QUANTIFYING TIDAL INUNDATION VARIATIONS IN NSW ESTUARIES

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Abstract

Communities and infrastructure within the estuaries of NSW are considered to be highly vulnerable to climate change with potential impacts related to inundation associated with sea level rise and possible changes to storm intensity and frequency. The effects of inundation due to sea level rise are likely to have the most significant impacts in estuarine areas primarily due to the number of properties in relatively close proximity to current high tide levels.

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. Further, 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. Thus mapping inundation in NSW estuaries using the current simple bathtub-type approach could lead to under/over estimation of water levels and the extent of risk.

The current work provides an updated statewide assessment of exposure to current ocean inundation hazard as well as the potential effects of sea level rise by mapping of potential inundation areas within low lying areas of all major estuarine systems. The assessment uses an intermediate-level method for water surface and inundation mapping based on existing estuarine water levels and is capable of accurately representing both current estuary water levels and changes to tidal ranges under future sea level rise scenarios. The inundation mapping is then used to quantify risk based on data from the geo-coded urban and rural addressing system database.

Introduction

It is expected that over the 21st century climate change will result in a rise in the mean sea level of the global oceans (IPCC, 2007). This will have a flow on effect in terms of water levels in estuarine systems that will change tidal inundation processes and thus the extent of risk to property and infrastructure within these systems.

Estuarine systems in NSW are considered to be particularly vulnerable to inundation due to sea level rise. The National Coastal Risk Assessment (DCC, 2009) identified NSW as having the highest potential exposure of any Australian state to the potential effects of sea level rise.

The oceanic tides along the NSW coast are semi diurnal with a significant diurnal inequality and the mean spring range is 1.2m while the mean neap range is 0.8m (AHO, 2011). The highest astronomical tide at Fort Denison (Sydney Harbour) is 2.1m above lowest astronomical tide. Tide range varies along the coast with an increase of around 0.2m from south to north (MHL, 2011).

Tidally induced water levels in estuaries vary from those seen offshore due to the effects of changing water depth and channel geometry (Druery et al., 1983). These tidal water levels vary depending on estuary type (e.g. Roy et al. 2001), with tidal amplification occurring in some systems while others display significant attenuation compared with ocean tidal levels.

Previous evaluations of inundation in estuarine systems have ranged between using the so called bathtub-type approach, which assumes ocean tide levels match those within estuaries, to complex and detailed numerical modelling efforts. The simplistic bathtub-type method can lead to under/over estimation of the risks since tidal characteristics are not taken into account (Morris et al. 2013) whilst the more complex methods are generally site specific and time consuming to implement. Within this study an intermediate approach is taken to assess estuarine inundation and risk in order to apply it on a statewide basis.

The general methodology used to undertake an updated NSW-wide assessment of tidal water level inundation exposure within the major estuarine systems is outlined in the following section. Results are then presented including revised estuary types for NSW estuaries based on analyses of tidal levels; use of a GIS-based model to improve inundation mapping and the use of a geo-coded urban and rural addressing system database to quantify risk. This is followed by a discussion and conclusions.

Methodology

Ocean Tides

As a first step toward quantifying tidal water level variations in NSW estuaries an investigation and compilation of the available oceanic tidal gauge data and general ocean tidal information for NSW was undertaken, primarily from reports supplied by Manly Hydraulics Laboratory (MHL, 2005, 2011, 2012).

NSW has an extensive network of ocean water level gauging locations, however notwithstanding this; the majority of estuaries have no direct measurement of oceanic tidal characteristics adjacent to their entrances. Additionally there is some concern that gauges located within river entrances (particularly on the north coast) may not fully reflect ocean tidal conditions. Thus, it was considered necessary to seek another source from which to provide oceanic tidal information for each estuary for use in the GIS water surface modelling tool. A tidal inversion model developed by Oregon State University, OSU Tidal Inversion Software (OTIS) was chosen for this purpose (Egbert et al., 1994). The OTIS model data used in this study is from the Pacific Ocean 1/12Deg data set (OTIS, 2013).

OTIS model performance was evaluated by comparing characteristics of model output with those of observations from the NSW tide gauge network (MHL, 2012). Using the major tidal harmonic constituents calculated, using the methods of Codiga, (2011), from both the OTIS model and the tide gauge network three key parameters were calculated, namely Total Tidal Range (R), High High Water Solstice Springs (HHWSS) and Indian Spring Low Water (ISLW).

These key tidal parameters are defined as follows (MHL, 2012);

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

$$ISLW = Z_0 – (M_2+S_2 + K_1 +O_1)$$

$$R = HHWSS - ISLW$$

where Z_0 is the mean sea level, set to zero relative to Australian Height Datum (AHD) and M_2, S_2, K_1, O_1 are the principal tidal harmonic constituents.

Estuarine Tidal Planes

The Tidal Planes (TP), which can also be referred to as 'tidal levels', were compiled for all of the 55 gauged estuaries in NSW based on harmonic analysis undertaken on the gauge data as reported in MHL (2012). Of primary interest here are High High Water Spring Solstice (HHWSS), Mean Sea Level (MSL), and Indian Spring Low (ISLW), as outlined above. The HHWSS tidal plane is used in this study as a proxy for the highest astronomic tide at any given location within an estuary, due to its simplicity in calculation, and hereafter is referred to as HW-TP. The HW-TP was compared with Highest Astronomical Tide (HAT) at Fort Denison (Sydney Harbour) the results of which showed that they are within 10cm of each other, thus it was deemed that the HW-TP provides a reasonable proxy.

At the entrance to each estuary the oceanic tidal levels were determined from the OTIS model output whilst the location and characteristics of the tidal limits were sourced from MHL (2006). These data, along with the tidal planes and locational information from the gauge network, were then combined to create a tidal plane information database for use in the GIS-based modelling.

Using this tidal plane information and based on the classifications of Roy et al. (2001) analyses of the characteristics of tidal propagation into the various NSW estuary types was undertaken. The object of this was to group estuaries that exhibit similar behaviour of the tide as it propagates from the ocean into the estuary. 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) led to a categorisation which was based on the use of physical metrics which are readily determined for each of the gauged estuaries.

The first metric applied was that of the gradient of the tidal plane for HHWSS (HW-TP) at the entrance to each estuary. This allowed a differentiation between estuaries where the HW-TP increased into the estuary, i.e. tidal high water was higher inside the estuary entrance than the ocean; and estuaries where HW-TP decreased, which was where there was attenuation of the tide into the estuary.

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, then the form was designated as having a value of zero (0). On the other hand if there was a change of the gradient of HW-TP, with areas of tidal amplification within the estuary, then the form was defined as one (1).

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

GIS-based Water Surface and Inundation Model

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, 2012). A flow chart outlining the structure of the model is shown in Figure 1.

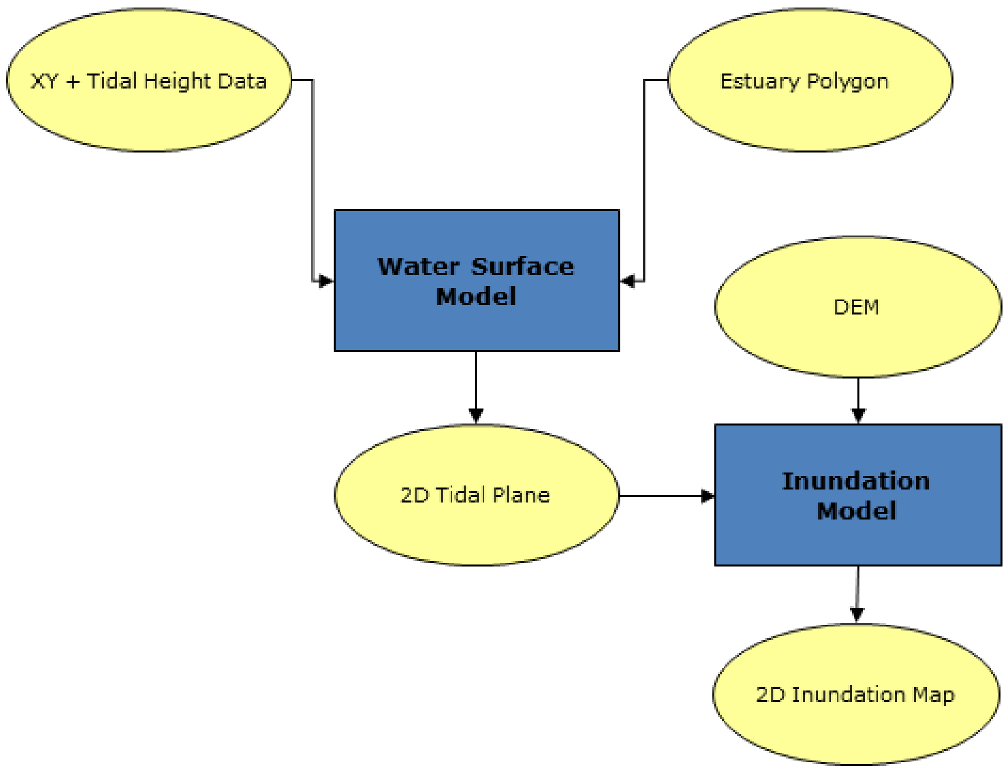

Figure 1. Flow chart showing structure of GIS-based Water Surface and Inundation Model

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 an estuaries spatial boundary (OEH Corporate Spatial DB, 2013) by 200m, whilst constraining the extent within the estuaries catchment area. The Tidal Plane Surface is then created from tidal plane information; here HHWSS is used, by utilising a minimum curvature spline technique (ESRI, 2103) with the AOA boundary as a barrier.

The TPS created is then used as one of the inputs to the GIS-based Inundation Model to estimate the spatial extent of inundation in a given estuary. A Digital Elevation Model (DEM) of the AOA is compiled from available data, with preference to the most recent/highest resolution which in the majority of cases for NSW is 1m LiDAR data. To improve performance the DEM of each AOA is further constrained by using only elevations that are less than 10m. 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 inundation areas spatial extent for the given estuary.

Inundation Exposure Risk (GURAS)

In order to undertake an assessment of the exposure risk due to tidal inundation in NSW estuaries a geo-coded addressing system database was used. Here the Geo-coded Urban and Rural Addressing System (GURAS) is used (LPI, 2012). This database contains spatial information on both public infrastructure, such as roads, railway etc., as well as private property.

The assessment is performed using the 2D inundation map for each estuary, produced using the GIS-based Inundation modelling, which is used to interrogate the GURAS database and determine assets which are coincident spatially with areas of potential inundation within the catchment of each estuary. More details of the GURAS database and its use for risk assessment can be found in Kinsela et al. (2013).

Results

Ocean Tides

Results from the comparison between tidal model output and tidal gauge data show that the OTIS model represents the observed tidal parameters well, as shown for HHWSS in Figure 2. Residuals at open ocean sites are generally within ±5cm, whilst for HHWSS and ISLW the same general pattern is observed with a reasonably good match, residuals generally being less than ±3cm. Overall, it was found that using the output of the OTIS inverse tidal model is sufficiently representative of the tidal water levels along the NSW coast to be used as an oceanic boundary condition for estuaries that do not have an oceanic tidal gauge in close proximity.

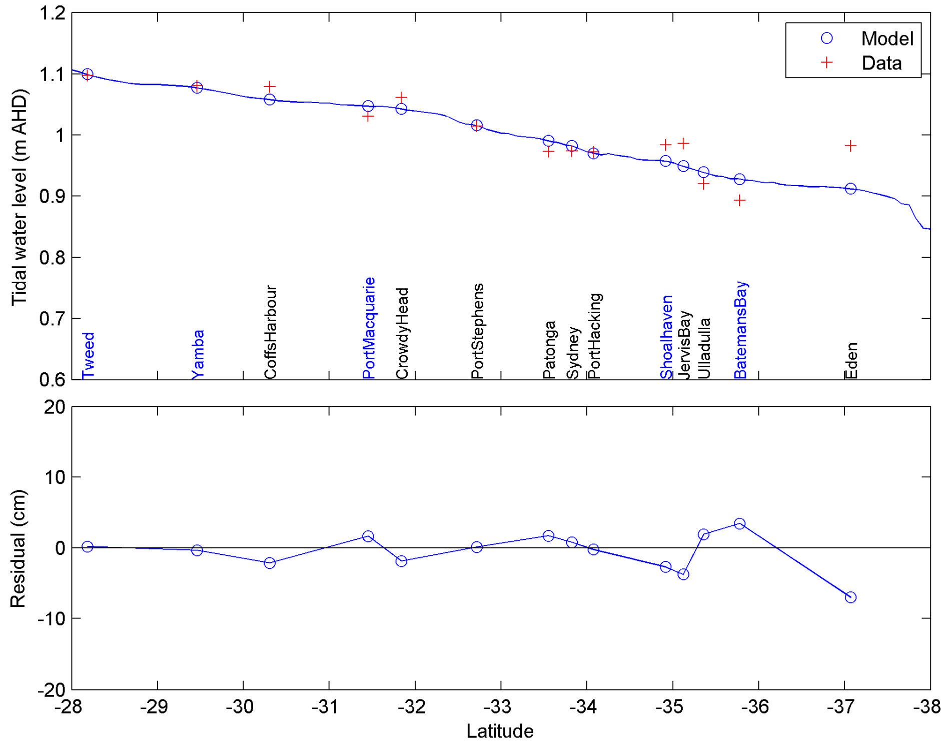

Figure 2. Results of comparison between High High Water Solstice Springs (HHWSS) values from OTIS and data for open ocean gauging locations (offshore gauges marked with blue text, harbour gauges in black).

NSW Estuary Types

NSW estuary types can be specified in terms of tidal propagation characteristics based on observed and modelled tidal plane characteristics, as outlined in the Methods section above. 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 are categorised as Drowned River Valleys, whilst most of the remainder of estuaries are separated into small or large barrier estuaries based on the form metric. If the form of the estuary is one (1) then it is categorised as a Large Barrier Estuary, otherwise it is categorised as a Small Barrier 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 barrier estuaries. The length of the shortest barrier estuary that had a change in form was used as the cut off in distinguishing between small and large barrier estuaries. Thus estuaries that may have been categorised as small barrier estuaries using the form metric are recategorised using the estuary length. The results of the categorisation of the gauged estuaries in NSW are shown in Figure 3, plotted as a comparison between HW-TP entrance gradient and estuary length.

Note that Tidal Lakes were categorised manually due to their unique tidal plane characteristics and small number of occurrences; they are included in Figure 3 for completeness. Further it should also be noted that the small number of ICOLLs that are gauged behave, when open, as Small Barrier Estuaries under this categorisation system.

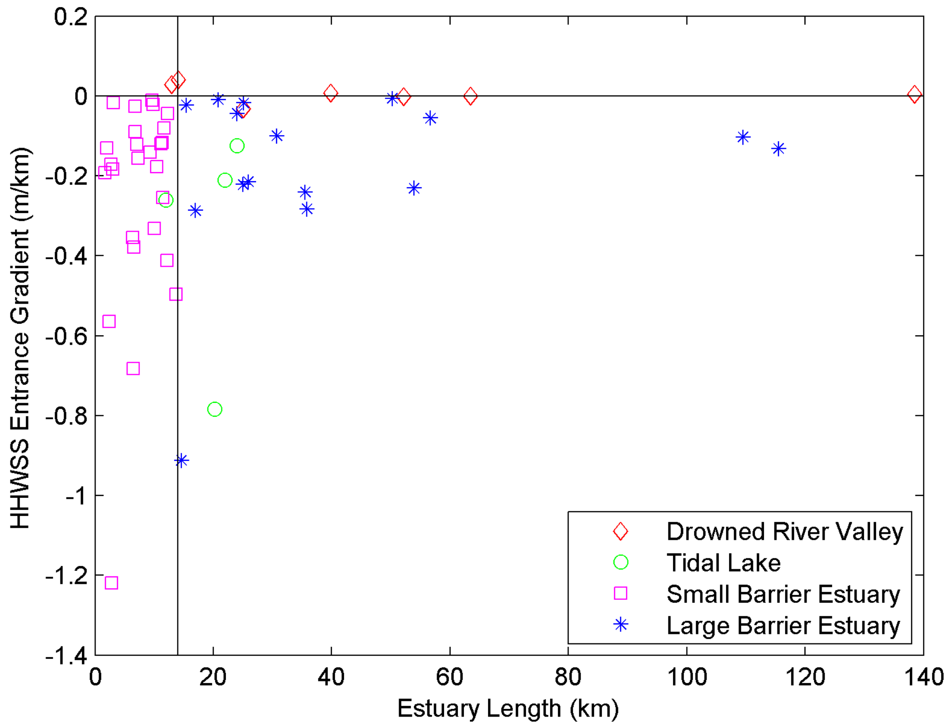

Figure 3. Plot showing categorisation of NSW estuary types using high water entrance gradient and length of estuary.

Thus, in terms of the characteristics of tidal propagation the estuaries in NSW can be usefully divided into five basic estuary types: Drowned River Valleys, Large Barrier Estuaries, Small Barrier Estuaries, Tidal Lakes and Intermittently Close and Open Lakes and Lagoons (ICOLLs) the characteristics of which are shown graphically in Figure 4. 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.

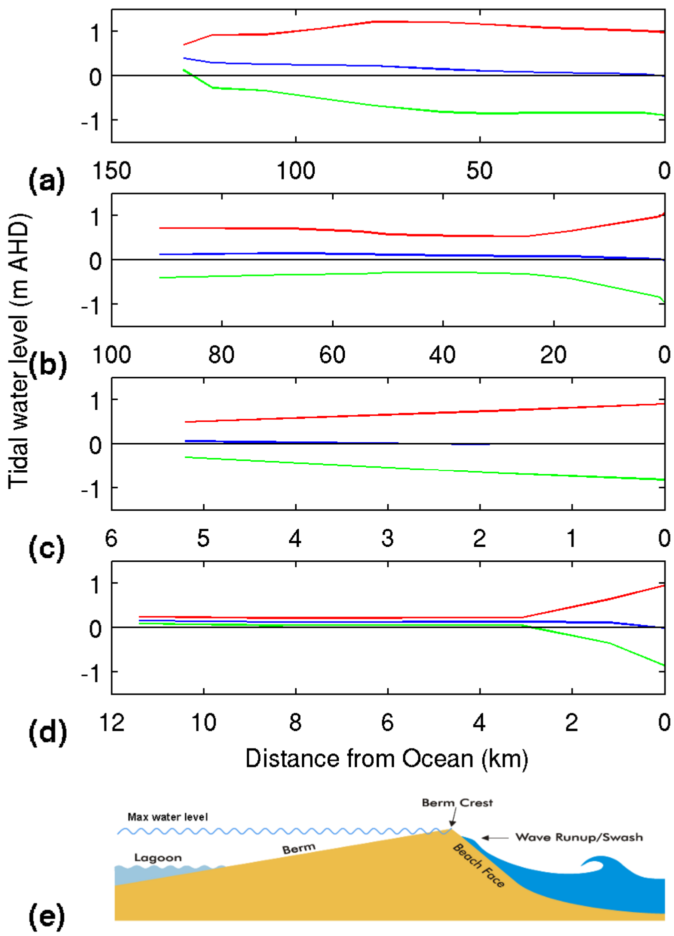

Figure 4. Estuary types in NSW based on tidal propagation: (a) Drowned River Valley, (b) Large Barrier Estuaries, (c) Small Barrier Estuaries, (d) Tidal Lakes, (e) ICOLLs. In (a) – (d) HHWSS in red, MSL in blue and ISLW in green.

Drowned River Valley estuaries have an observed amplification of the tidal range for large distances inland due to the landward narrowing of the channel (e.g. Broken Bay/Hawkesbury River estuary). This is further enhanced by tidal resonance due to the channel becoming shallower. The tidal range is only attenuated by the dampening of tidal flows in the upper reaches due to cumulative dissipative effects of bed friction.

An initial reduction of tidal range occurs due to frictional dissipation in both large and small barrier estuaries, particularly where a significant marine delta exists. This is typically followed by some mild amplification in the mid reaches of large barrier estuary systems (e.g. Hastings River) before complete damping of the tidal range around the head of the estuary, often due to the presence of sand bars or fluvial gravel. In small barrier estuary systems (e.g. Merimbula Lake) 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 (e.g. Lake Macquarie). 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.

Water levels in ICOLLs (e.g. Narrabeen Lagoon) vary depending on opening and closing regimes; whilst open they operate like small barrier estuaries or tidal lakes, while closed they gradually fill with water levels influenced by inflows and evaporation. Maximum water levels are generally controlled by beach berm height (Hanslow et al., 2000).

Water Surface and Inundation Mapping

The use of the GIS-based modelling allowed the tidal plane surface (TPS) to be obtained from the gauge data for each estuary. An example of the output of the Water Surface Model for a Small Barrier Estuary is shown in Figure 5.

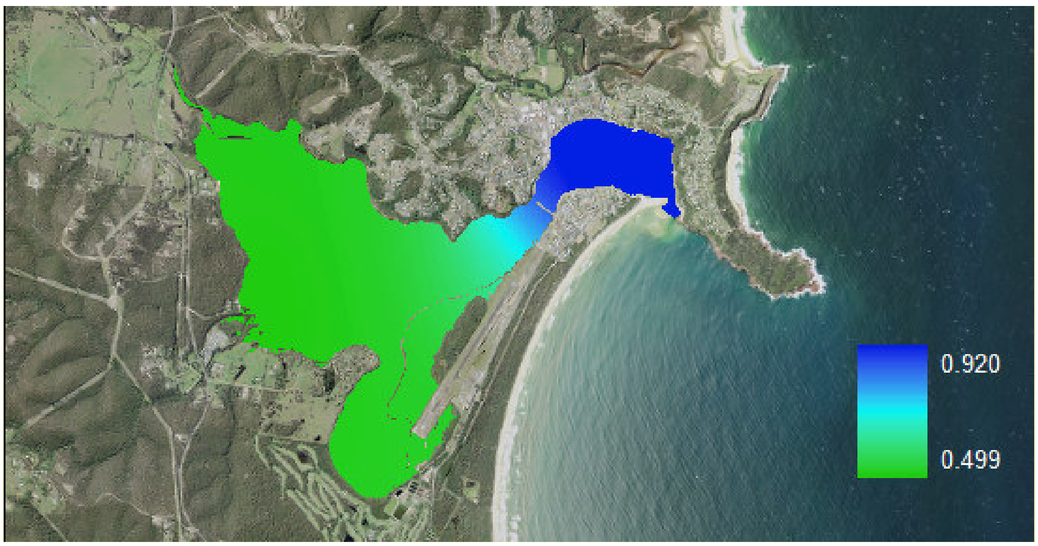

Figure 5. Example of the results of the GIS-based Water Surface Model used to generate a tidal plane surface within the estuary, present day HHWSS is shown relative to AHD (modified after Morris et al. 2013).

This TPS was then used as an input to the GIS-based Inundation Model which in turn provides the extent of inundation due to tidal water level variations within the given estuary. Examples of the results of the inundation model are shown in Figure 6 for a small barrier estuary. Areas of potential tidal inundation are shown for the current sea level along with two sea level rise scenarios, i.e. 0.4 and 0.9m).

Comparison between the tidal plane and the bathtub-type method can be made by using the GIS-based Inundation Model. An example of this for a small barrier estuary using a sea-level rise scenario of 0.9m is shown in Figure 7. It is clear from this example that in this case there is significant overestimation of the inundation when the bathtub-type approach is used, particularly in the upper reaches of the estuary.

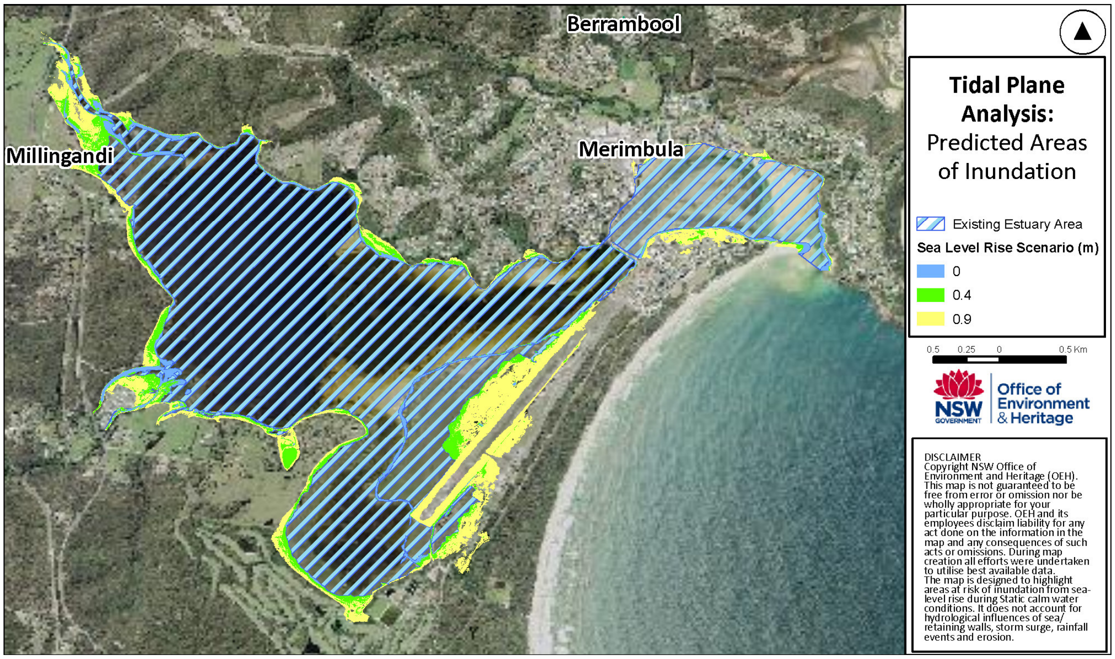

Figure 6. Plot showing example of predicted inundation areas under current sea level, 0.4 and 0.9 m sea level rise scenarios.

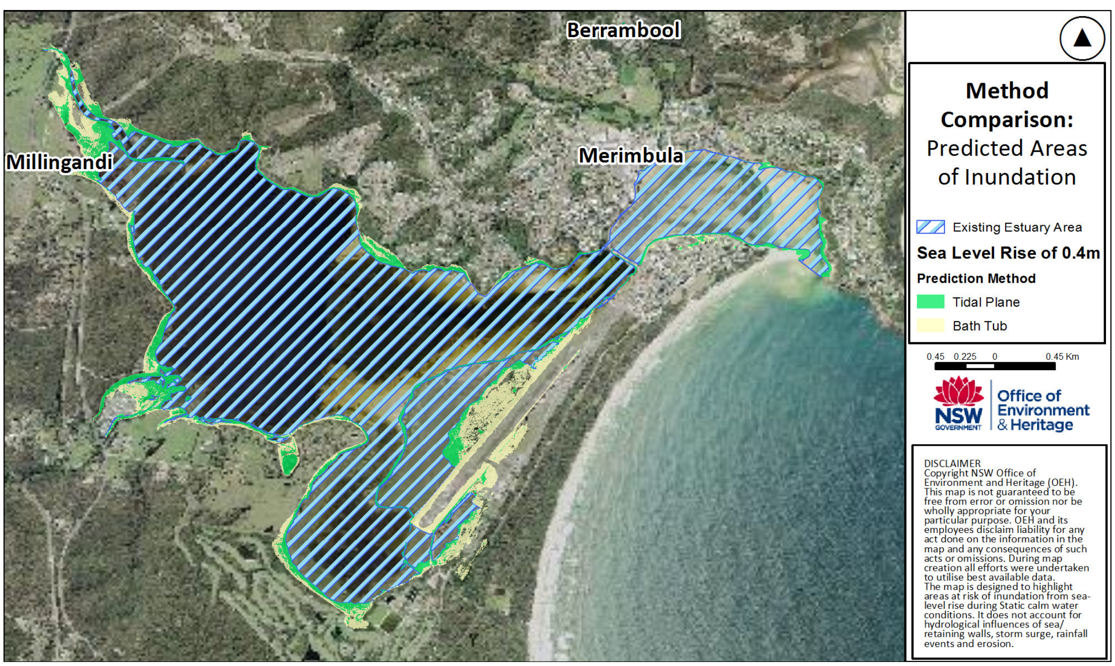

Figure 7. Plot showing example of comparison between predicted inundation using tidal plane and bath-tub methods.

Inundation Exposure Risk (GURAS)

By using the GURAS database in combination with the results of the GIS-based Inundation Model the exposure risk presented by tidal water level inundation in a given estuary can be assessed. An example of the use of the GURAS database to assess inundation exposure risk is shown in Figure 8. This example shows the potential inundation risk to property in the catchment of a Small Barrier Estuary under current conditions as well as two sea level rise scenarios. The total number of properties potentially affected can be assessed (Figure 8a) and can be broken down to show the extent of inundation of affected properties (Figure 8b).

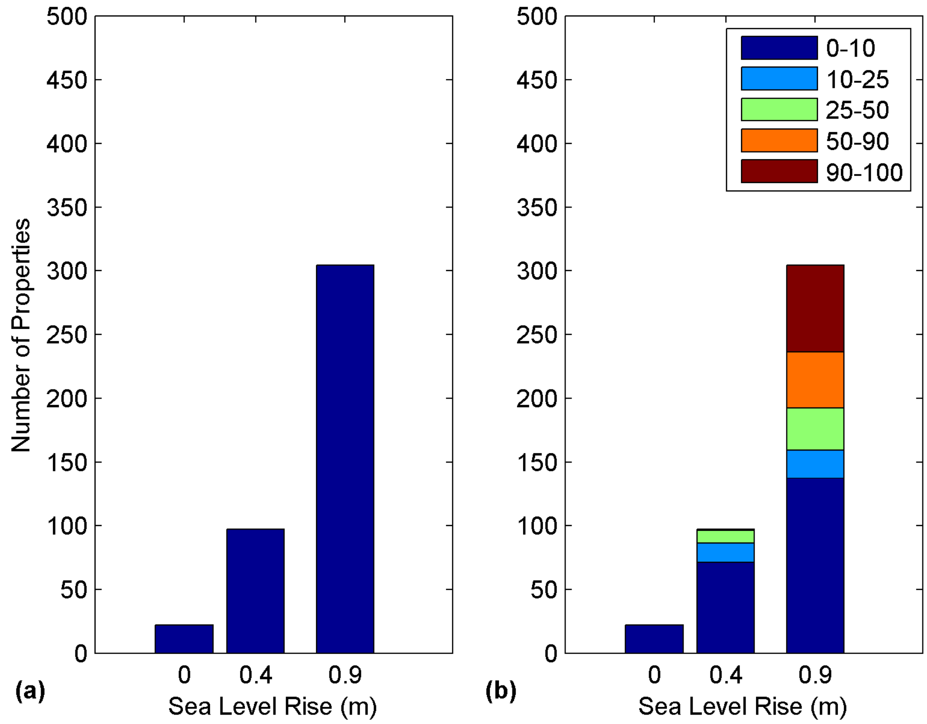

Figure 8. An example of output from use of the GURAS database and inundation modelling results. (a) Number of properties in the catchment affected. (b) Percentage of each property affected.

Discussion and Conclusions

Fundamental to the assessment of exposure to tidal inundation in estuaries is the understanding of the propagation of the tide into the estuarine systems. In undertaking an investigation into the NSW ocean tides and estuarine tidal planes a characterisation of the tidal propagation into estuaries was used to categorise estuary types. The fact that the different estuary types display different responses to tidal propagation indicates that using the bathtub-type approach to inundation is likely to give erroneous results.

By using the tidal plane information and the revised estuary types coupled with the GIS-based inundation model improved estimates of the extent of tidal inundation in estuaries were obtained. These improved estimates of tidal inundation both for current sea level and for future potential sea level rise scenarios are being used in conjunction with the GURAS database to undertake an assessment of the potential risk to assets within NSW estuarine systems.

Some limitations to the methods should be pointed out however including:

- The tidal plane surface is generated using only a small number of data points, with particular attention needed for the extrapolation to the tidal limits.
- There is a high dependence on the quality of the DEM for the inundation estimation.

Future work in this study will include:

- The generation of generic tidal planes for each estuary type for use in the GIS-based inundation modelling for estuaries without gauges
- Update and implementation of sea level rise scenarios following the recent release of the latest IPCC report.
- Completion of the evaluation of assets at risk in NSW estuarine systems based on tidal plane inundation modelling and asset databases

In summary, using various sea level rise scenarios and their effect on the tidal plane estimates for each estuary type allows the use of the GIS-based model to obtain an intermediate-level estimation of inundation. This in turn will enable the improvement of the quantification of risk to assets in NSW estuarine systems under present conditions and also under future potential sea-level rise scenarios.

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