Coastal Inundation Mapping for Tasmania - Stage 2

Version 1

For the Department of Premier and Cabinet

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Blue Wren Group

Purpose: *"To drive continuous improvement in the provision of high quality environmental data and information that is understandable and directly relevant to management purposes."*

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Summary

This report was prepared for the project "Coastal Inundation Stage 2" for the Tasmanian Department of Premier and Cabinet and accompanies a set of GIS datasets produced in that project. The project was concerned with mapping of a set of sea level rise scenarios around the Tasmanian coast. This report is of a technical nature and is primarily intended to document the methods used in the project. The sea level rise allowances used in this project have been supplied by the Tasmanian Government to create coastal inundation area maps to support the development of a coastal policy, and a coastal inundation planning code. The sea level rise allowances were based on a regional sea-level projections and the A1FI emission scenario.

Outputs include:

a) A polygon shapefile map showing extents of expected permanent inundation associated with 0.2, 0.4 and 0.8 metre sea level rise (coinciding with sea level rise scenarios above 2010 levels for years 2050, 2075 and 2100). These are mapped using the best available digital elevation model (DEM), this being the Climate Futures LiDAR DEM or the Tasmanian 25 metre DEM.

b) Maps of the inundation extents associated with a specified range of Annual Exceedance Probabilities (AEP)s of 0.005%, 0.05%, 0.5%, 1%, 2% and 5 % for each of years 2010, 2050, 2075 and 2100, with one polygon dataset per specified year. These are mapped using the best available DEM, this being the Climate Futures LiDAR DEM or the Tasmanian 25 metre DEM.

c) An updated version of the Tasmanian height references layer, produced in part C of the stage one project with inclusion of sea level rise heights in 0.1 metre increments to 1.2 metre at the 50% confidence level and the AEP heights specified in (b).

d) Documentation of methods, an example maps for communication purposes and metadata on the datasets.

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Definitions

A1FI	The IPCC's "high emission" scenario
ACE CRC	Antarctic Climate & Ecosystems Cooperative Research Centre
AEP	Annual Exceedance Probability
AHD	Australian Height Datum is the current official standard Australian height reference (ICSM, 2006). For Tasmania it is based on mean sea level at Burnie and Hobart tide gauges in 1972. For a number of reasons including suboptimal location of some tide gauges, limited period of the reference sea level determination and non-inclusion of sea level topography AHD is an approximation of mean sea level only.
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEM	Digital elevation model, a surface representing the surface heights of the land
DPaC	Department of Premier and Cabinet
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
ISHW	Indian springs high water. Defined as Mean Sea Level plus the amplitudes of the tidal constituents: M2 + S2 + O1 + K1.
ISLW	Indian springs low water. Defined as Mean Sea Level minus the amplitudes of the tidal constituents: M2 + S2 + O1 + K1.
LiDAR	Light detection and ranging (like "radar", or radio detection and ranging, but using laser light pulses instead of radio pulses)
MHW	The average of all high waters over a period of time (ICSM, 2007). For inundation modelling, the high water used was the "NTC High Water" (see below).
MSL	Mean Sea Level For a tidal station Mean Sea Level is the mean over a period of time of the hourly heights at that station (ICSM, 2007).
NTC	National Tidal Centre, Bureau of Meteorology
NTC High Water	The standard tidal range grid modelled by the National Tidal Centre (NTC) used to model the approximate high water mark, which in most cases also represents the historically mapped coastline well. The NTC tidal range is the height in metres between Mean Sea Level and Indian Spring Low Water multiplied by two to give an estimate of the complete tidal range. It is twice the sum of the amplitudes of the four main tidal constituents, M2, S2, O1 and K1. For Part a) inundation modelling, the high water used was the NTC modelled high water, which is at a height of half the NTC tide range above Mean Sea Level.
SLR	Sea level rise
Storm Tide	A combination of the tidal component plus any raised sea level due to wind set up or reduced air pressure. It is what is measured at tide gauges during a storm event.
UTAS	University of Tasmania

Introduction

This report was prepared for the project "Coastal Inundation Stage 2" for the Tasmanian Department of Premier and Cabinet (DPaC) and accompanies a set of GIS datasets produced in that project. The project was concerned with mapping of a set of sea level rise scenarios around the Tasmanian coast. This report is of a technical nature and is primarily intended to document the methods used in the project. The sea level rise allowances used in this project have been supplied by the Tasmanian Government to create coastal inundation area maps to support the development of a coastal policy, and a coastal inundation planning code. The sea level rise allowances were based on regional sea-level projections and the A1FI emission scenario.

Project aim and purpose

This project follows on from the coastal inundation stage one project, also known as the Tasmanian Coastal Inundation Mapping Project, Mount *et al.* (2010) and Mount *et al.* (2011) which consisted of the following components:

Part A. Mapping of locations potentially affected by sea level rise at 0.2 metre increments up to 1.2 metre plus 1.6 and 2.0 metre above a base tidal height.

Part B. Mapping of locations potentially affected by flooding associated with storm-tide exceedance events at exceedance probabilities of 25%, 50% and 75% averaged for the periods 2010-2050 and 2010-2100, with and without sea level rise.

Part C. Provided coastal reference heights in a 1 kilometre grid covering the entire Tasmanian coastline. This presented the height data from parts A and B and instead of mapping the heights onto the ground it could be used as a "look up" or "reference" map to identify key hazard threshold heights within specific (1 km square) areas. Reference sea level rise inundation heights were in most regions based on the modelled NTC tidal heights and were calculated at 5%, 50% and 95% confidence levels based on error estimates. Storm tide calculations were provided for LiDAR areas only.

The purpose of the current project was to conduct additional mapping of tidal inundation in areas not covered by the Climate Futures LiDAR DEM and to map storm tide as annual exceedance probabilities (AEPs) for specified years (2010, 2050, 2075 and 2100).
Specified components for the current project were:

- To provide a polygon shapefile map showing extents of expected permanent inundation associated with 0.2, 0.4 and 0.8 metre sea level rise (coinciding with sea level rise scenarios above 2010 levels for years 2050, 2075 and 2100). These were to be mapped using the best available DEM, this being the Climate Futures LiDAR DEM or the Tasmanian 25 metre DEM.
- To map the inundation extents associated a specified range of AEPs (0.005%, 0.05%, 0.5%, 1%, 2% and 5 %) for each of years 2010, 2050, 2075 and 2100, with one polygon shapefile per specified year. These were to be mapped using the best available DEM, this being the Climate Futures LiDAR DEM or the Tasmanian 25 metre DEM.
- Add to the Tasmanian height references layer, produced in part C of the stage one project, sea level rise heights in 0.1 metre increments to 1.2 metre at the 50% confidence level and the AEP heights specified in (b).
- Provide documentation of methods, an example map for communication purposes and metadata on the datasets.

Input Datasets

Following is a brief description of the input datasets used in the mapping. A number of issues are highlighted and the approaches taken to address those issues are presented.

LiDAR DEM

The Climate Futures LiDAR dataset as supplied via the Information & Land Services Division (ILS) of the Department of Primary Industries, Parks, Water and Environment (DPIPWE). The dataset was collected by Digital Mapping Australia (DiMAP) for the Antarctic Climate & Ecosystems Cooperative Research Centre (ACE CRC) under the Climate Futures for Tasmania project. DEM tiles are 1 km x 1 km in size with 50 metre fringe, giving a 100 m overlap of tiles. The individual grid cells are 1 m x 1 m and have stated horizontal and vertical accuracies of +/- 25 cm.

Preliminary assessment of the LiDAR dataset has revealed a number of limitations which constrained the reliability of the dataset for use in inundation mapping. The principal limitation was height discrepancies in a number of areas particularly where there were no nearby survey control points. Affected areas included large parts of Port Sorell, Pittwater and the Tasman Peninsula. Inundation mapping using the LiDAR DEM in these areas resulted in significant over or under estimation of inundation heights. In these areas the Tasmanian 25 metre DEM was substituted as the elevation reference. Figure 1 shows the extent of the Climate Futures LiDAR DEM. Areas considered unreliable (blue) were excluded from the inundation mapping.

There is some reason to believe that heights of some individual survey control points used in production of the LiDAR DEM were incorrect or the registered position was displaced from their correct position in relation to the LiDAR. Examples of this include wetlands in part of the upper Derwent and in the region of Knights Road, Connellys Marsh.

Thick vegetation that obscures the ground surface can also produce false LiDAR heights with an upward bias from the true ground surface. The height difference produced may be small but has the potential to be sufficient to have an effect on inundation modelling outcomes in some areas.

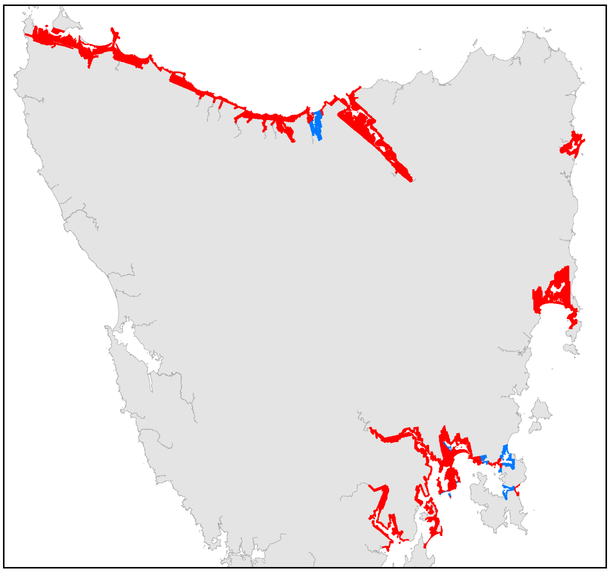

Figure 1. Extent of the Climate Futures LiDAR DEM showing areas considered reliable (red) and unreliable (blue) for inundation mapping. The unreliable areas were excluded from the inundation mapping.

Tasmanian 25m DEM

The Tasmanian 2nd Edition 25 metre DEM (Information & Land Services Division, DPIPWE) was used to fill in areas not covered by the LiDAR DEM or where the LiDAR DEM was considered unreliable. The 25 metre DEM has a floating point dataset and has been produced from 1:25,000 Series maps, primarily by interpolation between 10 metre contours. This interpolation method lends itself to errors in areas where contours are widely spaced such as low lying coastal areas. However this DEM is currently the best available alternative to the LiDAR DEM over coastal areas and can at least provide an indication of areas potentially subject to inundation due to sea level rise.

Tidal range data

Over the majority of the mapped area, the standard National Tidal Centre (NTC) modelled tidal range grid was used to determine the approximate high water mark. This was supplemented by additional published tidal height data for the Tamar Valley and Macquarie Harbour (Mount *et al* 2011).

The NTC tidal range data which is accessible via the Bureau of Meteorology (BOM) web site (www.bom.gov.au/oceanography/tides/index_range.shtml) was obtained from the National Tidal Centre in the form of a five minute resolution grid of points including coverage of Tasmanian coastal waters (ftp.bom.gov.au/anon/home/ntc/james/model/range_m_aus5min.zip).
The NTC tidal range is the height in metres between Mean Sea Level and Indian Spring Low Water multiplied by two to give an estimate of the complete tidal range. It includes the four main tidal constituents, M2, S2, O1 and K1, and was calculated as:

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

For inundation mapping purposes it was assumed that the midpoint in the NTC tidal range represents mean sea level (MSL) and that this height is also at zero metres AHD. Regional variations in tidal dynamics may mean that the midpoint in the range is not always MSL. Also MSL, although intended as the base datum of AHD, is only approximate due to errors in methods used to derive AHD. Sea level rise in the time since AHD was derived has also added an amount to MSL which will vary by region.

For the purposes of the current mapping, half the NTC tidal range was considered to represent an approximation of the difference between MSL and high tidal height, and when added to MSL the total height should approximate, though tend to be higher than, the height of the mapped coastal high water mark. In this report this height is referred to as “NTC High Water”.

The Average Recurrence Interval (ARI; same as return period) for Burnie, George Town and Hobart for both tidal predictions (i.e. tide only) and observations (tide + surge) for a level equal to "Indian Springs High Water" (ISHW, defined as Mean Sea Level plus the amplitudes of the tidal constituents: M2 + S2 + O1 + K1) were extracted and are presented in Table 1 below. The results are based on periods of approximately 30 years.

There is a lot of variation in the ARI, even around Tasmania and the inclusion of surges (i.e. within the observational data) has a significant effect. The main difference between the north (Burnie and George Town) and the south (Hobart) is that the main semidiurnal tide is much larger in the north, which reduces the influence of the other tidal constituents (including those not contributing to ISHW). Therefore, in the north, the ISHW is a better measure of the maximum possible tide whereas in the south, all the other constituents (not included in the definition of ISHW) make the highest tide significantly larger than ISHW. In the north, therefore, ISHW is exceeded much less often than in the south.

Table 1: Average Recurrence Intervals (ARI) for three Tasmanian port tide gauges – observed and predicted are for periods of approximately 30 years (Source: John Hunter, pers. comm.)

Port	**ISHW (m, AHD)**	**Average Recurrence Interval (days)**	
		Predictions (Tide only)	Observations (Tide plus surge)
Burnie	1.514	322	61
George Town	1.521	843	47
Hobart	0.658	39	21

However, when you include the effects of surges, the difference between north and south becomes less apparent. What this means is that it is appropriate to define the level chosen to be the base to which the sea level is added (i.e. labelled as the NTC modelled high water in this report) as “the sea level that is exceeded about every 1-2 months”. This base sea level is the combined effect of the tides and all other factors affecting the level of the sea such as the wind and air pressure. In colloquial terms, it could be thought of as the height found at the “back of the beach” or at the “height of the higher high tides”.

Note that tide ranges are complex phenomena and the modelling approach used by the NTC is not designed to precisely model tide ranges in estuaries and more enclosed embayments. Typically, though not always, tide ranges are reduced where the tidal wave passes through constrictions, such as estuary entrances, or over shallow water. In these circumstances, the inundation modelling will tend to overestimate the sea level as the tide range may not actually be as high as the NTC estimate.

Storm Tide AEP data

Modelled storm tide AEP predictions for the whole Tasmanian coast from the CSIRO (McInnes *et al.* 2009, McInnes *et al.* 2012; Appendix 2) were used as the source dataset in the AEP calculations. Heights for AEPs of 0.005%, 0.05%, 0.5%, 1%, 2% and 5% were extracted from the modelled exceedance probability curves. These were then adjusted upwards by 0.07 metres in order to best fit the observed AEP heights in 2000 at tidal gauges of Hobart and Burnie. A further upwards adjustment of 0.03 metres was then added to allow for the estimated sea-level rise from 2000 to 2010, yielding AEP heights relevant to the base year of the Tasmanian sea-level rise allowances (2010).

Tasmanian Sea-Level Rise Allowances

The Tasmanian sea-level rise allowances for 2050, 2075 and 2100, relative to 2010, are 0.2, 0.4 and 0.8 metres, respectively. These are based on the technique of Hunter (2012), observations of storm tides from the tide gauges at Hobart and Burnie, and regional projections of sea-level rise based on the IPCC A1FI emission scenario (Hunter et al., 2012). These allowances were added to the AEPs for 2010, to derive AEPs appropriate to 2050, 2075 and 2100. It has been assumed that the change in AEPs over this time period is dominated by the effect of sea-level rise on mean sea level; future change in the variability of sea-level around the mean (e.g. due to an increase in storminess) is believed to be small and has been neglected (Hunter, 2012).

Mapping of High Tides and SLR

The "**High Tides and SLR**" component of this mapping, used the "bathtub" inundation method (Eastman, 1993). The "bathtub" or "still water" method is essentially a simplified representation of reality generated with electronic mapping systems (GIS). The method assumes a calm still sea surface. The sea level components (including sea level rise levels and the tidal range) were combined with a digital elevation model (DEM) to calculate a spatial grid over the area of interest showing the locations likely to be inundated given the model settings and constraints. The positions of possible future, or "indicative", shorelines were extracted from the grid model. Given that the mapped coastline is usually at the high water mark and that most human activities are landwards of the high water mark, this was considered a useful base height to which to add the sea level rise estimates. The resultant "indicative" shorelines can be considered as new positions for the "back of the beach" in the simple virtual reality of the model.

The previous mapping presented in Mount *et al*. (2011) followed a probability based approach in which error probability levels were also calculated based on the error probabilities propagated from the input datasets. This approach produced output datasets representing 5%, 50% and 95% likelihoods that a new shore position was at or above the mapped height based on error inputs. Algorithms used in this mapping approach have been documented in Mount *et al*. (2011). The current mapping is required at the 50% probability level only, meaning that a much simpler additive mapping approach could be applied. Consequently reference to the 50% probability level has been omitted and is assumed.

Inputs to this mapping can be summarised as follows:

- The Climate Futures LiDAR DEM or where that was not available the Tasmanian 25 metre DEM was substituted,
- The Mean Sea Level (MSL) is assumed to equal 0 m Australian Height Datum (AHD),
- Tide estimates (in metres AHD), based on the NTC High Water Mark (see Definitions section) for the majority of the mapped area or published tidal data for Tamar River and Macquarie Harbour, and
- A series of sea level rise heights, these being 0.2, 0.4 and 0.8 metres.

The primary outputs were a series polygon datasets representing the most likely position of the shoreline with 0.2, 0.4 or 0.8 metre sea level rise allowance relative to 2010. Datasets were combined into a single polygon shapefile.

Geoprocessing implementation – "High Tides and SLR"

Existing SLR polygon datasets produced in the stage one project (Table 2) were used as the data inputs for the LiDAR areas. Methods that were used to produce these datasets are documented in Mount *et al*. (2011). New mapping was required for parts of the coast not covered by the Climate Futures LiDAR DEM. In those regions mapping was based on the Tasmanian 25 metre DEM as detailed below. For the 25 metre DEM areas the combined tidal inundation and sea level rise was rounded-up to the nearest whole metre. Mapped outputs for LiDAR and non-LiDAR areas were then combined into the final dataset. Geoprocessing was conducted using ArcGIS 10.0.

Table 2: Datasets used from the stage one project

Dataset from stage one project	Description
NTC_TR_20SLR_50pct.shp NTC_TR_40SLR_50pct.shp NTC_TR_80SLR_50pct.shp	Polygon mapping of expected tidal inundation with 20, 40 and 80 cm sea level rise in LiDAR areas excluding southern Tamar.
TamarSouth_MHW_20SLR_50pct.shp TamarSouth_MHW_40SLR_50pct.shp TamarSouth_MHW_80SLR_50pct.shp	Polygon mapping of expected tidal inundation with 20, 40 and 80 cm sea level rise in the southern part of the Tamar Valley, east of MGA 50200 metres.

SLR polygon generation and processing for non-LiDAR areas

Modelled tidal range data was available as points around the whole Tasmanian coast. The modelled points were all on the seaward side of the coastline and usually did not extend to the coast, especially in the vicinity of bays and estuaries. A spline interpolation with barriers was used to create the tidal range surface extending across the land. In Macquarie Harbour the tidal height as published by Koehnken L. (1996) was used.

Sea level rise increments to the specified heights were added to the tidal heights. For the 25 metre DEM areas only, the combined tidal inundation and sea level rise was then rounded-up to the nearest whole metre. Tidal surfaces with SLR were subtracted from the 25m DEM and cells of the resultant surface with a value less than zero were designated as inundated. Outputs were converted to polygon shapefiles which showed areas expected to be inundated under the modelled scenarios. The polygon shapefiles were clipped to a polygon version of the coastline.

Dataset combination

LiDAR based and non-LiDAR based datasets were combined into a single state-wide dataset. A polygon mask, identifying location of reliable LiDAR areas, was used to clip out those areas from the LiDAR based polygon outputs and to erase the same areas from the 25 metre DEM based outputs. LiDAR and 25 m DEM based datasets were then merged to produce the combined shapefile.

Output Dataset – "High Tides and SLR"

The output is a single combined polygon dataset representing the areas of permanent (tidal) inundation that can be expected for the years 2050, 2075 and 2100. Concentric polygon areas represent regions expected to be inundated by sea level rise of 0.2, 0.4 and 0.8 metre respectively above 2010 levels. The Climate Futures LiDAR DEM has been used as the height reference where it was available and considered to be reliable. The Tasmanian 25 metre DEM was used in all other areas. The sea level reference was the NTC modelled high water except is the Tamar Valley and Macquarie Harbour where alternative published mean high tide heights were used.

The output dataset name is "**TidalInundationModel_V2"** and is provided in file geodatabase (.gdb) format with the dataset having the same name as the geodatabase in which it is enclosed. The dataset is projected in GDA 94 MGA Zone 55. Attributes are listed in Table 3. Attribution has been included to allow selection of inundation polygons associated with each of the target years and also to distinguish between polygons that are contiguous or non-contiguous with the coast. Table 4 list queries in ArcGIS that can be used to select contiguous or non-contiguous inundation polygon extents.

Table 3: Attribute fields for TidalInundationModel_V2.shp

Field Name	Data type	Details
TR2050	Text	“0.2 m” indicates projected inundation level in 2050.
TR2075	Text	“0.4 m” indicates projected inundation level in 2075.
TR2100	Text	“0.8 m” indicates projected inundation level in 2100.
IC2050	Integer	(1 = contiguous with coast; 0 = not contiguous with coast) at 0.2 m inundation.
IC2075	Integer	(1 = contiguous with coast; 0 = not contiguous with coast) at 0.4 m inundation.
IC2100	Integer	(1 = contiguous with coast; 0 = not contiguous with coast) at 0.8 m inundation.
SL_Ref	Text	NTC_HW (= NTC modelled high water) NTC_HW Extr (= NTC modelled high water extrapolated in Tamar and on southern side of Robbins Island) MHT (= Mean high tide in Launceston area) MHT Mac Hb (= mean high tide Macquarie Harbour)
SLR	Text	Sea level rise level (in metres) in which the polygon appears “inundated”.
DEM_Ref	Text	CFL (= Climate Futures LiDAR) DEM25 (= State 25 m DEM) **Note: Inundation heights in the 25 m DEM areas have been rounded up to the nearest whole metre.**
Shape_Length	Floating point	Polygon perimeter in metres.
Shape_Area	Floating point	Polygon area in square metres.

Table 4: ArcGIS queries for selection of inundation extents that are contiguous or not contiguous with the coast from the tidal inundation dataset

To select	Query
Polygons contiguous with the coast that are expected to be inundated in 2050.	"TR2050" = '0.2 m' AND "IC2050" = 1
Polygons not contiguous but potentially inundation in 2050 under some circumstances.	"TR2050" = '0.2 m' AND "IC2050" = 0
Polygons contiguous with the coast that are expected to be inundated in 2075.	"TR2075" = '0.4 m' AND "IC2075" = 1
Polygons not contiguous but potentially inundation in 2075 under some circumstances.	"TR2075" = '0.4 m' AND "IC2075" = 0
Polygons contiguous with the coast that are expected to be inundated in 2100.	"TR2100" = '0.8 m' AND "IC2100" = 1
Polygons not contiguous but potentially inundation in 2100 under some circumstances.	"TR2100" = '0.8 m' AND "IC2100" = 0

Discussion – “High Tides and SLR”

It should be noted that not all variables relevant to the accurate modelling and prediction of new shoreline positions are currently available for all the locations of interest around the coast, that is, there are limitations on the available data inputs at the Tasmanian scale. For example,

- The high resolution Climate Futures LiDAR DEM currently only covers about a third of the more highly populated coastlines and is known to have inaccurate heights in some areas.
- The lower resolution 25 metre DEM may give an indication only of potential coastline positions with sea level rise.
- The tide range data for Tasmania is limited to either direct observations at the main tide gauges or, for other locations along the shore, to modelled estimates from the National Tidal Centre, Bureau of Meteorology. The tides in more enclosed bays and estuaries or around islands can be substantially different to those shown in the available data.
- Also, there is no consideration of the complex interactions between erosion, coastal recession and inundation. The “bathtub” or “still water” method is essentially a passive model and assumes a calm sea surface. It is useful because it is a simple, fast method that indicates locations with the potential for inundation and can, if used judiciously and with other lines of evidence, assist with prioritising further activity.

Storm Tide Event plus SLR

In the absence of sea-level rise, future flooding events from the sea depend on the tides, storm surges and waves. While the tides are predictable, future storm surges and waves may only be described in a statistical sense. For example, the time and height of high water at a given location is known at any future time from our knowledge of past tides and of the motions of the Sun and the Moon. However, future storm surges are generally quantified by the average time between events when a certain level is exceeded (the "return period" or "average recurrence interval"), or by the probability that a certain level is exceeded once or more during a given period (e.g. the "Annual exceedance probability" or AEP). Similar statistics may be applied to the occurrence of waves, although the effects of waves are not specifically included in the projections provided here. For the present work, tides and storm surges ("storm tides") around the Tasmanian coastline were derived from numerical modelling by Kathleen McInnes of CSIRO (see Appendix 2). From these results were derived heights for AEPs of 0.005%, 0.05%, 0.5%, 1%, 2% and 5%. As described in the Section "Storm Tide AEP Data", the modelled AEP heights were adjusted to best fit observations from Hobart and Burnie, and to relate to the year 2010, the base year for the Tasmanian sea-level rise allowances.

Under climate change, flooding events from the sea will become more frequent, mainly due to the effect of sea-level rise. Future sea level has been estimated by numerous modelling groups around the world and is regularly collated and summarised by the Intergovernmental Panel on Climate Change (IPCC) in their Assessment Reports. These estimates are, however, accompanied by significant uncertainty (both due to uncertainty in the science and uncertainty in future emissions of greenhouse gases). The sea-level rise allowances used in this project have been supplied by the Tasmanian Government to create coastal inundation area maps to support the development of a coastal policy, and a coastal inundation planning code. These allowances are based on the technique of Hunter (2012), observations of storm tides from the tide gauges at Hobart and Burnie, and regional projections of sea-level rise based on the IPCC A1FI emission scenario (Hunter *et a*l., 2012).

The Tasmanian sea-level rise allowances (0.2, 0.4 and 0.8 metres for 2050, 2075 and 2100, relative to 2010, respectively) were then added to the modelled heights for 2010 for AEPs of 0.005%, 0.05%, 0.5%, 1%, 2% and 5%, to yield the 24 data sets of heights used for the inundation mapping.

Geoprocessing implementation – "Storm Tide Event plus SLR"

Twenty four "Storm Tide plus SLR" height datasets representing the heights for each of the 6 AEPs (0.005%, 0.05%, 0.5%, 1%, 2% and 5%) and each of the four years (2010, 2050, 2075 and 2100) were geographically mapped. Each of the 24 AEP height datasets represented calculated storm tide plus sea level rise exceedance heights for sea level rise scenarios as specified by the Tasmanian Government to create coastal inundation area maps to support the development of a coastal policy, and a coastal inundation planning code.

GIS processing was conducted using ArcGIS 10.0 with the majority of processing being scripted using Python 2.6.5. The main geoprocessing steps are summarised as follows.

A spline with barriers interpolation method was used to calculate a series of height surfaces, from a set of AEP datasets for the year 2000. Sea level rise heights of 0.03, 0.23, 0.43 and 0.83 metre were added to the height surfaces to calculate AEP height surfaces for the years 2010, 2050, 2075 and 2100 respectively. LiDAR areas were processed as sixteen mosaicked regions and the 25 metre DEM was processed as a single state-wide region. For the 25 metre DEM areas only, the combined AEP inundation and sea level rise was rounded-up to the nearest whole metre. AEP height surfaces were subtracted from the LiDAR and 25m DEM surfaces and cells of the resultant surface with a value less than zero were designated as inundated. Outputs were converted to polygon shapefiles which showed areas expected to be inundated under the modelled scenarios. This polygonisation step used the "no_simplify" option. The polygon layers were then clipped to a polygon version of the coastline. For each target year a union step was used to combine the AEP level polygon datasets into single polygon dataset for each region. A series of erase steps were then used to remove overlapping areas before merging the sixteen LiDAR mapped regions into a combined shapefile for each target year. A polygon mask, identifying location of reliable LiDAR areas, was used to clip out those areas from the LiDAR based polygon outputs and to erase the same areas from the 25 metre DEM based outputs. LiDAR and 25 m DEM datasets were then merged to produce combined state-wide polygon shapefiles for each target year. Datasets were converted to geodatabase format to reduce file size and to speed up screen refresh times.

Output Datasets – "Storm Tide Annual Exceedance probabilities"

AEP datasets are listed in Table 5 and are provided in file geodatabase format with the dataset having the same name as the geodatabase in which it is enclosed. All of the datasets are projected in GDA 94 MGA Zone 55. Attributes of the datasets are listed in Table 6. Figure 2 illustrates how inundation extents are represented in each dataset as concentric polygons for each AEP level.

Table 5: Storm Tide AEP Datasets

Dataset Name	File geodatabase	Target Year	Projected sea level rise (m)
StormTide_AEP_2010_V2	Storm_Tide_AEP_2010_V2.gdb	2010	0
StormTide_AEP_2050_V2	Storm_Tide_AEP_2050_V2.gdb	2050	0.2
StormTide_AEP_2075_V2	Storm_Tide_AEP_2075_V2.gdb	2075	0.4
StormTide_AEP_2100_V2	Storm_Tide_AEP_2100_V2.gdb	2100	0.8

Table 6: Attributes of the Storm Tide AEP Datasets

Field Name	Data type	Details
AEP5pct	Text	"5%" indicates inundation at 5% AEP level.
AEP2pct	Text	"2%" indicates inundation at 2% AEP level.
AEP1pct	Text	"1%" indicates inundation at 1% AEP level.
AEP_5pct	Text	"0.5%" indicates inundation at 0.5% AEP level.
AEP_05pct	Text	"0.05%" indicates inundation at 0.05% AEP level.
AEP_005pct	Text	"0.005%" indicates inundation at 0.005% AEP level.
IC5pct	Integer	(1 = contiguous with coast; 0 = not contiguous with coast) at 5% AEP level.
IC2pct	Integer	(1 = contiguous with coast; 0 = not contiguous with coast) at 2% AEP level.
IC1pct	Integer	(1 = contiguous with coast; 0 = not contiguous with coast) at 1% AEP level.
IC_5pct	Integer	(1 = contiguous with coast; 0 = not contiguous with coast) at 0.5% AEP level.
IC_05pct	Integer	(1 = contiguous with coast; 0 = not contiguous with coast) at 0.05% AEP level.
IC_005pct	Integer	(1 = contiguous with coast; 0 = not contiguous with coast) at 0.005% AEP level.
AEP_Level	Text	First AEP level in which the polygon appears "inundated".
SLR	Text	Sea level rise for target year (2010, 0.0 m; 2050, 0.2 m; 2075, 0.4 m; 2100, 0.8 m).
DEM_Ref	Text	CFL (= Climate Futures LiDAR) DEM25 (= State 25 m DEM) **Note: Inundation heights in the 25 m DEM areas have been rounded up to the nearest whole metre.**
Shape_Length	Floating point	Polygon perimeter in metres.
Shape_Area	Floating point	Polygon area in square metres.

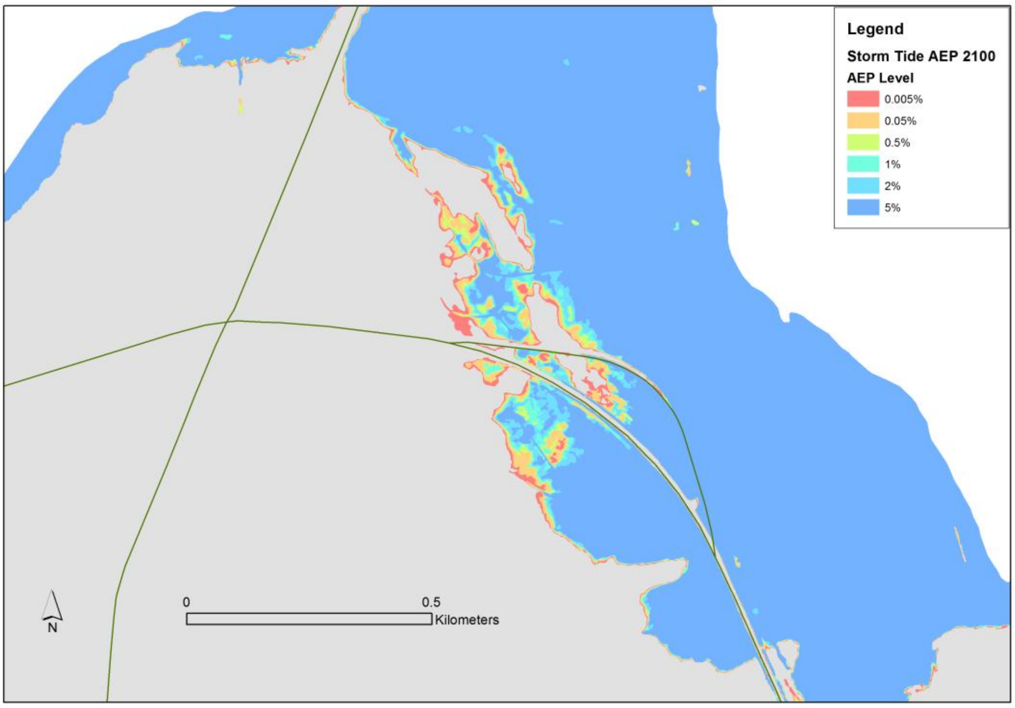

Figure 2. Example of the AEP inundation polygon mapping, illustrating how inundation extents are represented in each dataset as concentric polygons for each AEP level. Olive green lines on this map are roads, grey area is un-inundated land and white is seaward of the coast.

Attribution has been included to allow selection of inundation polygons associated with each of the target years and also to distinguish between polygons that are contiguous or non-contiguous with the coast. Table 7 lists queries in ArcGIS that can be used to select contiguous or non-contiguous inundation polygon extents for the AEP datasets.

Table 7: ArcGIS queries for selection of inundation extents that are contiguous or not contiguous with the coast from the AEP datasets

To select	Query
Polygons contiguous with the coast that are expected to be inundated at 5% AEP level.	"AEP5pct" = '5%' AND "IC5pct" = 1
Polygons not contiguous but potentially inundation at 5% AEP level under some circumstances.	"AEP5pct" = '5%' AND "IC5pct" = 0
Polygons contiguous with the coast that are expected to be inundated at 2% AEP level.	"AEP2pct" = '2%' AND "IC2pct" = 1
Polygons not contiguous but potentially inundation at 2% AEP level under some circumstances.	"AEP2pct" = '2%' AND "IC2pct" = 0
Polygons contiguous with the coast that are expected to be inundated at 1% AEP level.	"AEP1pct" = '1%' AND "IC1pct" = 1
Polygons not contiguous but potentially inundation at 1% AEP level under some circumstances.	"AEP1pct" = '1%' AND "IC1pct" = 0
Polygons contiguous with the coast that are expected to be inundated at 0.5% AEP level.	"AEP_5pct" = '0.5%' AND "IC_5pct" = 1
Polygons not contiguous but potentially inundation at 0. 5% AEP level under some circumstances.	"AEP_5pct" = '0.5%' AND "IC_5pct" = 0
Polygons contiguous with the coast that are expected to be inundated at 0.05% AEP level.	"AEP_05pct" = '0.05%' AND "IC_05pct" = 1
Polygons not contiguous but potentially inundation at 0.05% AEP level under some circumstances.	"AEP_05pct" = '0.05%' AND "IC_05pct" = 0
Polygons contiguous with the coast that are expected to be inundated at 0.005% AEP level.	"AEP_005pct" = '0.005%' AND "IC_005pct" = 1
Polygons not contiguous but potentially inundation at 0.005% AEP level under some circumstances.	"AEP_005pct" = '0.005%' AND "IC_005pct" = 0

Discussion – "Storm Tide Event plus SLR"

The areas covered by the Storm Tide AEP polygon mapping show a range of AEP percentages. Individual polygons have the attribute "AEP_Level" which specifies the mapped AEP percentage to which the polygon relates. The precise *landward extent* (i.e. edge or boundary) of the polygon represents the specified AEP for the prescribed year and the area within the remainder of the polygon has a higher exceedance probability.

For example, for a polygon with "AEP_Level" of 0.05% in the dataset StormTide_AEP_2100_V1_2:

- Anything lying at ground level at the landward edge (or boundary) of the polygon ("flood plain") has an AEP of 0.05% of being flooded by a storm tide once or more during 2100,
- Any land *seaward* of this line (i.e. lying inside this flooding zone) has a *higher* probability of being flooded, and
- Any land *landward* of this line (i.e. lying outside this flooding zone) has a *lower* probability of being flooded.

A number of caveats accompany these results:

- These storm-tide coastal flooding zones include the effects of tides, storm surges and sea-level rise only. They do not include the effects of wave set-up or wave run-up. Additional allowances ("freeboard") may therefore need to be made for effects associated with waves.
- The projections of sea-level rise used in these calculations involve considerable uncertainty, arising from an imperfect understanding both of the science and of the world's future emissions.
- These results relate to the increase in the probability of extreme events caused by a rise in mean sea level; they do not make any projections of changes in storm tides.

Coastal Inundation Height Reference Dataset

The approach for this dataset was to utilise all the input calculations to the SLR mapping presented earlier in this report and, instead of mapping those on a DEM, the results were stored in the form of 1 kilometre square grid tiles implemented as a GIS polygon vector layer. The "**Tasmania_Coastal_Heights_Ref_V3_2**" tiles consist of square polygons covering the whole of the Tasmanian shoreline inland from the coast to at least the 10 m contour. See the example in Figure 3 below. This is an updated version of the "HeightRefs" and "HeightRefs_Tas" shapefiles produced for the stage one project and combine height references for the range of tidal inundation and storm tide AEPs mapped areas. Some additional tiles have been added including additional islands in the northern end of Bass Strait.

The "**permanent sea level rise**" inundation heights are based on the tide range calculations plus added sea level rise in steps of 0.1 metre up to 1.2 metre. The calculated reference inundation heights are relative to the Australian Height Datum (AHD) at the centre of individual 1 km tiles.
In most cases the reference height if from the National Tidal Centre modelled tidal range grid (i.e. "NTC High Water"). For the Tamar region, mean high water (MHW) heights were used as published by Foster *et al*. (1986). Base height in Macquarie Harbour is from Koehnken L. (1996). Figures are a best estimate based on the input data but may not reflect actual conditions, particularly in rivers and estuaries, and require verification. Attributes of this shapefile are listed in Table 6 below.

The "**storm tide AEP plus sea level rise**" heights are for AEP heights for AEP percentages of 0.005%, 0.05%, 0.5%, 1%, 2% and 5% for the years 2010, 2050, 2075 and 2100 as listed in Table 6 below. Heights are relative to AHD.

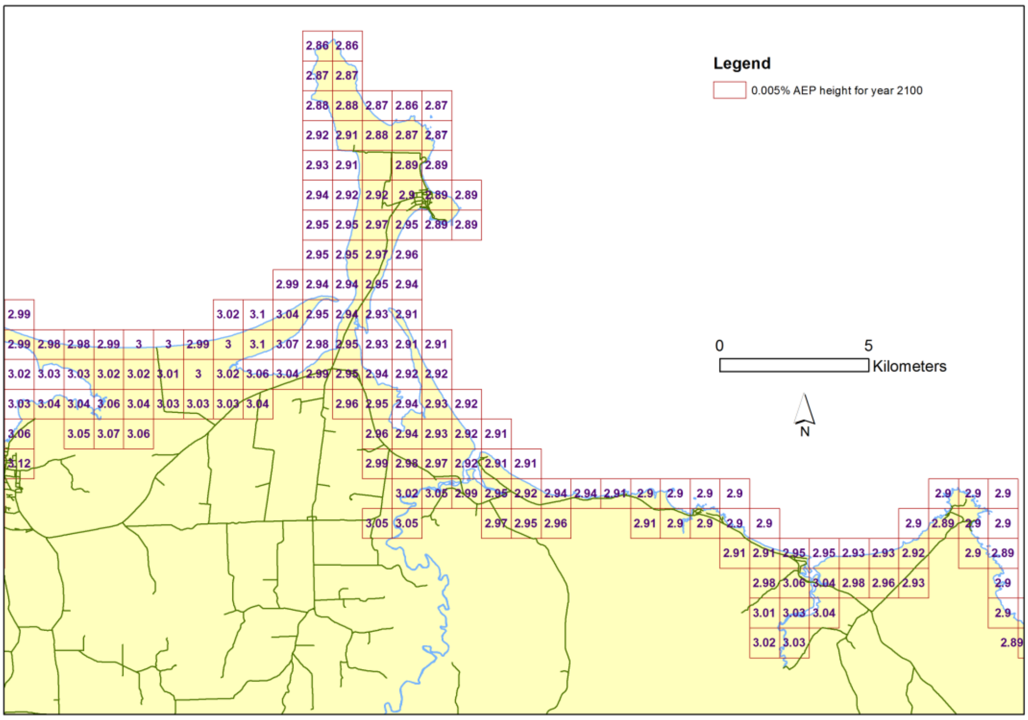

Figure 3. Example of the 1 km tiles showing the calculated 0.005% AEP height for the year 2100. Note the change in the heights across the area is generally small between adjacent tiles but is more significant across larger distances.

This dataset also includes the following attributes:

HAT (Highest Astronomical Tide). This is the highest tide that may be expected under normal meteorological conditions. Data was obtained from NTC in the form of a 5 minute grid of points (ftp.bom.gov.au/anon/home/ntc/james/model/ntc5_1.2.lathat.zip). A spline-with-barriers interpolation was used to interpolate this data to the Tasmanian coast. This data was not interpolated into estuaries or rivers or otherwise inland of the coast and has been provided as an additional reference to tidal heights.

Local Storm Surge, Wave Setup and Wave Runup. Attributes have been included for these factors. The concept of "local" storm surge depends on scale and is somewhat arbitrary. The storm-tide modelling of McInnes *et al*. (2012) (used to estimate the heights for each AEP) had a resolution of about 100 metres; all surges of a scale larger than this are therefore included in the AEP heights and only surges of scale around 100 metres or less are not included (we have no information on such small-scale surges). Also, wave setup and wave runup was not included in the storm tide modelling. Therefore, no data was available on these factors and they have been designated "unknown".

Output Dataset – Coastal Inundation Height Reference

The dataset **“TasHeightsRefV3_2”** is provided in ESRI personal geodatabase **“Tasmania_Coastal_Heights_Ref_V3_2.mdb”**. Attributes are listed in Table 6. The dataset is projected in GDA 94 MGA Zone 55 and heights are in metres AHD.

Table 8: Attribute of Height Reference layer V3.2

Field Name	**Details**
LL_Pos_EN	Tile lower left eastings and northings in kilometres, (eg. e473_n5448).
Easting	Tile centre easting in metres (MGA zone 55)
Northing	Tile centre northing in metres (MGA zone 55)
Base_Ht	Interpolated reference high water mark height at the centre of tile. In most cases this will be based on NTC tide range. See note 1.
Base_Ht_Ref	Source of height reference used in tile (NTC TR, NTC tide range; MHT Mac Hb, mean high tide for Macquarie Harbour; MHT Tamar, mean high tide Tamar).
TR_0SLR	Modelled inundation height for tile with 0 sea level rise at 50% probability level.
TR_10SLR	Modelled inundation height for tile with 10 cm sea level rise at 50% probability level.
TR_20SLR	Modelled inundation height for tile with 20 cm sea level rise at 50% probability level.
TR_30SLR	Modelled inundation height for tile with 30 cm sea level rise at 50% probability level.
TR_40SLR	Modelled inundation height for tile with 40 cm sea level rise at 50% probability level.
TR_50SLR	Modelled inundation height for tile with 50 cm sea level rise at 50% probability level.
TR_60SLR	Modelled inundation height for tile with 60 cm sea level rise at 50% probability level.
TR_70SLR	Modelled inundation height for tile with 70 cm sea level rise at 50% probability level.
TR_80SLR	Modelled inundation height for tile with 80 cm sea level rise at 50% probability level.
TR_90SLR	Modelled inundation height for tile with 90 cm sea level rise at 50% probability level.
TR_100SLR	Modelled inundation height for tile with 100 cm sea level rise at 50% probability level.
TR_110SLR	Modelled inundation height for tile with 110 cm sea level rise at 50% probability level.
TR_120SLR	Modelled inundation height for tile with 120 cm sea level rise at 50% probability level.
HAT	Modelled Highest Astronomic Tide from NTC. This data is included for reference and has not been used in tide height calculations. “-999” = No data. See Note 2.
Local_Storm_Surge	Local storm surge if known.
Wave_Setup	Wave setup if known.
Wave_Runup	Wave runup if known.
AEP_005pct2010	Modelled 0.005% Annual Exceedance Probability height for 2010.
AEP_05pct2010	Modelled 0.05% Annual Exceedance Probability height for 2010.
AEP_5pct2010	Modelled 0.5% Annual Exceedance Probability height for 2010.
AEP1pct2010	Modelled 1% Annual Exceedance Probability height for 2010.
AEP2pct2010	Modelled 2% Annual Exceedance Probability height for 2010.
AEP5pct2010	Modelled 5% Annual Exceedance Probability height for 2010.
AEP_005pct2050	Modelled 0.005% Annual Exceedance Probability height for 2050.
AEP_05pct2050	Modelled 0.05% Annual Exceedance Probability height for 2050.
AEP_5pct2050	Modelled 0.5% Annual Exceedance Probability height for 2050.
AEP1pct2050	Modelled 1% Annual Exceedance Probability height for 2050.
AEP2pct2050	Modelled 2% Annual Exceedance Probability height for 2050.
AEP5pct2050	Modelled 5% Annual Exceedance Probability height for 2050.
AEP_005pct2075	Modelled 0.005% Annual Exceedance Probability height for 2075.
AEP_05pct2075	Modelled 0.05% Annual Exceedance Probability height for 2075.
AEP_5pct2075	Modelled 0.5% Annual Exceedance Probability height for 2075.
AEP1pct2075	Modelled 1% Annual Exceedance Probability height for 2075.
AEP2pct2075	Modelled 2% Annual Exceedance Probability height for 2075.
AEP5pct2075	Modelled 5% Annual Exceedance Probability height for 2075.
AEP_005pct2100	Modelled 0.005% Annual Exceedance Probability height for 2100.
AEP_05pct2100	Modelled 0.05% Annual Exceedance Probability height for 2100.
AEP_5pct2100	Modelled 0.5% Annual Exceedance Probability height for 2100.
AEP1pct2100	Modelled 1% Annual Exceedance Probability height for 2100.
AEP2pct2100	Modelled 2% Annual Exceedance Probability height for 2100.
AEP5pct2100	Modelled 5% Annual Exceedance Probability height for 2100.
Shape_Length	Tile perimeter length in metres
Shape_Area	Tile area in square metres

Note 1
In most cases the reference height if from the National Tidal Centre modelled tidal range grid (i.e. “NTC High Water”). For the Tamar region, mean high tide (MHT) heights were used as published by Foster *et al*. (1986). Base height in Macquarie Harbour is from Koehnken L. (1996). Figures are a best estimate based on the input data but may not reflect actual conditions, particularly in rivers and estuaries, and require verification.

Note 2
Modelled HAT (Highest Astronomic Tide) has been included for reference and has not been used in tide height calculations. Interpolated values for rivers and estuaries are approximate and should only be used in those areas with caution. Values for locations inland from the open coast have been designated “no_data” and have been given a value of “-999”.

Discussion – Coastal Inundation Height Reference

The "**Coastal Inundation Height Reference**" tiles can be used to identify the heights of the water surfaces calculated according to the methods used for this project in "High Tides and SLR" and "Storm Tide Event plus SLR" sections of this report.

The data set is intended as a way of looking up threshold or trigger heights for parcels of land that fall either partly or entirely with any particular tile. For example,

- if a parcel of land does fall partly or entirely within the boundaries of a particular tile
    - AND
- if a particular height was designated by an appropriate authority to require (i.e. trigger) further action,
    - AND
- the parcel of land was found to be entirely or partially below that reference height
    - THEN
- the required action would be triggered.

Important note: As these reference heights have NOT been mapped onto the ground, this data set does NOT show mapped areas of land that are likely to be subject to inundation.

The Coastal Inundation Height Reference", has some limitations that should be acknowledged:

- The tide range data for Tasmania is limited to either direct observations at the main tide gauges or, for other locations along the shore, to modelled estimates from the National Tidal Centre, Bureau of Meteorology. The tides in more enclosed bays and estuaries or around islands can be substantially different to those shown in the available data. The Height Reference tiles may cover places with tidal ranges different to those used to calculate the tile heights. If this is the case, then the calculated heights may not reflect actual heights experienced at the shore.
- A single Height Reference tile may cover places with different tidal ranges and the calculated heights may not reflect actual heights experienced at the shore in one or more of those places.
- The IPCC projections of sea-level rise used in these calculations involve considerable uncertainty, arising from imperfect understanding both of the science and of the world's future emissions.
- These results relate to the increase in the probability of extreme events caused by a rise in mean sea level; they do not include any projections based on changes in storm tides.

References

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

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

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

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McInnes, K.L., O'Grady, J.G., Hemer, M., Macadam, I., Abbs, D.J., White, C.J., Bennett, J.C., Corney, S.P., Holz, G.K., Grose, M.R., Gaynor, S.M. and Bindoff, N.L. (2012), Climate Futures for Tasmania: extreme tide and sea level events technical report, Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania.

Mount, R.E., Lacey, M.J. and Hunter, J.R. (2010) Tasmanian Coastal Inundation Mapping Project Report Version 1.2, Tasmanian Planning Commission [Consultants Report]

Mount, R.E., Lacey, M.J. and Hunter, J.R. (2011) Tasmanian Coastal Inundation Mapping Project Report Version 2.0, Tasmanian Planning Commission [Consultants Report]

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

Appendix 1. Draft Metadata

Coastal High Water plus Sea Level Rise Inundation Modelling metadata – Tasmania, Version 2

Draft metadata prepared by Dr Michael Lacey, School of Geography and Environmental Studies, University of Tasmania 21st September 2012.

General Properties	
File Identifier	
Hierarchy Level	series
Hierarchy Level Name	series
Standard Name	ANZLIC Metadata Profile: An Australian/New Zealand Profile of AS/NZS ISO 19115:2005, Geographic information - Metadata
Standard Version	1.1
Date Stamp	2012-09-21
Resource Title	Coastal High Water plus Sea Level Rise Inundation Model – Tas., Version 2
Other Resource Details	M.J. Lacey, J.R. Hunter and R.E. Mount (2012) Coastal Inundation Mapping for Tasmania – Stage 2 Version 1. Report to the Department of Premier and Cabinet by the Blue Wren Group, School of Geography and Environmental Studies, University of Tasmania and the Antarctic Climate and Ecosystems Cooperative Research Centre
Key Dates and Languages	
Date of creation	2012-09
Date of publication	2012-09
Metadata Language	eng
Metadata Character Set	utf8
Dataset Languages	eng
Dataset Character Set	utf8
Abstract	A digital dataset that represents modelled potential inundation effects of a set of combined sea level rise and high tide scenarios for coastal areas of Tasmania and adjoining land regions within the extent of the Climate Futures LiDAR DEM or alternatively the Tasmanian 25 metre DEM where the LiDAR DEM was not available. Sea level rise scenarios include 0.2, 0.4 and 0.8 metres above 2010 level. At each sea level rise scenario high water modelling is based on modelled tide range data provided by the National Tidal Centre. Some extrapolation of input data was required to extend tide data into the Tamar Estuary and coastal and estuarine areas at the eastern end of Boullanger Bay and into Robbins Passage and Duck Bay.
Purpose	This dataset was prepared to assist in the identification of regions that may be subject to the effects of sea level rise such as coastal flooding.
Metadata Contact Information	
Name of Individual	Name withheld
Organisation Name	
Position Name	
Role	author
Voice	
Facsimile	
Email Address	
Address	
	Australia

Resource Contacts	
Name of Individual	
Organisation Name	
Position Name	
Role	pointOfContact
Voice	
Facsimile	
Email Address	
Address	
	Australia
Lineage Statement	Inputs: Digital Elevation Models LIDAR information as supplied via the Information & Land Services Division (ILS) of the Department of Primary Industries, Parks, Water and Environment (DPIPWE) or the Land Information System Tasmania (LIST), May 2008. Tasmanian 25 metre DEM (second edition) as supplied via the Information & Land Services Division (ILS) of the Department of Primary Industries, Parks, Water and Environment (DPIPWE) or the Land Information System Tasmania (LIST) SLR The sea level rise allowances are based on regional sea-level projections and the A1FI emission scenario. The allowances used in this dataset have been supplied by the Tasmanian Government to create coastal inundation area maps to support the development of a coastal policy, and a coastal inundation planning code. Tidal Range The standard tidal range modelled data was obtained from the National Tidal Centre (NTC) in the form of a five minute resolution grid of points extending from longitude 111º to 116º East and from latitude 9º to 45º South. This model represents tidal amplitudes in metres between Mean Sea Level and Indian Spring Low Water multiplied by two to give an estimate of the complete tidal range. It includes the four main tidal constituents, M2, S2, O1 and K1, and was calculated as: Tidal amplitude = (M2 + S2 + O1 + K1) amplitudes * 2 The NTC tide range grid needed to be extrapolated to extend into Boullanger Bay, Robbins Passage and Duck Bay. Additional points were first interpolated midway between the NTC grid points and extrapolated toward the coast to produce a 2.5 minute grid of points using the following criteria: • Outside the coastal area, points were interpolated from the existing points to produce a smooth surface. • Known tidal heights for Stack Island, Montague River and Duck Bay were included. • Mean High Water was estimated for the remaining region from the height of the lower edge of saltmarsh. • The height of one of the NTC tidal range points off the western end of Robbins Island was adjusted up to match newly calculated heights for eastern Boullanger Bay. A mean high water grid surface was then produced by spline interpolation from the 2.5 minute point grid. The NTC tide range grid also needed to be extrapolated to extend into the Tamar Estuary. Mean high water (MHW) heights for nine locations along the Tamar were sourced from Foster *et al*. (1986). An equation relating MHW at tide stations around Tasmania to the NTC tide range was derived and used to calculate comparable tide range heights for the nine Tamar locations. Calculated tide heights were then extrapolated across the region. For the Tamar Valley east of 502000 metres MGA Zone 55 the MHW height was used. For Macquarie Harbour MHW height was used as published by Koehnken (1996).

Inundation Modelling Method:
Inundation modelling used the “bathtub” inundation method (Eastman, 1993). This is the identical used for the Australian Coastal Vulnerability Assessment project (DCC, 2009). In this approach, sea level components (including sea level rise estimates and tidal range) together with their associated error estimates are combined with a digital elevation model (DEM) to calculate a spatial grid over the area of interest showing the locations likely to be inundated given the model settings and constraints.

Inundation heights in the 25 m DEM areas have been rounded up to the nearest whole metre.

The inundation method was implemented in ESRI ArcGIS 9.3 and ArcGIS 10.0 using the Python scripting environment.

The output is a single combined polygon dataset representing the areas of permanent (tidal) inundation that can be expected for the years 2050, 2075 and 2100. Concentric polygon areas represent regions expected to be inundated by sea level rise of 0.2, 0.4 and 0.8 metre respectively above 2010 levels. The dataset name is “TidalInundationModel_V2” and is provided in file geodatabase (.gdb) format with the dataset having the same name as the geodatabase in which it is enclosed.

Attributes:

Attribute	Details
TR2050	“0.2 m” indicates projected inundation level in 2050.
TR2075	“0.4 m” indicates projected inundation level in 2075.
TR2100	“0.8 m” indicates projected inundation level in 2100.
IC2050	(1 = contiguous with coast; 0 = not contiguous with coast) at 0.2 m inundation.
IC2075	(1 = contiguous with coast; 0 = not contiguous with coast) at 0.4 m inundation.
IC2100	(1 = contiguous with coast; 0 = not contiguous with coast) at 0.8 m inundation.
SL_Ref	NTC_HW (= NTC modelled high water) NTC_HW Extr (= NTC modelled high water extrapolated in Tamar and on southern side of Robbins Island) MHT (= Mean high tide in Launceston area) MHT Mac Hb (= mean high tide Macquarie Harbour)
SLR	Sea level rise level (in metres) in which the polygon appears “inundated”.
DEM_Ref	CFL (= Climate Futures LiDAR) DEM25 (= State 25 m DEM) **Note: Inundation heights in the 25 m DEM areas have been rounded up to the nearest whole metre.**
Shape_Length	Polygon perimeter in metres.
Shape_Area	Polygon area in square metres.

Inundated areas contiguous or non-contiguous with the coast in each year can be selected using a combination of two attributes. For example query "TR2050" = '0.2 m' AND "IC2050" = 1 will select polygons contiguous with the coast that are expected to be inundated in 2050.

References:

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DCC (2009) Climate Change Risks to Australia’s Coast: A First Pass National Assessment. Canberra, Department of Climate Change.

Foster, D.N., R., Nittim and J. Walker, (1986). Tamar River Siltation Study; WRL Technical Report No. 85/07.

Koehnken L. (1996) Macquarie Harbour – King River Study. Technical Report, DELM

Jurisdictions	
	Tasmania
Search Words	
	CLIMATE-AND-WEATHER-Climate-change
	CLIMATE-AND-WEATHER-Extreme-weather-events
	HAZARDS-Flood
	HAZARDS-Severe-local-storms
	MARINE
Themes and Categories	
Topic Category	elevation
Topic Category	geoscientificInformation
Topic Category	environment
Status and Maintenance	
Status	completed
Maintenance and Update Frequency	notPlanned
Date of Next Update	
Reference system	
Reference System	GDA94
Spatial Representation Type	
Spatial Representation Type	vector
Metadata Security Restrictions	
Classification	
Authority	
Use Limitations	
Dataset Security Restrictions	
Classification	
Authority	
Use Limitations	
Extent - Geographic Bounding Box	
North Bounding Latitude	-40
South Bounding Latitude	-44
West Bounding Longitude	144
East Bounding Longitude	149
Additional Extents - Geographic	
Identifier	TAS
Distribution Information	
Distributor 1	
Distributor 1 Contact	
Name of Individual	Name withheld
Organisation Name	
Position Name	
Role	distributor
Voice	
Facsimile	
Email Address	
Address	
	Australia

Storm Tide plus Sea Level Rise Inundation Modelling metadata – Tasmania, Version 2

Draft metadata prepared by Dr Michael Lacey, School of Geography and Environmental Studies, University of Tasmania 21st September 2012.

General Properties	
File Identifier	
Hierarchy Level	series
Hierarchy Level Name	series
Standard Name	ANZLIC Metadata Profile: An Australian/New Zealand Profile of AS/NZS ISO 19115:2005, Geographic information - Metadata
Standard Version	1.1
Date Stamp	2012-09-21
Resource Title	Storm Tide plus Sea Level Rise Inundation Model – Tas., Version 2
Other Resource Details	M.J. Lacey, J.R. Hunter and R.E. Mount (2012) Coastal Inundation Mapping for Tasmania – Stage 2 Version 1. Report to the Department of Premier and Cabinet by the Blue Wren Group, School of Geography and Environmental Studies, University of Tasmania and the Antarctic Climate and Ecosystems Cooperative Research Centre
Key Dates and Languages	
Date of creation	2012-09
Date of publication	2012-09
Metadata Language	eng
Metadata Character Set	utf8
Dataset Languages	eng
Dataset Character Set	utf8
Abstract	A series of digital datasets that represent modelled potential inundation effects of combined sea level rise and storm tide scenarios for coastal areas of Tasmania and adjoining land regions covered by the Climate Futures LiDAR or alternatively the Tasmanian 25 metre DEM where the LiDAR DEM was not available. The boundaries of these flooding zones indicate specific annual exceedance probabilities (AEP) of 0.005%, 0.05%, 0.5%, 1%, 2% or 5% for years 2010, 2050, 2075 or 2100 with sea level rise allowances based on the technique of Hunter (2012), observations of storm tides from the tide gauges at Hobart and Burnie, and regional projections of sea-level rise based on the IPCC A1FI emission scenario (Hunter et al., 2012). The allowances used in this dataset have been supplied by the Tasmanian Government to create coastal inundation area maps to support the development of a coastal policy, and a coastal inundation planning code.
Purpose	This dataset was prepared to assist in the identification of regions that may be subject to the effects of sea level rise such as coastal flooding.
Metadata Contact Information	
Name of Individual	Name withheld
Organisation Name	
Position Name	
Role	author
Voice	
Facsimile	
Email Address	
Address	

	Australia
Resource Contacts	
Name of Individual	
Organisation Name	
Position Name	
Role	pointOfContact
Voice	
Facsimile	
Email Address	
Address	 Australia
Lineage Statement	Inputs: Digital Elevation Model LIDAR information as supplied via the Information & Land Services Division (ILS) of the Department of Primary Industries, Parks, Water and Environment (DPIPWE) or the Land Information System Tasmania (LIST), May 2008. Tasmanian 25 metre DEM (second edition) as supplied via the Information & Land Services Division (ILS) of the Department of Primary Industries, Parks, Water and Environment (DPIPWE) or the Land Information System Tasmania (LIST) “Storm Tide plus SLR” height datasets Data prepared by John Hunter, ACE CRC, UTAS with the assistance of information on tides and storm surges ("storm tides") around the Tasmanian coastline derived from numerical modelling by Kathleen McInnes of CSIRO. The boundaries of these flooding zones indicate specific annual exceedance probabilities (AEP) of 0.005%, 0.05%, 0.5%, 1%, 2% or 5% for years 2010, 2050, 2075 or 2100 with sea-level rise allowances based on the technique of Hunter (2012), observations of storm tides from the tide gauges at Hobart and Burnie, and regional projections of sea-level rise based on the IPCC A1FI emission scenario (Hunter et al., 2012). Twenty four Storm-Tide plus-SLR height datasets representing the specified percentage AEPs for the specified time periods were geographically mapped. GIS processing was conducted using ESRI ArcGIS 10.0 with the majority of processing being scripted using Python 2.6.5. The main geoprocessing steps are summarised as follows. A spline with barriers interpolation method was used to calculate a series of height surfaces, from a set of AEP datasets for the year 2000. Sea level rise heights of 0.03, 0.23, 0.43 and 0.83 metre were added to the height surfaces to calculate AEP height surfaces for the years 2010, 2050, 2075 and 2100 respectively. LiDAR areas were processed as sixteen mosaicked regions and the 25 metre DEM was processed as a single state-wide region. For the 25 metre DEM areas only, the combined AEP inundation and sea level rise was rounded-up to the nearest whole metre. AEP height surfaces were subtracted from the LiDAR and 25m DEM surfaces and cells of the resultant surface with a value less than zero were designated as inundated. Outputs were converted to polygon shapefiles which showed areas expected to be inundated under the modelled scenarios. This polygonisation step used the “no_simplify” option. The polygon layers were then clipped to a polygon version of the coastline. For each target year a union step was used to combine the AEP level polygon datasets into single polygon dataset for each region. A series of erase steps were then used to remove overlapping areas before merging the sixteen LiDAR mapped regions into a combined shapefile for each target year. A polygon mask, identifying location of reliable LiDAR areas, was used to clip out those areas from the LiDAR based polygon outputs and to erase the same areas from the 25 metre DEM based outputs. LiDAR and 25 m DEM datasets were then merged to produce combined state-wide polygon shapefiles for each target year. Datasets were converted to geodatabase format to reduce file size and to speed up screen refresh times.

AEP datasets are listed in Table 1 and are provided in file geodatabase (.gdb) format with the dataset having the same name as the geodatabase in which it is enclosed. All of the datasets are projected in GDA 94 MGA Zone 55. Attributes of the datasets are listed in Table 2.

Table 1: Storm Tide AEP Datasets

Dataset Name	Target Year	Projected sea level rise (m)
StormTide_AEP_2010_V2	2010	0
StormTide_AEP_2050_V2	2050	0.2
StormTide_AEP_2075_V2	2075	0.4
StormTide_AEP_2100_V2	2100	0.8

Table 2: Attributes of the Storm Tide AEP Datasets

Field Name	Details
AEP5pct	“5%” indicates inundation at 5% AEP level.
AEP2pct	“2%” indicates inundation at 2% AEP level.
AEP1pct	“1%” indicates inundation at 1% AEP level.
AEP_5pct	“0.5%” indicates inundation at 0.5% AEP level.
AEP_05pct	“0.05%” indicates inundation at 0.05% AEP level.
AEP_005pct	“0.005%” indicates inundation at 0.005% AEP level.
IC5pct	(1 = contiguous with coast; 0 = not contiguous with coast) at 5% AEP level.
IC2pct	(1 = contiguous with coast; 0 = not contiguous with coast) at 2% AEP level.
IC1pct	(1 = contiguous with coast; 0 = not contiguous with coast) at 1% AEP level.
IC_5pct	(1 = contiguous with coast; 0 = not contiguous with coast) at 0.5% AEP level.
IC_05pct	(1 = contiguous with coast; 0 = not contiguous with coast) at 0.05% AEP level.
IC_005pct	(1 = contiguous with coast; 0 = not contiguous with coast) at 0.005% AEP level.
AEP_Level	First AEP level in which the polygon appears “inundated”.
SLR	Sea level rise for target year (2010, 0.0 m; 2050, 0.2 m; 2075, 0.4 m; 2100, 0.8 m).
DEM_Ref	CFL (= Climate Futures LiDAR) DEM25 (= State 25 m DEM) **Note: Inundation heights in the 25 m DEM areas have been rounded up to the nearest whole metre.**
Shape_Length	Polygon perimeter in metres.
Shape_Area	Polygon area in square metres.

Inundated areas contiguous or non-contiguous with the coast in each year can be selected using a combination of two attributes. For example query "AEP5pct" = '5%' AND "IC5pct" = 1 will select polygons contiguous with the coast that are expected to be inundated at 5% AEP level.

References:

Hunter, J., 2012. A simple technique for estimating an allowance for uncertain sea-level rise, Climatic Change, 113, 239-252, DOI: 10.1007/s10584-011-0332-1. (http://staff.acecrc.org.au/~johunter/hunter_2012_author_created_version_merged.pdf)

Hunter, J.R., Church, J.A., White, N.J. and Zhang, X,, 2012. Towards a global regionally-varying allowance for sea-level rise , Ocean Engineering (submitted).

Jurisdictions

Tasmania

Search Words

CLIMATE-AND-WEATHER-Climate-change
CLIMATE-AND-WEATHER-Extreme-weather-events
HAZARDS-Flood
HAZARDS-Severe-local-storms

	MARINE
Themes and Categories	
Topic Category	elevation
Topic Category	geoscientificInformation
Topic Category	environment
Status and Maintenance	
Status	completed
Maintenance and Update Frequency	notPlanned
Date of Next Update	
Reference system	
Reference System	GDA94
Spatial Representation Type	
Spatial Representation Type	vector
Metadata Security Restrictions	
Classification	
Authority	
Use Limitations	
Dataset Security Restrictions	
Classification	
Authority	
Use Limitations	
Extent - Geographic Bounding Box	
North Bounding Latitude	-40
South Bounding Latitude	-44
West Bounding Longitude	144
East Bounding Longitude	149
Additional Extents - Geographic	
Identifier	TAS
Distribution Information	
Distributor 1	
Distributor 1 Contact	
Name of Individual	Name withheld
Organisation Name	
Position Name	
Role	distributor
Voice	
Facsimile	
Email Address	
Address	
	Australia

Coastal Inundation Height Reference metadata – Tasmania Version 3.2

Draft metadata prepared by Dr Michael Lacey, School of Geography and Environmental Studies, University of Tasmania 17th August 2012.

General Properties	
File Identifier	
Hierarchy Level	series
Hierarchy Level Name	series
Standard Name	ANZLIC Metadata Profile: An Australian/New Zealand Profile of AS/NZS ISO 19115:2005, Geographic information - Metadata
Standard Version	1.1
Date Stamp	2012-08-17
Resource Title	Coastal Inundation Height Reference (Tas), Version 3.2
Other Resource Details	M.J. Lacey and J. Hunter (2012) Coastal Inundation Mapping for Tasmania – Stage 2 Version 1. Report to the Department of Premier and Cabinet by the Blue Wren Group, School of Geography and Environmental Studies, University of Tasmania and the Antarctic Climate and Ecosystems Cooperative Research Centre
Key Dates and Languages	
Date of creation	2012-08
Date of publication	2012-08
Metadata Language	eng
Metadata Character Set	utf8
Dataset Languages	eng
Dataset Character Set	utf8
Abstract	A digital dataset representing 1 km square polygon tiles covering the entire Tasmanian shoreline (up to the 10 metre contour) where each tile is attributed with modelled potential inundation heights for a number of tidal, combined sea level rise and high tide or storm tide scenarios. The purpose of the data set is to provide a reference for “looking up” potential inundation heights around the Tasmanian coast. The reason the heights vary around the coast is that the height of the high water mark varies with the tidal range around the coast from approximately 1 to 3+ metres. The sea level rise reference heights include modelled high tide in 0.1metre increments to 1.2 metre. At each sea level rise scenario high calculated water heights are based on modelled tide range data provided by the National Tidal Centre except for the Tamar Valley and Macquarie Harbour where published mean high water (MHW) heights were used. Data also includes modelled storm tide inundation heights associated with specific annual exceedance probabilities (AEP) of 0.005%, 0.05%, 0.5%, 1%, 2% or 5% for years 2010, 2050, 2075 or 2100 with sea level rise allowances based on regional sea-level projections and the A1FI emission scenario. Note that the calculated heights are the most likely based on the calculation inputs, though this is NOT necessarily the most likely position of the sea level in the future. Some extrapolation was required to extend tide data into areas inland from the open coast including estuarine areas.
Purpose	This dataset was prepared to assist in the identification of regions that may be subject to the effects of sea level rise such as coastal flooding by providing a reference for “looking up” potential inundation heights around the Tasmanian coast.
Metadata Contact Information	
Name of Individual	Name withheld
Organisation Name	

Position Name	
Role	author
Voice	
Facsimile	
Email Address	
Address	
	Australia
Resource Contacts	
Name of Individual	
Organisation Name	
Position Name	
Role	pointOfContact
Voice	
Facsimile	
Email Address	
Address	
	Australia
Lineage Statement	Inputs:

SLR
The sea level rise allowances are based on regional sea-level projections and the A1FI emission scenario. The allowances used in this dataset have been supplied by the Tasmanian Government to create coastal inundation area maps to support the development of a coastal policy, and a coastal inundation planning code.

Tidal Range
The standard tidal range modelled data was obtained from the National Tidal Centre (NTC) in the form of a five minute resolution grid of points extending from longitude 111º to 116º East and from latitude 9º to 45º South. This model represents tidal amplitudes in metres between Mean Sea Level and Indian Spring Low Water multiplied by two to give an estimate of the complete tidal range. It includes the four main tidal constituents, M2, S2, O1 and K1, and was calculated as:
Tidal amplitude = (M2 + S2 + O1 + K1) amplitudes * 2

Tidal heights were interpolated across the Tasmanian land surface using the spline with barriers method.

For the Tamar region, mean high water (MHW) heights were used instead of NTC high water and were based on MHW heights for nine locations along the Tamar sourced from Foster *et al*. (1986) and were extrapolated across the region.

The tide range grid was also extrapolated into Macquarie harbour using the base heights reported in Koehnken (1996).

A spline with barriers interpolation method was used to calculate a series of height surfaces, from a set of AEP datasets for the year 2000. Sea level rise heights of 0.03, 0.23, 0.43 and 0.83 metre were added to the height surfaces to calculate AEP height surfaces for the years 2010, 2050, 2075 and 2100 respectively.

In most cases heights were extracted from the inundation surfaces at the tile centre points. AEP heights in tiles that intersect the coast are the average of input data points at 100 metre spacing along the coast that fall within that tile.

The dataset **"TasHeightsRefV3_2**" is provided in ESRI personal geodatabase **"Tasmania_Coastal_Heights_Ref_V3_2.mdb"**. Attributes are listed in Table 1. The dataset is projected in GDA 94 MGA Zone 55 and heights are in metres AHD.

Table 1: Attributes of TasHeightsRefV3_2

Attribute	Details
LL_Pos_EN	Tile lower left eastings and northings in kilometres, (eg. e473_n5448).
Easting	Tile centre easting in metres (MGA zone 55)
Northing	Tile centre northing in metres (MGA zone 55)
Base_Ht	Interpolated reference high water mark height at the centre of tile. In most cases this will be based on NTC tide range except where otherwise stated in this metadata.
Base_Ht_Ref	Source of height reference used in tile (NTC TR, NTC tide range; MHT Mac Hb, mean high tide for Macquarie Harbour; MHT Tamar, mean high tide Tamar).
TR_0SLR	Modelled inundation height for tile with 0 sea level rise at 50% probability level.
TR_10SLR	Modelled inundation height for tile with 10 cm sea level rise at 50% probability level.
TR_20SLR	Modelled inundation height for tile with 20 cm sea level rise at 50% probability level.
TR_30SLR	Modelled inundation height for tile with 30 cm sea level rise at 50% probability level.
TR_40SLR	Modelled inundation height for tile with 40 cm sea level rise at 50% probability level.
TR_50SLR	Modelled inundation height for tile with 50 cm sea level rise at 50% probability level.
TR_60SLR	Modelled inundation height for tile with 60 cm sea level rise at 50% probability level.
TR_70SLR	Modelled inundation height for tile with 70 cm sea level rise at 50% probability level.
TR_80SLR	Modelled inundation height for tile with 80 cm sea level rise at 50% probability level.
TR_90SLR	Modelled inundation height for tile with 90 cm sea level rise at 50% probability level.
TR_100SLR	Modelled inundation height for tile with 100 cm sea level rise at 50% probability level.
TR_110SLR	Modelled inundation height for tile with 110 cm sea level rise at 50% probability level.
TR_120SLR	Modelled inundation height for tile with 120 cm sea level rise at 50% probability level.
HAT	Modelled Highest Astronomic Tide from NTC. Interpolated values for rivers and estuaries are approximate and should only be used in those areas with caution. Values for locations inland from the open coast have been designated “no_data” and have been given a value of “-999”.
Local_Storm_Surge	Local storm surge if known.
Wave_Setup	Wave setup if known.
Wave_Runup	Wave runup if known.
AEP_005pct2010	Modelled 0.005% Annual Exceedance Probability height for 2010.
AEP_05pct2010	Modelled 0.05% Annual Exceedance Probability height for 2010.
AEP_5pct2010	Modelled 0.5% Annual Exceedance Probability height for 2010.
AEP1pct2010	Modelled 1% Annual Exceedance Probability height for 2010.
AEP2pct2010	Modelled 2% Annual Exceedance Probability height for 2010.
AEP5pct2010	Modelled 5% Annual Exceedance Probability height for 2010.
AEP_005pct2050	Modelled 0.005% Annual Exceedance Probability height for 2050.
AEP_05pct2050	Modelled 0.05% Annual Exceedance Probability height for 2050.
AEP_5pct2050	Modelled 0.5% Annual Exceedance Probability height for 2050.
AEP1pct2050	Modelled 1% Annual Exceedance Probability height for 2050.
AEP2pct2050	Modelled 2% Annual Exceedance Probability height for 2050.
AEP_005pct2075	Modelled 0.005% Annual Exceedance Probability height for 2075.
AEP_05pct2075	Modelled 0.05% Annual Exceedance Probability height for 2075.
AEP_5pct2075	Modelled 0.5% Annual Exceedance Probability height for 2075.
AEP1pct2075	Modelled 1% Annual Exceedance Probability height for 2075.
AEP2pct2075	Modelled 2% Annual Exceedance Probability height for 2075.
AEP5pct2075	Modelled 5% Annual Exceedance Probability height for 2075.
AEP_005pct2100	Modelled 0.005% Annual Exceedance Probability height for 2100.
AEP_05pct2100	Modelled 0.05% Annual Exceedance Probability height for 2100.
AEP_5pct2100	Modelled 0.5% Annual Exceedance Probability height for 2100.
AEP1pct2100	Modelled 1% Annual Exceedance Probability height for 2100.
AEP2pct2100	Modelled 2% Annual Exceedance Probability height for 2100.
AEP5pct2100	Modelled 5% Annual Exceedance Probability height for 2100.
Shape_Length	Tile perimeter length in metres
Shape_Area	Tile area in square metres

References:

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

Foster, D.N., R., Nittim and J. Walker, (1986). Tamar River Siltation Study; WRL Technical Report No. 85/07.

Koehnken L. (1996) Macquarie Harbour – King River Study. Technical Report, DELM

Jurisdictions	
	Tasmania
Search Words	
	CLIMATE-AND-WEATHER-Climate-change
	CLIMATE-AND-WEATHER-Extreme-weather-events
	HAZARDS-Flood
	HAZARDS-Severe-local-storms
	MARINE
Themes and Categories	
Topic Category	elevation
Topic Category	geoscientificInformation
Topic Category	environment
Status and Maintenance	
Status	completed
Maintenance and Update Frequency	notPlanned
Date of Next Update	
Reference system	
Reference System	GDA94 MGA Zone 55
Spatial Representation Type	
Spatial Representation Type	vector
Metadata Security Restrictions	
Classification	
Authority	
Use Limitations	
Dataset Security Restrictions	
Classification	
Authority	
Use Limitations	
Extent - Geographic Bounding Box	
North Bounding Latitude	-40
South Bounding Latitude	-44
West Bounding Longitude	144
East Bounding Longitude	149
Additional Extents - Geographic	
Identifier	TAS
Distribution Information	
Distributor 1	
Distributor 1 Contact	
Name of Individual	Name withheld
Organisation Name	
Position Name	
Role	distributor
Voice	
Facsimile	
Email Address	
Address	
	Australia

Appendix 2. CSIRO Storm Tide Modelling

Evaluation of storm tide surfaces associated with 1 in 100 year return periods

Author: Kathy McInnes, 2009

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

Storm surge

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

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

Table 1: Summary of the tide gauge records used for event selection in each state.

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

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

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

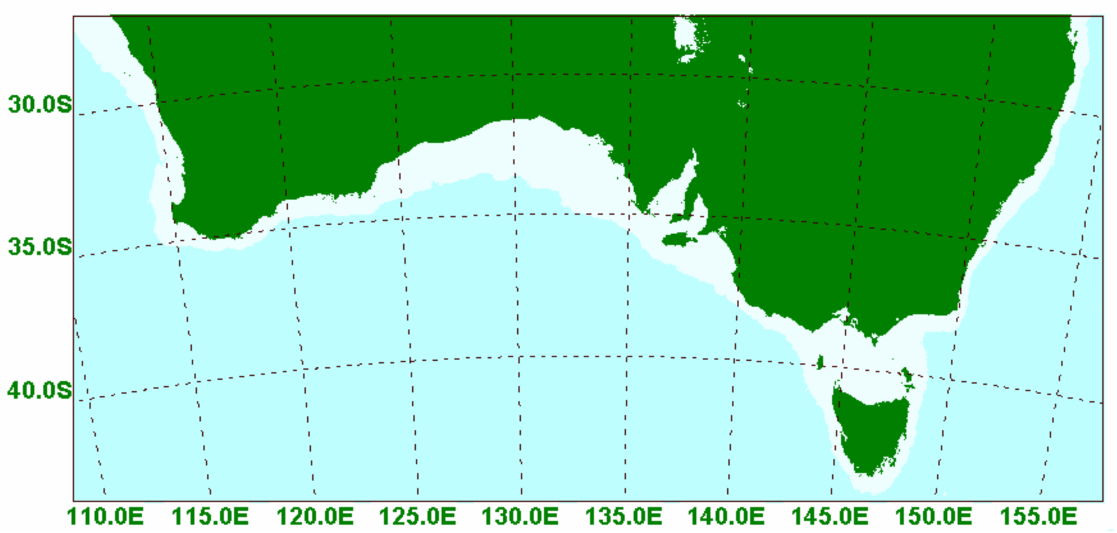

Figure 1: Region over which hydrodynamic modelling was undertaken on a 5 km resolution grid.

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

Astronomical Tides

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

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

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

Estimation of storm tide return periods

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

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

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

The methodology used in this study is illustrated schematically in Figure 2 for the Victorian coast. This illustrates the spatial pattern of the estimated 1 in 100 year storm surge height over this region with the largest surges occurring within Western Port Bay. Also shown is the 99th percentile tide height from the tide frequency histogram indicating that the highest tides occur in central Bass Strait. The 1 in 100 year storm tide surface reflects how the contributions from the tides and surge combine to produce the highest storm tides on the coastline between Western Port Bay and Wilson’s Promontory. On the other hand, in Port Phillip Bay, where the magnitude of the 1 in 100 year storm surge is similar to that on the adjacent Bass Strait coastline, the combination with tides (which are considerably attenuated within Port Phillip Bay) yields lower 1 in 100 year storm tides compared to the adjacent Bass Strait coastline. The storm tide values as represented in Figure 2 for the Victorian coastline, were then interpolated to a series of latitude and longitude coordinates which represent the Smartline, that has been generated for the National Coastal Vulnerability Assessment, which comprises a line of points around the coastline of Australia to which a range of coastal characteristics and attributes such as 1 in 100 year storm tide height can be assigned..

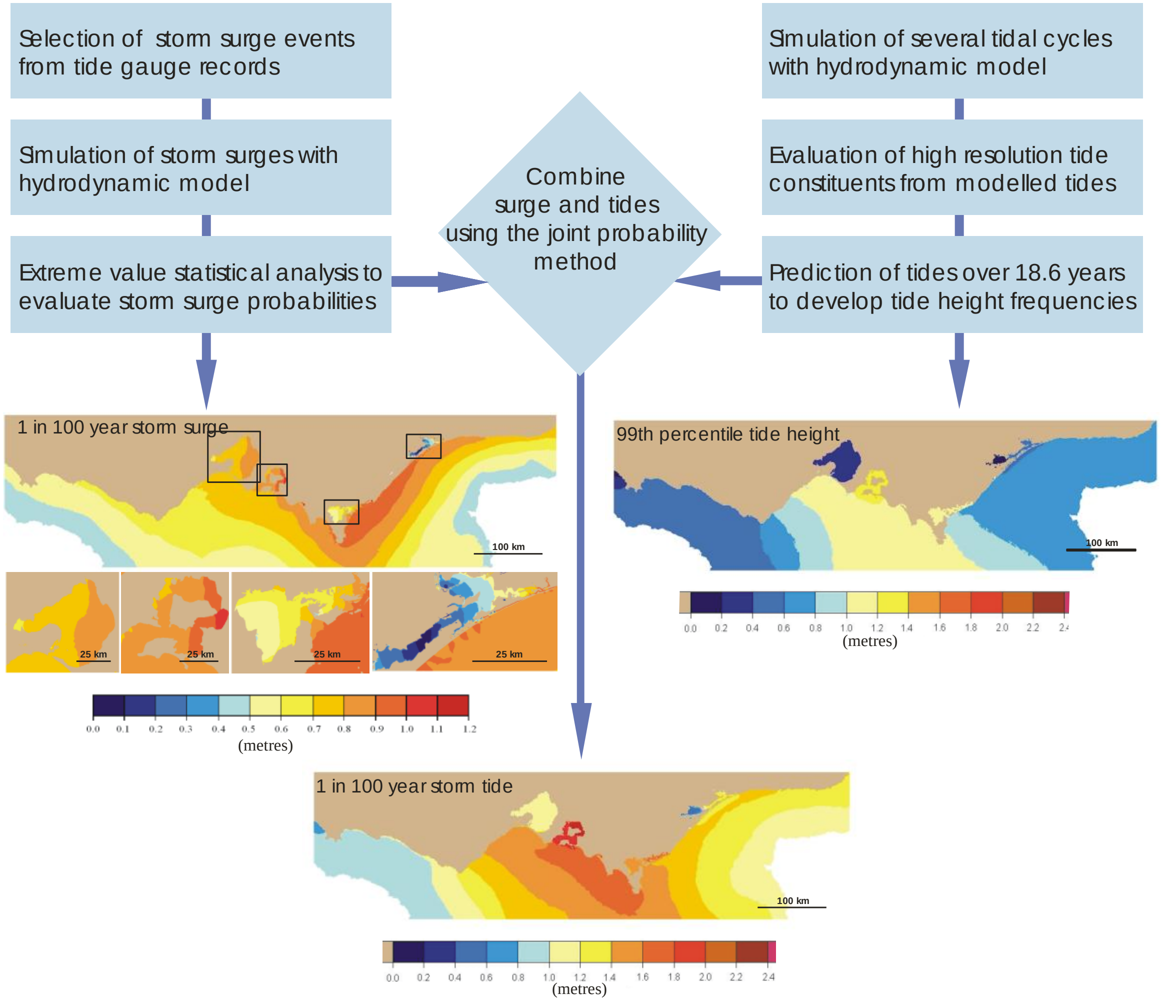

Figure 2: Schematic diagram illustrating the methodology used to evaluate storm tide return periods. The illustrations present examples of the spatial variation of the 1 in 100 year storm surge and storm tide surfaces and the 99th percentile tide height.

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