NSW Estuary Tidal Inundation Exposure Assessment

Acknowledgements

Funding for this study was provided by the Natural Disasters Resilience Program. Water level data was kindly provided by Manly Hydraulics Laboratory. Terrain data was provided by Land and Property Information (LPI), Coffs Harbour City Council, Tweed Shire Council and Great Lakes Council. Many thanks to Dr John Church and Professor Bruce Thom for their peer review of the report.

Published by:

Office of Environment and Heritage
59 Goulburn Street, Sydney NSW 2000
PO Box A290, Sydney South NSW 1232
Phone: +61 2 9995 5000 (switchboard)
Phone: 131 555 (environment information and publications requests)
Phone: 1300 361 967 (national parks, general environmental enquiries, and publications requests)
Fax: +61 2 9995 5999
TTY users: phone 133 677, then ask for 131 555
Speak and listen users: phone 1300 555 727, then ask for 131 555
Email: info@environment.nsw.gov.au
Website: www.environment.nsw.gov.au

Report pollution and environmental incidents
Environment Line: 131 555 (NSW only) or info@environment.nsw.gov.au
See also www.environment.nsw.gov.au

ISBN 978-1-76039-958-0
OEH 2017/0635
July 2018

Find out more about your environment at:

www.environment.nsw.gov.au

Contents

List of figures

List of tables

Executive summary

Key findings

Communities and infrastructure along the coast of New South Wales are highly vulnerable to climate change. In this study, we assess exposure of current development to inundation associated with a range of potential, future sea level rise (SLR) scenarios.

Results show that 23,653 properties are exposed to tidal inundation (at the High High Water Solstice Springs level) if sea level rises by 0.5 m (metres), 50,744 if sea level rises by 1 m and 74,379 with 1.5 m of SLR.

On a proportion-of-lot basis the analysis shows many properties are only subject to minor inundation, although as sea levels increase the proportion of properties subject to major or complete inundation increases. Numbers of properties subject to greater than 50% inundation are 4186 for 0.5 m of SLR, 21,582 for 1 m of SLR and 42,950 for 1.5 m of SLR. Numbers of properties subject to greater than 90% inundation are 1,620 for 0.5 m of SLR, 13,456 for 1 m of SLR, and 33,104 for 1.5 m of SLR.

Allowing for storm surge and other non-tidal contributors to ocean water levels (≈100 year annual return interval (ARI)), 51,557 properties are exposed to ocean inundation if sea level rises by 0.5 m, and 74,746 if sea level rises by 1 m. Numbers of properties subject to greater than 50% inundation are 20,263 for 0.5 m of SLR and 40,607 for 1 m of SLR. The number of properties subject to greater than 90% inundation is 15,061 for 0.5 m of SLR and 33,789 for 1 m of SLR.

Greatest exposure occurs around tidal lakes and adjacent to the large and more heavily populated coastal river systems. Within tidal lakes, reduced tidal range in combination with extensive coastal flats has allowed development to occur in relative proximity to sea level. For coastal rivers, exposure is associated with the extensive nature of the tidal rivers on the north coast and with high levels of development in the Sydney region.

Using state planning regions, greatest exposure occurs in the North Coast region, contributing to around 31.5% of the statewide exposure across all scenarios. This is followed by the Metropolitan Sydney region with 22% of the statewide exposure. High levels of exposure are also found in the Hunter and Central Coast regions. Lowest exposure is found in the Illawarra and the South East and Tablelands regions with 7.5% and 3% of statewide exposure respectively.

On a proportion-of-area basis, the Central Coast region is the most exposed in the state and Lake Macquarie is the most exposed individual estuary. Overall the Hunter and Central Coast regions contribute 18% each to the statewide exposure across all scenarios. Here extensive development has occurred on the low-lying areas adjacent to the coastal lake systems.

Context

Global mean sea levels are rising and this is expected to continue for centuries, even if greenhouse gas emissions are curbed and their atmospheric concentrations stabilised.

The United Nations Intergovernmental Panel on Climate Change fifth assessment (IPCC 2013) projections indicate global mean sea level rise under a business-as-usual scenario (RCP8.5) of between 0.52 m and 0.98 m, by 2100 relative to 1986–2005 or 0.28 m and 0.61 m with significant reduced emissions (RCP2.6). The rate of SLR over the 21st century is projected to very likely exceed recently observed rates of SLR. For business-as-usual emissions (RCP8.5) projected rates of SLR reach 8–16 mm (millimetres) per year by the end of the century. With significantly reduced emissions (RCP2.6) the projected rate of rise becomes roughly constant (central projection about 4.5 mm per year) before the middle of the century, and subsequently declines slightly.

SLR is not uniformly distributed and most coastlines around the world are projected to experience sea level change within about 20% of the global average. For New South Wales, mean model predictions suggest SLR of 0–10% above the global average (Church et al. 2013).

Beyond 2100 the IPCC (2013) conclude that it is virtually certain that global mean SLR will continue for many centuries due to thermal expansion of the oceans and melting glaciers and ice sheets. Assuming lowest emission scenarios, modelling indicates global mean SLR above the pre-industrial level by 2300 will be less than one metre, however for higher emissions the projected rise is one metre to more than three metres. These models likely underestimate the Antarctic ice sheet contribution, resulting in an underestimate of projected SLR beyond 2100.

The IPCC (2013) predict warming greater than a threshold above 1°C but less than about 4°C would lead to the near-complete loss of the Greenland ice sheet. This would result in a global mean SLR of up to seven metres over a millennium or more. They also suggest abrupt and irreversible ice loss from a potential instability of marine-based sectors of the Antarctic ice sheet in response to climate forcing is possible, but current evidence and understanding is insufficient to make a quantitative assessment.

Approach

In this study, we assess exposure to current development from inundation associated with a range of SLR scenarios. We focus on risk in estuaries, largely because these areas have considerable development in relatively close proximity to sea level, while the open coast is characterised by dunes that provide some level of protection against inundation. We exclude erosion, which will be addressed in a separate study.

We focus on exposure to tidal inundation at the High High Water Solstice Springs (HHWSS) level and or berm height in mostly closed coastal lakes and lagoons. The HHWSS tidal plane is consistent with levels for higher (king) tides. At ocean tide gauge sites, this level is exceeded on average 25 days a year due to contributions from non-tidal processes including storm surge, coastal trapped waves, etc. SLR scenarios of 0.5 m, 1.0 m and 1.5 m are assessed. The use of a 0.5 m water level offset also allows a first order estimation of effects of less frequent inundation at around the 100-year annual return level associated with storm surge and other non-tidal processes (excluding wave setup, runup and riverine flooding effects).

The study uses a mid-level approach to the modelling and mapping of water levels within estuaries. The approach adopted is based on measured tidal plane data and allows for variation in tidal levels both between and along estuaries. The method thus improves on simple bathtub type approaches used in previous assessments.

We utilise tide gauge data for 56 estuaries (MHL 2012) for current estuarine water levels. This data is also used to categorise NSW estuary planes and identify characteristic tidal plane types for application to non-gauged estuaries.

The water surface mapping methodology adopted uses an interpolated tidal plane created from gauge data or berm heights for mostly closed lakes and lagoons. Tidal planes are overlain on digital elevation models derived from high resolution data. The resulting spatial model of inundation greatly improves the representation of current inundation hazard areas and allows for improved assessment of the inundation hazard associated with potential SLR. Inundation mapping is undertaken and the extents are used to quantify risk based on data from the Geocoded Urban and Rural Addressing System (GURAS) database. The degree of inundation is examined through quantification of the proportion of each lot inundated.

Limitations

The assessment of exposure is underpinned by a number of assumptions and limitations related to available data. The approach adopted, while allowing for variation in water levels between and along individual estuaries, still remains a broadscale assessment. It does not replace the need to undertake flood or inundation studies for individual estuaries and results should not be used to assess risk to individual properties and assets.

The study adopts the HHWSS tidal plane and or berm heights for water surface mapping. This tidal plane is slightly lower than highest astronomical tide (HAT) and thus does not represent the full extent of tidal inundation. Additionally, this tidal plane does not include non-tidal processes including storm surge, although the 0.5 m sea level offset may also be representative of a first order allowance for 100-year ARI non-tidal water level variations. However, this excludes effects of wave setup, runup and coincident rainfall-related flooding.

The tidal planes fitted within estuaries should be considered approximate only. Within gauged estuaries the planes are limited by the availability of data and the accuracy of the formulations used to calculate the plane. In ungauged estuaries, we adopt planes from gauged estuaries of the same estuary type, thus assuming average conditions by type. Estimated accuracies of average tidal planes for each estuary type are: Drowned River Valleys ±0.06 m, Large Rivers ±0.11 m, Small Rivers ±0.15 m and Tidal Lakes ±0.10 m.

Three scenarios are considered: SLRs of 0.5 m, 1 m and 1.5 m. These are selected to be representative of a range of future sea levels relevant to structure design as well as land-use planning. They are not tied to particular planning horizons and importantly should not be considered an upper bound for potential long-term SLR which may need to be considered for future development.

SLRs are added to the existing tidal planes and thus assume no change in tidal range or form. Inundation extents are mapped by overlying tidal plane surfaces on digital elevation models derived from LiDAR data, which have a vertical accuracy of around 0.3 m. The exposure assessments assume geomorphology remains unchanged with future sea level except within ICOLLs (intermittently closed and open coastal lake or lagoons) where an increase in berm height is applied.

Exposure is quantified using data from the GURAS database. Major limitations associated with this relate to the fact that an exposed address may not equate to an exposed asset, as asset elevation is not considered. The exposure assessment is limited to broadscale quantification of the inundation of property and infrastructure. Many impacts on the environment and ecosystem services are also likely with SLR, but these have not been considered in this assessment.

Recommendations

This assessment shows a considerable amount of development along the NSW coast is at risk from SLR. The assessment highlights the importance of, and need for, coastal zone and floodplain management planning to manage risk to current development and to avoid unnecessary expansion of risk in the future.

In relation to coastal risk management we recommend:

- review of existing coastal zone and/or floodplain management plans and their adequacy for managing risks associated with SLR
- preparation or update of coastal zone and/or floodplain management plans as required to manage current and potential future risk
- implementation of these plans to reduce current and potential future exposure to SLR

- management using risk management principles which consider likelihood (and uncertainty) and hazard with a focus on solutions that are flexible and robust
- adoption of strategies that address the ongoing nature of SLR (beyond 2100), including measures to avoid the expansion of development in areas likely to be subject to future inundation or alternatively, adoption of measures that recognise the temporary nature of such areas (temporary occupancy)
- education concerning SLR and coastal processes and hazards
- mapping and assessment of actual (built) and planned/potential (land-use zoning) risk exposure at regular intervals (5–10 years) for a prescribed set of sea level scenarios.

In relation to improvement of risk assessment techniques we recommend:

- further research on open coast hazards including wave runup on beaches and coastal erosion
- further research on potential morphodynamic changes to coastal systems associated with SLR. This should include effects of potential changes to entrance configuration and marine delta sedimentation on tidal processes in different estuary types, as well as foreshore erosion/accretion and wetland response
- further research on impacts of SLR on rainfall-related flooding and coincident events.

1. Introduction

1.1 Context

Global mean sea levels are rising and this rise is expected to continue for centuries, even if greenhouse gas emissions are curbed and their atmospheric concentrations stabilised. As global temperature increases, rising ocean heat content causes ocean thermal expansion and sea level rise. Other contributions to sea level rise come from the melting of land ice, including glaciers and ice caps, as well as the major ice sheets of Antarctica and Greenland.

Around the Australian coast sea levels are also rising. Rates of rise here are generally thought to be consistent with the global average, with a recent review finding the Australian average rate of relative sea level rise (SLR) between 1966 and 2009 was 2.1 ± 0.2 mm per year and from 1993 to 2009 the rate was 3.1 ± 0.6 mm per year (White et al. 2014).

The United Nations Intergovernmental Panel on Climate Change (IPCC) projections indicate global mean sea mean level rise under a business-as-usual scenario (RCP8.5) of between 0.52 m and 0.98 m by 2100, relative to 1986–2005, or 0.28 m and 0.61 m with significantly reduced emissions (RCP2.6) (IPCC 2013). The rate of SLR over the 21st century is projected to very likely exceed recently observed rates of SLR. For business-as-usual emissions (RCP8.5) projected rates of SLR reach 8 to 16 mm per year by the end of the century. With significantly reduced emissions (RCP2.6) the projected rate of rise becomes roughly constant (central projection about 4.5 mm per year) before the middle of the century, and subsequently declines slightly.

SLR is not uniformly distributed and most coastlines around the world are projected to experience sea level change within about 20% of the global average. For New South Wales, mean model predictions suggest SLR of 0–10% above the global average (Church et al. 2013 Figure 13.21).

Beyond 2100 the IPCC (2013) conclude that it is virtually certain that global mean SLR will continue for many centuries due to thermal expansion of the oceans. Assuming lower emission scenarios, global mean SLR above the pre-industrial level by 2300 will be less than one metre; however, this significantly increases for higher emissions as the projected rise is from one metre to more than three metres. These models likely underestimate the Antarctic ice sheet contribution, resulting in an underestimate of projected SLR beyond 2100.

Sustained warming greater than a threshold above 1°C (low confidence) but less than about 4°C (medium confidence) would lead to the near-complete loss of the Greenland ice sheet over a millennium or more, causing a global mean SLR of up to seven metres. Abrupt and irreversible ice loss from a potential instability of marine-based sectors of the Antarctic ice sheet in response to climate forcing is possible, but current evidence and understanding is insufficient to make a quantitative assessment.

Communities in Australia are considered highly vulnerable to SLR. Chen and McAneney (2006) estimate that approximately 711,000 addresses in Australia are located within three kilometres of the shore and in areas below six metres above sea level, and over 60% of those addresses are in Queensland and New South Wales. This analysis also found that the majority of addresses are adjacent to lakes, lagoons, rivers and estuaries, rather than the open ocean.

The National Coastal Vulnerability Assessment (DCC 2009; DCCEE 2011; Cechet et al. 2011, 2012) further refined the above estimate to identify between 157,000 and 247,600 existing residential buildings in Australia at risk of inundation with a sea level rise of 1.1 m. In NSW between 40,800 and 62,400 residential buildings were identified as being at risk from the combined effect of 1.1 m of SLR and a 100-year annual return period storm tide.

Incorporating commercial addresses brings the total exposure to between 41,550 and 63,650 (Cechet et al. 2012).

The impacts of SLR are likely to include the erosion of sandy beaches and the increased frequency, depth and extent of coastal flooding. Increased ocean water levels during storms are virtually certain to result in more frequent coastal inundation, higher wave runup levels, higher water levels in lakes and estuaries and more flooding in coastal rivers. This suite of changes will have a progressively increasing impact on existing low-lying coastal development.

Developments along the NSW coast that are near current high tide levels will be susceptible to more frequent tidal and ocean inundation. Additionally, as sea levels rise, stormwater drainage is likely to become less effective, impacting urban areas near coastal rivers, lakes and estuaries. Communities currently susceptible to the combined effects of marine and catchment flooding will be further affected with SLR; the scale of impacts will vary dependent on the vulnerability of each location.

Dunes on the open coast tend to be elevated significantly above sea level and thus provide some level of protection against inundation (but are subject to erosion). Estuarine areas are typically characterised by extensive low-lying areas however, often with considerable development in relatively close proximity to sea level. It is these areas that are the focus of the current investigation.

1.2 Aim and scope of the assessment

In this study, we undertake a statewide assessment of the impact of inundation in estuaries associated with projected SLR on the NSW coast. The aim of the study is to refine estimates of the extent of current exposure of properties and infrastructure to potential SLR to help assess the need for, and prioritisation of, adaptation planning and action.

The study focuses on risk to development surrounding estuary foreshores. This is because considerable development is located in low-lying areas adjacent to estuarine foreshores and is potentially vulnerable to inundation. In many areas, inundation of low-lying streets and foreshores occurs now and highlights potential vulnerability to SLR (see Figure 1.2.1). On the open coast, beaches tend to be backed by relatively high dunes and bounded by headlands. Historically inundation of these areas has not been a major concern except at isolated locations (although erosion is a major concern). Wave setup and runup play a significant role in inundation on the open coast with measured runup heights on steep, exposed beaches during storms exceeding 7 m. (PWD 1988; Nielsen & Hanslow 1991). Assessment of wave setup and wave runup requires detailed modelling which is beyond the scope of the current study. We exclude erosion, which will be addressed in separate study.

Figure 1.2.1. Tidal inundation of low-lying urban areas in Newcastle 14/12/2009 (photos: B Coates)

We focus on exposure to tidal inundation at the High High Water Solstice Springs (HHWSS) level although our approach also allows first order assessment of less frequent ocean inundation at around the 100-year annual return level (excluding wave setup, runup and coincident catchment flooding). The study uses a mid-level approach to the modelling and mapping of water levels within estuaries. The method adopted is based on measured tidal plane data which allows for variation in tidal levels both between and along estuaries, and thus improves on simple bathtub type approaches used in previous assessments (e.g. DCC 2009).

Tides along the NSW coast are semi-diurnal with a significant diurnal equality, and tidal range varies along the coast increasing from south to north. Tidal levels in estuaries vary depending on estuary type, with some systems exhibiting tidal amplification while others display significant attenuation compared with ocean tidal levels (NSW Government 1992; Druery et al. 1983).

Interpolated tidal planes are created from gauge data and mapped tidal limits and applied in conjunction with high resolution elevation data. The resulting spatial model of inundation greatly improves the representation of current inundation hazard areas and allows for improved assessment of the inundation hazard associated with potential SLR.

Data from the Geocoded Urban and Rural Addressing System (GURAS) are used to identify and quantify properties that are predicted to be exposed to inundation under SLR scenarios of 0.5 m, 1.0 m and 1.5 m.

The exposure assessment is limited to broadscale quantification inundation to property and infrastructure. Many impacts on the environment and ecosystem services are also likely with SLR but these have not been considered in this assessment. Other exclusions include the effects of wave setup and runup and coincident catchment flooding. While all these effects are likely to be important, their assessment requires work which was beyond the scope of this assessment

2. The NSW coast

2.1 Introduction

The NSW coast stretches for some 1590 kilometres from the Queensland border to the Victorian border (Short 2007). The coast is exposed to the predominant south east swell and experiences a moderate to high energy wave regime. The shoreline is comprised of areas of rocky cliffs and headlands joined by sandy beaches (Chapman et al. 1982).

On the coast south of Sydney, the beaches are predominantly pocket beaches isolated by rocky headlands with little alongshore sand exchange from compartment to compartment. In the north of the state, these beaches tend to be longer and alongshore rates of sand movement are higher, with sand moving from compartment to compartment, predominantly from south to north. Beaches are typically backed by high dunes which provide some protection against storm surge and wave inundation but experience episodic erosion.

There are approximately 184 significant estuaries along the NSW coast. These vary significantly in shape and size, ranging from large coastal embayments and drowned river valleys, such as the Hawkesbury River, to coastal lakes, such as Lake Macquarie and Wallis Lake, and smaller intermittently open coastal lakes and lagoons, such as Manly Lagoon and Tabourie Lake (NSW Government 1992; Roper et al. 2011). Estuaries support many different habitat types and species, highly valued by local communities.

In many estuaries, considerable development is located on the low-lying land immediately adjacent to foreshores and much of this is prone to occasional inundation, both as a result of storm and floods but also simply as a result of high ocean levels and/or prevailing entrance conditions. For many estuaries, the entrances are managed to reduce this flooding risk either through permanent structures (breakwaters and training walls), or in the smaller lakes, through the artificial opening of the entrances by local councils to control water levels (NSW Government 1992).

2.2 Regional setting and estuary types

The present character of the NSW coast is the result of multiple phases of sea level fluctuation over millions of years. Over this time, the bedrock valleys in which estuaries lie have been gradually infilled with marine and terrestrial sediment. During periods of SLR, vast quantities of marine sand were reworked and transported landward as transgressing sand sheets and barriers. In many locations along the NSW coast, separate barriers can be recognised, corresponding to cycles of sea level variation.

The onshore transport of this marine sand enclosed rivers and estuaries. These vary in character depending on the degree of barrier formation and the nature of the inherited coastal topography (Roy & Thom 1981; Roy 1984).

As sea level approached present day mean sea level, extensive sand barriers were formed across the mouths of broad, shallow embayments. Landward of these barriers, estuaries were created in the form of broad tidal lakes connected to the ocean by narrow tidal inlets through the barrier.

Deep narrow mouthed embayments, such as Port Jackson and the Hawkesbury–Broken Bay System, led to a different form of estuary evolution. The transgressing sand sheets were unable to completely fill the mouths of deep embayments before sea level stabilised. The incipient barriers remained submerged and the estuaries developed as drowned river valleys with wide mouths which extended across the width of the embayment.

Roy et al. (2001) classify eastern Australian coastal water bodies into a range of groups and types based on the degree of marine influence. These estuary groups include: bays, tide dominated estuaries, wave dominated estuaries, intermittent estuaries and freshwater bodies (Table 2.2.1).

Table 2.2.1. Types of water bodies in eastern Australia (source: after Roy et al. 2001)

Estuary group	Type	Mature form
Bays	Ocean embayments	
Tide dominated estuaries	Funnel shaped macro tidal estuaries	Tidal estuaries
	Drowned river valley estuaries	
	Tidal basins	
Wave dominated estuaries	Barrier estuaries	Riverine estuaries
	Barrier lagoons	
	Interbarrier estuaries	
Intermittent estuaries	Saline coastal lagoons	Saline creeks
	Small coastal creeks	
	Evaporative lagoons	
Freshwater bodies	Brackish barrier lakes	Terrestrial swamps
	Perched dune lakes	
	Backswamps	

The main estuary types found in NSW are drowned river valleys, barrier estuaries and coastal lakes.

2.2.1 Drowned river valley estuaries

Drowned river valley estuaries are easily recognisable because of their wide bedrock-flanked mouths, the presence of a submerged flood tidal delta and the absence of a sub-aerial sand barrier at their entrances (NSW Government 1992). Examples include the Hawkesbury River and Sydney Harbour. The basic form of the drowned river valley is a steep sided bedrock valley which deepens and widens in the seawards direction. Upper catchment sediments typically reclaim the upstream reaches of drowned river valleys, which today consist of extensive floodplains with tidal river channels. Downstream of these areas, the size and depth of the relict drowned valley is dependent upon the dimensions of the parent valley and the relative sediment supply from the upper catchment. For instance, in Port Hacking, which has only a small upper catchment and therefore a relatively low sediment yield, there is a difference of 30 metres in depth between the upper fluvial delta (formed from terrestrial sediments) and the shoals of the submerged tidal delta at the entrance (formed from marine sediments).

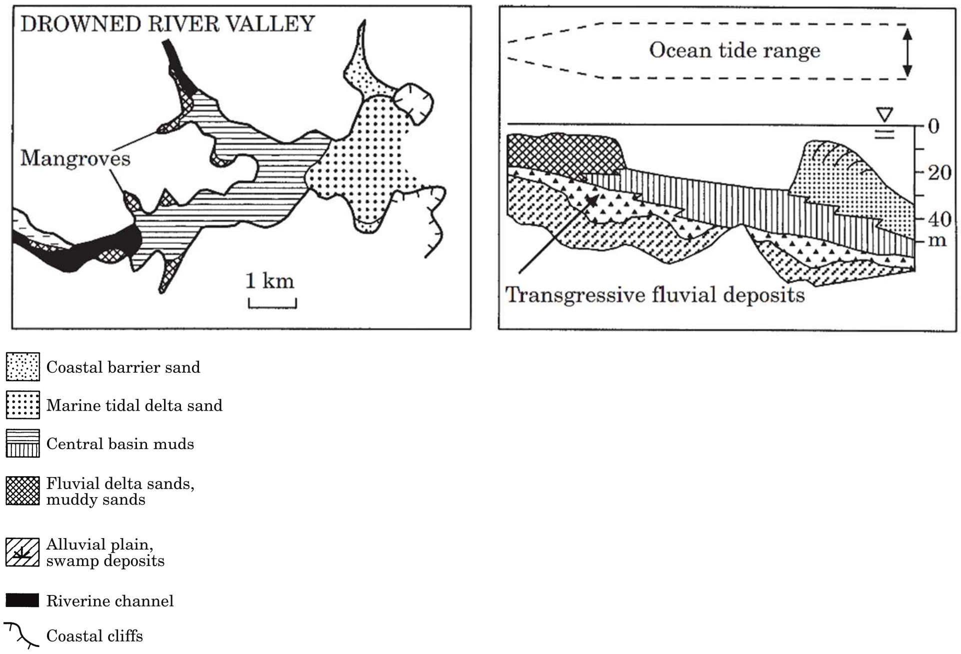


Figure 2.2.1. Characteristics of drowned river valleys (source: Roy et al. 2001)

2.2.2 Barrier estuaries

Young barrier estuaries exist as tidal lakes. They are characterised by relatively small upper catchments. Consequently, the sedimentation that has occurred since sea levels stabilised has not been sufficient to infill the initial back barrier lake.

The shape, depth and size of the tidal lakes are variable depending on the size of the parent embayment and the rates of sediment supply from the catchment. They vary from very small systems like Narrabeen Lagoon to Lake Macquarie, the largest tidal lake in Australia (see Figure 2.2.2).

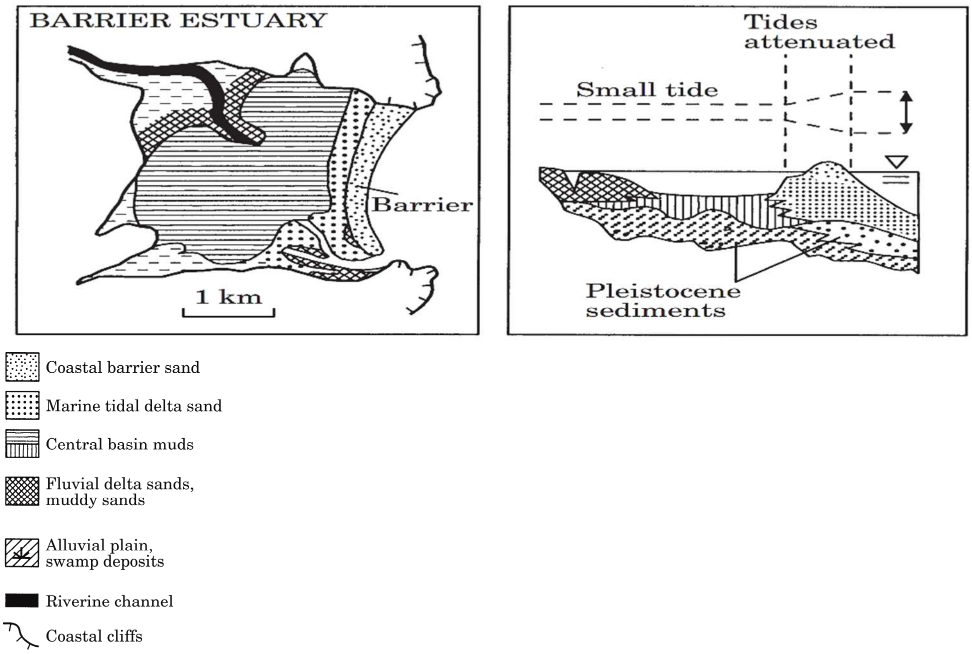


Figure 2.2.2. Characteristics of young barrier estuaries (source: Roy et al. 2001)

Mature barrier estuaries have been created by extensive river systems with relatively high sediment loads. The high sediment loads have infilled the initial back barrier lake with alluvium, causing the development of sinuous river channels discharging directly into the ocean (*tidal rivers*). Contiguous floodplains with backwater swamps and cut-off bays are vague reminders of the former back barrier lakes.

Mature barrier estuaries range in size from large systems like the Clarence, Richmond and Hunter rivers to small systems like Coffs, Bonville and Currumbene creeks (see Figure 2.2.3).

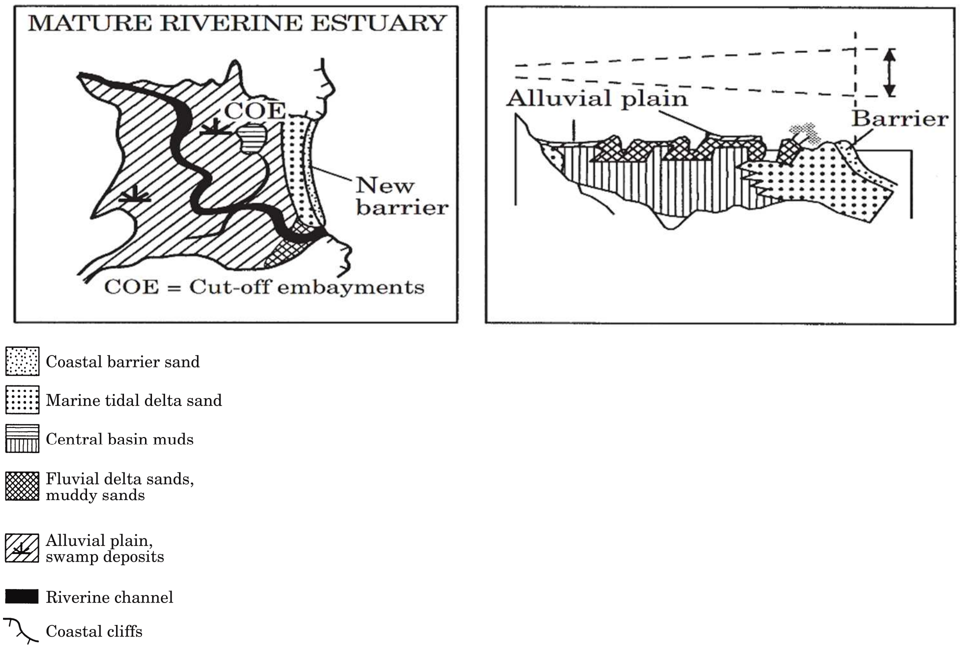


Figure 2.2.3. Characteristics of mature barrier estuaries (source: Roy et al. 2001)

2.2.3 Saline coastal lagoons/intermittently closed and open lakes and lagoons

Saline coastal lagoons are small systems which have intermittent entrances that are closed to the ocean for most of the time (NSW Government 1992). These have become known as intermittently closed and open lakes and lagoons (ICOLLs) (Haines et al. 2006). Under natural conditions, the ocean entrance opens only when a large build-up of catchment runoff breaches the beach berm. Saline coastal lakes comprise mostly small systems such as Dee Why and Manly lagoons, but they can include larger systems such as Wollumboola Lake (see Figure 2.2.4).

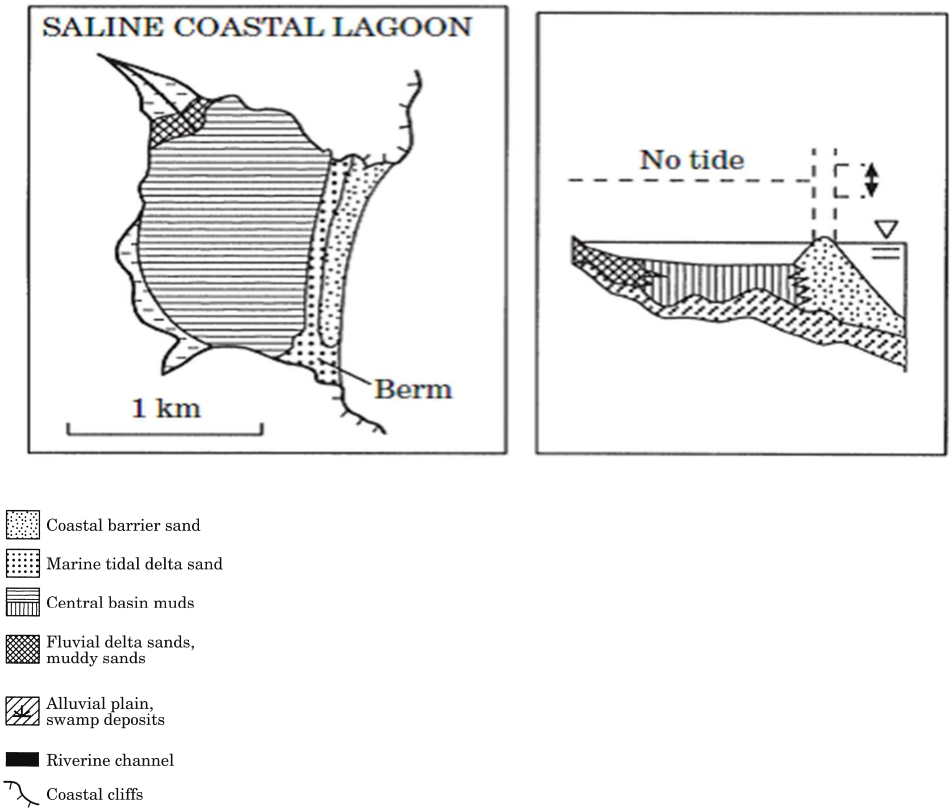


Figure 2.2.4. Characteristics of saline coastal lakes (source: Roy et al. 2001)

2.3 Tidal characteristics

2.3.1 Ocean tides

Tides along the NSW coastline are semi-diurnal in nature, i.e. high water and low water occur about twice daily (the actual period of a tidal cycle is about 12.5 hours). They are sinusoidal in shape and have a pronounced diurnal inequality (successive high tides differ markedly).

The mean spring range is 1.2 m while the mean neap range is 0.8 m (AHO 2011; MHL 2012). The mean range at Sydney is 1.0 m, with mean high water of 0.52 m AHD (Australian Height Datum) and mean low water of –0.48 m AHD (MHL 2012). Tidal range varies slightly along the coast with an increase of around 0.2 m from south to north (MHL 2011).

2.3.2 Tides within estuaries

The rise and fall of ocean water levels travels along an estuary as a long wave. The speed of travel or celerity of this wave varies with water depth; the deeper the water, the faster the wave celerity.

As the tide propagates into the shallow waters of an estuary it is subject to a number of changes (NSW Government 1992). These include:

- **Tidal lag** – the delay between a standard state of the tide at the estuary mouth, such as high tide, and the occurrence of the same state of tide inside the estuary.

- **Tidal distortion –** relates to the shape of the tidal wave as it moves landward. It occurs because the speed of propagation of the tide at high water is faster than at low water. As a consequence, the tide rises faster than it falls and peak flood tide velocities are generally greater than peak ebb tide velocities.
- **Elevation of half-tide levels or tidal pumping** – the higher celerity of the flood tide compared to the ebb tide results in a tendency for greater upstream movement of water on the flood tide compared to downstream movement on the ebb tide. This leads to a dynamic trapping of water in the upper reaches of the estuary, as reflected in a super-elevation of half-tide level. Elevated half-tide levels act to increase the seaward flow of water and so provide an overall flow balance.
- **Amplification of fortnightly tides** – this is thought to be related to the trapping of water in the upstream reaches of an estuary. Variation in the volume of trapped water during the fortnightly spring–neap tide cycle can produce a significant fortnightly variation in half-tide level (*the fortnightly tide*). This effect is particularly noticeable in large coastal lakes.

The tidal range in estuaries is affected by several processes (Dyer 1997; McDowell & O'Connor 1977; Savenije 2005; Prandle 2009; Van Rijn 2010), including:

- inertia related to acceleration and deceleration effects
- amplification associated with the decrease of the width and depth (convergence)
- attenuation due to bottom friction particularly across the flood tidal delta
- partial reflection at abrupt changes of the cross-section and at the landward end of the estuary (in the absence of a river).

These processes result in fundamentally different patterns of tidal behaviour in different estuaries. Some estuaries experience tidal amplification while others are characterised by tidal attenuation (Van Rijn 2010). In New South Wales differences in tidal behaviour within estuaries have been recognised for some time (Roy & Thom 1981; Druery et al. 1983; Roy 1984, NSW Government 1992; MHL 1995a, b; MHL 2002; MHL 2003; MHL 2005; MHL 2012).

NSW Government (1992) describes the tidal behaviour of NSW estuaries on the basis of estuary shapes which generally correspond to the estuary types described above. However, different estuary types can, in some instances, share similar tidal behaviour; for example, mature barrier estuaries, such as the Hunter River, display similar tidal behaviour to a mature drowned river valley estuary, such as the Karuah River, probably because the entrance bar and delta complex has been dredged to allow for port activities.

The main estuary shapes influencing tidal behaviour are as follows:

Drowned river valley estuaries – The younger stages of drowned river valley estuaries are characterised by channels which generally deepen and widen in the seawards direction. The landward narrowing of the channel promotes tidal amplification through the concentration of flow. As the channel shallows, tidal resonance also helps to maintain a high tidal range. River valley estuaries display no initial attenuation but often exhibit amplification of the ocean tidal range.

In such estuaries, the tidal range is only attenuated in the upstream reaches where the cumulative dissipative effects of bed friction dampen tidal flows. For example, amplification occurs over most of the length of the Hawkesbury River, with the tidal range at Wisemans Ferry, which is approximately midway along the estuary, 16% greater than the ocean range.

The tidal range at Windsor, which is 123 kilometres upstream from the estuary mouth, is slightly less than ocean range. Upstream of Windsor, the presence of coarse shallow sand shoals abruptly reduces tidal range to 26% of the ocean value (NSW Government 1992) (see Figure 2.3.1a).

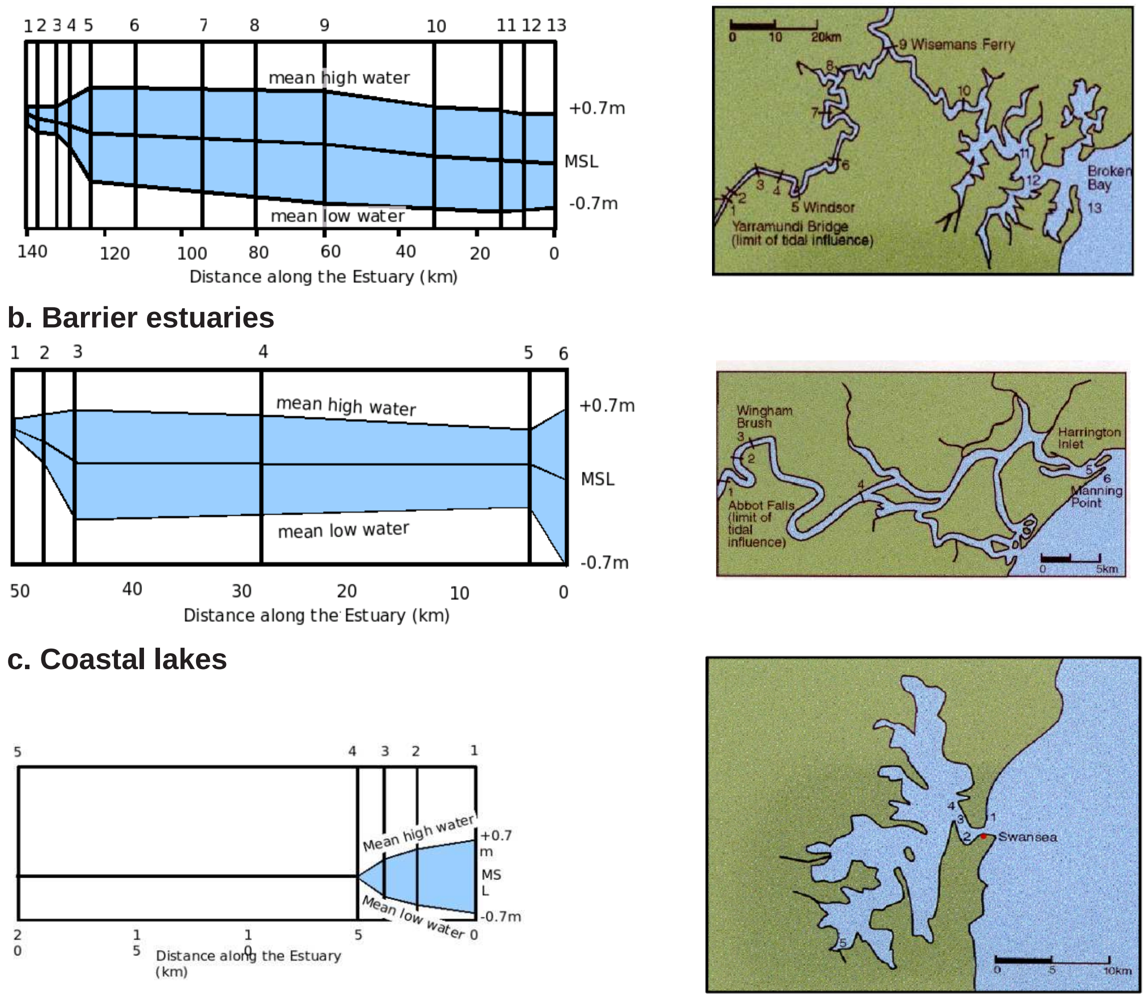


Figure 2.3.1. Tidal characteristics in different estuary types (source: NSW Government 1992); note differences in scale

River estuaries (mature barrier estuaries) – Tidal rivers in New South Wales are characterised by relatively narrow and shallow entrance channels of relatively constant width and constant depth, consisting predominantly of sandy bed sediments. They include the mature stages of barrier estuaries and drowned river valley estuaries.

The shallow nature of the channels promotes tidal resonance which is counter-balanced by energy losses across entrance shoals and frictional dissipation at the sandy bed. Consequently, the tidal range along the estuary nearly always displays initial attenuation, followed by mild amplification before complete damping at fluvial gravel and sand bars around the head of the estuary (NSW Government 1992).

This behaviour is illustrated by the Manning River (see Figure 2.3.1b). At Manning Point, only three kilometres upstream from the estuary mouth, the tidal range is only 50% of the ocean value (because of the dissipative effects of the entrance bar).

In these systems, some long-term morphodynamic variation in tidal range can occur with changing entrance shoals (MHL 2012).

Tidal lakes (young barrier estuaries) – Tidal lakes are characterised by a broad expanse of tidal water, connected to the ocean by a relatively small tidal channel, referred to as a tidal inlet (see Figure 2.3.1c). The depth of water in the lake is always greater than that of the inlet. They show severe attenuation of the tidal range due to frictional effects in the entrance channel. Tide ranges in these systems may be as little as 10% of that offshore and tidal pumping can significantly amplify the magnitude of the fortnightly tide (McLean & Hinwood 2011).

Nielsen and Gordon (2011) show several tidal lake systems in New South Wales are undergoing long-term morphodynamic adjustment following the installation of river entrance training walls, including ongoing increases in tide range and discharge as a result of entrance scour and increasing entrance efficiency. Examples include Lake Macquarie, Wallis Lake and Lake Illawarra.

Intermittently closed and open lakes and lagoons (ICOLLs) – Smaller lake systems are usually characterised by intermittent entrance opening and closing. While open they operate like tidal lakes, while closed they gradually fill with water levels influenced by inflows and evaporation (Haines et al. 2006).

In these systems, maximum water levels are generally controlled by beach berm height (Hanslow et al. 2000; Haines 2006). Berms are wave built features and result from the onshore transport of sand. Berm height is dependent on wave runup which in turn is controlled by wave height and period and beach slope or grain size (Hanslow et al. 2000; Weir et al. 2006).

2.4 Non-astronomic contributors to water levels

Variations in water level due to non-astronomic factors (i.e. factors not included in tidal predictions) are common along the NSW coast and are associated with a range of oceanographic and meteorological processes. MHL (1992) shows that anomalies of 0.3 m occur at return intervals of months, and thus become a significant addition to tidal predictions. Drivers of tidal anomalies include variations in air pressure and wind stress which during storms is known as 'storm surge'; coastal trapped waves; ocean currents; steric effects; seiches; tsunamis; Rossby waves, etc. At gauges located in riverine settings they can also include effects of freshwater flow (flooding). These processes operate over a wide range of time frames.

Studies of the Fort Denison tide record show inter-annual and multi-decadal variability linked with both the El Niño Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) (Holbrook et al. 2010; MHL 2011). These oscillations see variation in annual mean sea level of around 10 centimetres. At higher frequencies, many factors contribute to anomalies but the largest are associated with storm surge and/or coastal trapped waves (CTWs).

CTWs are large-scale waves which propagate along continental margins. They have long wave lengths (around 2000 kilometres) and periods (around 10–20 days) and are generated by weather disturbances. The majority of CTWs have been shown to propagate as continuous features between south Western Australia and north eastern Australia although some CTWs on the east coast are also generated by strong winds in Bass Strait. They have average wave heights of around 0.2 m, sometimes up to 0.5 m, and can elevate coastal water levels for several days (SMEC & UQ 2013; Church et al. 1986a, b; Maiwa et al. 2010, Woodham et al. 2013). Larger CTWs are generally thought to be associated with reinforcement by strong wind forcing on the southern part of the east coast and/or Bass Strait. It is likely that the large size of one particular CTW was a result of ongoing reinforcement associated with the series of frontal systems that impacted southern Victoria and Bass Strait over the second week of May.

Storm surge (the combined effect of reduced air pressure and wind setup), while smaller than on many coasts worldwide, can still raise water levels along Australia's east coast by over 50 centimetres above normal (e.g. NSW Government 1992). In NSW, the duration of storm surges varies from short-lived events of less than a day to several days depending on storm characteristics and propagation.

Annual anomalies increase slightly from south to north along the NSW coast (MHL 2011). Storm surge is usually the largest single contributor to tidal anomalies and extreme ocean levels; however, joint coincidence with other drivers also needs to be considered.

Within river entrances water depth and entrance morphology play a significant role both in modifying tidal behaviour and in wave breaking, which may influence mean water levels through wave setup. These effects are likely to vary significantly between different estuary types.

Wave setup on beaches results in significant super-elevation of mean water levels particularly near the beach face, however water depths in most river entrances are likely to mean wave setup is significantly lower than on beaches (Hanslow & Nielsen 1992). Measurements from the Brunswick River entrance in northern NSW suggest wave setup is minor within moderate sized trained river entrances (e.g. Nielsen & Hanslow 1995; Hanslow et al. 1996).

Examination of extreme value distributions by You et al. (2012) has similarly demonstrated limited evidence of wave setup in trained river entrances in New South Wales. They show reduced extreme water levels at the trained river entrances compared with offshore sites and suggest this is likely due to the attenuation in tidal range through the river entrances. It is probable that the trained entrance water depths in these systems are too deep to generate significant wave setup. Additionally, the presence of training walls, which extend into the surf zone, may introduce a physical barrier to higher mean water levels from wave setup on the neighbouring sandy beaches (Hanslow & Nielsen 1992).

You et al. (2012) highlight however that their results may not be applicable to smaller coastal systems (e.g. lagoons or creeks) where water depths may become shallow enough to allow wave setup or in untrained river systems where there is no physical barrier between the beach/swash zone and the entrance. Most smaller, estuarine systems tend to be only intermittently open to the sea and thus berm heights become important for determining extreme water levels (Haines 2006).

With climate change, there are numerous potential changes to non-astronomic water level drivers including both oceanographic processes and those associated with catchment-related flooding; for example, changes to the intensity of storms and storm surge and changes to oceanographic processes associated with the warming and strengthening of the East Australian Current. The magnitude and likelihood of these changes however, remains uncertain.

McInnes et al. (2007) show only minor changes to storm surge with climate change for Wooli and Batemans Bay on the north and south coasts of New South Wales respectively. Wave modelling by Hemer et al. (2012) suggests a minor decrease in mean significant wave height (<0.2 m) by the end of the 21st century compared to the present due to a projected decrease in regional storm wave energy, and a shift to a more southerly wave direction, consistent with a projected southward shift of the subtropical ridge. Church et al. (2013) caution however that in general there is low confidence in wave model projections because of uncertainties regarding future wind states, particularly storm geography, the limited number of model simulations used in the ensemble averages, and the different methodologies used to downscale climate model results to regional scales.

2.4.1 Joint coincidence with catchment flooding

Storm surge-related tidal anomalies may be generated by weather phenomena that also contribute to coastal rainfall and potentially flooding, thus considerations concerning joint coincidence become more important. For these events however, numerous questions need to be examined. These concern the:

- influence of ocean conditions on the tidal waterway
- relative scale of coastal and catchment flooding events
- relative timing of peak rainfall and flood relative to the peak of ocean conditions
- type of storm cell (synoptic type) that is likely to lead to significant catchment flooding and/or significant coastal flooding and whether they correspond
- importance of the catchment size, shape and available waterway volume
- relative location of the community in relation to the waterway and its entrance.

Several studies have identified the synoptic storm types critical to the generation of extreme wave and water level conditions along the NSW coast (Shand et al. 2011; Blain, Bremner and Williams 1985). These appear to have much in common with those identified as contributing to heavy rain events (e.g. Speer et al. 2009). Speer et al. (2009) note that systems that develop within subtropical easterly wind regimes, namely inland trough lows and easterly trough lows, account for 71% of the significant rain events and when combined with the ex-tropical cyclone category, account for 84% of the heavy rain events. These types also make up a significant proportion of the synoptic types resulting in wave heights over five metres along the NSW coast (Shand et al. 2011).

Recent preliminary studies on joint coincidence of rainfall and ocean events suggest some coincidence, particularly where catchment and coastal flooding are both being driven by the same synoptic type (McPherson et al. 2012). The exact nature of the coincidence of coastal and catchment flooding is likely to vary with estuary type and size.

3. Sea level rise

3.1 Past sea level fluctuations

Sea level is not static but has undergone numerous fluctuations throughout geological history. Over the last two million years there have been 30–40 major oscillations in sea level, some in excess of 120 metres (Imbrie et al. 1984; Lowe & Walker 1984; Peltier 1999). These oscillations have had a significant influence on the evolution of the coastal zone we know today, and are responsible for the complex array of beach barrier and estuary systems which make up the current coastline.

These fluctuations are thought to be initiated by the orbital motions of the Earth and result in major shifts in climate between glacial and interglacial phases. As the Earth orbits around the sun and spins around its axis, several quasi-periodic variations occur. These oscillations, known as Milankovitch cycles, relate to the Earth's eccentricity, obliquity and precession. They change the amount and location of solar radiation reaching the Earth and have a significant influence on long-term climate. Once initiated, these variations lead to positive feedback with greenhouse gases in the atmosphere, promoting major climatic shifts.

The last full interglacial/glacial cycle occurred over the last 125,000 years and has seen sea levels fluctuate by 120 metres. The cessation of the last glacial phase resulted in a global rise in sea level from levels around 120 metres below current sea level to its present level. This rise began about 18,000 years ago with sea levels approaching their current levels around 7000–8000 years ago.

Relative sea level records from sites around the world however, show great diversity in the maximum height reached and in the timing of the peaks. The causes for these regional variations is a complex interaction of geomorphic and geological controls including tectonism, climate, sediment discharge and/or compaction, tidal changes, local geoid perturbations and isostatic warping. Regionally and even locally these factors create vertical changes in the elevation of the ground, thus offsetting or enhancing changes in sea level.

In south eastern Australia, recent compilations of geomorphic evidence for sea level change over the last 10,000 years include those undertaken by Lewis et al. (2012) and Sloss et al. (2007). This suggests sea level reached its current level around 7000–8000 years ago. This work shows that for much of the last 7000 years relative sea level has been slightly above present levels. There has however, continued to be much debate about the exact timing of when sea level reached its current level and whether a Holocene highstand occurred (see Murray-Wallace & Woodroffe 2014 for summary).

3.2 Historical global mean sea level rise

Church and White (2011) use monthly sea level data from the Permanent Service for Mean Sea Level (PSMSL; Woodworth & Player 2003) and satellite altimeter data to show that between 1880 and 2009 the global average sea level increased by about 210 mm (Figure 3.2.1). Rhein et al. (2013) determine that it is very likely that the average rate of mean SLR was 1.7 ± 0.2 mm per year between 1901 and 2010 and that this rate increased to 3.2 ± 0.4 mm per year between 1993 and 2010.

3.2.1 Regional distribution of sea level rise

While global mean SLR is relatively consistent, there are significant regional variations throughout the ocean basins of the world. These are attributable to variations in the distribution of thermal expansion, local and regional meteorological effects, ocean circulation, and regional responses to modes of climate variability; for example, the ENSO and the Pacific Decadal Oscillation (PDO).

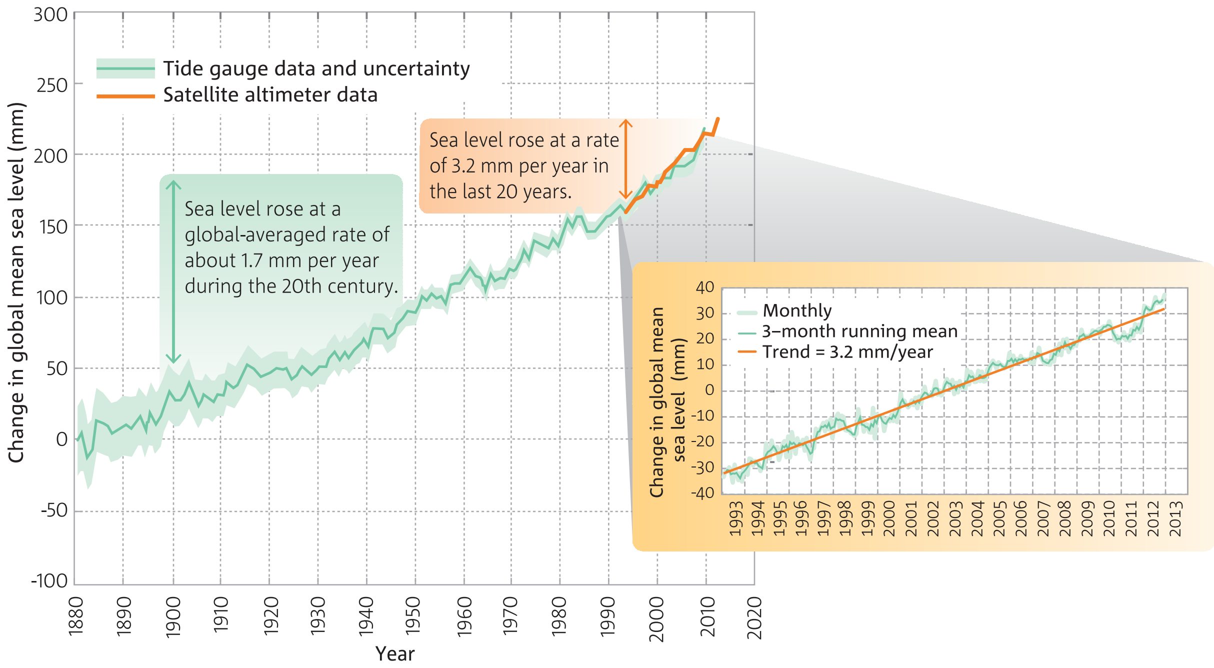


Figure 3.2.1. Global mean sea level from 1880 to 2012

High-quality global sea level measurements from satellite altimetry since the start of 1993 (orange line), in addition to the longer-term records from tide gauges (green line, with shading providing an indication of the confidence range of the estimate).

Inset: Sea level increase since 1993 from the satellite altimetry. The light green line shows the monthly data, the dark green line the three-month moving average, and the orange line the linear trend.

(Source: BOM &CSIRO 2015)

Sea level at any particular location contains the influences of all of these local and regional effects and thus is subject to significant short to medium-term variability (more than an order of magnitude greater than for global mean sea level), with this variability often extending over multiple decades. The regional variation in SLR over the period 1993–2011 as measured from satellite altimeter is shown in Figure 3.2.2.

While overall rates around Australia are generally consistent with the global average (White et al. 2014), rates of SLR vary considerably around the coast and are generally higher to the north (Figure 3.2.3; CSIRO & Bureau of Meteorology 2015). White et al. (2014) review tide gauge records from around Australia and note most of the differences in sea level trends observed between locations around Australia are closely related to the ENSO, with the strongest influence on Australia's northern and western coasts. Once the influence of the ENSO, Glacial Isostatic Adjustment (GIA) and air pressure are removed, Australian mean sea level trends are close to global mean trends from 1966 to 2009, including an increase in the rate of rise in the early 1990s. They find the Australian average rate of relative SLR between 1966 and 2009 was 2.1 ± 0.2 mm per year. From 1993 to 2009 the rate was 3.1 ± 0.6 mm per year.

White et al. (2014) show the scale of variation of mean SLR is in the order of thousands of kilometres. For comparison, the NSW coastline is approximately 1100 kilometres from end to end; however, land movement issues can still be important at local scales.

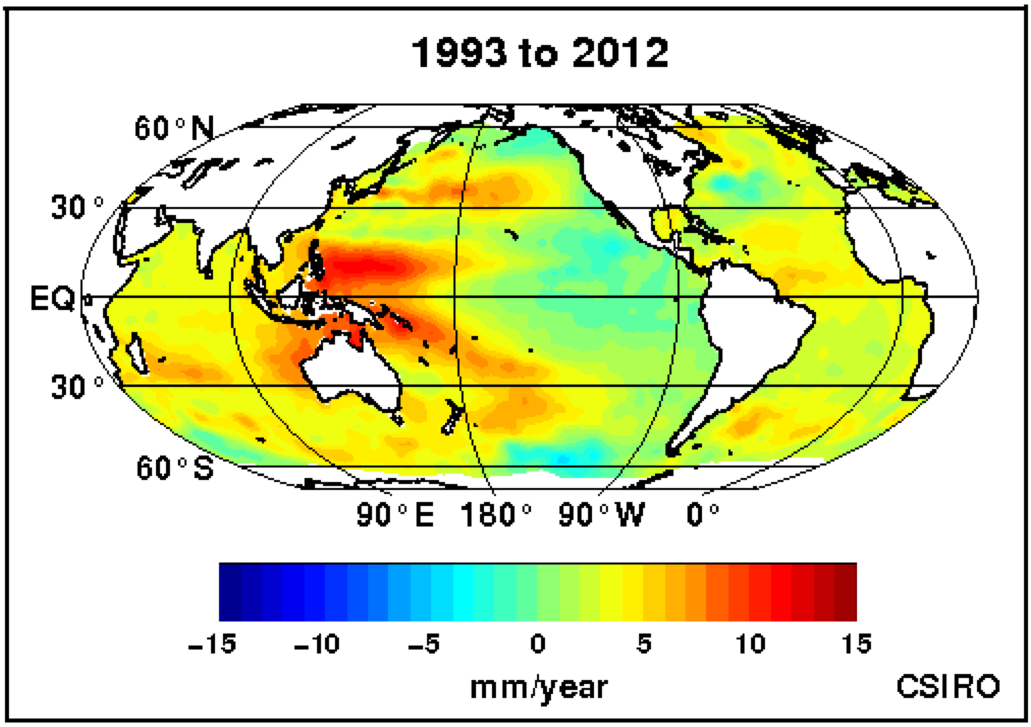


Figure 3.2.2. Regional distribution of sea level trends from 1993 to 2011, based on satellite altimeter data

(source: CSIRO, www.cmar.csiro.au/sealevel/sl_hist_last_decades.html)

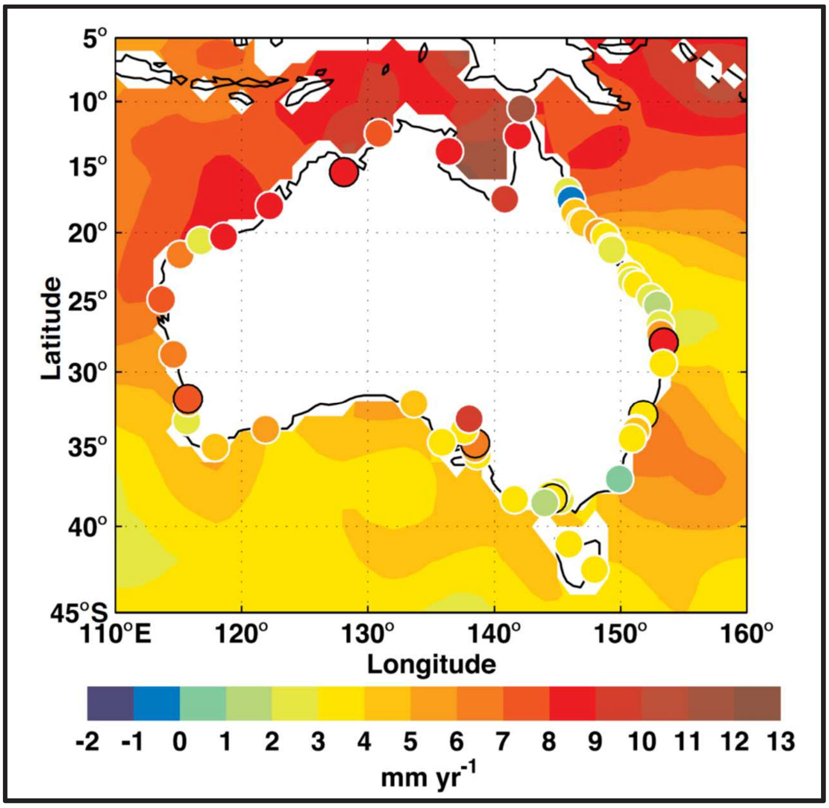


Figure 3.2.3. Observed sea level trends from Jan. 1993 to Dec. 2011 in the Australian region from satellite altimeter data (colour contours) and tide gauges (coloured dots); both after correction for GIA

(Source: CSIRO & Bureau of Meteorology 2015)

Off the NSW coast there is a maximum in the rate of SLR at a latitude of about 35ºS in the Tasman Sea which is consistent with the spinup of the South Pacific subtropical gyre by increased wind stress curl (Roemmich et al. 2007; Church et al. 2012). Along the coast of NSW tide gauge data over the corresponding timeframe indicate a lower rate of rise suggesting a gradient in sea level trends between the Tasman Sea and the coast, which is explained by an increased strength and southward flow of the East Australian Current (Hill et al. 2008, 2011; Church et al. 2012; Deng et al. 2010).

NSW sea level records are influenced by many factors such as tides, waves, storm surges, seasonal temperature effects, and longer-term effects due to large-scale phenomena like the ENSO and IPO. In many cases tide gauges are located within estuaries which have undergone significant modification including entrance training and dredging, which may impact on measured water levels. Considerable care must therefore be used in the interpretation of sea level trends. Additionally, given ongoing climate change it is unlikely that past rates of sea level change will be representative of the future. To forecast future sea level, models are required to account for potential future scenarios associated with changing atmospheric gas composition and ocean/atmosphere interaction.

3.3 Future sea level projections

Changes to global mean sea level over the last century are associated with global warming as a result of increasing greenhouse gas concentrations in the atmosphere (IPCC 2013). The IPCC (2013) conclude it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century and future changes to climate are likely to be dependent on future greenhouse gas emissions.

3.3.1 Global mean sea level

The IPCC (2013) projections indicate global mean sea mean level rise under a business-as-usual scenario (Representative Concentration Pathway RCP8.5) of between 0.52 m and 0.98 m by 2100, relative to 1986–2005, or 0.28 m and 0.61 m with significantly reduced emissions (RCP2.6), giving a range of between 0.28 m and 0.98 m by 2100 relative to 1986–2005 (Figure 3.3.1). They also suggest the possibility of up to several tens of centimetres above these values if marine-based sectors of the Antarctic ice sheet collapse.

The rate of SLR over the 21st century is projected to very likely exceed recently observed rates of SLR. For business-as-usual emissions (RCP8.5) projected rates of SLR reach 8–16 mm per year by the end of the century. With significantly reduced emissions (RCP2.6), the projected rate of rise becomes roughly constant (central projection about 4.5 mm per year) before the middle of the century, and subsequently declines slightly.

Beyond 2100 the IPCC (2013) conclude that it is virtually certain that global mean SLR will continue for many centuries due to thermal expansion of the oceans. Assuming lower emission scenarios (RCP2.6), global mean SLR above the pre-industrial level by 2300 will be less than 1 m; however, for higher emissions (RCP8.5), the projected rise is 1 m to more than 3 m (medium confidence). SLR of 1–3 m per degree of warming is expected if the warming is sustained for several millennia (low confidence) (Church et al. 2013). These models likely underestimate the Antarctic ice sheet contribution, resulting in an underestimate of projected SLR beyond 2100.

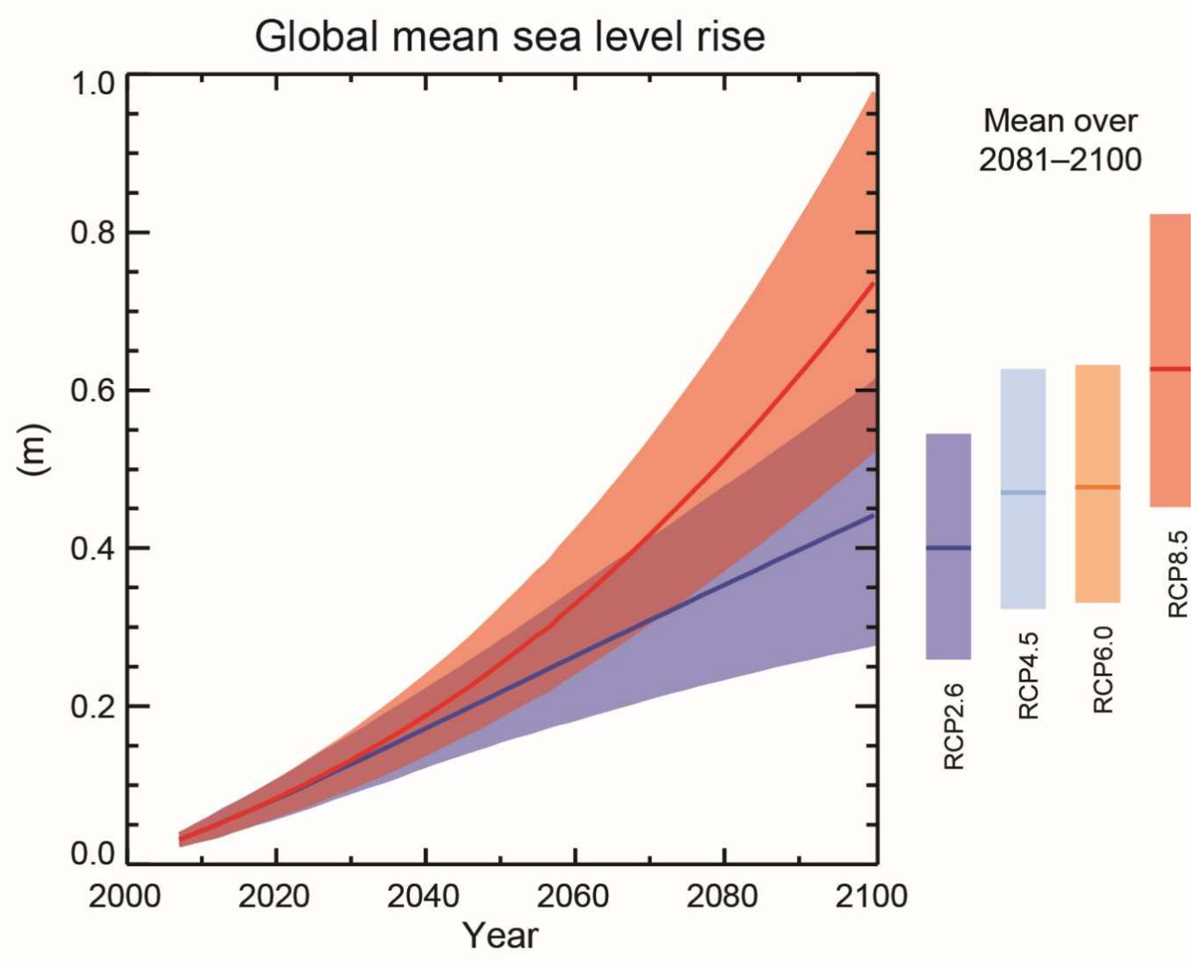


Figure 3.3.1 Projections of global mean SLR over the 21st century relative to 1986–2005, for RCP2.6 and RCP8.5

Source IPCC (2013)

The IPCC (2013) also conclude there is high confidence that sustained warming greater than some threshold would lead to the near-complete loss of the Greenland ice sheet over a millennium or more, causing a global mean SLR of up to seven metres. Current estimates indicate that the threshold is greater than about 1°C (low confidence) but less than about 4°C (medium confidence). Abrupt and irreversible ice loss from a potential instability of marine-based sectors of the Antarctic ice sheet in response to climate forcing is possible, but current evidence and understanding is insufficient to make a quantitative assessment.

Recent work on the west Antarctic ice sheet suggests that collapse of large sectors of the ice sheet is now inevitable, and that this area will contribute significantly to SLR in the decades and centuries to come (Rignot et al. 2014). Specifically, satellite observations indicate a general acceleration in ice loss from sectors of west Antarctica, including grounding line retreat of significant glaciers (McMillan et al. 2014; Rignot et al. 2014), while numerical modelling suggests that ice sheet collapse has already begun to occur in the Thwaites Glacier Basin (Joughin et al. 2014).

3.3.2 Regional mean sea level rise

Significant broad regional variation is expected in future sea level (both above and below the global average) due to differences in oceanographic processes and land level change.

Figure 3.3.2 shows the percentage of the deviation of the ensemble mean net regional sea level change between 1986–2005 and 2081–2100 from the global mean value. The figure was computed for a medium level emissions scenario (RCP4.5), but to first order is representative for all scenarios (Church et al. 2013). This suggests that SLR along the south east coast of Australia might be 0–10% above the global average by 2100 relative to 1986–2005, with higher rates offshore.

As for global mean SLR, ongoing regional sea level increase beyond 2100 is expected due to the long response timescale of the oceans. Thus, SLR is expected to persist for many centuries even if emissions of greenhouse gases are stopped.

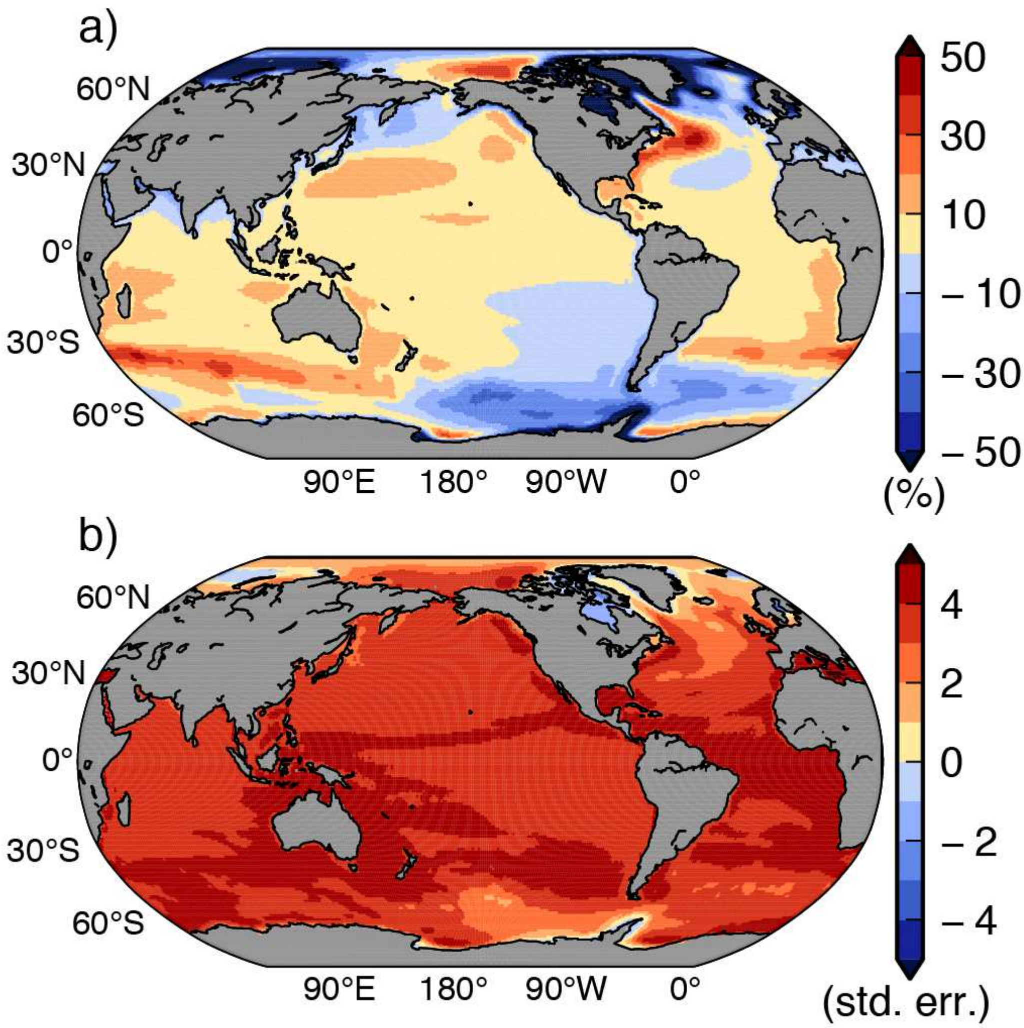


Figure 3.3.2. (a) Percentage of the deviation of the ensemble mean net regional sea level change between 1986–2005 and 2081–2100 from the global mean value; (b) Total RCP4. 5 sea level change (plus all other components) divided by the combined standard error of all components

Assuming a normal distribution, or a t-distribution given the number of models as an approximation of the number of degrees of freedom, a region passes the 90% confidence level where the change is greater than 2 standard errors, which is most of the ocean except for limited regions around western Antarctica, Greenland, and high Arctic regions. (source Church et al. 2013)

3.4 Land movement

Relative sea level change can also result from land level change. Many geological processes can contribute to this, including tectonism, GIA and local factors such as sediment compaction and/or withdrawal of groundwater, etc.

The main long-term geological contributor to sea level is GIA (Tamisiea & Mitrovica 2011). This is associated with the response of the Earth's crust to the unloading of ice following the last glaciation. This process means some areas of the globe that were loaded by ice are now rebounding, in some cases by up to 7mm per year (e.g. much of northern Eurasia and North America), while other areas are sinking (e.g. the east coast of the USA).

Australia is generally considered to be relatively tectonically stable (Middelmann 2007) and rates of GIA are generally low. Along the NSW coast rates of GIA are thought to be around 0.2 mm per year (Peltier 2004).

4. Approach to the risk assessment

4.1 Introduction

In this study, we assess exposure of current development to inundation associated with a range of SLR scenarios. We do not examine expected effects associated with erosion, which are addressed in a separate study. Additionally, our approach excludes examination of wave setup and runup and coincident catchment flooding, which require detailed modelling.

Offshore tidal levels along the coast of New South Wales are derived from a tidal inversion model developed by Oregon State University (Egbert et al. 1994) using OSU Tidal Inversion Software (OTIS). Modelled tide levels and tide range are compared with measured values from selected NSW tide gauge data sourced from work undertaken by Manly Hydraulics Laboratory (MHL) and documented in MHL (2012).

Within estuaries we utilise an extensive set of tidal plane data (MHL 2012) derived from gauge data and or berm heights in mostly closed ICOLLs (intermittently closed and open coastal lake or lagoons). Unlike previous studies which have utilised the simple bathtub type approach (e.g. DCC 2009), which assumes onshore tide levels correspond with those measured offshore, we apply an improved method based on the measured tidal plane data allowing for variation in tidal levels both between and along estuaries.

Within gauged estuaries an interpolated tidal plane is created from measured gauge data and tidal limits. This is then applied in conjunction with the best available elevation data to map inundation extents. For ungauged estuaries, we use an interpolated tidal plane shape created from gauge data derived from other estuaries of the same type or berm heights for mostly closed ICOLLs.

Inundation extents are mapped by overlaying the tidal plane surface over available terrain data. We model and map coastal inundation associated with a range of different SLR scenarios.

Exposure is quantified using data from the GURAS. This database is used to identify properties that are predicted to be exposed to inundation under different SLR scenarios.

4.2 Tidal planes

Tidal planes adopted for use in this study are obtained from MHL (2012). Here average tidal planes for the period from 1990 to 2010 are calculated using annual data. These are calculated for most NSW tide gauges using the Foreman tidal analysis package (Foreman 1977; Godin 1972). The Foreman package divides the tide into 45 astronomical constituents and 24 shallow water constituents which are calculated using harmonic analysis. The dominant constituents are the principal semi-diurnal lunar constituent (M_2), the principal semi-diurnal solar constituent (S_2), the luni-solar diurnal constituent (K_1) and the principal lunar diurnal constituent (O_1) Table 4.2.1.

Table 4.2.1. Major constituents used in tidal plane calculations (MHL 2012)

Constituent	Origin	Period (hrs)	Angular speed (minutes/degrees)
M_2 (semi-diurnal)	Principal lunar	12.42	2.07
S_2 (semi-diurnal)	Principal solar	12.00	2.00
K_1 (diurnal)	P. lunar/p. solar	23.93	3.99

O_1 (diurnal)	Principal lunar	26.82	4.30

By using combinations of the constituents M_2, S_2, K_1 and O_1 a series of tidal planes, ranges and phases can be calculated for a given tidal gauge (MHL 1995a, b).

For this study, we use HHWSS and Indian Spring Low Water (ISLW). These are calculated using formulations from MHL (1995a, b, 2005, 2012) where:

$$HHWSS = Z_0 + M_2 + S_2 + 1.4(K_1 + O_1)$$

and

$$ISLW = Z_0 - (M_2 + S_2 + K_1 + O_1)$$

Z_0 is the mean sea level, calculated annually and adjusted to AHD using the conversions in MHL (2010).

In Appendix A, we compare the HHWSS levels with highest astronomical tide (HAT) for selected ocean gauges. On average, the HHWSS tidal plane is approximately 13 centimetres lower than HAT. The HHWSS tidal plane is consistent with predicted levels for higher (king) tides but at ocean tide gauge sites is exceeded on average 25 days a year due to contributions from non-tidal processes including storm surge, coastal trapped waves, etc.

4.3 Offshore tidal boundary conditions

4.3.1 Tides

New South Wales has a wide network of tide gauges (see Figure 4.3.1), however many of these gauges, particularly on the north coast of New South Wales, are located within estuary or river mouths and thus are not fully representative of the ocean tide (MHL 2005). MHL (2005) shows tide ranges at river entrance sites are reduced 0.2–0.3 m compared with ocean gauges. To overcome this limitation, we use the output of the tidal inversion model developed by Oregon State University (Egbert et al. 1994) using OSU Tidal Inversion Software (OTIS 2013). The OTIS model data is from the Pacific Ocean 1/12Deg data set (OTIS 2013).

Variation in the calculated tide range (R) along the NSW coast as predicted from the OTIS 2013 model is shown in Figure 4.3.2.

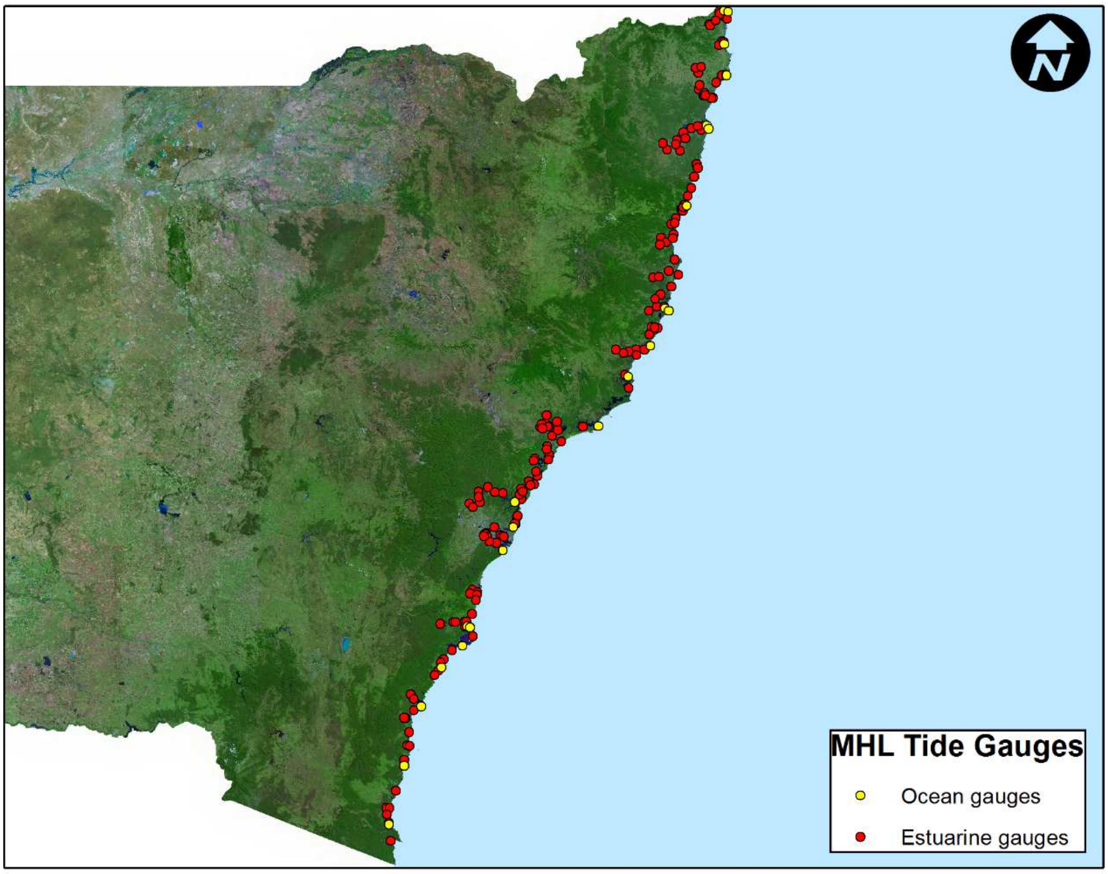


Figure 4.3.1. Map of New South Wales showing location of MHL tide gauges

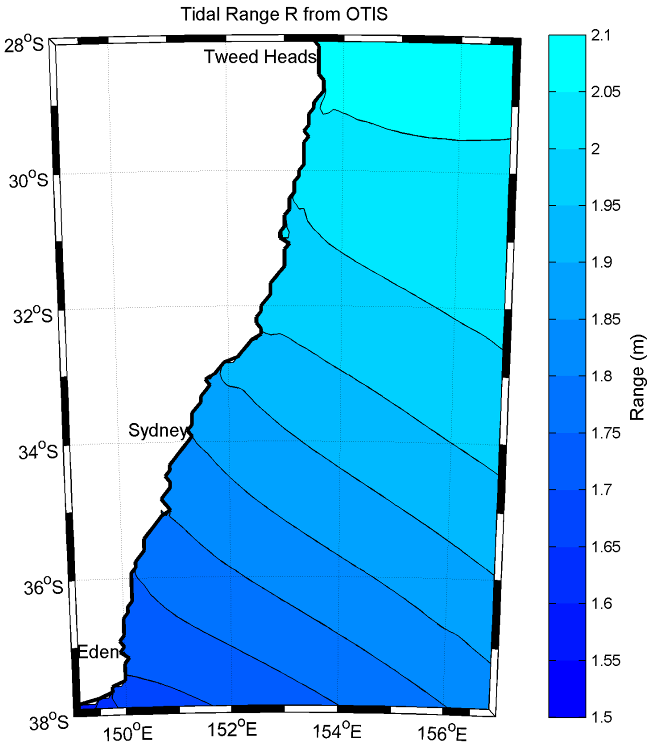


Figure 4.3.2. Plot of tidal range R for New South Wales extracted from OTIS model; map is on Universal Transverse Mercator (UTM) projection

Here (R) is given by:

$$R = 2\ (M_2 + S_2 + 1.2\ K_1 + 1.2\ O_1)$$

(MHL 1995, 2005, 2012).

Comparisons of OTIS modelled HHWSS and MHL data are shown in Figure 4.3.3 and Appendix A. Here data are presented for open ocean gauge locations (named in blue) and for onshore open ocean gauging locations excluding river sites (named in black). Residuals are generally less than 0.05 m although the fit appears slightly poorer on the south coast.

This comparison shows the OTIS inverse tidal model is sufficiently representative of the tidal water levels along the NSW coast to be used as an oceanic model boundary condition for estuaries that do not have an oceanic tidal gauge in close proximity.

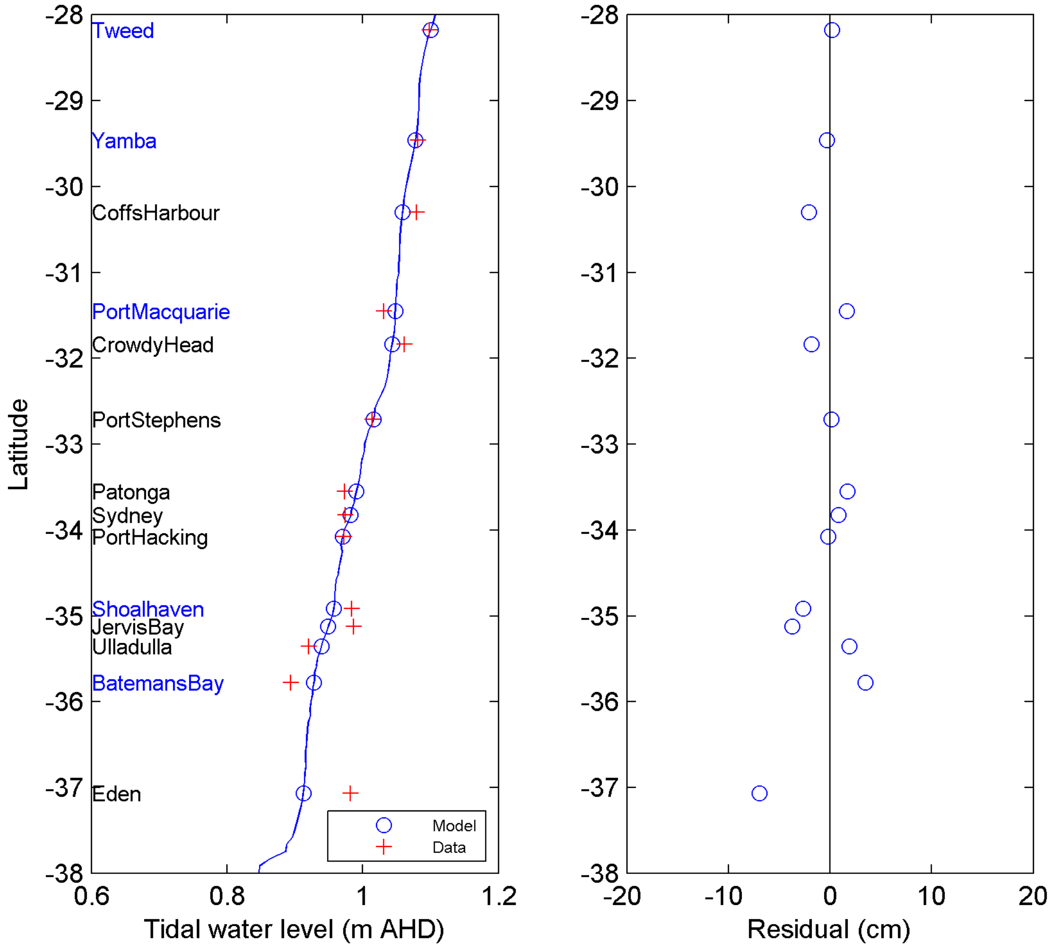


Figure 4.3.3. Plots showing comparison between HHWSS values from OTIS and data for open ocean locations (named in blue) and onshore open ocean gauging locations (named in black)

4.3.2 Non-astronomic water level variations

As discussed in Section 2.4 many non-astronomic factors also affect observed water levels. MHL (1992) showed that anomalies of 0.3 m occur at return intervals of months, and thus become a significant addition to predicted tidal levels.

SMEC and UQ (2013) provide estimates of the 100-year annual return interval (ARI) extreme water levels for the various offshore, bay and port gauges along the NSW coast. Comparison between the 100-year ARI levels and the HHWSS tidal plane at each site is presented in Figure **4.3.4**. On average, the 100-year ARI water level is around 0.4–0.5 m above the respective HHWSS tidal plane and is fairly consistent along the NSW coast, as seen in Figure **4.3.4**.

Since there is general consistency in the non-astronomic water level variations along the NSW open coast, the adopted sea level offsets of +0.5 m (see Section 4.7) are also used as the first order allowance for 100-year ARI non-tidal water level variations. This allowance however, excludes effects of wave setup and wave runup, which may be significant at some sites.

No account is taken of coincident riverine flooding, which while likely to be significant, is beyond the scope of this study.

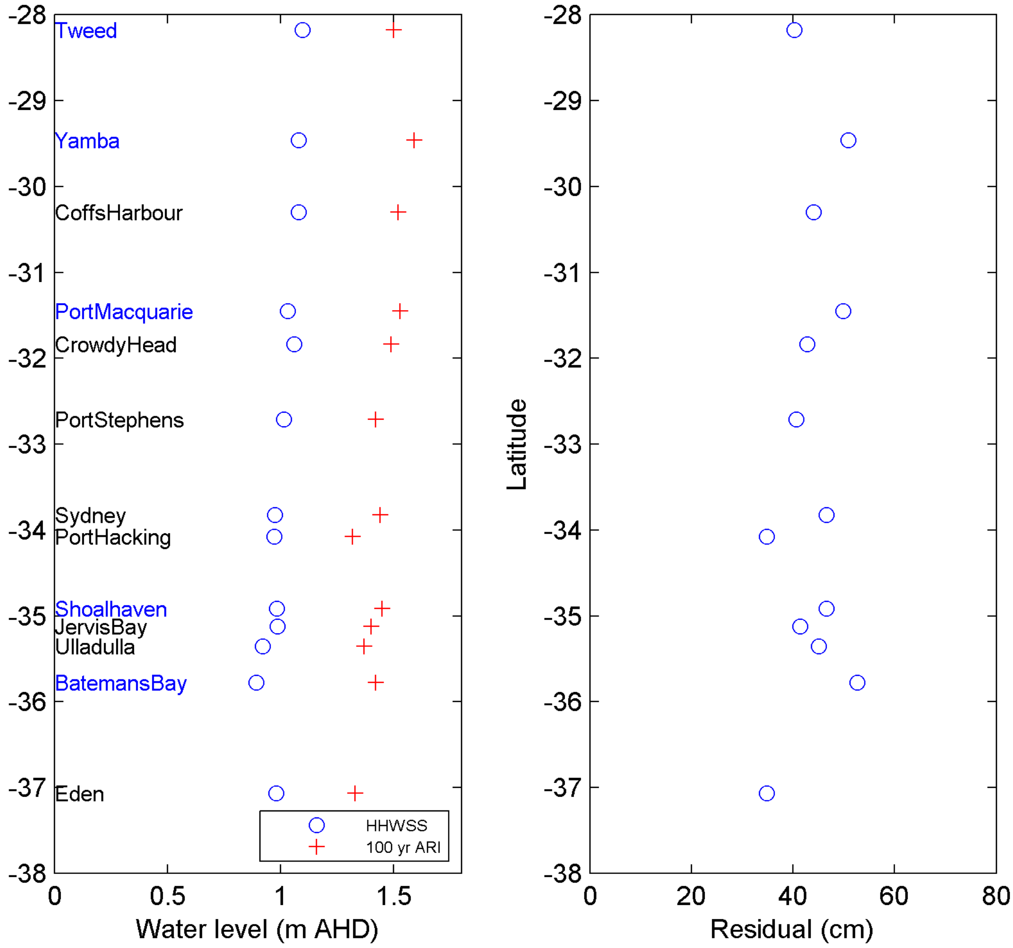


Figure 4.3.4. **Along coast variation in extreme (100-year ARI) water level and HHWSS for open ocean (named in blue) and onshore open ocean gauging locations (named in black)**

4.4 Estuarine tidal plane evaluation

4.4.1 Estuary classification

As described in Section 2.2 there are several classification schemes for estuaries in New South Wales based on a variety of parameters. For this study, we group estuaries according to tidal behaviour using the methods outlined in the sections below. Adopted estuary types include:

- Drowned River Valley (DRV)
- Large River (LR)
- Small River (SR)
- Tidal Lake (TL)

- Intermittently Closed and Open Lakes and Lagoons (ICOLLs & NGI[1])
- Embayment (EM).

4.4.2 Gauged estuaries

As outlined in Section 2.3.2, tides within estuaries vary from those in the open ocean due to a number of processes including frictional attenuation and resonance.

To improve representation of estuarine tidal levels we compiled a database which contains information on the NSW tidal gauge network maintained by Manly Hydraulics Laboratory (MHL). This information includes site details such as location name, estuarine system and AWRC (Australian Water Resource Council) number, location in both MGA94 eastings/northings and latitude/longitude (WGS84) and chainage (distance from ocean). To enable use as input to the GIS water surface modelling tool the database also contains tidal range information such as MSL, HHWSS and ISLW derived from harmonic tidal analysis of the tidal gauge data. The location and tidal information was sourced from MHL (2012).

The tidal planes (TP), were compiled for all of the 56 gauged estuaries in New South Wales based on harmonic analysis undertaken on the gauge data as reported in MHL (2012), see Figure 4.3.1. At the entrance to each estuary the oceanic tidal levels were determined from the OTIS model output while the location and characteristics of the tidal limits were sourced from MHL (2006).

Individual tidal planes for each gauged estuary are presented in Appendix B and some examples are shown in Figure 4.4.1.

[1] NGI = non-gauged ICOLLs

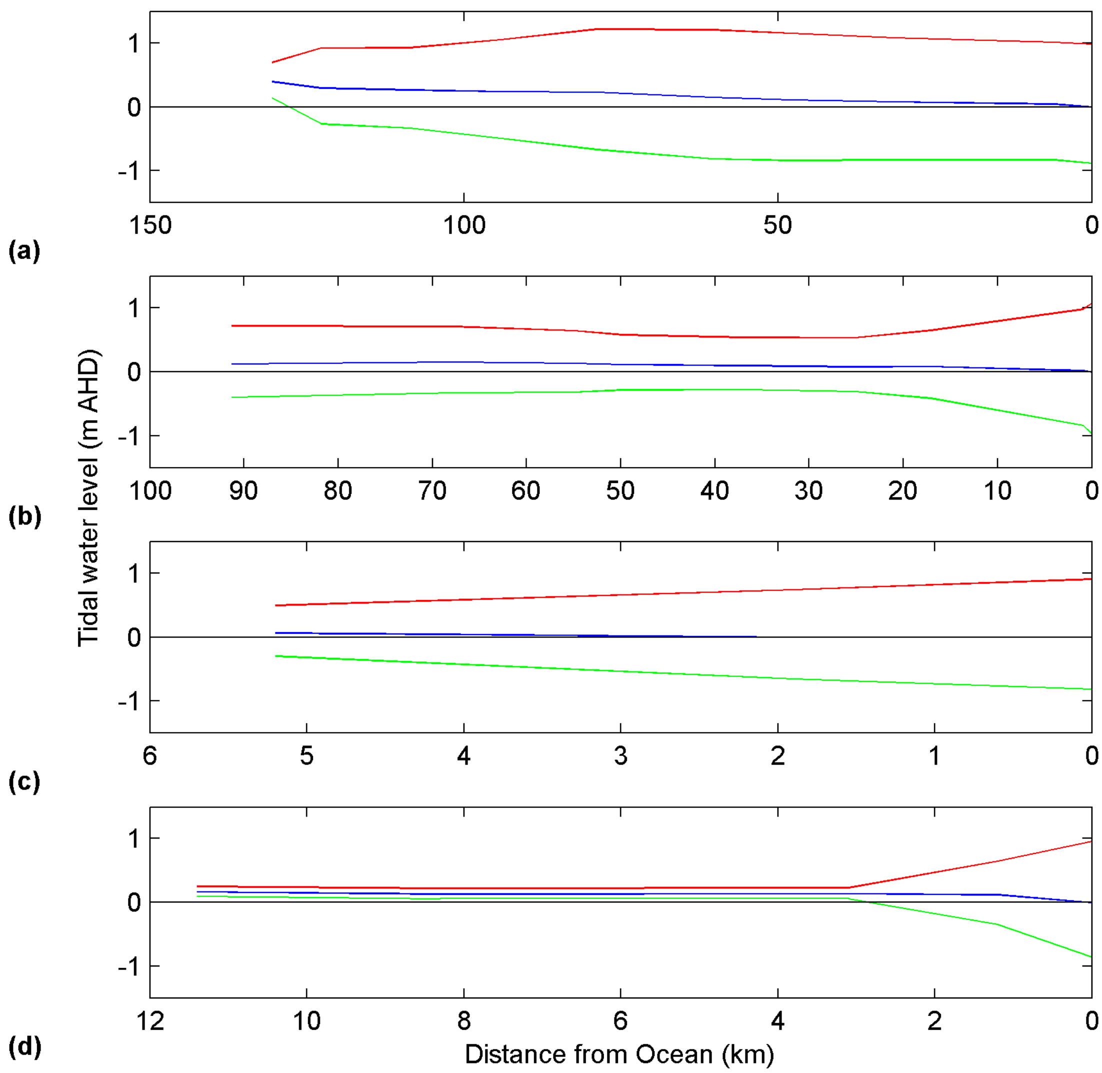


Figure 4.4.1. Examples of tidal planes for different estuary types: (a) Drowned River Valley (Hawkesbury River), (b) Large River (Clarence River), (c) Small River (Merimbula Lake), (d) Tidal Lake (Lake Illawarra), HHWSS in red, MSL in blue and ISLW in green

4.4.3 Non-gauged estuaries

For non-gauged estuaries, we used data from gauged estuaries of a similar type to derive average tidal planes, which were then applied to approximate the estuary water surface where no gauge data is available.

Analyses of the characteristics of tidal form of the various NSW estuary types was undertaken using this tidal plane data. A method was developed using physical metrics which are readily determined for each of the gauged estuaries. This was based on an examination of the behaviour of the tidal planes along with the configuration of the estuary and its effect on the tide (Druery et al. 1983).

The first metric applied was that of the gradient of the tidal plane for HHWSS (HW-TP) at the entrance to each estuary. This differentiates between estuaries where the HW-TP either increases or decreases into the estuary, i.e. between estuaries with tidal amplification and those with tidal attenuation.

The next metric used was the ‘form’ of the HW-TP, which was determined by calculating whether a change in the gradient of the HW-TP occurred within the estuary. If the sign of the gradient of HW-TP was constant, i.e. the values of HW-TP continually decreased or were constant along the length of the estuary, the form was designated as having a value of zero (0). On the other hand, if there was a change in the gradient of HW-TP, with areas of tidal amplification within the estuary, the form was defined as one (1).

The final metric was the length of the estuary as defined by the distance along the thalweg (the line following the deepest part of the estuary) from the ocean entrance to the location of the tidal limit, sourced from MHL (2006). The application of these three metrics resulted in a tidal characteristic-based categorisation of estuary types which is outlined in the section below.

To characterise NSW estuary types in terms of tidal characteristics the three metrics HW-TP entrance gradient, HW-TP form, and estuary length, were determined for each gauged estuary. Estuaries that have a positive HW-TP entrance gradient correspond with drowned river valleys, while most of the remaining estuaries are separated into Small or Large River estuaries based on the form metric. If the form of the estuary is one (1), then it is categorised as a Large River Estuary, otherwise it is categorised as a Small River Estuary.

To take into account the fact that some estuaries have a limited number of water level gauges which may not be sufficient to capture the characteristics of the tidal plane, particularly in the upper estuary, the estuary length was used to further differentiate between Small and Large River estuaries. The length of the shortest river estuary that had a change in form was used as the cut-off in distinguishing between Small and Large River estuaries. Thus, estuaries that may have been categorised as Small River Estuaries using the form metric are re-categorised using the estuary length. The results of the categorisation of the gauged estuaries in New South Wales are shown in Figure 4.4.2, plotted as a comparison between HW-TP entrance gradient and estuary length.

Tidal Lakes were categorised manually due to their unique tidal plane characteristics and small number of occurrences; they are included for completeness. It should also be noted that the small number of ICOLLs that are gauged behave, when open, as Small River Estuaries or Tidal Lakes (depending on the degree of entrance constriction) under this categorisation system.

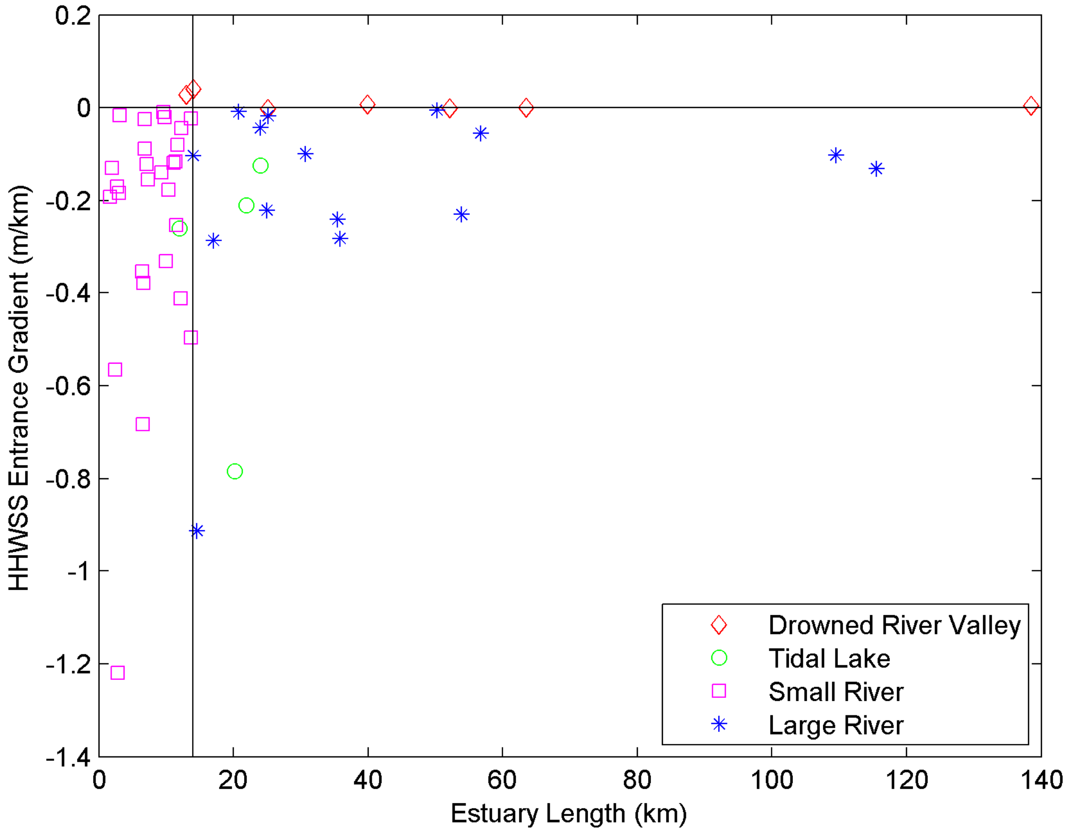


Figure 4.4.2. Plot showing categorisation of NSW estuary types using high water entrance gradient and length of estuary

Thus, in terms of the characteristics of tidal propagation the estuaries in New South Wales can be usefully divided into four basic estuary types: Drowned River Valleys, Large Rivers, Small Rivers, and Tidal Lakes.

A typical tidal plane for each estuary type is calculated by averaging available gauge data for that estuary type as shown in Figure 4.4.3. These estuary types are directly related to the classification system of Roy et al. (2001), being a simplification of their system in that the grouping is based primarily on tidal characteristics, thus having a smaller number of estuary types, and further does not take into account other factors such as the geology or geomorphology of each system.

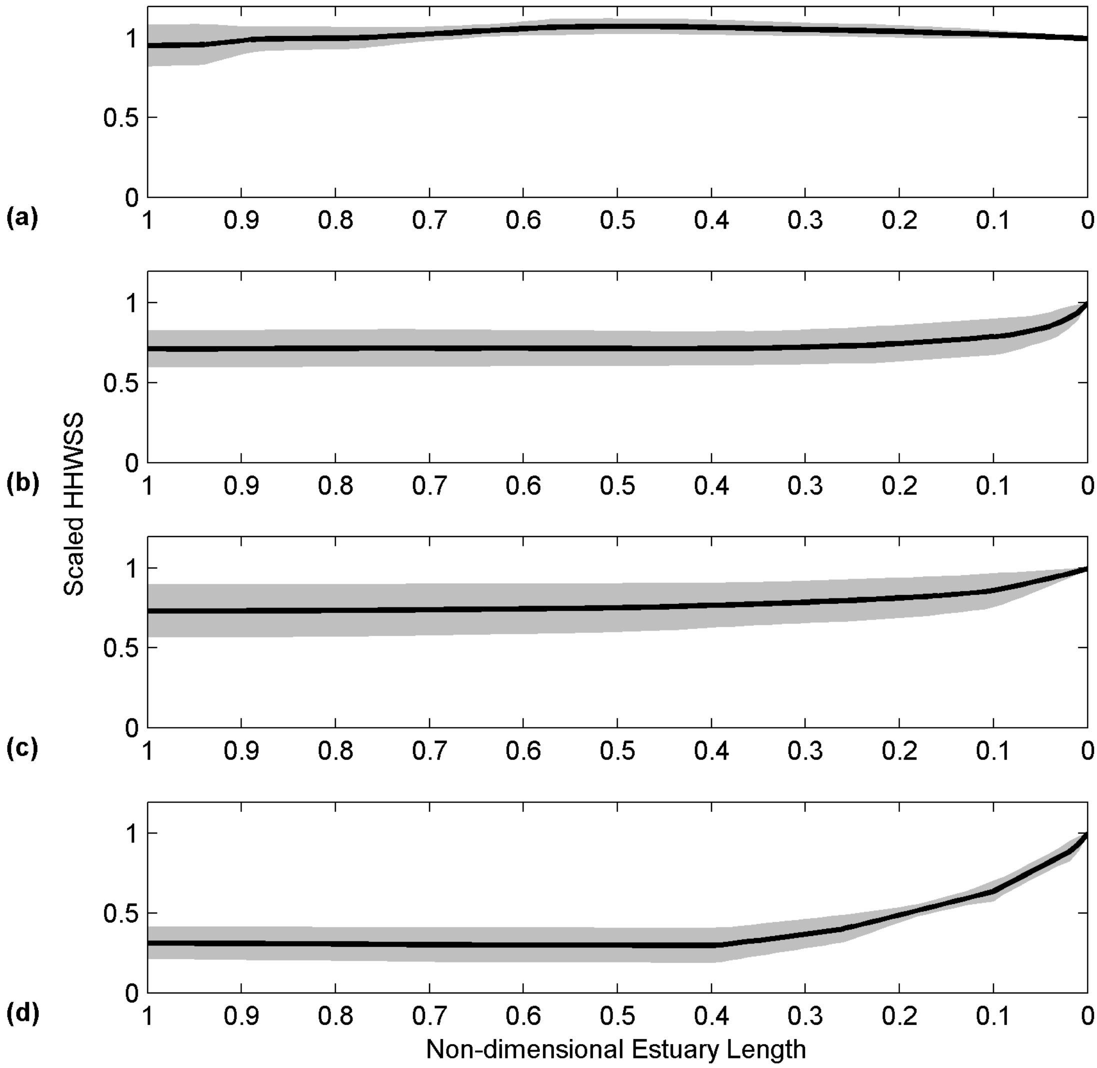


Figure 4.4.3. Average HHWSS tidal plane for different estuary types: (a) Drowned River Valley, (b) Large River, (c) Small River, and (d) Tidal Lakes

Drowned river valley estuaries are characterised by amplification of the tidal range for large distances inland, while tidal rivers experience an initial reduction of tidal range. In Large Rivers, this is typically followed by very mild amplification in the mid-reaches of Large River Estuary systems (e.g. Hastings River) before complete damping of the tidal range around the head of the estuary. In Small River Estuary systems, the amplification of the tidal range in the mid-reaches often does not occur, rather there is a gradual attenuation toward the tidal limits.

Tidal Lakes are characterised by severe attenuation of the tidal range due to frictional effects in the entrance channel. Tide ranges in these systems may be as little as 10% of the offshore tide range and tidal pumping can be significant amplifying the magnitude of the fortnightly tide (McLean & Hinwood 2011). To address this, we add an additional 0.2 m to the lake level based on exceedence statistics from MHL (2014).

Water levels in ICOLLs (e.g. Narrabeen Lagoon) vary depending on opening and closing regimes; while open they operate like Small River Estuaries or Tidal Lakes, while closed they gradually fill, with water levels influenced by inflows and evaporation. For ICOLL's that are closed most of the time, we use berm height to approximate maximum water levels. Berm height is known to be dependent on wave height and period and beach slope which is in turn influenced by grain size (Hanslow et al. 2000). As local wave conditions are generally unavailable for individual entrances we use a formulation for berm height (BH) based on beach grain size from Hanslow et al. (2000), such that:

$$BH = 3.92*D_{50} + 1.12$$

where D_{50} is the medium grain size, except where actual measurements of berm height are available.

In embayment type estuaries, we use the adjacent ocean HHWSS from OTIS (2013). This assumes tidal levels are equivalent to open ocean. Adopted levels at various ocean embayments are detailed in Appendix B.

4.4.4 Limitations

The approximations used to derive the tidal planes are known to be subject to limitations. In the open ocean, the Foreman method of tidal planes analysis using these four main constituents is thought to be accurate to 10% of the tidal range (DOD 2001; MHL 2005).

As tides propagate into estuaries the importance of higher order tidal constituents increases. Due to the dominance of M_2, the most significant overtide formed in estuaries is M_4, the first harmonic of M_2. M_4 is small offshore, but increases within estuaries due to bottom friction and channel geometry (see Speer & Aubrey 1985; Parker 1991). Non-linear interaction between other constituents is also possible in shallow estuaries.

MHL (2005) investigate the accuracy of the tidal plane approximations using a variety of methods. They show increasing significance of high order constituents at upstream sites compared with the ocean. Comparison between the statistical method of calculation and the tidal plane approximation shows differences of around 0.1 m in the estimation of mean high water springs. Underestimation was observed at the drowned river valley site (Windsor) and the coastal lake site (Marmong Point), and overestimation at the river site (Billinudgel).

Within tidal lakes, tidal signals show amplification of the fortnightly and longer period tides (MHL 2005, 2009). In these systems, the constricted nature of the entrance channels contributes to spring neap pumping which results in the amplification of the fortnightly constituent. Thus, in tidal lakes the tidal planes are likely to underestimate the tidal highs and lows. To address this, we add an additional 0.2 m to the lake level based on exceedence statistics from MHL (2014).

Use of berm heights for ICOLLs assumes natural entrance closing regimes in these systems. This assumption may overestimate inundation where entrance management policies are used to lower berm heights or where break out policies are used to reduce flood heights. However, as such practices may change over time and are subject to operational constraints (e.g. access during extreme events) it was considered belter to assume natural processes.

4.5 Terrain data

For this project, we sourced the best available digital elevation data for each estuary. For most areas, we accessed 1 m digital elevation model (DEM) data derived from Light Detection and Ranging (LiDAR) data collected for Land and Property Information (LPI), LPI (2012). These DEM data have a horizontal accuracy of 0.8 m, vertical accuracy of 0.3 m (95% CI) and meet Intergovernmental Committee on Surveying and Mapping (ICSM) guidelines for digital elevation data.

Full details of the data used are shown in Appendix B (Table B.5). The main exception to the 1 m DEM data is on the Central Coast, where 2 m LiDAR data are used where horizontal accuracy is ±0.6 m and accuracy is ±0.2 m at 95% confidence.

4.6 Inundation mapping

In order to estimate and map the extent of inundation within the estuaries of NSW a GIS-based model was developed consisting of two main parts: The Water Surface Model and the Inundation Model. This model utilises ArcDesktop geoprocessing and spatial analysis functions (ESRI 2013). A flowchart outlining the structure of the model is shown in Figure 4.6.1.

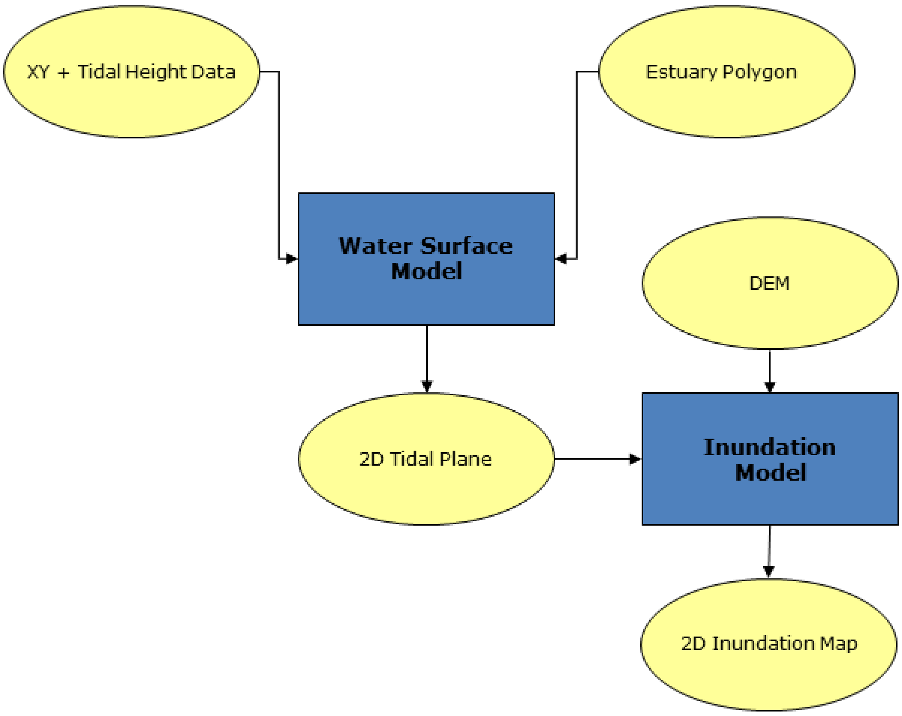


Figure 4.6.1. Flowchart showing simplified structure of GIS-based Water Surface Model and Inundation Model

The GIS-based Water Surface Model is used to obtain an estuary wide tidal plane surface (TPS) as outlined in Foulsham et al. (2012). For a given estuary the tidal plane information is extracted from the tidal plane information database which includes the offshore (OTIS) and gauge tidal planes as well as the tidal limit locations. An area of analysis (AOA) for an estuary is then created by buffering the estuary's spatial boundary (OEH Corporate Spatial DB 2013) by 200 metres, while constraining the extent within the estuary's catchment area. The TPS is then created from tidal plane information; here HHWSS is used, by utilising a minimum curvature spline technique (ESRI 2014) with the AOA boundary as a barrier; example results are shown in Figure 4.6.2.

The TPS created is then used as one of the inputs to the GIS-based Inundation Model to estimate the spatial extent of tidal inundation in a given estuary. A DEM of the AOA is compiled from available data. Preference is given to the most recent/highest resolution data which in the majority of cases for NSW estuaries is 1 m LiDAR data. To improve performance, the DEM of each AOA is further constrained by using only elevations that are less than 10 m AHD. The TPS is then spatially joined to the DEM and inundation status calculated by assessing the tidal plane height against the elevation at each data point, as well as a consideration of flowpaths so as to exclude depressions isolated from the estuary. This inundation status is then applied to an area equivalent to the spatial resolution of the DEM at each point, to map the spatial extent of the inundation area for the given estuary.

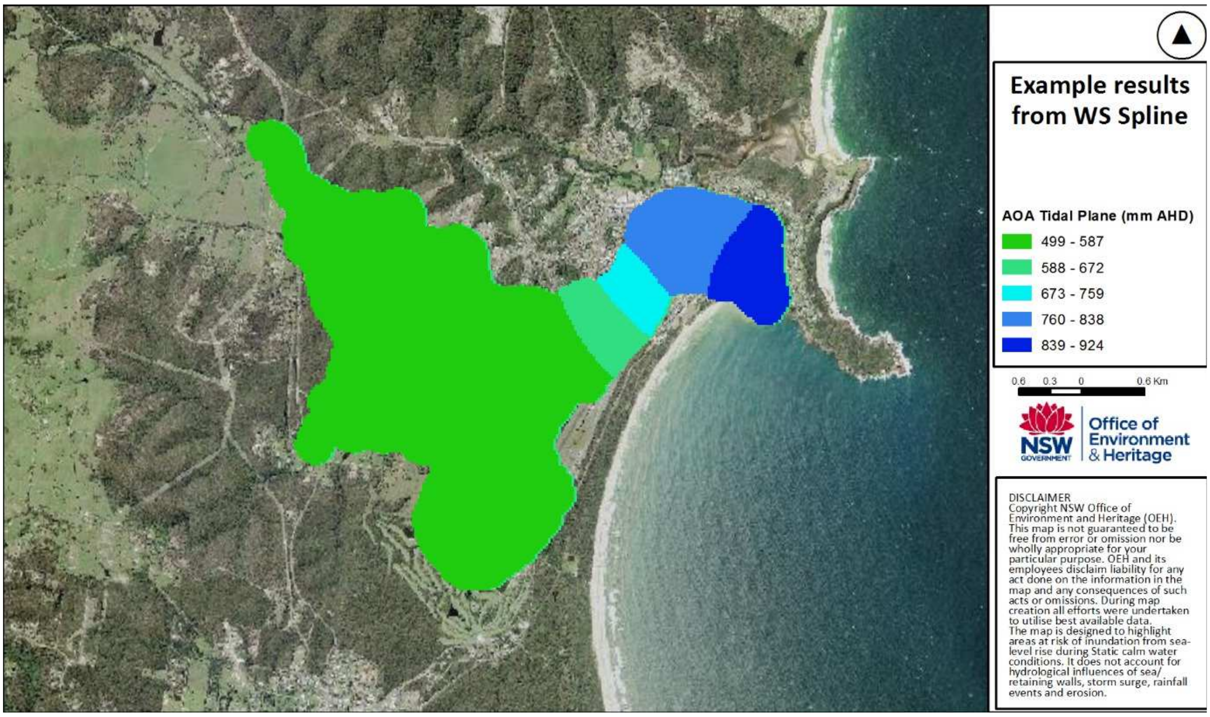


Figure 4.6.2. Plot showing example results of WS-spline tool from the Water Surface Model

4.7 Sea level rise scenarios

Management of SLR is a complex issue requiring consideration of uncertainty associated with future possibilities over the variety of time horizons relevant to the use and occupation of the coastal zone. As outlined in Section 3, SLR ranging between 0.28 m and 0.98 m is predicted by 2100 relative to 1986. Additionally, ongoing SLR beyond 2100 is expected due to the long response time scale of the oceans.

No one scenario is appropriate for risk assessment for current development or for future planning that involves the consideration of different time horizons and likelihoods. However, consideration of many possible scenarios or a full probabilistic approach may be equally problematic for a statewide assessment like the current project. Thus, in the current assessment we consider three scenarios: SLRs of 0.5 m, 1 m and 1.5 m. These are selected to be representative of a range of scenarios relevant to structure design as well as land-use planning. They are not tied to a particular planning horizon and importantly should not be treated as an upper bound for potential long-term SLR which may need to be considered for future development.

4.8 Exposure assessment

4.8.1 GURAS address data

The NSW Geocoded Urban and Rural Addressing System (GURAS) was used to identify properties that were predicted to be exposed to inundation under each scenario. The GURAS database is the authoritative property addressing system for NSW. It is systematically maintained through updates to the digital cadastral database (DCDB) and property description and address updates from the Valnet2 system (LPI 2012, 2014).

The GURAS database was used in preference to cadastral data, because the cadastre provides no indication of the addresses associated with each land parcel; for example, some cadastral lots may contain numerous addresses, while some addresses may occupy multiple cadastral lots. Furthermore, the cadastre includes many undeveloped lots in the coastal zone that remain public land, and which should be excluded from the assessment.

The GURAS database stores address point data within cadastral lots. The database distinguishes between primary addresses (e.g. houses, strata blocks) and secondary addresses (e.g. individual apartments, units), which may be relevant for assessing exposure to coastal hazards.

Only primary addresses were considered in this assessment, as coastal inundation hazards are not anticipated to impact many secondary addresses, which are often situated above ground level. However, for strata blocks with secondary addresses in single-level (ground floor) developments, it is expected that the procedure will under-predict total exposure to inundation.

The GURAS database also contains coded and text identifiers, which were used to select and discard a variety of ‘public’ address types (e.g. beaches, reserves, car parks, wharfs, utilities, etc.) prior to the calculation of exposure statistics.

Figure 4.8.1 shows the procedure that was used to restrict the assessment only to the ‘valid’ address types of interest. This method was developed by OEH (2014). Here, valid addresses included houses, unit/apartment blocks (but not individual units within), and commercial and industrial premises. The procedure included the following steps:

1. Secondary addresses were removed such that only primary addresses were considered.
2. Address points falling within Crown Lands and National Parks areas were removed.
3. Text tags were used to remove remaining address types that were not of interest.

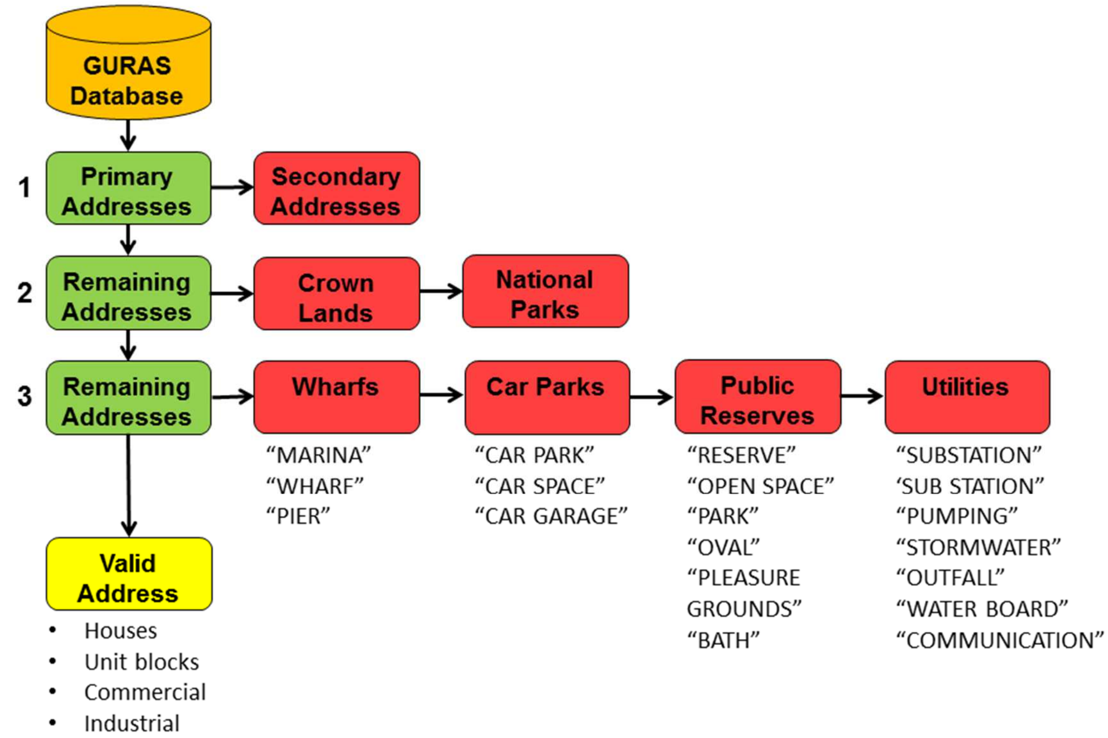


Figure 4.8.1. Procedure used to identify valid address types for the coastal inundation exposure assessment (source: OEH 2014)

4.8.2 Exposure to inundation and proportion-of-lot assessment

The method developed to assess the exposure of relevant lots to inundation is as follows:

1. The inundation extent layers for each water level scenario were overlain on GURAS property-boundary data, to identify exposed lots.
2. Exposed lots were used to select all GURAS address points within each of the exposed lots.
3. The selected address points were then queried to remove any addresses associated with public spaces, utilities or infrastructure.

The outcome of this method was that only primary addresses associated with residential, commercial and industrial properties were preserved; however, while the procedure was successful in isolating only the address points of interest, it did not provide any measure of exposure to inundation for each property, or the relative likelihood of impacts to assets.

To address the above limitation, the proportion of each property (<10%, 10–25%, 25–50%, 50–90% and 90–100%) that was predicted to be exposed to inundation was calculated, and appended to the address details (see Table 4.8.1). The 10% threshold was deemed suitable to isolate potentially negligible exposure, particularly for the case of steep foreshore properties surrounding drowned river valley estuaries.

The exposure of transport infrastructure to inundation was also quantified using an overlay method, which identified road, railway and pathway line-geometry data that fell within the inundation hazard extents. For each scenario, total lengths of potentially exposed transport infrastructure were calculated. The assessment was limited to road, railway and pathway lengths that are classified as 'on ground', and thus excluded any raised (bridges, overpasses) or buried (tunnels) infrastructure. Road infrastructure was analysed by 'function hierarchy' to identify the potential significance of impacts, and heavy and light railway infrastructure was also considered separately.

Similarly, areas of Crown reserves and national parks predicted to be inundated were also identified.

Table 4.8.1. Proportion-of-lot inundation categories used to differentiate between different levels of exposure

Percentage-of-lot inundated	Label	Description of potential exposure
90–100%	Complete	Entire lot subject to inundation
50–90%	Significant	> half of lot subject to inundation
25–50%	Moderate	> quarter of lot subject to inundation
10–25%	Minor	< quarter of lot subject to inundation
1–10%	Minimal*	Lot subject to very minor inundation

** 1–10% proportion-of-lot inundation may not always imply minimal exposure of assets (e.g. if the location and design of assets contributes to exposure); however, this threshold is used here as a means to isolate potentially negligible exposure for steep foreshore properties.*

5. Results of the exposure assessment

5.1 Introduction

Inundation extents for each estuary were combined data from the GURAS to identify properties exposed to inundation under each scenario.

5.2 Statewide exposure

5.2.1 Properties

On a statewide basis, the results indicate:

- 23,653 properties are exposed to risk from inundation at the HHWSS level if sea level rises by 0.5 m
- 50,744 if sea level rises by 1 m, and
- 74,379 if sea level rises by 1.5 m (Figure 5.2.1).

Figure 5.2.1 and Table 5.2.1 also show the numbers of properties exposed on a proportion-of-lot basis. This analysis shows that many properties are only subject to minor inundation although as sea levels increase the proportion of properties subject to major or complete inundation increases.

Numbers of properties subject to greater than 50% inundation are 4,343 for 0.5 m of SLR, 22,122 for 1 m of SLR and 43,312 for 1.5 m of SLR.

Numbers of properties subject to greater than 90% inundation are 1,620 for 0.5 m of SLR, 13,456 for 1 m of SLR, and 33,104 for 1.5 m of SLR.

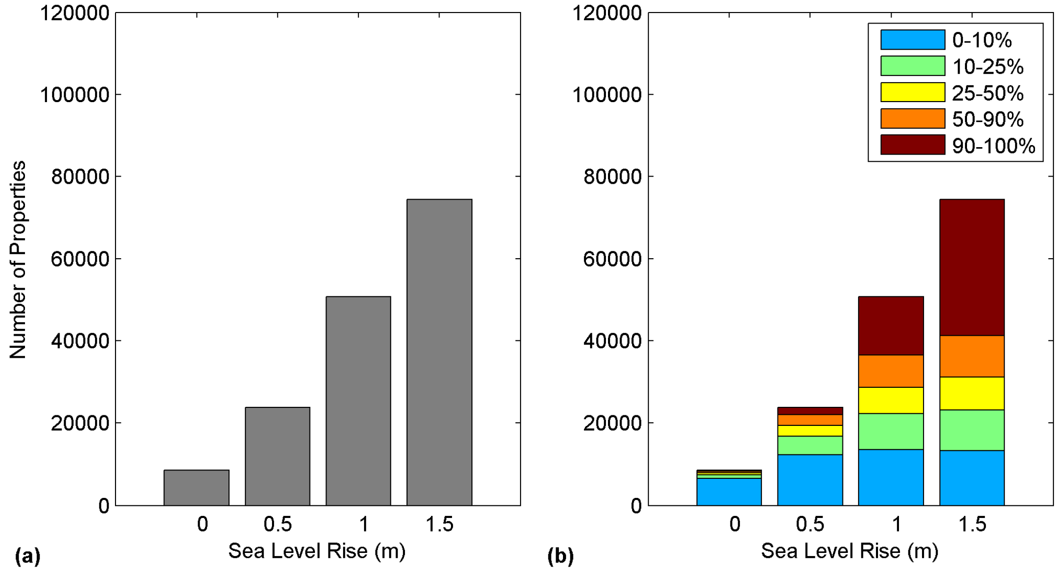


Figure 5.2.1. (a) Total numbers of properties exposed to inundation (HHWSS) for all NSW estuaries under 0, 0.5, 1.0 and 1.5 m SLR; (b) As for (a) but including percentage-of-lot inundated

Table 5.2.1. Number of properties statewide exposed to inundation (HHWSS) on a proportion-of-lot basis

Percentage-of-lot inundated	No. of properties exposed under SLR scenarios			
	0 m	0.5 m	1.0 m	1.5 m
90–100%	202	1,620	13,456	33,104
50–90%	434	2,723	8,800	10,208
25–50%	493	2,616	6,366	7,938
10–25%	879	4,450	7,903	9,818
1–10%	6,488	12,244	14,219	13,311
Total	8,496	23,653	50,744	74,379

When allowing for storm surge and other non-tidal contributors to ocean water levels (assuming 0.5m above HHWSS is approximates a 100-year ARI surge), Figure 5.2.2 and Table 5.2.2 show the numbers of properties exposed on a proportion-of-lot basis. This analysis shows:

- 51,557 properties are exposed to ocean inundation if sea level rises by 0.5 m
- 74,746 properties are exposed to ocean inundation if sea level rises by 1 m.

Numbers of properties subject to greater than 50% inundation are 23,000 for 0.5 m of SLR and 43,852 for 1 m of SLR (Figure 5.2.2).

Numbers of properties subject to greater than 90% inundation are 15,061 for 0.5 m of SLR and 33,789 for 1 m of SLR.

In this calculation we adopt HHWSS plus 0.5 m for DRV, LR, SR, TL and berm height for all ICOLLs.

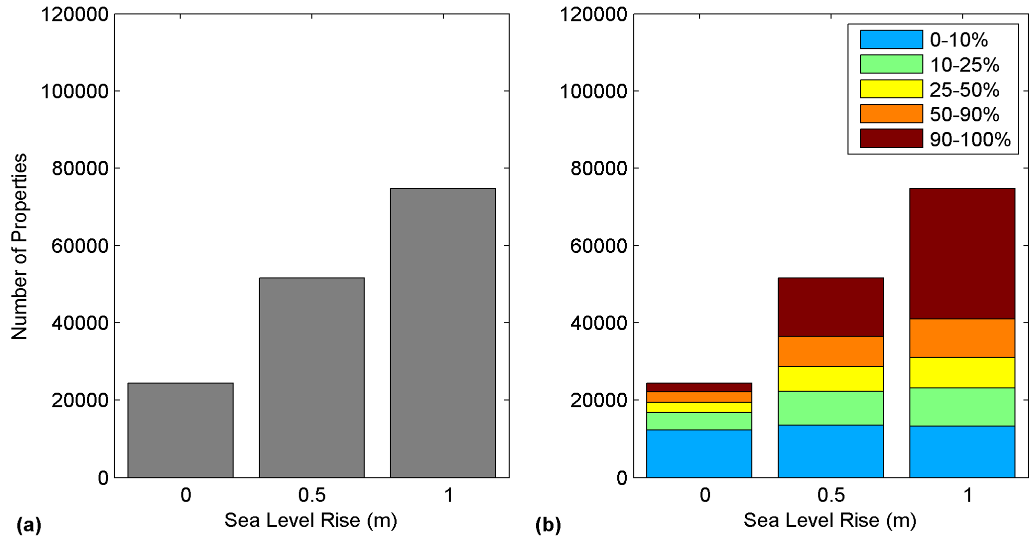


Figure 5.2.2. (a) Total numbers of properties exposed to inundation (100-year ARI water levels assuming HHWSS plus 0.5 m for DRV, LR, SR, TL – and berm height for all ICOLLs) for all NSW estuaries under 0, 0.5 and 1.0 m SLR; (b) As for (a) but including percentage-of-lot inundated

Table 5.2.2. Number of properties statewide exposed to inundation (100-year ARI water levels) on a proportion-of-lot basis

% of lot inundated	No. of properties exposed under SLR scenarios		
	0 m	0.5 m	1.0 m
90–100%	2,205	15,061	33,789
50–90%	2,766	7,939	10,063
25–50%	2,662	6,314	7,861
10–25%	4,417	8,795	9,793
1–10%	12,289	13,448	13,240
Total	24,339	51,557	74,746

The total number of exposed propertied in the 10 most exposed estuary systems in NSW are shown in Figure 5.2.3 and Figure 5.2.4. These most exposed systems are:

1. Lake Macquarie
2. Georges River
3. Brisbane Water
4. Tuggerah Lake
5. Richmond River
6. Hunter River
7. Tweed River
8. Clarence River
9. Parramatta River
10. Port Stephens.

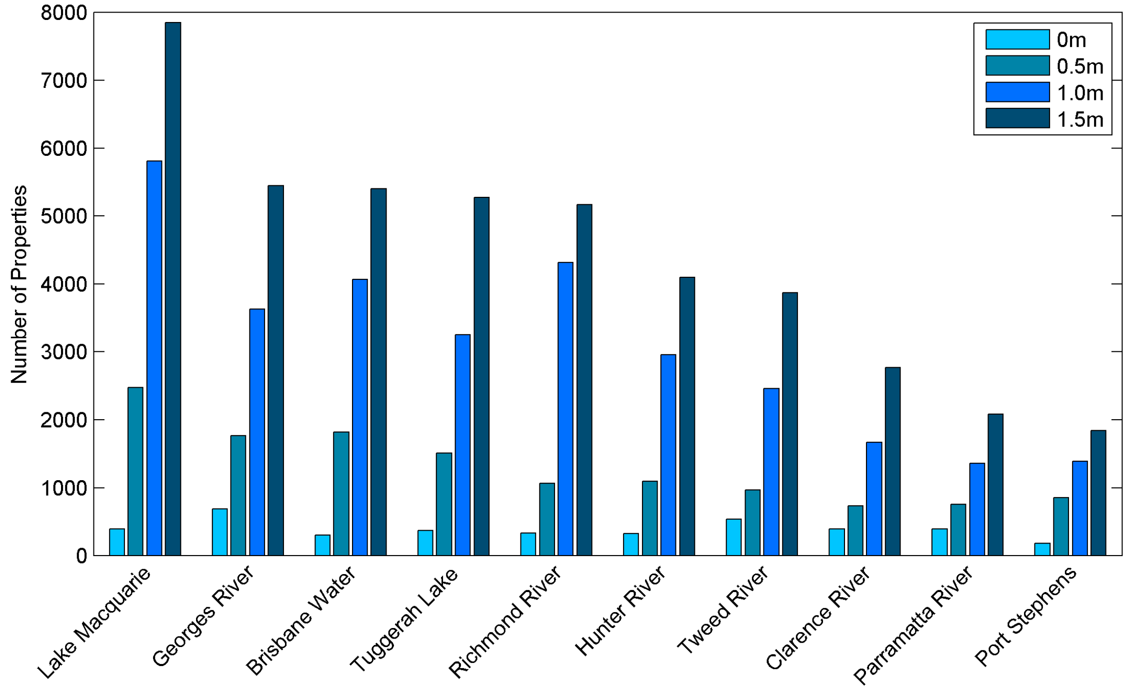


Figure 5.2.3. Total numbers of properties exposed to inundation (HHWSS) for the 10 most exposed NSW estuaries under 0, 0.5, 1.0 and 1.5 m SLR

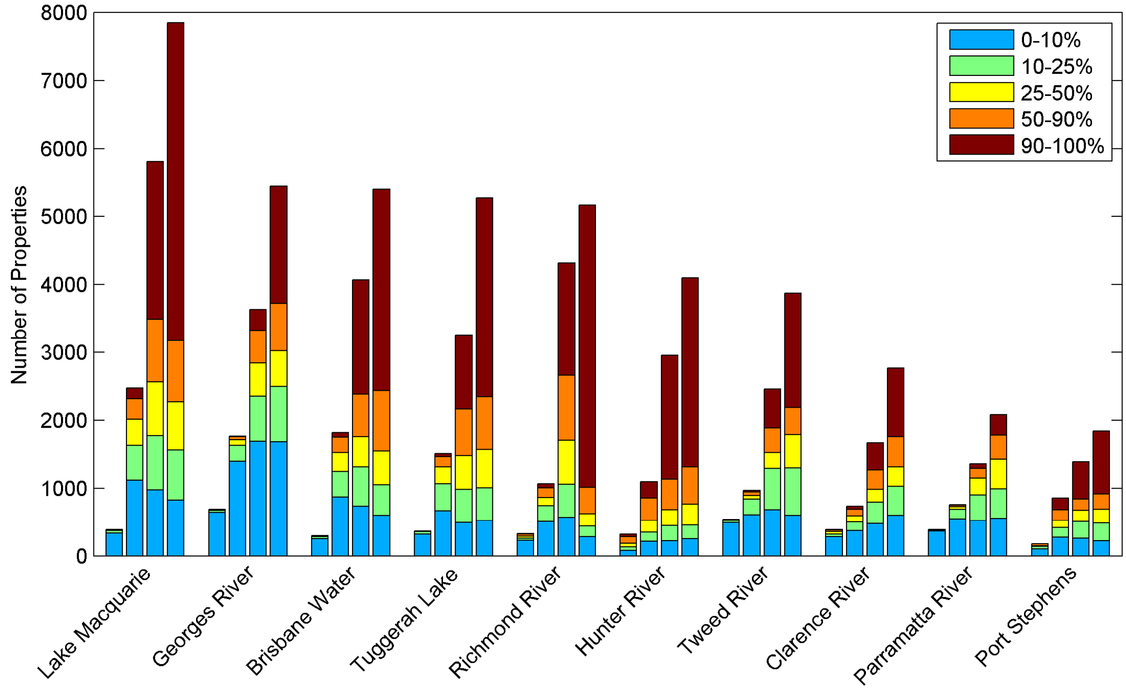


Figure 5.2.4. Total numbers of properties exposed to inundation (HHWSS) for the 10 most exposed NSW estuaries, including proportion-of-lot, under 0, 0.5, 1.0 and 1.5 m SLR

5.2.2 Infrastructure

The results of exposed infrastructure including roads (Figure 5.2.5), power lines (Figure 5.2.6) and rail and airports (Figure 5.2.7) show:

- 832 km of road is exposed to risk from inundation if sea level rises by 0.5 m, 2,128 km if sea level rises by 1 m and 3,458 km if sea level rises by 1.5 m.
- 1.5 km of railway is exposed to risk from inundation if sea level rises by 0.5 m, 9.5 km if sea level rises by 1 m and 25.5 km if sea level rises by 1.5 m.
- 849 km of power lines are exposed to risk from inundation if sea level rises by 0.5 m, 2,239 km if sea level rises by 1 m and 4,189 km if sea level rises by 1.5 m.
- 8 airfields are exposed to risk from inundation if sea level rises by 0.5 m, 11 if sea level rises by 1 m and 13 if sea level rises by 1.5 m.

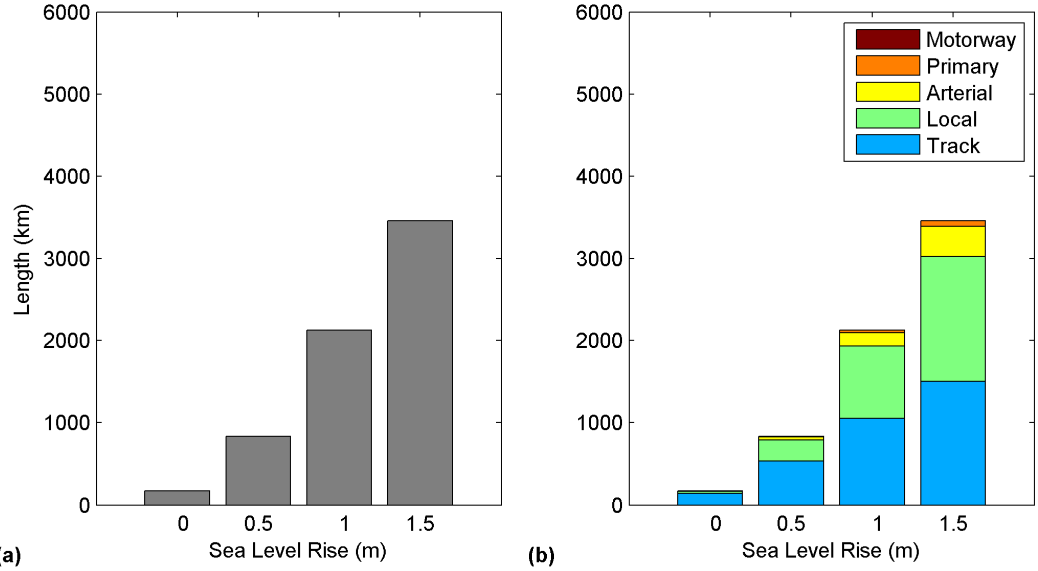


Figure 5.2.5. (a) Kilometres of roads exposed and (b) Kilometres of roads including breakdown of road type for all NSW estuaries under 0, 0.5, 1.0 and 1.5 m SLR

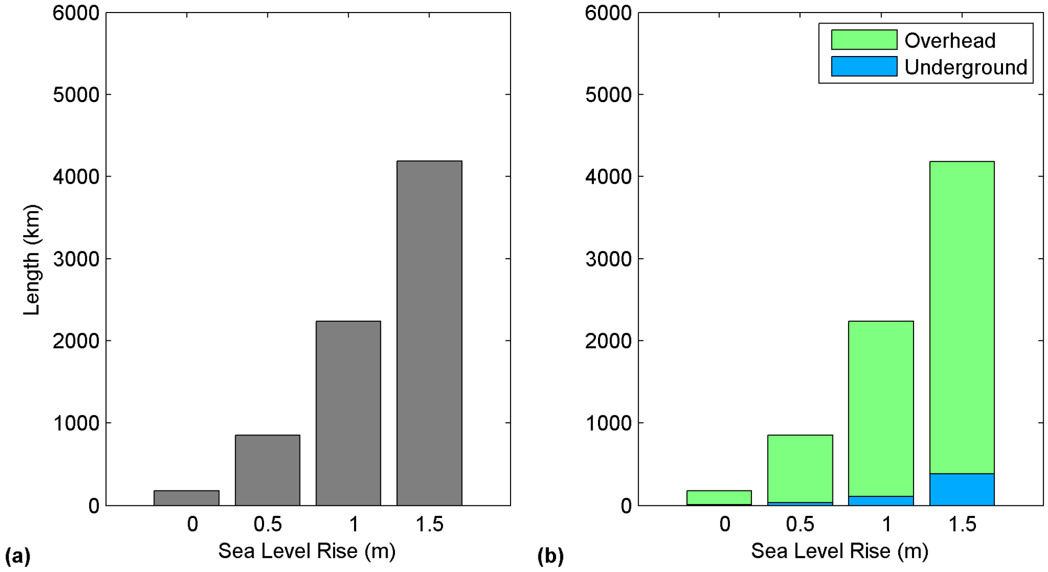


Figure 5.2.6. (a) Kilometres of power lines exposed and (b) Kilometres of power lines including breakdown of power line type for all NSW estuaries under 0, 0.5, 1.0 and 1.5 m SLR

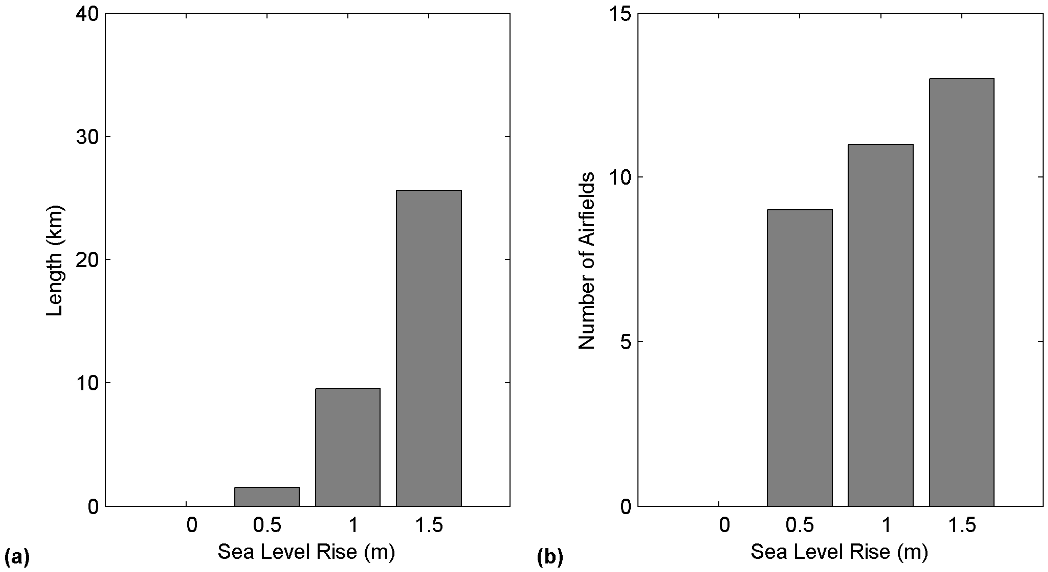


Figure 5.2.7. (a) Kilometres of railways exposed and (b) numbers of airfields exposed for all NSW estuaries under 0, 0.5, 1.0 and 1.5 m SLR

5.3 Regional exposure

In this section, we present results on a regional basis using the extents of the 2015 NSW Government planning regions, shown in Figure 5.3.1.

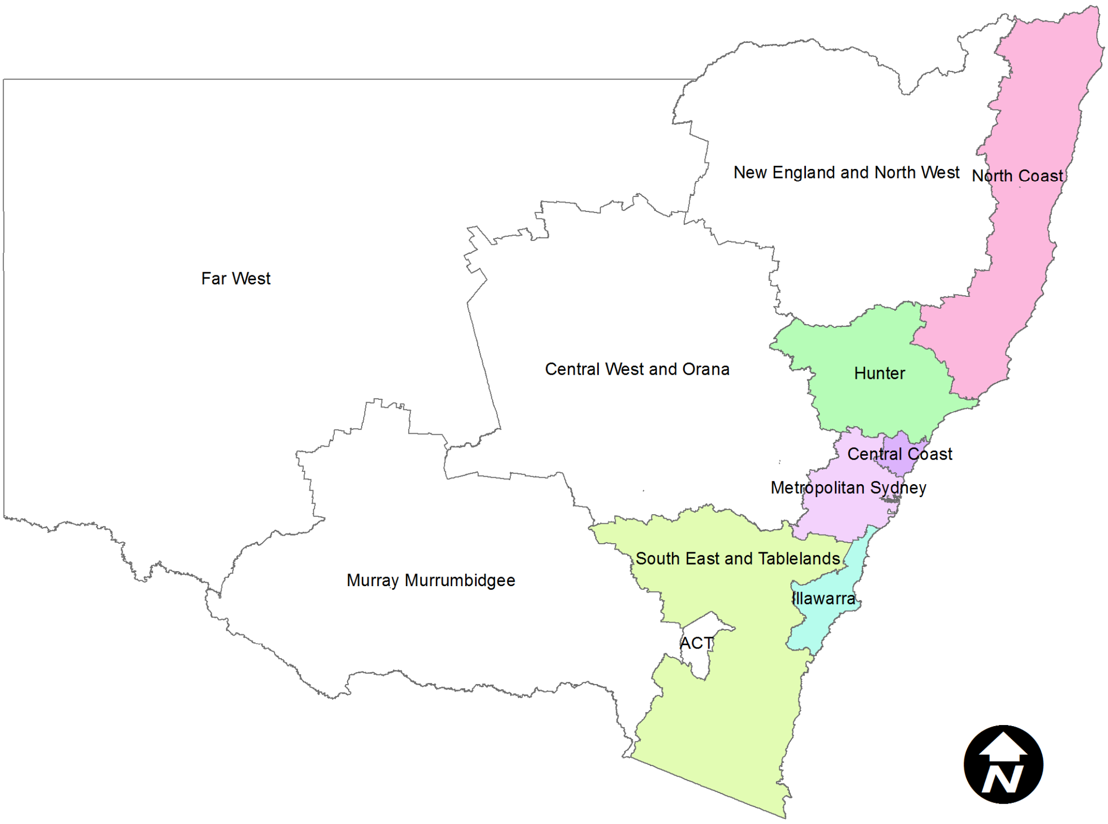


Figure 5.3.1. Map showing boundaries of NSW planning regions

Numbers of properties exposed for each region are presented in Figure 5.3.2 and Table 5.3.1. The greatest exposure occurs in the North Coast region, contributing to around 31.5% of the statewide exposure across all scenarios. Here exposure is associated with the extensive nature the region and the tidal rivers on the north coast. This is followed by the Metropolitan Sydney region with 22% of the statewide exposure, associated with the high levels of development within the Sydney region.

High levels of exposure are also found in the Hunter and Central Coast regions. They contribute 18% each to the statewide exposure across all scenarios. Here extensive development has occurred on the low-lying areas adjacent to the coastal lake systems. Reduced tidal range has allowed development to occur in relative proximity to the lake edge, increasing exposure to potential future SLR. Lowest exposure is found in the Illawarra and the South East and Tablelands regions with 7.5% and 3% of statewide exposure respectively. The south coast in particular is characterised by lower levels of development.

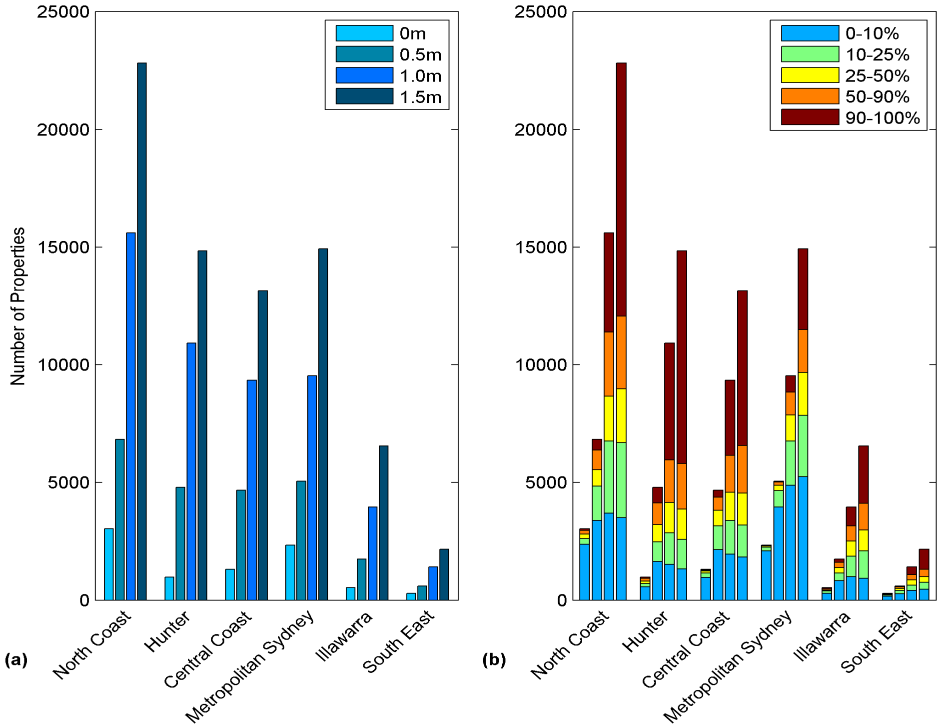


Figure 5.3.2. (a) Total numbers of properties exposed to inundation (HHWSS) for each region under 0, 0.5, 1.0 and 1.5 m SLR; (b) As for (a) but including percentage-of-lot inundated

Table 5.3.1. GURAS database and inundation modelling statistics of properties affected for each NSW planning region

Planning region	No. of properties by SLR scenario				Percentage of statewide exposure				Av. % exposure
	0 m	0.5 m	1.0 m	1.5 m	0 m	0.5 m	1.0 m	1.5 m	
North Coast	3,030	6,816	15,593	22,808	36	29	31	31	31.5
Hunter	996	4,791	10,906	14,839	12	20	21	20	18
Central Coast	1,318	4,656	9,339	13,124	16	20	18	18	18
Metropolitan Sydney	2,340	5,041	9,530	14,916	28	21	19	20	22
Illawarra	524	1,748	3,954	6,524	6	7	8	9	7.5
South East & Tablelands	288	601	1,422	2,168	3	3	3	3	3
All	8,496	23,653	50,744	74,379					

Allowing for storm surge and other non-tidal contributors to ocean water levels (≈100 year ARI), Figure 5.3.3 and Table 5.3.2 show numbers of properties exposed for each region. As for tidal inundation, greatest exposure occurs in the North Coast region. In this region 15,341 properties are exposed with 0.5 m SLR, and 22,239 with 1.0 m.

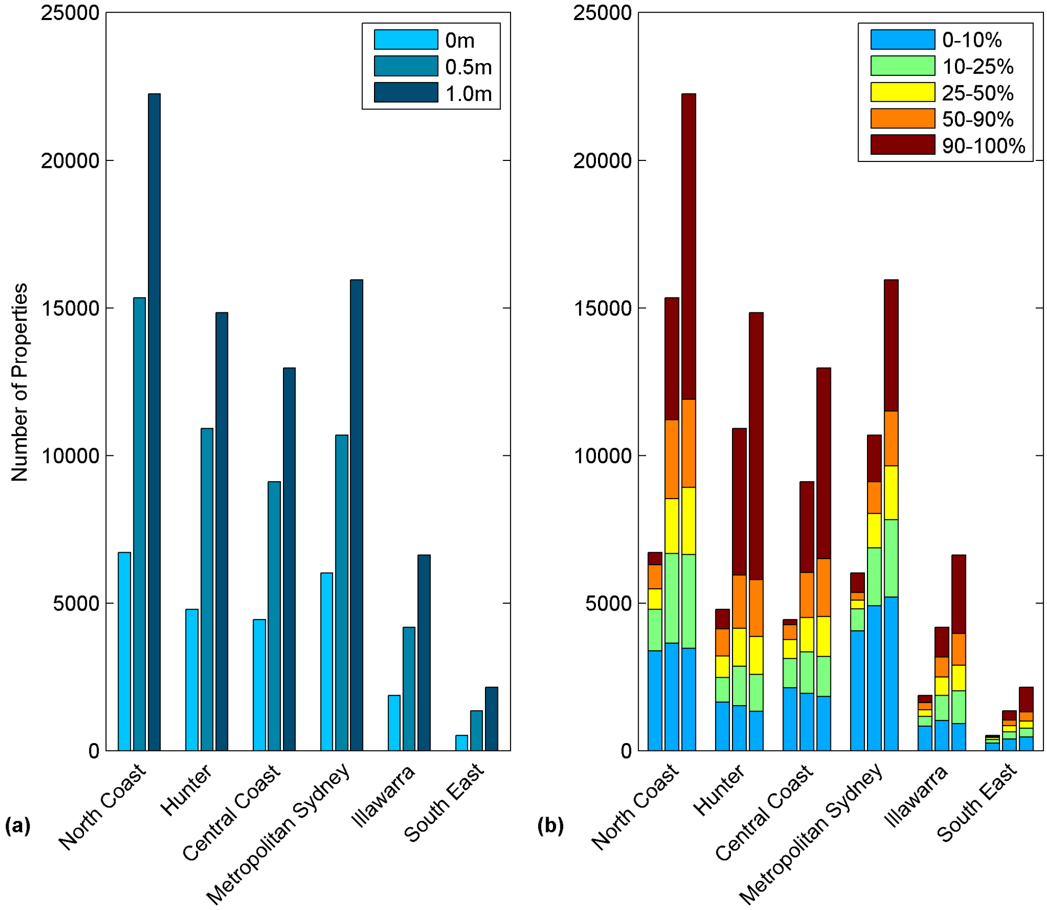


Figure 5.3.3. (a)Total numbers of properties exposed to inundation (100-year ARI water levels assuming HHWSS plus 0.5 m for DRV, LR, SR, TL and berm height for ICOLLs) for each region under 0, 0.5 and 1.0 m SLR; (b) As for (a) but including percentage-of-lot inundated

Table 5.3.2. GURAS database and inundation modelling statistics of properties affected (≈100 year ARI) for each NSW planning region

Planning region	No. of properties by SLR scenario			% of statewide exposure			Av. % exposure
	0 m	0.5 m	1.0 m	0 m	0.5 m	1.0 m	
North Coast	6,708	15,341	22,239	28	30	30	29
Hunter	4,791	10,906	14,839	20	21	20	20
Central Coast	4,433	9,105	12,946	18	18	17	18
Metropolitan Sydney	6,020	10,676	15,950	25	21	21	22
Illawarra	1,869	4,171	6,623	8	8	9	8
South East & Tablelands	518	1,358	2,149	2	3	3	3
All	24,339	51,557	74,746				

Results by planning region for roads, rail and power lines are presented in Figure 5.3.4, Figure 5.3.5 and Figure 5.3.6, and Table 5.3.3, Table 5.3.4 and Table 5.3.5, respectively. Greatest exposure occurs in the North Coast region for roads and power lines, with 461.94 km of road and 401.67 km of power lines exposed with 0.5 m SLR, 1,190.85 km of road and 897.74 km of power lines with 1.0 m, and 1,907.24 km of road and 1,905.41 km of power lines with 1.5 m. The Hunter region has the greatest exposure for rail, with 0.93 km of rail exposed with 0.5 m SLR, 6.57 km with 1.0 m, and 17.72 km with 1.5 m. High levels of exposure of roads and power lines are also found in the Hunter region. Lowest exposure is found in the Illawarra, and South East and Tablelands regions for roads, power lines and rail.

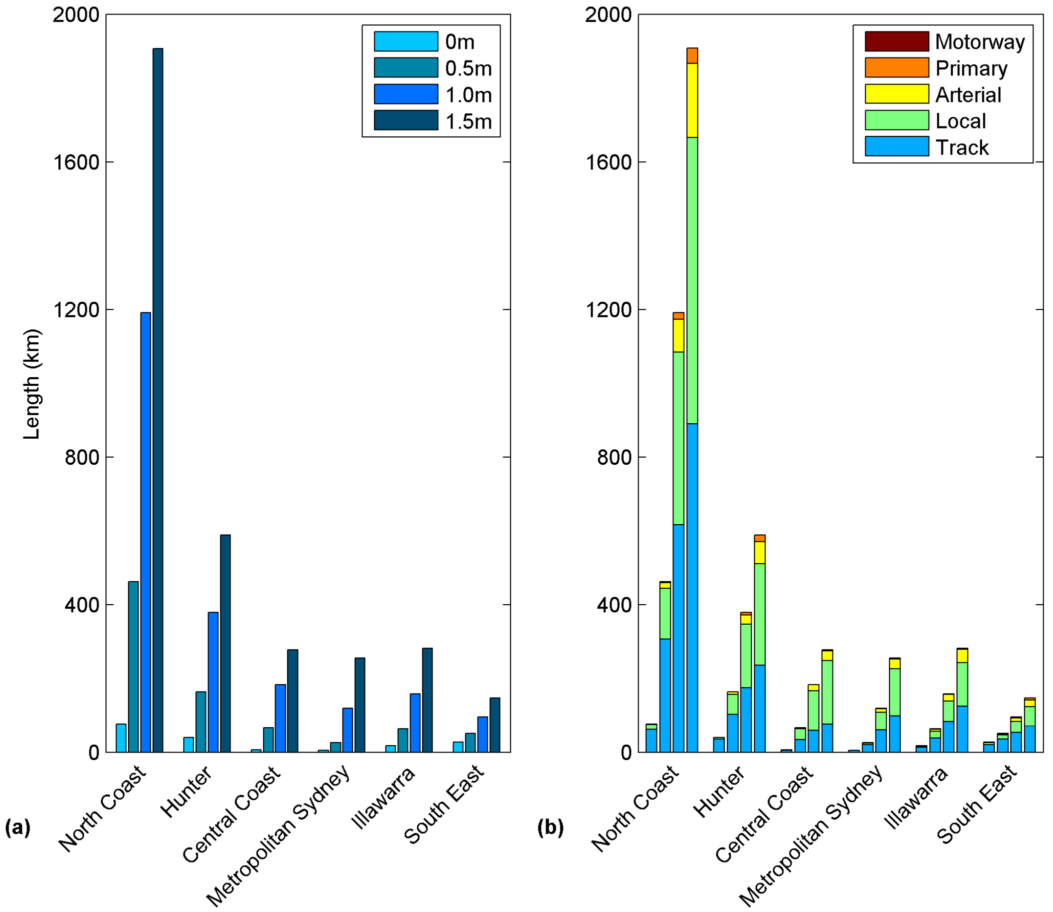


Figure 5.3.4. (a) Kilometres of roads exposed and (b) Kilometres of roads including breakdown of road type for each region, under 0, 0.5, 1.0 and 1.5 m SLR

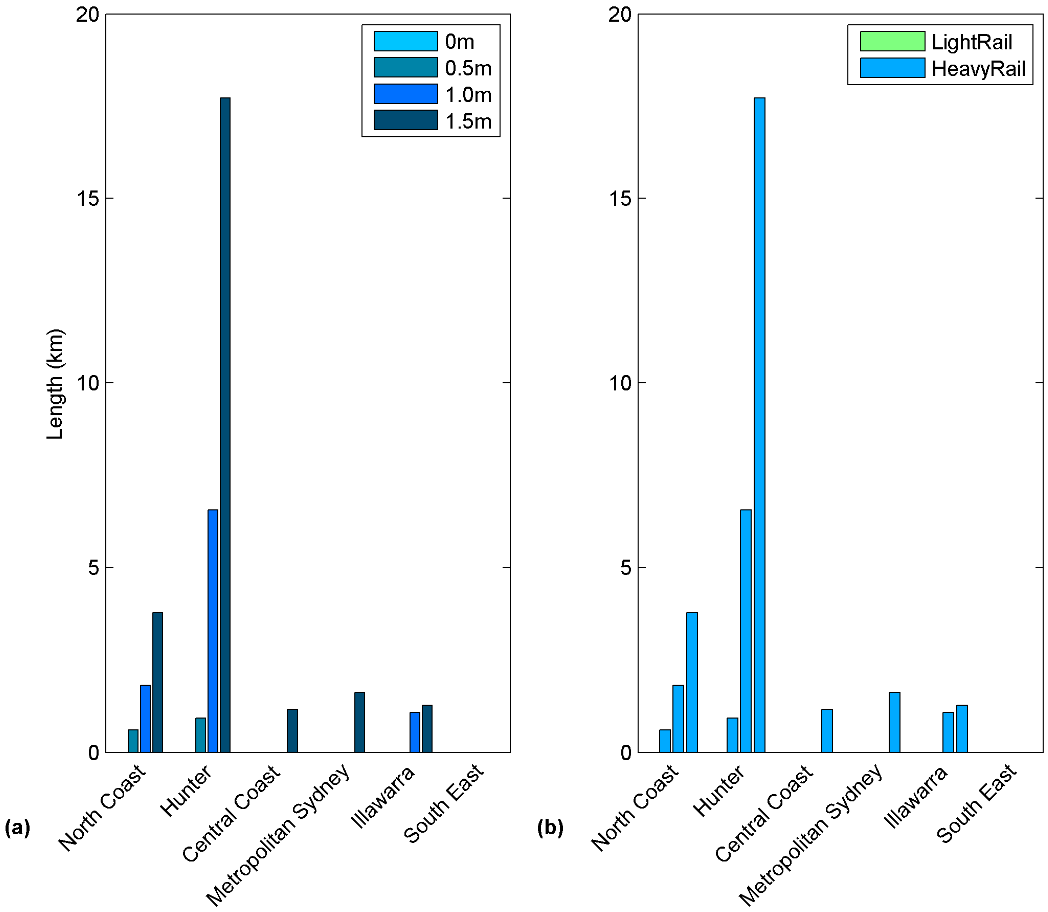


Figure 5.3.5. (a) Kilometres of railways exposed and (b) Kilometres of railways including breakdown of railway type for each region, under 0, 0.5, 1.0 and 1.5 m SLR

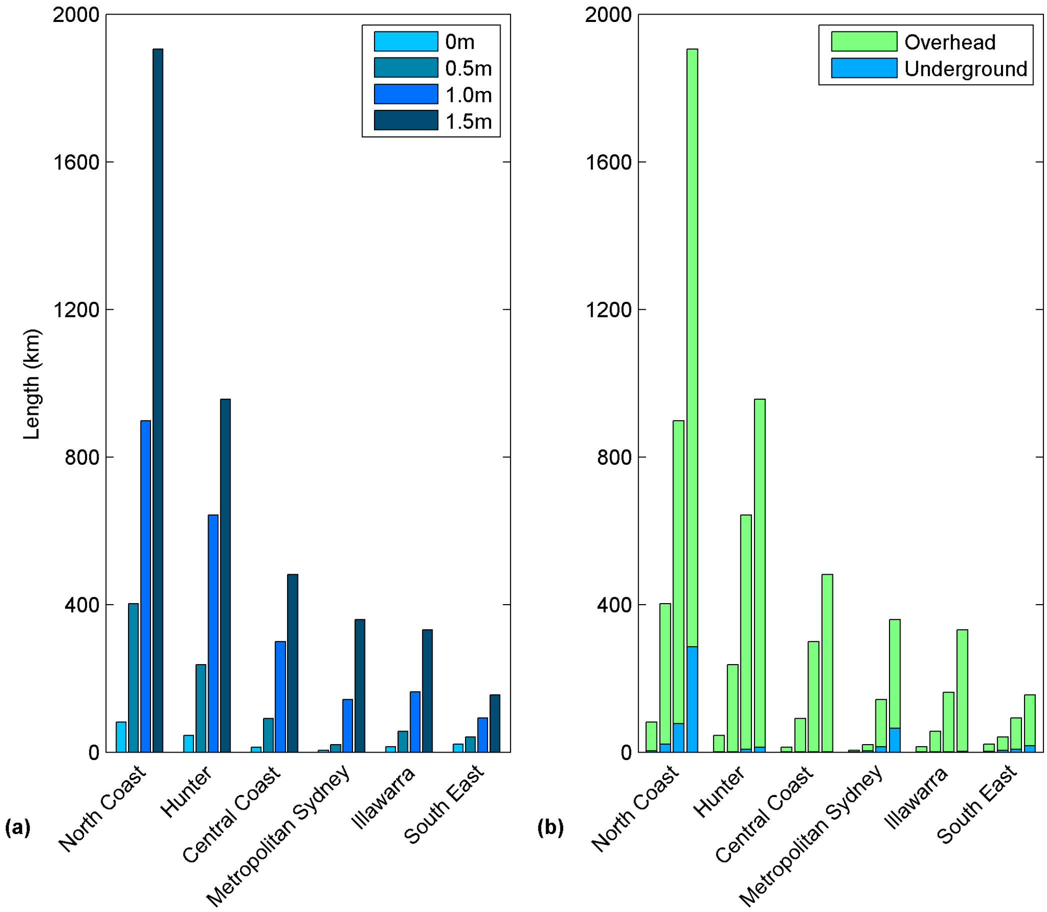


Figure 5.3.6. (a) Kilometres of power lines exposed and (b) Kilometres of power lines including breakdown of power line type for each region, under 0, 0.5, 1.0 and 1.5 m SLR

Table 5.3.3. GURAS database and inundation modelling statistics of roads affected for each NSW planning region

Planning region	Length of road (km) by SLR scenario			
	0 m	0.5 m	1.0 m	1.5 m
North Coast	76.63	461.94	1,190.85	1,907.24
Hunter	39.35	164.60	378.09	589.60
Central Coast	6.67	66.23	183.64	277.01
Metropolitan Sydney	4.79	25.62	119.26	255.06
Illawarra	17.10	62.97	158.89	281.59
South East & Tablelands	27.41	50.62	96.77	147.95
All	171.95	831.98	2,127.50	3,458.45

Table 5.3.4. GURAS database and inundation modelling statistics of railway affected for each NSW planning region

Planning region	Length of railway (km) by SLR scenario			
	0 m	0.5 m	1.0 m	1.5 m
North Coast	0	0.60	1.82	3.79
Hunter	0	0.93	6.57	17.72
Central Coast	0	0	0	1.17
Metropolitan Sydney	0	0	0	1.63
Illawarra	0	0	1.09	1.28
South East & Tablelands	0	0	0	0
All	0	1.53	9.48	25.59

Table 5.3.5. GURAS database and inundation modelling statistics of power lines affected for each NSW planning region

Planning region	Length of power lines (km) by SLR scenario			
	0 m	0.5 m	1.0 m	1.5 m
North Coast	82.01	401.67	897.74	1,905.41
Hunter	44.53	237.56	642.51	955.69
Central Coast	12.87	92.23	299.36	481.65
Metropolitan Sydney	4.34	19.98	142.99	359.46
Illawarra	14.48	55.85	163.33	331.88
South East & Tablelands	21.47	41.37	92.88	155.37
All	179.70	848.66	2,238.81	4,189.46

5.3.1 North Coast region

In the North Coast region 6,816 properties are exposed to tidal inundation (HHWSS) with 0.5 m of SLR, 15,593 with 1 m, and 22,808 with 1.5 m.

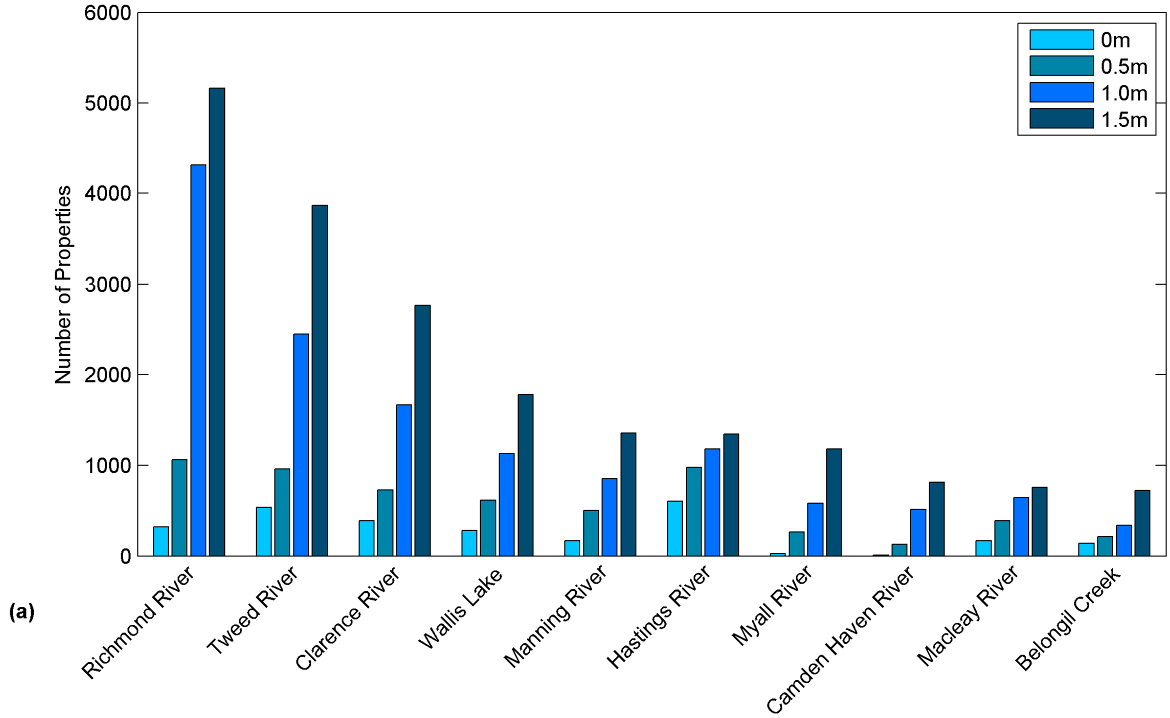
Numbers of properties subject to greater than 50% inundation are 1281 for 0.5 m of SLR, 6934 for 1 m of SLR, and 13,836 for 1.5 m of SLR.

Numbers of properties subject to greater than 90% inundation are 454 for 0.5 m of SLR, 4226 for 1 m of SLR, and 10,762 for 1.5 m of SLR.

Allowing for storm surge and other non-tidal contributors to ocean water levels (≈100 year ARI) 15,341 properties are exposed with 0.5 m SLR and 22,239 with 1.0 m.

The 10 most exposed estuary systems in the North Coast region are shown in Figure 5.3.7. The most exposed systems are:

1. Richmond River
2. Tweed River
3. Clarence River
4. Wallis Lake
5. Manning River
6. Hastings River
7. Myall River
8. Camden Haven River
9. Macleay River
10. Belongil Creek.



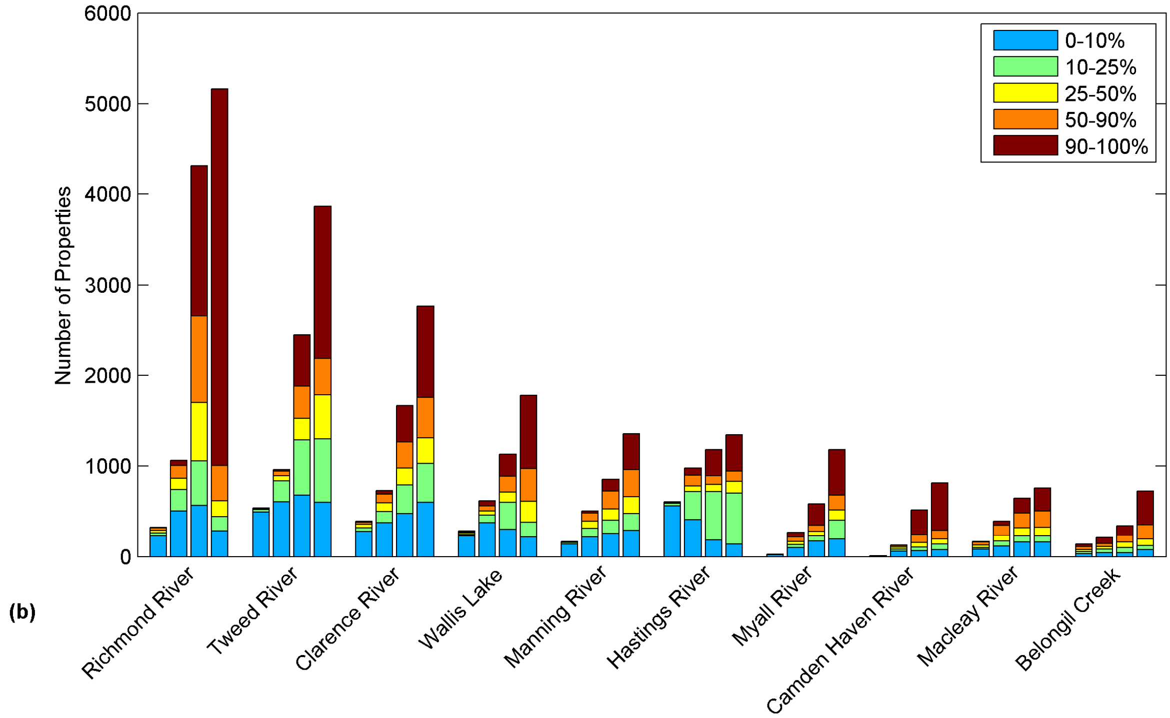


Figure 5.3.7. Total numbers of properties exposed to inundation (HHWSS) for the 10 most exposed estuaries in the North Coast region under 0, 0.5, 1.0 and 1.5 m SLR: (a) Number of properties affected; (b) Percentage of each property affected

5.3.2 Hunter region

In the Hunter region 4,791 properties are exposed to tidal inundation (HHWSS) with 0.5 m SLR, 10,906 with 1.0 m and 14,839 with 1.5 m.

Numbers of properties subject to greater than 50% inundation are 1590 for 0.5 m of SLR, 6754 for 1 m and 10,964 for 1.5 m.

Numbers of properties subject to greater than 90% inundation are 670 for 0.5 m of SLR, 4964 for 1 m, and 9,048 for 1.5 m.

Allowing for storm surge and other non-tidal contributors to ocean water levels (≈100 year ARI) 10,906 properties are exposed with 0.5 m SLR and 14,839 with 1.0 m.

The most exposed estuary systems in the Hunter region (noting that there are fewer than 10 systems) are shown in order in Figure 5.3.8. In order, the most exposed systems are:

1. Lake Macquarie
2. Hunter River
3. Port Stephens
4. Tilligerry Creek
5. Glenrock Lagoon
6. Middle Camp Creek
7. Moonee Beach Creek.

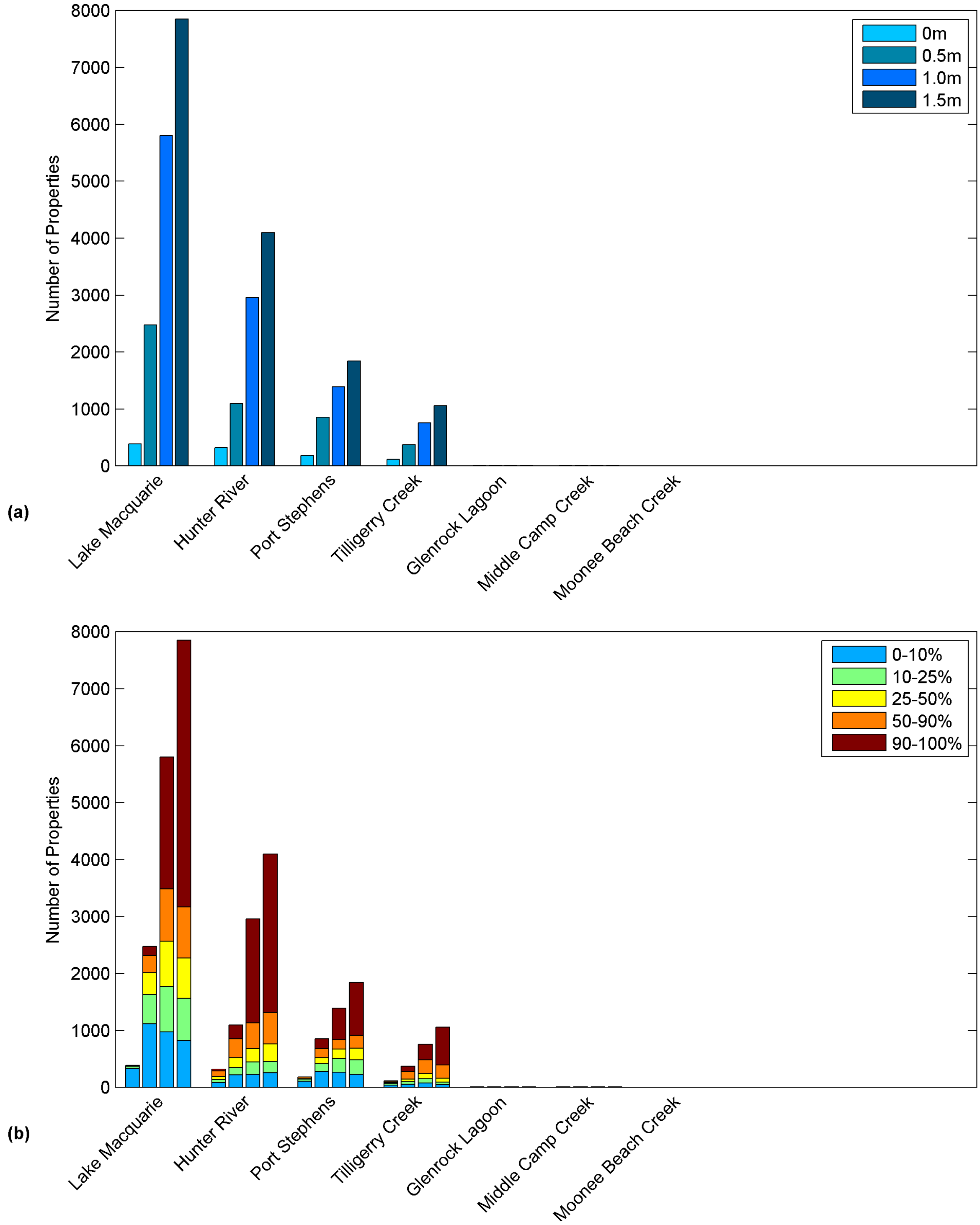


Figure 5.3.8. Total numbers of properties exposed to inundation (HHWSS) for the seven estuaries in the Hunter region under 0, 0.5, 1.0 and 1.5 m SLR: (a) Number of properties affected; (b) Percentage of each property affected

5.3.3 Central Coast region

In the Central Coast region 4,656 properties are exposed to tidal inundation (HHWSS) with 0.5 m SLR, 9,339 with 1.0 m and 13,124 with 1.5 m.

Numbers of properties subject to greater than 50% inundation are 844 for 0.5 m of SLR, 4764 for 1 m and 8575 for 1.5 m.

Numbers of properties subject to greater than 90% inundation are 286 for 0.5 m of SLR, 3203 for 1 m and 6581 for 1.5 m.

Allowing for storm surge and other non-tidal contributors to ocean water levels (≈100 year ARI) 9,105 properties are exposed with 0.5 m SLR and 12,946 with 1.0 m.

The most exposed estuary systems in the Central Coast region (noting that there are fewer than 10 systems) are shown in Figure 5.3.9. In order, the most exposed systems are:

1. Brisbane Water
2. Tuggerah Lake
3. Hawkesbury River
4. Terrigal Lagoon
5. Avoca Lake
6. Wamberal Lagoon
7. Broken Bay
8. Cockrone Lake.

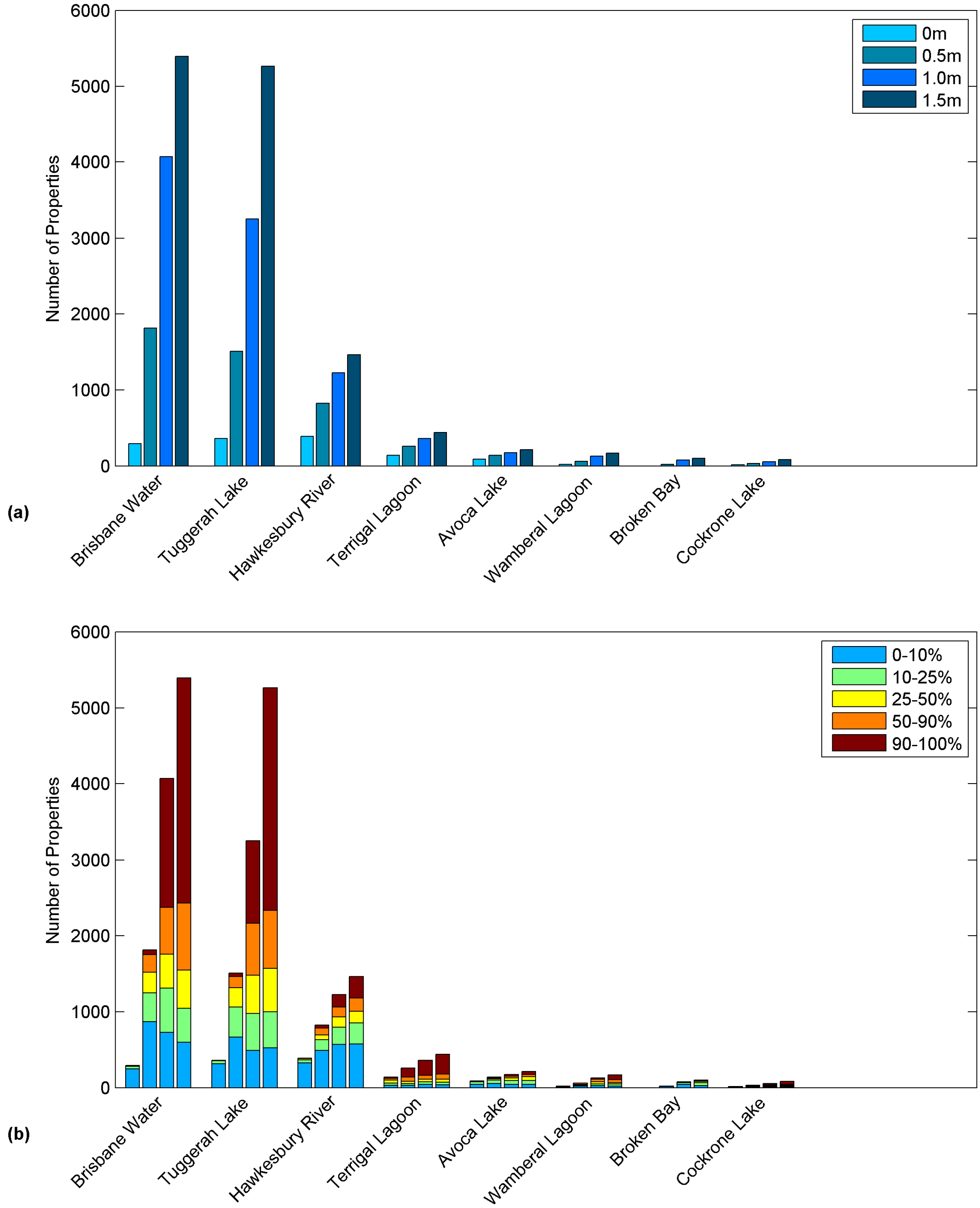


Figure 5.3.9. Total numbers of properties exposed to inundation (HHWSS) for the eight estuaries in the Central Coast region under 0, 0.5, 1.0 and 1.5 m SLR: (a) Number of properties affected; (b) Percentage of each property affected

5.3.4 Metropolitan Sydney region

In the Metropolitan Sydney region 5,041 properties are exposed to tidal inundation (HHWSS) with 0.5 m of SLR, 9,530 with 1 m, and 14,916 with 1.5 m.

Numbers of properties subject to greater than 50% inundation are 174 for 0.5 m of SLR, 1663 for 1m and 5251 for 1.5 m.

Numbers of properties subject to greater than 90% inundation are 34 for 0.5 m of SLR, 701 for 1 m, and 3445 for 1.5 m.

Allowing for storm surge and other non-tidal contributors to ocean water levels (≈100 year ARI) 10,676 properties are exposed with 0.5 m SLR and 15,950 with 1.0 m.

The 10 most exposed estuary systems in the Metropolitan Sydney region are shown in Figure 5.3.10. The most exposed systems are:

1. Georges River
2. Parramatta River
3. Port Hacking
4. Pittwater
5. Port Jackson
6. Cooks River
7. Botany Bay
8. Middle Harbour Creek
9. Lane Cove River
10. Narrabeen Lagoon.

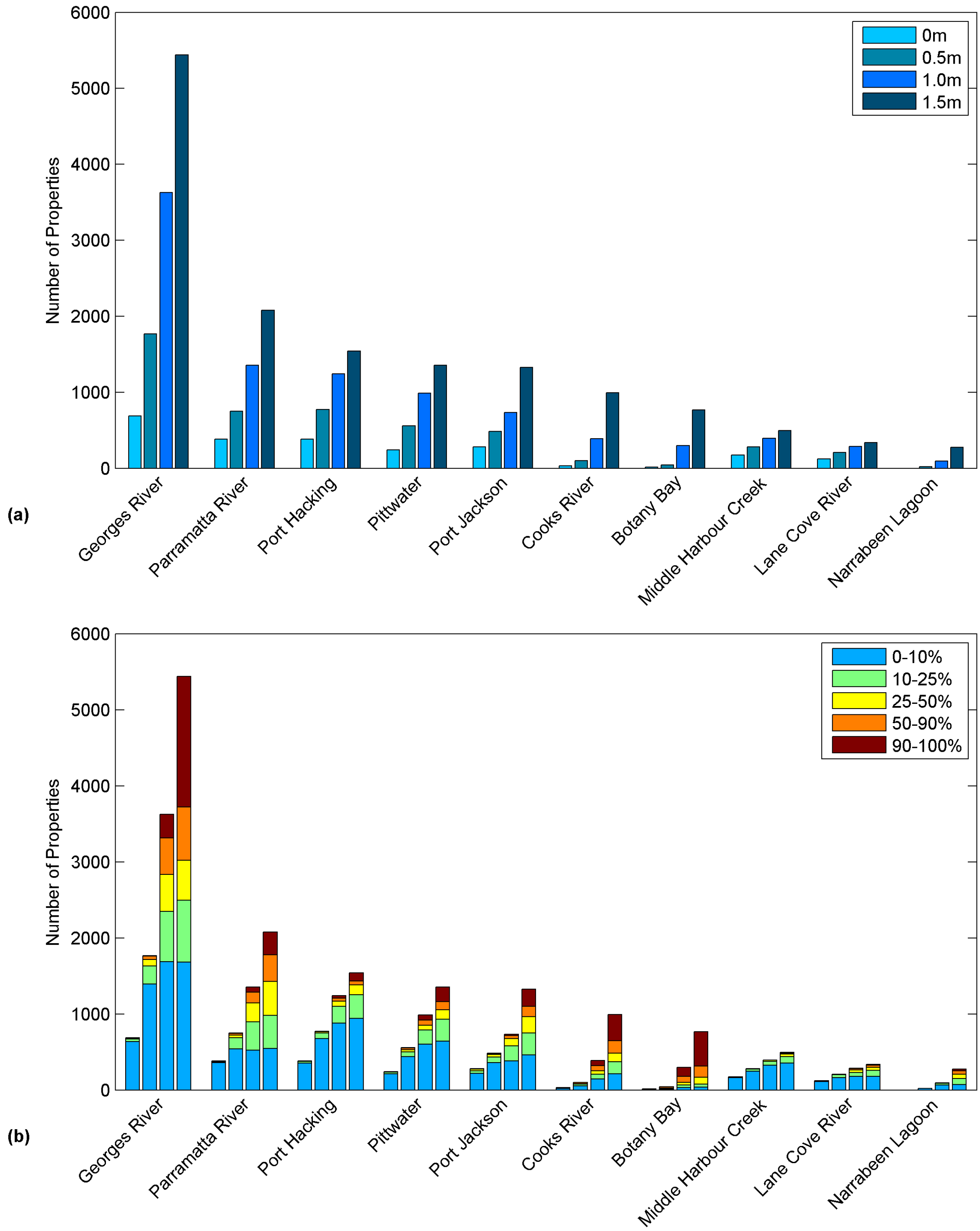


Figure 5.3.10. Total numbers of properties exposed to inundation (HHWSS) for the 10 most exposed estuaries in the Metropolitan Sydney region under 0, 0.5, 1.0 and 1.5 m SLR: (a) Number of properties affected; (b) Percentage of each property affected

5.3.5 Illawarra region

In the Illawarra region 1,748 properties are exposed to tidal inundation (HHWSS) with 0.5 m of SLR, 3,954 with 1 m, and 6,524 with 1.5 m.

Numbers of properties subject to greater than 50% inundation are 351 for 0.5 m of SLR, 1443 for 1 m and 3534 for 1.5 m.

Numbers of properties subject to greater than 90% inundation are 136 for 0.5 m of SLR, 795 for 1 m, and 2418 for 1.5 m.

Allowing for storm surge and other non-tidal contributors to ocean water levels (≈100 year ARI) 4,171 properties are exposed with 0.5 m SLR and 6,623 with 1.0 m.

The 10 most exposed estuary systems in the Illawarra region are shown in Figure 5.3.11. The most exposed systems are:

1. St Georges Basin
2. Lake Illawarra
3. Shoalhaven River
4. Burrill Lake
5. Fairy Creek
6. Elliot Lake
7. Towradgi Creek
8. Currambene Creek
9. Moona Moona Creek
10. Conjola Lake.

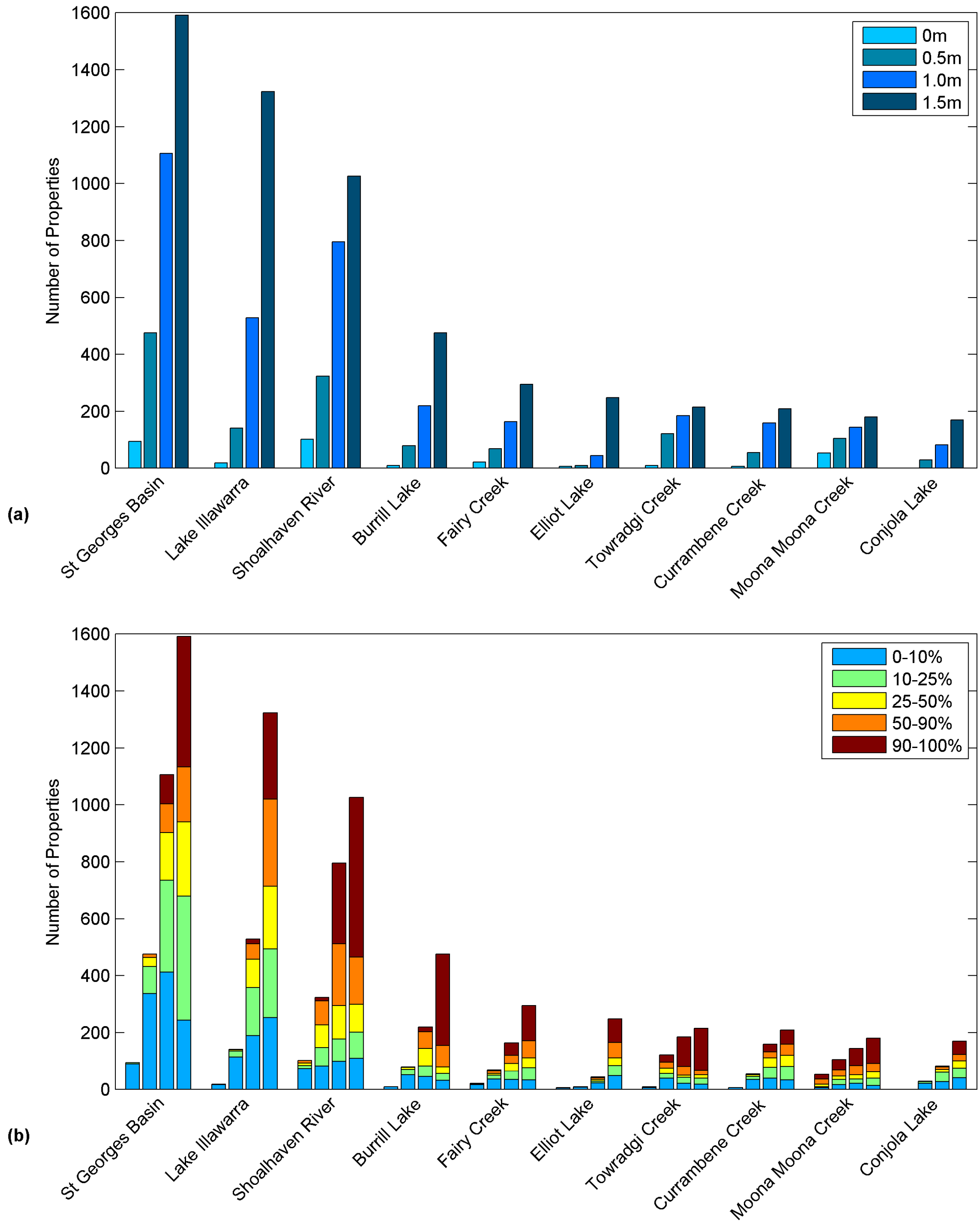


Figure 5.3.11. Total numbers of properties exposed to inundation (HHWSS) for the 10 most exposed estuaries in the Illawarra region under 0, 0.5, 1.0 and 1.5 m SLR: (a) Number of properties affected; (b) Percentage of each property affected

5.3.6 South East and Tablelands region

In the South East and Tablelands region 601 properties are exposed to tidal inundation (HHWSS) with 0.5 m of SLR, 1,422 with 1 m, and 2,168 with 1.5 m.

Numbers of properties subject to greater than 50% inundation are 103 for 0.5 m of SLR, 564 for 1 m and 1152 for 1.5 m.

Numbers of properties subject to greater than 90% inundation are 40 for 0.5 m of SLR, 330 for 1 m, and 850 for 1.5 m.

Allowing for storm surge and other non-tidal contributors to ocean water levels (≈100 year ARI) 1,358 properties are exposed with 0.5 m SLR and 2,149 with 1.0 m.

The 10 most exposed estuary systems in the South East and Tablelands region are shown in Figure 5.3.12. The most exposed systems are:

1. Batemans Bay
2. Clyde River
3. Wagonga Inlet
4. Moruya River
5. Merimbula Lake
6. Tomaga River
7. Lake Mummuga
8. Bermagui River
9. Durras Lake
10. Tuross River

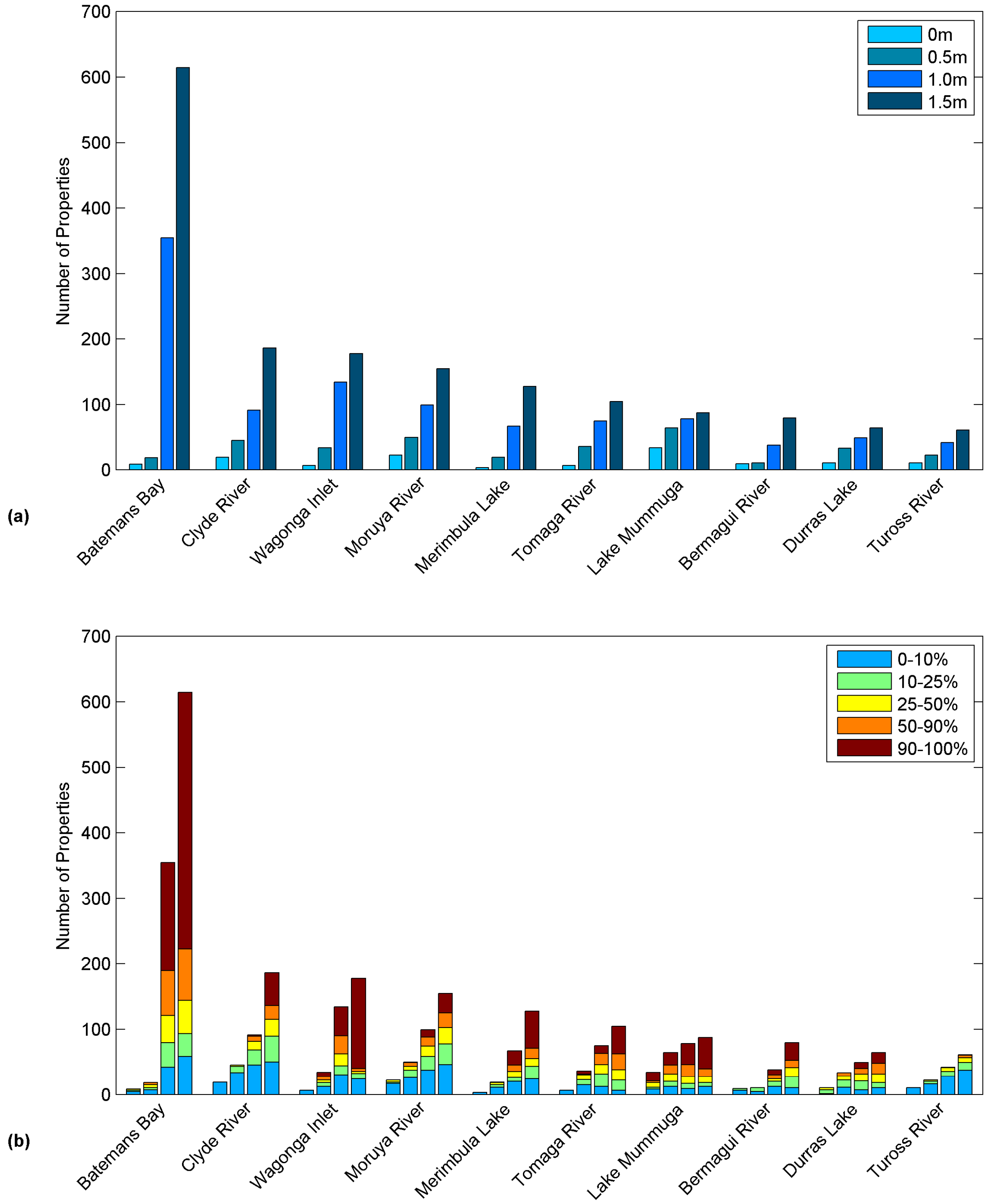


Figure 5.3.12. Total numbers of properties exposed to inundation (HHWSS) for the 10 most exposed estuaries in the South East and Tablelands region under 0, 0.5, 1.0 and 1.5 m SLR: (a) Number of properties affected; (b) Percentage of each property affected

6. Findings

6.1 Summary

Results show:

- 23,653 properties are exposed to risk from inundation if sea level rises by 0.5 m, 50,744 if sea level rises by 1 m and 74,379 if sea level rises by 1.5 m.
- Including non-tidal contributors to water levels 51,557 properties are exposed to ocean inundation (≈100 year ARI) if sea level rises by 0.5 m and 74,746 if sea level rises by 1 m.
- 783 km of road is exposed to risk from inundation if sea level rises by 0.5 m, 1,977 km if sea level rises by 1 m and 3,220 km if sea level rises by 1.5 m.
- 2 km of railway is exposed to risk from inundation if sea level rises by 0.5 m, 9 km if sea level rises by 1 m and 26 km if sea level rises by 1.5 m.
- 7 airfields are exposed to risk from inundation if sea level rises by 0.5 m, 10 if sea level rises by 1 m and 12 if sea level rises by 1.5 m.

On a proportion-of-lot basis the analysis shows many properties are only subject to minor inundation, although as sea levels increase, the proportion of properties subject to major or complete inundation increases. Numbers of properties subject to greater than 50% inundation are 4,186 for 0.5 m of SLR, 21,582 for 1 m of SLR and 42,950 for 1.5 m of SLR. Numbers of properties subject to greater than 90% inundation are 1,620 for 0.5 m of SLR, 13,456 for 1 m of SLR, and 33,104 for 1.5 m of SLR.

Allowing for storm surge and other non-tidal contributors to ocean water levels (≈100 year ARI) numbers of properties subject to greater than 50% inundation are 20,263 for 0.5 m of SLR and 40,607 for 1 m of SLR. Numbers of properties subject to greater than 90% inundation are 15,061 for 0.5 m of SLR and 33,789 for 1 m of SLR.

Greatest exposure occurs in the North Coast region, contributing to around 31.5% of the statewide exposure across all scenarios. Here exposure is associated with the extensive nature of the tidal rivers on the north coast. This is followed by the Metropolitan Sydney region with 22% of the statewide exposure, associated with the high levels of development within the Sydney region.

High levels of exposure are also found in the Hunter and Central Coast regions. They contribute 18% each to the statewide exposure across all scenarios. Here extensive development has occurred on the low-lying areas adjacent to the coastal lake systems. Reduced tidal range has allowed development to occur in relative proximity to the lake edge, increasing exposure to potential future SLR. Lowest exposure is found in the Illawarra, and the South East and Tablelands regions with 7.5% and 3% of statewide exposure respectively. The south coast in particular is characterised by lower levels of development.

6.2 Limitations

The assessment of exposure is underpinned by a number of assumptions and limitations related to available data. The approach adopted, while allowing for variation in water levels between and along individual estuaries, still remains a broadscale assessment. It does not replace the need to undertake flood or inundation studies for individual estuaries and results should not be used to assess risk to individual properties and assets.

The study focuses on risk to development, particularly surrounding estuary foreshores, largely because the open coast is characterised by headlands or beaches backed by relatively high dunes, and inundation has not historically been a major concern except at isolated locations. Wave setup and runup play a significant role in inundation on the open coast, requiring detailed modelling which was beyond the scope of the current study.

The study adopts the HHWSS tidal plane for water surface mapping. This tidal plane is slightly lower (~13 cm) than highest astronomical tide (HAT), thus does not represent the full extent of tidal inundation. Additionally, this tidal plane does not include non-tidal processes including storm surge and other processes that contribute to observed water levels. At ocean tide gauges 100-year ARI levels are approximately 0.5 m higher than HHWSS, thus the 0.5 m offset is used as a first order approximation for inundation at the 100-year ARI level.

Within individual estuary systems we used existing gauge data and fitted a tidal plane using a minimum curvature spline fitting technique. In many systems, available gauge data is quite limited, thus the modelled water surface may be approximate only.

For non-gauged estuaries, we used the existing gauge data to derive an average tidal plane for each estuary type, which was then applied to estuaries with no available data. Considerable variability in tidal planes is seen for each type which is probably associated with differences in estuary geometry. Estimated accuracies of average tidal planes for each estuary type are: Drowned River Valleys ±0.06 m, Large Rivers ±0.11 m, Small Rivers ±0.15 m, Tidal Lakes ±0.10 m.

The approximations used to derive the tidal planes are known to be subject to limitations. In the open ocean, the Foreman method of tidal planes analysis using these four main constituents is thought to be accurate to 10% of the tidal range (DOD 2001, MHL 2005). As tides propagate into estuaries the importance of higher order tidal constituents increases.

MHL (2005) investigate the accuracy of the tidal plane approximations using a variety of methods. Comparison between the statistical method of calculation and the tidal plane approximation shows differences of around 0.1 m in the estimation of mean high water springs. Underestimation was observed at the drowned river valley site (Windsor) and the coastal lake site (Marmong Point), and overestimation at the river site (Billinudgel).

Within tidal lakes, tidal signals show amplification of the fortnightly and longer period tides (MHL 2005, 2009). In these systems, the constricted nature of the entrance channels contributes to spring–neap pumping that results in the amplification of the fortnightly constituent. Thus, in tidal lakes the tidal planes are likely to underestimate the tidal highs and lows. To address this, we add 0.2 m to the lake level based on exceedence statistics from MHL (2014).

The use of tidal planes as the basis for the mapping means non-astronomic contributors to water levels are not included. As many other factors contribute to observed water levels the tidal planes do not represent the full potential extent of inundation. Comparison between 100-year ARI levels and the HHWSS plane indicates the 0.5 m sea level may also be indicative of a first order allowance for 100 year ARI non-tidal water level variations (excluding effects of wave setup and runup, wind waves and coincident rainfall-related flooding). This assumes uniform penetration of non-tidal contributors into the estuary.

We consider three scenarios: SLRs of 0.5 m, 1 m and 1.5 m. These are selected to be representative of a range of scenarios relevant to structure design as well as land-use planning. They are not tied to a particular planning horizon and importantly should not be considered an upper bound for potential long-term SLR, which may need to be considered for future development. Long-term SLR for many centuries is likely, irrespective of strategies to reduce greenhouse gas emissions, and consideration of ongoing SLR should be a key issue when considering future use of the coastal zone.

SLRs are added to the existing tidal planes and thus assume no change in tidal range or form. SLR may result in greater water depth in entrance channels (depending on marine delta response) and thus may increase entrance efficiency thereby increasing tide range.

This effect would likely be most significant in coastal lakes where tidal attenuation is greatest. In these systems, increasing tide range may potentially add to the effects of SLR.

For each SLR scenario we overlay tidal planes on existing terrain, except within ICOLLs where we increase the berm height. In reality, many changes in geomorphology are likely. These include changes to entrance configuration, marine delta sedimentation, foreshore erosion and accretion, and wetland accretion (e.g. Rogers et al. 2012; Fitzgerald et al. 2008).

The assumption that berm height will increase follows Hanslow et al. (2000) and Dean and Maurmeyer (1983). Berms are a wave built feature. Their height is related to the wave runup which is dependent on water level, wave height and period and beach slope. As local wave parameters are generally unavailable we use a relationship for berm height based on grain size from Hanslow et al. (2000).

Properties exposed to inundation under the various SLR scenarios are quantified using data from the Geocoded Urban and Rural Addressing System (GURAS). Although this regional-scale exposure assessment is a significant improvement on previous analyses, it remains subject to the limitations of the datasets and approach, as follows:

- Ground floor secondary addresses (e.g. units, apartments, suites) were not considered in the exposure statistics.
- Proportion-of-lot inundation does not account for the location of assets within a cadastral lot (e.g. minimal-level (<10%) inundation may still impact assets).
- The assessment does not consider the depth of inundation in distinguishing different levels of exposure.
- It does not consider vulnerability attributes that may enhance or moderate the potential impacts of coastal inundation (e.g. elevated floors, protective works).
- A minimal number of unmarked public addresses may remain in the exposure statistics.

6.3 Recommendations

This assessment shows a considerable amount of development along the NSW coast is at risk from SLR. Areas at greatest risk include the Hunter and Central Coast regions, followed by the North East and Greater Sydney regions.

The assessment highlights the importance of, and need for, coastal zone and floodplain management planning to manage risk to current development and to avoid unnecessary expansion of risk in the future.

In relation to coastal risk management we recommend:

- review of existing coastal zone and/or floodplain management plans and their adequacy for managing risks associated with SLR
- preparation or update of coastal zone and/or floodplain management plans as required to manage current and potential future risk
- implementation of these plans to reduce current and potential future exposure to SLR
- management using risk management principles which consider likelihood (and uncertainty) of hazard with a focus on solutions that are flexible and robust
- adoption of strategies that address the ongoing nature of SLR (beyond 2100) including measures to avoid the expansion of development in areas likely to be subject to future inundation or alternatively, the adoption of measures that recognise the temporary nature of such areas (temporary occupancy)
- education concerning SLR and coastal processes and hazards

- mapping and assessment of actual (built) and planned/potential (land-use zoning) risk exposure at regular intervals (5–10 years) for a prescribed set of sea level scenarios.

In relation to improvement of risk assessment techniques we recommend:

- further research on open coast hazards including wave runup on beaches and coastal erosion
- further research on potential morphodynamic changes to coastal systems associated with SLR. This should include effects of potential changes to entrance configuration and marine delta sedimentation on tidal processes in different estuary types, as well as foreshore erosion/accretion and wetland response
- further research on impacts of SLR on catchment-related flooding and the possibility of changes to extreme rainfall with climate change.

7. References

AHO, 2011, *Australian National Tide Tables 2012*, Australian Hydrographic Publication 11, Australian Government Department of Defence, Australian Hydrographic Service.

BOM and CSIRO 2015, *State of the Climate 2014*, Bureau of Meteorology and CSIRO, www.bom.gov.au/state-of-the-climate/

Blain, Bremner and Williams Pty Ltd 1985, *Elevated Ocean Levels – storms affecting the NSW coast 1880–1980*, PWD report number 85041, Blain, Bremner and Williams Pty Ltd, Brisbane.

Cechet, RP, Hazelwood, MC, Anderson, H, Dunford, M, Power, L, Jones, T and Nadimpalli, K, 2012, *Impacts of climate change on human settlements and other nationally significant infrastructure*, National Coastal Vulnerability Assessment, Geoscience Australia, Canberra.

Cechet, B, Taylor, P, Griffin, C and Hazelwood, M, 2011, 'Australia's coastline: adapting to climate change: Assessing infrastructure vulnerability to rising sea-levels', *AusGeo News*, March 2011, issue no. 101.

Chapman, DM, Geary, M, Roy, PS and Thom, BG 1982, *Coastal Evolution and Coastal Erosion in New South Wales*, Coastal Council of NSW, Sydney, 341pp.

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

Church, JA, White, NJ, Clarke, AJ, Freeland, HJ and Smith, RL 1986a, 'Coastal trapped waves on the east Australian continental shelf, Part 1: Propagation of modes', *Journal of Physical Oceanography*, vol.16(11), pp.1929–1943.

Church, JA, Freeland, HJ and Smith, RL 1986b, 'Coastal- trapped waves on the east Australian continental shelf, Part 2: Model verification', *Journal of Physical Oceanography*, vol.16(11), pp.1945–1957.

Church, J and White, N 2011, 'Sea-level rise from the late 19th to the early 21st century', *Surveys in Geophysics*, vol.32(4–5), pp.585–602, DOI 10.1007/s10712-011-9119-1.

Church, JA, White, NJ, Hunter, JR and McInnes, KL 2012, 'Sea level', in ES Poloczanska, AJ Hobday and AJ Richardson (eds), *A Marine Climate Change Impacts and Adaptation Report Card for Australia 2012*, www.oceanclimatechange.org.au, ISBN: 978-0-643-10928-5.

Church, JA, Clark, PU, Cazenave, A, Gregory, JM, Jevrejeva, S, Levermann, A, Merrifield, MA, Milne, GA, Nerem, RS, Nunn, PD, Payne, AJ, Pfeffer, WT, Stammer, D and Unnikrishnan, AS 2013, 'Sea Level Change', in TF Stocker, D Qin, G-K Plattner, M Tignor, SK Allen, J Boschung, A Nauels, Y Xia, V Bex and PM Midgley (eds), *Climate Change 2013: The Physical Science Basis*, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, USA, pp.1137–1216, doi:10.1017/ CBO9781107415324.026.

CSIRO and Bureau of Meteorology 2015, *Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report*, CSIRO and Bureau of Meteorology, Canberra.

DCC 2009, *Climate Change Risks to Australia's Coast: A first pass national assessment*, Australian Government Department of Climate Change, Canberra, November 2009.

DCCEE 2011, *Climate Change Risks to Coastal Buildings and Infrastructure A Supplement to the First Pass National Assessment*, Australian Government Department of Climate Change and Energy Efficiency, Canberra.

Dean, RG and Maurmeyer, EM 1983, 'Models for Beach Profile Response', in PD Komar (ed.) *CRC Handbook of Coastal Processes and Erosion*, CRC Press, Boca Raton, pp.151–165.

Deng, X, Griffin, DA, Ridgway, K, Church, JA, Featherstone, WE, White, N and Cahill, M 2010, 'Satellite altimetry for geodetic, oceanographic and climate studies in the Australian region', in S Vignudelli, AG Kostianoy, P Cipollini and J Benveniste (eds), *Coastal Altimetry*, Springer-Verlag, Berlin, Heidelberg, doi: 10.1007/978-3-642-12796-0_18.

DOD 2001, *Australian National Tide Tables 2001*, Australian Hydrographic Publication 11, Department of Defence, Canberra.

Druery, BM, Dyson, AR and Greentree, GS 1983, 'Fundamentals of Tidal Propagation in Estuaries', *Proceedings of 6th Australian Conference on Coastal and Ocean Engineering, Gold Coast, Australia*.

Dyer, KR 1997, *Estuaries: a physical introduction*, Wiley and Sons, Aberdeen, UK.

Egbert, GD, Bennett, AF and Foreman, MGG 1994, 'TOPEX/POSEIDON tides estimated using a global inverse model', *Journal of Geophysical Research*, vol.99(C12), pp.24 821–24, 852.

ESRI 2013, *ArcGIS Desktop: Release 10.1*, Environmental Systems Research Institute, Redlands, CA, USA.

ESRI, 2014, *ESRI ArcGIS Support Website*, Environmental Systems Research Institute, Redlands, CA, USA, retrieved from http://support.esri.com/en/.

Fitzgerald, DM, Fenster, MS, Argow, BA and Buynevich, IV 2008, 'Coastal Impacts Due to Sea-Level Rise', *Annual Review of Earth and Planetary Sciences*, vol.36, pp.601–647.

Foreman, MGG 1977, *Manual for Tidal Heights Analysis and Prediction*, Pacific Marine Science Report 77-10, (2004 revision), Institute of Ocean Sciences, Patricia Bay, Sidney, BC, 58pp.

Foulsham, E, Morris, B and Hanslow, D 2012, 'Considering tidal modification when mapping inundation hazard in NSW estuaries', *Proceedings of the 21st NSW Coastal Conference, Kiama, Australia*.

Godin, G 1972, *The Analysis of Tides*, University of Toronto Press, Toronto, 264pp.

Haines, PE 2006, 'Physical and chemical behaviour and management of Intermittently Closed and Open Lakes and Lagoons (ICOLLs) in NSW', PhD thesis, Griffith University, Gold Coast, QLD, 505pp.

Haines, P, Tomlinson, R and Thom, B 2006, 'Morphometric assessment or intermittently open/closed coastal lagoons in New South Wales, Australia', *Estuarine, Coastal and Shelf Science*, vol.67, pp.321–332.

Hanslow, DJ and Nielsen, P 1992, 'Wave setup on beaches and in river entrances', *International Conference on Coastal Engineering*, pp.240–252.

Hanslow, DJ, Nielsen, P and Hibbert, K 1996, 'Wave Setup at River Entrances', *Proceedings of the 25th International Conference on Coastal Engineering*, pp.241–252.

Hanslow, DJ, Davis, GA, You, BZ and Zastawny, J 2000, 'Berm height at lagoon entrances in NSW', *Proceedings of 10th NSW Coastal Conference, Yamba, Australia*.

Hemer, MA, McInnes, KL and Ranasinghe, R 2012, 'Projections of climate change driven variations in the offshore wave climate off south eastern Australia', *International Journal of Climatology*, vol.33, pp.1615–1632.

Hill, KL, Rintoul, SR, Coleman, R and Ridgway, KR 2008, ‘Wind-forced low frequency variability of the East Australian Current’, *Geophysical Research Letters*, vol.35, L08602, doi:10.1029/2007GL032912.

Hill, KL, Rintoul, SR, Ridgway, KR and Oke, PR 2011, ‘Decadal changes in the South Pacific western boundary current system revealed in observations and ocean state estimates’, *Journal of Geophysical Research*, vol.16, C01009. doi:10.1029/2009JC005926.

Holbrook, N, Goodwin, ID, McGregor, S, Molina, E and Power, SB 2010, ‘ENSO to multidecadal timescale changes in East Australian Current transports and Fort Denison sea level: Oceanic Rossby waves as the connecting mechanism’, *Deep-Sea Research II*, vol.58(5), (2011), pp.547–558.

Imbrie, J, Hays, JD and Martinson, DG 1984, ‘The orbital theory of Pleistocene climate: support from a revised chronology of the marine 180 record’, in AL Berger, J Imbrie, J Hays, G Kukla and B Saltzman (eds), *Milankovitch and Climate: Understanding the Response to Astronomical Forcing*, Reidel, Dordrecht, pp.269–305.

IPCC 2013, ‘Summary for Policymakers’, in TF Stocker, D Qin, G-K Plattner, M Tignor, SK Allen, J Boschung, A Nauels, Y Xia, V Bex and PM Midgley (eds), *Climate Change 2013: The Physical Science Basis*, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, USA, pp.1–30, doi:10.1017/CBO9781107415324.004.

Joughin, I, Smith, BE and Medley, B 2014, ‘Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica’, *Science*, vol.344 (6185), pp.735–738.

Lewis, SE, Sloss, CR, Murray-Wallace, CV, Woodroffe, CD and Smithers, SG 2012, ‘Post-glacial sea-level changes around the Australian margin: a review’, *Quaternary Science Reviews*, vol.74, pp.115–138, http://dx.doi.org/10.1016/j.quascirev.2012.09.006.

Lowe, JJ and Walker, MJC 1984, *Reconstructing Quaternary Environments*, 2nd Edition, Longman, London, 446pp.

LPI 2012, *LPI Mapping and Spatial Services*, NSW Land & Property Information, Sydney.

LPI 2014, *LPI NSW Spatial Data Catalogue: NSW Addressing*, NSW Land & Property Information, Sydney, sdi.nsw.gov.au/sdi.nsw.gov.au/catalog/search/resource/details.page?uuid=%7B2530F1AF-C19C-41AF-BC5D-BC4A183A290C%7D

McDowell, DM and O’Connor, BA 1977, *Hydraulic behaviour of estuaries*, MacMillan Press, London, UK.

McInnes, KL, Abbs, AJ, O’Farrell, SP, Macadam, I, O’Grady, J and Ranasinghe, R 2007, *Projected Changes in Climatological Forcing for Coastal Erosion in NSW*, a project undertaken for the NSW Department of Environment and Climate Change, CSIRO, Canberra.

McLean, EJ and Hinwood, JB 2011, ‘Spring Tidal Pumping’, *Proceedings of the 34th IAHR World Congress, Brisbane, Australia*, pp.1109–1116.

McMillan, M, Shepherd, A, Sundal, A, Briggs, K, Muir, A, Ridout, A, Hogg, A and Wingham, D 2014, ‘Increased ice losses from Antarctica detected by CryoSat-2’, *Geophysical Research Letters*, vol. 41, pp.3899–3905, doi: 10.1002/2014GL060111.

McPherson, B, McLuckie, D, Hanslow, D and Collins, L 2012, ‘Preliminary Examination of Coastal and Catchment Flooding Interaction from the Data’, *Proceedings of the Australian Floodplain Managers Association Conference*.

Maiwa, K, Masumoto, Y and Yamagata, T 2010, ‘Characteristics of coastal trapped waves along the southern and eastern coasts of Australia’, *J. Oceanogr.*, vol.66, pp.243–258, doi:10.1007/s10872-010-0022-z.

MHL 1992, *Mid New South Wales Coastal Region Tide-Storm Surge Analysis*, Manly Hydraulics Laboratory Report 621, October 1992, Manly Hydraulics Laboratory, Manly Vale, NSW.

MHL 1995a, *The Harmonic Analysis of NSW Tide Gauge Network, Volume 1 – Tidal Planes*, Manly Hydraulics Laboratory, MHL Report 604, Manly Hydraulics Laboratory, Manly Vale, NSW.

MHL 1995b, *The Harmonic Analysis of NSW Tide Gauge Network, Volume 2 – Tidal Phases*, Manly Hydraulics Laboratory, MHL Report 604, Manly Hydraulics Laboratory, Manly Vale, NSW.

MHL 2002, *DLWC NSW Tidal Planes Data Compilation 2001, Volume 2 Tidal Phase Analyses*, Manly Hydraulics Laboratory MHL Report 1098, August 2002, Manly Hydraulics Laboratory, Manly Vale, NSW.

MHL 2003, *DLWC NSW Tidal Planes Data Compilation 2001, Volume 1 Tidal Plane Analyses*, Manly Hydraulics Laboratory, MHL Report 1098, March 2003, Manly Hydraulics Laboratory, Manly Vale, NSW.

MHL 2005, *Investigation into Tidal Planes Compilation: DNR NSW Tidal Planes Data Compilation Stage 3*, Manly Hydraulics Laboratory, Report MHL1269, November 2005, Manly Hydraulics Laboratory, Manly Vale, NSW.

MHL 2006, *DNR Survey of Tidal Limits and Mangrove Limits in NSW Estuaries 1996-2005*, Manly Hydraulics Laboratory, Report MHL1286, April 2006, Manly Hydraulics Laboratory, Manly Vale, NSW.

MHL 2009, *DECCW Lake Illawarra Tidal Data Collection February 2008 to February 2009* Manly Hydraulics Laboratory Report MHL1826, November 2009, Manly Hydraulics Laboratory, Manly Vale, NSW.

MHL 2010,

MHL 2011, *New South Wales Ocean Water Levels*, Manly Hydraulics Laboratory for Department of Environment, Climate Change and Water (DECCW), Report MHL1881, March 2011, Manly Hydraulics Laboratory, Manly Vale, NSW.

MHL 2012, *OEH NSW Tidal Planes Analysis: 1990–2010 Harmonic Analysis*, Manly Hydraulics Laboratory, Report MHL2053, October 2012, Manly Hydraulics Laboratory, Manly Vale, NSW.

MHL 2014, *OEH NSW Water Level Frequency Distribution Analysis*, Manly Hydraulics Laboratory Report MHL2100, March 2014, Manly Hydraulics Laboratory, Manly Vale, NSW.

Middelmann, MH 2007, *Natural Hazards in Australia: Identifying Risk Analysis Requirements*, Geoscience Australia, ISBN 0 978-1-921236-61-7.

Murray-Wallace, CV and Woodroffe, CD 2014, *Quaternary Sea Level Changes: A Global Perspective*, Cambridge University Press, Cambridge, UK.

Nielsen, AF and Gordon, AD 2011, 'The Impact of Entrance Breakwaters on Large Estuaries', in EM Valentine, CJ Apelt, J Ball, H Chanson, R Cox, R Ettema, G Kuczera, M Lambert, BW Melville and JE Sargison (eds), *Proceedings of the 34th World Congress of the International Association for Hydro- Environment Research and Engineering: 33rd Hydrology and Water Resources Symposium and 10th Conference on Hydraulics in Water Engineering, Barton, ACT*, Engineers Australia, pp.1117–1124.

Nielsen, P and Hanslow, DJ 1991, 'Wave Runup Distributions on Natural Beaches', *Journal of Coastal Research*, vol.7, no.4, pp.1139–1152.

Nielsen, P and Hanslow, DJ 1995, 'Wave Setup at River Entrances', *Proceedings of the 12th. Australasian Conference on Coastal and Ocean Engineering*, pp.109–112.

NSW Government 1992, *Estuary Management Manual*, NSW Government Printer, Sydney.

OEH Corporate Spatial DB 2013, *NSW Government, Office of Environment and Heritage Corporate Spatial Database*, [Data Set], Office of Environment and Heritage, Sydney.

OEH 2014, *Mapping & Responding to Coastal Inundation: Exposure Assessment for Sydney Coastal Councils Group*, Office of Environment and Heritage Report for Sydney Coastal Councils Group, December 2014.

OTIS 2013, *Oregon State University Regional Tidal Solutions Website*, retrieved from http://volkov.oce.orst.edu/tides/PO.html.

Parker, BB 1991, *Tidal Hydrodynamics*, John Wiley & Sons, New York, USA.

Peltier, WR 1999, 'Global SLR and glacial isostatic adjustment', *Global and Planetary Change*, vol.20, pp.93–123.

Peltier, WR 2004, 'Global Glacial Isostasy and the Surface of the Ice-Age Earth: The ICE-5G (VM2) Model and GRACE', *Ann. Rev. Earth and Planet. Sci.*, vol.32, pp.111–149.

Prandle, D 2009, *Estuaries*, Cambridge University Press, Cambridge, UK.

PWD 1988, *Coastal Storms in NSW August & November 1986 and their Effect on the Coast*, Public Works Department, Coastal Branch Report, 1988.

Rhein, M, Rintoul, SR, Aoki, S, Campos, E, Chambers, D, Feely, RA, Gulev, S, Johnson, GC, Josey, SA, Kostianoy, A, Mauritzen, C, Roemmich, D, Talley, LD and Wang, F 2013 'Observations: Ocean', in TF Stocker, D Qin, G-K Plattner, M Tignor, SK Allen, J Boschung, A Nauels, Y Xia, V Bex and PM Midgley (eds), *Climate Change 2013: The Physical Science Basis*, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, USA, pp. 255–316, doi:10.1017/CBO9781107415324.010.

Rignot, E, Mouginot, J, Morlighem, M, Seroussi, H and Scheuchl, B 2014, 'Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith and Kohler glaciers, West Antarctica from 1992 to 2011', *Geophysical Research Letters*, vol.41(10), pp.3502–3509, doi: 10.1002/2014GL060140.

Roemmich, D, Gilson, J, Davis, R, Sutton, P, Wijffels, S and Riser, S 2007, 'Decadal spinup of the South Pacific subtropical gyre', *Journal of Physical Oceanography*, vol.37, pp.162–173.

Rogers, K, Saintilan, N and Copeland, C 2012, 'Modelling wetland surface elevation and its application to forecasting the effects of sea-level rise on estuarine wetlands', *Ecological Modelling*, vol.244, pp.148–57.

Roper, T, Creese, B, Scanes, P, Stephens, K, Williams, R, Dela-Cruz, J, Coade, G, Coates B and Fraser, M 2011, *Assessing the condition of estuaries and coastal lake ecosystems in NSW, Monitoring, evaluation and reporting program*, Technical report series, Office of Environment and Heritage, Sydney.

Roy, PS 1984, 'New South Wales estuaries - their origin and evolution', in BG Thom (ed.), *Developments in Coastal Geomorphology in Australia*, Academic Press, New York, pp. 99–121.

Roy, PS and Thom, BG 1981, 'Late Quaternary marine deposition in New South Wales and southern Queensland – an evolutionary model', *Journal of the Geological Society of Australia*, vol.28, pp.471–489.

Roy, PS, Williams, RJ, Jones, AR, Yassini, I, Gibbs, PJ, Coates, B, West, RJ, Scanes, PR, Hudson, JP and Nichol, S 2001, 'Structure and Function of South-east Australian Estuaries', *Estuarine, Coastal and Shelf Science*, vol.53, pp.351–384.

Savenije, HHG 2005, *Salinity and tides in alluvial estuaries*, Elsevier.

Shand, TD, Goodwin, ID, Mole, MA, Carley, JT, Browing, S, Coghlan, IR, Harley, MD and Peirson, WL 2011, *NSW Coastal Inundation Hazard Study: Coastal Storms and Extreme Waves*, University of NSW Tech Rep 2010/6.

Short, AD 2007, *Beaches of the New South Wales Coast*, (2nd edition), Sydney University Press.

Sloss, CR, Murray-Wallace, CV and Jones, BG 2007, 'Holocene sea-level change on the southeast coast of Australia: a review', *The Holocene*, vol.17, pp.999–1014.

SMEC and UQ 2013, *Flooding Tailwater Levels for NSW Coastal Entrances*, report for Office of Environment and Heritage, SMEC Australia and University of Queensland.

Speer, PE and Aubrey, DG 1985, 'A study of non-linear tidal propagation in shallow inlet/estuarine systems Part II: Theory', *Estuarine, Coastal and Shelf Science*, vol.21(2), pp.207–224.

Speer, MS, Wiles, P and Pepler, A 2009, 'Low pressure systems off the New South Wales coast and associated weather: establishment of a database', *Australian Meteorological and Oceanographic Journal*, vol.58, pp.29–39.

Tamisiea, ME and Mitrovica, JX 2011, 'The moving boundaries of sea level change: Understanding the origins of geographic variability', *Oceanography*, vol.24(2), pp.24–39, doi:10.5670/ oceanog.2011.25.

Van Rijn, L 2010, *Tidal phenomena in the Scheldt Estuary*, 1202016-000 Deltares, 2010

Weir, FM, Hughes, MG and Baldock, TE 2006, 'Beach face and berm morphodynamics fronting a coastal lagoon', *Geomorphology*, vol.82(3–4), pp.331–346.

White, NJ, Haigh, ID, Church, JA, Koen, T, Watson, CS, Pritchard, T, Watson, PJ, Burgette, RJ, McInnes, KL, You, B, Zhang, X and Tregoning, P 2014, 'Australian Sea Levels – Trends, Regional Variability and Influencing Factors', *Geophysical Journal International*, vol.136, pp.155–174, doi:10.1016/j.earscirev.2014.05.011.

Woodham, R, Brassington, GB, Robertson, R and Alves, O 2013, 'Propagation characteristics of coastally trapped waves on the Australian Continental Shelf', *Journal of Geophysical Research*, *Oceans*, vol.118(9), pp.4461–4473, doi:10.1002/jgrc.20317.

Woodworth, PL and Player, R 2003, 'The permanent service for mean sea level: an update to the 21st century', *J Coastal Res*, vol.19, pp.287–295.

You, Z, Nielsen, P, Hanslow, D and Pritchard, T 2012, 'Elevated Water Levels at Trained River Entrances', *Coastal Engineering Proceedings*, 1(33), currents.48. doi:10.9753/icce.v33.currents.48

8. Appendices

Appendix A: Ocean tide evaluation

Appendix B: Estuarine tidal plane evaluation

Appendix C: GURAS assets evaluation