Fraser Coast Coastal Hazard Adaptation Strategy (CHAS)

Coastal Futures: Planning Our Changing Coastline

Phase 3 – Storm Tide Hazard Assessment & Mapping
Technical Report

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BMT Commercial Australia Pty Ltd
Level 8, 200 Creek Street
Brisbane Qld 4000
Australia
PO Box 203, Spring Hill 4004

Tel: +61 7 3831 6744
Fax: + 61 7 3832 3627

ABN 54 010 830 421

www.bmt.org

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Title:	Fraser Coast CHAS Phase 3 – Storm Tide Hazard Assessment & Mapping Technical Report
Project Manager:	Matthew Barnes
Author:	Jessie Cullen, Matthew Barnes, Bruce Harper
Client:	Fraser Coast Regional Council
Client Contact:	Jasmine Butler
Client Reference:	

Synopsis: **Technical report describing the storm tide hazard assessment and mapping to support the Fraser Coast Coastal Hazard Adaptation Strategy**

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Executive Summary

Storm tide hazard assessment and mapping assessment has been completed. This work was identified priority gap study needed to support the development of the Fraser Coast Regional Council Coastal Hazards Adaptation Strategy (CHAS), known locally as the *Coastal Futures: Planning Our Changing Coastline* project.

The storm tide inundation and extreme wave assessments provide statistics up to the 1,000 year Average Recurrence Interval (or 0.1% Average Exceedance Probability) across the local government area. The assessments consider extreme water levels associated with tropical cyclone and non-tropical cyclone weather systems.

The hazard mapping will be used to support ongoing stakeholder consultation and a risk assessment process in accordance with AS/NZS ISO 31000:2009, the State Planning Policy (SPP) and QCoast$_{2100}$ Minimum Standards & Guidelines.

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1 Introduction

1.1 Purpose of the Report

The Fraser Coast Regional Council (FCRC) has identified potential risks to the community, assets and values associated with coastal hazards, including:

- Temporary flooding of coastal areas due to storm tide;
- Temporary loss of land due to coastal erosion; and
- Permanent loss of land due to coastal erosion and sea level rise.

The assessments described in this report consider the storm tide hazard for the current climate (2019 to 2030) and 2050 and 2100 future climates. As discussed below in Section 2.3, the future scenarios require consideration of forecast changes to the climate, such as an increase to mean sea level and changes to Tropical Cyclone (TC) climatology statistics.

Section 3 describes the detailed assessment of storm tide hazard throughout the region and considers water levels generated by both TC and non-TC weather events. This has involved a statistical analysis of recorded water levels and historical TCs that have impacted the region, application of the SEAsim parametric model for estimating extreme water level associated with TC activity, and the development of a detailed numerical modelling system to estimate potential storm tide inundation areas.

The outcomes of statistical and deterministic modelling have been used to develop storm tide inundation hazard maps to support a natural hazard risk assessment process that complies with the Australian Standard for Risk Management (AS/NZS ISO 31000:2009), in accordance with the QCoast$_{2100}$ Minimum Standards and Guidelines (LGAQ & DEHP 2016) and State Planning Policy (SPP).

1.2 QCoast$_{2100}$ Program

The QCoast$_{2100}$ Program is governed by a Board comprising members from the Local Government Associated of Queensland (LGAQ), Department of Environment and Science (DES) and Department of Local Government, Racing and Multicultural Affairs (DLGRMA). The program has been designed to assist Queensland coastal councils with funding and technical support to progress the preparation of plans and strategies to address climate change related coastal hazard risks. The program is intended to guide decision-making across key areas of local government planning and operations, including:

- Corporate and operational planning and financial planning;
- Land use planning and development assessment;
- Infrastructure planning and management including roads, stormwater and foreshores;
- Asset management and planning including nature conservation, recreation, cultural heritage values and other public amenities;
- Community planning; and

- Emergency management.

The QCoast$_{2100}$ Minimum Standards & Guidelines (MS&G) provide guidance to local government wishing to prepare a CHAS. The guidelines set minimum requirements that are to be included in a CHAS as well as providing information on leading practices to facilitate continuous improvement. The minimum standards set a benchmark for undertaking such studies in Queensland so that coastal hazard adaptation decision-making is approached in a consistent and systematic manner. The MS&G are structured to address the key phases of a CHAS which are illustrated in Figure 1-1. This report is a key output of Phase 3 – the identification of areas exposed to current and future coastal hazards.

This report and associated mapping represent just one of several 'tools' that will be used to support stakeholder consultation and the risk assessment process.

Figure 1-1 QCoast$_{2100}$ Phases

1.3 Phase 2 Scoping Study

The Phase 2 Scoping Study report summarises the data and information needed to undertake a coastal hazard risk assessment in accordance with AS/NZS ISO 31000:2009.

A detailed storm tide hazard assessment, the subject of this report, was identified as a priority study needed to progress the Fraser Coast CHAS (known locally as the *Coastal Futures: Planning Our Changing Coastline* project). The planning horizons agreed for the CHAS are present-day (2019 to 2030), 2050 and 2100 and therefore hazard mapping representative of these years is required. The CHAS adopts the 100-year Average Recurrence Interval (ARI) as the base likelihood (or probability of occurrence) for land use planning decision making, consistent with Queensland Government approach to assessing future climate coastal hazards. It is noted that climate change assumptions for other projects, such as coastal engineering design, should follow the best practice guidelines (e.g. Harper 2012, 2017) and relevant standards and may require consideration of different planning horizons and likelihoods than those adopted for the CHAS.

The assessments presented in this report are of a 'coastal compartment scale' and more detailed 'site based' assessments may be required to inform some planning and development decisions. Figure 1-2 illustrates these concepts and summarises the spatial scales of mapping typically used to coastal hazard climate change adaptation planning.

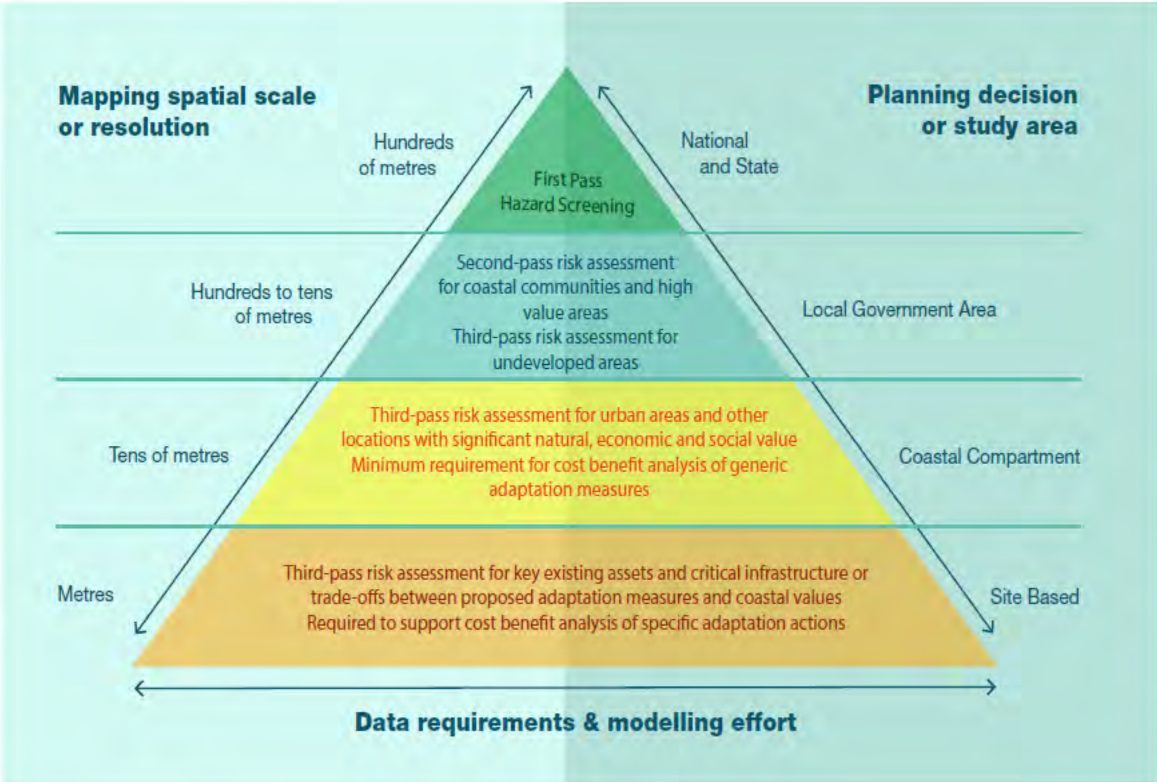


Figure 1-2 Spatial Scales of Coastal Hazard Mapping (CoastAdapt, Barnes 2017)

2 State Policy Context & Key Assumptions for Storm Tide Assessment in Queensland

2.1 Background

The Queensland DES has prepared default storm tide inundation mapping to assist with land use planning and development assessment decisions in the absence of a detailed, site specific storm tide hazard and risk assessment study.

For all areas outside of south east Queensland, including the Fraser Coast local government area, the default storm tide inundation area is all land up to 2 m above the Highest Astronomical Tide (HAT) in 2100. This water level threshold includes a 0.8 m allowance for sea-level rise. The State defined storm tide inundation areas are classified as either:

- Medium Hazard (temporary inundation depth less 1 m); or
- High Hazard (temporary inundation depth greater than 1 m).

These mapping products are useful for first-pass risk screening but do not contain the detail required for some planning decisions and the next phases of the CHAS.

The detailed storm tide hazard assessment described in this Chapter may have application beyond the CHAS, including:

- Establishing design water levels and/or floor levels within the coastal floodplain for planning and development assessment;
- Strategic planning for future growth areas; and
- Disaster management planning.

However, it is noted that specific interpretation and tailoring of the outputs and mapping products would be required before the assessment results are used for these purposes.

2.2 State Policy Context & Legislative Framework

Regarding coastal hazards, the SPP deals specifically with storm tide inundation and erosion prone areas. The policy requires:

- In an erosion prone area within a coastal management district, development does not occur unless it cannot be feasibly located elsewhere and is coastal dependent development; temporary, readily relocatable or able to be abandoned; essential community infrastructure or minor redevelopment of an existing permanent building;
- In a storm tide inundation or erosion prone area but outside of a coastal management district, development avoids natural hazard areas or, where not possible, mitigates the risks to people and property to an acceptable or tolerable level;
- In all other circumstances, development:
    - Supports and does not hinder disaster management response or recovery capacity;
    - Directly, indirectly and cumulatively avoids an increase in the severity of the natural hazard;

- ○ Avoids risks to public safety and the environment from the storage of hazardous materials; and
- ○ Maintains or enhances the natural processes and protective function of landforms and vegetation that can mitigate risks associated with the natural hazard.

Outcomes of the coastal hazard risk assessment undertaken for the CHAS will provide guidance on risk appropriate development that aligns with the SPP.

2.3 Future Climate Considerations

In accordance with the SPP and the QCoast$_{2100}$ MS&G (DEHP 2016), future climate scenarios should be considered in long-term coastal risk assessment and planning along the Queensland coast, with the principal impacts likely to be felt in low-lying coastal margins due to gradual sea-level rise.

Following the Engineers Australia Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering (Harper 2012, 2017), the topics addressed here that are deemed relevant to the region include:

- Sea-level rise and astronomic tide; and
- Tropical cyclones (tracks, intensity, frequency, rainfall).

2.3.1 Sea Level Rise

Global sea levels have been rising because of enhanced greenhouse warming of the earth (IPCC 2013). The observed rate of global average sea-level rise measured by satellite altimetry during the decade 1993 to 2012 was 3.2 ± 0.4 mm p.a., although there are large regional differences. For example, Figure 2-1 from CSIRO & BOM (2016) summarises the observed sea-level rise around Australia as measured by satellite observations from 1993 to 2015. It notes that rates of sea-level rise vary from year to year and spatially and that is partly due to the natural variability of the climate system from large scale influences such as El Niño and La Niña.

Global sea levels are projected to continue to rise at an estimated total rate of 2.8 ± 0.7 mm p.a. based on the following climate-related contributions, in order of decreasing contribution (IPCC 2013):

- An accelerating thermal expansion throughout the 21st century;
- The melting of glaciers;
- Retreat of the Greenland ice shelf; and
- Antarctic ice losses.

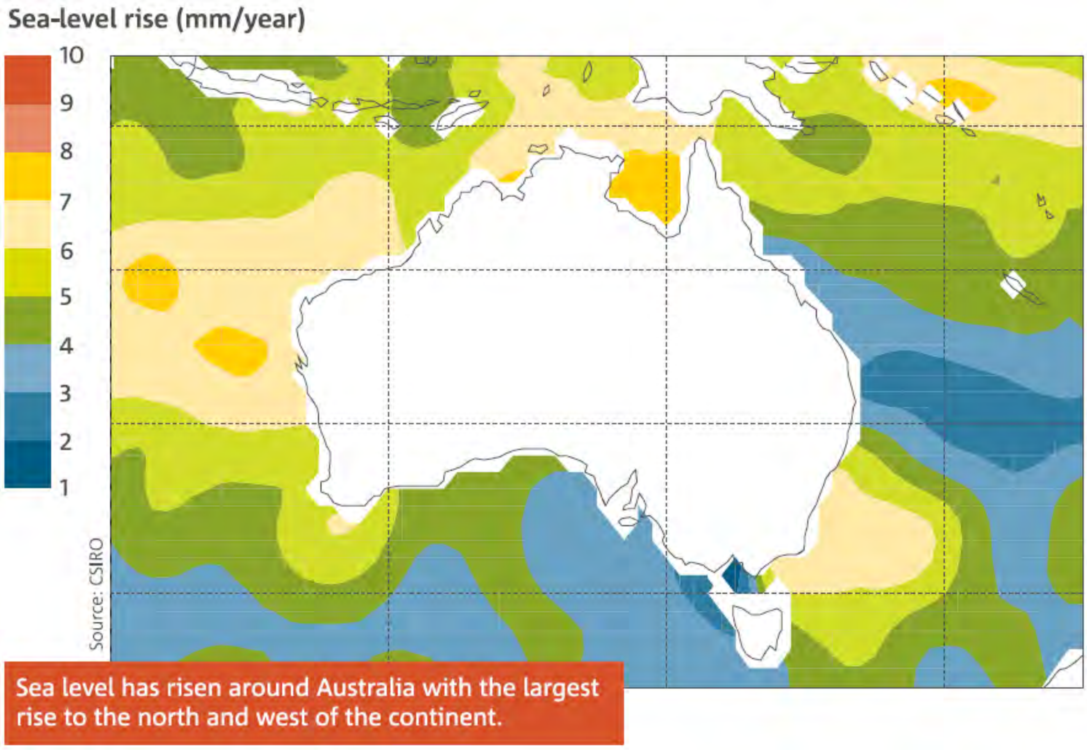


Figure 2-1 Sea-level rise around Australia from 1993-2015 (CSIRO & BOM 2016)

The official projections of global average sea level rise by 2100 are in the range 0.28 to 0.98 m from the IPCC (2013) 'Assessment Report 5' (AR5) and are relative to the average sea level in 1995. This represents nominally 5% to 95% confidence levels for 5 Representative Concentration Pathway (RCP) gas emission scenarios using the Coupled Model Intercomparison Project, Phase 5 (CMIP5) model (a collaborative climate modelling process coordinated by the World Climate Research Programme).

Quoting IPCC (2013) directly and based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the 'likely' range during the 21st century. There is medium confidence that this additional contribution would not exceed several tenths (30 cm) of a metre of sea level rise during the 21st century.

The presently projected IPCC (2013) sea level trends are displayed in Figure 2-2. Although the year 2100 is normally quoted as the most distant future planning horizon, it is important to note that if greenhouse gas concentrations were stabilised (even at present levels), sea level is nonetheless predicted to continue to rise for hundreds of years due to thermal expansion alone.

CSIRO & BOM (2015) provides coastal and marine sea-level rise projections for Australia, recognising that the rates are not uniform around the country. These projections build on local data analysis and the CMIP5 model using downscaling techniques and report sea-level rise projections for the range of RCPs used by the IPCC. In addition to sea-level rise, projections for 'sea allowance' are provided which represent the minimum distance required to raise an asset to maintain the current frequency of breaches under projected sea-level rise. The sea allowance projections broadly consider the nature of extreme sea levels (storm surge) along the Australia coastline.

With reference to the Fraser Coast region, Brisbane is the closest location reported by CSIRO & BOM (2015) and the sea-level rise projections are summarised in Table 2-1. These projections, together with considerations of IPCC AR5 and State policy recommendations, form the basis for sea-level rise allowances adopted for the current study (discussed further in Section 2.3.3).

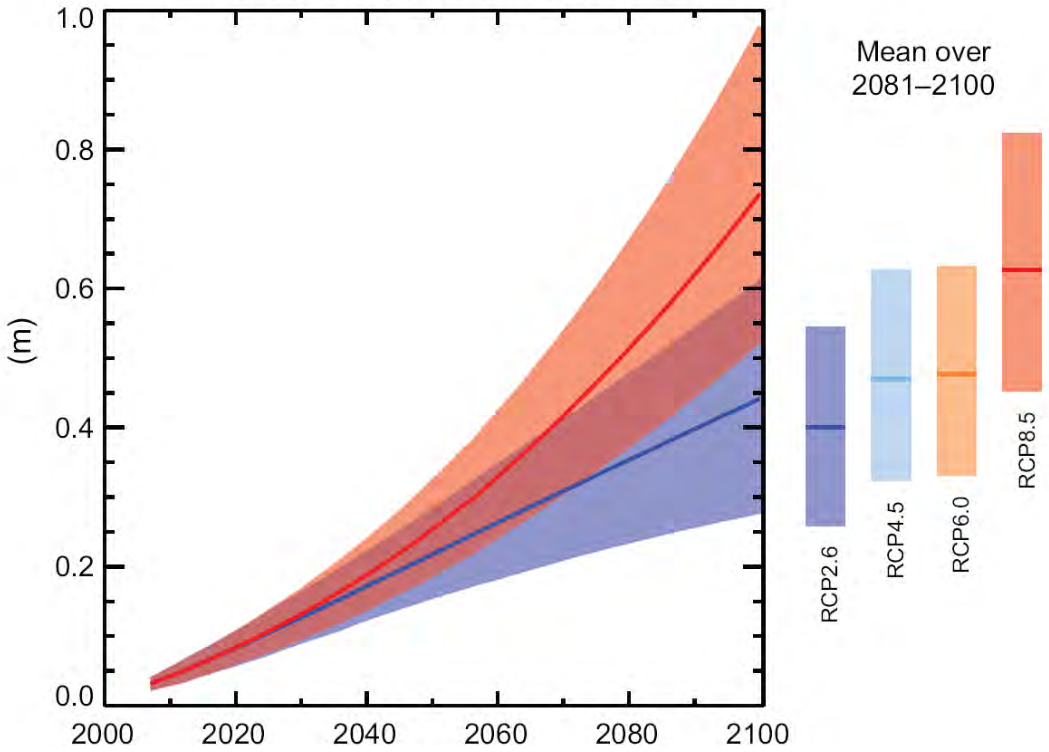


Figure 2-2 Projections of Global SLR Relative to 1986-2005 Mean Sea Level (IPCC 2013)

Table 2-1 Projected Mean Sea Level Rise Brisbane (CSIRO & BOM 2015)

Scenario	2030 Mean & *likely* range (m)	2090 Mean & *likely* range (m)
RCP2.6	0.13 (0.08 to 0.17)	0.39 (0.23 to 0.55)
RCP4.5	0.13 (0.09 to 0.18)	0.47 (0.31 to 0.65)
RCP8.5	0.14 (0.09 to 0.18)	0.65 (0.45 to 0.87)

2.3.2 Tropical Cyclones

IPCC (2013) notes that global climate model projections for the 21st century show it is likely that the global frequency of TCs will either decrease or remain essentially unchanged, but there may be an increase in both global mean TC maximum wind speed and rain rates. This is a significant change from the previous IPCC report in 2007, which predicted increased frequency and intensity and did not have the benefit of a World Meteorological Organization (WMO) consensus statement formed in the late 2000s.

Subsequently, a WMO-endorsed published study by Knutson et al. (2010)[1] summarised the status of current research in this area and it was concluded that there is an agreed likely increase in the Maximum Potential Intensity (MPI) of tropical cyclones with rises of 3 to 5% per degree Celsius of mean global temperature rise. Assuming a 2 to 4°C temperature range is possible, this may lead to an upper level increase in peak wind speeds of as much as 10% by 2100. This could translate into a 20% increase in central pressure deficit.

Knutson et al. (2010) also reports that the consensus from many advanced modelling studies is rather for a potential reduction in the global number of TCs of as much as 34%, although regional differences can be high. Regarding tracks, the most likely change might be a slight poleward movement in some regions. For the Fraser Coast region, it is not possible to describe a specific change in storm tracks under future climate scenarios, but the current literature suggests there may be fewer storms.

CSIRO & BOM (2016) notes that the number of TCs in the Australian region varies with El Niño and La Niña events and that when this sometimes-high variability is accounted for there is a statistically significant downward trend in the number of TCs in the Australian region using satellite-derived data since 1982.

2.3.3 Adopted Future Climate Parameters

The adopted future climate conditions for this study are summarised in Table 2-2, which follow State policy recommendations for planning purposes at 2100, IPCC intensity estimates and a nominal allowance of a 10% reduction in TC frequency by 2100 discussed above.

Table 2-2 Projected climate change parameters

Parameter	2050	2100
Increase to mean sea level (m)[2]	0.3	0.8
TC Maximum Potential Energy (MPI)		
- Wind speed (m/s)	5%	10%
- Atmospheric pressure deficit (hPa)	10%	20%
TC Frequency[1]	-5%	-10%

[1] Tom Knutson advised that this summary is still valid as at 2016 (B Harper, pers. comm)
[2] Present-day mean sea level is defined by MSQ (2019) and is based on the 1992 – 2011 tidal epoch

3 Storm Tide Hazard Assessment

3.1 SEAsim Tropical Cyclone Modelling

The TC event assessment is based on analyses using the recently-developed SEAsim model, which is a variant of the real-time storm tide forecasting model SEAtide (SEA 2018) currently utilised by the Bureau of Meteorology (BoM) in Queensland and the Northern territory and the Queensland State Government. SEAtide is a further development of BoM-sponsored parametric TC storm surge model development following the Queensland Climate Change Study initiative (e.g. Harper 2001; SEA 2002).

SEAsim differs from SEAtide in that, rather than simulating the effects of individual real-time TCs, it simulates the long-term statistical storm tide response across many coastal locations. It achieves this by coupling with an Australia-wide synthetic climatology of TCs (Harper and Mason 2016). SEAsim has been used to simulate storm tide risks around the entire Australian coastline that is subject to TC impacts. For example, the Northern Territory Government Department of Land Resource Management (SEA 2016) recently utilised SEAsim estimates for risk assessment of remote indigenous communities across the ‘Top End’ if Australia.

SEAsim replaces and extends the earlier functionality of the SATSIM model that has provided statistical storm tide design water levels throughout Australia since the mid-1980s (e.g. Harper 2001). The new model combines regional parametric storm tide response models with the synthetic TC climatology and the astronomical tide variability to generate the equivalent synthetic time history of storm tide events, including nearshore wave conditions and estimated breaking wave setup.

The approach used in this study is to select several candidate extreme TC events from the SEAsim statistical simulation and for each of these events to be modelled in greater detail by full hydrodynamic models forced by the SEAsim-generated wind and pressure fields.

3.1.1 Model Description for the Fraser Coast Region

SEAsim is built on TC scenarios modelled by the 2D barotropic hydrodynamic model MMUSURGE and the 3rd generation spectral wave model WAMGBR with 24 directions and 25 frequencies (each described in Harper 2001). Both models are built on published navigation chart soundings and implement sub-grid reef and bank representations. A nested uniform (spherical) grid system was used, with details near the study site shown in the top panel of Figure 3-1 at the adopted ‘B’ grid 2.78 km resolution, which is adequate for reproducing the regional long-wave storm tide response. The bottom panel of Figure 3-1 shows the nested ‘C’ grid 550 m resolution, which resolves the Great Sandy Strait and the Fraser Coast coastal communities of interest. An associated outer 12.8 km ‘A’ grid encompasses 1500 km alongshore and 650 km offshore. The model provides statistical storm tide estimates for a wide range of ARIs at each of the indicated grid locations.

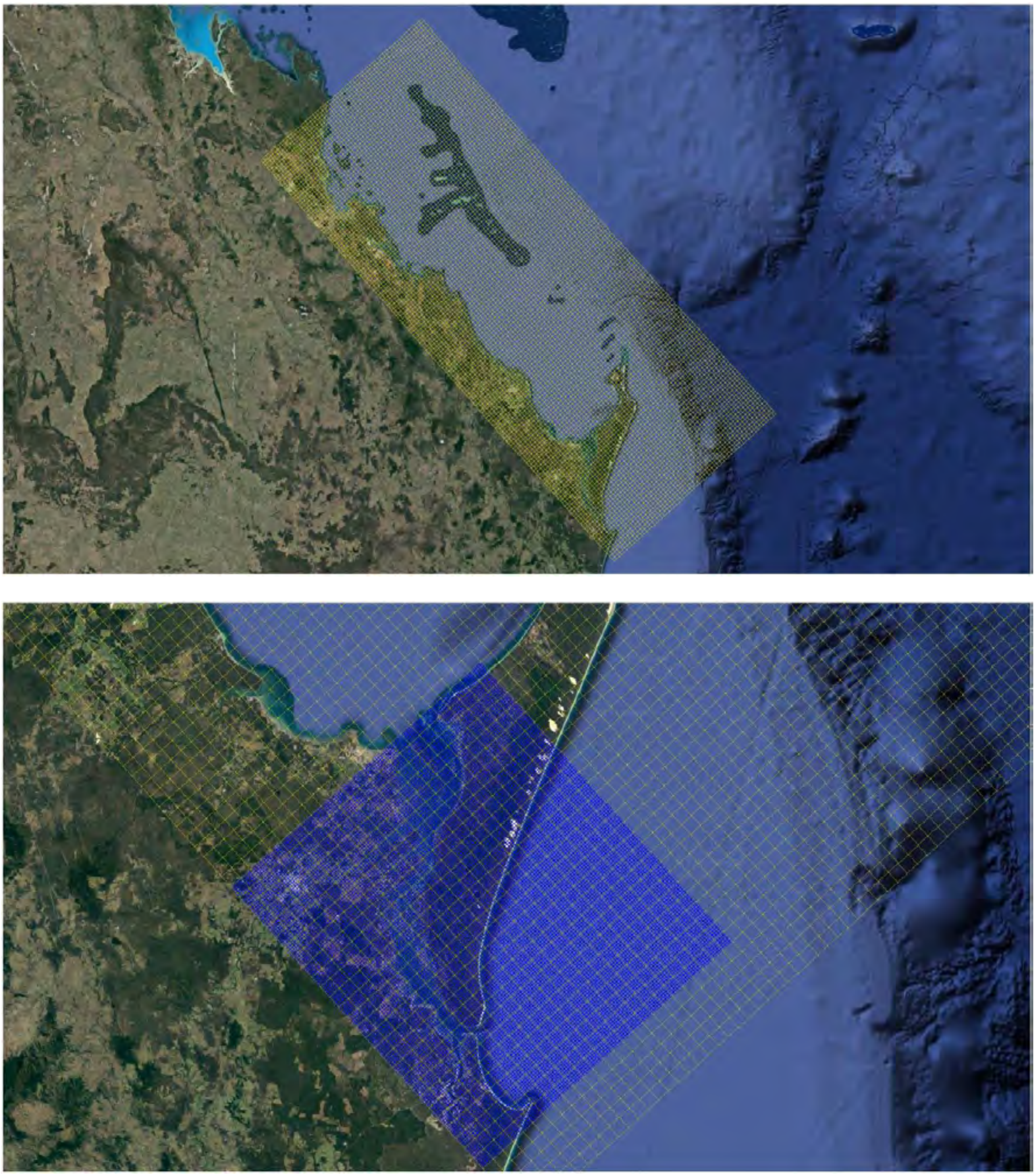


Figure 3-1 SEAsim model nested grids at the location of interest: 2.78 km resolution 'B' grid (top) and 550 m resolution 'C' grid (bottom)

3.1.2 Astronomic Tide

Tides throughout the study region are mixed semi-diurnal and have a range varying between 3.5 to 4.5 m, which provide a degree of protection against storm surge inundation. SEAsim utilises interpolation between published tidal constituents where available and combines statistically-sampled tidal time series with the estimated storm surge to produce the storm tide response needed for determining the probability of exceedance of the hazard. Selected official MSQ (2019) tidal planes showing the variability between Hervey Bay, Great Sandy Straits and Fraser Island are given below in Table 3-1.

Table 3-1 Published tidal planes (MSQ 2019)

Tidal Plane	Urangan (mAHD)	River Heads (mAHD)	Tuan (mAHD)	Happy Valley (mAHD)
Highest Astronomical Tide (HAT)	2.24	2.43	1.56	1.36
Mean High Water Springs (MHWS)	1.45	1.53	0.97	0.74
Mean Sea Level (MSL)	0.05	0.00	0.18	0.12
Mean Low Water Springs (MLWS)	-1.36	-1.53	-0.77	-0.51
Lowest Astronomical Tide (LAT)	-2.04	-2.17	-1.19	-1.01

3.1.3 Synthetic Tropical Cyclone Climatology

SEAsim utilises a synthetic TC climatology founded on a so-called 'double Holland' wind profile that has produced well-verified extreme winds speeds across Australia (refer Harper and Mason 2016). Figure 3-2 shows a comparison between historical TC tracks for Australia and an equivalent period of the synthetic tracks.

Figure 3-3 summarises the statistical climate matching with various historical TC parameters for storms that track within 300 km of Heron Island (the adopted centroid for the Fraser Coast zone of influence). The correspondence is between the modelled (blue) and the original historical data (red) for the indicated frequency, intensity speed and direction parameters.

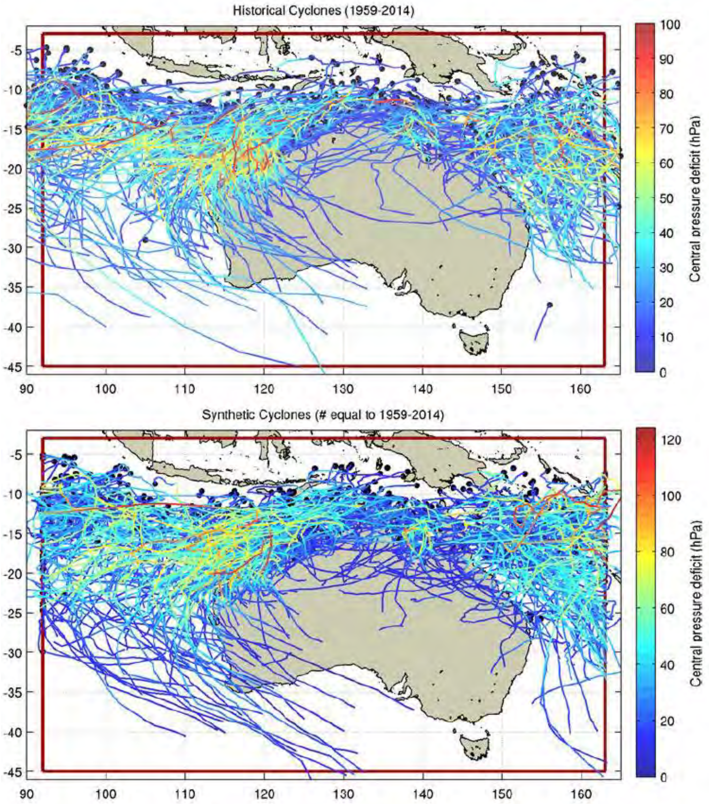


Figure 3-2 Example of the synthetic TC climate modelling: full sample of the BoM historical tracks and intensities (top panel); equivalent year sample extract from the synthetically generated dataset (bottom panel)

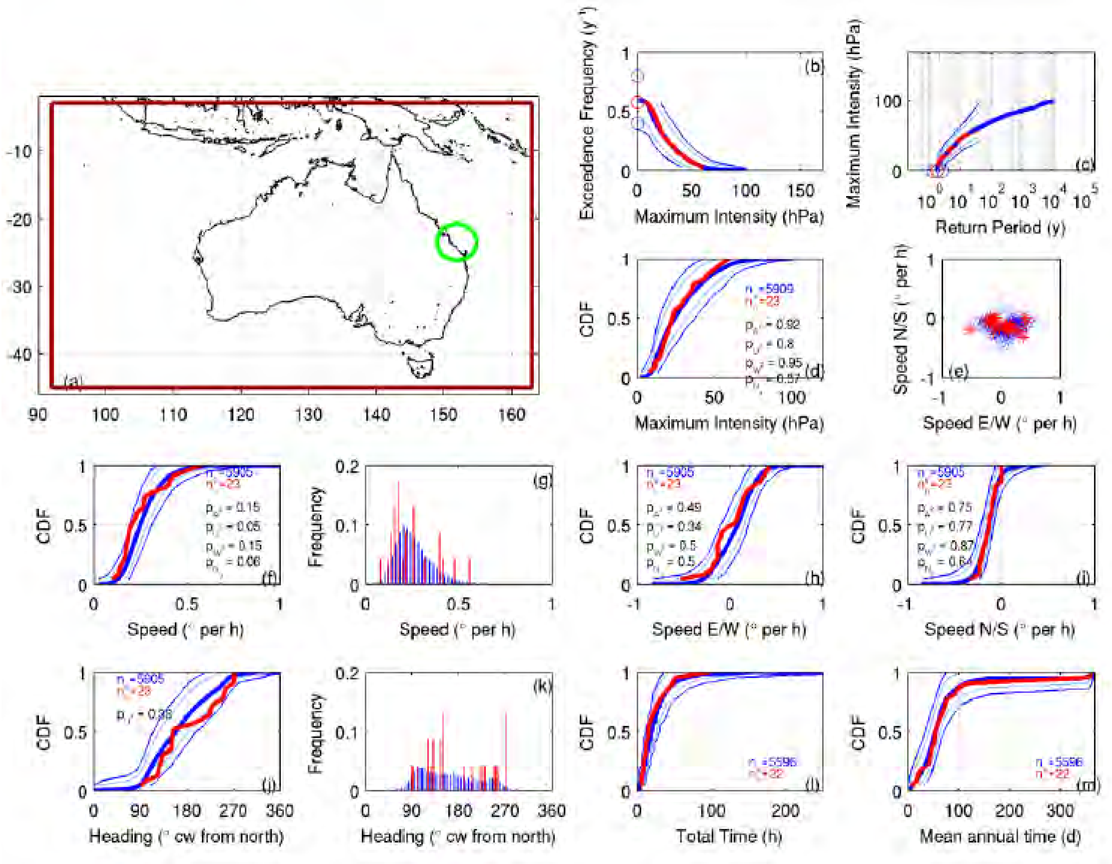


Figure 3-3 Statistical fits of a variety of TC track parameters comparing the original historical data (red) and the synthetic track data (blue) for TCs crossing any part of the coast within a 300 km radius of Heron Island

3.1.4 SEAsim Simulation

SEAsim can be operated in parametric or discrete mode. In the rapid parametric mode, the predicted wind, surge and wave magnitude response at each of the sites of interest is generated from pre-computed results, interpolating as necessary between the available modelled scenarios. This approach is well suited to 'open coast' locations. In discrete mode, the full hydrodynamic surge response is modelled. For the current study, discrete mode was considered necessary for simulating surge propagation inside the Great Sandy Strait (which is not well resolved by the parametric model).

The estimated surge time history is superimposed on the background astronomical tide for the date and time, with allowance for surge-tide interaction. This is repeated for 10,000 years of synthetic storms and associated tide sequences. The exceedance statistics of the combined total water level at each site for each TC event then forms the basis of the probabilistic storm tide level predictions.

To illustrate the model operation across the study area, Figure 3-4 presents SEAsim output of the estimated 1,000 year ARI 'tide plus surge' levels relative to AHD under present TC climate. The 'tide plus surge' levels peak near Toogoom in Hervey Bay and inside Great Sandy Strait near River Heads and Kingfisher Bay (west coast of Fraser Island). Further south the levels reduce significantly, and the lowest levels are estimated to be along the open southeast coast of Fraser Island.

Outputs from the SEAsim simulation are discussed further in Section 3.3 and detailed modelling of selected SEAsim events is described in Section 3.4.

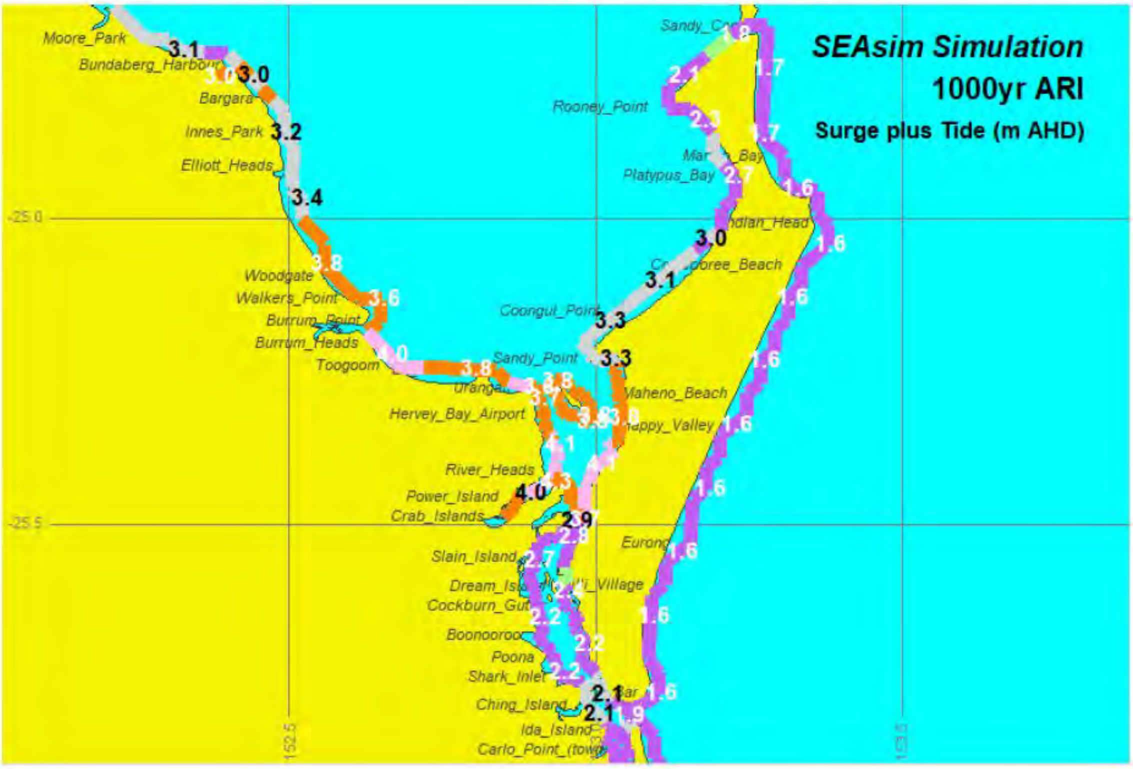


Figure 3-4 SEAsim TC tide plus surge 1,000 year ARI estimates (m AHD)

3.2 Non-Tropical Cyclone Modelling

The analysis described above in Section 3.1 focuses on extreme water levels associated with TC events. It is also necessary to determine statistics for the extreme water level events associated with non-TC weather systems and other coastal phenomena. The method used here was originally described in Hardy et al. (2004) and used for estimating extra-tropical storm surge contributions in the Townsville region. The so-called and Tidal Residual Recombination Model (TRRM), it is based on the re-sampling of unique tidal residual events from suitably long and reliable tide gauge records in the region of interest. It is assumed that the residual and the astronomical tide are uncorrelated and occur in random combination to produce the total storm tide level recorded by each gauge. Recombination of the randomly re-sampled residual (excluding TC events) effectively extends the available record.

The incidence of the non-TC storms of interest is relatively frequent and a data record of the order of 30 years is highly likely to have sampled close to the maximum ocean forcing possible from these events. Implicitly it is then assumed that the available record of ocean water levels from tide gauges has sufficiently captured the inherent range of variability of non-TC storm surges in the region. It does not allow for any extrapolation of storm surge magnitudes beyond those already measured but, as the analysis shows, this is not a constraint on the effectiveness of the technique to represent water level statistics at ARIs higher than available from the original record.

Once available, the independently derived TC and non-TC statistics can then be 'blended' to produce a total storm tide return period curve. This is discussed further in Section 3.3.

3.2.1 Analysis of Tidal Data

The observed tidal water level dataset from Urangan was provided by the Tidal Unit of Maritime Safety Queensland (MSQ). The data consists of tidal heights at hourly intervals commencing in 1981 and 10-minute intervals after 1996 when digital data collection technology was introduced. Tidal analysis was carried out separately for the hourly and 10-minute sections of the tide gauge data. The tide predictions were based on 152 constituents derived from each section of the raw tide data at each gauge site. The residuals obtained from the hourly sections of data were interpolated to 10-minute intervals and amalgamated with the residual already at 10-minute intervals. The residuals are then filtered with a low-pass filter (cut-off = 24 h) to remove any 'bad' data, which are often seen as spikes in the residual.

TC events are then removed from the records by identifying periods when the historical tracks of such storms were within 5 degrees of latitude (~550 km) of the study region. The resulting amalgamated tidal residuals shown in Figure 3-5 can be seen to be both positive and negative in magnitude with several maxima occurring each year. Additionally, multi-year variations in water levels are evident in the record, undoubtedly associated with large scale climate processes such as El Niño.

The recombination process requires whole-year periods be available in the record to ensure any correlation between seasonal variation in tide and storm occurrence is accommodated. Because of the gaps in dataset, the adopted approach yielded 29 years of data.

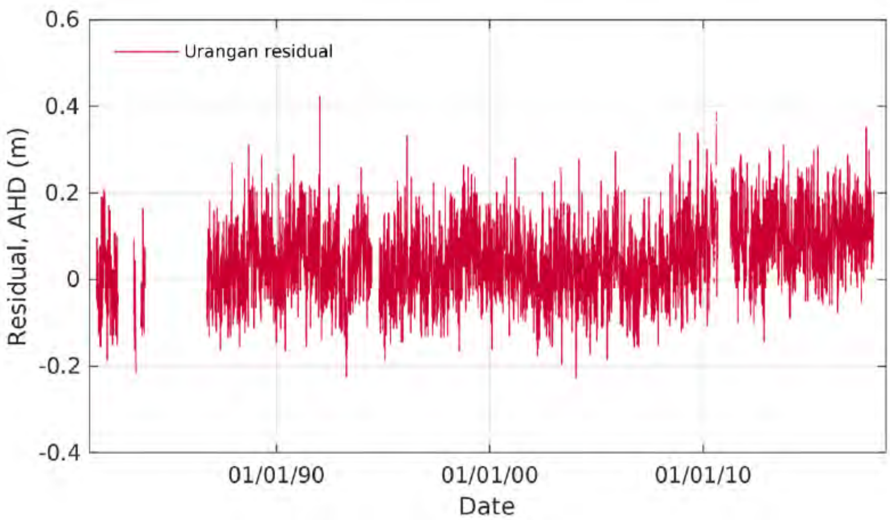


Figure 3-5 Tidal residual with TC events removed at Urangan

3.2.2 Simulation of Synthetic Water Level Time Histories

A fundamental assumption of TRRM is that the timing of the tide and the spring/neap cycle is uncorrelated to the residual but that there may be some correlation between the annual cycle of storm events and the annual patterns in the tide. It also assumes that the astronomical tide is largely predictable, and that tide and residual can be linearly added to produce a combined result with only small errors.

Firstly, 30 separate tidal predictions were generated with each prediction set arbitrarily 50 years apart but starting on the same hour, day and month as the original set and with a 10-minute interval and duration that matches the amalgamated residual sets. This is simply a means of separating and sampling the natural tidal variability and providing a long time-base for overlaying the measured residuals.

Next, each tidal prediction was recombined with the measured residual but with the starting date of the residual randomly offset by up to ±1 week (±168 hours). The random offset was in 10-minute intervals equivalent to the time step of the amalgamated residuals. The maximum of 1 week offset is small enough to ensure retention of the principle seasonal couplings between tide variability and the occurrence of storms of interest. Finally, this 'tide plus residual' recombination process was repeated 12 times with different time offsets to provide a synthetic water level record of around 10,000 years. The yearly maxima were then extracted and ranked to produce the summary statistical plots as shown below in Figure 3-6.

The re-sampling method can be directly used to estimate the variability of the ARI estimates, as shown in Figure 3-7. This figure illustrates, in blue, the simulated estimate predicted for Urangan and, in red, the measured and ranked annual maximum tide gauge levels over the past 34 years, excluding periods of TC activity. In grey are then the 360 re-sampled periods of tide and residuals, which together produce the averaged blue line. The spread of the grey around the blue indicates the sampled natural variability imposed on the system by the effect of random tide phasing combined with the residual signal, which is generally much larger than other components represented by the residual. The measured ARI estimate (red) can be seen to lie close to the mean of the modelled data (blue) but, given that it is a single (actual) realisation of combined tide and residual possibilities, this has no special significance.

While the SEAsim model provides TC storm tide statistics of relevance to each geographic site, the non-cyclonic water level data applies only to the Urangan site. To allow for likely variation of the non-cyclonic response as a function of the regional tidal plane variation, the reference statistics are then adjusted by the ratio of estimated HAT at each site to that of Urangan as summarised in Table 3-2.

The blending of the independently derived TC and non-TC water level statistics is presented in below Section 3.3.

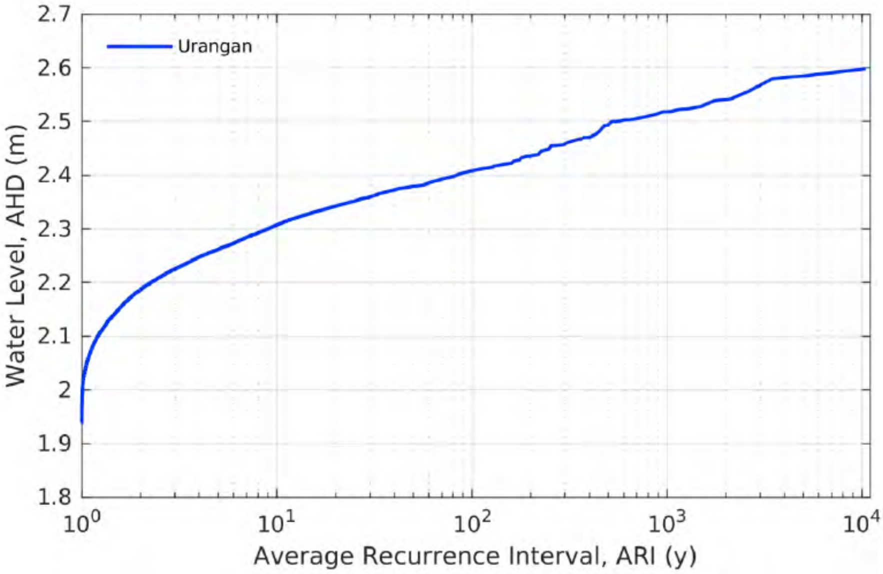


Figure 3-6 Non-Cyclonic water level statistics for Urangan

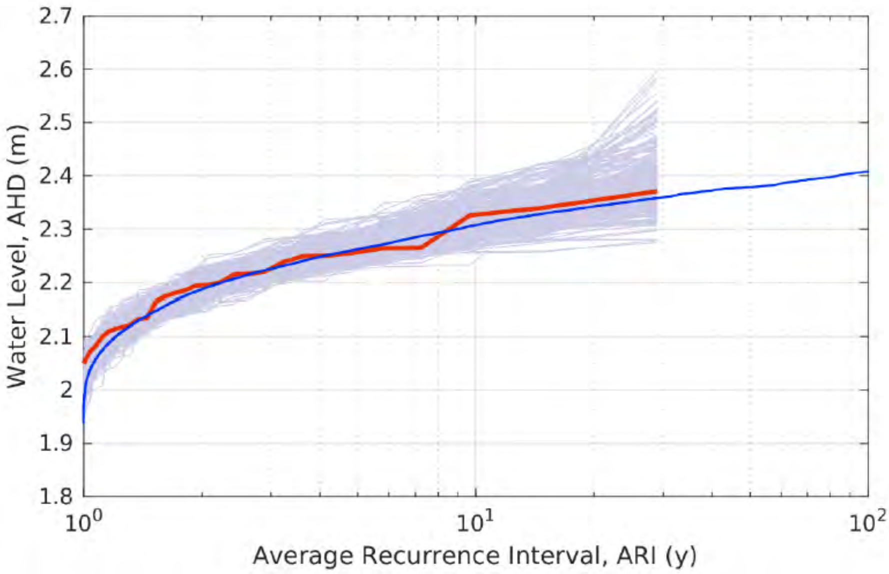


Figure 3-7 Tide-phase imposed variability for Urangan

Table 3-2 Applied site-specific tide range ratios

Location	HAT Estimate* (mAHD)	Applied Tide Ratio relative to Urangan
Burrum Heads	2.12	0.97
Toogoom	2.14	0.98
Toogoom East	2.15	0.99
Dundowran Beach	2.18	1
Point Vernon West	2.2	1.01
Point Vernon	2.21	1.02
Scarness	2.2	1.01
Torquay	2.18	1
Urangan	2.18	1
Urangan Boat Harbour	2.17	1
Mangrove Point	2.27	1.04
River Heads	2.4	1.1
Maaroom	1.8	0.82
Boonooroo	1.49	0.68
Tuan	1.42	0.65
Poona	1.54	0.71
Tinnanbar	1.52	0.7
Kingfisher Bay	2.32	1.07
Happy Valley	1.23	0.56
Eurong	1.23	0.56

*based on model-derived tidal constituents used by SEAsim

3.3 Blending TC & Non-TC Tide plus Surge Statistics

The combined extreme water level hazard due to each of the independently derived TC (Section 3.1) and non-TC (Section 3.2) events have been statistically combined using the method originally described by Gomes and Vickery (1977):

$$R = \left[\frac{1}{Rtc} + \frac{1}{Rnc} - \frac{1}{Rtc * Rnc} \right]^{-1}$$

Equation 3-1

Where *Rtc* is the ARI of the TC water level and *Rnc* is the ARI of the non-TC water level.

The resulting combined ‘tide plus surge’ ARI curves for selected Fraser Coast sites are shown in Figure 3-8, together with the TC and non-TC components. Table 3-3 presents an estimate of HAT and a selection of ARI water levels for the current climate scenario. Table 3-4 provides the equivalent water level statistics for the future climate scenarios.

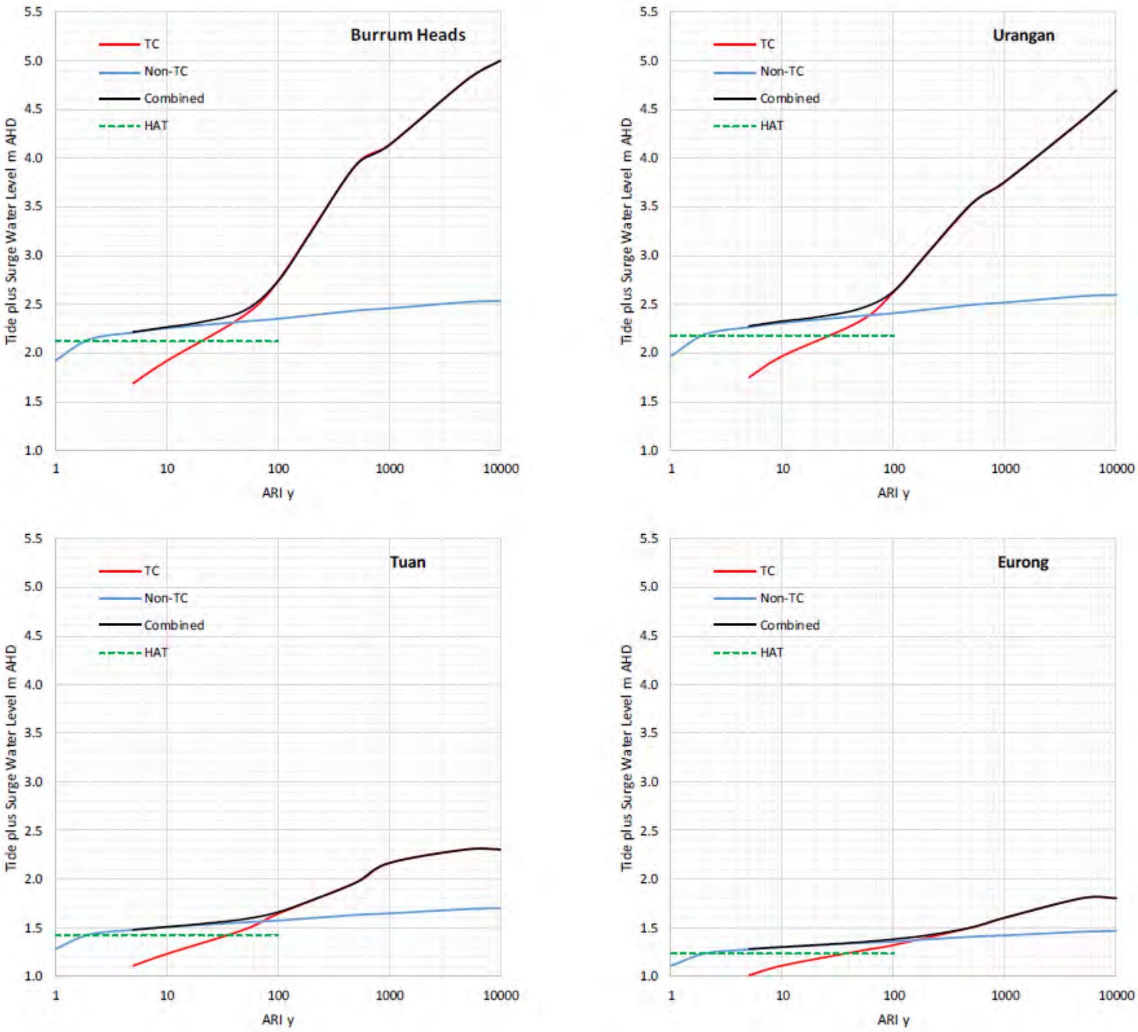


Figure 3-8 Current climate blended TC and non-TC tide plus surge extreme water levels for key locations

Table 3-3 Present climate (2019-2030) blended non-TC and TC tide plus surge water level statistics

Location	HAT estimate	5 yr ARI	10 yr ARI	50 yr ARI	100 yr ARI	500 yr ARI	1000 yr ARI
	2019-2030 climate blended non-TC and TC surge plus tide levels (mAHD)						
Burrum Heads	2.12	2.21	2.26	2.43	2.73	3.92	4.13
Toogoom	2.14	2.23	2.28	2.42	2.68	3.87	4.05
Toogoom East	2.15	2.24	2.29	2.43	2.68	3.87	4.05
Dundowran Beach	2.18	2.27	2.32	2.43	2.58	3.58	3.8
Point Vernon West	2.2	2.29	2.33	2.45	2.58	3.53	3.77
Point Vernon	2.21	2.3	2.35	2.47	2.62	3.52	3.9
Scarness	2.2	2.29	2.34	2.47	2.66	3.61	4
Torquay	2.18	2.27	2.32	2.45	2.65	3.56	3.82
Urangan	2.18	2.27	2.32	2.45	2.63	3.53	3.76
Urangan Boat Harbour	2.17	2.26	2.31	2.44	2.65	3.54	3.75
Mangrove Point	2.27	2.37	2.42	2.57	2.83	3.73	3.95
River Heads	2.4	2.5	2.55	2.7	2.94	3.88	4.2
Maaroom	1.8	1.87	1.91	1.98	2.03	2.21	2.27
Boonooroo	1.49	1.55	1.58	1.65	1.71	1.98	2.12
Tuan	1.42	1.48	1.51	1.59	1.66	1.96	2.16
Poona	1.54	1.6	1.63	1.7	1.76	2.05	2.21
Tinnanbar	1.52	1.58	1.61	1.68	1.73	2.03	2.2
Kingfisher Bay	2.32	2.42	2.47	2.6	2.79	3.58	4.1
Happy Valley	1.23	1.28	1.31	1.36	1.39	1.52	1.6
Eurong	1.23	1.28	1.3	1.35	1.38	1.5	1.6

Table 3-4 Future climate 2050 blended non-TC and TC tide plus surge water level statistics

Location	HAT estimate	5 yr ARI	10 yr ARI	50 yr ARI	100 yr ARI	500 yr ARI	1000 yr ARI
	2050 blended non-TC and TC surge plus tide levels (mAHD)						
Burrum Heads	2.42	2.52	2.57	2.79	3.21	4.49	4.65
Toogoom	2.44	2.53	2.58	2.75	3.15	4.45	4.6
Toogoom East	2.45	2.54	2.59	2.76	3.14	4.42	4.63
Dundowran Beach	2.48	2.57	2.62	2.76	2.99	4.08	4.42
Point Vernon West	2.5	2.59	2.64	2.77	2.98	4.07	4.34
Point Vernon	2.51	2.6	2.65	2.79	3.03	3.99	4.52
Scarness	2.5	2.59	2.64	2.79	3.08	4.17	4.62
Torquay	2.48	2.57	2.62	2.78	3.09	4.09	4.51
Urangan	2.48	2.57	2.62	2.77	3.05	4.05	4.38
Urangan Boat Harbour	2.47	2.56	2.61	2.77	3.09	3.99	4.38
Mangrove Point	2.57	2.67	2.72	2.91	3.27	4.23	4.67
River Heads	2.7	2.8	2.86	3.02	3.34	4.45	4.82
Maaroom	2.1	2.17	2.21	2.29	2.35	2.66	2.66
Boonooroo	1.79	1.85	1.88	1.96	2.05	2.39	2.59
Tuan	1.72	1.78	1.82	1.9	2.02	2.39	2.63
Poona	1.84	1.9	1.93	2.01	2.09	2.47	2.7
Tinnanbar	1.82	1.88	1.92	1.99	2.05	2.47	2.69
Kingfisher Bay	2.62	2.72	2.77	2.91	3.16	4.02	4.59
Happy Valley	1.53	1.58	1.61	1.7	1.79	2.08	2.15
Eurong	1.53	1.58	1.6	1.65	1.69	1.84	1.94

Table 3-5 Future climate 2100 blended non-TC and TC tide plus surge water level statistics

Location	HAT estimate	5 yr ARI	10 yr ARI	50 yr ARI	100 yr ARI	500 yr ARI	1000 yr ARI
	2100 blended non-TC and TC surge plus tide levels (mAHD)						
Burrum Heads	2.92	3.02	3.07	3.37	3.91	5.24	5.46
Toogoom	2.94	3.03	3.08	3.32	3.84	5.25	5.44
Toogoom East	2.95	3.04	3.09	3.32	3.8	5.22	5.45
Dundowran Beach	2.98	3.07	3.12	3.28	3.62	4.78	5.16
Point Vernon West	3	3.09	3.14	3.3	3.6	4.82	5.16
Point Vernon	3.01	3.11	3.16	3.32	3.68	4.76	5.27
Scarness	3	3.09	3.14	3.33	3.74	4.92	5.49
Torquay	2.98	3.08	3.13	3.31	3.73	4.83	5.25
Urangan	2.98	3.07	3.12	3.3	3.71	4.72	5.17
Urangan Boat Harbour	2.97	3.06	3.11	3.3	3.74	4.76	5.16
Mangrove Point	3.07	3.17	3.23	3.45	3.92	5.02	5.44
River Heads	3.2	3.31	3.36	3.57	4.02	5.19	5.74
Maaroom	2.6	2.67	2.71	2.8	2.89	3.32	3.32
Boonooroo	2.29	2.35	2.38	2.48	2.62	3.04	3.22
Tuan	2.22	2.29	2.32	2.42	2.59	3.04	3.27
Poona	2.34	2.4	2.44	2.53	2.66	3.07	3.26
Tinnanbar	2.32	2.38	2.42	2.5	2.61	3.08	3.35
Kingfisher Bay	3.12	3.22	3.28	3.47	3.92	4.97	5.59
Happy Valley	2.03	2.09	2.12	2.27	2.48	2.91	3.09
Eurong	2.03	2.08	2.1	2.15	2.2	2.42	2.54

3.4 Numerical Modelling of Tropical Cyclones

Detailed numerical modelling of selected representative 100, 500 and 1000-year ARI TC events has been undertaken to simulate inundation of the coastal floodplain and provide high-resolution outputs to support mapping of the storm tide hazard magnitude and extent throughout the local government area. The model development and calibration/validation are described in the following sections.

3.4.1 Hydrodynamic Model Description

The hydrodynamic modelling component of these assessments has been undertaken using the TUFLOW FV software, which is developed and distributed by BMT (https://www.tuflow.com/Tuflow%20FV.aspx). TUFLOW FV is a numerical model for the two-dimensional (2D) and three-dimensional (3D) Non-Linear Shallow Water Equations (NLSWE). The model is suitable for solving a wide range of hydrodynamic systems ranging in scale from open channels and floodplains, through estuaries to coasts and oceans.

The Finite-Volume (FV) numerical scheme employed by TUFLOW FV solves the NLSWE on both structured rectilinear grids and unstructured meshes comprised of triangular and quadrilateral elements. The flexible mesh allows for seamless boundary fitting along complex coastlines or open channels as well as accurately and efficiently representing complex bathymetries with a minimum number of computational elements. The flexible mesh capability is particularly efficient at resolving a range of scales in a single model without requiring multiple domain nesting. Further details regarding the numerical scheme employed by TUFLOW FV are provided in the TUFLOW FV Science Manual (BMT WBM 2013).

3.4.1.1 Model Domain, Mesh and Bathymetry

The hydrodynamic model domain is shown in Figure 3-9 and extends from Bribie Island in the south to Mackay in the north and east to beyond the continental shelf.

The model consists of 282,518 mesh cells with resolution varying from 10 km (approximate mesh cell side length) at the offshore boundary, increasing to ~40 m across the coastal floodplain. Figure 3-10 shows detail of the model mesh in the vicinity of Urangan. Large coastal structures, such as the Urangan Harbour breakwater, are resolved by the model; however, it is noted that subscale structures on the coastal floodplain that may influence flow patterns (such as culverts) are not resolved by this modelling approach.

Topographic and bathymetric Digital Elevation Models (DEMs) have been derived from the following sources, listed in decreasing order of priority:

- Topographic LiDAR survey acquired in 2015.
- Topographic LiDAR survey acquired in 2009.
- 30 m resolution depth model for the Great Barrier Reef (Beaman 2017).

The hydrodynamic model configurations and parameterisations are summarised in Table 3-6, including the bottom roughness length scales for the generic bed surfaces represented throughout the model domain. The adopted model parameters are typically “default” values and/or within the range of accepted literature values.

Table 3-6 Summary of Hydrodynamic Model Configuration and Parameterisations

Model Configuration Description	Model/Value
Momentum mixing model	Smagorinsky
Bottom drag model	Derived from application of the "log-law"
Bottom roughness length scales: Default (offshore areas, rivers and creeks) Coastal floodplain	 0.05 m 1.00 m

3.4.1.2 Boundary Conditions

The local hydrodynamics simulated by TUFLOW FV are influenced by boundary condition inputs. Hydrodynamic forcing for the study area was obtained from the following sources:

- Output from the TOPEX/Poseidon global ocean tide model (Egbert et al. 2002). Due to the large extent of the model domain, astronomic tidal elevations vary spatially and temporally along the length of the offshore boundary.
- Output from the SEAsim model described in Section 3.1 (TC parametric wind and atmospheric pressure fields).

3.4.1.3 Hydrodynamic Model Validation

Two independent methods for validating the detailed hydrodynamic model have been completed, including:

(1) Modelled tide compared to MSQ tidal predictions at Urangan, Bundaberg and Mooloolaba. This demonstrates model skill in terms of water level variation due to astronomical forcing (and in the absence of atmospheric forcing).

(2) Modelled 'tide plus surge' compared to SEAsim peak water levels. This demonstrates model skill in terms of surge response and consistency with the SEAsim statistical model outputs for the selected representative ARI TC events.

Astronomical Tide

Throughout the study area the tide wave is significantly modified by the network of offshore reefs and islands and the relatively shallow continental shelf. These features cause tidal amplification at some locations, including within Hervey Bay. Model validation to astronomic tidal predictions at Bundaberg, Urangan and Mooloolaba is provided in Figure 3-11. The model predictive skill with respect to tides and summarised using the Root Mean Square Error (RMSE) is as follows:

- Bundaberg: 0.08
- Urangan Harbour: 0.08
- Mooloolaba: 0.06

RMSE = 0 represents perfect model fit. In the context of the present study, a RMSE < 0.1 across the three standard port locations indicates satisfactory model skill.

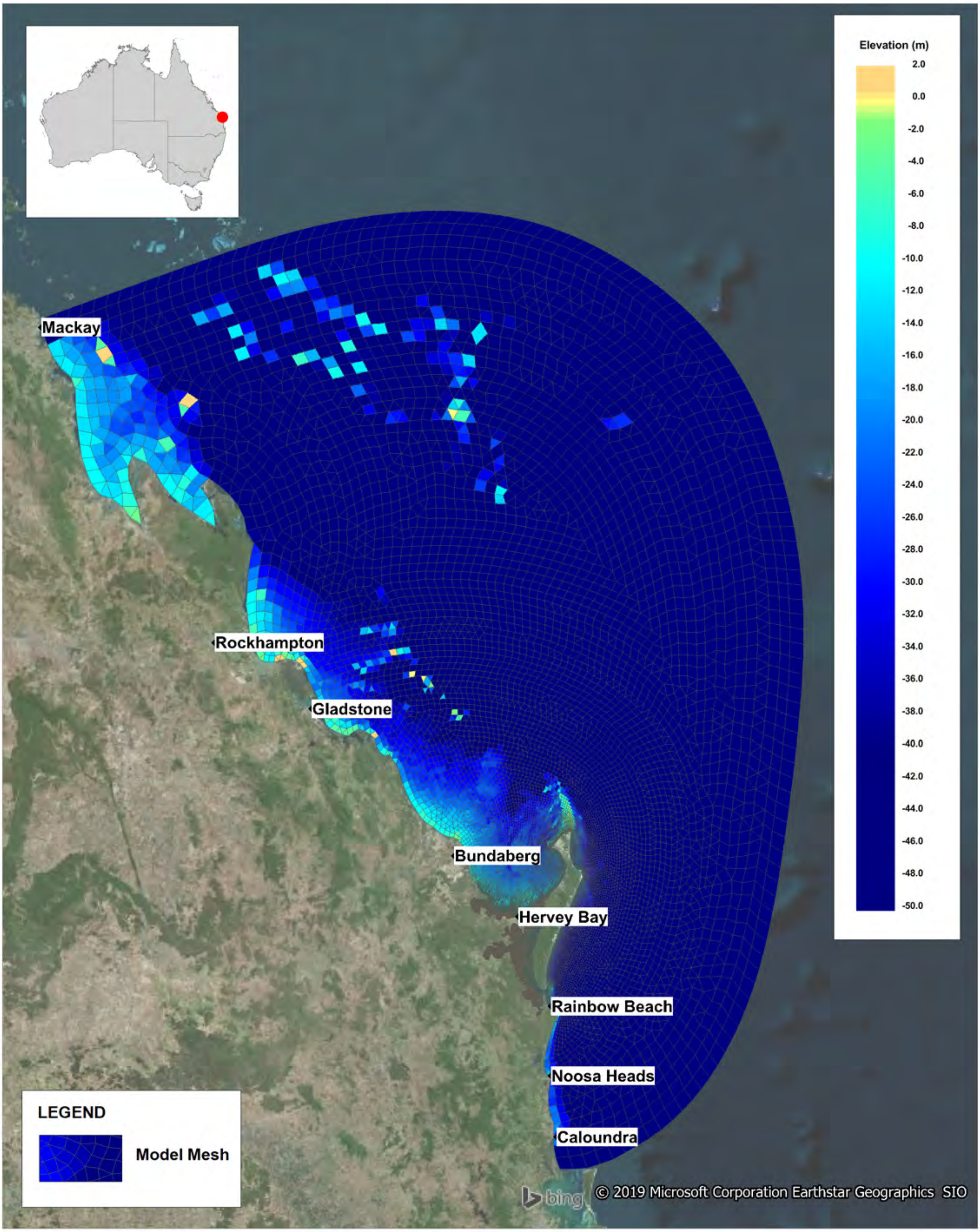
Tide plus Surge

Model validation to the peak 'tide plus surge' level estimated by the SEAsim statistical model simulation is illustrated below:

- Figure 3-12 for a representative present climate TC event that causes a water level close to the 100 year ARI; and
- Figure 3-13 for a representative 2100 climate TC event that causes a water level close to the 1000 year ARI.

Comparison between the model and SEAsim is generally very good[3], noting that water level precision cannot be expected when comparing statistical and deterministic model outputs.

[3] Background to SEAsim (a variant of SEAtide) is provided in Section 3.1 and SEA (2018)



Title:

Hydrodynamic Model Extent and Bathymetry

Figure: 3-9

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Approx. Scale

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Hydrodynamic Model Mesh Detail

Figure: 3-10

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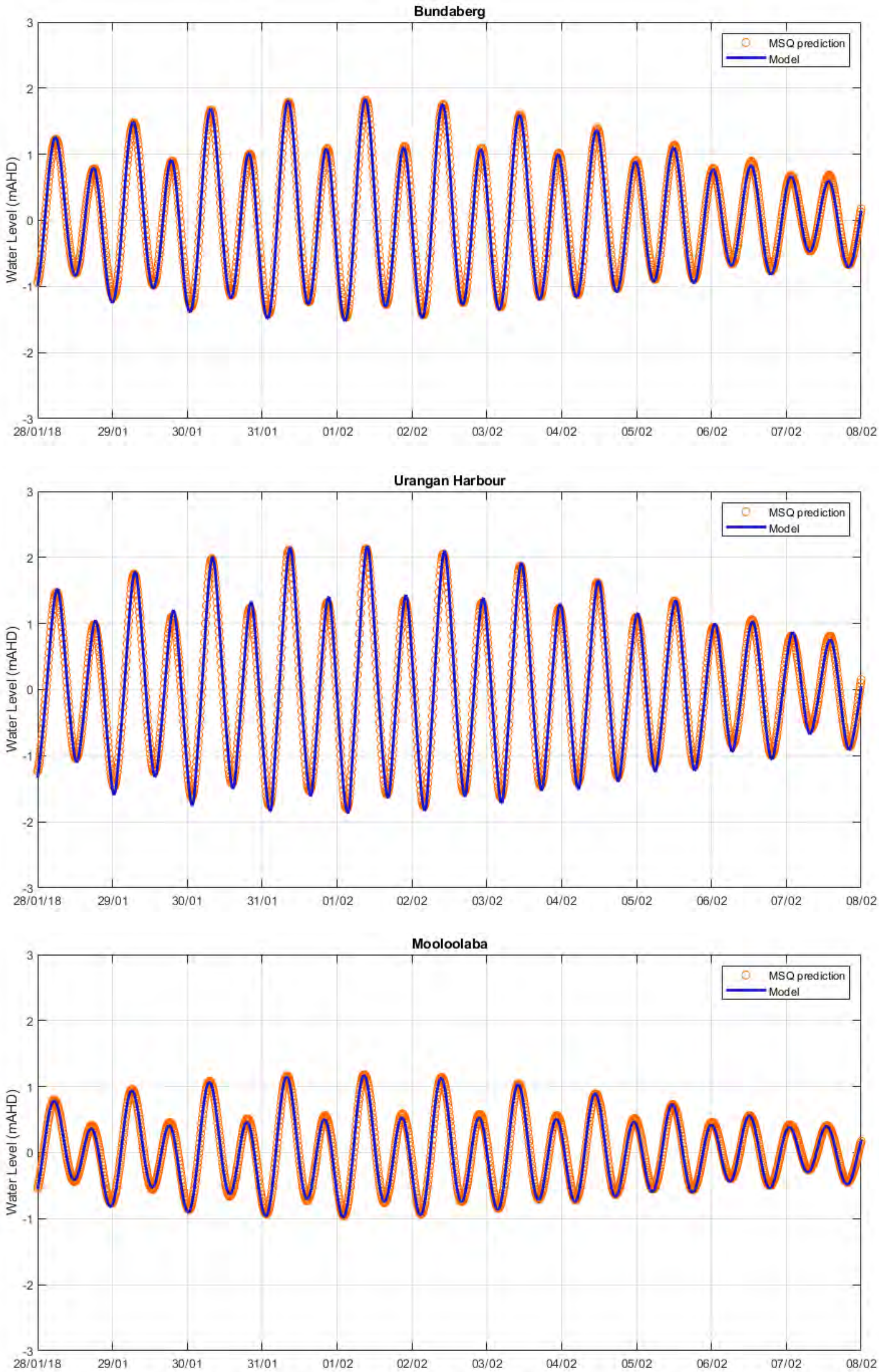


Figure 3-11 Modelled astronomic tide validation

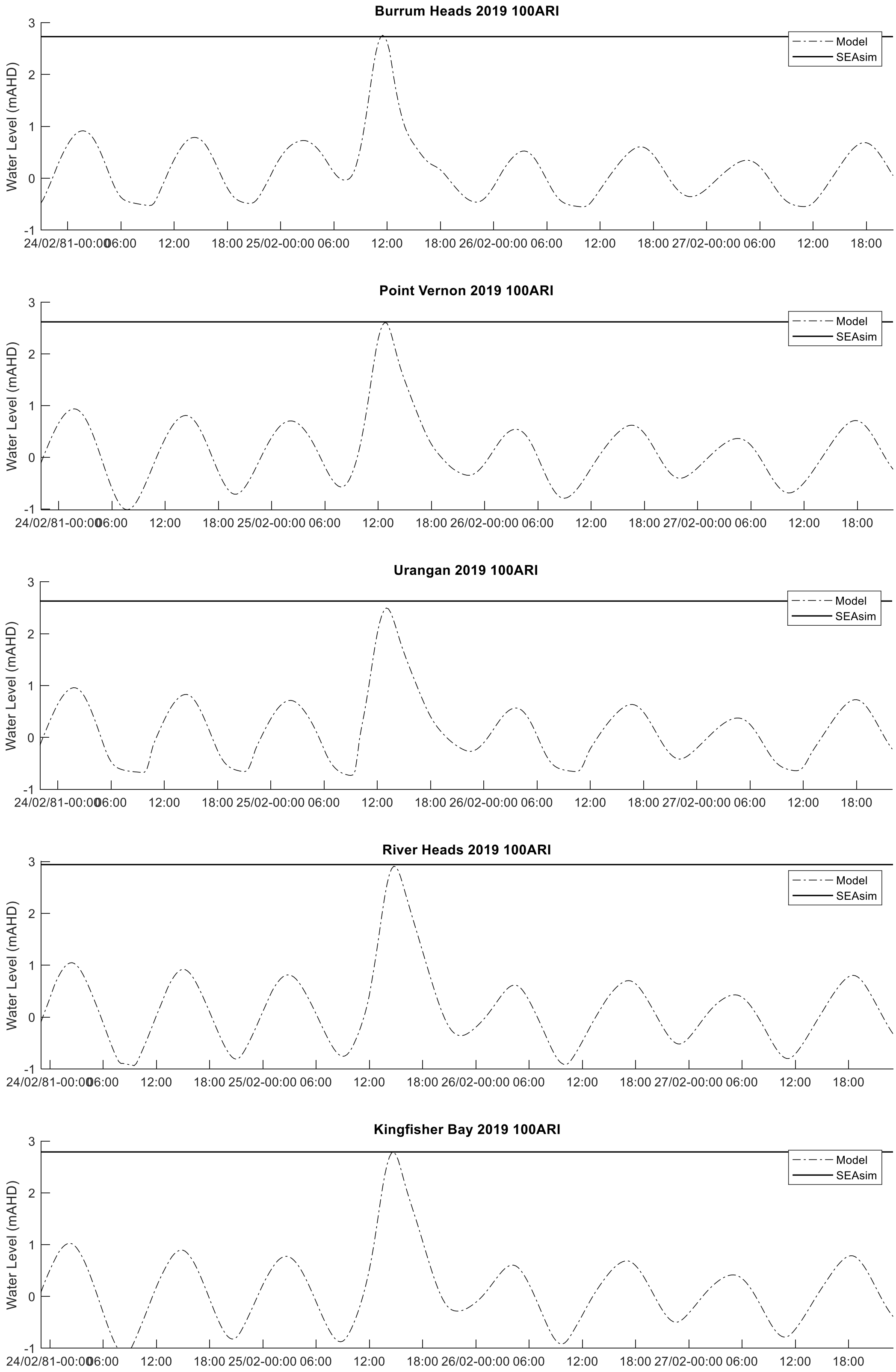


Figure 3-12 Modelled 'tide plus surge' validation with SEAsim peak water level: 2019 climate, 100 yr ARI

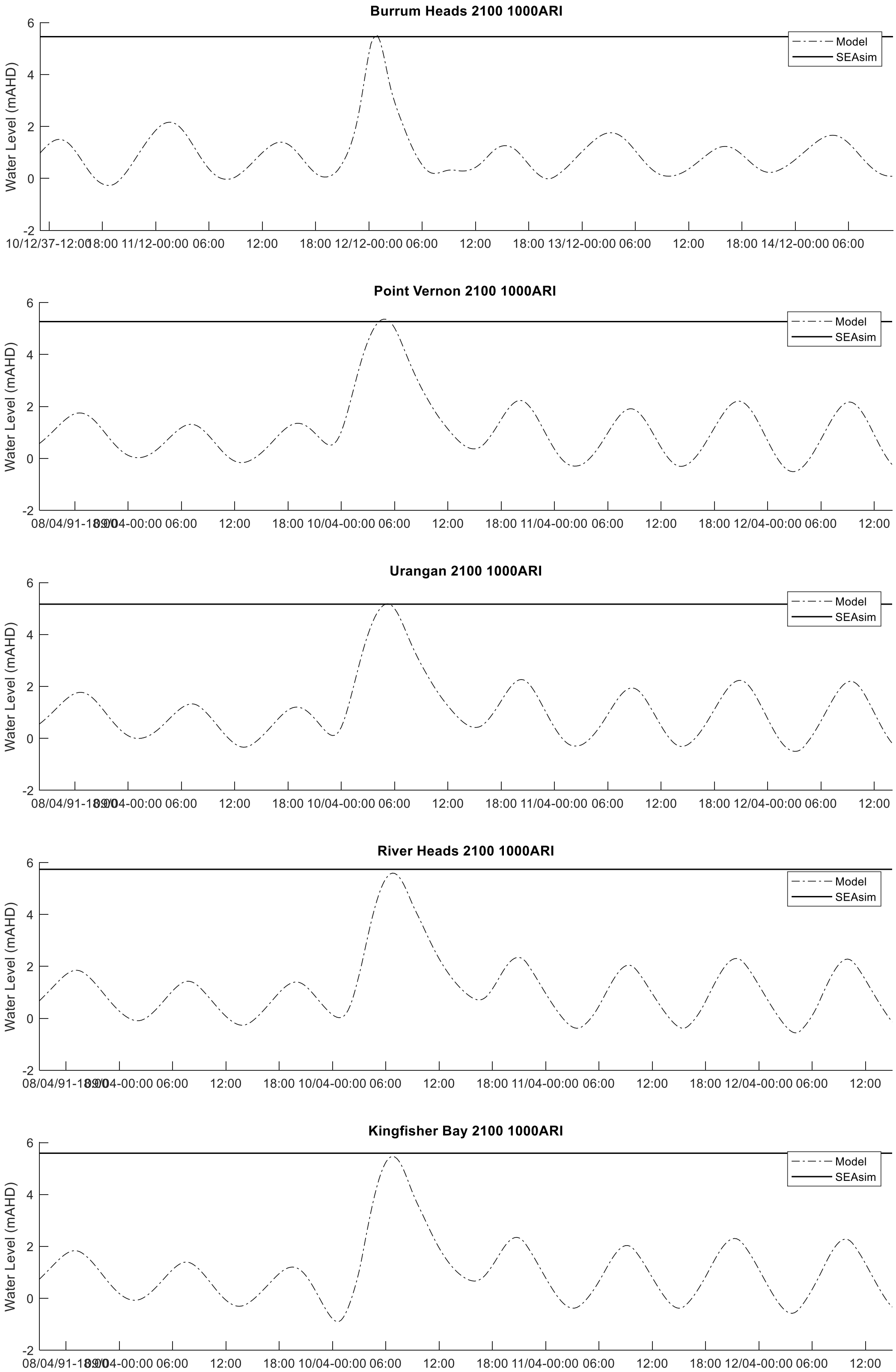


Figure 3-13 Modelled 'tide plus surge' validation with SEAsim peak water level: 2100 climate, 1000 yr ARI

3.5 Wave Setup & Runup Modelling

Storm tide assessments typically consider the contribution of wave setup and runup processes to the extreme water level for open coast locations. In this context, 'open coast' is defined as any location where breaking waves could occur during a storm, including the Hervey Bay and Fraser Island coastlines. Within the Great Sandy Strait, rivers and coastal creeks and across the coastal floodplain, the contribution of wave driven processes to the extreme water level is assumed to be minor and insignificant.

Representative wave setup and wave runup allowances have been estimated by modelling selected SEAsim TC events and using the calculated significant wave height and wave peak period as input to an empirical formula. This approach is described in the following sections.

3.5.1.1 Wave Model Description

SWAN (Delft University of Technology 2006) is a third-generation spectral wave model, which simulates the generation of waves by wind, dissipation by whitecapping, depth-induced wave breaking, bottom friction and wave-wave interactions in both deep and shallow water. SWAN simulates wave/swell propagation in two-dimensions, including shoaling and refraction due to spatial variations in bathymetry, water level and currents[4]. This is a global industry standard modelling package that has been applied with reliable results to many investigations worldwide.

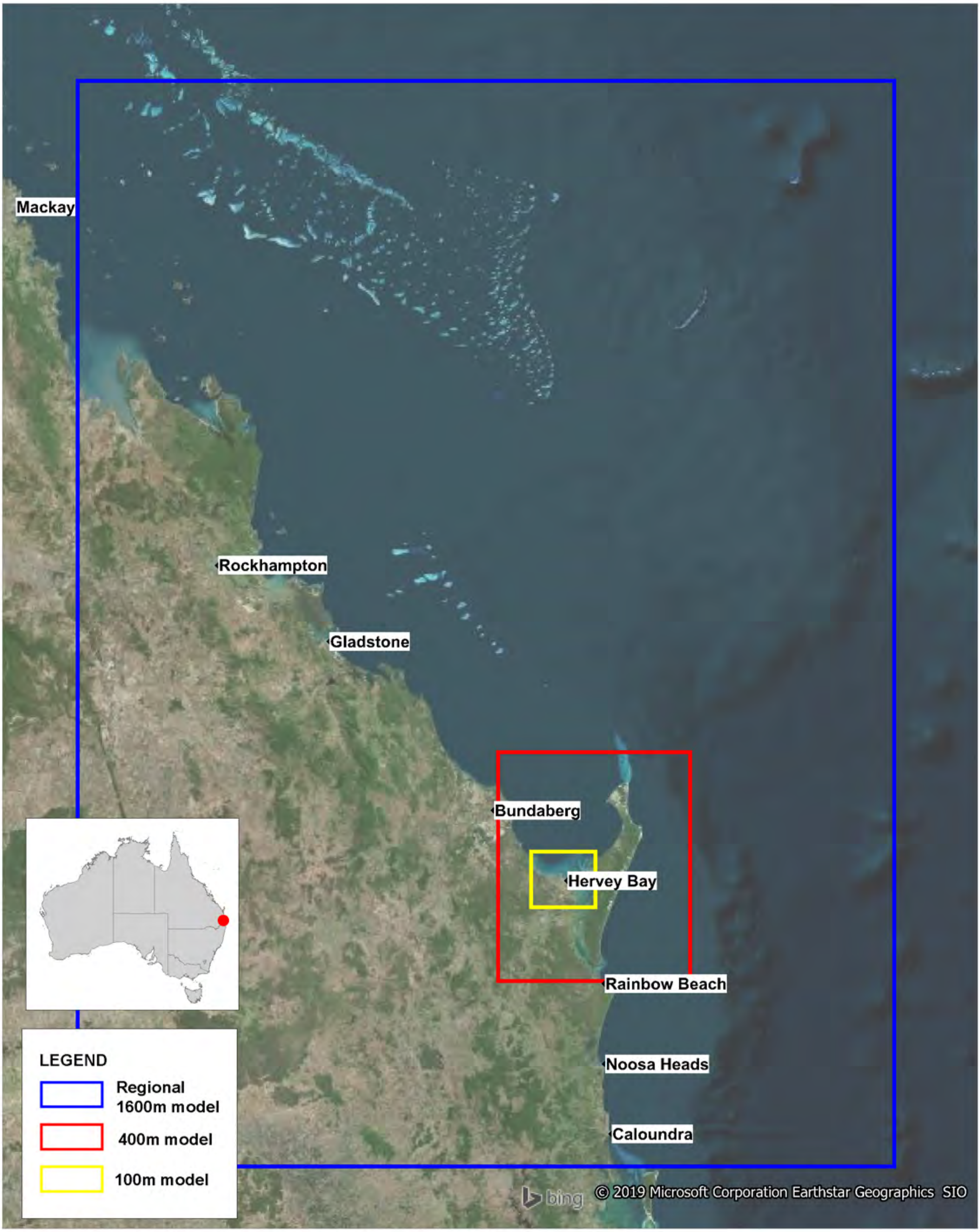
A nested grid wave modelling approach has been adopted and is shown in Figure 3-14. The nested system comprises a regional (1600 m grid resolution) model with the same approximate extent as the hydrodynamic model, extending from Bribie Island in the south to Mackay in the north and east to beyond the continental shelf. Wave propagation throughout the region has been assessed using a 400 m grid resolution sub-model with an additional 100 m resolution sub-model covering Hervey Bay, extending east from Burrum Heads to Fraser Island and south to River Heads. The wave model bathymetry has been derived from the same sources adopted for hydrodynamic modelling and listed in Section 3.5.

3.5.1.2 Wave Model Validation

Regional wave model validation with data recorded by the Mooloolaba and Bundaberg wave buoys (operated by the Queensland DES) is presented in Figure 3-15, noting that these are the closest wave monitoring sites to the study area. Measurements of significant wave (Hs), wave peak period (Tp) and wave peak direction (Dir) are available at Mooloolaba. The wave buoy at Bundaberg is non-directional and only Hs and Tp measurements are available at this location.

The model and data comparisons are generally very good, noting an over-prediction of the peak wave height at Bundaberg for the simulation period. It remains uncertain whether this tendency to over-predict the peak wave conditions extends into Hervey Bay due to the lack of data within the study area. In the context of the storm tide assessment, the consequence of a relatively small over (or under) prediction in wave height on the overall extreme water level is relatively minor.

[4] Simulation of TC events for the present study has adopted stationary water level corresponding to the event peak 'tide plus surge' condition.



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Nested Wave Model Extents

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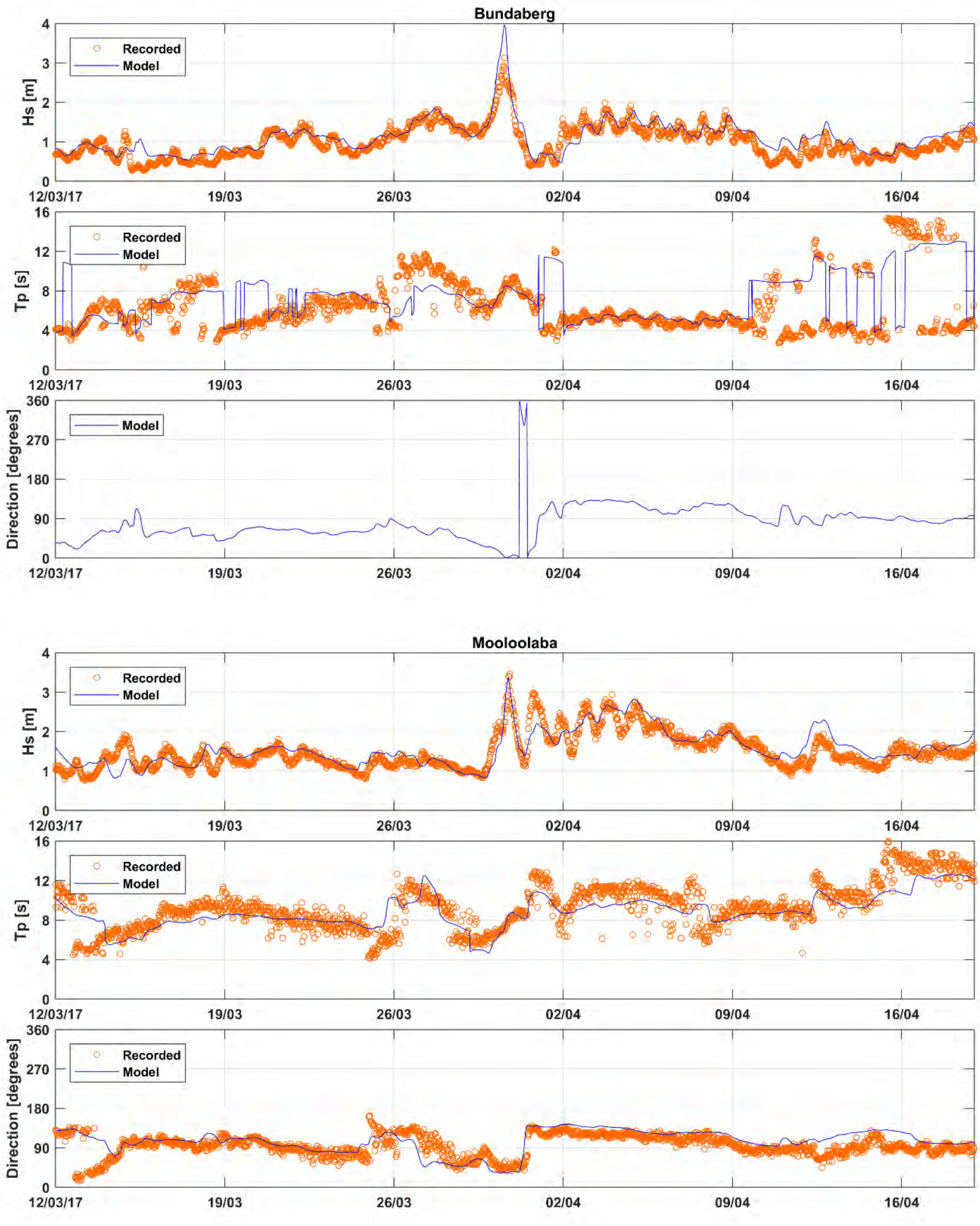

Figure 3-15 Regional Wave Model Validation Mooloolaba (top) and Bundaberg (bottom)

3.5.1.3 Wave Setup and Runup

The contribution of wave setup and runup processes to the extreme water level has been considered along the Hervey Bay and Fraser Island coastlines. Within the Great Sandy Strait, rivers, creeks and across the coastal floodplain the contribution of wave driven processes to the extreme water level is assumed to be insignificant.

Wave setup is an elevation of the mean (time averaged) water surface due to the pumping effect of waves. Wave setup has the potential to cause a small to moderate increase in water levels in the coastal waterways and floodplains. The wave setup contribution to the mean water level along exposed coastal locations can be of the order 0.5 to 1.0 m.

Wave runup is the intermittent process of advancement and retreat of the instantaneous shoreline position on a timescale that is of the order of the incoming wave period (~10 s for cyclone generated waves). Along exposed coastlines the wave runup can be a significant contributor to the peak water levels and inundation associated with the overtopping of coastal barriers. Furthermore, the large quantity of energy contained in individual wave runup can pose a serious risk to coastal barriers (natural or man-made) within the wave runup zone.

The wave setup and runup contribution to shoreline water levels within the coastal zone has been estimated using the SWAN model output and an empirical formulation based on 10 dynamically diverse field experiments described in Stockdon et al (2006). The runup height predicted with this formula is the level above the offshore mean water level that is exceeded by 2% of runup events (R2). This formulation was demonstrated in previous studies to provide robust estimates of surveyed debris levels associated with TC Winifred, TC Larry and TC Yasi (e.g. BMT WBM 2008, BMT WBM 2016). The general expression for wave setup and wave runup on beaches provided in Stockdon et al. (2006):

Wave setup

$$S_{shoreline} = 0.35\beta_f (H_0 L_0)^{1/2}$$

Equation 3-2

Wave runup

$$R_2 = 1.1\left(S_{shoreline} + \frac{H_0 L_0 \left(0.563\beta_f^2 + 0.004\right)^{1/2}}{2} \right)$$

Equation 3-3

Where β_f is the foreshore slope, H_0 is the deep water significant wave height and L_0 is the deep water wave length.

The inputs to Equation 3-2 and Equation 3-3 and resulting wave setup and runup estimates for the locations where there is an assumed potential for waves to influence the extreme water level is summarised in Table 3-7, Table 3-8 and Table 3-9. It is noted that the tables only represent a small subset of the total locations where estimates have been produced.

Table 3-7 Present climate (2019-2030) wave statistics and estimates of setup and runup potential

Location	100 year ARI				500 year ARI (mAHD)				1000 year ARI (mAHD)			
	Hs (m)	Tp (s)	Setup* (m)	2% Runup** (m)	Hs (m)	Tp (s)	Setup* (m)	2% Runup** (m)	Hs (m)	Tp (s)	Setup* (m)	2% Runup** (m)
Burrum Heads	1.39	6.96	0.32	0.79	1.82	7.00	0.37	0.90	1.93	7.79	0.43	1.04
Toogoom	1.51	7.83	0.38	0.92	2.00	8.33	0.46	1.13	2.10	8.60	0.49	1.19
Toogoom East	1.73	8.13	0.42	1.02	2.22	8.51	0.50	1.21	2.31	8.68	0.52	1.26
Dundowran Beach	1.64	11.36	0.57	1.39	2.16	11.50	0.66	1.62	2.23	12.06	0.71	1.73
Point Vernon West	2.12	11.39	0.65	1.59	2.63	11.52	0.74	1.79	2.69	11.60	0.75	1.82
Point Vernon	2.63	12.03	0.77	1.87	3.03	12.89	0.88	2.15	3.16	13.07	0.92	2.23
Scarness	2.30	6.08	0.36	0.88	2.70	6.91	0.45	1.09	2.80	12.84	0.85	2.06
Torquay	1.59	6.85	0.34	0.83	2.10	11.79	0.67	1.64	2.11	12.52	0.72	1.74
Urangan	1.36	6.60	0.30	0.74	1.87	11.61	0.62	1.52	1.92	12.60	0.69	1.67
Urangan Boat Harbour	1.75	5.13	0.27	0.65	2.13	5.74	0.33	0.80	2.20	5.80	0.34	0.82
Mangrove Point	1.35	4.08	0.19	0.45	1.77	4.52	0.24	0.58	1.84	4.53	0.24	0.59
River Heads	1.25	4.36	0.19	0.47	1.69	4.92	0.25	0.61	1.74	5.06	0.26	0.64
Kingfisher Bay	1.91	5.03	0.27	0.67	2.17	5.37	0.31	0.76	2.54	5.55	0.35	0.85
Happy Valley	3.08	9.51	0.29	0.99	4.01	12.54	0.44	1.49	4.08	12.90	0.46	1.55
Eurong	3.60	8.97	0.30	1.01	4.51	9.96	0.37	1.26	4.85	10.49	0.40	1.37

** Following Equation 3-2. Estimated foreshore slopes: 1 in 11 for Hervey Bay locations; 1 in 25 for Fraser Island east coast locations (Happy Valley and Eurong)*

*** Following Equation 3-3. Estimated foreshore slopes: 1 in 11 for Hervey Bay locations; 1 in 25 for Fraser Island east coast locations (Happy Valley and Eurong)*

Table 3-8 Future climate 2050 wave statistics and estimates of setup and runup potential

Location	100 year ARI				500 year ARI (mAHD)				1000 year ARI (mAHD)			
	Hs (m)	Tp (s)	Setup* (m)	2% Runup** (m)	Hs (m)	Tp (s)	Setup* (m)	2% Runup** (m)	Hs (m)	Tp (s)	Setup* (m)	2% Runup** (m)
Burrum Heads	1.56	7.22	0.36	0.86	2.04	8.16	0.46	1.12	2.14	8.33	0.48	1.17
Toogoom	1.72	8.57	0.44	1.07	2.23	8.81	0.52	1.26	2.32	9.03	0.54	1.32
Toogoom East	1.93	8.72	0.48	1.16	2.46	8.90	0.55	1.34	2.53	9.02	0.56	1.37
Dundowran Beach	1.85	11.34	0.61	1.48	2.40	11.45	0.70	1.70	2.45	12.22	0.75	1.83
Point Vernon West	2.32	11.09	0.66	1.62	2.87	11.47	0.76	1.86	2.90	11.67	0.78	1.90
Point Vernon	2.82	12.90	0.85	2.08	3.24	12.99	0.92	2.24	3.35	13.22	0.95	2.32
Scarness	2.47	7.18	0.44	1.08	2.92	12.89	0.87	2.11	2.99	12.93	0.88	2.14
Torquay	1.82	7.08	0.38	0.91	2.30	11.85	0.71	1.72	2.31	12.62	0.76	1.84
Urangan	1.58	6.77	0.33	0.81	2.09	11.83	0.67	1.64	2.13	12.70	0.73	1.78
Urangan Boat Harbour	1.97	5.29	0.29	0.71	2.31	5.97	0.36	0.87	2.37	6.02	0.36	0.89
Mangrove Point	1.53	4.52	0.22	0.54	1.97	4.64	0.26	0.62	2.02	4.64	0.26	0.63
River Heads	1.47	4.77	0.23	0.55	1.89	5.15	0.28	0.68	1.91	5.27	0.29	0.70
Kingfisher Bay	2.24	5.38	0.32	0.77	2.31	5.48	0.33	0.80	2.71	5.68	0.37	0.90
Happy Valley	3.96	12.64	0.44	1.49	4.25	12.97	0.47	1.59	4.35	13.15	0.48	1.63
Eurong	4.72	10.11	0.38	1.30	4.88	10.55	0.41	1.38	5.11	10.80	0.43	1.45

** Following Equation 3-2. Estimated foreshore slopes: 1 in 11 for Hervey Bay locations; 1 in 25 for Fraser Island east coast locations (Happy Valley and Eurong)*

*** Following Equation 3-3. Estimated foreshore slopes: 1 in 11 for Hervey Bay locations; 1 in 25 for Fraser Island east coast locations (Happy Valley and Eurong)*

Table 3-9 Future climate 2100 wave statistics and estimates of setup and runup potential

Location	100 year ARI				500 year ARI (mAHD)				1000 year ARI (mAHD)			
	Hs (m)	Tp (s)	Setup* (m)	2% Runup** (m)	Hs (m)	Tp (s)	Setup* (m)	2% Runup** (m)	Hs (m)	Tp (s)	Setup* (m)	2% Runup** (m)
Burrum Heads	1.82	7.96	0.42	1.03	2.33	7.99	0.48	1.17	2.48	8.60	0.53	1.30
Toogoom	1.99	9.27	0.52	1.25	2.54	9.41	0.59	1.44	2.66	9.44	0.61	1.48
Toogoom East	2.21	9.33	0.55	1.33	2.77	9.42	0.62	1.50	2.88	9.43	0.63	1.53
Dundowran Beach	2.14	10.84	0.62	1.52	2.71	11.69	0.76	1.84	2.79	12.51	0.82	2.00
Point Vernon West	2.61	11.24	0.71	1.74	3.18	11.84	0.83	2.02	3.24	11.91	0.84	2.05
Point Vernon	3.08	13.06	0.90	2.20	3.53	13.15	0.97	2.36	3.71	13.55	1.03	2.50
Scarness	2.73	7.64	0.50	1.21	3.18	12.98	0.91	2.22	3.30	13.10	0.94	2.28
Torquay	2.08	7.47	0.42	1.03	2.60	11.78	0.75	1.82	2.61	12.78	0.81	1.98
Urangan	1.86	6.98	0.37	0.91	2.39	11.74	0.71	1.74	2.48	12.87	0.80	1.94
Urangan Boat Harbour	2.19	4.51	0.26	0.64	2.55	6.25	0.39	0.96	2.71	6.48	0.42	1.02
Mangrove Point	1.78	4.78	0.25	0.61	2.23	4.85	0.29	0.69	2.35	5.16	0.31	0.76
River Heads	1.72	5.10	0.26	0.64	2.15	5.55	0.32	0.78	2.26	5.78	0.34	0.83
Kingfisher Bay	2.40	5.52	0.34	0.82	2.50	5.77	0.36	0.87	2.89	5.93	0.40	0.97
Happy Valley	4.29	12.80	0.46	2.21	4.69	12.95	0.49	1.67	5.46	15.96	0.65	2.21
Eurong	5.19	10.73	0.43	2.31	5.42	11.07	0.45	1.53	6.56	15.20	0.68	2.31

** Following Equation 3-2. Estimated foreshore slopes: 1 in 11 for Hervey Bay locations; 1 in 25 for Fraser Island east coast locations (Happy Valley and Eurong)*

*** Following Equation 3-3. Estimated foreshore slopes: 1 in 11 for Hervey Bay locations; 1 in 25 for Fraser Island east coast locations (Happy Valley and Eurong)*

4 Storm Tide Water Level Statistics

4.1 Nearshore Water Levels

The present climate (2019 to 2030) and future climate 2050 and 2100 storm tide water levels for key locations throughout the study area are summarised in Table 4-1, Table 4-2 and Table 4-3. These represent 'nearshore levels' and are not intended to guide the setting of minimum habitable floor levels for the locations listed. Mapping of the storm tide hazard vulnerability zone to inform the CHAS is discussed further in Section 4.2, together with the proposed approach for developing products to support other planning purposes.

The 'sustained peak' water level considers the combined non-TC and TC 'tide plus surge' statistics following the methodology described in Section 3.3. For open coast locations (namely the Hervey Bay and Fraser Island coastlines), the sustained peak also includes an allowance for wave setup (following Equation 3-2 and defined in Table 3-7, Table 3-8 and Table 3-9) and is assumed to persist long enough to inundate the coastal floodplain up to this level.

The 'coastal zone' levels apply to location where wave breaking and wave runup occurs and is assumed to influence only a limited distance landward of the coastline. These levels represent the peak elevation of the intermittent process of advancement and retreat of the shoreline associated with wave processes during a storm tide inundation event and include an allowance for wave setup and wave runup (following Equation 3-3 and defined in Table 3-7, Table 3-8 and Table 3-9). The coastal zone levels are not expected to be sustained for an extended period. Where overtopping of the coastal barrier occurs due to wave processes, 'coastal zone' water levels are expected to be conservatively high. In the context of the CHAS, open coast locations behind the coastal barrier and below the estimated level are considered high hazard areas.

The water levels provided in Table 4-1, Table 4-2 and Table 4-3 do not include an additional freeboard allowance and, as described above, are not intended to serve as guidance for setting minimum habitable floor levels.

Table 4-1 Present climate (2019 to 2030) nearshore water level ARIs at key locations (not to be used as planning levels)

Location	HAT estimate (mAHD)	100 year ARI (mAHD)			500 year ARI (mAHD)			1000 year ARI (mAHD)		
		Tide plus Surge Peak	Sustained Peak*	Coastal Zone Peak**	Tide plus Surge Peak	Sustained Peak*	Coastal Zone Peak**	Tide plus Surge Peak	Sustained Peak*	Coastal Zone Peak**
Burrum Heads	2.12	2.73	3.05	3.52	3.92	4.29	4.82	4.13	4.56	5.17
Toogoom	2.14	2.68	3.06	3.60	3.87	4.33	5.00	4.05	4.54	5.24
Toogoom East	2.15	2.68	3.10	3.70	3.87	4.37	5.08	4.05	4.57	5.31
Dundowran Beach	2.18	2.58	3.15	3.97	3.58	4.24	5.20	3.8	4.51	5.53
Point Vernon West	2.2	2.58	3.23	4.17	3.53	4.27	5.32	3.77	4.52	5.59
Point Vernon	2.21	2.62	3.39	4.49	3.52	4.40	5.67	3.9	4.82	6.13
Scarness	2.20	2.66	3.02	3.54	3.61	4.06	4.70	4	4.85	6.06
Torquay	2.18	2.65	2.99	3.48	3.56	4.23	5.20	3.82	4.54	5.56
Urangan	2.18	2.63	2.93	3.37	3.53	4.15	5.05	3.76	4.45	5.43
Urangan Boat Harbour	2.17	2.65	2.92	3.30	3.54	3.87	4.34	3.75	4.09	4.57
Mangrove Point	2.27	2.83	3.02	3.28	3.73	3.97	4.31	3.95	4.19	4.54
River Heads	2.4	2.94	3.13	3.41	3.88	4.13	4.49	4.2	4.46	4.84
Maaroom	1.8	2.03	NA	NA	2.21	NA	NA	2.27	NA	NA
Boonooroo	1.49	1.71	NA	NA	1.98	NA	NA	2.12	NA	NA
Tuan	1.42	1.66	NA	NA	1.96	NA	NA	2.16	NA	NA
Poona	1.54	1.76	NA	NA	2.05	NA	NA	2.21	NA	NA
Tinnanbar	1.52	1.73	NA	NA	2.03	NA	NA	2.2	NA	NA
Kingfisher Bay	2.32	2.79	3.06	3.46	3.58	3.89	4.34	4.1	4.45	4.95
Happy Valley	1.23	1.39	1.68	2.38	1.52	1.96	3.01	1.6	2.06	3.15
Eurong	1.23	1.38	1.68	2.39	1.5	1.87	2.76	1.6	2.00	2.97
Maryborough	2.70	3.2	NA	NA	4.21	NA	NA	4.45	NA	NA

** For open coast locations, the 'sustained peak' includes tide, surge and wave setup*

*** For open coast locations where wave breaking and wave runup processes occur, the 'coastal zone' includes tide, surge, wave setup and 2% wave runup potential*

Table 4-2 Future climate 2050 nearshore water level ARIs at key locations (not to be used as planning levels)

Location	HAT estimate (mAHD)	100 year ARI (mAHD)			500 year ARI (mAHD)			1000 year ARI (mAHD)		
		Tide plus Surge Peak	Sustained Peak*	Coastal Zone Peak**	Tide plus Surge Peak	Sustained Peak*	Coastal Zone Peak**	Tide plus Surge Peak	Sustained Peak*	Coastal Zone Peak**
Burrum Heads	2.42	3.21	3.57	4.07	4.49	4.95	5.61	4.65	5.13	5.82
Toogoom	2.44	3.15	3.59	4.22	4.45	4.97	5.71	4.6	5.14	5.92
Toogoom East	2.45	3.14	3.62	4.30	4.42	4.97	5.76	4.63	5.19	6.00
Dundowran Beach	2.48	2.99	3.60	4.47	4.08	4.78	5.78	4.42	5.17	6.25
Point Vernon West	2.5	2.98	3.64	4.60	4.07	4.83	5.93	4.34	5.12	6.24
Point Vernon	2.51	3.03	3.88	5.11	3.99	4.91	6.23	4.52	5.47	6.84
Scarness	2.5	3.08	3.52	4.16	4.17	5.04	6.28	4.62	5.50	6.76
Torquay	2.48	3.09	3.47	4.00	4.09	4.80	5.81	4.51	5.27	6.35
Urangan	2.48	3.05	3.38	3.86	4.05	4.72	5.69	4.38	5.11	6.16
Urangan Boat Harbour	2.47	3.09	3.38	3.80	3.99	4.35	4.86	4.38	4.74	5.27
Mangrove Point	2.57	3.27	3.49	3.81	4.23	4.49	4.85	4.67	4.93	5.30
River Heads	2.7	3.34	3.57	3.89	4.45	4.73	5.13	4.82	5.11	5.52
Maaroom	2.1	2.35	NA	NA	2.66	NA	NA	2.66	NA	NA
Boonooroo	1.79	2.05	NA	NA	2.39	NA	NA	2.59	NA	NA
Tuan	1.72	2.02	NA	NA	2.39	NA	NA	2.63	NA	NA
Poona	1.84	2.09	NA	NA	2.47	NA	NA	2.7	NA	NA
Tinnanbar	1.82	2.05	NA	NA	2.47	NA	NA	2.69	NA	NA
Kingfisher Bay	2.62	3.16	3.48	3.93	4.02	4.35	4.82	4.59	4.96	5.49
Happy Valley	1.53	1.79	2.23	3.28	2.08	2.55	3.67	2.15	2.63	3.78
Eurong	1.53	1.69	2.07	2.99	1.84	2.25	3.22	1.94	2.37	3.39
Maryborough	3	3.93	NA	NA	4.72	NA	NA	5.01	NA	NA

** For open coast locations, the 'sustained peak' includes tide, surge, wave setup and 0.3 m sea level rise allowance and applies across the coastal floodplain*

*** For open coast locations where wave breaking and wave runup processes occur, the 'coastal zone' includes tide, surge, wave setup, 2% wave runup and 0.3 m sea level rise allowance*

Table 4-3 Future climate 2100 nearshore water level ARIs at key locations (not to be used as planning levels)

Location	HAT estimate (mAHD)	100 year ARI (mAHD)			500 year ARI (mAHD)			1000 year ARI (mAHD)		
		Tide plus Surge Peak	Sustained Peak*	Coastal Zone Peak**	Tide plus Surge Peak	Sustained Peak*	Coastal Zone Peak**	Tide plus Surge Peak	Sustained Peak*	Coastal Zone Peak**
Burrum Heads	2.92	3.91	4.33	4.94	5.24	5.72	6.41	5.46	5.99	6.76
Toogoom	2.94	3.84	4.36	5.09	5.25	5.84	6.69	5.44	6.05	6.92
Toogoom East	2.95	3.8	4.35	5.13	5.22	5.84	6.72	5.45	6.08	6.98
Dundowran Beach	2.98	3.62	4.24	5.14	4.78	5.54	6.62	5.16	5.98	7.16
Point Vernon West	3	3.6	4.31	5.34	4.82	5.65	6.84	5.16	6.00	7.21
Point Vernon	3.01	3.68	4.58	5.88	4.76	5.73	7.12	5.27	6.30	7.77
Scarness	3	3.74	4.24	4.95	4.92	5.83	7.14	5.49	6.43	7.77
Torquay	2.98	3.73	4.15	4.76	4.83	5.58	6.65	5.25	6.06	7.23
Urangan	2.98	3.71	4.08	4.62	4.72	5.43	6.46	5.17	5.97	7.11
Urangan Boat Harbour	2.97	3.74	4.00	4.38	4.76	5.15	5.72	5.16	5.58	6.18
Mangrove Point	3.07	3.92	4.17	4.53	5.02	5.31	5.71	5.44	5.75	6.20
River Heads	3.2	4.02	4.28	4.66	5.19	5.51	5.97	5.74	6.08	6.57
Maaroom	2.6	2.89	NA	NA	3.32	NA	NA	3.32	NA	NA
Boonooroo	2.29	2.62	NA	NA	3.04	NA	NA	3.22	NA	NA
Tuan	2.22	2.59	NA	NA	3.04	NA	NA	3.27	NA	NA
Poona	2.34	2.66	NA	NA	3.07	NA	NA	3.26	NA	NA
Tinnanbar	2.32	2.61	NA	NA	3.08	NA	NA	3.35	NA	NA
Kingfisher Bay	3.12	3.92	4.26	4.74	4.97	5.33	5.84	5.59	5.99	6.56
Happy Valley	2.03	2.48	2.94	4.69	2.91	3.40	4.58	3.09	3.74	5.30
Eurong	2.03	2.2	2.63	4.51	2.42	2.87	3.95	2.54	3.22	4.85
Maryborough	3.50	4.62	NA	NA	5.78	NA	NA	6.09	NA	NA

** For open coast locations within Hervey Bay, the 'sustained peak' includes tide, surge, wave setup and 0.8 m sea level rise allowance and across the coastal floodplain*

*** For open coast locations where wave breaking and wave runup processes occur, the 'coastal zone' includes tide, surge, wave setup, 2% wave runup and 0.8 m sea level rise*

4.2 Comparison with Previous Studies

Over the past ~10 years there have been several tropical cyclone storm tide hazard assessments for Fraser Coast communities (e.g. GHD 2011a, GHD 2011b, NDRP 2014). These studies, at times overlapping in spatial extent, have estimated extreme coastal water levels and inundation areas. The recent previous work has built on the statistical basis for regional storm tide established as part of the *Queensland Climate Change Ocean Hazards Assessment Study Ocean Hazard Assessment Stage 2, Tropical Cyclone Induced Water Levels and Waves: Hervey Bay and Sunshine Coast* (Hardy et al. 2004). This so-called 'QCC study' has been used as the 'reference' study for subsequent assessments.

Present climate outputs from the QCC study and current study are compared in Table 4-4. Water level statistics presented in the QCC study are representative of the 'tide plus surge' or 'tide, surge plus wave setup' (equivalent to the 'sustained peak') levels. The QCC study did not consider the wave runup potential at locations where wave breaking occurs. The comparison indicates the following:

- At the 100 year ARI differences are relatively small across all locations and within 0.1 m at Scarness, Toogoom East, Torquay, Urangan Boat Harbour and Urangan. The largest difference (+0.4 m) is at Point Vernon; and
- At the 500 and 1000 year ARI, the differences are larger and generally between 0.3 and 0.8 m.

The exact cause for differences between the studies, particularly for the rarer ARIs, cannot be precisely known. In discussions with Mr Lou Mason, who was the principal investigator in the QCC study and a contributor to the current study, it is believed that the differences are principally due to the improved Harper and Mason (2016) 10,000-year synthetic TC climatology compared with the earlier developmental 5,000-year set adopted by the QCC study. While statistically robust for its time, the QCC study relies on a relatively short record of TC characteristics measured between 1969 and 2001. Harper and Mason (2016) use an additional ~16 years of reliable TC data, during which time many significant events have developed in the Coral Sea and impacted the Queensland east coast. This additional data increases the historical record by ~30% and therefore improves the statistical basis for the current study.

Table 4-4 Water level statistics comparison: QCC 2004 (Hardy et al. 2004) and the current study

Location	100 year ARI			500 year ARI			1000 year ARI		
	QCC Study (mAHD)	Current Study (mAHD)	*Difference (m)*	QCC Study (mAHD)	Current Study (mAHD)	*Difference (m)*	QCC Study (mAHD)	Current Study (mAHD)	*Difference (m)*
Burrum Heads	2.79	3.05	*0.26*	3.46	4.29	*0.83*	3.73	4.56	*0.83*
Dundowran Beach	2.96	3.15	*0.19*	3.69	4.24	*0.55*	4.03	4.51	*0.48*
Mangrove Point*	2.54*	2.83*	*0.29*	3.12*	3.73*	*0.61*	3.36*	3.95*	*0.59*
Point Vernon West	2.98	3.23	*0.25*	3.66	4.27	*0.61*	4.00	4.52	*0.52*
Point Vernon	3.02	3.39	*0.37*	3.68	4.40	*0.72*	3.99	4.82	*0.83*
River Heads*	2.62*	2.94*	*0.32*	3.30*	3.88*	*0.58*	3.58*	4.20*	*0.62*
Scarness	3.11	3.02	*-0.09*	3.82	4.06	*0.24*	4.15	4.85	*0.70*
Toogoom East	3.00	3.10	*0.10*	3.75	4.37	*0.62*	4.07	4.57	*0.50*
Toogoom	2.88	3.06	*0.18*	3.58	4.33	*0.75*	3.88	4.54	*0.66*
Torquay	3.03	2.99	*-0.04*	3.68	4.23	*0.55*	4.01	4.54	*0.53*
Urangan Boat Harbour	2.93	2.92	*-0.01*	3.51	3.87	*0.36*	3.75	4.09	*0.34*
Urangan	2.98	2.92	*-0.06*	3.58	4.15	*0.57*	3.83	4.45	*0.62*

** tide plus surge only, wave setup assumed negligible*

5 Storm Tide Inundation Depth Mapping

Broadscale storm tide hazard vulnerability mapping developed specifically for the CHAS is provided in Appendix A. This mapping shows the potential depth of inundation for the 100 year ARI for the present (2019 to 2030), 2050 and 2100 climates and is based on a combination of the statistical and deterministic modelling described in Section 3. Maps have also been produced for the 500 and 1000-year ARIs but are not shown in Appendix A.

The adopted mapping methodology involves extrapolating nearshore peak water level across the adjacent coastal land, with ground elevations derived from the available topographic LiDAR survey datasets. A total of 1,628 unique nearshore locations underpin the mapping and the following key assumptions have been made:

- The potential influence of wave processes is considered within a 200 m buffer landward of the coastline and the peak water level within this region is defined by the 'coastal zone' estimate.
- Across the coastal floodplain beyond the 200 m landward buffer, the influence of waves is assumed to reduce and therefore the 'sustained peak' level is applied in these areas.
- Throughout the Great Sandy Strait and within the Mary and Burrum Rivers, the 'tide plus surge' peak water levels apply.

It is noted that the mapped storm tide hazard vulnerability zone does not explicitly account for wind shear stresses over land. Wind across land is not expected to significantly influence inundation depths; however, it is acknowledged that severe winds may slightly alter inundation extents.

Effort has been made to only map inundation in areas with a hydraulic connection to the sea; however, inundation may be shown in some locations that are not directly connected but fall below the criteria water level. The mapping also assumes that there is enough time and water available from the overtopping of coastal barriers to fill potential holding basins up to the given water level. In this respect, the mapped inundation areas may be conservative. Some of this assumed conservatism could be removed if the modelling approach explicitly resolved overtopping of the coastal barriers and overland flow. Such an approach would require detailed, high-resolution bathymetry datasets of the nearshore region and is beyond the scope of assessments needed to support strategic planning decision making.

5.1 Additional Mapping for Other Planning Purposes

The CHAS requires a specific mapping product that describes the potential magnitude and extent of inundation associated with storm tide. In addition to mapping the depth of inundation, outputs from the current study could also be used to inform the setting of minimum habitable floor levels within the vulnerability zone.

As discussed in Section 4.1, freeboard requirements, planning periods and risk tolerance all need to be considered when determining habitable floor levels which are set by Council policy. In the case of storm tide inundation, different freeboard allowances may apply to different areas depending on the relative exposure to coastal processes or concern regarding other unresolved processes. For example, in areas not directly exposed to wave processes the 'standard' freeboard allowance applied to the broader floodplain is likely to be appropriate. For 'coastal zone' areas, location specific wave setup and wave runup estimates provided in this report may help to inform an appropriate additional allowance to account for the greater uncertainty in peak water levels at these locations. Once a preferred approach is known, planning level mapping products that incorporate the outcomes of this study and are consistent with Council policy can be developed.

6 Storm Tide Assessment Limitations

The following limitations of the assessment approach and modelling introduce uncertainty in the results of this study:

- The first source of uncertainty arises from fitting and extrapolating statistical distributions to a very limited historical dataset (in this case, approximately 50 years of historical tropical cyclone data). It is not possible to estimate the resulting storm tide prediction bias associated with this approach.
- Another source of uncertainty arises from the wind and pressure model adopted for the study. Experience gained from the calibration phase of this and other similar studies suggests that representation of real TCs with a simple parametric wind models has its limitations. Real TC wind fields often display complexities not resolved by the parametric wind model, such as strong asymmetries and/or sub scale features such as meso-vortices. Any limitation in the parametric wind model will directly translate to the predicted storm surge.
- The ability to predict wave runup over and beyond the sloping beach profile (into the residential and populated areas) is limited and has been approximated using an empirical relationship. Quantifying the risks to the community and/or existing assets from inundation and wave action are limited by the availability of accurate nearshore hydrographic survey data and the assumption of a static coastal barrier. Site-based assessments of inundation and overtopping potential, building on the work described in this report, should be completed in support of detailed planning and design projects.
- It is difficult to estimate the order of magnitude of the combination of these uncertainties due to the highly dynamic nature of storm tide events and the infinite variation in the physical parameters involved. However, recent experience with model calibration for this and previous studies has indicated that prediction of water levels (excluding wave effects) is mostly within 0.5 m and the prediction of peak runup levels is often within 1 m. It should be noted that statistical analysis, where thousands of events are used to provide long term estimates, will generally tend to average out the variables and provide better accuracy in the result than that predicted for a single deterministic event.

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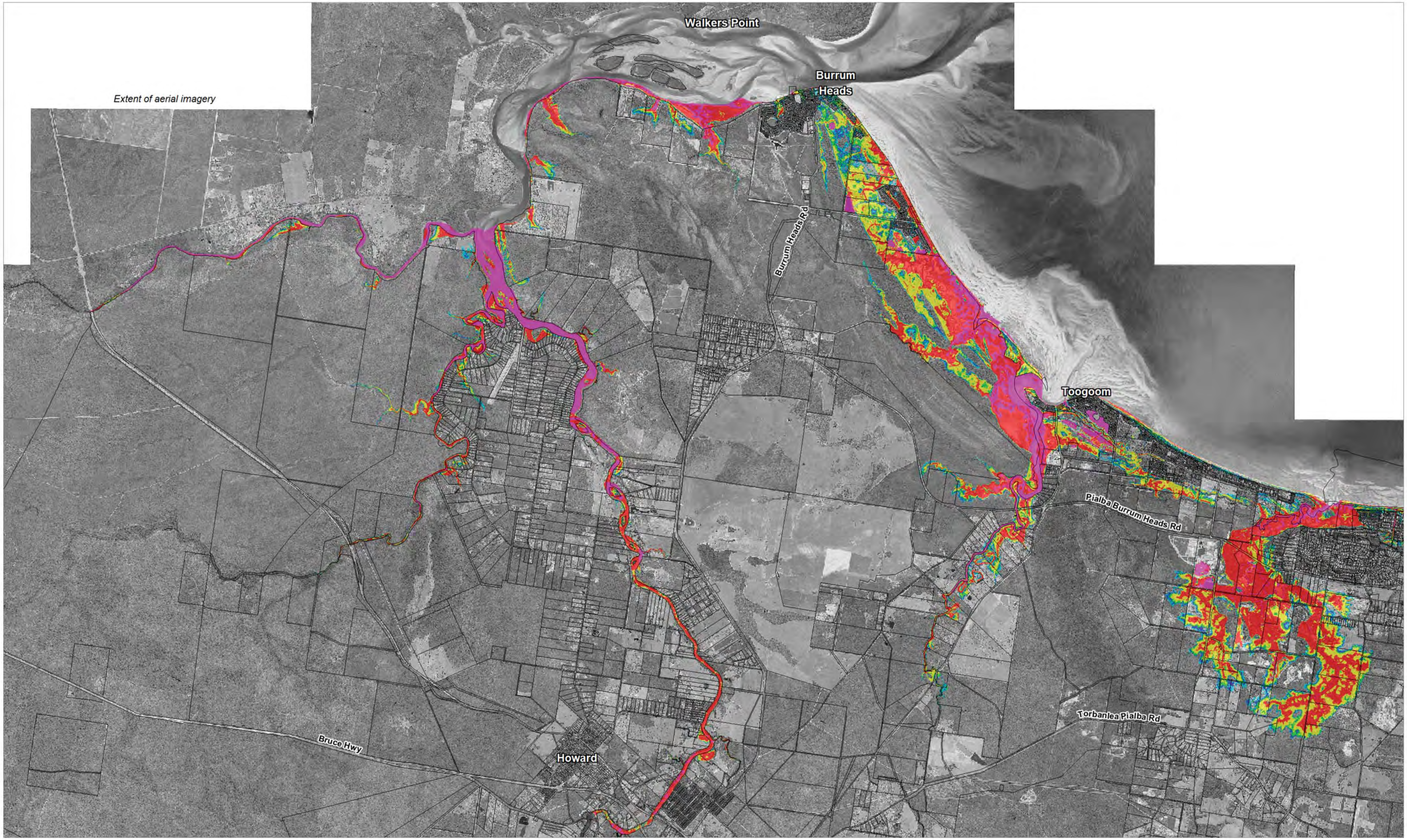
Appendix A Storm Tide Vulnerability Zone Mapping



LEGEND

Cadastral Boundaries

Inundation Depth (m)

- 0.00 to 0.15
- 0.15 to 0.30
- 0.30 to 0.50
- 0.50 to 1.00
- 1.00 to 2.00
- Greater than 2.00

Title:

Storm Tide Vulnerability Zone
1 in 100 ARI in 2019

Figure:

Rev: **A**

N

0 2 4km

Approx. scale

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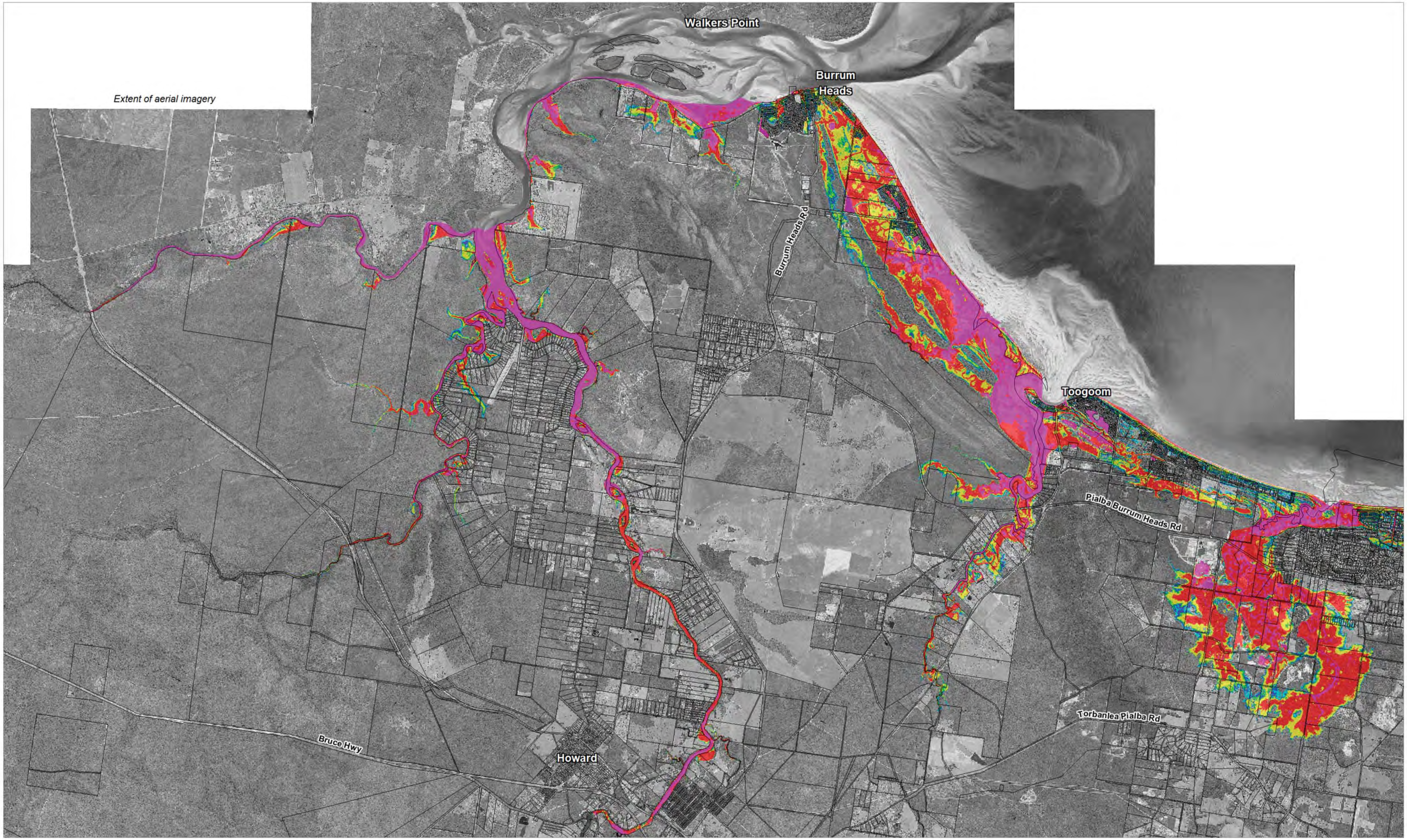

LEGEND

Cadastral Boundaries

Inundation Depth (m)

- 0.00 to 0.15
- 0.15 to 0.30
- 0.30 to 0.50
- 0.50 to 1.00
- 1.00 to 2.00
- Greater than 2.00

Title:

Storm Tide Vulnerability Zone
1 in 100 ARI in 2050

Figure:

Rev: **A**

N

0 2 4km

Approx. scale

BMT
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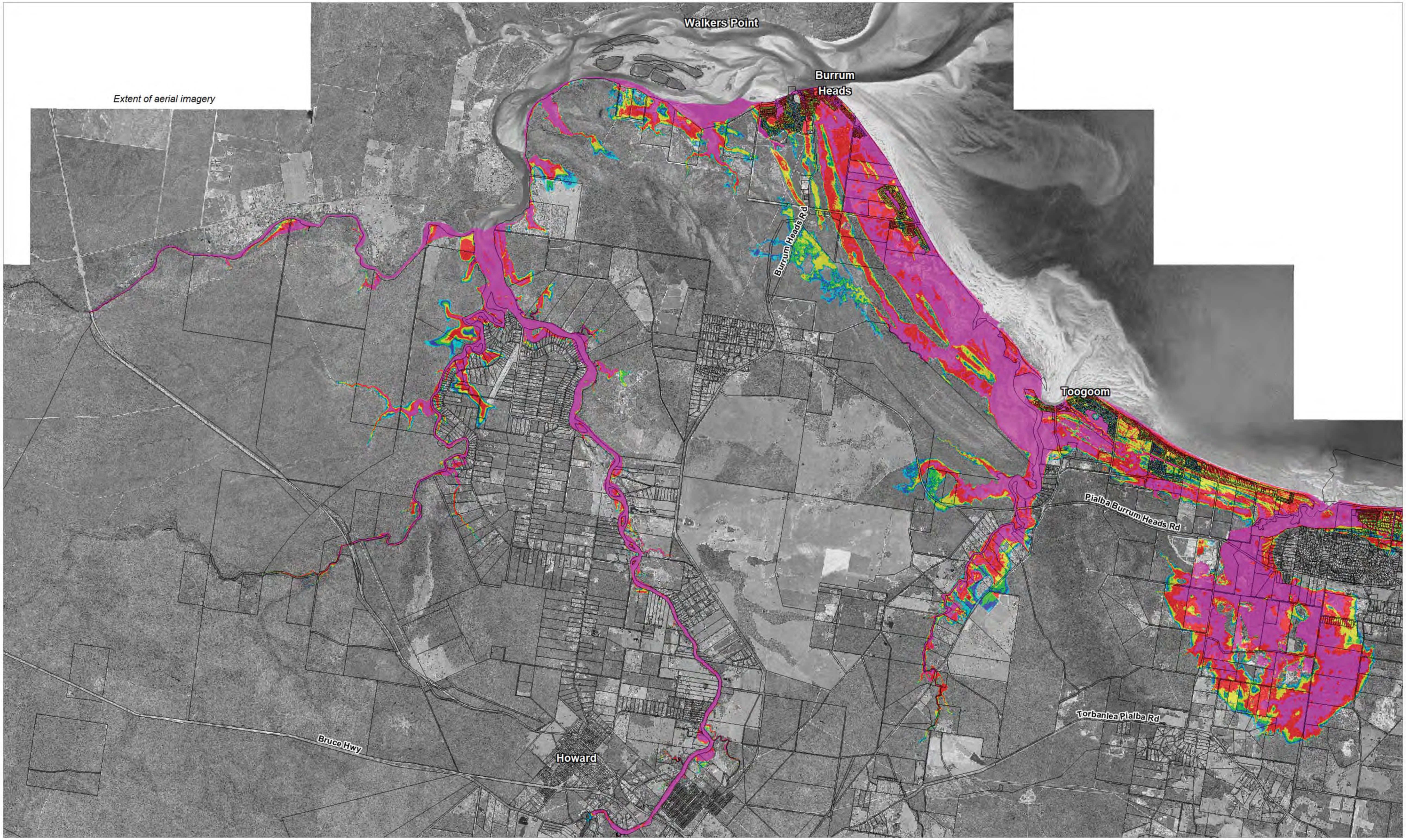

LEGEND

Cadastral Boundaries

Inundation Depth (m)

- 0.00 to 0.15
- 0.15 to 0.30
- 0.30 to 0.50
- 0.50 to 1.00
- 1.00 to 2.00
- Greater than 2.00

Title:

Storm Tide Vulnerability Zone
1 in 100 ARI in 2100

Figure:

Rev: **A**

N

0 2 4km
Approx. scale

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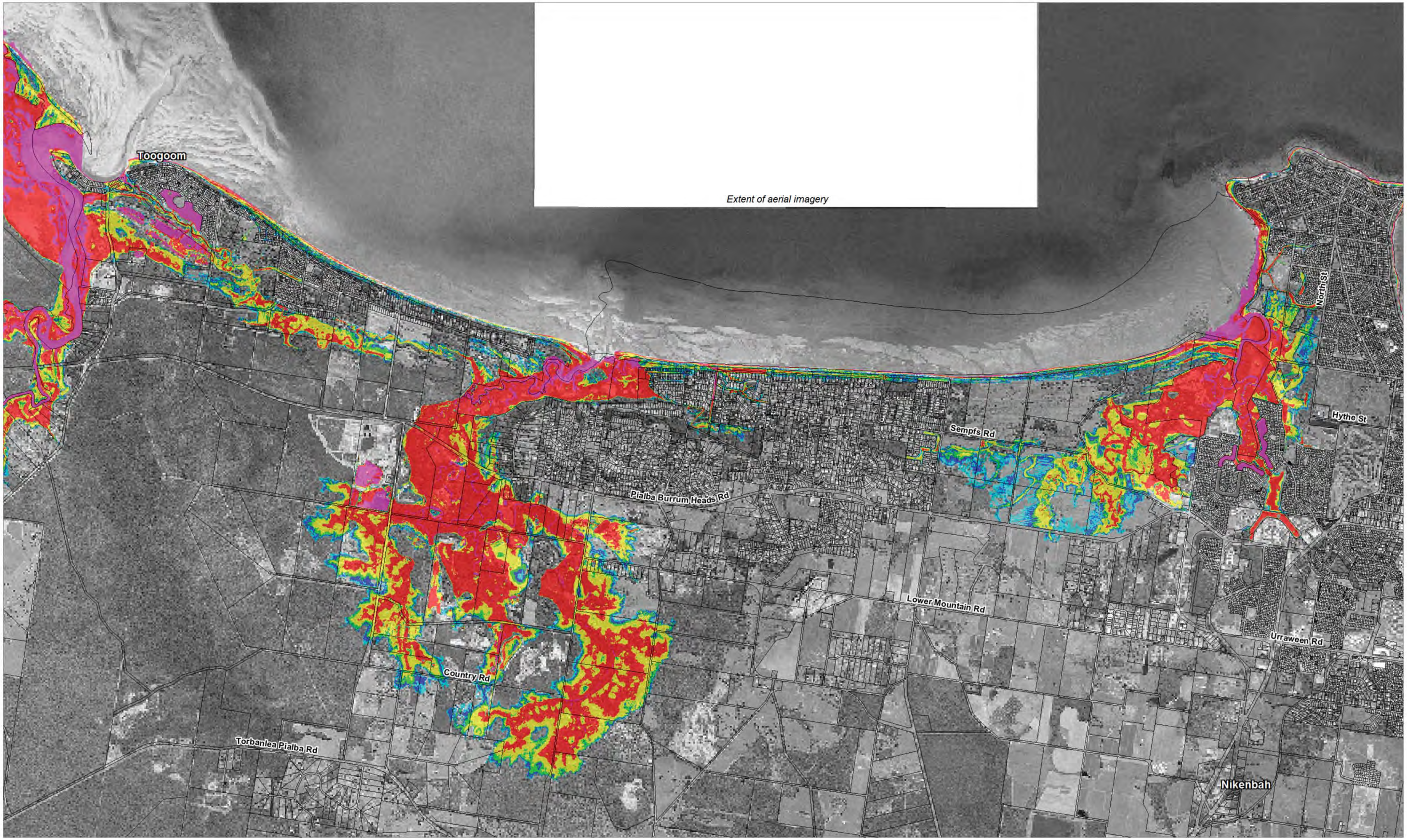

LEGEND

Cadastral Boundaries

Inundation Depth (m)

- 0.00 to 0.15
- 0.15 to 0.30
- 0.30 to 0.50
- 0.50 to 1.00
- 1.00 to 2.00
- Greater than 2.00

Title:

1 in 100 Year ARI Storm Tide Vulnerability Zone in 2019

Figure:

Rev: **A**

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N

0 1 2km

Approx.Scale

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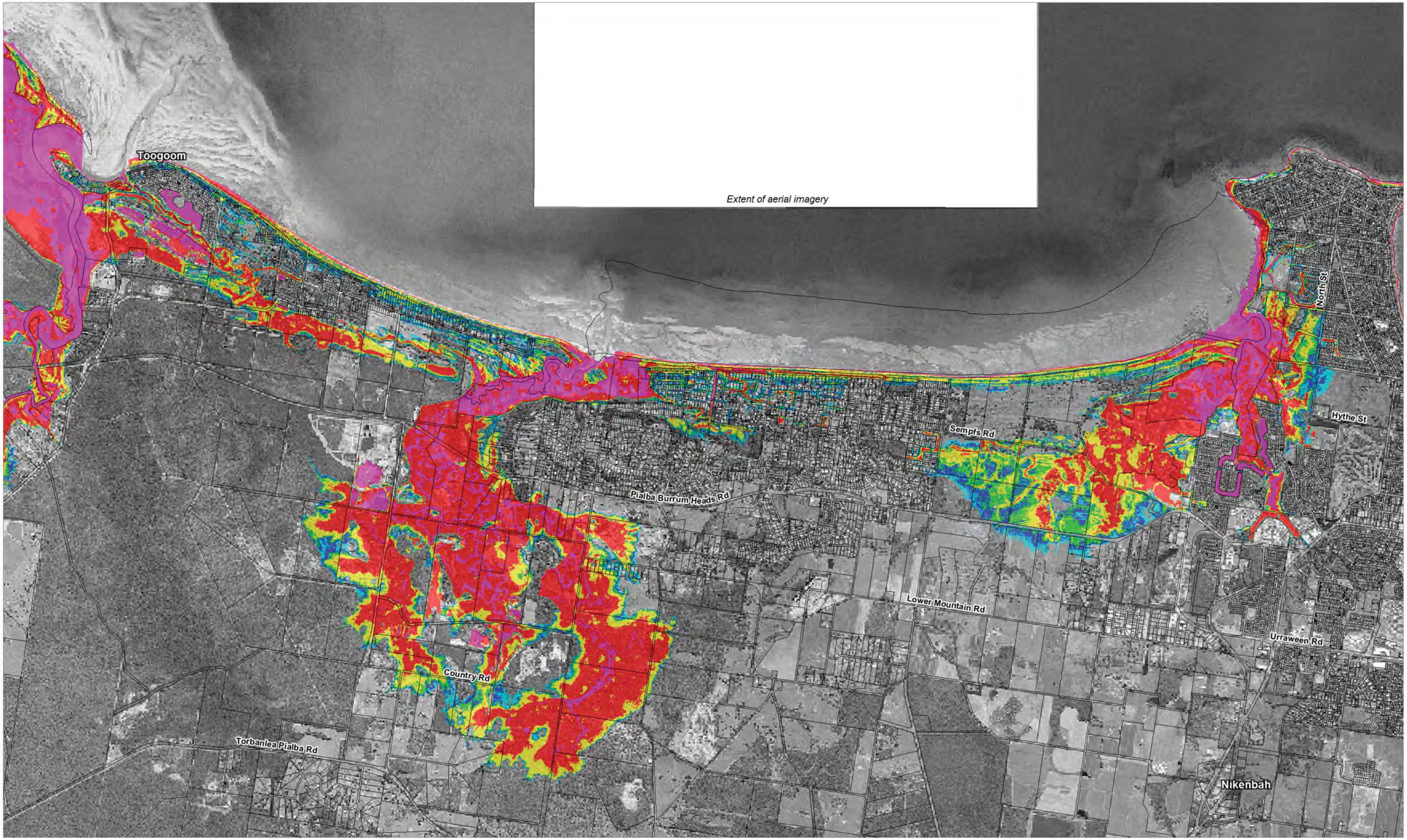

LEGEND

Cadastral Boundaries

Inundation Depth (m)

- 0.00 to 0.15
- 0.15 to 0.30
- 0.30 to 0.50
- 0.50 to 1.00
- 1.00 to 2.00
- Greater than 2.00

Title:

1 in 100 Year ARI Storm Tide Vulnerability Zone in 2050

Figure:

Rev: **A**

N

0 1 2km

Approx.Scale

www.bmt.org

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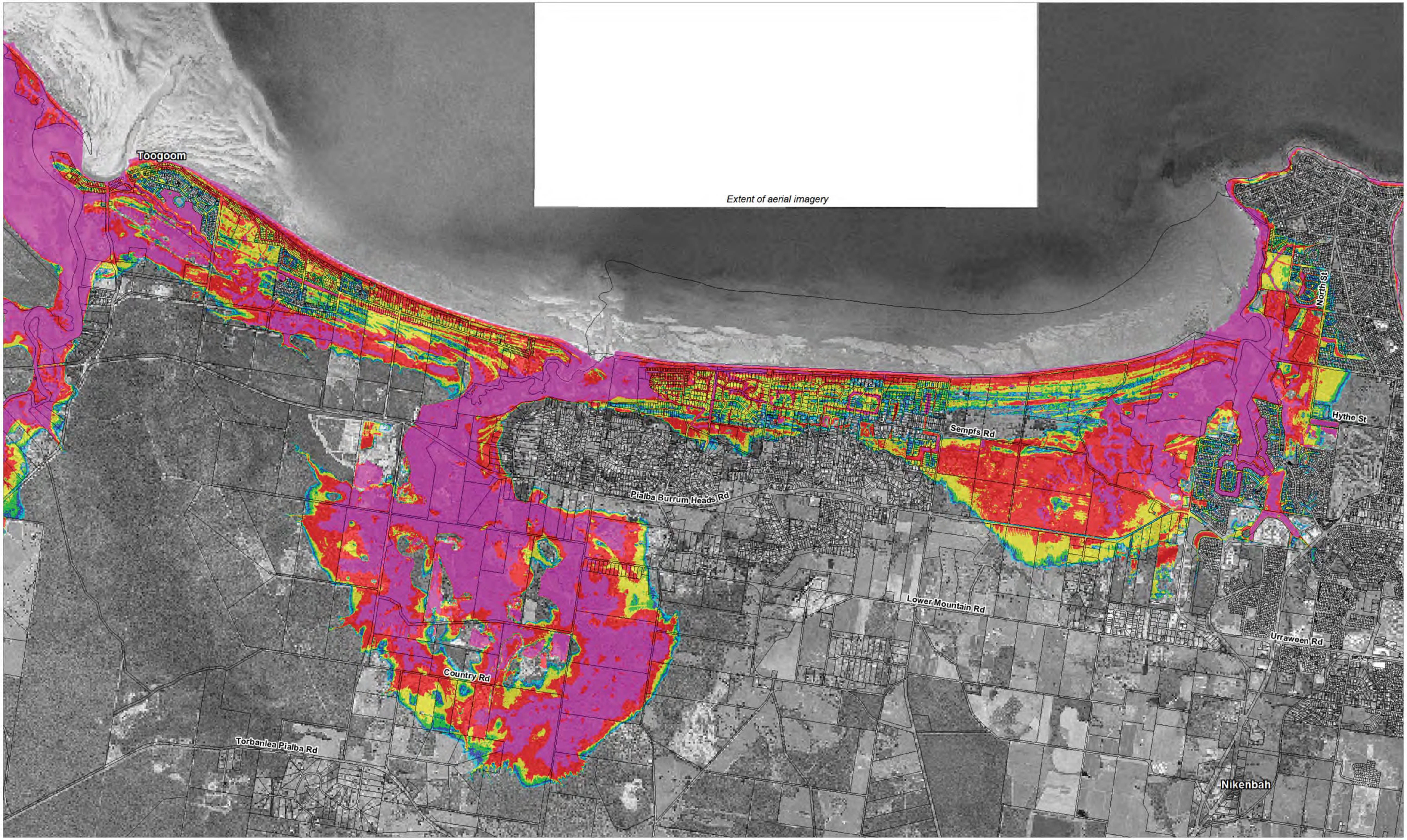

LEGEND

Cadastral Boundaries

Inundation Depth (m)

- 0.00 to 0.15
- 0.15 to 0.30
- 0.30 to 0.50
- 0.50 to 1.00
- 1.00 to 2.00
- Greater than 2.00

Title:

1 in 100 Year ARI Storm Tide Vulnerability Zone in 2100

Figure:

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0 1 2km

Approx.Scale

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LEGEND

Cadastral Boundaries

Inundation Depth (m)

- 0.00 to 0.15
- 0.15 to 0.30
- 0.30 to 0.50
- 0.50 to 1.00
- 1.00 to 2.00
- Greater than 2.00

Title:

1 in 100 Year ARI Storm Tide Vulnerability Zone in 2019

Figure:

Rev: **A**

N

0 2 4km

Approx. scale

BMT
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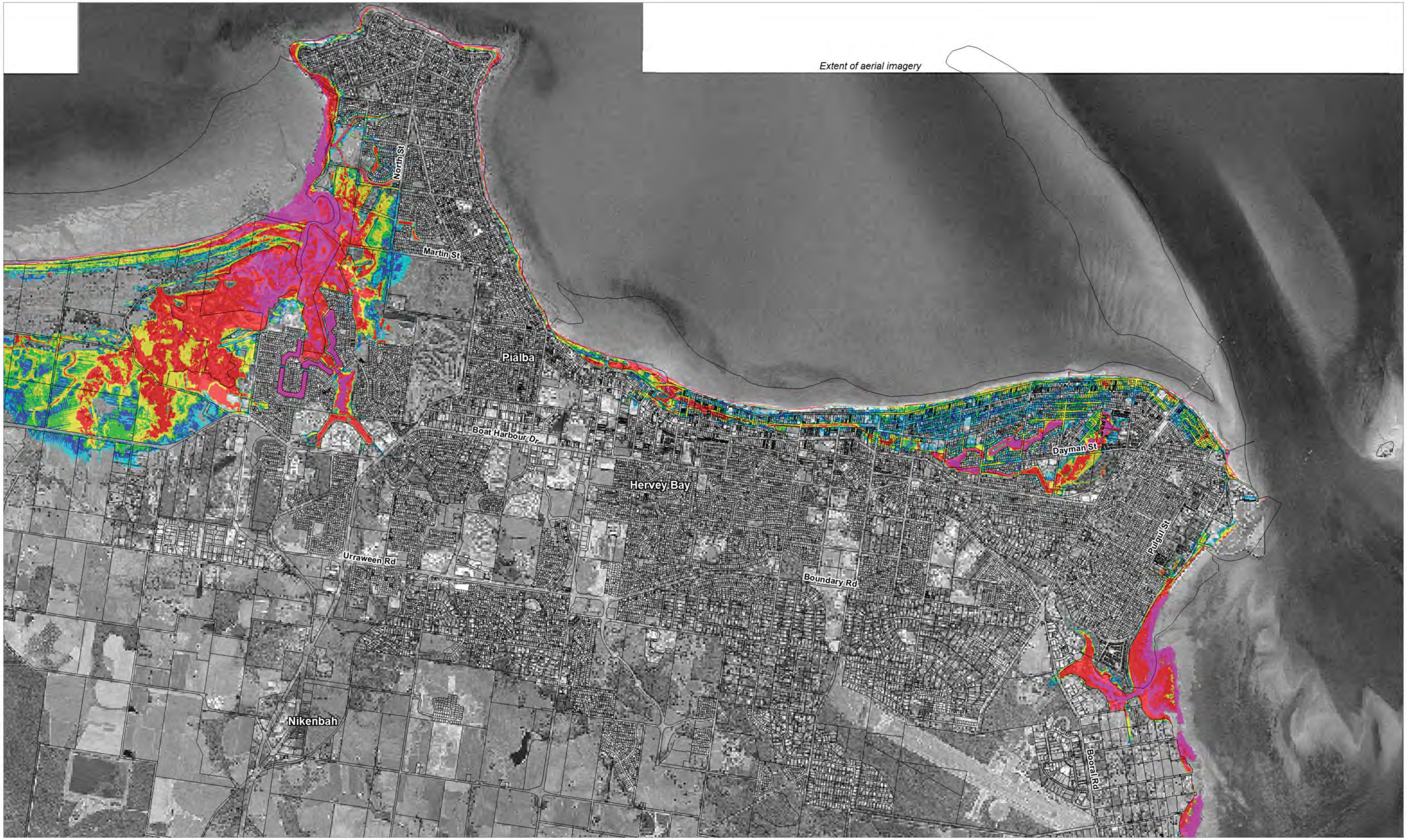

LEGEND

Cadastral Boundaries

Inundation Depth (m)

- 0.00 to 0.15
- 0.15 to 0.30
- 0.30 to 0.50
- 0.50 to 1.00
- 1.00 to 2.00
- Greater than 2.00

Title:

1 in 100 Year ARI Storm Tide Vulnerability Zone in 2050

Figure:

Rev: **A**

N

0 2 4km

Approx. scale

BMT
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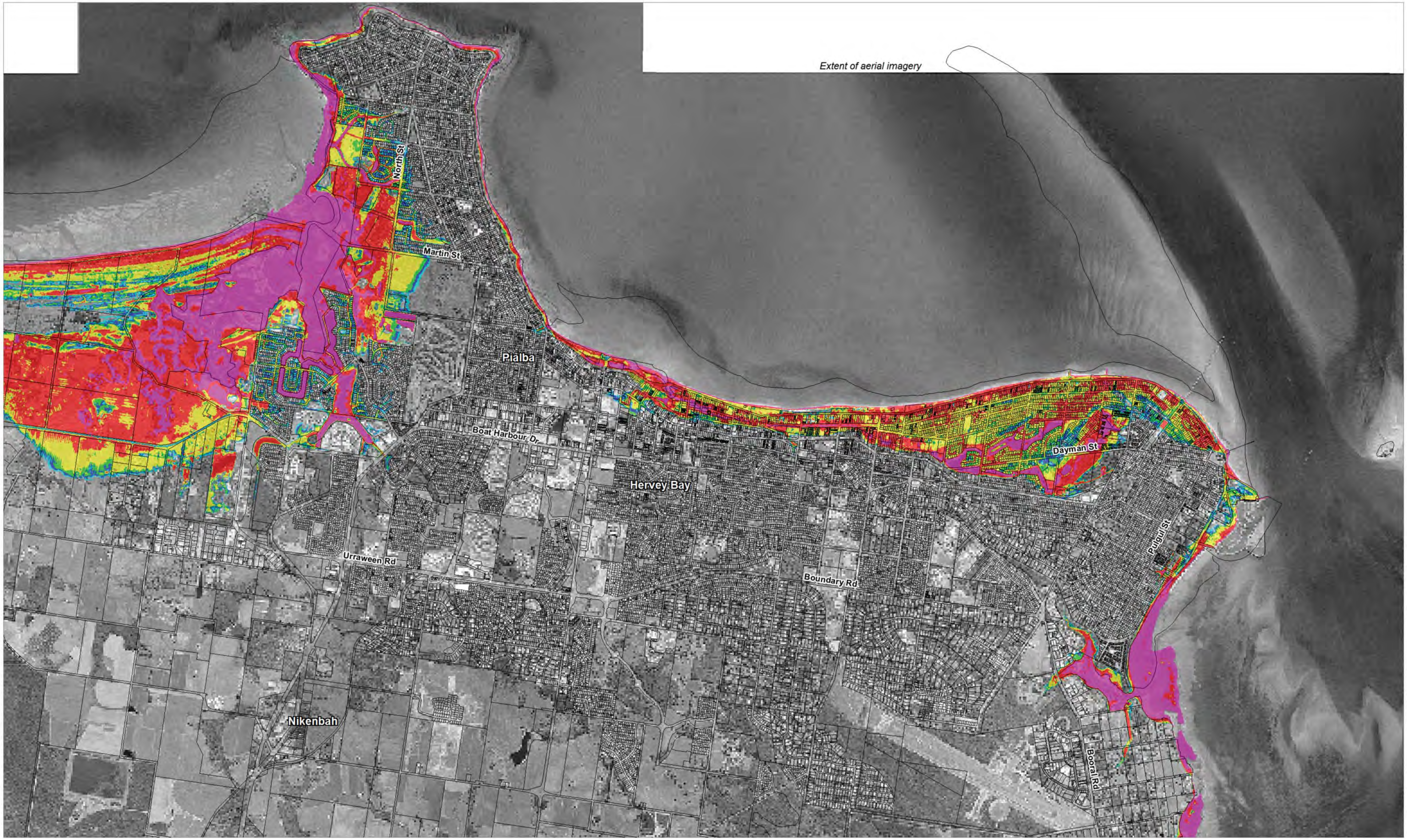

LEGEND

Cadastral Boundaries

Inundation Depth (m)

- 0.00 to 0.15
- 0.15 to 0.30
- 0.30 to 0.50
- 0.50 to 1.00
- 1.00 to 2.00
- Greater than 2.00

Title:

1 in 100 Year ARI Storm Tide Vulnerability Zone in 2100

Figure:

Rev: **A**

N

0 2 4km

Approx. scale

BMT

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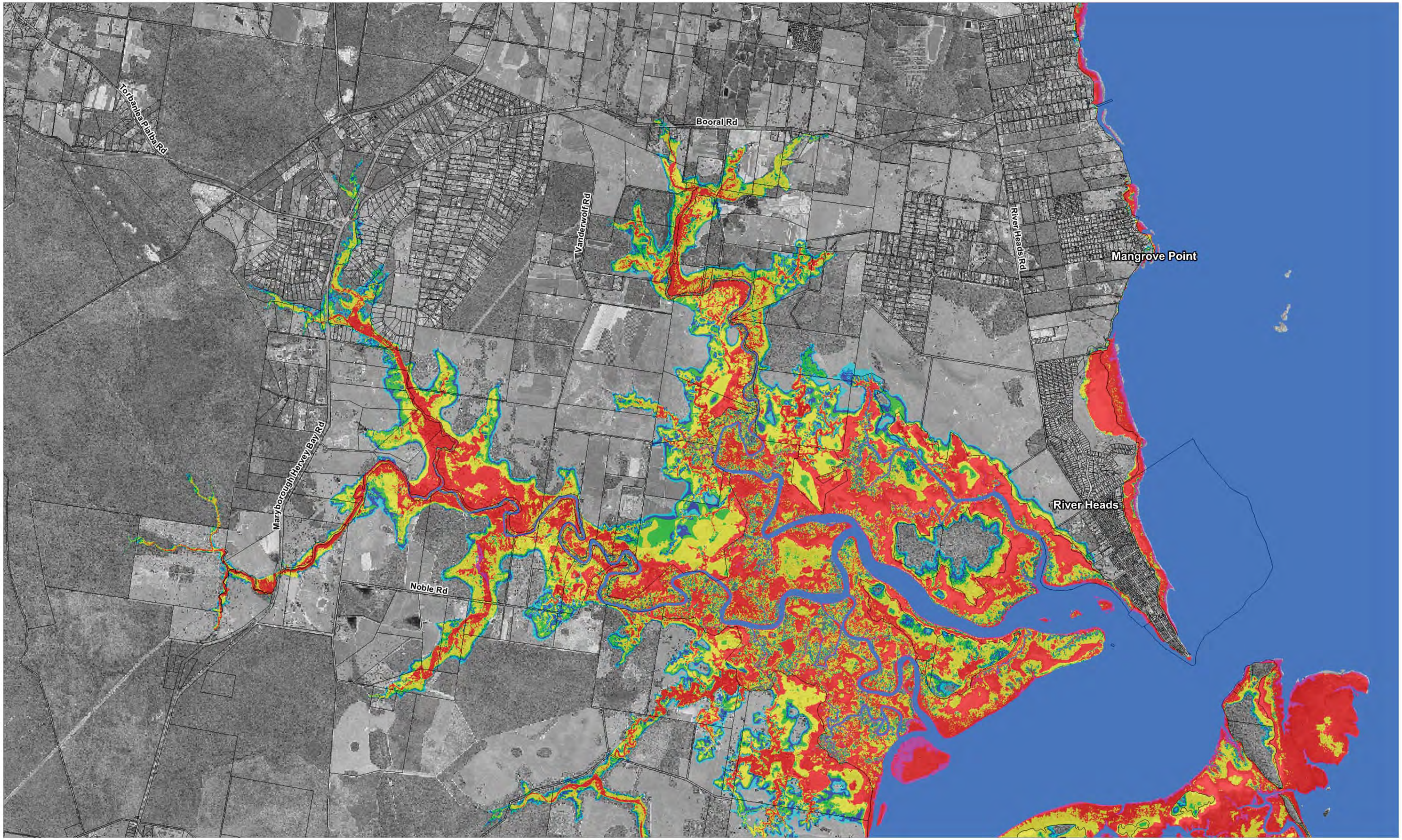

LEGEND

Cadastral Boundaries

Sea or Tidal Watercourse

Inundation Depth (m)

- 0.00 to 0.15
- 0.15 to 0.30
- 0.30 to 0.50
- 0.50 to 1.00
- 1.00 to 2.00
- Greater than 2.00

Title:

1 in 100 ARI Storm Tide Vulnerability Zone in 2019

Figure:

Rev: A

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0 2 4km

Approx. scale

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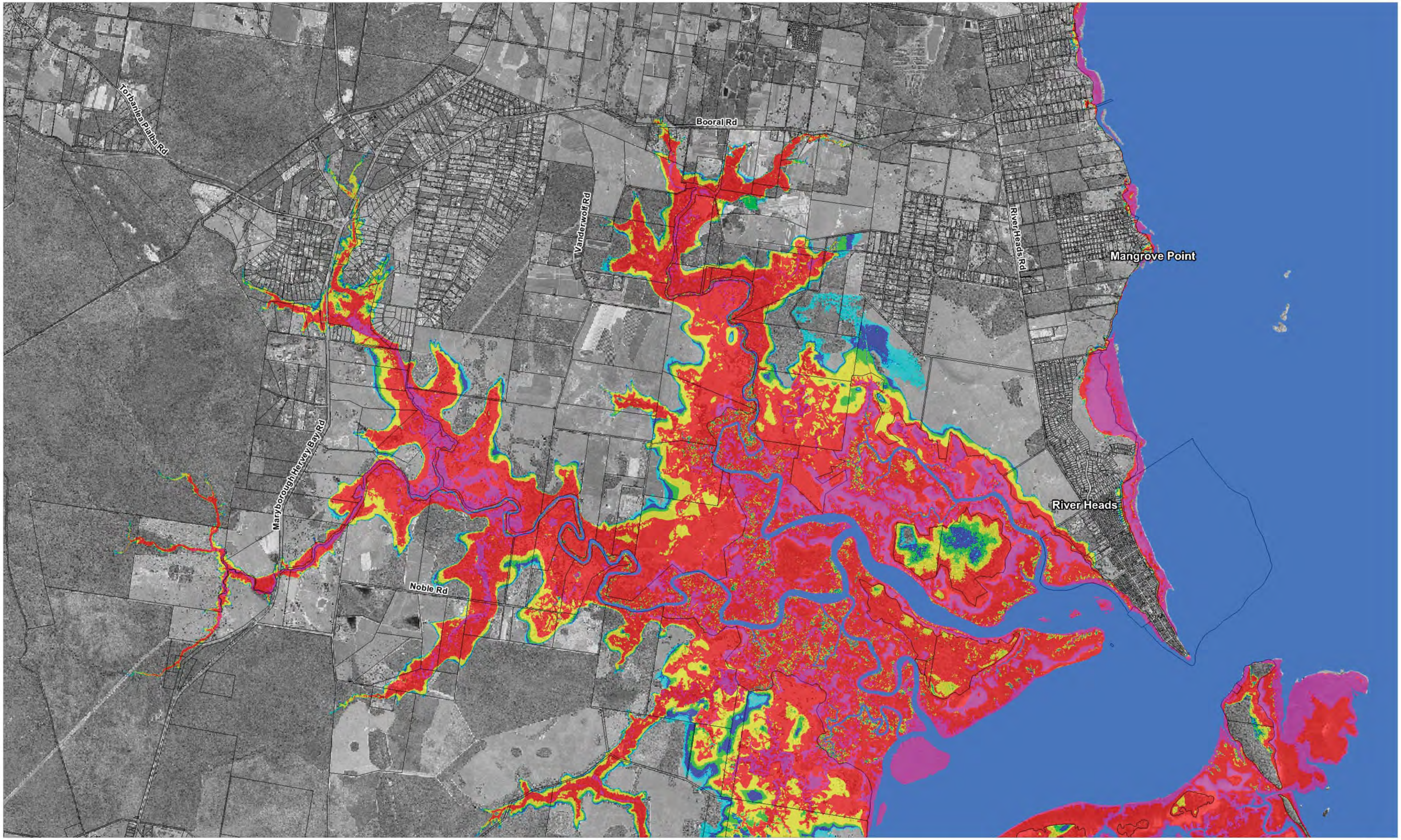

LEGEND

Cadastral Boundaries

Sea or Tidal Watercourse

Inundation Depth (m)

- 0.00 to 0.15
- 0.15 to 0.30
- 0.30 to 0.50
- 0.50 to 1.00
- 1.00 to 2.00
- Greater than 2.00

Title:

1 in 100 Year ARI Storm Tide Vulnerability Zone in 2050

Figure:

Rev: **A**

N

0 2 4km

Approx. scale

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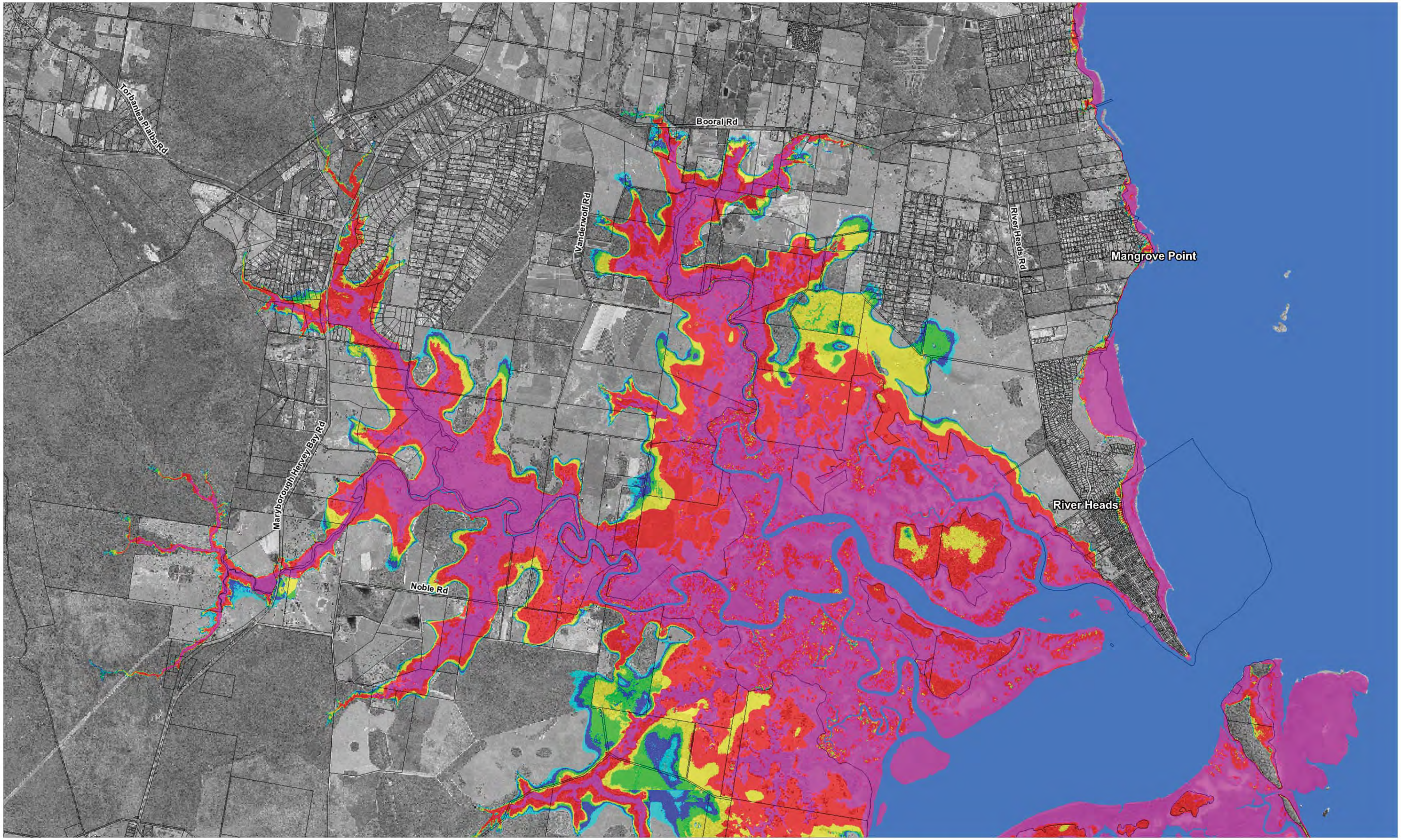

LEGEND

- Cadastral Boundaries
- Sea or Tidal Watercourse

Inundation Depth (m)

- 0.00 to 0.15
- 0.15 to 0.30
- 0.30 to 0.50
- 0.50 to 1.00
- 1.00 to 2.00
- Greater than 2.00

Title:

1 in 100 Year ARI Storm Tide Vulnerability Zone in 2100

Figure:

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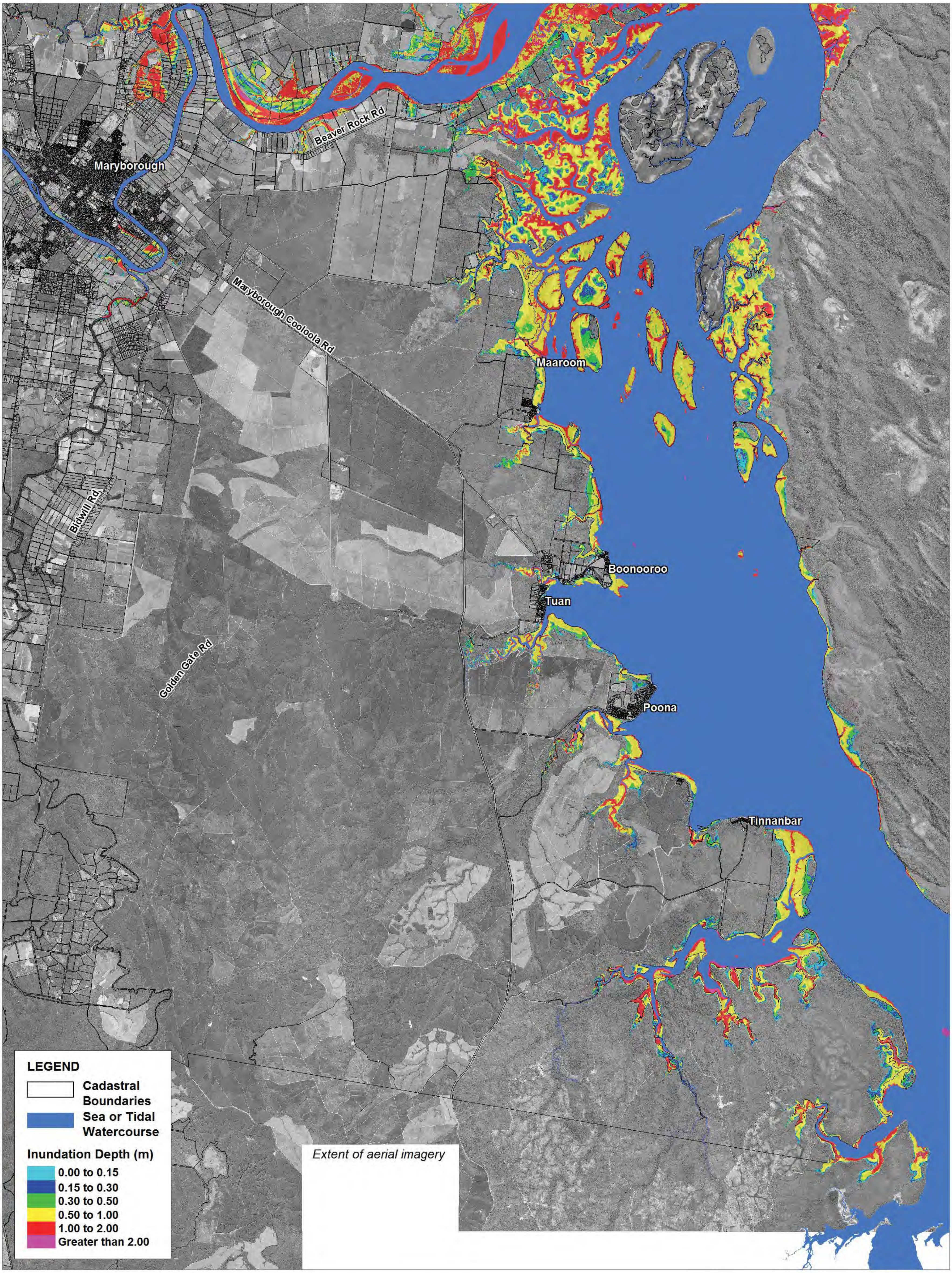

Title:

1 in 100 Year ARI Storm Tide Vulnerability Zone in 2019

Figure:

Rev: A

N

0 2 4km

Approx. scale

BMT

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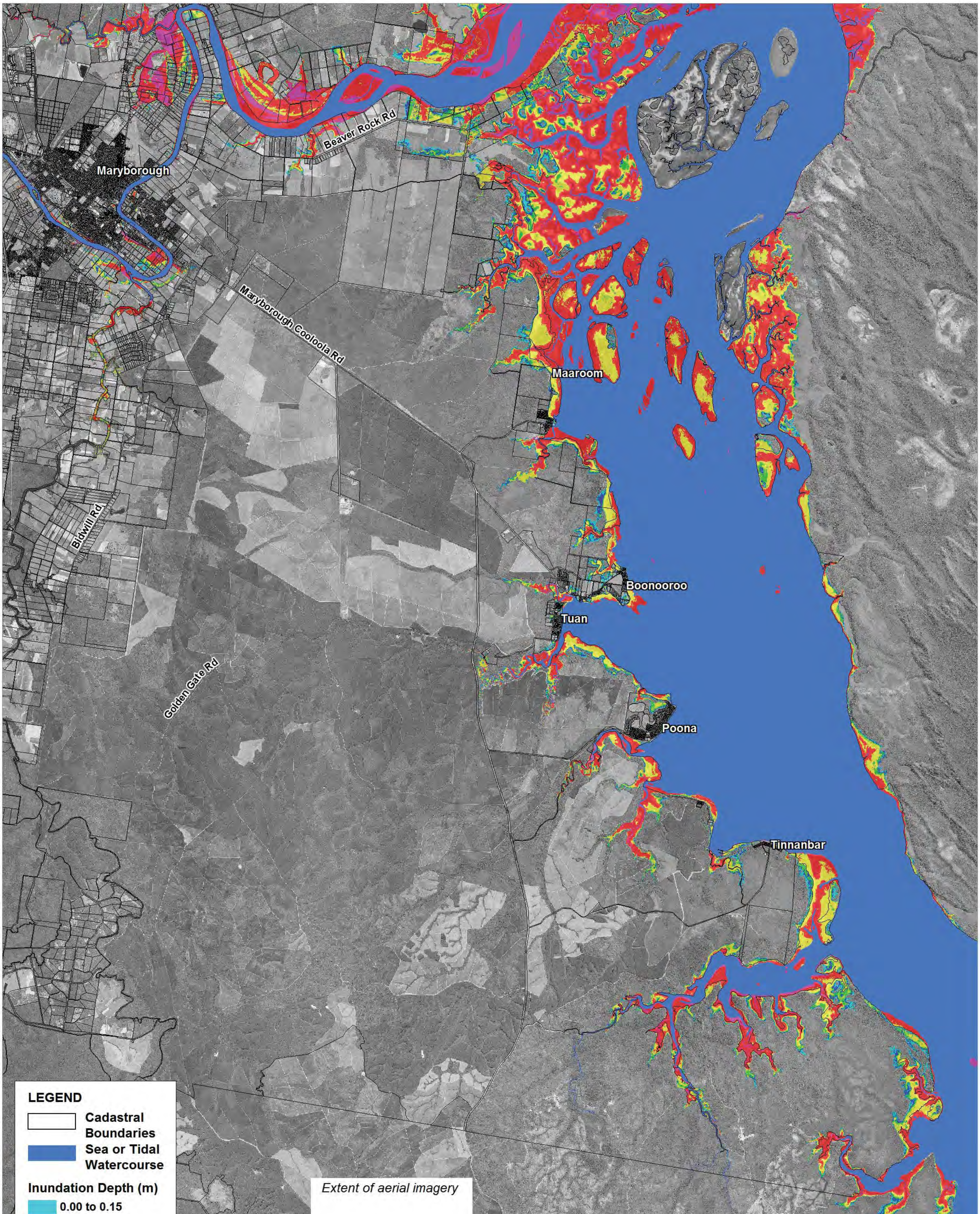

Title:

1 in 100 Year ARI Storm Tide Vulnerability Zone in 2050

Figure:

Rev: **A**

N

0 2 4km

Approx. scale

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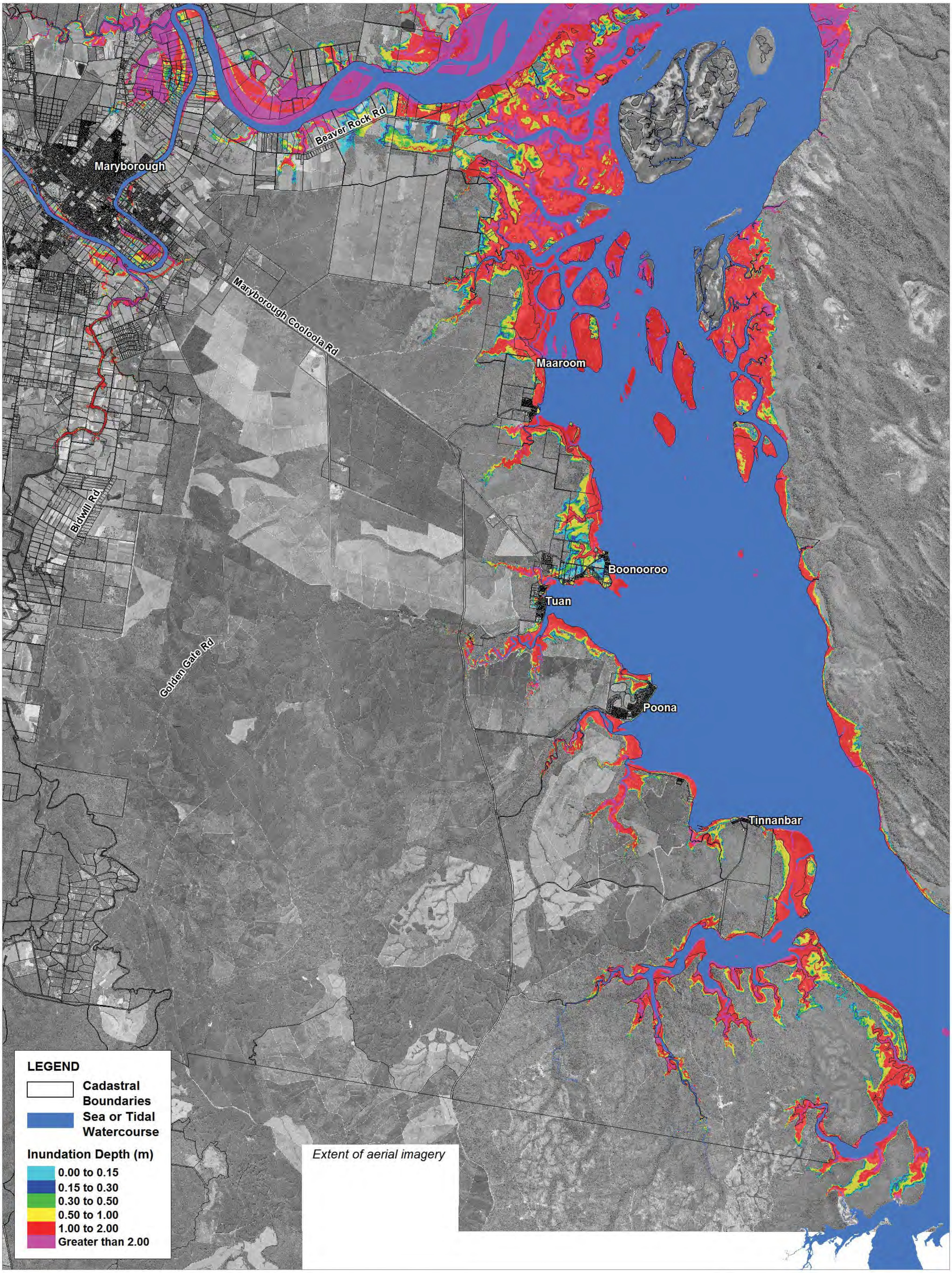

Title:

1 in 100 Year ARI Storm Tide Vulnerability Zone in 2100

Figure:

Rev: **A**

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Approx. scale

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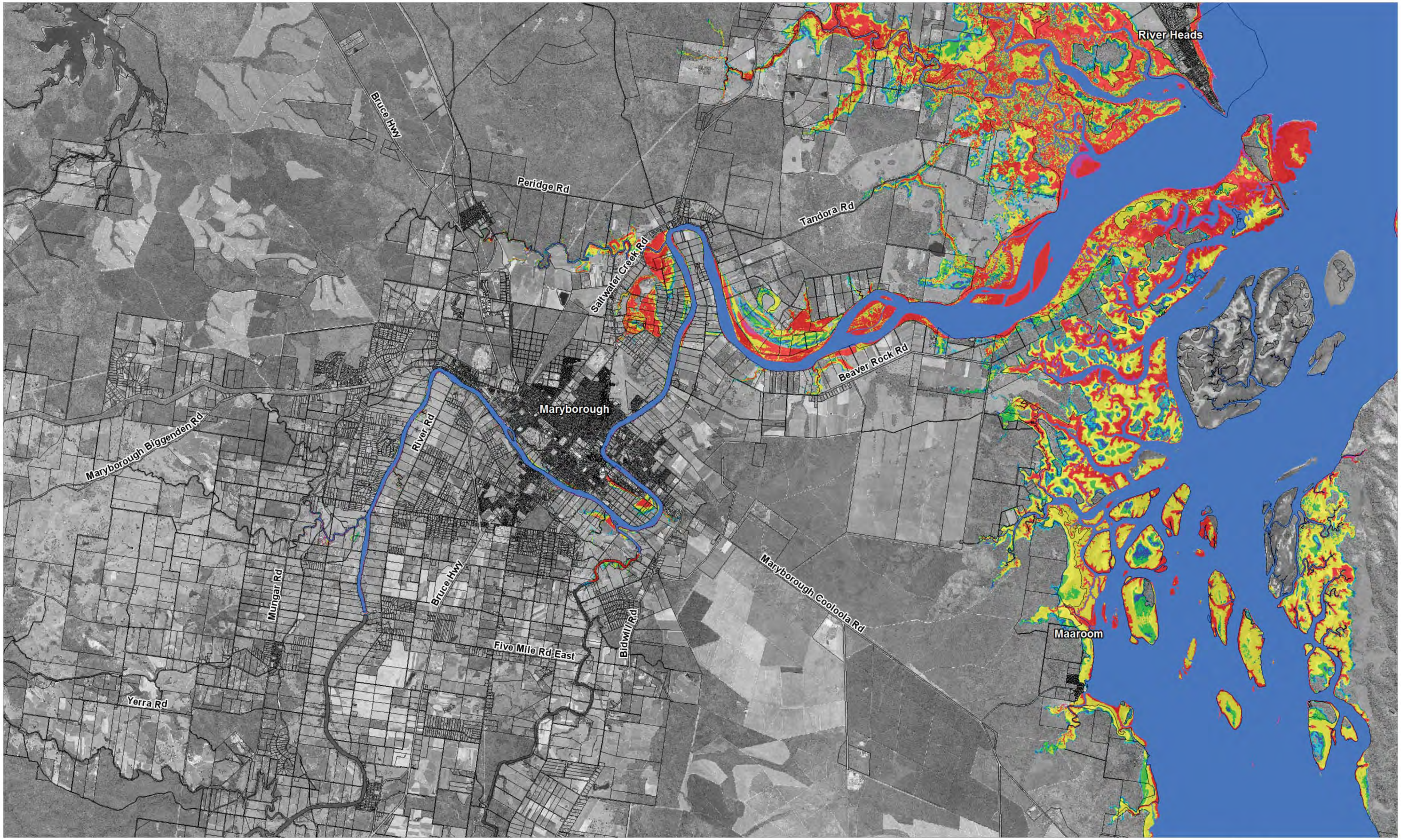

LEGEND

Cadastral Boundaries

Sea or Tidal Watercourse

Inundation Depth (m)

- 0.00 to 0.15
- 0.15 to 0.30
- 0.30 to 0.50
- 0.50 to 1.00
- 1.00 to 2.00
- Greater than 2.00

Title:

1 in 100 Year ARI Storm Tide Vulnerability Zone in 2019

Figure:

Rev: **A**

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N

0 2 4km

Approx. scale

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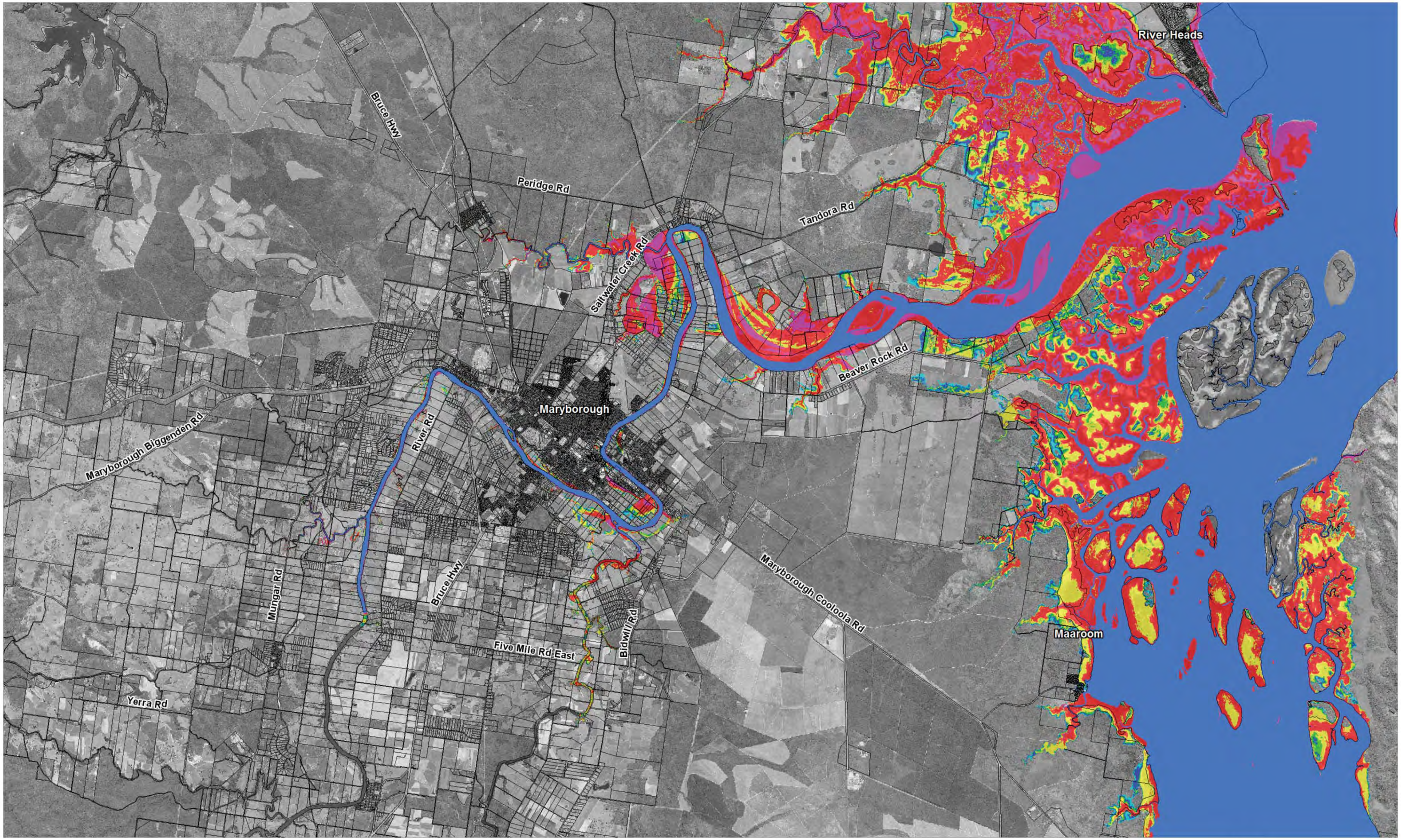

LEGEND

Cadastral Boundaries

Sea or Tidal Watercourse

Inundation Depth (m)

- 0.00 to 0.15
- 0.15 to 0.30
- 0.30 to 0.50
- 0.50 to 1.00
- 1.00 to 2.00
- Greater than 2.00

Title:

1 in 100 Year ARI Storm Tide Vulnerability Zone in 2050

Figure:

Rev: **A**

N

0 2 4km

Approx. scale

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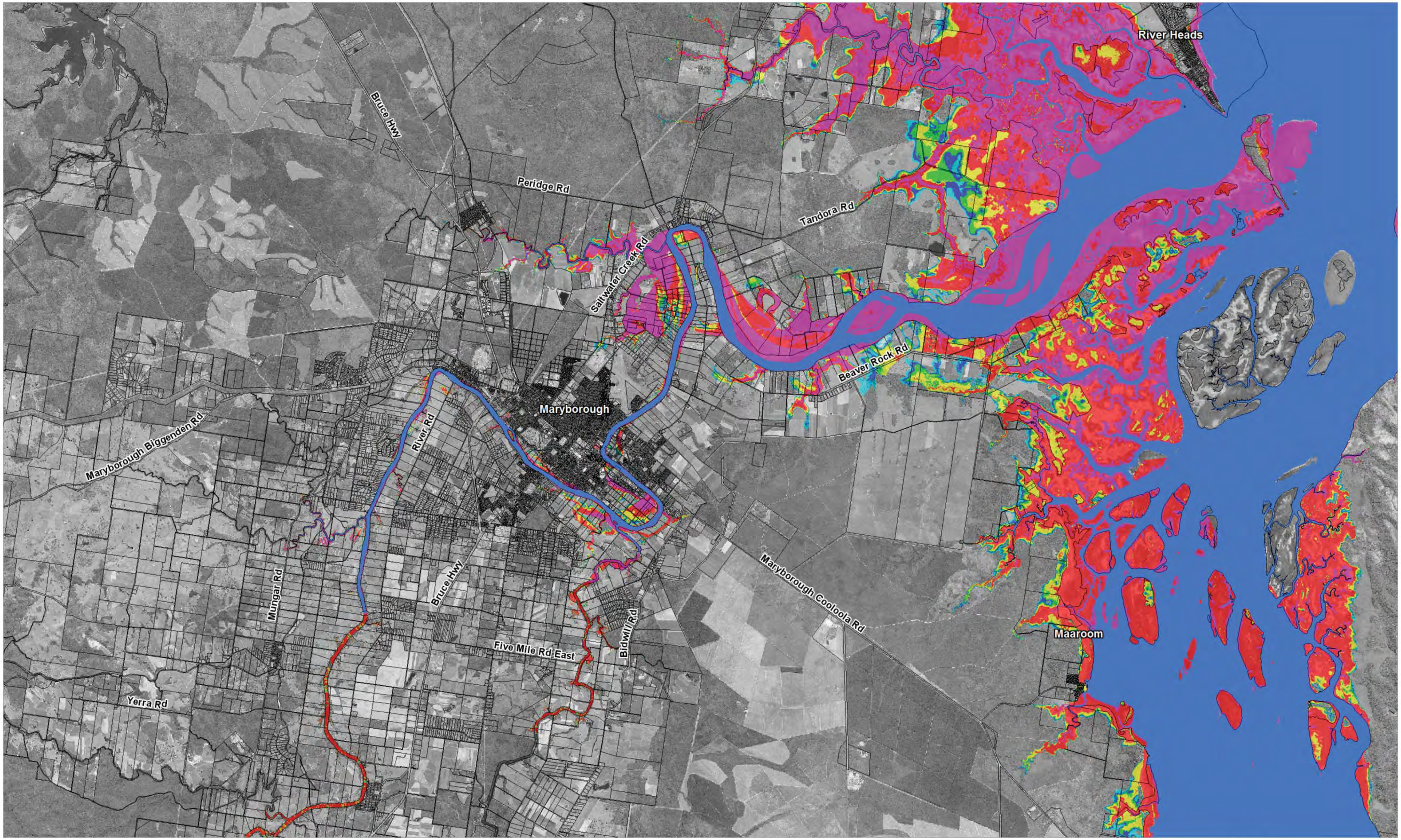

LEGEND

- Cadastral Boundaries
- Sea or Tidal Watercourse

Inundation Depth (m)

- 0.00 to 0.15
- 0.15 to 0.30
- 0.30 to 0.50
- 0.50 to 1.00
- 1.00 to 2.00
- Greater than 2.00

Title:

1 in 100 Year ARI Storm Tide Vulnerability Zone in 2100

Figure:

Rev: A

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0 2 4km

Approx. scale

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Level 8, 200 Creek Street
Brisbane Queensland 4000
PO Box 203 Spring Hill Queensland 4004
Australia
Tel +61 7 3831 6744
Fax +61 7 3832 3627
Email brisbane@bmtglobal.com

Melbourne
Level 5, 99 King Street
Melbourne Victoria 3000
Australia
Tel +61 3 8620 6100
Fax +61 3 8620 6105
Email melbourne@bmtglobal.com

Newcastle
126 Belford Street
Broadmeadow New South Wales 2292
PO Box 266 Broadmeadow
New South Wales 2292
Australia
Tel +61 2 4940 8882
Fax +61 2 4940 8887
Email newcastle@bmtglobal.com

Adelaide
5 Hackney Road
Hackney Adelaide South Australia 5069
Australia
Tel +61 8 8614 3400
Email info@bmtdt.com.au

Northern Rivers
Suite 5
20 Byron Street
Bangalow New South Wales 2479
Australia
Tel +61 2 6687 0466
Fax +61 2 6687 0422
Email northernrivers@bmtglobal.com

Sydney
Suite G2, 13-15 Smail Street
Ultimo Sydney New South Wales 2007
Australia
Tel +61 2 8960 7755
Fax +61 2 8960 7745
Email sydney@bmtglobal.com

Perth
Level 4
20 Parkland Road
Osborne Park Western Australia 6017
PO Box 2305 Churchlands Western Australia 6018
Australia
Tel +61 8 6163 4900
Email wa@bmtglobal.com

London
Zig Zag Building, 70 Victoria Street
Westminster
London, SW1E 6SQ
UK
Tel +44 (0) 20 8090 1566
Email london@bmtglobal.com

Leeds
Platform
New Station Street
Leeds, LS1 4JB
UK
Tel: +44 (0) 113 328 2366
Email environment.env@bmtglobal.com

Aberdeen
11 Bon Accord Crescent
Aberdeen, AB11 6DE
UK
Tel: +44 (0) 1224 414 200
Email aberdeen@bmtglobal.com

Asia Pacific
Indonesia Office
Perkantoran Hijau Arkadia
Tower C, P Floor
Jl: T.B. Simatupang Kav.88
Jakarta, 12520
Indonesia
Tel: +62 21 782 7639
Email asiapacific@bmtglobal.com

Alexandria
4401 Ford Avenue, Suite 1000
Alexandria, VA 22302
USA
Tel: +1 703 920 7070
Email inquiries@dandp.com