimated length of existing roads in New South Wales potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.

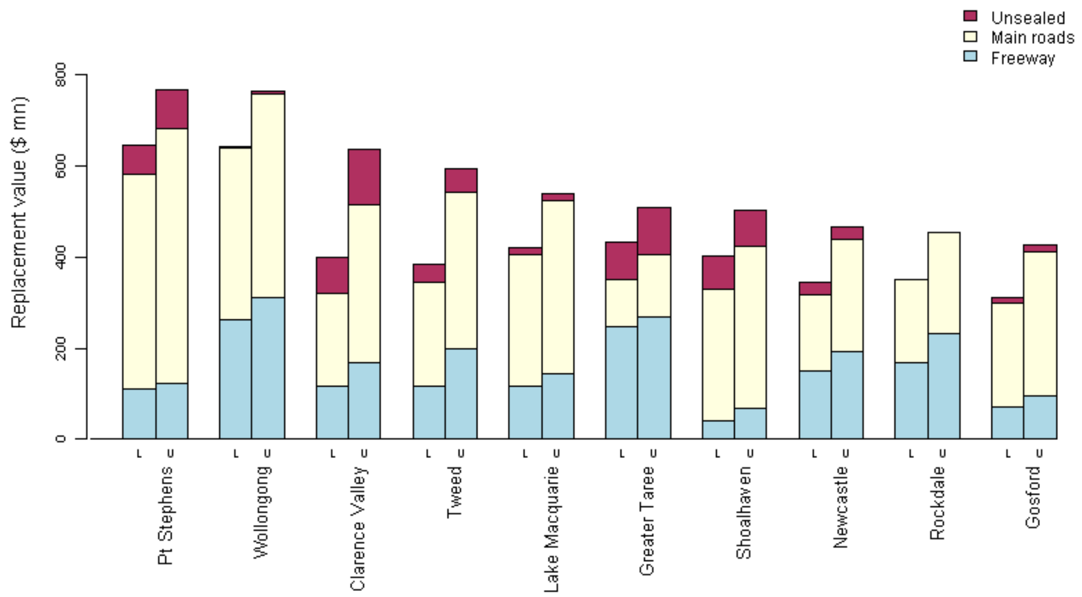


Figure A3.6: *Lower and upper estimated replacement value of existing roads in New South Wales potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

A3.2 Northern Territory

The Northern Territory only has between 260 and 400 residential structures potentially at risk from the combined impacts of inundation and recession under both the upper and lower 2100 estimates (Figure A3.7). The LGA of Darwin contains the greatest risk to residential buildings with between 180 and 200 buildings potentially vulnerable by 2100 (Figure A3.8). The LGA of Darwin also has the highest replacement value for buildings at between $77 and 81 million dollars.

Most (98%) of the light industrial buildings at risk to inundation and recession in the Northern Territory are concentrated outside Darwin, with a replacement value up to $133 million (Figure A3.9). Darwin contains all the commercial assets at risk in the state, up to $540 million.

The majority of the roads that are identified as vulnerable to potential inundation or recession in the Northern Territory are unsealed (Figure A3.10). The LGA of Victoria-Daly has the seventh greatest length of vulnerable road exposure in Australia, between 500 and 610km. More than 99% of this length is unsealed. However, in terms of value, freeways and main roads represent a significant portion of the road exposure at risk (Figure A3.11). Nearly all the rail exposure at risk is located in the LGAs of 'Unincorporated NT', Palmerston and Litchfield. These LGAs contain a total value of vulnerable rail exposure between $47 million and $129 million, which represents over 95% of the total value in the Northern Territory.

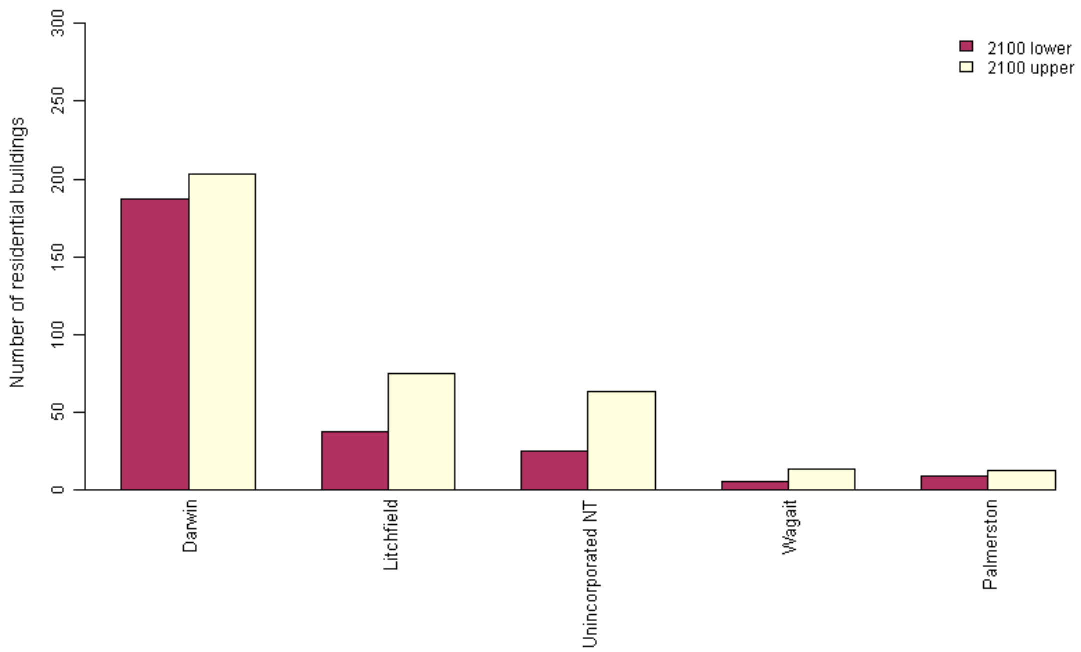


Figure A3.7: *Lower and upper estimated number of existing residential buildings in Northern Territory potentially at risk from the combined impact of inundation and recession by 2100. LGAs most at risk are shown.*

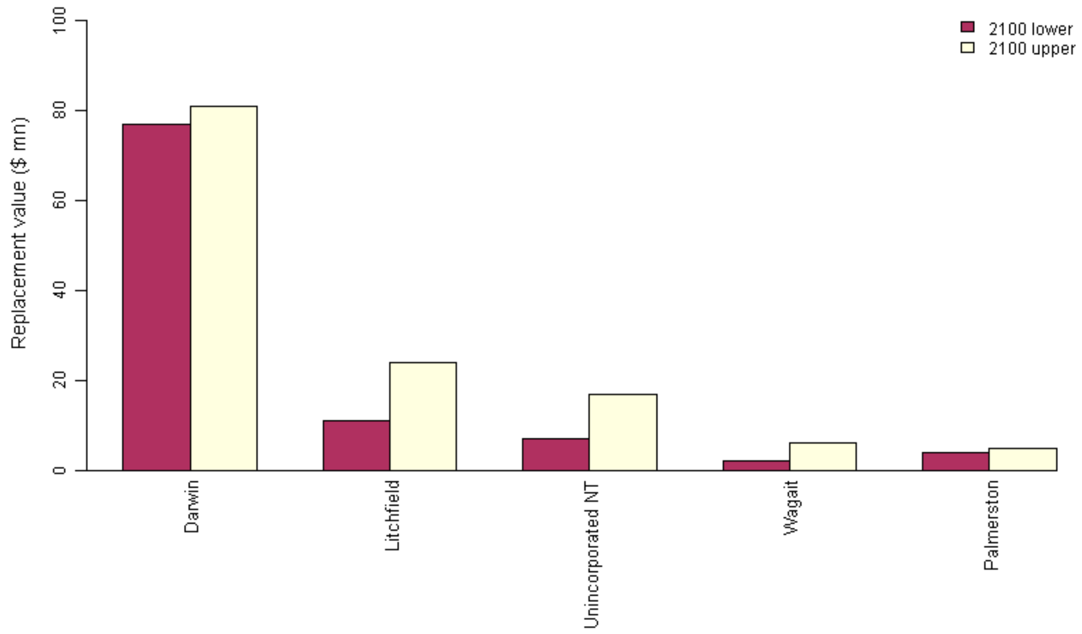


Figure A3.8: *Lower and upper estimated replacement value of existing residential buildings in Northern Territory potentially at risk from the combined impact of inundation and recession by 2100. LGAs most at risk are shown.*

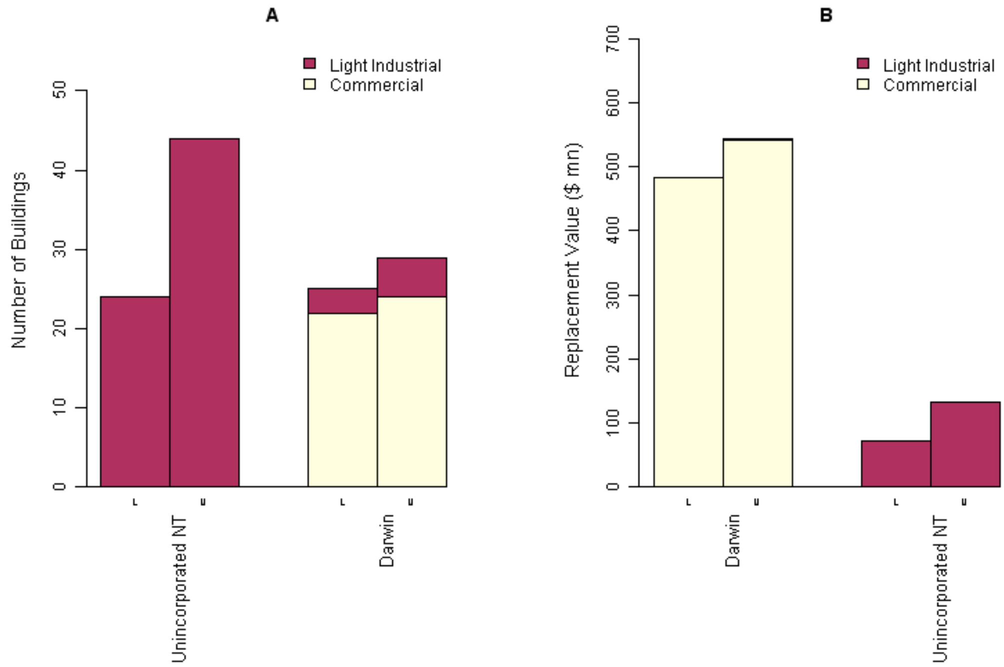


Figure A3.9: *The lower and upper estimated A) number and B) replacement value of existing commercial and light industrial buildings in Northern Territory potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

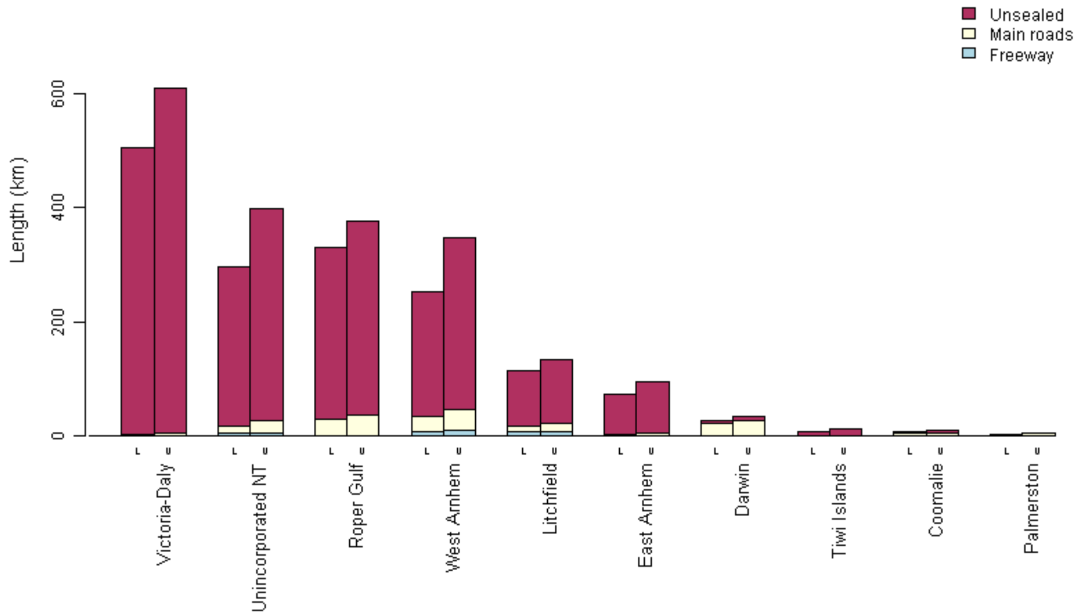


Figure A3.10: *Lower and upper estimated length of existing roads in Northern Territory potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

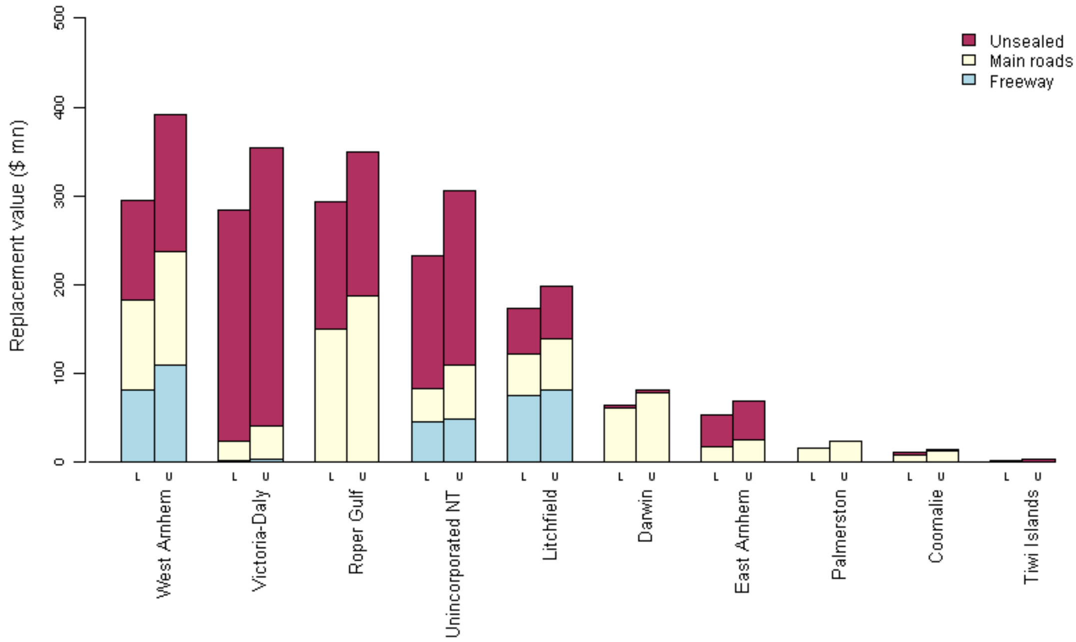


Figure A3.11: *Lower and upper estimated replacement value of existing roads in Northern Territory potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

A3.3 Queensland

Queensland has highest number of residential structures potentially at risk from the combined impacts of inundation and recession due to climate change by 2100. The state has the five of the top ten LGAs at risk nationally. The LGA of Moreton Bay contains the greatest risk to with between 10,400 and 15,000 buildings potential vulnerable by 2100, followed by the LGAs of Gold Coast, Mackay and the Fraser Coast (Figure A3.12). However, the Gold Coast LGA contains highest replacements value for residential buildings at between $3.4 billion and $4.2 billion dollars by 2100, closely followed by Moreton Bay with between $2.9 billion and $3.9 billion. Collectively the total replacement costs of residential buildings by 2100 in excess of $20 billion dollars, with the top ten LGAs accounting for over 90% of this value (Figure A3.6).

Queensland contains between 2,100 and 3,200 commercial and light industrial buildings identified to be at risk from inundation and recession by 2100, at a total value of between $10.9 billion and $16.7 billion. Queensland contains nearly 30% of the national total number and replacement value of light industrial structures at risk: 1,800 buildings at a value of $2 billion. More than 90% of the Queensland commercial and light industrial risk is contained in the ten LGAs shown in Figures A3.14 and A3.15. The Gold Coast and Moreton Bay alone have more than $7.9 billion commercial and light industrial assets at risk, in addition to their considerable vulnerable residential exposure.

With between $9.7 billion and $12 billion of roads and around $2 billion of rail identified to be potentially at risk, Queensland has the highest value of vulnerable roads and rail exposure in Australia. The Gold Coast, Mackay and the Fraser Coast rank among the ten LGAs that have the highest length and value of vulnerable road exposure in the country. Together, these three LGAs contain over 4% of the national replacement value of roads, although their combined road exposure represents less than 30% of the total road exposure at risk in Queensland. The roads at risk in Queensland are predominantly main roads, with unsealed roads and freeways only contributing a small proportion of the total length and value of exposure (Figures A3.16 and A3.17). Up to half of the rail exposure at risk in Queensland, between $316 million and $1.1 billion, is located in the LGAs of Burdekin, Mackay, Bundaberg and Rockhampton.

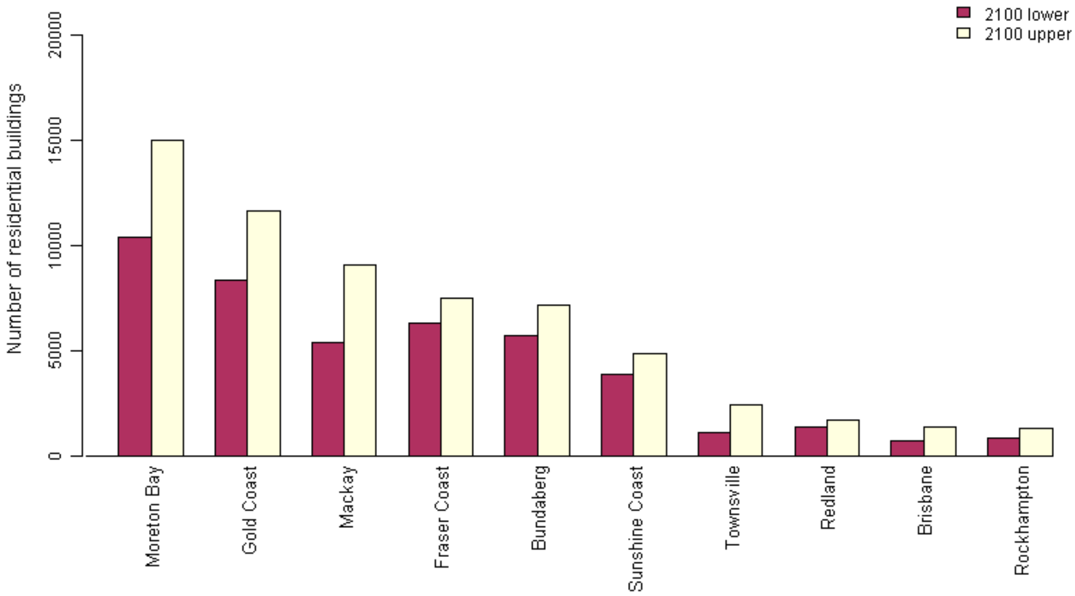


Figure A3.12: *Lower and upper estimated number of existing residential buildings in Queensland potentially at risk from the combined impact of inundation and recession by 2100. LGAs most at risk are shown.*

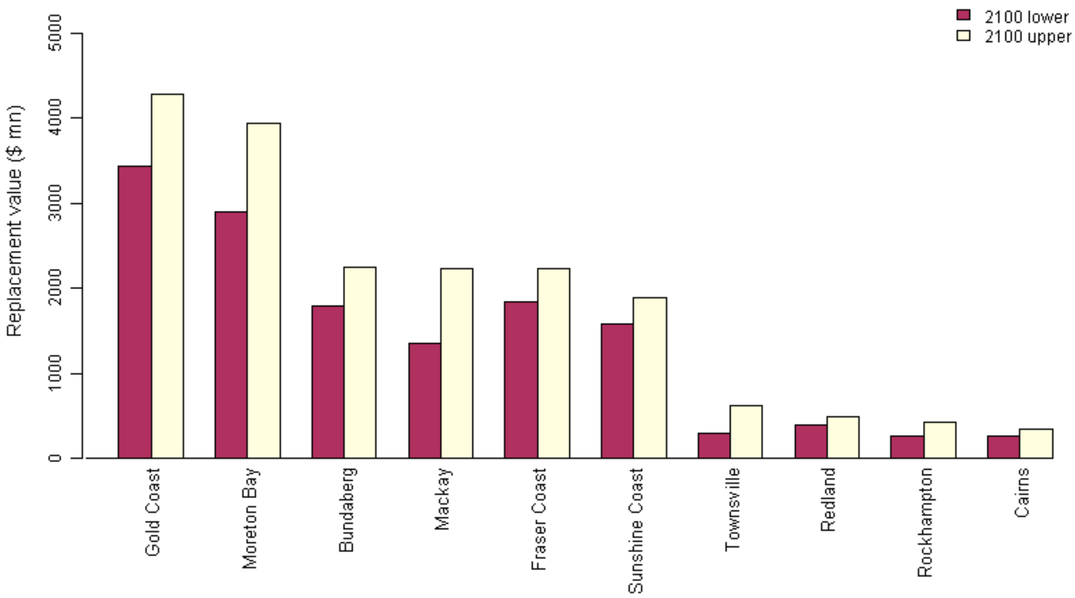


Figure A3.13: *Lower and upper estimated replacement value of existing residential buildings in Queensland potentially at risk from the combined impact of inundation and recession by 2100. LGAs most at risk are shown.*

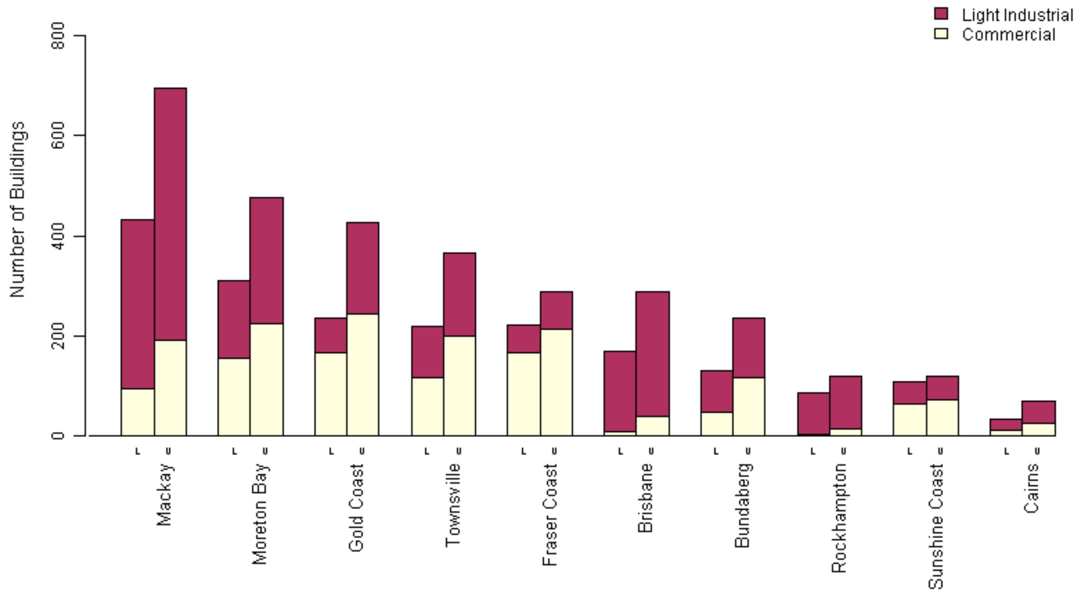


Figure A3.14: *Lower and upper estimated number of existing commercial and light industrial buildings in Queensland potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

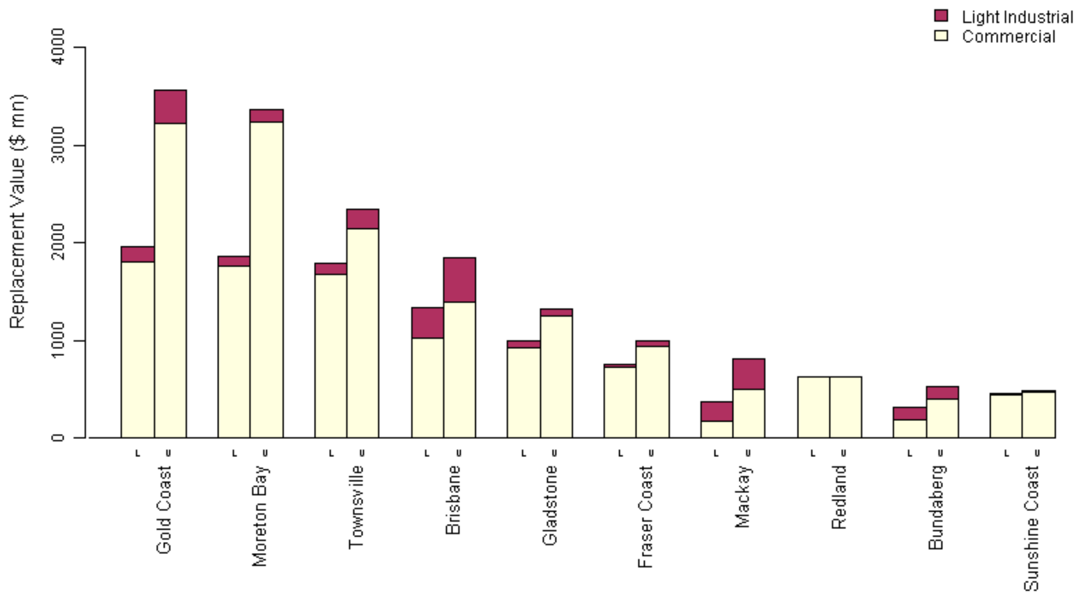


Figure A3.15: *Lower and upper estimated replacement value of existing commercial and light industrial buildings in Queensland potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

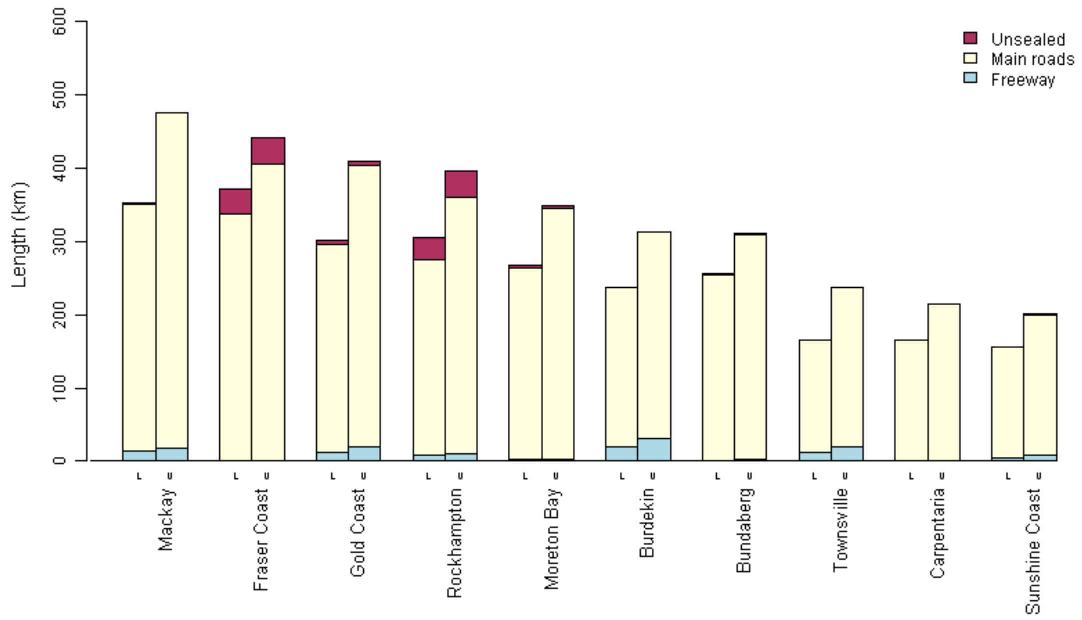


Figure A3.16: *Lower and upper estimated length of existing roads in Queensland potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

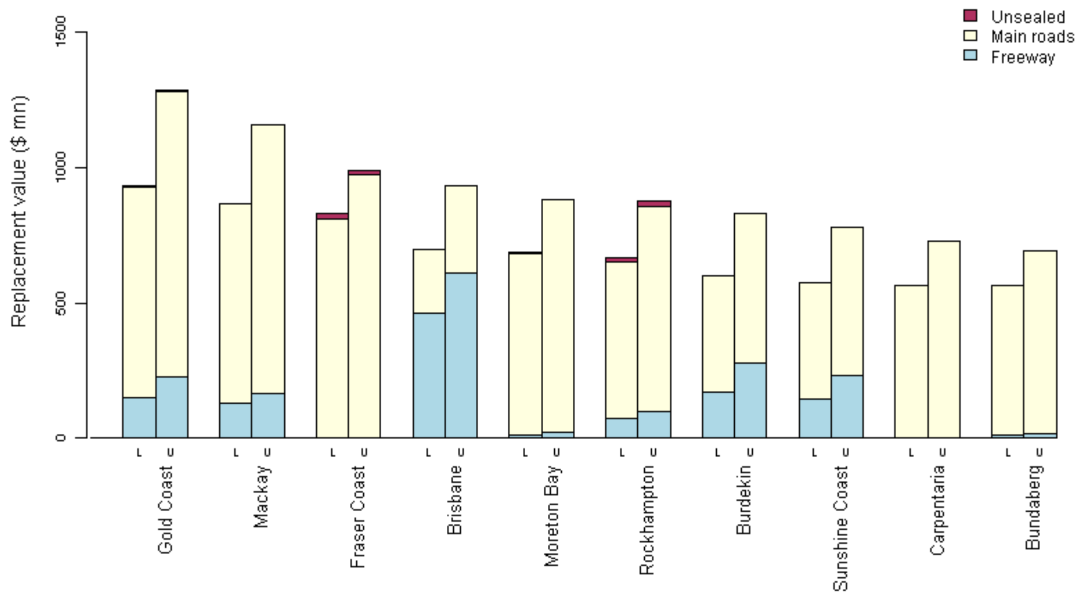


Figure A3.17: *Lower and upper estimated replacement value of existing roads in Queensland potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

A3.4 South Australia

South Australia has between 31,000 and 48,000 residential structures potentially at risk from the combined impacts of inundation and recession under by 2100. The inner city Adelaide LGA of Charles Sturt contains the greatest risk to residential buildings with between 10,000 and 15,000 buildings potentially vulnerable by 2100, followed by the LGA of Port Adelaide Enfield with 5,500 to 10,700 buildings (Figure A3.18). These two LGAs are amongst the most vulnerable LGAs nationally; second and fourth most vulnerable respectively. They account for approximately half of the total number of residential buildings vulnerable by 2100 in South Australia. Predictably, the LGA of Charles Sturt also has the highest replacement value for buildings at between $1.5 billion and $2.2 billion. Collectively, the total replacement value of residential buildings at risk by 2100 is in excess of $8.3 billion, with the top ten LGAs accounting for over 80% of this value (Figure A3. 19).

South Australia is the most vulnerable state in terms of commercial and industrial assets to inundation and recession. In total, between 1,300 and 2,600 commercial and industrial buildings, between $22.5 billion and $27.9 billion, are identified to be in a zone vulnerable to inundation or recession by 2100. Most of the commercial and industrial assets at risk in South Australia are located in the LGA of Port Adelaide Enfield. Especially the commercial exposure is heavily concentrated in this LGA, which contains more than 75% of the commercial exposure at risk in the state, amounting to over $20 billion in replacement costs. Up to 26% of the value of commercial and 10% of industrial exposure at risk nationally is concentrated in this single LGA (Figures A3.20 and A3.21).

South Australia has more than $9.5 billion of roads and over $900 million of rail exposure identified to be vulnerable to inundation and erosion. In terms of length, these roads are concentrated in Yorke Peninsula and the Coorong (Figure A3.22). Unsealed roads constitute a large portion of the vulnerable roads in Yorke Peninsula, and in many other LGAs in South Australia, and this means they can rank less high in terms of road replacement value (Figure A3.23). However, between them, the ten most vulnerable LGAs in South Australia contain between $4.8 billion and $6.1 billion of road exposure at risk, over 10% of the national figure. The Coorong, Port Adelaide Enfield and Kingston are among the ten LGAs with the highest value of road exposure at risk in Australia, and contribute over 5% to the total national replacement value of vulnerable road exposure. More than half of the rail at risk in South Australia is located in Port Adelaide Enfield, Port Pirie City and Districts, Port Augusta and Mount Remarkable (up to $539 million).

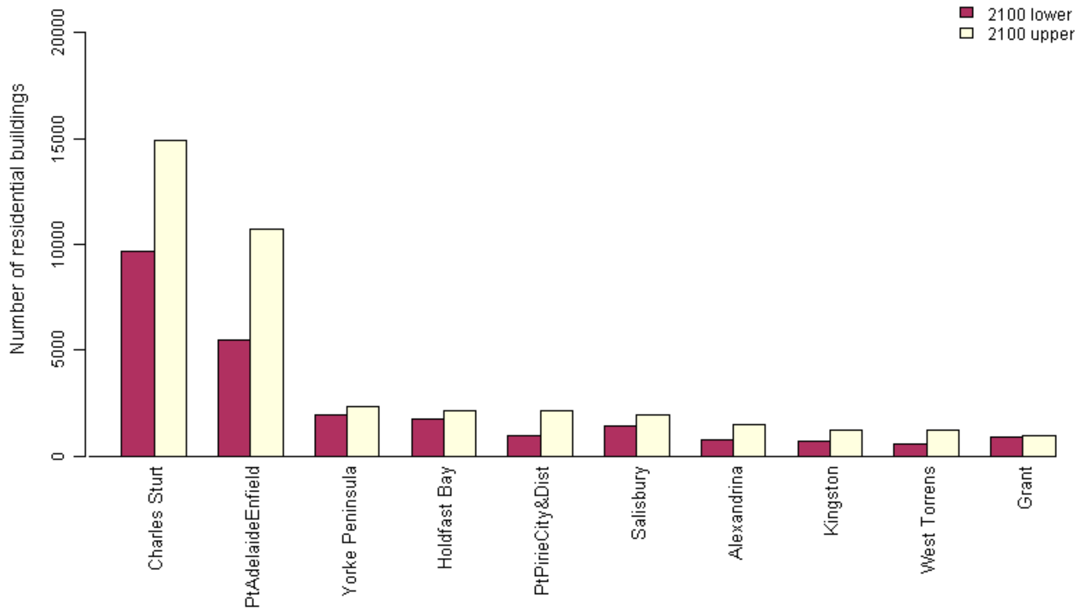


Figure A3.18: Lower and upper estimated number of existing residential buildings in South Australia potentially at risk from the combined impact of inundation and recession by 2100. LGAs most at risk are shown.

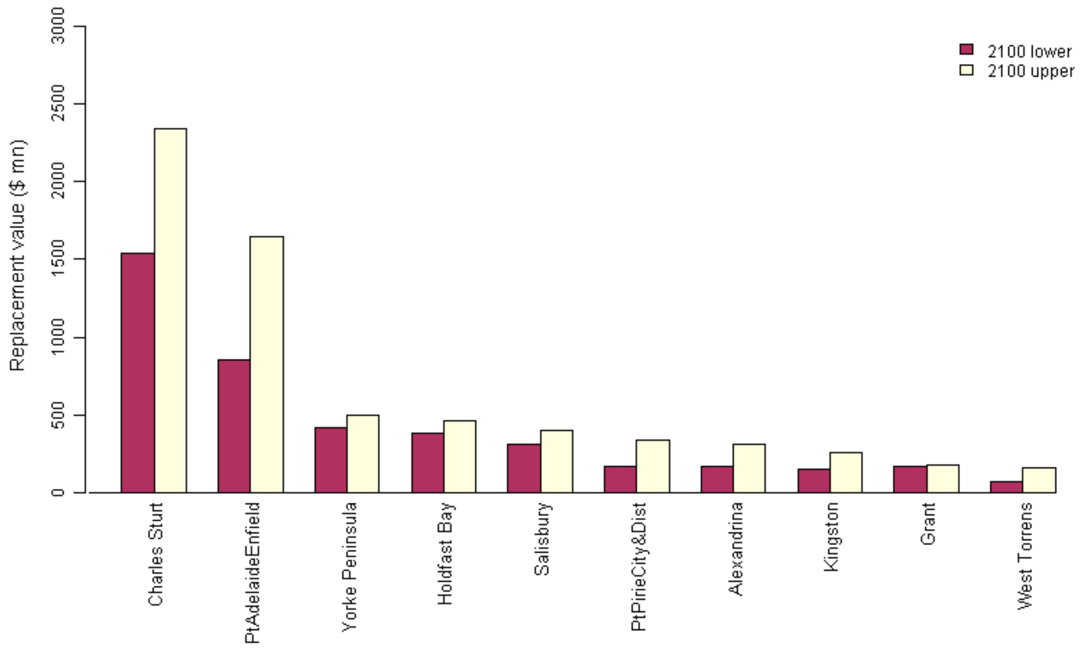


Figure A3.19: *Lower and upper estimated replacement value of existing residential buildings in South Australia potentially at risk from the combined impact of inundation and recession by 2100. LGAs most at risk are shown.*

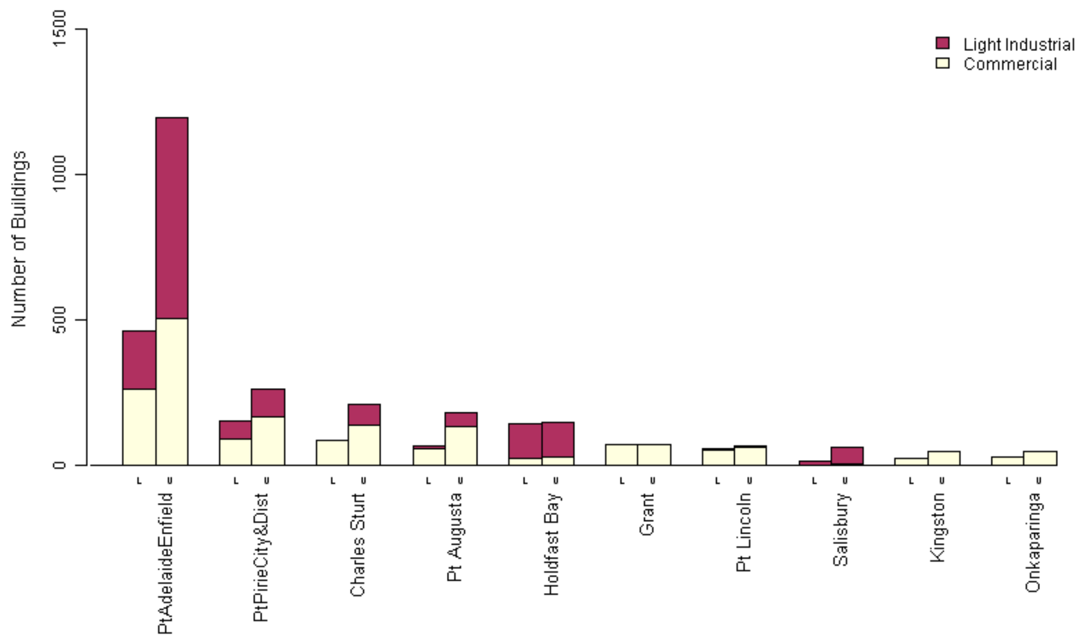


Figure A3.20: *Lower and upper estimated number of existing commercial and light industrial buildings in South Australia potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

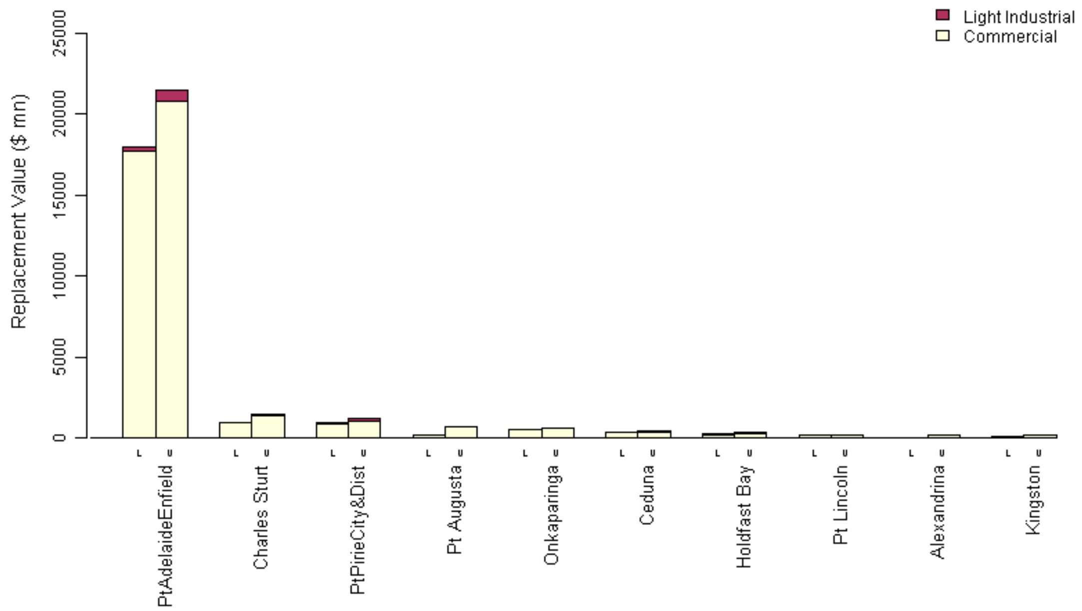


Figure A3.21: *Lower and upper estimated replacement value of existing commercial and light industrial buildings in South Australia potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

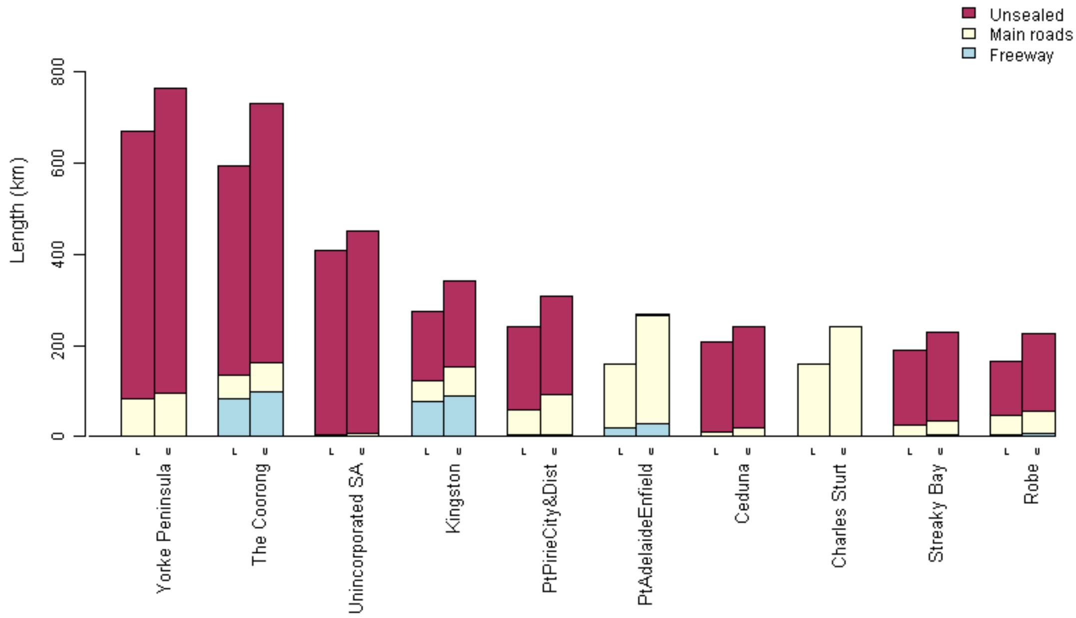


Figure A3.22: *Lower and upper estimated length of existing roads in South Australia potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

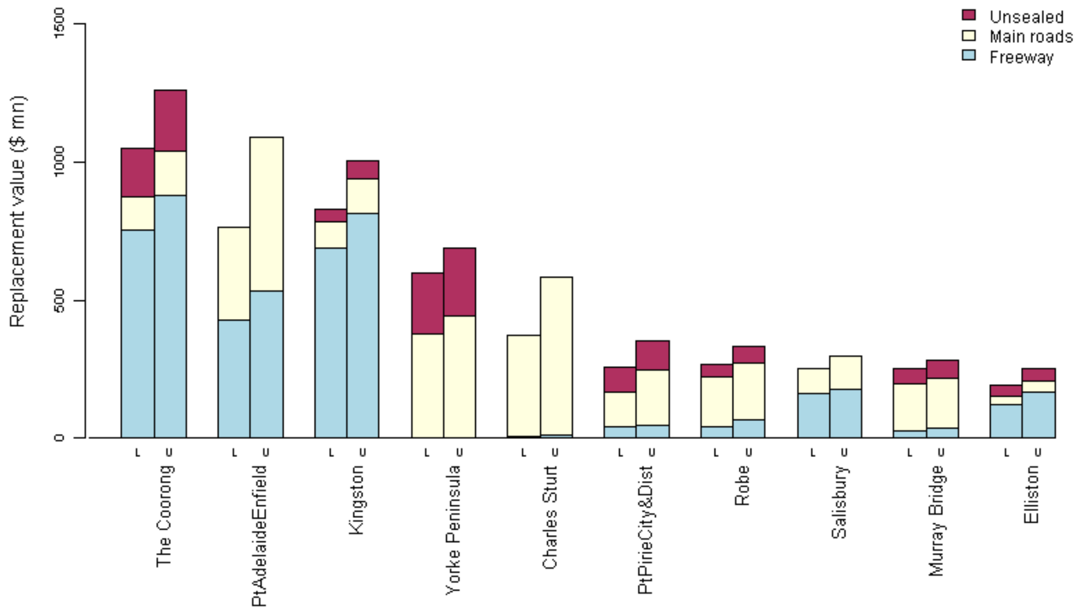


Figure A3.23: *Lower and upper estimated replacement value of existing roads in South Australia potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

A3.5 Tasmania

Tasmania has between 12,000 and 15,000 residential structures potentially at risk from the combined impacts of inundation and recession under by 2100. The LGA of Clarence contains the greatest risk to residential buildings with between 2,000 and 2,400 buildings potentially vulnerable by 2100, followed by the LGAs of Central Coast and Break O'Day (Figure A3.24). The LGA of Clarence also has the highest replacement value for buildings at between $540 and $650 million. Collectively, the total replacement value of residential buildings at risk by 2100 is in excess of $3.2 billion, with the top ten LGAs accounting for about 75% of this value (Figure A3. 25).

Between 420 and 580 commercial and industrial buildings in Tasmania may be exposed to the combined impact of inundation and recession, amounting to between $1.1 billion and $1.5 billion (Figures A3.27 and A3.28). Most of this is commercial exposure at risk, which may be up to $1.15 billion. Up to 72% of the commercial and 37% of the industrial exposure at risk in Tasmania is located in the LGAs of Hobart, Huon Valley and Burnie

Tasmania has between 1740 and 2040km of roads vulnerable to inundation and erosion, which could represent over $4.48 billion of replacement value (Figures A3.29 and A3.30). The rail at risk is predominantly located in the LGAs of Burnie, Devonport, the Central Coast and Waratah-Wynyard, which together contain between $120 million and $460 million in terms of replacement value.

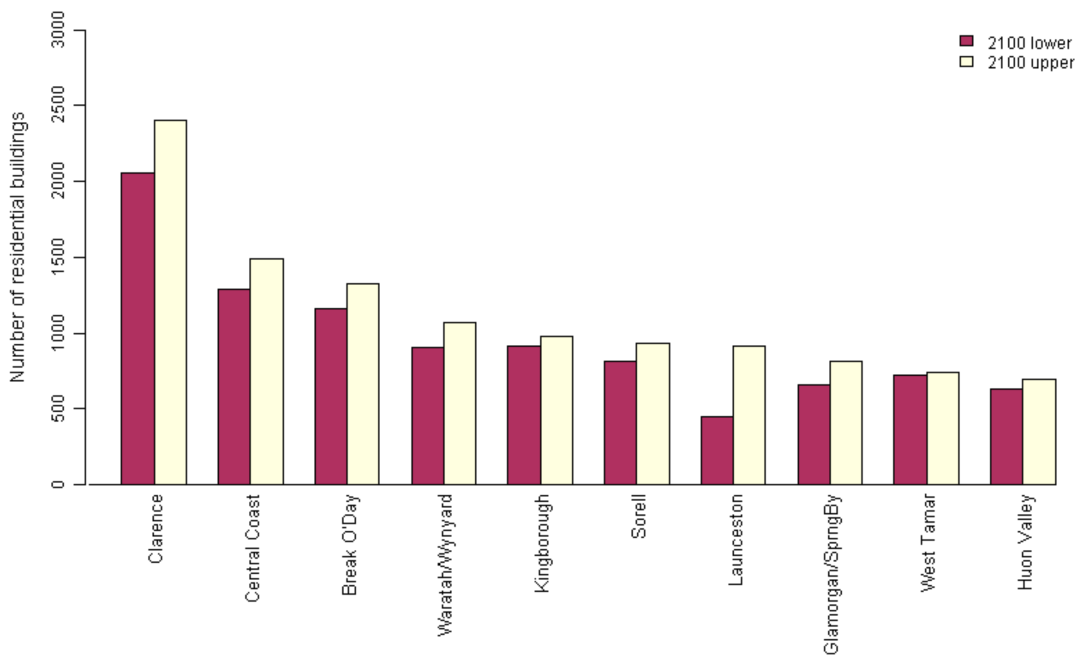


Figure A3.24: *Lower and upper estimated number of existing residential buildings in Tasmania potentially at risk from the combined impact of inundation and recession by 2100. LGAs most at risk are shown.*

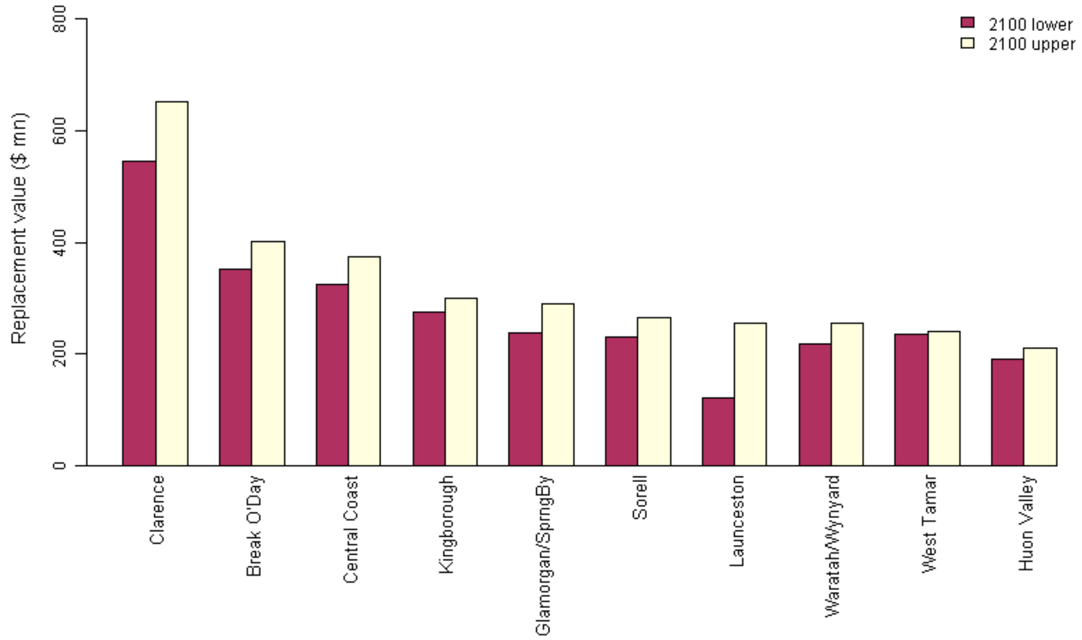


Figure A3.25: *Lower and upper estimated replacement value of existing residential buildings in Tasmania potentially at risk from the combined impact of inundation and recession by 2100. LGAs most at risk are shown.*

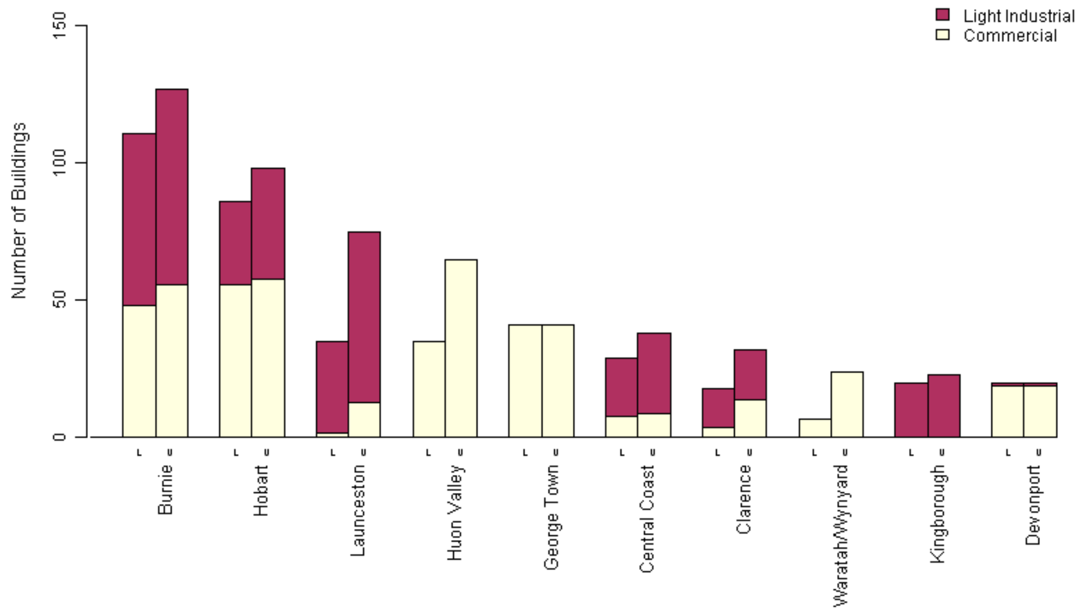


Figure A3.26: *Lower and upper estimated number of existing commercial and light industrial buildings in Tasmania potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

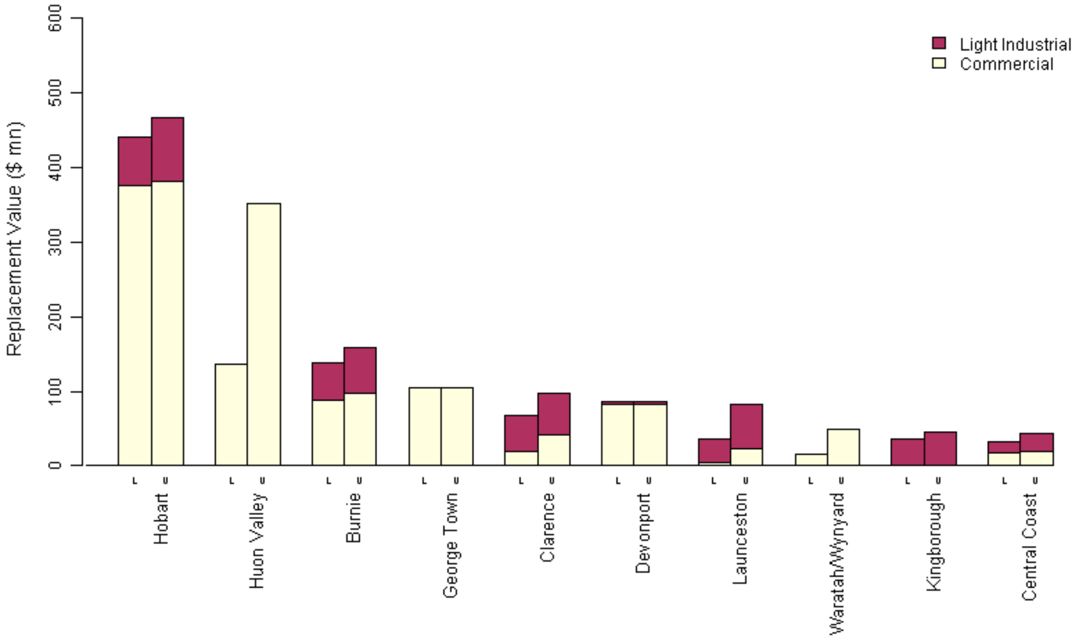


Figure A3.27: *Lower and upper estimated replacement value of existing commercial and light industrial buildings in Tasmania potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

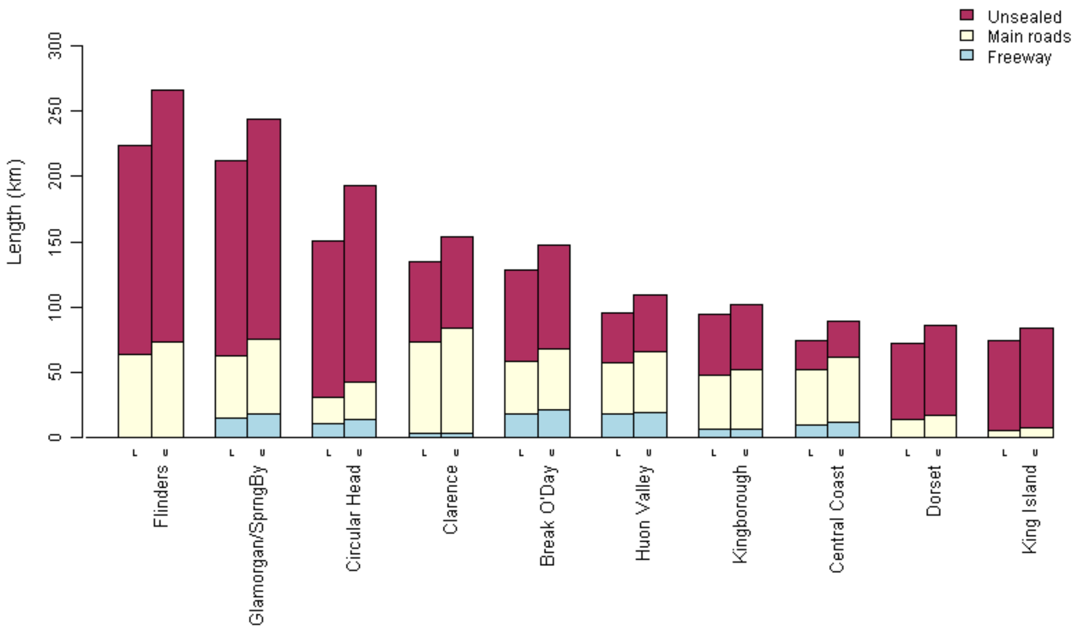


Figure A3.28: *Lower and upper estimated length of existing roads in Tasmania potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

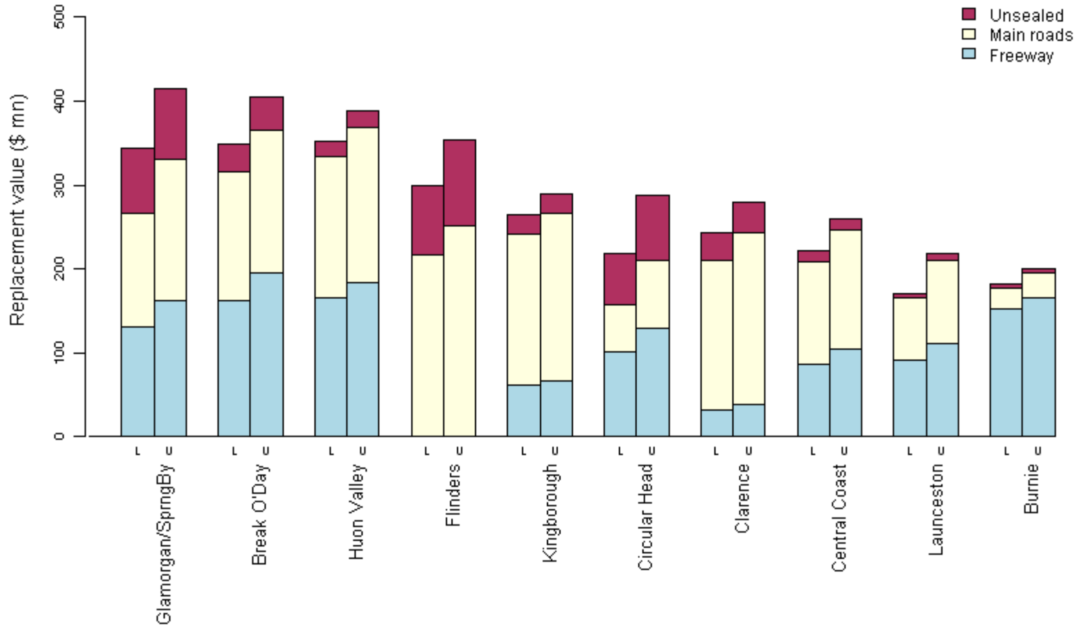


Figure A3.29: *Lower and upper estimated replacement value of existing roads in Tasmania potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

A3.6 Victoria

Victoria has between 31,000 and 48,000 residential structures potentially at risk from the combined impacts of inundation and recession under both the upper and lower 2100 scenarios. The LGA of Kingston contains the greatest risk to residential buildings with between 6,800 and 9,300 buildings potentially vulnerable by 2100, followed by the LGAs of Hobsons Bay and Greater Geelong (Figure A3.30). These 3 LGAs and the LGA of Wellington are included in the 20 most vulnerable LGAs nationally. The top ten LGAs in Victoria account for approximately 90% (or greater than 42,500 buildings) of the total number of residential buildings vulnerable by 2100. The LGA of Kingston also has the highest replacement value for buildings at between $1.3 billion and $1.9 billion dollars. Collectively, the total replacement value of residential buildings at risk by 2100 is in excess of $11.4 billion, with the top ten LGAs accounting for over 85% of this value (Figure A3.31).

Victoria contains between 2,100 and 3,000 industrial and commercial buildings potentially at risk by 2100, which corresponds to between $8.2 billion and $12.3 billion. The LGA of Melbourne ranks as the second most vulnerable LGA in Australia in terms of the value of its commercial and industrial exposure at risk from inundation and recession by 2100. While it does not contain the highest number of buildings at risk (up to 84), Melbourne contains over 4% of the vulnerable national commercial and light industrial exposure in terms of value (Figures A3.32 and A3.33). In addition to Melbourne, Kingston also is among the ten most vulnerable LGAs nationally for replacement value of commercial and light industrial exposure at risk. Greater Geelong, Surfcoast and Frankston are among the ten LGAs with the largest number of vulnerable buildings in these categories across the continent.

Roads at risk from inundation and erosion in Victoria are particularly located in Wellington, Greater Geelong and East Gippsland (Figure A3.34). Wellington has the third greatest length of vulnerable roads in Australia (between 640 and 775km). Together, these three LGAs contain between 1400 and 1650km of vulnerable roads. Wellington and Greater Geelong (Figure 4.35) rank among the ten LGAs with the highest replacement value of vulnerable road exposure in Australia. Between $100 and 350 million of vulnerable rail, more than 60% of the total replacement value of rail at risk in Victoria, is situated in the LGAs of Melbourne, Cardinia, Hobson's Bay, and Casey. Nearly a third of the total value of Victorian rail at risk is in the LGA of Melbourne itself.

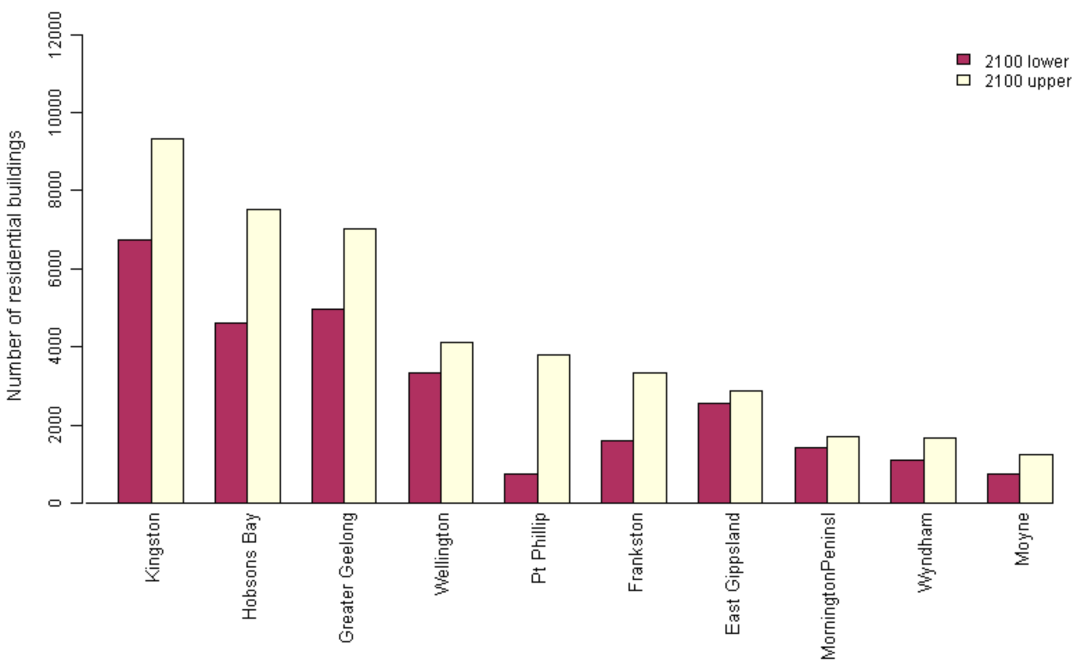


Figure A3.30: *Lower and upper estimated number of existing residential buildings in Victoria potentially at risk from the combined impact of inundation and recession by 2100. LGAs most at risk are shown.*

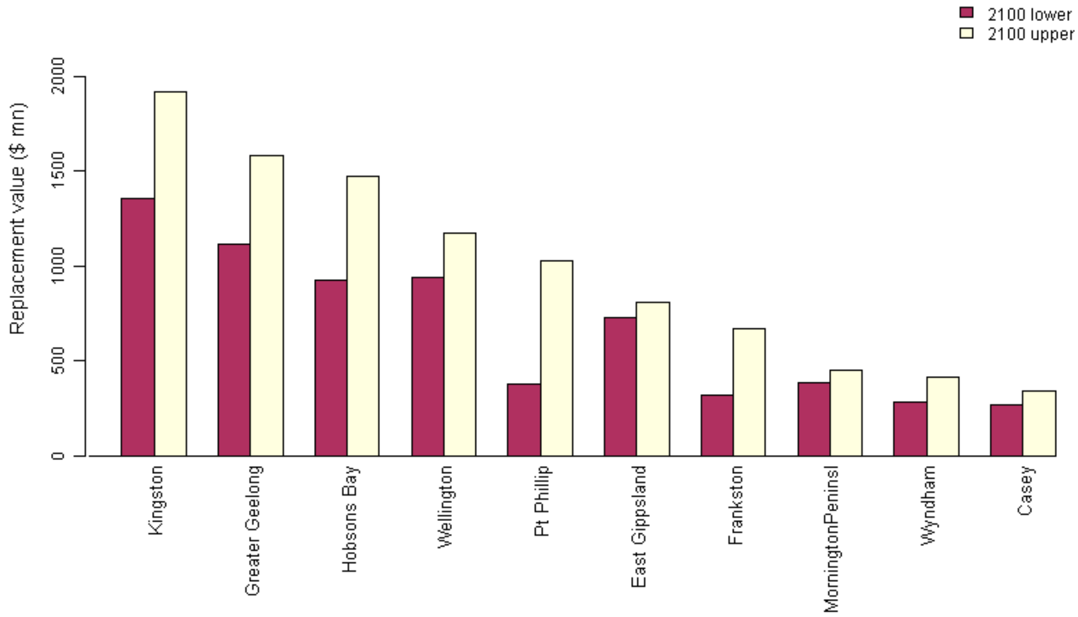


Figure A3.31: *Lower and upper estimated replacement value of existing residential buildings in Victoria potentially at risk from the combined impact of inundation and recession by 2100. LGAs most at risk are shown.*

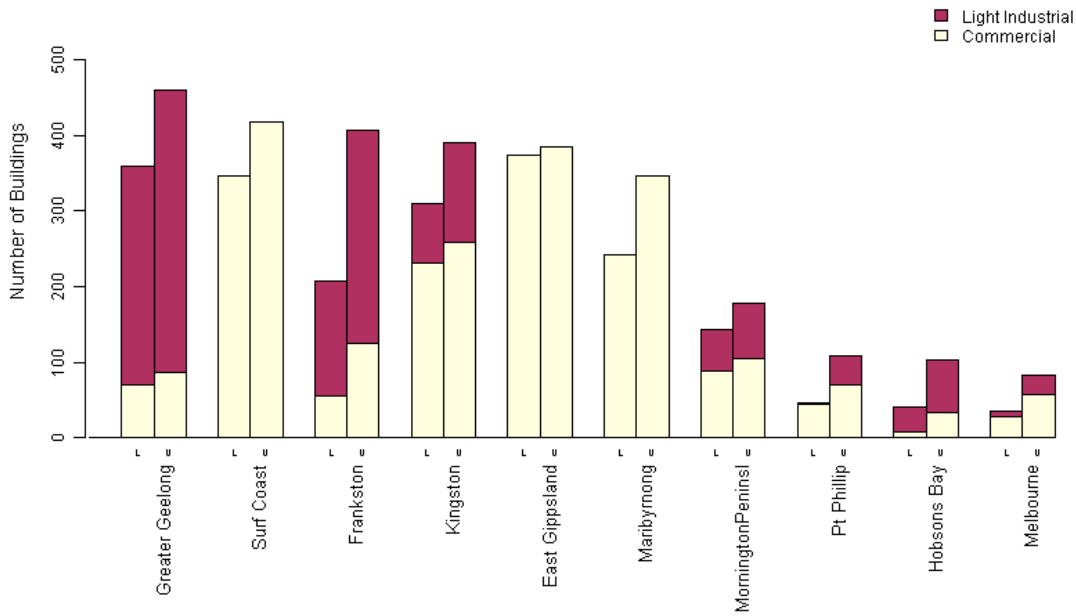


Figure A3.32: *Lower and upper estimated number of existing commercial and light industrial buildings in Victoria potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

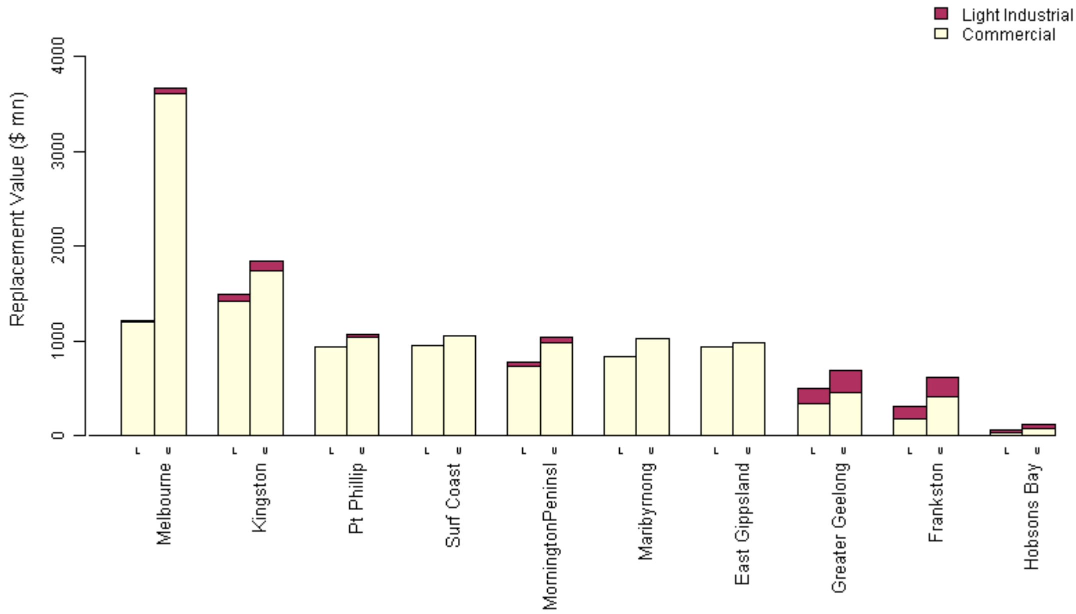


Figure A3.33: *Lower and upper estimated replacement value of existing commercial and light industrial buildings in Victoria potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

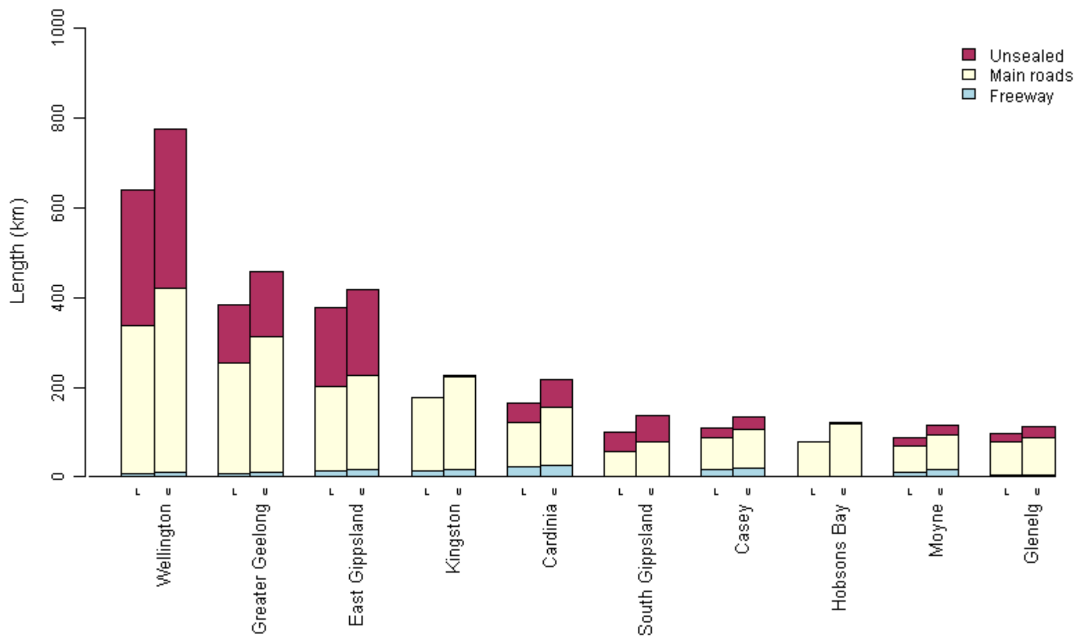


Figure A3.34: *Lower and upper estimated length of existing roads in Victoria potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

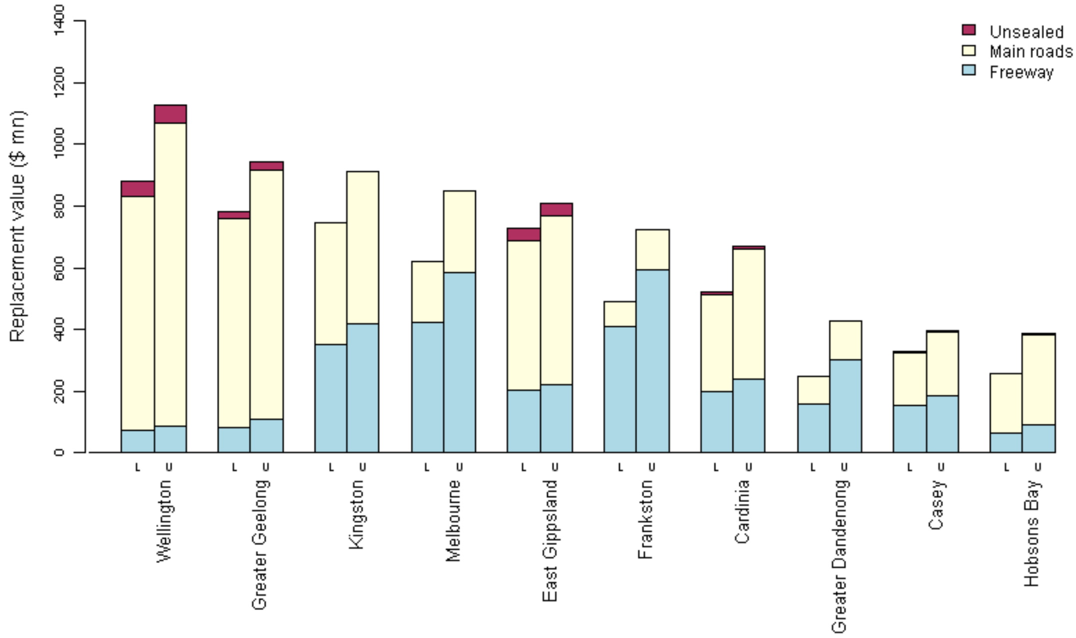


Figure A3.35: *Lower and upper estimated replacement value of existing roads in Victoria potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

A3.7 Western Australia

Western Australia has between 20,000 and 30,000 residential structures potentially at risk from the combined impacts of inundation and recession under by 2100. The LGA of Busselton contains the greatest risk to residential buildings with between 6,800 and 9,300 buildings potentially vulnerable by 2100, followed by the LGAs of Mandurah and Rockingham (Figure A3.36). These three LGAs are amongst the most vulnerable LGAs nationally; seventh, 20th and 21st most vulnerable respectively. The top ten LGAs in Western Australia account for approximately 83% (or greater than 25,000 buildings) of the total number of residential buildings vulnerable by 2100. The LGA of Busselton also has the highest replacement value for buildings at between $2 billion and $2.2 billion. Collectively, the total replacement value of residential buildings at risk by 2100 is in excess of $8 billion, with the top ten LGAs accounting for over 80% of this value (Figure A3.37)

Western Australia has the highest number of commercial buildings potentially exposed to inundation and recession impacts across the continent. Between 1,500 and over 2,100 commercial buildings are identified as vulnerable, representing nearly a quarter of the national commercial building stock at risk (Figure A3.38). Up to 23% of these are located in Bunbury. In total, the replacement value of commercial buildings at risk in WA by 2100 is between $12 billion and $17 billion. WA also has between 600 and 900 light industrial buildings at risk, with a value up to a billion. More than 75% of this exposure is located in Port Hedland, Busselton, Broome and Bunbury (Figure A3.39).

After Queensland, Western Australia has the highest value of roads at risk from erosion and inundation in Australia; between $8.7 billion and $11.3 billion. The LGA of Broome has both the greatest length and value of roads at risk of the entire continent (up to 2056km, or $1.4 billion). Carnarvon has the second greatest length of vulnerable road in the country (up to 930km).The ten LGAs with the largest value of vulnerable road exposure in WA (Figure A3.41) together contain up to $6.4 billion in replacement value, which is more than 10% of the total value of roads at risk in Australia. Vulnerable rail exposure in Western Australia is concentrated in the LGAs of Port Hedland, Roebourne, Kwinana, Bunbury and Busselton, which together contain between $40 million and $330 million, nearly 70% of the rail at risk in Western Australia.

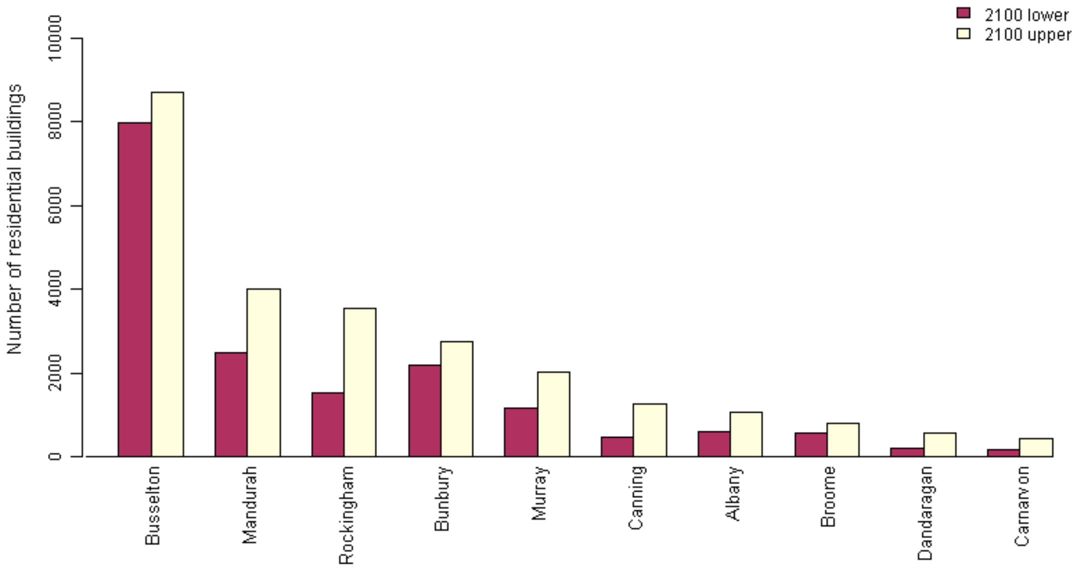


Figure A3.36: *Lower and upper estimated number of existing residential buildings in Western Australia potentially at risk from the combined impact of inundation and recession by 2100. LGAs most at risk are shown.*

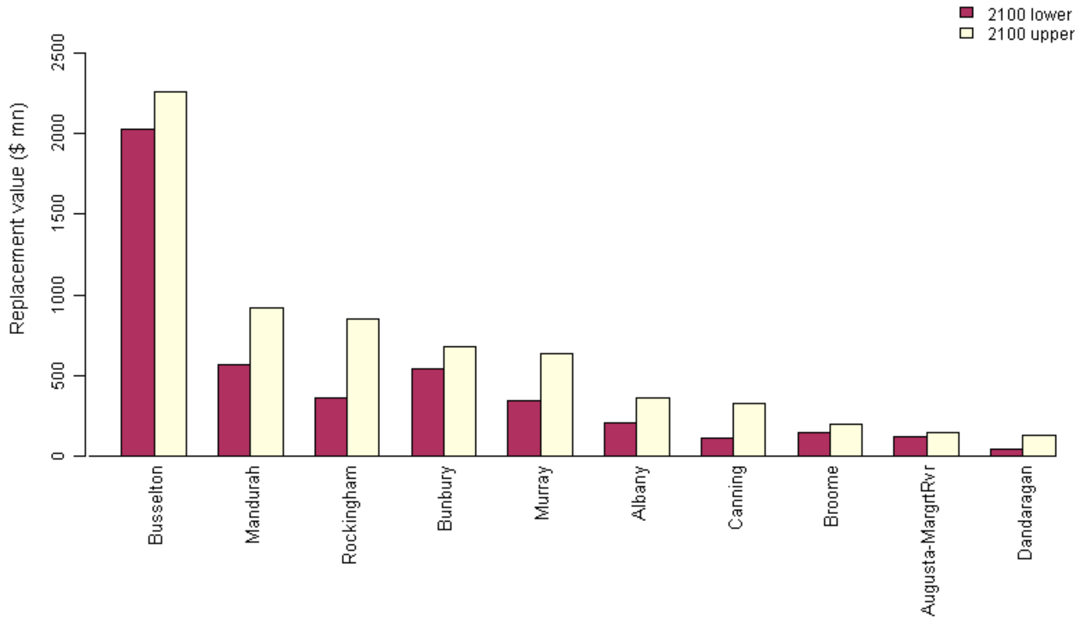


Figure A3. 37: *Lower and upper estimated replacement value of existing residential buildings in Western Australia potentially at risk from the combined impact of inundation and recession by 2100. LGAs most at risk are shown.*

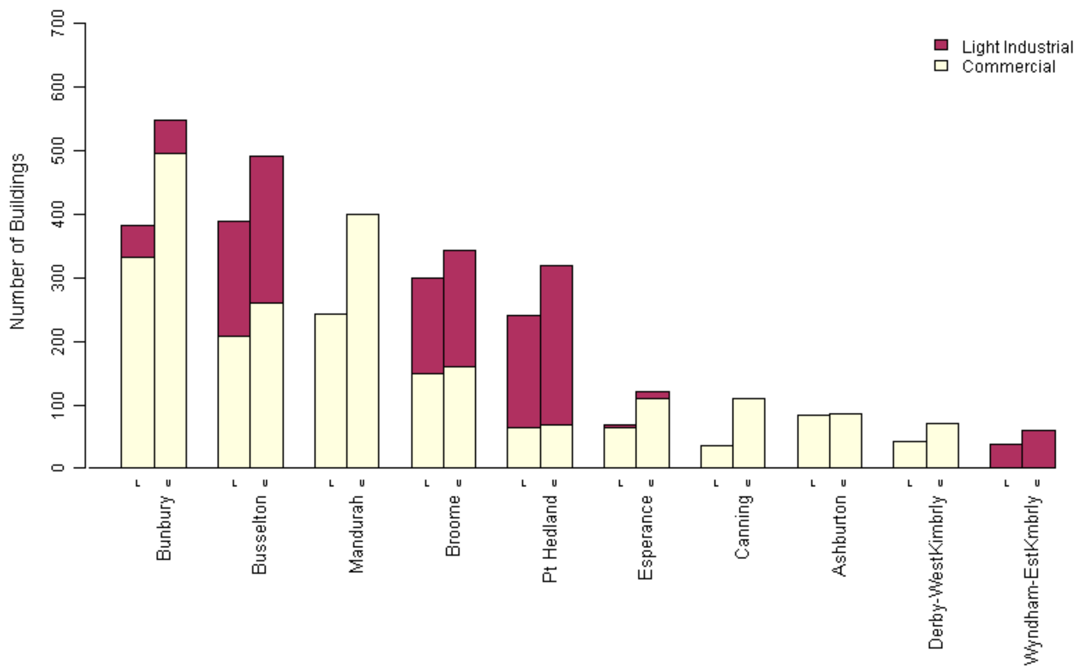


Figure A3.38: *Lower and upper estimated number of existing commercial and light industrial buildings in Western Australia potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

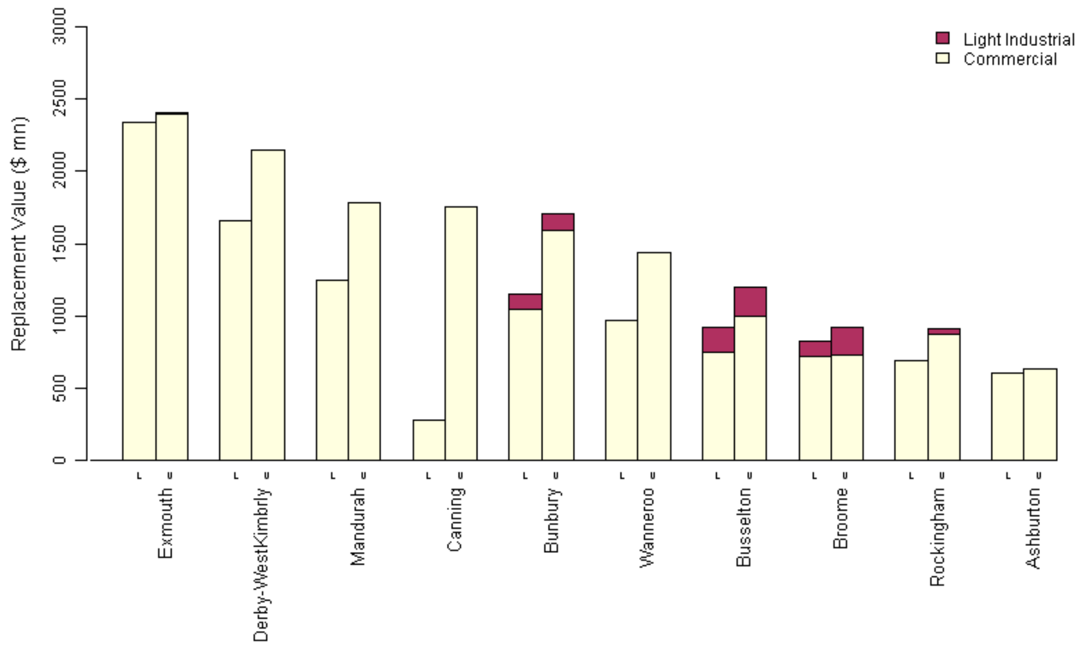


Figure A3.39: *Lower and upper estimated replacement value of existing commercial and light industrial buildings in Western Australia potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

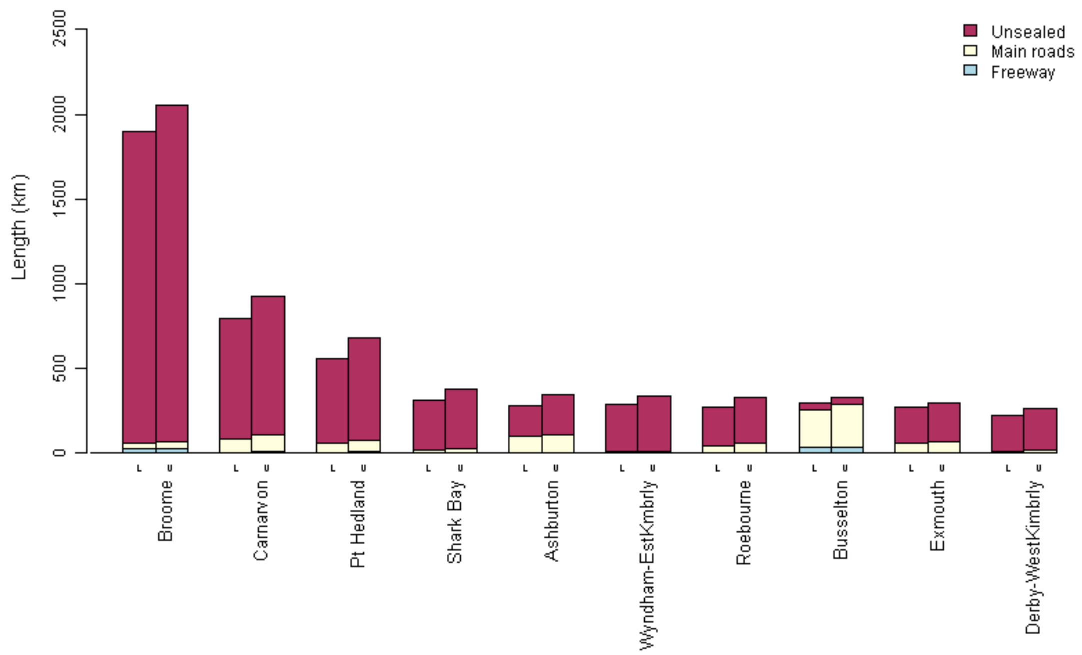


Figure A3.40: *Lower and upper estimated length of existing roads in Western Australia potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*

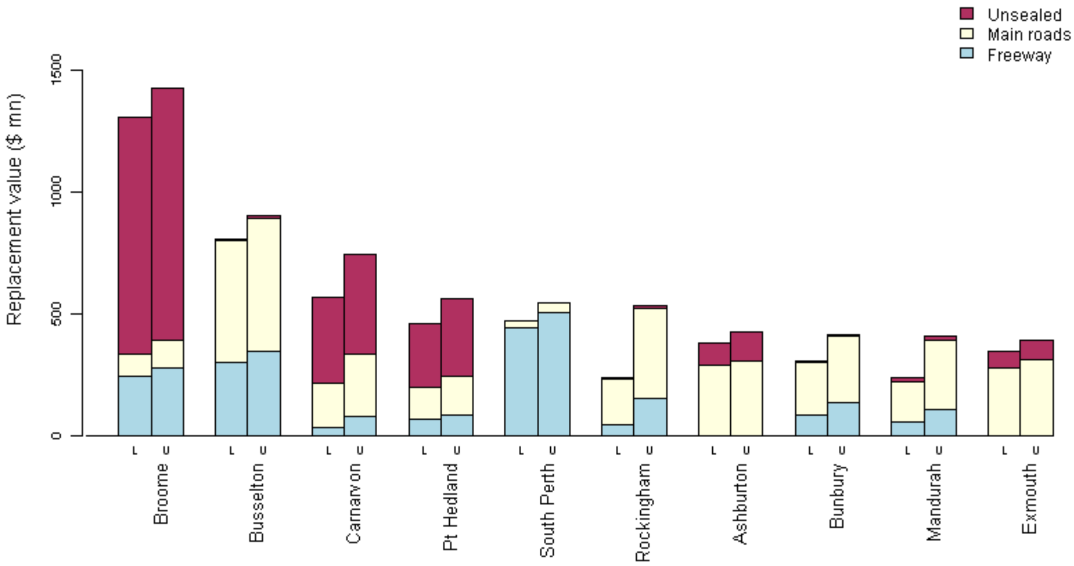
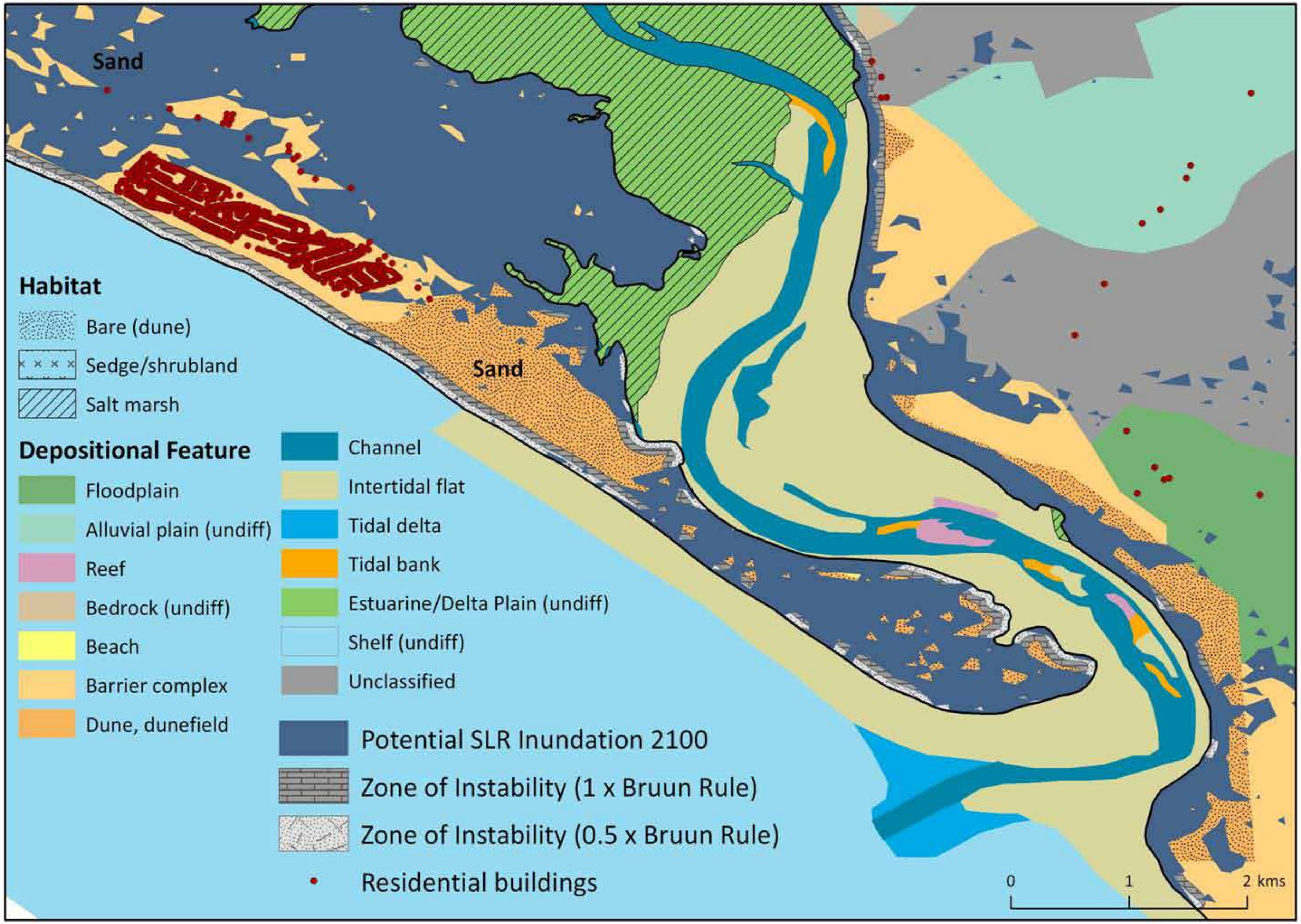


Figure A3.41: *Lower and upper estimated replacement value of existing roads in Western Australia potentially at risk from the combined impact of inundation and recession by 2100. The Lower (L) and upper (U) estimates are shown for the LGAs most at risk.*


Sand
Sand
Habitat
Bare (dune)
Sedge/shrubland
Salt marsh
Depositional Feature
Floodplain
Alluvial plain (undiff)
Reef
Bedrock (undiff)
Beach
Barrier complex
Dune, dunefield
Channel
Intertidal flat
Tidal delta
Tidal bank
Estuarine/Delta Plain (undiff)
Shelf (undiff)
Unclassified
Potential SLR Inundation 2100
Zone of Instability (1 x Bruun Rule)
Zone of Instability (0.5 x Bruun Rule)
Residential buildings
0
1
2 kms