Gingin Coastal Inundation Study (CIS)

Lancelin, Ledge Point, Seabird and Guilderton

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Gingin Coastal Inundation Study (CIS)

Lancelin, Ledge Point, Seabird and Guilderton

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Revision	Date	Status	Comments	Prepared	Reviewed	Approved
A	6 May 2020	Draft	Issued for Client Review	JC	DT	JC
0	26 June 2020	Final	Issued for Release	JC	DT	JC
1	1 July 2020	Final	Update to TC Mangga description. Issued for Release	JC	DT	JC

Executive Summary

Baird Australia (Baird) have undertaken a Coastal Inundation Study (CIS) for the Shire of Gingin which examines extreme water levels in coastal areas during severe storms and tsunami events. The study has determined design water levels that will be used to inform coastal planning in the Shire at the key coastal townsites of Lancelin, Ledge Point, Seabird and Guilderton, consistent with the guidelines of the State Coastal Planning Policy 2.6 (SPP2.6).

Baird's established and validated numerical model of the West Australian coast was adopted in the CIS to examine extreme events:

- The model was used to simulate historical cyclone cases which have impacted the study area, providing a basis for understanding magnitude of storm surge in extreme cyclone events and demonstrating model performance.
- Design (cyclonic) storm cases were developed and used to define the 20yr-ARI, 100yr-ARI and 500-year ARI inundation level for the four towns of the study area.
- Sea level rise projections based on current State policy (DoT 2010) were applied over a range of planning periods to define the final design water level recommendations for the present day (2020), 2040, 2070 and 2120.

The final design water levels at locations through the study area are summarised in Table E.1 based on the present day (2020) sea level.

Table E.1: Design water level across the four towns in the Gingin study area.

ARI (yr)	Lancelin North (m AHD)	Lancelin Mid (m AHD)	Lancelin South (m AHD)	Ledge Point North (m AHD)	Ledge Point South (m AHD)	Seabird (m AHD)	Guilderton (m AHD)
20	1.3	1.2	1.2	1.2	1.1	1.3	1.3
100	1.5	1.3	1.3	1.3	1.2	1.4	1.4
500	2.0	2.0	1.8	1.9	1.8	1.7	1.8

The TC Mangga storm which occurred in May 2020 is a recent example of the type of severe storm event that produces extreme water levels for the Gingin coast. During that event, the peak water level measured at Jurien Bay just north of the Gingin study area was 1.18m AHD which was approximately 0.75m above the normal tide level due to the storm surge associated with the event. Based on the design water levels in Table E.1 this is just below the 1 in 20-year event.

The design water levels in Table E.1 have been used to produce spatial mapping for the four towns of the study area for the present day and under future sea level rise scenarios. The mapping is presented in Appendix C, representing the risk of storm surge inundation (S4 inundation, SPP2.6). The following is noted:

- Inundation risk is highest for Lancelin, where the foredune provides a barrier that protects the lower lying inland areas from ocean-based flooding during extreme events. The stability of the foredune in severe storm events when subjected to elevated water level and large waves was assessed, to determine if there was potential for dune breaching which could lead to flooding of the inland areas.
  - For the section of coast north from Grace Darling Park, there is the potential for dune breaching of the foredune in severe events. The dune system is estimated to be able to withstand the 20yr ARI

event and the 100yr ARI event in the present day (2020). Under future sea level rise scenarios for the 2070 planning period (+0.4m) and beyond, breaching of the foredune may occur. A storm event of 500yr ARI magnitude is estimated to breach the dune system in the present day and all future planning periods.
    - For the section of coast south of Grace Darling Park, the dune system is significant and breaching of the dune would not occur in any of the extreme events, including under future sea level rise scenarios.
- For Ledge Point, Seabird and Guilderton the developed areas are not at risk of inundation, with the natural topography set well above the extreme design water levels, including under future sea level rise scenarios.
- The foreshore areas at all study locations are susceptible to the impacts of wave run-up in design storm cases, which may result in overtopping of dunes and foreshore structures.

An assessment of the hazard associated with tsunami within the study area was completed using Geoscience Australia's 2018 Australian Probabilistic Tsunami Hazard Assessment (PTHA, Geoscience Australia, 2018). Baird applied its hydrodynamic model to model a validation case of the 2006 Boxing day Tsunami which showed good agreement to measured peak water level captured at tide gauges in Geraldton and Lancelin. A 500yr ARI magnitude tsunami event for the Gingin study area was examined in the model with peak water level results shown in Table E.2. The tsunami inundation risk is comparable (within 0.1m) with the design water levels from the modelled 500yr ARI cyclone event for Lancelin and Ledge Point (refer Table E.1). At Seabird and Guilderton, the peak modelled water level for the design 500yr ARI Tsunami is 0.4m to 0.5m higher than the 500yr ARI cyclone event.

Table E.2: Tsunami event at 500yr ARI – Modelled Water Level (Datum m AHD)

Return Period	500yr ARI Modelled Tsunami – Peak Water Level			
Timeframe	Lancelin	Ledge Point	Seabird	Guilderton
2020	1.9	2.1	2.1	2.2
2040	2.0	2.2	2.2	2.3
2070	2.3	2.5	2.5	2.6
2120	2.8	3.0	3.0	3.1

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1. Introduction

1.1 Overview of Project

Baird Australia (Baird) have undertaken a Coastal Inundation Study (CIS) for the Shire of Gingin to identify potential areas subject to coastal inundation risk through coastal locations of the Shire at Lancelin, Ledge Point, Seabird and Guilderton.

The project outcomes will be used to improve the understanding of coastal inundation hazard for the Shire now and in future planning timeframes under projected sea level rise, to inform risk management and adaptation planning.

1.2 Project Brief

The purpose of the project is to clearly identify areas that are potentially subject to coastal inundation risks over the following planning timeframes for the townsites of Guilderton, Seabird, Ledge Point and Lancelin: present day (2020), 2040, 2070 and 2120.

The assessment will be used:

- For coastal adaptation planning purposes in accordance with Western Australia's State Planning Policy 2.6 (Coastal Planning Policy); and
- For the Shire to communicate the current and future inundation risks with private landowners and the broader community.

The Shire of Gingin recently completed a Coastal Hazard Risk Management and Adaption Plan (CHRMAP). However, the CHRMAP does not include an assessment of coastal inundation. In this study, the Coastal Inundation Hazard is defined for the Shire of Gingin coastal townships of Guilderton, Seabird, Ledge Point and Lancelin. The aim of the assessment is to clearly identify areas that are potentially subject to a range of coastal inundation risks over a range of planning timeframes.

The recently completed CHRMAP found stretches of the Gingin coastline and key assets are at risk of coastal erosion over a range of planning timeframes. The Coastal Inundation Hazard Assessment will need to consider erosion on the topography of each coastal town and the influence this may have on the extent of coastal inundation.

It is anticipated the Coastal Inundation Hazard Assessment will form part of an updated CHRMAP, in a future review process. This will ensure the updated CHRMAP includes adaptation options for coastal erosion and inundation.

The coastal inundation hazard has been determined for a range of future planning periods (2020, 2040, 2070, 2120) which incorporate sea level rise in accordance with SPP2.6 recommendations (WAPC2010). The inundation levels have been determined at three return periods – 20yr ARI, 100yr ARI and 500yr ARI. Detailed flood mapping at appropriate resolution in the four key areas has been produced to show inundation extents and depth in shoreline areas.

1.3 Project Location and Key Sites of Interest

The study focus is along the shoreline of the Shire of Gingin which is located approximately 70km north of Perth in Western Australia. There are four key towns of interest in this study as shown in Figure 1.1 from north to south as Lancelin, Ledge Point, Seabird and Guilderton.

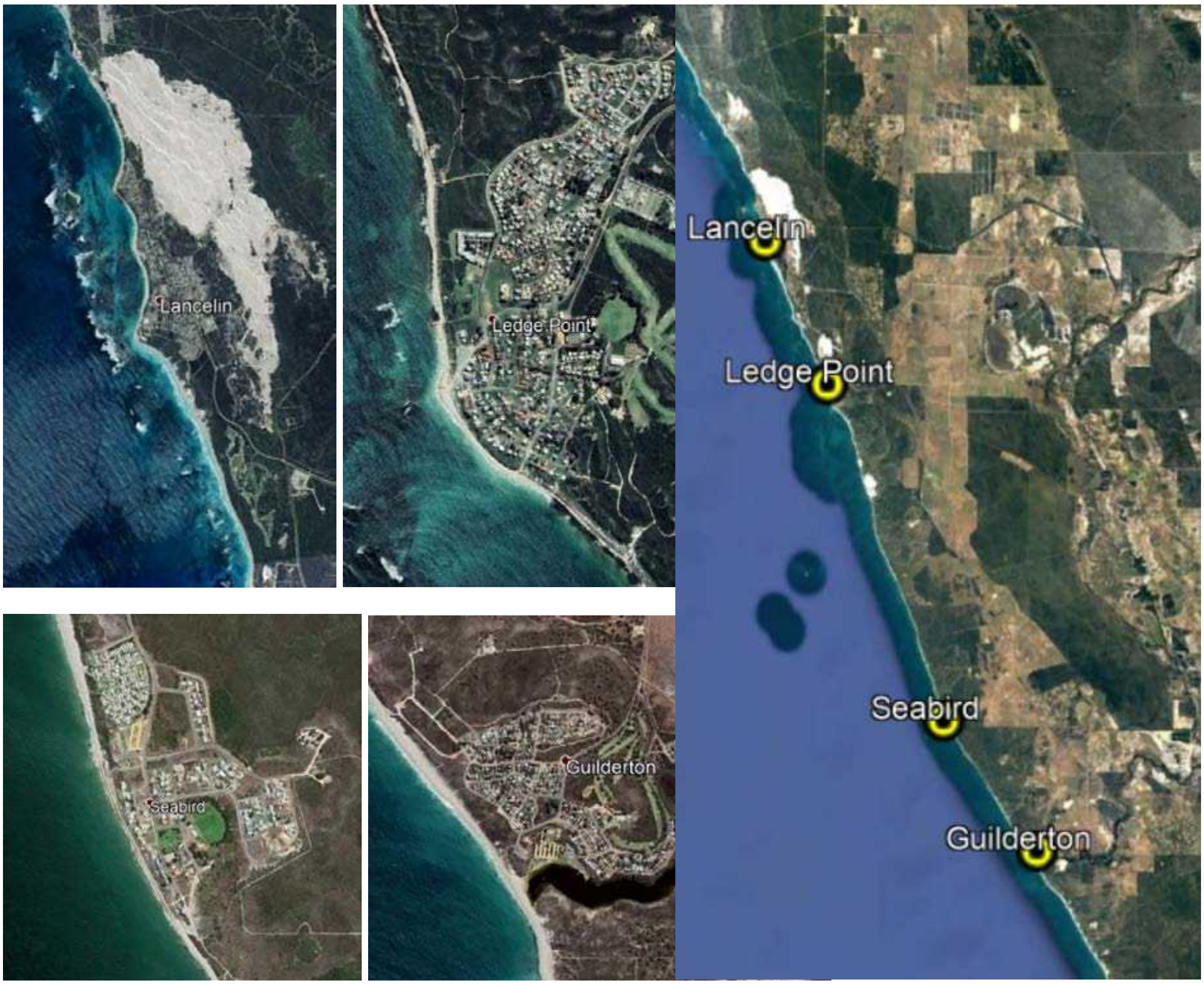

Figure 1.1: Study Area showing key towns of interest – Lancelin, Ledge Point, Seabird, Guilderton (Google Earth).

2. Background Information

There are a range of background reports and data sources that were reviewed to inform the inundation study. The literature review and background information is outlined in this section.

2.1 Literature Review

The documents that were reviewed as part of the literature review are summarised in Table 2.1. A summary of the findings from each of the literature review items and relevance to this study is provided.

Table 2.1: Literature Review Documents and Key Findings for the Current Study

Reference	Key Findings
[1] Department of Environment. (2002). Water Quality and Hydrodynamics of the Moore River Estuary and Surrounds: March – November 2002 – Final Report to the Community. Reference: 500811, 556.047 (941) MOO. Prepared by Department of Environment, Western Australia.	Recorded water levels (reproduced in Figure 2.1) in the Moore River Estuary and status of the bar blocking estuary from the ocean. Water levels in the estuary peaked at about 2m AHD during the measurement campaign from January 2002 to the start of December 2002. The stability of the bar decreased over the winter months with the bar being breached frequently and maximum water levels prior to the bar breaching tended to decrease. By the end of October, the bar became more stable and started to remain closed for longer periods of time as the river discharge decreased and the bar started to build up again. Whilst, there is no analysis of long term extreme inundation level of the estuary, the mechanism for controlling extreme river level at Guilderton namely the breaching of the bar is well captured and is considered in the joint probability assessment (Section 5.5) where extreme coastal storm tide levels as well as catchment flooding could combine. Baird contacted Department of Water and Environmental Regulation (pers comm J.Churchill-S.Rogers) to request flood studies for Guilderton. The Department indicated they have no flood studies or floodplain mapping for Guilderton, but provided a flood study for the Bidaminna area, approximately 35 kms upstream of Guilderton. Oblique photos of large flood events where the Moore River has broken the bar in 1995 and 1999 were provided (presented in Section 5.5.1 of this report).

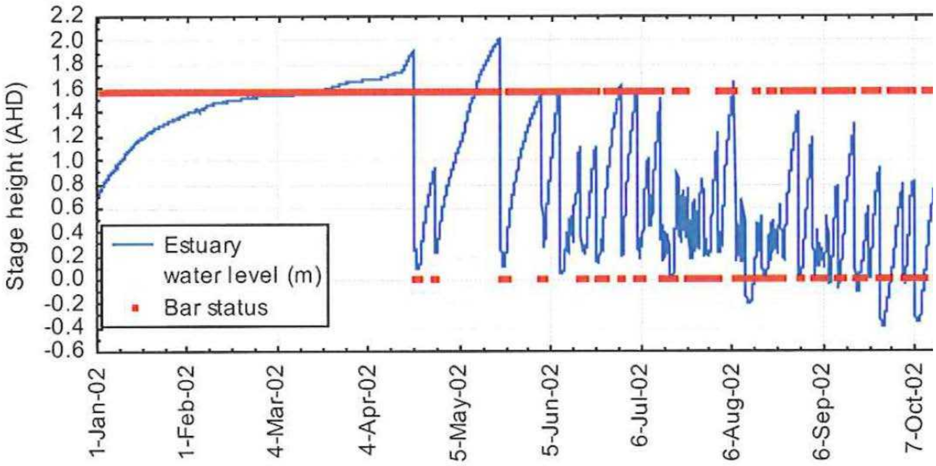

Figure 2.1: Water levels in the Moore River Estuary and indication of when the bar was open or closed [1].

Reference	Key Findings
[2] MP Rogers & Associates (2018). Ledge Point Boat Harbour – Coastal Processes Assessment. R1020 Rev 2. Prepared for the Shire of Gingin.	Outlines a coastal processes study for the Ledge Point Boat Harbour located to the south of Ledge Point Township. The document provides some context on water level climate at the site, specifying that the mean sea level in the southwest of Australia rises 0.1 m during winter and fall 0.1 m during summer due to seasonal shifts in meteorological and oceanographic effects. Whilst no statistical context is provided, the document comments that storm surge can exceed 1 m above the astronomical tide level in rare storms and in winter storms, storm surge often reaches 0.4 m.
[3] MP Rogers & Associates (2019). Grace Darling Park Seawall – Technical Specification. R1275 Rev 0. Prepared for the Shire of Gingin.	Reference to the Grace Darling Park Seawall. Is a technical specification for the construction works and is not entirely relevant for the Gingin Inundation Study, however the document does contain design drawings of the seawall. According to the design drawings, the seawall had a crest level of 2.7m AHD (and toe level of -0.5 m AHD). No basis of design was provided and hence design water levels was not available.
[4] MP Rogers & Associates (2019). Grace Darling Park Seawall – Safety in Design Report. R1284 Rev 0. Prepared for the Shire of Gingin.	Reference to the Grace Darling Park Seawall. Is a Safety in Design document and does not provide any context on design criteria or assumptions.
[5] MP Rogers & Associates (2015). Shire of Gingin Boat Launching Facility Planning Study. R528 Rev 1. Prepared for the Shire of Gingin.	Report to identify a safe site for ocean boat launching within the Shire of Gingin with sites investigated at Lancelin, Ledge Point, Seabird and Guilderton. The report provides analysis of the available metocean data to present summary of the coastal environment and coastal processes at each location. This includes a detailed summary of wind, wave and current conditions for each location. The summary of astronomical tides comments the astronomical tides along the Shire of Gingin coastline are predominantly diurnal (one tidal cycle each day) and relatively limited in range. The daily range is typically about 0.5 metres during spring tides and less than 0.2 metres during neap tides. The Two Rocks tidal submergence curve from the DoT is used as a reference for water levels across the study area. Similar to document [2] there is comment the mean sea level at the Study Area rises 0.1 metre during winter and falls 0.1 metre during summer. Inter-annual variations in the Leeuwin Current can cause variations in the mean sea level of a similar magnitude. Regarding extreme water levels and storm surge it is stated extreme storms and cyclones can exceed 1 metre above the astronomical tide level. In addition to the storm surge inshore setup is discussed with MRA analysis showing the more usual winter storms often cause inshore setup of about 0.4 to 0.6 metres.

<table>
<tr><th>Reference</th><th>Key Findings</th></tr>
<tr><td>[6] Seashore Engineering (2018). Design Storms for Western Australian Coastal Planning: Tropical Cyclones. Document prepared for Department of Transport Seashore Engineering Report No. SE015-01-RevB</td><td>

The Seashore document provides guidance on Design Storms for WA coastal regions to determine coastal hazard assessment under the Western Australian State Coastal Planning Policy SPP 2.6 (SPP2.6). The approach is intended to define erosion and inundation hazard zones associated with tropical cyclones. For the Gingin Study area, tropical cyclones are deemed the inundation design storm for calculation of the S4 inundation component of coastal hazard under SPP2.6. Baird has been provided with an updated set of cyclone tracks based on TC Ned in Ref [15].

For the Gingin study area (Area 3 for Design Storm Identification) the process of extra-tropical transition is significant, as it causes large increases to the effective radius of maximum winds as the storm system travels southward. The influence of shelf waves is noted as important for consideration. The Bureau of Meteorology track data has been used to provide an estimate of scale suitable for use with a vortex model. In the report it is noted that alternate methods based on a combination of local vortex and regional wind fields may provide a more accurate representation of the tropical cyclone wind fields through the process of extra-tropical transition.

Analysis of cyclonic water level records from tide gauges and tropical cyclone tracks associated with the highest recorded surges have identified TC Ned (March 1989) and TC Alby (April 1978) as key for the region around the study area (Area 3). For the towns of Seabird and Lancelin the design storm is based on TC Ned (1989). The cyclone track of the reference storm has been adjusted to provide the 'worst-case' path required for scenario modelling (refer Figure 2.2 and Figure 2.3).

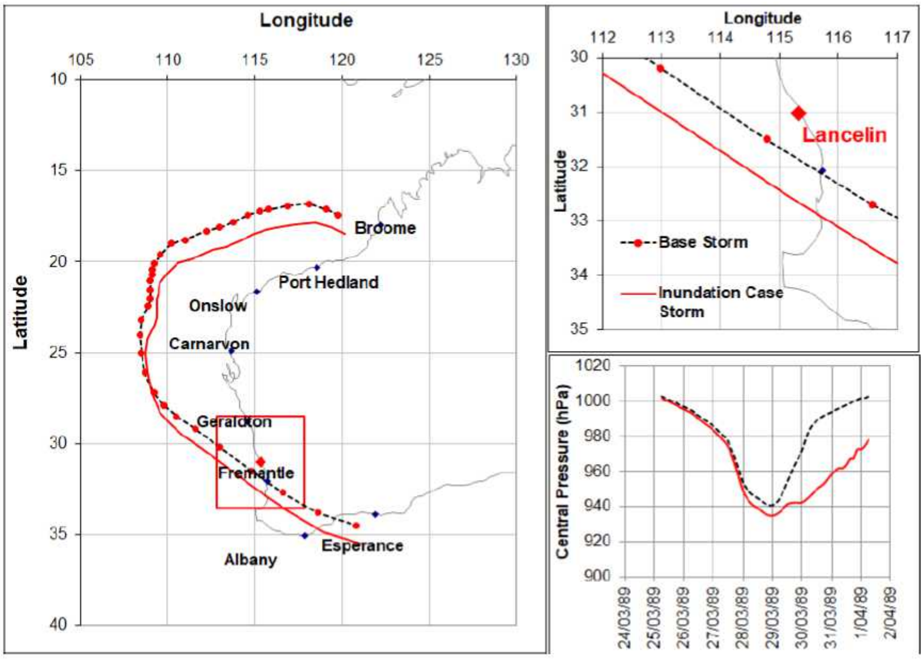

Figure 2.2: Design Storm for Lancelin developed in Seashore (2020) with track and pressure based on 'worst case' TC Ned (March 1989)

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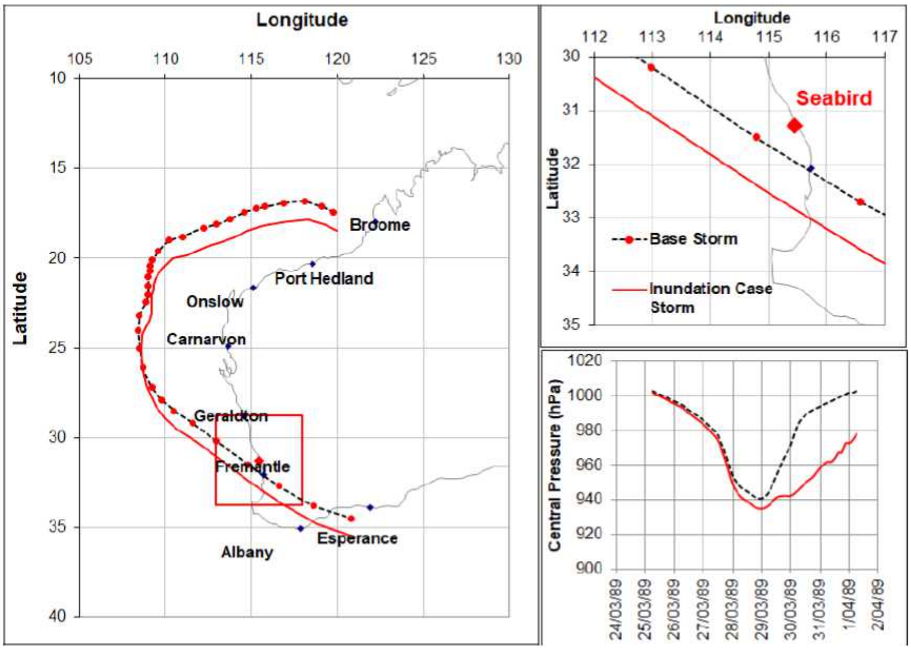
</table>

Reference	Key Findings
	 Figure 2.3: Design Storm for Seabird developed in Seashore (2020) with track and pressure based on 'worst case' TC Ned (March 1989)
[7] Department of Transport (2010). Sea Level Change in Western Australia. Application to Coastal Planning. Report 59917806 Dated 2/2/2010	The DoT document makes recommendations for appropriate sea level rise allowance to apply for future planning considerations in Western Australia. The recommended sea level rise allowances are based on the IPCC 2000 report using the upper bound projection of the IPCC AR4 case (95th percentile of the SRES scenario A1FI). It is recommended that a vertical sea level rise of 0.9 m be adopted when considering the setback distance and elevation to allow for the impact of coastal processes over a 100-year planning timeframe for the period 2010 to 2110. For planning timeframes beyond the 2110 timeframe a vertical sea level rise of 0.01 m/year be added to 0.9 m for every year beyond 2110. Recent discussions with the DoT and DPLH (pers comm-JChurchill-B.Bassett-F.Li-L.Roncevich) were used to clarify the appropriate sea level rise allowance beyond the 2110 planning timeframe. Based on this discussion, for a planning timeframe that starts in year 2020, the 100-year sea level rise allowance at year 2120 is 0.9m. In this study this 100-year allowance will be adopted. Interim values for sea level rise (eg at 20-year timeframe planning year to 2040 and 50-year timeframe to planning year 2070) will be determined from examination of the recommended allowance for sea level rise in coastal planning for WA graph presented in DoT 2010.

Reference	Key Findings
[8] Cardno (2019). Final Coastal Hazard Risk Management and Adaptation Plan, Prepared for Shire of Gingin. Rev0 17 June 2019.	[8] The Cardno report focuses on the impacts of coastal erosion and shoreline recession processes and presents risk management and adaptation planning advice without consideration of the inundation risk. It is noted that the Lancelin coastal zone is predominantly low lying, and coastal inundation is expected to be a major factor in future decision making and adaptation planning. The current study will inform future revisions of the CHRMAP.
[9] MP Rogers & Associates Pty Ltd. (2015) Seabird Coastal Erosion Hazard Mapping Technical Note Report to the Shire of Gingin by MP Rogers and Associates.	
[10] M P Rogers and Associates (2016a) Seabird Coastal Erosion Hazard Mapping Technical Note Report to the Shire of Gingin by MP Rogers and Associates.	The coastal erosion hazard lines were calculated by MRA over future planning timeframes 2020, 2030, 2050, 2070 and 2110. The hazard lines will be considered in the context of how the potential changes to shoreline position through the study area may influence the coastal inundation hazard in future planning periods. Of particular relevance at Lancelin where the foredune is a controlling feature that provides a natural barrier to areas on the landward side from extreme ocean storm tide level.
[11] M P Rogers and Associates (2016b) Coastal Erosion Hazard Assessment, Ledge Point, Lancelin and Cervantes. Report to the Shires of Gingin and Dandaragan by MP Rogers and Associates.	

Reference	Key Findings
	Report identified that no existing long-term water level data was available in the study area and hence Fremantle tide gauge data was used as it contained digital data back to 1959. Whilst the site is 100km south of the study area, they state that Fremantle tide data has close correlation to Jurien Bay and Geraldton and hence was considered sufficient for the study. They also state that the water level signal is strongly influenced by non-tidal forcing including surges and mean sea level variation, such that the total water level range at Fremantle from 1959 to 2016 was 2.15 m which is roughly twice the astronomic tidal range. Seasonal variation was observed by Seashore noting that high water levels mainly occurring during intense winter storms from May through to July, and low water levels between October and February. They also note that there were occasional high water levels due to meteorological events such as Tropical Cyclone Alby in 1978 (1.79 m CD), as well as due to resonant phenomena, such as shelf waves. Report also discussed the wind climate, however inundation levels are likely determined by cyclonic events and hence not too relevant to the study. The study also noted the wave transmission to the coastline was complex due to the nearshore reefs in the study area.
[12] Seashore Engineering (2017). Seabird, Ledge Point, Lancelin – Coastal Monitoring Action Plan. Document prepared for Department of Transport. Seashore Engineering Report No. SE045-01-Rev0.	Provides a summary of the influence of fluctuations in water level on coastal erosion and accretion trends, as well as providing a summary of available metocean data in the study area. The document states that due to the relatively small tidal range (0.6 m from Mean Higher High Water to Mean Lower Low Water) and complex wave attenuation due to reefs and islands, fluctuations in water level can have a significant impact on the coastline evolution. Figure 2.4 is reproduced from [12] and shows the mean sea level fluctuations at Fremantle (30-day running mean water level). This shows seasonal and inter-annual variation of up to around 30cm each since 1959, with recent periods of unusually high mean sea levels in 1999-2000 and 2011-2013 likely to have contributed to observed erosion at Seabird, Ledge Point and Lancelin. These fluctuations have been linked to the El Niño/La Niña cycle, with higher water levels occurring during the la Niña phase along with correlation to the strength of the Leeuwin Current.

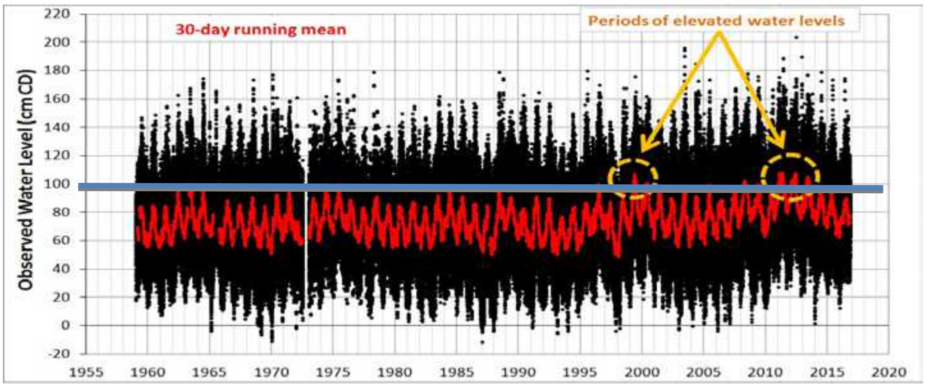


Figure 2.4: Record of observed hourly water level at Fremantle from 1959 – 2016. ***Australian Height Datum (AHD) is 76cm above Chart Datum (CD) at Fremantle [12].***

<table>
<tr><th>Reference</th><th>Key Findings</th></tr>
<tr><td>[13] Coastal Focus (2013). Data and Information Gap Analysis For Coastal Hazard & Risk Management – Gingin Dandaragan Coast (Hill Primary Coastal Compartment). Prepared for the Northern Agricultural Catchments Council, The shires of Gingin and the Shire of Dandaragan. September 2013.</td><td>Describes the coastal processes involved in completing a coastal hazard and risk management study for the Gingin Dandaragan Coast. The document also summarises a data gap analysis for the study. The key message from the report in terms of this inundation study is that extreme storm surges in the study area are due to major storms such as extra tropical and tropical cyclones. The study identifies that the longest water level records are at Geraldton and Fremantle, however further study of extreme weather events is required with regards to water levels</td></tr>
<tr><td>[14] Damara WA Pty Ltd (2012). The coast of the Shires of Gingin and Dandaragan, Western Australia: Geology, Geomorphology and Vulnerability. Prepared for the Department of Planning. March 2012.</td><td>
Provides strategic planning guidance and management strategies on appropriate land uses for coastal land in the Shire of Gingin and the Shire of Dandaragan, by assessing and understanding the coastal erosion hazards. Completed various studies, including an analysis of water level data at Geraldton (1966 – 2008) and Fremantle (1959 – 2008). The water level time series were decomposed into approximations for mean sea level (30 day running mean), tide (Doodson-x_0 filter) and surge (residual), with some overlap between the approximations. The analysis tries to understand the range of water level components contributing to the total water level. The results are reproduced in Table 2.2. Results show that non-tidal components such as storm surge have a large ratio to the astronomical tide component.
Table 2.2: Mean Sea Level, Surge and Tide Approximations for Geraldton and Fremantle [14].
<table>
<tr><th rowspan="2">Water Level Component</th><th colspan="2">Geraldton (1966 – 2008)</th><th>Fremantle (1959 – 2008)</th></tr>
<tr><th>Range</th><th>Standard Deviation</th><th>Range</th></tr>
<tr><td>Water Level (cm CD)</td><td>-28 to 180</td><td>24</td><td>-11 to 197</td></tr>
<tr><td>Mean Sea Level (cm)</td><td>36 to 97</td><td>11</td><td>49 to 107</td></tr>
<tr><td>Surge (cm)</td><td>-35 to 50</td><td>10</td><td>-38 to 50</td></tr>
<tr><td>Tide (cm)</td><td>-37 to 41</td><td>18</td><td>-35 to 39</td></tr>
</table>
Also discusses the atmospheric surge associated with extra-tropical storms peaking around May to July. Tropical cyclones are often combined with resonant
</td></tr>
</table>

Reference	Key Findings
	phenomena, such as continental shelf waves. A continental shelf wave of 0.75m, generated by Tropical Cyclone Bianca, was recorded at Fremantle and Geraldton in March 2011. The document also states that the relative timing of tide, mean water level and extra-tropical surge controls the potential for high water levels which occurs in June in Fremantle and May to June in Geraldton. Whilst, they say that the timing of this high water level is generally out of phase with tropical cyclone season, they do note that high water levels occur with tropical cyclones, for example TC Glynis in 1970. States that a hydrology study to estimate 10, 25 and 100 year average recurrence interval flood levels for the Moore River at Moora (90km upstream from the mouth) was prepared by GHD in 1991 and revised by Water Studies in 2000. However, extreme water levels are not presented in the report and being so far from the river mouth would provide limited benefit to the study.
[15] Seashore Engineering (2020). Design Storms for Western Australian Coastal Planning: Revised Design Storms based on TC Ned. Doc: Revised Design Storms based on TC Ned.pdf	Provides the latest design storm information for the study area and has been used in the consideration of the design storm event (500-year ARI) in the final sections of this memo.
[16] DWER (2020). Department of Water and Environmental Regulation water data is available via:www.water.wa .gov.au	Provides the links to the measured water level data (stream gauge information) from the DWER. The data will be used to evaluate the water levels in Moore River for joint occurrence flooding consideration. The measured data from sites around the Guilderton section of the river are of limited duration (1 to 2 years). The longest record back to the 1960’s at the Quinns Ford location approximately 35km upstream of Guilderton.

2.2 Coastal Inundation Processes

The following section provides a general overview of coastal inundation processes that are important for the current study.

Coastal inundation is comprised of a number of components that will vary on a range of spatial and temporal scales. These include: the astronomical tide, storm surge due to extreme wind events such as tropical cyclones, elevated water levels due to wave action, and seasonal and longer-term variations in mean sea level. These components are summarised in Figure 2.5.

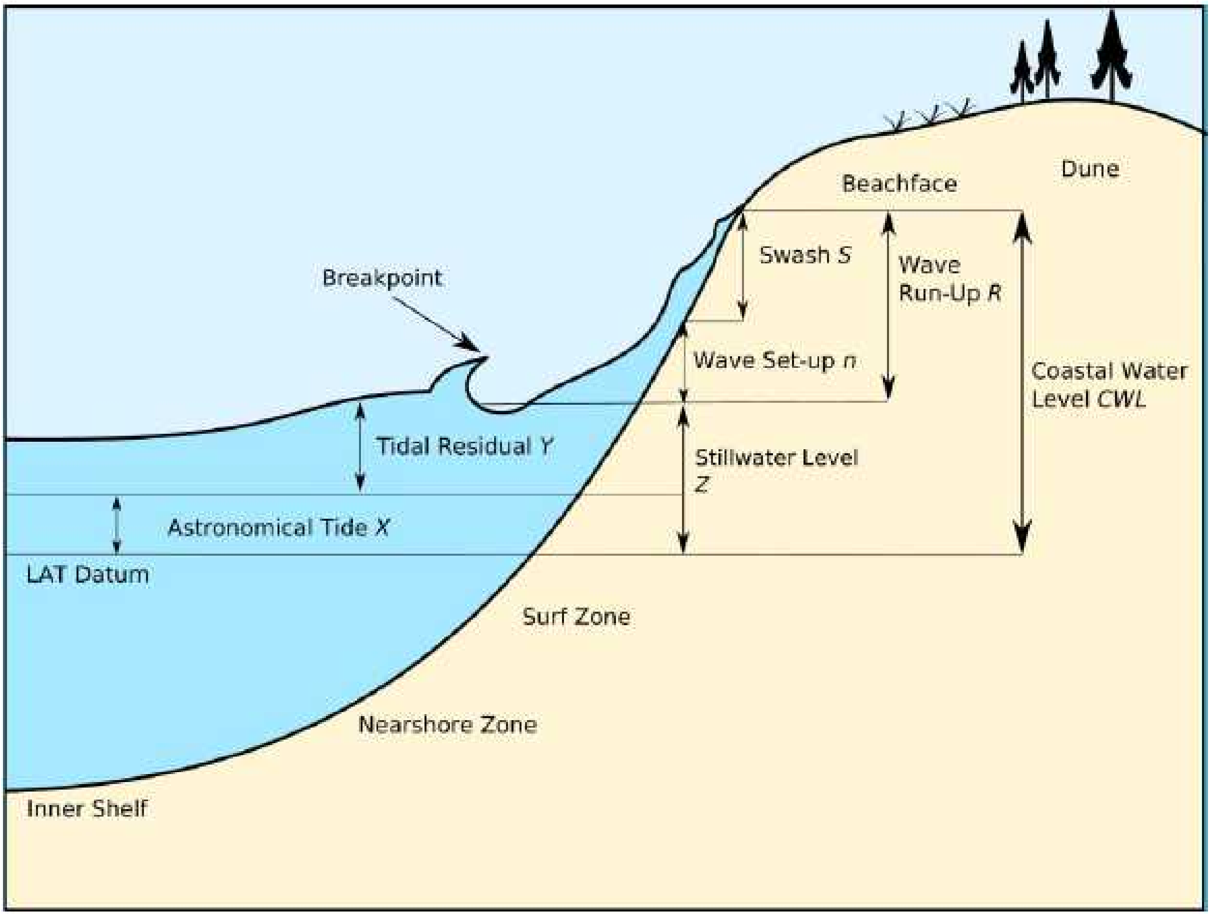


Figure 2.5: Schematic diagram illustrating components of coastal inundation

2.2.1 Tropical Cyclones

Tropical cyclones are intense rotating low-pressure systems consisting of a calm eye surrounded by strong winds rotating clockwise and radially inwards in the Southern Hemisphere. They form over tropical waters that have surface temperatures greater than 26.5 °C and can persist over oceans with lower temperatures, although the energy tends to dissipate over cooler waters and land. Other factors contributing to cyclogenesis include low vertical wind shear, atmospheric instability, high humidity and a pre-existing atmospheric disturbance. A cyclone's intensity is categorised based on the severity of its winds.

Tropical cyclones are divided by the Bureau of Meteorology (BoM) into five categories, ranging from Category 1 (minor) to Category 5 (extreme) as summarised in Table 2.3. The intensification of tropical cyclones is limited by energy loss through friction and the maximum temperature of sea water.

Table 2.3: Australian tropical cyclone category scale used by the Bureau of Meteorology

Category	Maximum Wind Gust (km/h)	Potential Damage
1	< 125	Minor
2	125-170	Moderate
3	170-225	Major
4	225-280	Devastating
5	> 280	Extreme

The cyclone wind field is typically almost axisymmetric, being low at the eye, peaking at the radius to maximum winds which is typically located in the eyewall of the cyclone, then decaying more gradually further away from the eye. This characteristic makes the simulation of cyclonic wind fields amenable to empirical methods in tropical areas in the north of Australia, and a parametric vortex model can be applied in numerical models to simulate the cyclone wind field characteristics (eg Holland 2010).

However, at the latitude of southern Western Australia where the Gingin area is located, the axisymmetric characteristics of the wind field tend to breakdown and parametric methods to define the cyclone wind field which work well in tropical regions become unreliable.

2.2.2 Ex-tropical Cyclones

A transitioning tropical cyclone which is no longer subject to convective energy forcing as occurs in warmer, tropical waters can interact with a significant southerly cold front coming up from the southern Indian Ocean which can increase the intensity and scale of the storm system. In these situations, as occurred with TC Alby in April 1978, the system transitions into an extra-tropical cyclone where the scale and fetch of the wind-field which generated a large storm surge and extreme waves on the coastal shelf is not well described by a parametric vortex model.

A significant gap in the physics for a transitioning cyclone is noted for surface wind speed as a result of the forward speed asymmetry. In the case of a transitioning storm the fast translation speed of the storm when it is offshore is a challenge to recreate in a parametric model. There are a range of parametric and boundary layer cyclone wind and pressure models that compute forward speed wind asymmetry to a reasonable degree of accuracy. For example, Baird's *Cycwind* model which computes tropical cyclone winds using the Holland (2010) parametric vortex model and solves forward speed asymmetry using the McConochie (2004) model.

Hybrid storms that are comprised of a transitioning tropical cyclone interacting with a frontal system are not well described with parametric models and the phenomena of forward track speed causing enhanced wind speeds in the forward right quadrant (southern hemisphere, forward left in northern hemisphere) is not consistently observed in hybrid storms. A large research effort on transitioning cyclones (typhoons) and hybrid storms has been undertaken in Japan due to the frequency and severity of transitioning and hybrid storms that impact on Japan each typhoon season. Some recent literature of note identified the following regarding the wind field structure of storms during and after extra-tropical transition in the northwest Pacific:

- Loridan *et al* (2013) noted that for 67% of events storms in a 31-year reanalysis data set that underwent extra-tropical transition did not exhibit forward left quadrant wind asymmetry that was consistently observed for storms when they were in their tropical cyclone phase.
- Evan *et al* (2007) examined storm event forecasting for typhoons (cyclones) that underwent extratropical transition. Whilst definitive conclusions lack statistical confidence, the results of that study

supported the hypothesis that inserting a synthetic vortex with forward speed asymmetry can improve the tropical phase structure forecasts. The accuracy of the forecast once extra-tropical transition commenced was degraded as the synthetic vortex model did not generate the wind field characteristics that were observed with the transitioning storm.

Bieli *et al* (2019a and 2019b) completed a global review of cyclones that underwent extratropical transition and compared re-analysis data sets (JRA-55 and ECMWF interim reanalysis) with best track storm data during the extra-tropical transition phase. The JRA-55 re-analysis data set consistently had the best validation metrics compared to the best track storm data. Further details on the track characteristics of historical storms that exhibited extra-tropical transition offshore of southwest Western Australia is presented in Section 2.2.2.1.

The Australian cyclone season extends from November through to April with an average of 10 cyclones per year, although not all make landfall. The extreme winds and intense low pressure associated with tropical cyclones produce storm surge at the coastline. On the west coast of Australia, the onshore winds occur to the north of the location of the cyclone's landfall. The highest surge tends to occur near the radius of maximum winds, or where the strongest winds of the cyclone occur, which is typically 10 to 50 km northeast of the cyclone eye. These systems are frequently associated with heavy rainfall that can cause significant flooding. The Australian cyclone region generally has a low frequency of extra-tropical transition compared to other basins including the northwest Pacific and North Atlantic basins.

2.2.2.1 Track Characteristics of Storms Exhibiting Extra-Tropical Transition

As noted in the previous section, extra-tropical transition is an important process in the context of the design inundation events presented in Seashore Engineering (2020) which will be considered in this study for the Gingin region. A tropical cyclone which undergoes extra-tropical transition, for example Tropical Cyclone Alby which occurred in 1978 resulting in significant coastal inundation in the Busselton region or Tropical Cyclone Ned in 1989, occur infrequently but is likely to be the result of a southwards tracking tropical cyclone intersecting with an approach cold front offshore of southwest Western Australia.

Hetzel and Pattiaratchi (2014) provides a summary of extra tropical cyclone transitions in the contest of the Western Australia coastline and a discussion of notable events between 1970 and 2014. Whilst TC Alby is the notable event in the last 50 to 100 years to impact on southwest Western Australia, between 1970 and 2014 Hetzel and Pattiaratchi (2014) identify a total of 8 tropical cyclones impacting along the Western Australian coastline which showed evidence of extra-tropical transition, 5 of which track south of -28^{o}S latitude.

Table 2.4 presents a summary of the 5 tropical cyclones identified in Hetzel and Pattiaratchi (2014) which had characteristics of extra-tropical transition offshore of southwest Western Australia. Since 2014, no other notable events have been identified. Table 2.4 clearly indicates that TC Alby is unique and extreme with respect to intensity between the Tropic of Capricorn and -34^{o}S, and storm scale as defined by the radius of gale force winds. The extent of gale force winds for TC Alby, approximately 500 km in the northeast quadrant from the storm eye, is significantly larger than the other 4 events where the radius to gales near -34^{o}S is more typical of frontal storm systems. As noted in Table 2.4 and Table 5.2, there is limited scale and intensity data for TC Ned during the period it was experiencing extra tropical transition.

Hetzel and Pattiaratchi (2014) summarise some observations that correlate with storms that undergo extra tropical transition offshore of the Western Australia coastline. A key observation is that these storms are most likely to occur late in the cyclone season, in March and April, when cold fronts are more likely to track from the west towards the southwestern Western Australia coastline. This important joint occurrence requirement (southwards tracking tropical cyclone interacting with large scale frontal system) is likely to significantly reduce the likelihood of extra-tropical cyclone transition, compared to a tropical cyclone decaying in intensity and scale over the cooler water south of the Tropic of Capricorn.

Table 2.4: Tropical Cyclones which Tracked South (to -34ºS) which Exhibited Extra-Tropical Transition Characteristics by Hetzel and Pattiaratchi (2014).

Event	Tropic of Capricorn -23.43ºS	Mid Latitude band -28 ºS	Port Geographe -34 ºS		Data Source for Radius to Gales
	Cent. Pres (hPa)	Cent. Pres (hPa)	Cent. Pres (hPa)	Radius Gales (R34, km)	
TC Vida	982	986	991	140	BoM event report, estimated from ship observations.
TC Alby	938	955	955	500	JRA-55 hindcast
TC Idylle	980	990	990	300	BoM event report, estimated from ship observations. Well offshore in Indian Ocean. Force 10 winds @ 190 km from eye.
TC Ned	984	998	998	N/A	
TC Vincent	966	978	991	205	BoM event report, best track analysis.

2.2.3 Astronomical Tide

The astronomical tide is the periodic rise and fall of the sea surface caused by the combination of the gravitational force exerted by the moon and the Sun upon the Earth and the centrifugal force due to rotations of the Earth and moon, and the Earth and the Sun around their common centre of gravity.

Tides are subject to spatial variability due to hydrodynamic, hydrographic and topographic influences. In the study area, tides are typically diurnal (1 high water and 1 low water per day) and the tide range is typically small as described in Section 3.1.1.

2.2.4 Storm Surge

Storm surge is a long-gravity wave with a period of hours to days resulting in the elevation or depression of the sea surface which develops in response to storm activity. Storm surge is generated by two main processes: the inverse barometric effect and the wind set-up against the coastline. There are a range of weather systems capable of generating storm surge around Australia, including tropical cyclones, east coast lows, mid-latitude lows, and cold fronts. Typically, the most important component of the storm surge is the wind set-up component, particularly when the storm event crosses the coast where cross-shore wind set-up is in the order of metres whereas the inverse barometric set-up is in the order of 0.5 m or less for southwest Western Australia.

A conceptual diagram of storm surge development is presented in Figure 2.6. The most severe storm surges are generated by severe tropical cyclones in areas with broad and shallow continental shelves, especially when coinciding with high tide.

The term storm water level refers to the absolute water level resulting from the combination of storm surge and the astronomical tide, referred to a vertical datum such as Lowest Astronomical Tide (LAT) or Australian Height Datum (AHD).

The coastline of Western Australia is vulnerable to the occurrence of storm surge; however for southwest Western Australia (between Geraldton and Bunbury) storm surge is not always the dominate component in coastal water levels and wave processes, including setup inshore of an outer reef, can dominate the residual water level.

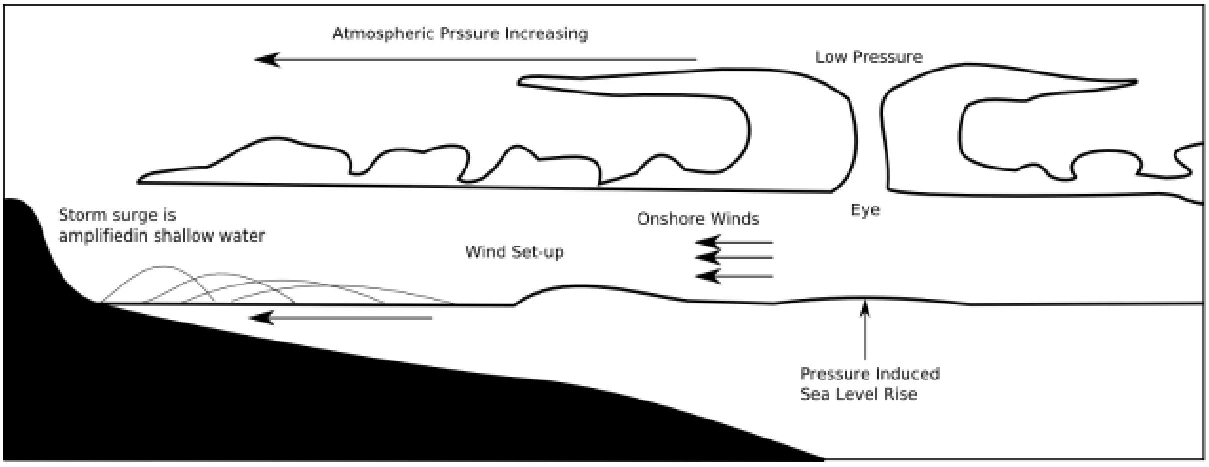


Figure 2.6: Conceptual diagram showing the development of storm surge due to barometric set-up and wind set-up in a tropical cyclone.

The inverse barometric effect is a vertical force exerted on the ocean surface, caused as low pressure creates a local rise in sea level. Approximately one hectapascal (hPa) decrease in air pressure leads to a one-centimetre increase in sea level, providing that low pressure persists for a sufficient length of time. This effect is for a static storm system, and can be enhanced for a moving system, especially if it is moving at a speed close to that of a shallow water wave, forming travelling resonance (Dean and Dalrymple 2004). The inverse barometric set-up is independent of water depth and is the main contributor of tidal residual for offshore non-continental waters. For storm tide at the coastline induced by tropical cyclones, the elevated water level due to the inverse barometric effect is secondary to the wind set-up.

Wind set-up results from strong onshore winds pushing surface waters against the coastline. Wind stress occurs parallel to the ocean surface as energy and momentum is transferred to the water. Wind stress, or drag, is proportional to the square of wind speed. The effect of wind set-up is not instantaneous and is acted upon by the Coriolis force as the Earth rotates. The rate at which the wind increases in speed also affects storm surge elevation, with rapid wind speed acceleration leading to larger surge maximum.

Theoretically, the wind set-up in the one-dimensional case is inversely proportional to depth. As such, wider and shallower continental shelf waters are subject to higher wind set-up than locations with a steeper continental shelf. Coastal topographies such as shallow bays and funnel shaped estuaries may amplify the storm surge level.

Storm surge development is complex and its height is dependent on a number of factors for any given cyclone event and location. Even for a cyclone of a given category, the storm surge height can vary dramatically depending on the location of impact and the cyclone’s specific characteristics:

- Cyclone intensity: A more intense cyclone has stronger winds and lower atmospheric pressure which generates a larger storm surge and also larger waves.

- Cyclone scale: The extent of a cyclone's wind field influences the height of its storm surge. A cyclone with a large wind field will create a greater surge as the storm is forcing on a larger area of ocean water. Additionally, a larger storm will affect a larger given area of coastline for a longer period of time.
- Translational speed: The forward speed of the cyclone, being the rate at which it moves over time, also affects the height of the storm surge. A cyclone moving forward quickly has higher wind speeds than one moving more slowly and can generate a larger surge on the open coast. However, a slower storm may impact a given location for longer, leading to larger surge in bays and estuaries.
- Angle of approach: A cyclone will produce a larger surge in a given location when it approaches the coast head-on, while a cyclone that approaches the coast at an oblique angle or tracking parallel to the coast will result in a lower surge as the surge is highly sensitive to the wind direction. However, as the coastline changes orientation and has complex bays and inlets, the surge may develop more in some areas than others.
- Bathymetry: The depth and slope of the ocean floor (offshore bathymetry) influences the storm surge development. For example, an area with a wide, shallow coastal shelf, would experience greater surge with relatively smaller waves. Conversely, a coastline with a narrow, steep shelf will experience lower surge but much higher waves.
- Coastline topography and orientation: Variations in local coastline features, such as open or narrow estuaries and bays, also influence storm surge compared to an open coastline. The shallow waters of bays amplify the surge as the friction of the shallow seabed slows the water down, allowing it to pile up. Storm surge can be further amplified in open estuaries that become narrow.

Given the complexity of storm surge development, its behaviour is best modelled using hydrodynamic modelling techniques. Modelled surface wind and atmospheric pressure fields are the forcing mechanisms required for hydrodynamic simulation of storm surge.

2.2.5 Wave Action – Setup and Runup

The strong winds in a tropical cyclone can generate extreme wave conditions. When impacting the coastline, these waves contribute to the total water level through wave run-up.

Wave runup and setup is the maximum vertical extent of wave uprush on a beach. The wave runup is superimposed on setup (refer Figure 2.5). Wave set-up is the super-elevation of the time-averaged water level landward of the initial wave breaking point. It is caused by the cross-shore gradient in wave radiation stresses which result from wave breaking (Longuet-Higgins and Stewart 1963 and 1964). Swash is the motion of the water line up and down the beach face due to wave uprush (Nielsen and Hanslow 1991). The impact of waves on a given coastline depends on its local setting, including the exposure along the fetch of the cyclonic winds and local bathymetry, and effect of islands.

For southwest Western Australia, wave action can be a particularly significant component of coastal water levels due to the complex bathymetry, including outer reef features, and the large waves that can be generated from severe frontal system and extra-tropical cyclones.

Wave run-up increases with the increasing wave height, wave period and beach slope. Waves that occur during cyclones can reach areas not usually reached and can carry immense power that also lead to coastal erosion and breaching of dunes. A 2% exceedance value for wave runup is commonly used in coastal engineering applications (Holman 1986), which is calculated based on the cumulative probability density function of the run-up elevations.

It should also be noted that that the elevated water levels caused by wave set-up will not propagate far inland after overtopping frontal dunes flowing over low-lying areas or proceeding through inlets (Hardy et al. 2004).

The dynamics of wave set-up at river entrances is different to that observed on the open beach. The physics of the river entrance hydrodynamics, particularly with regard to wave set-up, is extremely complex and further complicated by the influence of significant freshwater discharges and the behaviour of storm tide propagation through the entrance during extreme conditions.

2.2.6 Overland Inundation

Coastal inundation occurs when storm surge leads to an ocean water level that is higher than the general tide range at a location. This causes flooding of land areas that are usually elevated above the influence of the ocean. The elevation of ocean water levels during extreme events is caused by the combination of the processes discussed in this section. At the local scale, the elevation reached by the storm tide inundating the land can be amplified over its nearshore level by the, 'local' wind set-up. This is the same phenomenon as the wind set-up discussed above occurring on a localised scale as the intense cyclonic wind forcing continues to act on the water surface in increasingly shallow water, which can force water up a slope where the wind stress exceeds the gravitational force down the slope and the bottom friction losses. This phenomenon is site specific and the balance of the friction losses and the wind stress will be controlled by local conditions. In numerical modelling, this will be somewhat a function of the spatial resolution of the model mesh or grid as the land surface is discretised and the slope of the land is not smooth but consists of steps.

Broadly, there are three 'modes' by which storm tide inundates the land:

1. The storm tide level intersects the beach face and water piles up against beach face. If onshore winds are present when the storm tide impacts the shoreline, 'local' wind set-up may amplify the resultant onshore storm tide levels.
2. The storm tide level exceeds the elevation of beach face / dune crest and continues to propagate overland. The resultant storm tide level may be amplified from its nearshore level due to 'local' wind set-up as the fetch length increases.
3. The storm tide propagates through waterway entrances and combines with rainfall discharges. The 'local' wind set-up may also act on the water surface along the fetch of the estuary, and in theory, potentially increasing the storm tide level relative to the open coast. Overland flow from waterways would then inundate low lying areas.

2.2.7 Variations in Mean Sea Level

Further, the background sea level can be affected by other phenomenon such as seasonal fluctuations related to El Nino/La Nina cycles, relative position of ocean currents and eddies to the shoreline, coastally trapped waves and persistent monsoon winds. Church et al. (2004b) identify that the north-western and western Australian coasts have the strongest interannual variations in mean sea level due to the ENSO (El Nino Southern Oscillation) cycle. Such effects will be investigated in this study as non-cyclonic influences on mean sea level.

2.2.8 Catchment Rainfall / Runoff and Overland Flow

Catchment rainfall and runoff has not been addressed in this study. However, a discussion of water levels and available flood information for the Moore River is presented in Section 2.1 and the potential impacts of riverine flooding in conjunction with elevated coastal water levels for Guilderton is discussed in Section 5.5.

2.2.9 Tsunami

Tsunami are long period waves that may be generated by earthquakes, volcanic activity, underwater landslides and possibly meteors landing in the sea. They have much greater destructive force than storm waves due to their long wavelength and hence greater power. Tsunami do not break at the shoreline, instead propagating inland as a bore with significantly more wave power than storm waves.

Potential tsunami inundation impacts are presented in Section 8.

2.3 Water Level Components not Considered in this Study

The coastal inundation risk posed by the following processes is not considered within the context of this report:

- Coastally trapped waves; and
- Stormwater run-off and localised flash flooding.

Coastal water levels can also vary due to coastally trapped waves or shelf waves. They are low amplitude, long period waves that may be initiated by atmospheric disturbances associated with storms of intense frontal systems remote to the site affected. These are driven by differences in density, and result in the movement in the interior of the ocean with a small surface signal. For example, coastally trapped waves that affect the NSW coastline propagate northwards from Bass Strait and can generate variations in ocean level of up to 0.2 m with periods of up to 10 days (Freeland et al. 1986, Buchwald & Kachoyan 1987). Shelf waves are also known to propagate from the North West Shelf down the Western Australian coastline, where the coastally trapped wave can propagate along the coast and impact water levels thousands of kilometres away from the event (Pattiaratchi et al, 2016).

The 2016 report on continental shelf waves in Western Australia undertaken by the University of Western Australia in 2016 (Pattiaratchi et al, 2016) determined that the cyclones path, speed and category all impact the generation and propagation of the continental shelf wave. Key findings from Pattiaratchi *et al* (2016) on the regional scale modelled events were;

- Model simulations were undertaken of 70 synthetic category 5 events with various paths and speed;
- The greater the cyclone category the higher the amplitude of the generated shelf wave;
- Coast parallel cyclones generated the largest shelf waves along the Western Australia coastline, including southwest WA; however, shelf wave amplitude was largest when the forward track speed of a cyclone was between 7.6 and 10 m/s and the shelf wave was a ‘forced’ wave propagating at a velocity similar to the cyclone track. When cyclone track speed was above 10 m/s the amplitude of shelf waves decreased significantly, and the shelf wave along the coast trailed behind the storm track.

Pattiaratchi *et al* (2016) demonstrated some model skill for hindcasting shelf waves along the Western Australia coastline using a shelf scale hydrodynamic model with wind and pressure forcing. The most relevant historical event analysed in Pattiaratchi *et al* (2016) that generated a distinct shelf wave south of Exmouth was Tropical Cyclone Bianca. The track and intensity of TC Bianca is presented in Figure 2.7. The track followed a predominantly coast-parallel track between Broome and Geraldton before weakening and dissipating below tropical low strength approximately 300 km offshore of the coast, just north of Perth. Figure 2.8 presents the analysis of tide gauge data as presented in Pattiaratchi *et al* (2016) for TC Bianca. A low water trough from the shelf wave is initially observed along the coast (see red line) before a peak shelf wave height is observed 24 to 48 hours later. TC Bianca maintained a steady track speed between 5 to 7 m/s from its formation offshore of Broome until it dissipated offshore of Perth. At the tide gauges south of Carnarvon where a distinct propagating shelf wave was observed (see Figure 2.8), the peak height of the shelf wave was observed after TC Bianca had tracked south of the site. At Fremantle, the peak amplitude of the shelf wave was approximately 12-hours after the storm had dissipated below tropical strength.

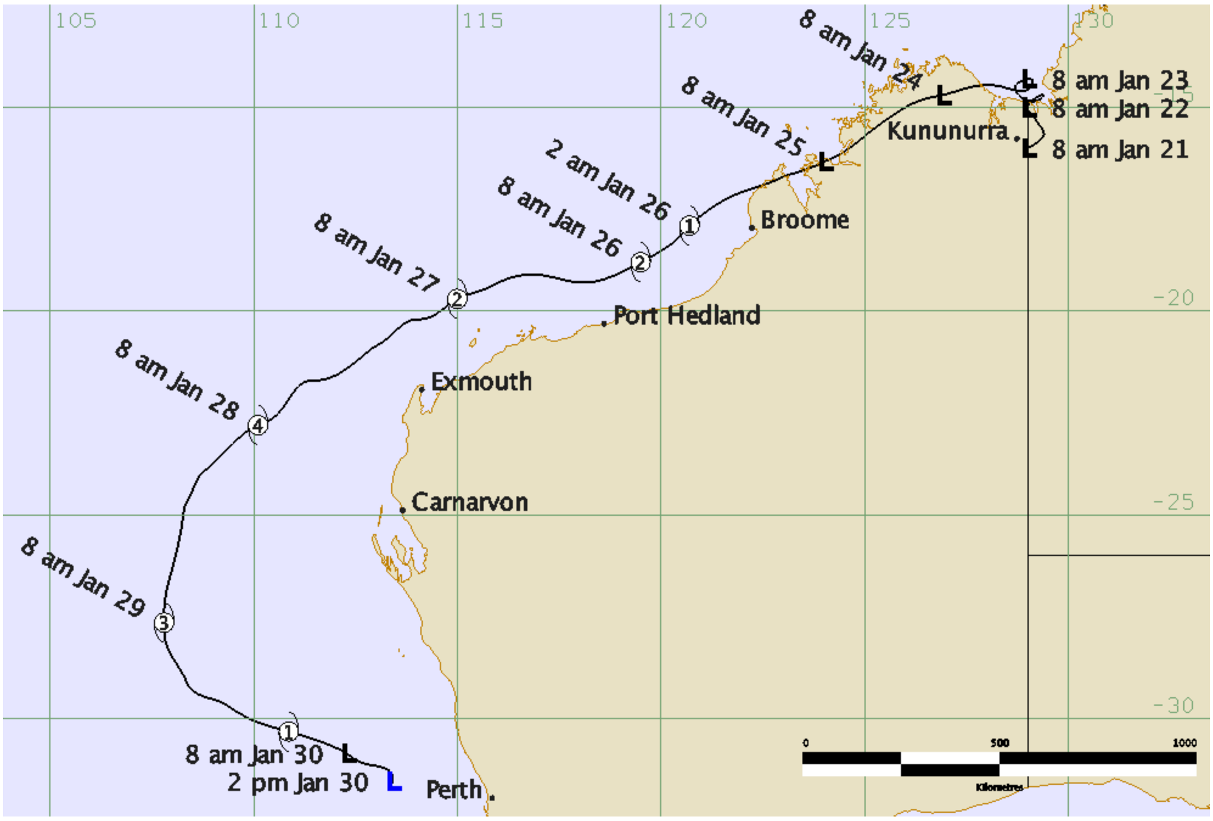


Figure 2.7: Track and Intensity of Tropical Cyclone Bianca (BoM, 2011).

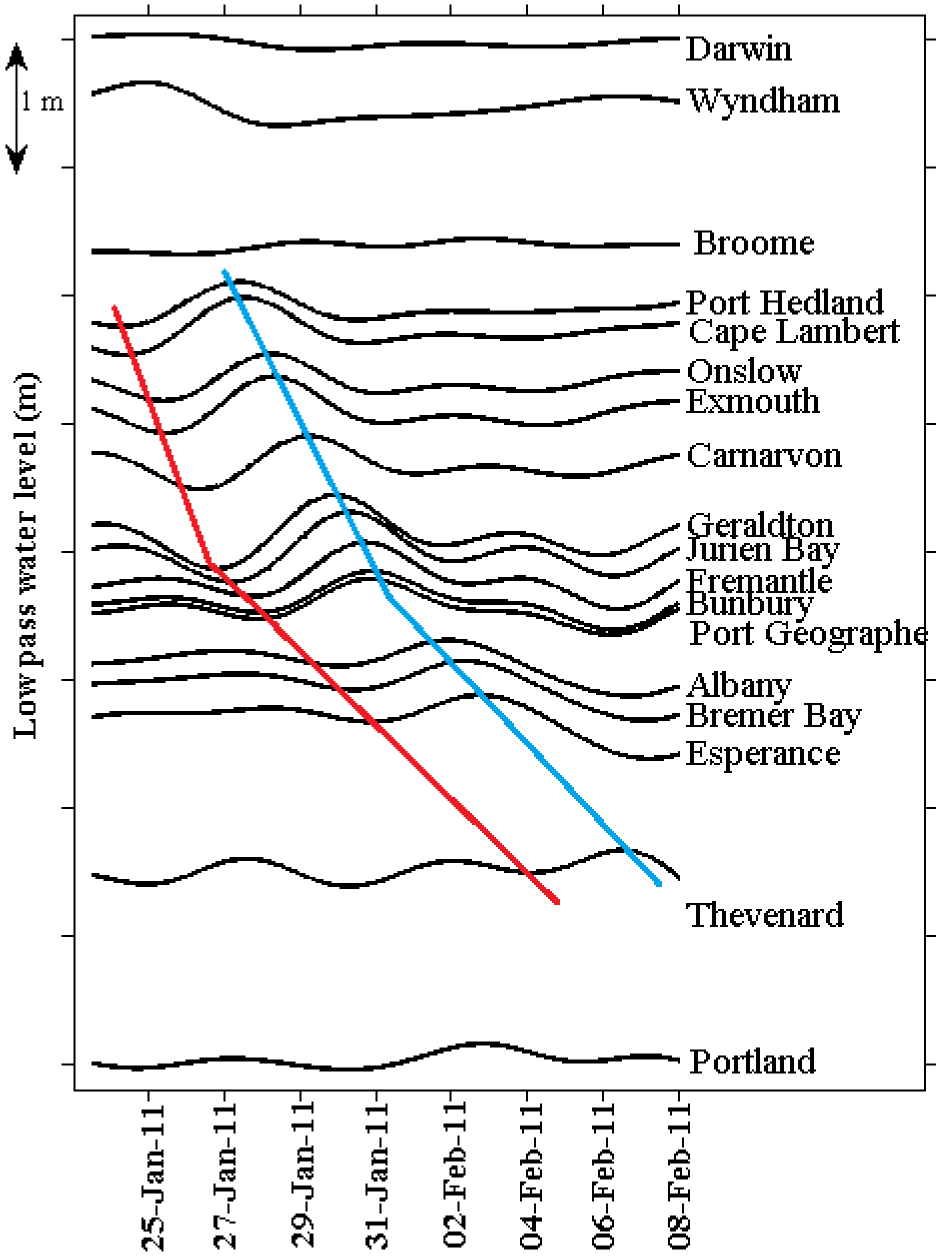


Figure 2.8: Continental Shelf Wave Evident in Measured Tide Gauge data for the 2011 TC Bianca Event showing the Low Water (red) Preceding the Highest Amplitude in Wave Height (blue) Travelling South down the WA Coast (Pattiaratchi et al, 2016)

Shelf waves generated from transitioning tropical cyclones offshore of the southwest Western Australian coastline have not be investigated in the same detail as shelf waves from tropical cyclones. For the design coastal inundation event modelled in this study that is based on Tropical Cyclone Ned, the effect of a continental shelf wave on the peak coastal water level in the Gingin study area has been assessed as small compared to the potential variability in storm surge as a result of wind speed, storm track and storm scale for a latitude of -30˚S and further south. The basis for this assessment is:

- TC Ned had a very fast forward track speed which was above 15 m/s south of -30° latitude and Pattiaratchi *et al* (2016) identified that cyclone track speeds greater than 10 m/s had reduced shelf wave amplitudes;

- Any significant shelf wave that may be observed in the Gingin study area would occur after the peak storm surge from direct wind stress and pressure forcing as the propagation speed of the storm track is significantly greater than the propagation speed of any shelf wave.

It should be noted that as discussed in Section 5.4, based on analysis of measured water levels in the study area (see Section 2.1), a positive water level residual of 0.30 m has been included in the design inundation event simulations to account for non-cyclonic positive water level residual and the potential impact of a shelf wave acting in addition to the peak storm surge during the design events. The +0.3m is included as a fixed baseline to the water level in the simulations with further discussion in Section 6.

3. Data Sources

A summary of the survey data and assumptions applied in the modelling and analysis for the CIS is provided in this section.

3.1 Ocean Levels and Datum

3.1.1 Tidal Planes

A summary of the tidal planes through the study area are presented in Table 3.1 based on tidal submergence curve information provided by the DoT for Jurien Bay, Lancelin and Two Rocks Marina.

Table 3.1: Tidal Planes (based on DoT submergence curves).

Tidal Level	Jurien Bay[1] (m CD)	Jurien Bay (m AHD)	Lancelin[2] (m CD)	Lancelin (m AHD)	Two Rocks Marina[3] (m CD)	Two Rocks Marina (m AHD)
Highest Astronomical Tide (HAT)	1.41	0.53	1.39	0.41	1.39	0.52
Mean High High Water (MHHW)	1.14	0.26	1.15	0.17	1.14	0.27
Mean Low High Water (MLHW)	1.04	0.16	1.05	0.07	1.04	0.17
Australian Height datum (AHD)	0.88	0	0.98	0	0.87	0
Mean Sea Level (MSL)	0.80	-0.08	0.81	-0.17	0.80	-0.07
Mean High Low Water (MLLW)	0.57	-0.31	0.58	-0.40	0.56	-0.31
Mean Low Low Water (MLLW)	0.46	-0.42	0.48	-0.50	0.46	-0.41
Lowest Astronomical Tide (LAT)	0.24	-0.64	0.24	-0.74	0.24	-0.63

Notes:

1. Compilation 31/10/2016. Datum: Jurien, Lowest Low Tide 1985. 2.136 m below benchmark HLR 117, [formerly titled JUR 2001]. 0.88 m below AHD (2014).
2. Datum: Lancelin, Lowest Low Tide 1976. 2.512 m below benchmark PWD WA, A 420. 0.98 m below AHD (2013).
3. Compilation 21/3/2018, Datum: Two Rocks Lowest Low Tide 1976. 5.468m below benchmark PWD WA A 431. 0.87m below Australian Height Datum (AHD).

The datum conversion to AHD for the Lancelin location was verified with DoT to confirm the conversion from MSL to AHD. The conversion looks inconsistent with the Jurien Bay and Two Rocks locations (MSL to AHD conversion is -0.17m at Lancelin vs -0.08m and -0.07m at Jurien Bay and Two Rocks respectively). The Lancelin AHD datum has been confirmed as correct with tides at DoT. The anomaly of the Lancelin

AHD is attributed to establishment of AHD between the primary tide stations of Geraldton and Fremantle Stations (Lowry 2020).

The tide level adopted in the design cyclone model simulations is MHHW (refer Section 5.4).

3.1.2 Sea Level Rise

Based on the recommendations from DoT 2010, the sea level rise allowance that will be applied to design water levels over the 100-year planning period for this study are summarised in Table 3.2.

Table 3.2: Sea Level Rise Allowance in Future Planning Periods

Planning Year	Sea Level Rise Allowance
2020	0m
2040	0.10 m
2070	0.35 m
2120	0.90 m

3.2 Bathymetric and Survey Data

Table 3.3 summarises the bathymetry and landside survey data available for this study. The key survey and bathymetric sources are shown in Figure 3.1 and Figure 3.2.

Table 3.3: Summary of Bathymetry Data relevant to the study

Description	Type	Date	Comments	Reference
Horrocks to Hillarys and Houtman Abrolhos LiDAR Bathymetric Survey	LiDAR Bathymetric Survey	2016	Highest priority – used to define all nearshore areas from Wedge Island to Yanchep (refer Figure 3.1 Areas named LA,LP,SE,TR)	DoT
Composite Surfaces - Lancelin	Multibeam-LiDAR Laser	Unknown	Used to fill gaps in LiDAR Bathymetric Survey	DoT
Western Australia Two Rocks to Cape Naturaliste Bathymetry and Seabed Survey	Multibeam Bathymetric Survey	2009	Used to define bathymetry in coastal regions from Two Rocks to Cape Naturaliste in the model systems	DoT
AusENC	Soundings and Contours State-wide	2016	Digital Version of Navigational Charts used for offshore areas	Australian Hydrographic Office

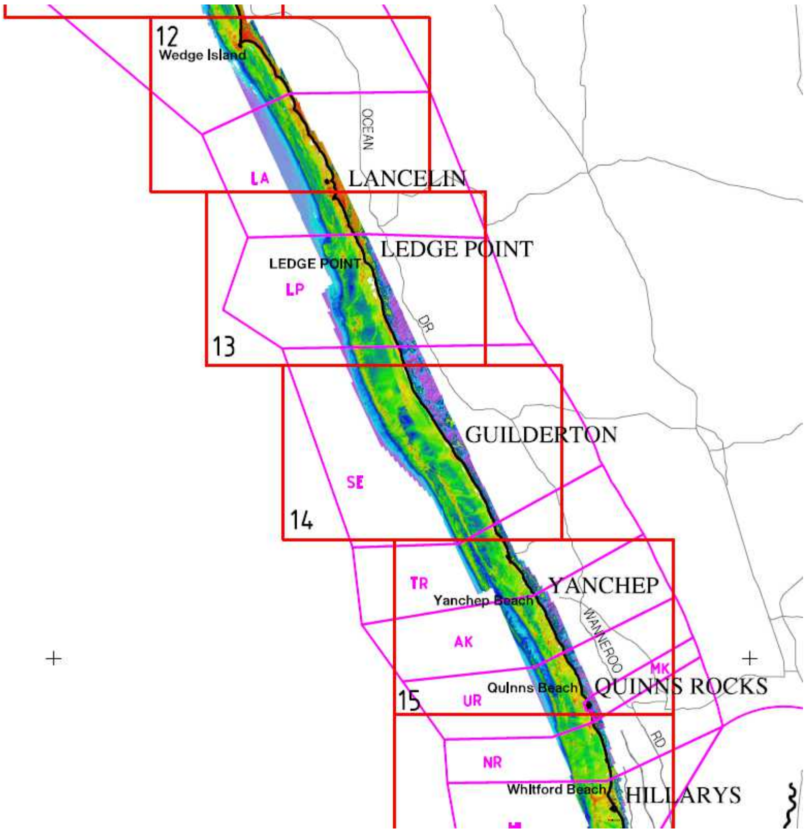


Figure 3.1: Locality of key LiDAR Bathymetric survey data. LiDAR data was made available for blocks; LA, LP, SE and TR (DoT 2016).

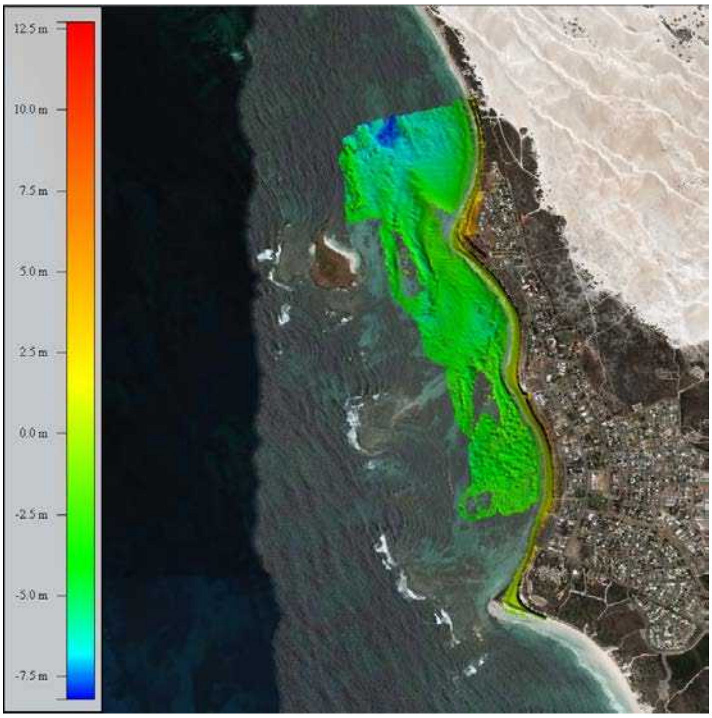


Figure 3.2: Lancelin Composite 32bit survey data.

3.3 Metocean Data

The metocean data available for the coastal inundation study is summarised in Table 3.4. The locality of the metocean data collection sites are shown in Figure 3.3 and Figure 3.4.

Table 3.4: Summary of Metocean data for use in the study.

Site	Lon.	Lat.	Param.	Start	End	Comment	Ref.
Fremantle (Fishing Boat Harbour)	115.748056	-32.065556	Water Level	1986	Present		DoT
Hillary's	115.738578	-31.825535	Water Level	1991	2003		DoT
Jurien Bay	115.042778	-30.287222	Water Level	1991	Present		DoT
Lancelin	115.316667	-31.016667	Water Level	22/6/1993 1/1/2003	29/7/1997 19/7/2012		DoT
Two Rocks Marina	115.568055	-31.494444	Water Level	01/02/2013	11/05/2016		DoT
Ledge Point (Location 4)	115.380917	-31.127144	Water Level, Currents, Waves, Temp.	31/01/2003	2/04/2003	AWAC	DoT
				9/04/2003	1/07/2003	AWAC	
				7/08/2003	2/10/2003	AWAC	
				7/11/2003	13/02/2004	AWAC	
				25/02/2004	19/05/2004	AWAC	
				15/06/2004	16/09/2004	AWAC	
Ledge Point (Location 5)	115.366388	-31.099444		7/08/2003	2/10/2003	AWAC	
				7/11/2003	13/02/2004	AWAC	
				25/02/2004	19/05/2004	AWAC	
				15/06/2004	16/09/2004	AWAC	
Ledge Point (Study)	115.373717	-31.115567		03/04/2017	25/07/2017	AWAC	
				25/07/2017	11/12/2017	AWAC	
				11/12/2017	16/05/2018	AWAC	
Jurien Bay South	115.022883	-30.295517	Water Level, Currents,	29/05/2014	1/10/2014	AWAC	DoT
				1/10/2014	26/02/2015	AWAC	
				26/02/2015	24/07/2015	AWAC	

Site	Lon.	Lat.	Param.	Start	End	Comment	Ref.
			Waves, Temp.	24/07/2015	29/10/2015	AWAC	
				29/10/2015	20/01/2016	AWAC	
				20/01/2016	27/05/2016	AWAC	
				27/05/2016	15/12/2016	AWAC	
				15/12/2016	4/04/2017	AWAC	
				4/04/2017	10/08/2017	AWAC	
				10/08/2017	5/10/2017	AWAC	
Sea Bird	115.434094	-31.244628	Water Level, Currents, Waves, Temp.	30/01/2003	03/04/2003	AWAC	DoT
				08/04/2003	08/07/2006	AWAC	
Two Rocks	115.568055	-31.494444	Water Level, Currents, Waves, Temp.	1/02/2013	12/04/2013	AWAC	DoT
				11/04/2013	5/08/2013	AWAC	
				2/08/2013	21/11/2013	AWAC	
				21/11/2013	27/02/2014	AWAC	
				26/02/2014	6/06/2014	AWAC	
				5/06/2014	15/09/2014	AWAC	
				12/09/2014	5/12/2014	AWAC	
				5/12/2014	15/06/2015	AWAC	
				15/06/2015	9/10/2015	AWAC	
				9/10/2015	4/02/2016	AWAC	
				4/02/2016	11/05/2016	AWAC	
Two Rocks (Marina 3)	115.581367	-31.496033	Water Level, Currents, Waves, Temp.	6/12/2016	28/03/2017	AWAC	DoT
				28/03/2017	20/06/2017	AWAC	
				23/06/2017	14/09/2017	AWAC	
Two Rocks (Breakwater West)	115.576139	-31.487972	Water Level, Currents, Waves, Temp.	6/12/2016	28/03/2017	AWAC	DoT
				28/03/2017	20/06/2017	AWAC	
				20/06/2017	14/09/2017	AWAC	
				14/09/2017	30/11/2017	AWAC	

Site	Lon.	Lat.	Param.	Start	End	Comment	Ref.
Ledge Point LDG45	-31.1347222	115.31444	Wave Param.	5/6/2002	18/10/2004	Non-Dir WRB	DoT
Guilderton Offshore (33m)	115.427778	-31.404722	Wave Param.	11/04/1988	10/02/1989	Non-Dir WRB	DoT
Guilderton Inshore (10m)	115.4819	-31.3597	Wave Param.	Apr/1988	Jul/1989	Non-Dir WRB	DoT
Jurien Bay	115.0336111	-30.292222	Wave Param.	02/01/1998	23/10/2009	Non-Dir WRB	DoT
Jurien Bay	115.0336111	-30.292222	Wave Param.	27/10/2009	31/12/2018	Dir. WRB	DoT

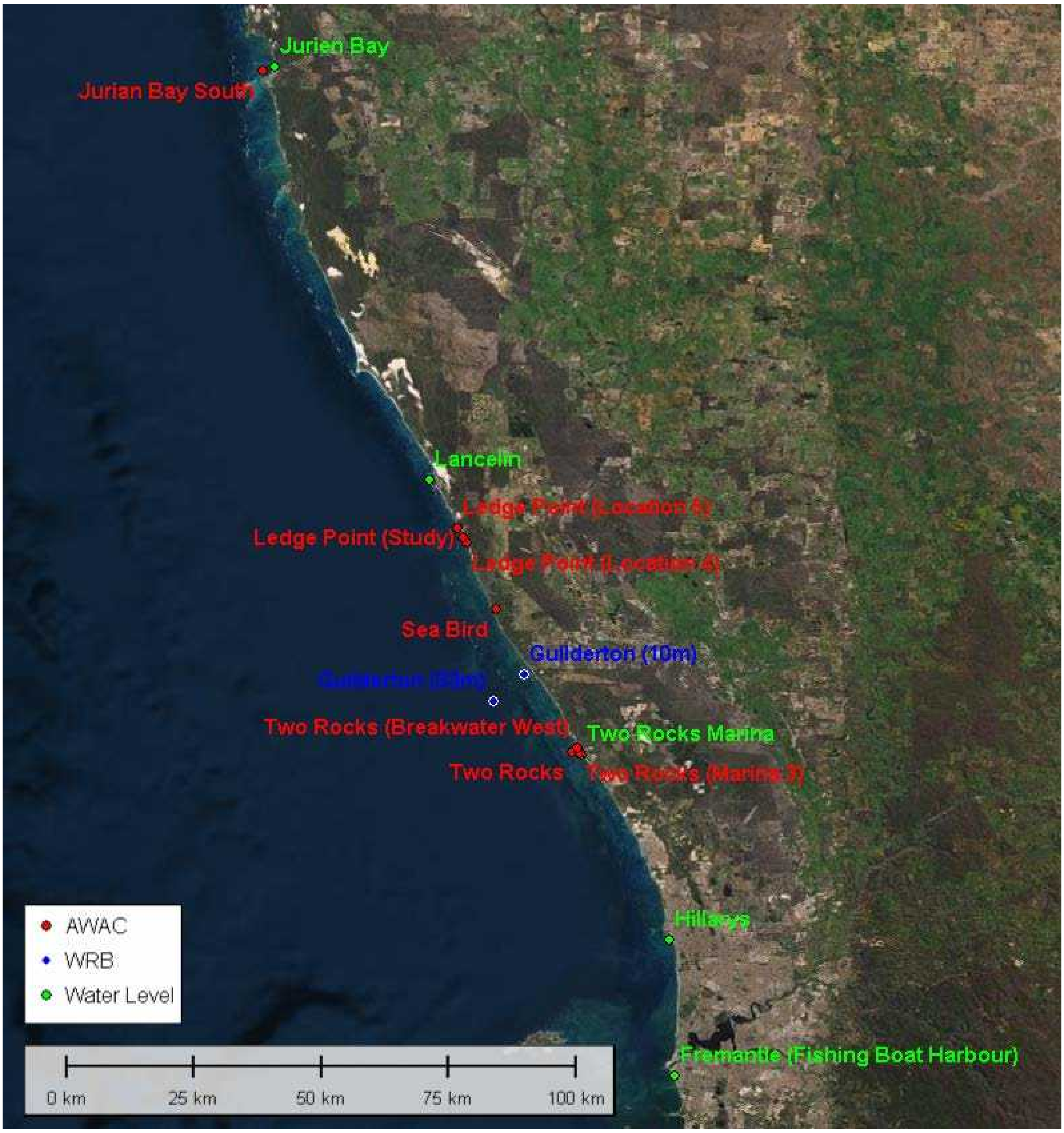


Figure 3.3: Summary of Metocean Data Collection Sites.

Figure 3.4: Summary of Metocean Data Collection Sites Near the Study Area.

3.4 Wind Data

Historical wind data was sourced from the Bureau of Meteorology (BoM) locations around the Gingin study area including Lancelin (station 9114) and Jurien Bay (station 9131).

Wind and pressure data was accessed from the Japanese Reanalysis atmospheric model (JRA-55). Spatial 3-hourly and 6-hourly U and V wind speed components and atmospheric pressure were extracted for the hindcast cyclone events at a 0.56-degree resolution.

4. Numerical Model System

4.1 Model Overview

Baird's established and validated numerical model of the West Australian coast was used as a baseline for this study. This hydrodynamic model system has been applied for a number of similar studies in Western Australia and was developed by Baird using the Deltares numerical model *Delft3D Flexible Mesh Suite* (Delft-FM). The Delft-FM modelling suite has been developed to offer a fully integrated modelling framework for a multi-disciplinary approach in coastal, river and estuarine areas (Deltares 2020). It can carry out simulations of flows, sediment transport, waves, water quality and morphological changes and has been applied in similar studies by Baird to determine waves, water levels and currents in extreme cyclonic conditions. The numerical model applied in this study is comprised of a dynamically coupled hydrodynamic model and wave model driven by a wind model outlined in the sections to follow.

4.2 Wind Model

The wind model adopted in this study is Baird's *Cycwind* model system that adopts a Holland (2010) spatial cyclone vortex model. The cyclone wind field has adopted track parameters from the BoM's best track database (BoM, 2019) with adjustment of the Radius to Gales (R34) and Radius to Outer Closed Isobar (ROCI) parameters to better describe the windfield along the coastal waters of southwestern WA as the system track south. The design cyclone tracks for the Gingin study area presented in Seashore Engineering (2020) are based on the TC Ned track, but experiencing a stronger extra-tropical transition. The scale and fetch of the windfield for a storm undergoing extra-tropical transition is not well described by a parametric vortex model (i.e. Holland, 2010), even when scale parameters (R34, ROCI) are including in the parameterisation. As discussed in Section 2.2.1, extratropical transition adds significant complexity to the spatial characteristics of the storm wind field.

A significant gap in the physics for a transitioning cyclone like TC Ned (a key cyclone for the Gingin study area) is that the impact on surface wind speed as a result of forward speed asymmetry due to the fast translation speed and relatively large scale of storm winds of the storm when it is offshore of the Gingin study area is not well defined. Loridan *et al* (2013) noted that the majority of transitioning tropical cyclones did not exhibit forward speed wind asymmetry. However, the specification of the design cyclone track parameters in Seashore Engineering (2018) lends to the application of a parametric vortex model to model the windfield, even for southwestern Western Australia.

For the Seashore Engineering (2020) design cyclone tracks for Gingin region (Lancelin and Seabird storms), forward speed asymmetry was not included in the modelled wind field due to the scale and speed of the storm being beyond the conditions which tropical cyclone forward speed asymmetry models (including the McConochie (2004) that are adopted in *Cycwind* . For the Gingin area the TC Alby event is particularly difficult to model, with parametric cyclone vortex models not well suited at describing the spatial characteristics of the wind field of an extra-tropical cyclone. For hindcasting TC Alby and TC Ned, JRA-55 hindcast winds were also applied to the storm surge model and generally improved the agreement between modelled and measured water levels and this is consistent with a recently completed CIS completed for a site at Busselton (Baird, 2020a). However, it should be noted that the grid resolution of the JRA-55 (≈50 km) was not sufficient to represent the intensification of TC Ned which occurred as it approved the coastline near the Gingin study area.

4.3 Hydrodynamic Model

The Delft-FM model extent covers the entire west coast of Western Australia from Northwest Cape to Cape Leeuwin as shown in in Figure 4.1. There is varying model resolution, highest along the coastline areas. The model grid was refined spatially from Lancelin to Guilderton and customised for this study. Spatial resolution as fine as 15m was used around Lancelin, Ledge Point, Seabird and Guilderton, with resolutions ranging from 15m to 150m between the towns. The model extent and resolution at the four towns are shown in Figure 4.1.

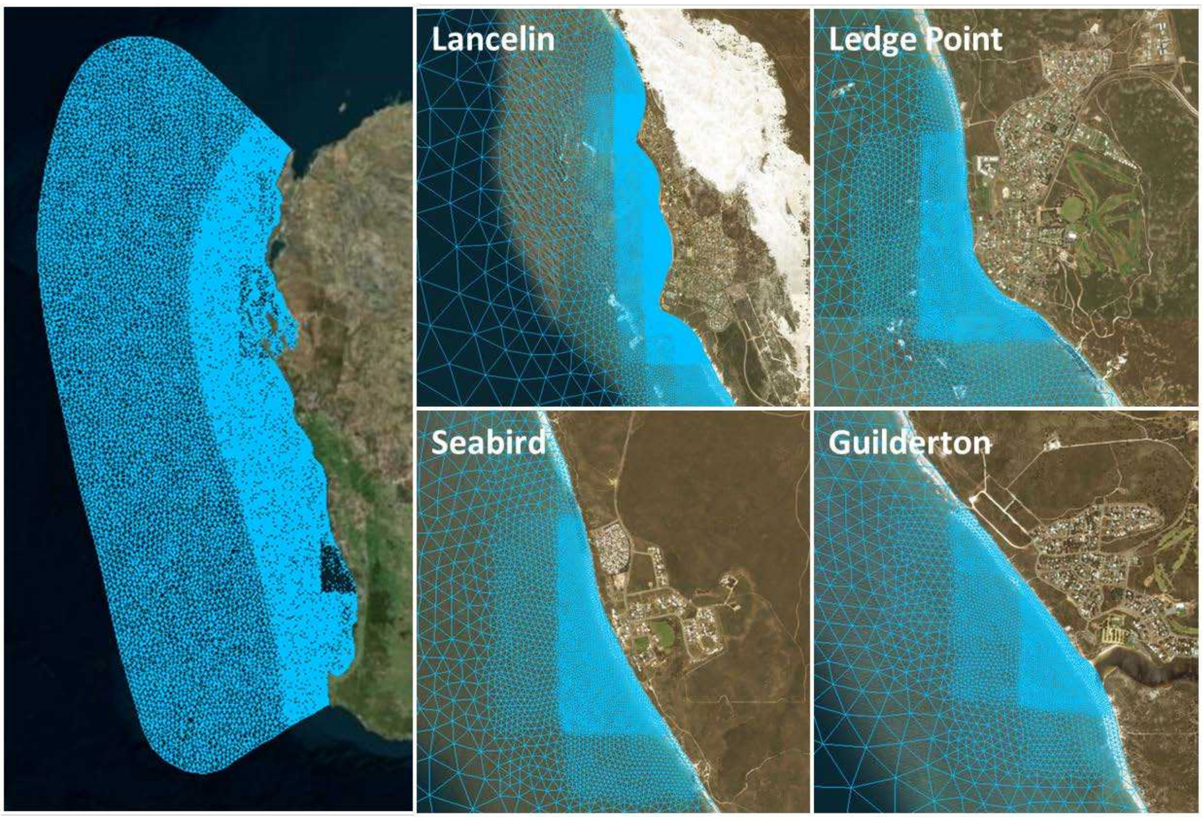


Figure 4.1: Hydrodynamic model grid extent and resolution at Lancelin, Ledge Point, Seabird and Guilderton. The spatial grid resolution increases in the nearshore areas to approximately 15m

It is noted for Guilderton that the Moore River is not included in the model grid extent shown in Figure 4.1. It is expected that coastal inundation levels nearshore at Guilderton in extreme events will dominate over catchment based flooding and these will transfer inside the Moore River at Guilderton in extreme events (further discussed in Section 5.5).

The nearshore seabed areas along the Gingin study region have been defined in the model incorporating the high-resolution bathymetry sets outlined in Table 3.3. Offshore bathymetry has been defined using hydrographic chart data and bathymetric models (Figure 4.2).

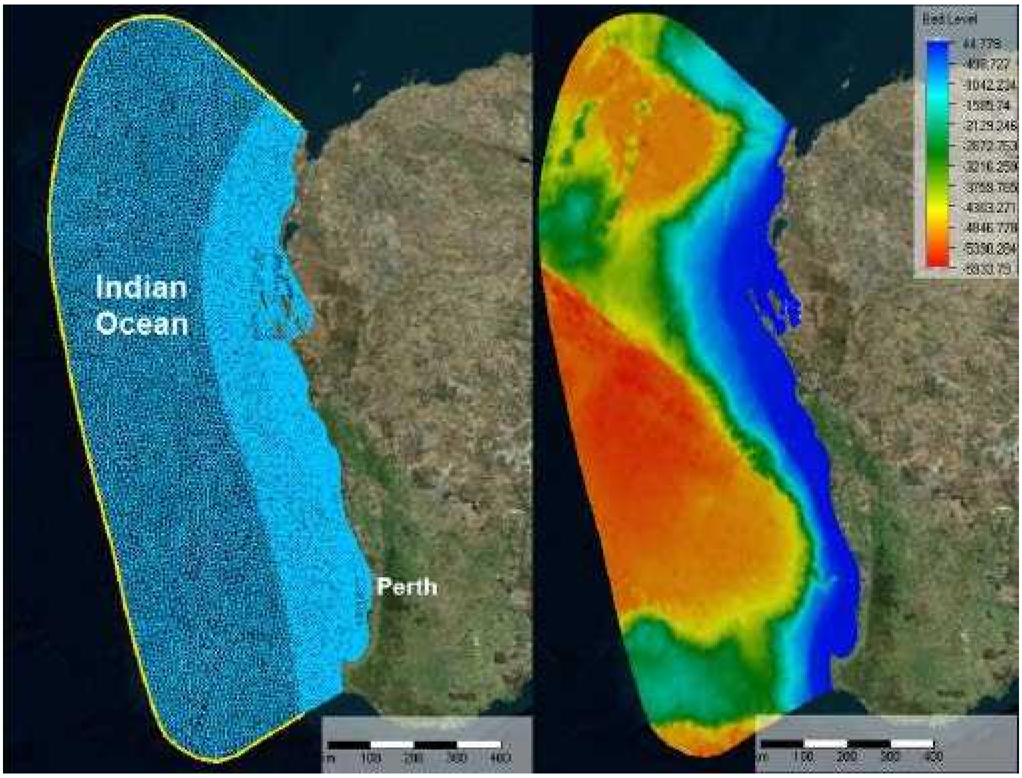


Figure 4.2: Model Bathymetry

4.4 Wave Model

The wave model adopted for the simulation of wave conditions in this study is the industry standard SWAN wave model (Simulating Waves Near Shore) developed at Delft University of Technology in the Netherlands. SWAN is a third generation spectral wave model which computes wave propagation, wave generation by wind, non-linear wave-wave interactions and dissipation, for a given bottom topography, wind field, water level and current field (Deltares 2019).

The SWAN model accounts for (refractive) propagation due to current and depth and represents the processes of wave generation by wind, dissipation due to whitecapping, bottom friction and depth-induced wave breaking and non-linear wave-wave interactions (both quadruplets and triads) explicitly with state-of-the-art formulations. Wave blocking by currents is also explicitly represented in the model (Deltares 2019).

A coupled SWAN model was established across the same extent as the hydrodynamic model, comprised of five nested grids which increase in resolution approaching the Gingin Study area at 5km, 1km, 500m, 100m and 50m resolutions. The positions of the grids are displayed in Figure 4.3 and Figure 4.4.

The bed roughness applied in the model is based on a standard Chezy formulation (U =65 and V =65). The nearshore reef systems along the coast are described in the wave model system in terms of bathymetric changes but specific roughness for the features has not been included in the model settings.

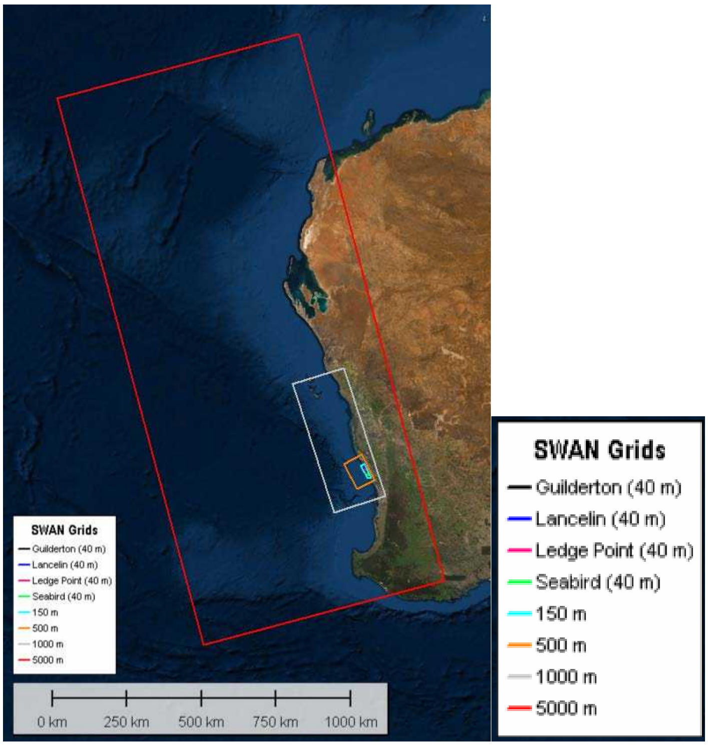


Figure 4.3:: SWAN Model Grid extending across entire D-FM Model Domain (5000m grid size)

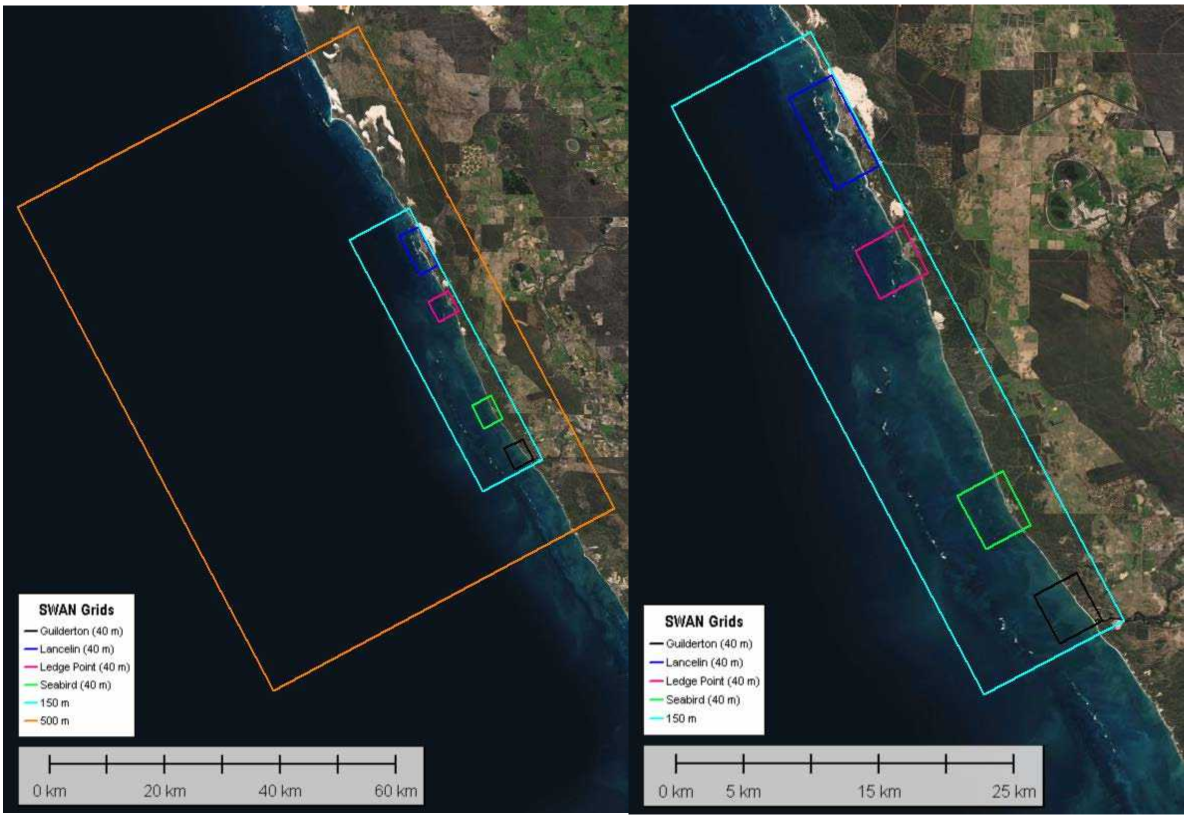


Figure 4.4: Nested SWAN model grids showing Lancelin, Ledge Point, Seabird, and Guilderton.

4.5 Coupled Model approach

The Deltares model system allows for coupling of the wave conditions and hydrodynamics through the duration of a cyclone simulation. The modelling approach is termed FLOW-WAVE-FLOW with the water levels in the model evaluated in the hydrodynamic model (FLOW) and the wave conditions separately evaluated in the waves module (WAVE). Typically, the FLOW-WAVE-FLOW is run with a Delft3D structured or unstructured grid, in this case we have used the Delft-FM (flexible mesh) model for hydrodynamics.

The key processes affecting water level including radiation stresses are passed across and updated in the hydrodynamic model during the simulation. The coupled process runs continuously through the cyclone event to update and interchange wave and water level information. The effect of waves on current (via forcing, enhanced turbulence and enhanced bed shear stress) and the effect of flow on waves (via set-up, current refraction and enhanced bottom friction) are accounted for within this coupled modelling approach (Deltares, 2015).

Spatial wind and pressure fields active over the model domains influence the wind growth of waves and wind/pressure setup of the water level in the hydrodynamics. Spatial wind and pressure fields were updated every 6 hours in the cyclone simulations, and the input forcing the coupling interval of hydrodynamics and waves was set to between 30 minutes (production Cases) and 120 minutes (validation cases).

4.6 Hydrodynamic Model Validation to Tides

For the Gingin study area, the hydrodynamic model was validated against predicted water levels at key locations across the study area based on a one-year simulation of tides (2011). The model validation is shown in Figure 4.5 and shows excellent agreement with time series and validation statistics for modelled and predicted tides from the model at Hillary's, Jurien Bay, Lancelin and Two Rocks Marina. The validation metrics are excellent with little bias and RMS error of about 0.01-0.02 m. The model validation provides confidence the hydrodynamic model can be applied as a basis for the study in the phases to follow.

The validated tide model was applied to examine some key extreme events in the historical record in the next section with the inclusion of wind and pressure in the model simulations. The model performance in reproducing storm surge in extreme events is presented by comparing model performance against measured data where available.

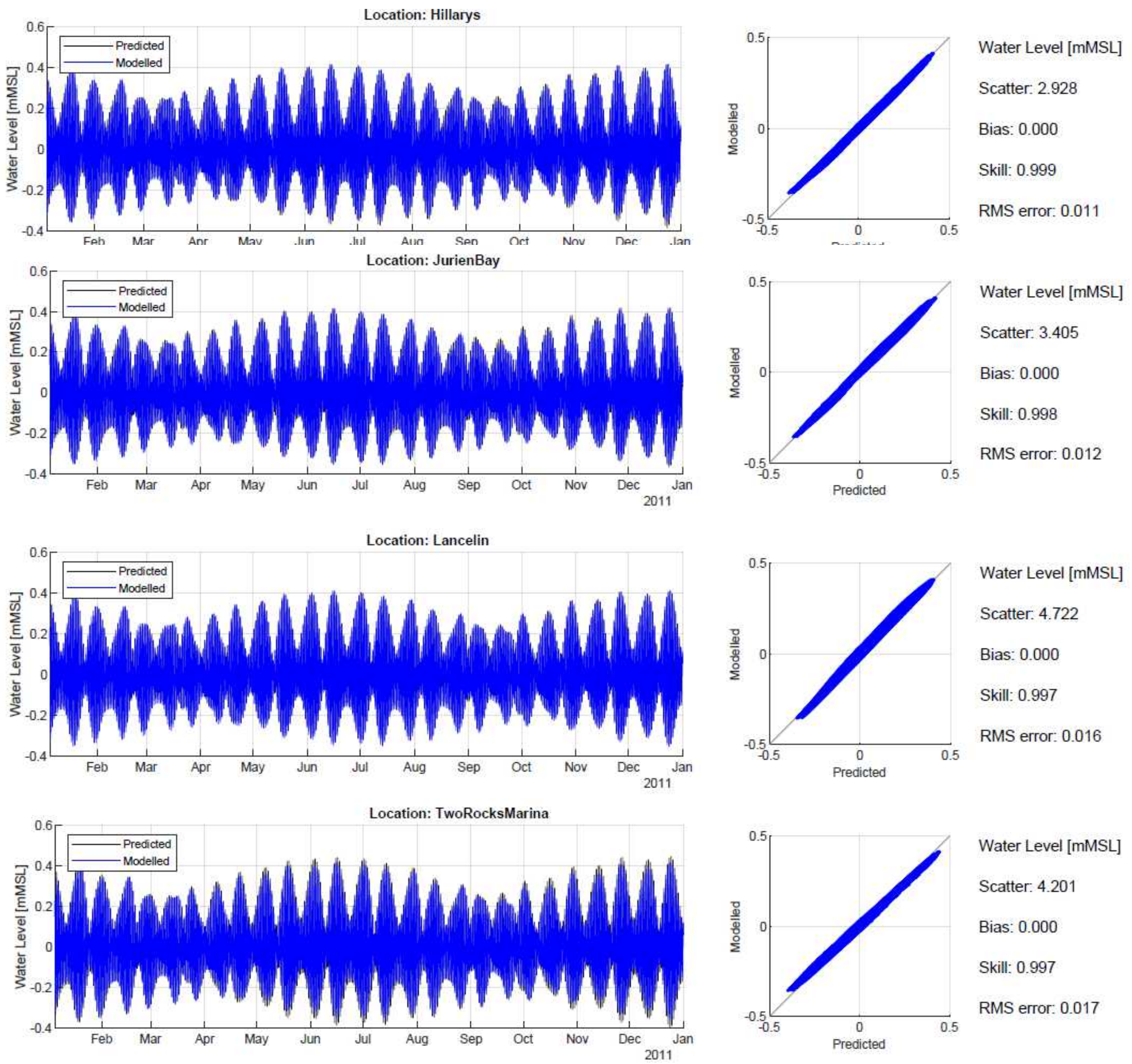


Figure 4.5: Hydrodynamic model validation showing comparison of modelled water level and predicted water level at locations around the study area - Hillary's, Jurien Bay, Lancelin and Two Rocks Marina. Validation Metrics show excellent agreement between modelled and predicted water level at all locations

4.7 Tropical Cyclone Validation Events

The setup and validation of Baird's cyclone storm surge and tide models for the whole of Australia, including Western Australia, is specifically addressed in the following references:

- Burston et al (2015) and Burston et al (2017): Description and validation of Baird's Monte Carlo cyclone track model system and large-scale, high resolution tide and storm surge models.
- Churchill et al (2017): Detailed model validation completed for historical events impacting on Dampier and Karratha resulting in revised wind drag coefficients for wind speeds less than 20 m/s.
- Taylor et al (2018): Summary of the overall Australia wide model including tide and surge model validation Australia-wide.

For this project, the southern Western Australia model presented in has been adopted, with the wind drag coefficients recommended in Churchill (2017). The model has been calibrated with a large number of cyclone events across Western Australia as documented in Churchill et al (2017), Burston et al (2017) and Taylor et al (2018). The modelling of extreme events undergoing extra-tropical transition through the south of the State and application of the model to derive 500yr ARI inundation levels under SPP2.6 requirements was examined in detail for the Busselton location by Baird in 2019-2020.

For the Gingin study area, the model validation for extreme storm cases has been undertaken for four key cyclone events that tracked south and impacted the region. A summary of the historical tropical cyclones follows:

- **TC Alby (27 March – 4 April 1978):** TC Alby formed off the Pilbara coast with an estimated minimum central pressure of 930 mb. During Tuesday 4 April TC Alby accelerated towards the lower west coast as it slowly weakened to an extra-tropical depression. As it passed to the southwest of the continent it caused strong to storm force winds over a large area of the southwest of Western Australia.
- **TC Ned (25 March – 1 April 1989):** TC Ned developed on 26 March well north of the Pilbara coast. Ned intensified reaching category 4 intensity early on 29 March to the west northwest of Exmouth. Ned then weakened owing to increasing wind shear as it moved southwards. A strong mid-latitude trough approaching from the southwest accelerated the remains of Ned to the southeast crossing near Perth on the morning of 1 April. Strong winds were reported at Rottnest Island and in the Rockingham area, and caused power disruptions and isolated roof damage.
- **TC Bianca (21 January – 30 January 2011):** TC Bianca formed offshore of Broome and tracked west-southwest, parallel to the Pilbara coastline. The system intensified, reaching Category 3 intensity at 2 pm AWST 27 January. Bianca then moved southwest and reached a peak intensity of Category 4 at 8 am AWST 28 January. Bianca began to weaken by 2 am AWST 29 January as it moved south over cooler sea surface temperatures and experienced increased wind shear. The system eventually dissipated over open water to the west of Perth, never crossing the Western Australian coastline.
- **TC Iggy (23 January – 3 February 2012):** TC Iggy remained offshore for the majority of its track, weakening to a low pressure system before crossing the coast between Geraldton and Jurien Bay on the 3rd of February 2012. A pronounced tidal surge was recorded at most towns from Onslow to Perth as *Iggy* moved south along the west coast. The peak was 80 cm recorded at Geraldton and 70 cm at Fremantle on 2 February with no apparent damage reported from any locations

It is noted that TC Mangga which occurred in May 2020 occurred at the conclusion of this study and was not analysed in detail as one of the historical storms. A summary of the storm is presented in Section 4.1.5.

Cyclone tracks have been extracted from the Bureau of Metrology's Best Track database and the Japanese 55-year Reanalysis (JRA-55) data. Cyclone tracks are shown in Figure 4.6.

For each of the validation cases, the hydrodynamic model simulations include the general tides (predicted tide) with environmental forcing based on the cyclone track pressure and wind field, along with wave stresses (and consequently wave setup) from a coupled wave model. The modelled water levels through the event are compared against available measured data where this was available in the historical record. The storm surge residual is calculated as the difference between the predicted tide and the actual water level during the event. With the exception of TC Alby, the historical cyclone events presented for model validation have relatively low storm intensity when tracking close to the study area compared to the design events presented in Section 5. A brief discussion of the validation events follows.

The detailed validation cases are presented in Appendix B at the model datum of mean sea level (MSL). For reference, the adjustment to Australian height datum (mAHD) is as follows:

- Fremantle: AHD = MSL - 0.01m
- Jurien Bay: AHD = MSL - 0.08m
- Two Rocks Marina: AHD = MSL - 0.07m

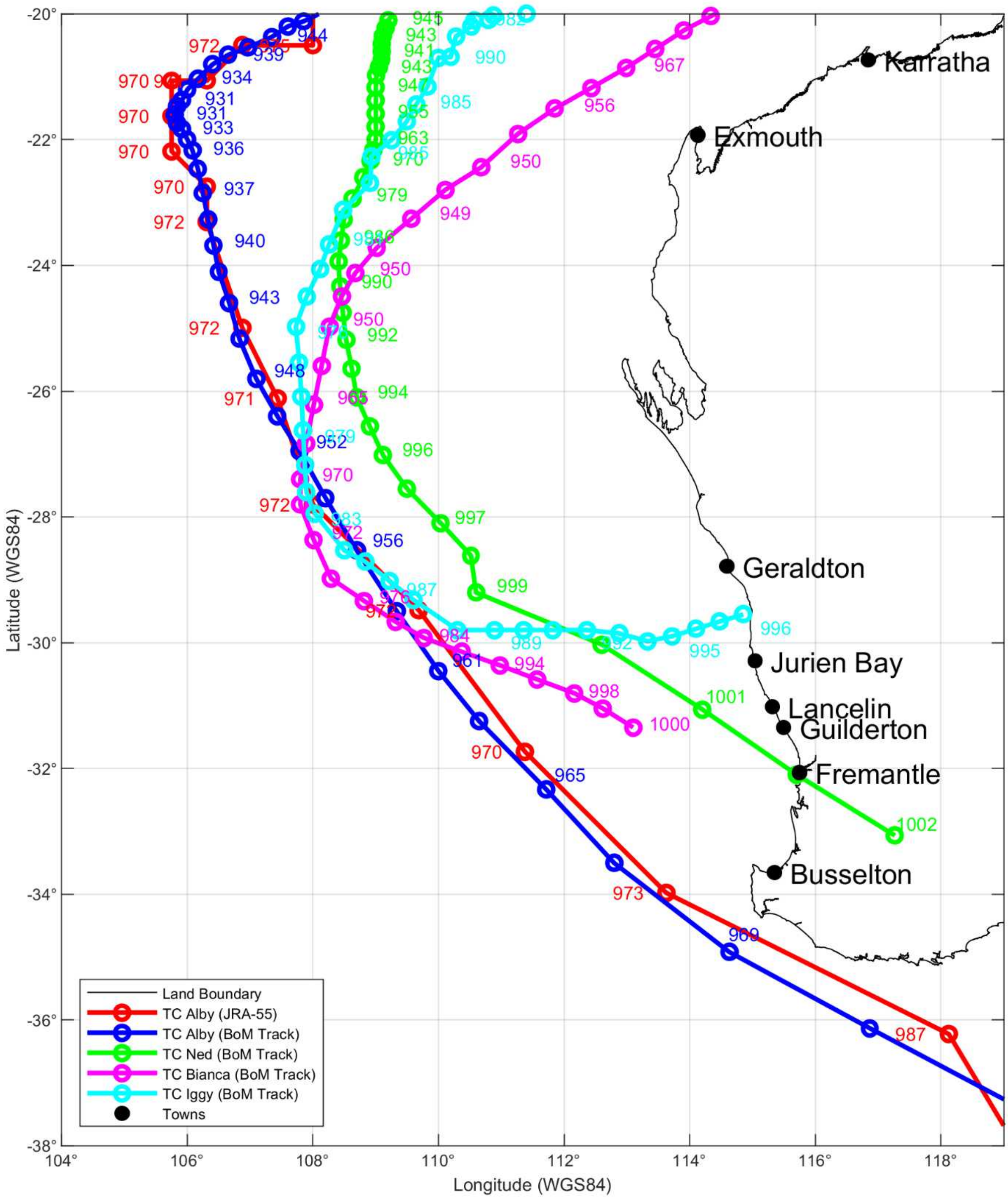


Figure 4.6: Cyclone tracks with central pressure (hPa).

4.7.1 TC Alby (Apr 1978) Model Validation

Measured data was available from Fremantle location only during TC Alby. The model results and validation metrics are presented against the predicted tide at locations across the study area and for Fremantle in Appendix B.1. Whilst TC Alby did not track close to the study area, by the time it reached southern WA, it was a very large-scale storm and storm surge along the southern WA coastline including the study area was significant. Model results indicate a storm surge of approximately 0.5 to 0.7 m across the study site, with larger surge towards the south, which was closer the cyclone track.

Bureau of Meteorology summary reporting of TC Alby (BoM Tropical Cyclone Summary) indicates that as TC Alby tracked down the WA coast there were significant storm surges for the area between Lancelin and Cape Naturaliste. For Fremantle the measured peak water level of approximately 1m above mean sea level (1.8m CD) compares very closely with the modelled (coupled) result in the upper plot of Figure 4.7. The water level residual of 0.8m shown in the lower plot is very closely matched by the model case.

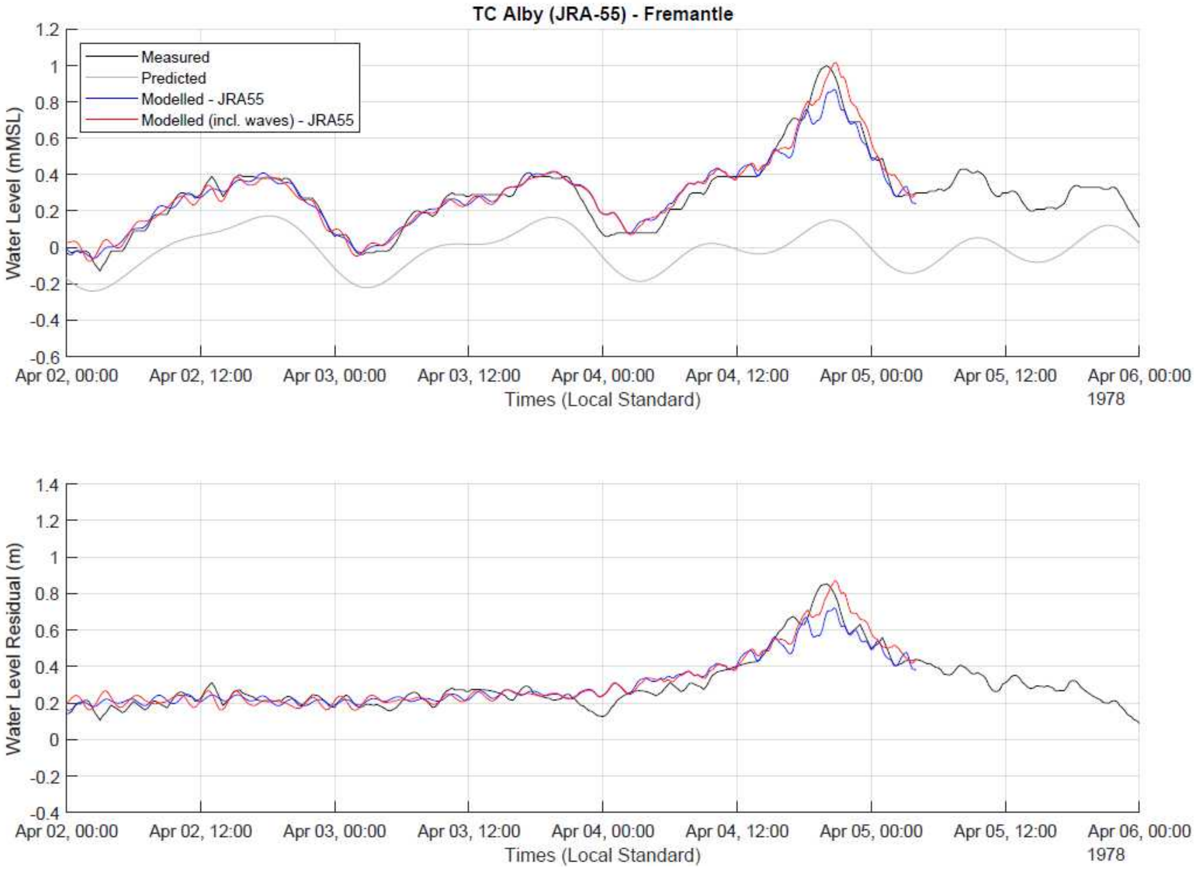


Figure 4.7: Modelled and predicted water level (upper) and water level residual (lower) at Fremantle for TC Alby. Based on JRA-55 data. Datum of Mean Sea Level is 0.01m below AHD.

4.7.2 TC Ned (Mar 1989) Model Validation

For TC Ned, measured data was available at the Fremantle tide gauge. The model results and validation metrics are presented against the predicted tide at locations across the study area and for Fremantle in Appendix B.2.

Since TC Ned had weakened in strength as it reached the southern WA coastline, the parametric cyclone wind field model applied in the simulation of the event was not applicable due to the low intensity of the event. Instead the model was forced with JRA-55 and CFSR wind datasets.

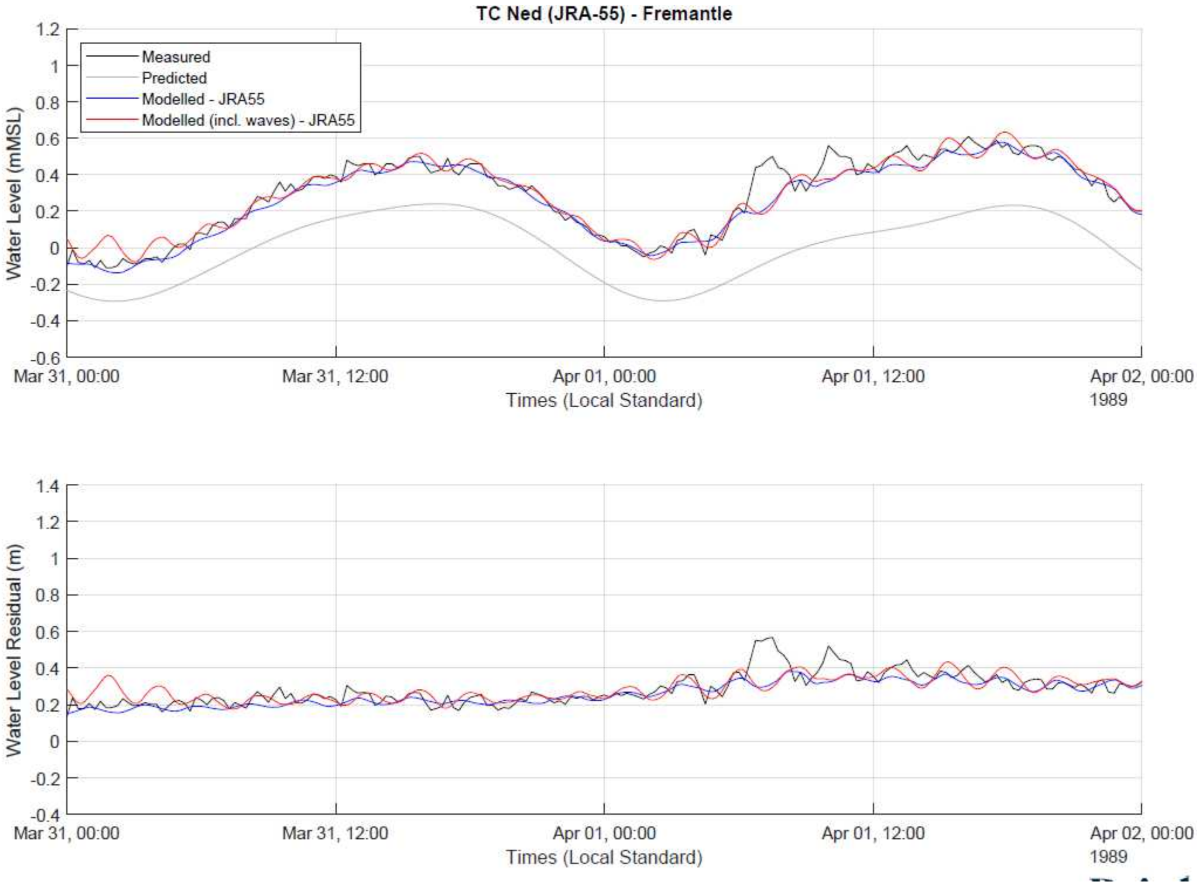


Figure 4.8: Modelled and predicted water level (upper) and water level residual (lower) at Fremantle for TC Ned. Based on JRA-55 data. Datum of Mean Sea Level is 0.01m below AHD.

Based on the model outcomes for the TC Ned case, it is concluded that for low intensity, weakening cyclone events the parametric model is not suited to reproducing a suitable windfield.for the cyclone simulations in the model. However, for the design cyclone cases that will be recommended for application in this study (eg 100yr ARI and 500yr ARI event), the cyclone wind field model will be suitable as these will be a more intense cyclone that can be described by a parametric wind model.

4.7.3 TC Bianca (2011) Model Validation

For TC Bianca water level measurements were available at Fremantle, Lancelin and Jurien Bay. The model results and validation metrics are presented against the predicted tide at locations across the study area and for Fremantle in Appendix B.3.

Similar to TC Ned, TC Bianca had weakened by the time it reached the southern WA coastline and hence the parametric cyclone wind field model is not suited to reproducing a suitable windfield.for the cyclone, so the modelled winds were derived from the high resolution CFSR dataset. The model comparisons of the peak storm surge from the model vs measured data at Fremantle, Lancelin and Jurien Bay showed the model was underpredicting the peak storm surge by approximately 0.3m. For this case the winds are taken solely from CFSR and its likely the wind and pressure in the CFSR dataset for TC Bianca are not a good representation of the actual event. CFSR has known limitations in the nearshore region due to the land sea interface and this is likely affecting the wind and pressure inputs for TC Bianca.

4.7.4 TC Iggy (Feb 2012) Model Validation

For TC Iggy water level measurements were available at Lancelin, Fremantle and Jurien Bay. The model results and validation metrics are presented against the predicted tide at locations across the study area and for Fremantle in Appendix B.4.

TC Iggy also had weakened by the time it reached the southern WA coastline and hence the cyclone wind field model is not suitable for application in the model, so the modelled winds were derived from the high resolution CFSR dataset.

Measured water levels at Lancelin are compared to modelled water levels in Figure 4.9. Comparisons to the measured data show a close agreement through the peak of the storm surge of approximately 0.6 m at Lancelin.

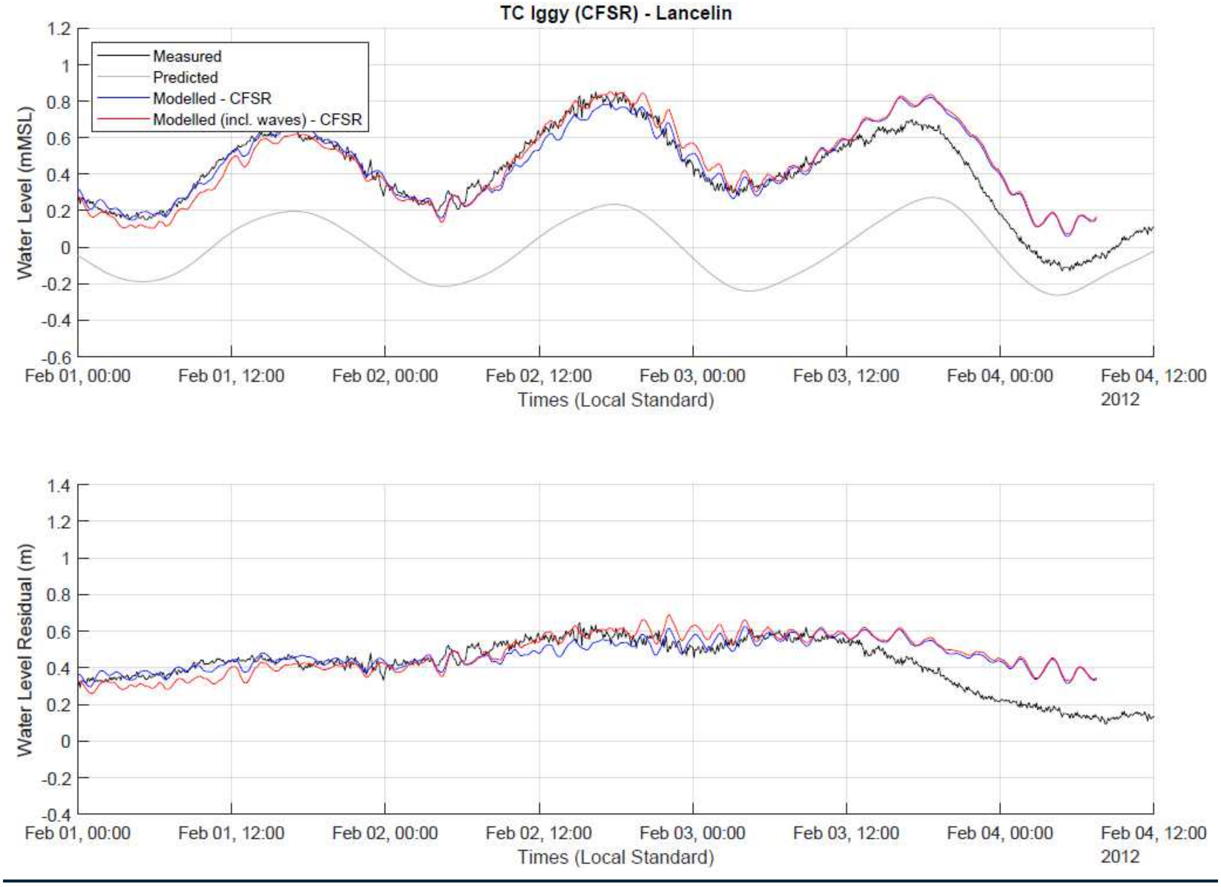


Figure 4.9: Modelled and predicted water level (upper) and water level residual (lower) at Lancelin for TC Iggy 2012. Based on CFSR data. Datum of Mean Sea Level is 0.07m below AHD.

4.7.5 TC Mangga (May 2020) Overview

The TC Mangga storm which occurred in May 2020 was an ex-tropical cyclone that tracked south and interacted with a frontal system in the southern Indian Ocean to produce extreme winds, waves and water levels for the entire west coast of western Australia.

The satellite image for the event is presented in Figure 4.10 and shows the extent of the storm across the Western coast of Australia.

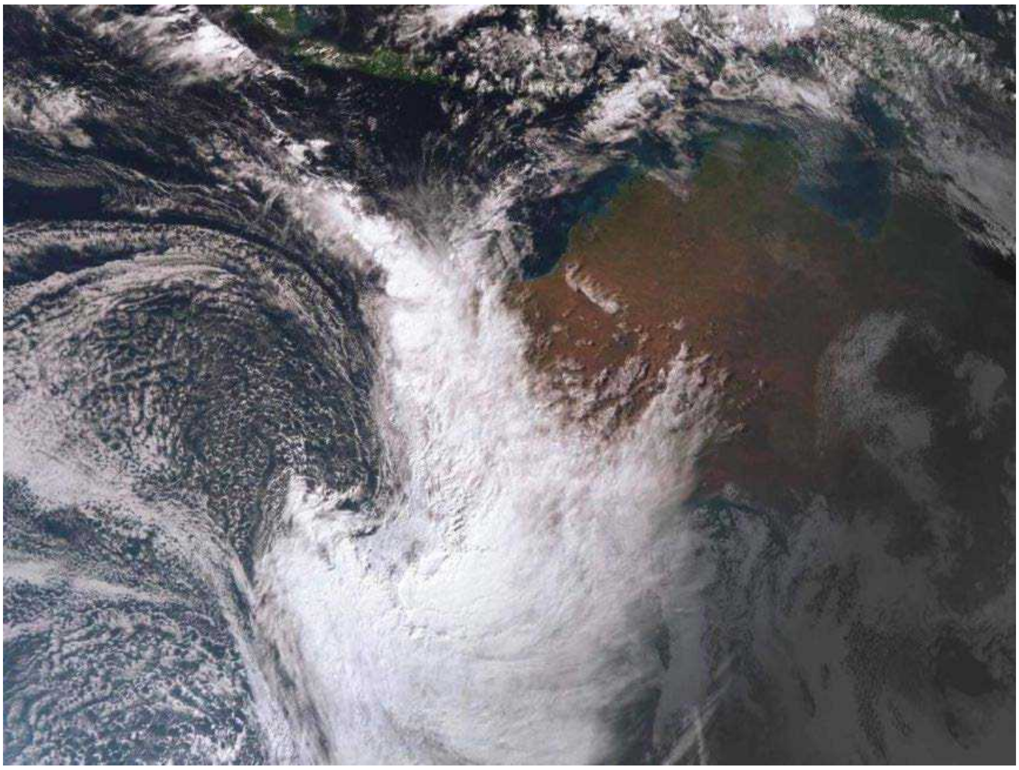


Figure 4.10: TC Mangga satellite image (ABC 2020, sourced from BOM)

For the section of coast through the study area of Gingin, the water levels through the event were captured by the DoT tide gauges at Jurien Bay to the north and Two Rocks to the south.

- The peak water level measured at Jurien Bay just north of the Gingin study area was at 10.30am on 25th May 2020 as 1.18m AHD (2.06m CD). This is the highest water level ever recorded at Jurien Bay over the approximate 30-year period the tide gauges have been active. At the time of the peak water level there was a residual of approximately +0.75m above the predicted astronomical tide level (i.e. the increase in the measured tide level above the normal astronomical tide level). The peak residual (surge) occurred a few hours earlier and was approximately +0.84m (DoT 2020a); and
- At Two Rocks to the south of the study area the tide gauge did not capture the peak of the event due to instrument failure, however the tide gauge showed that in the lead up to the peak that there was a residual of approximately +0.7m (DoT 2020b).

The analysis of the measured water level data through the event at Jurien Bay is shown in Figure 4.11 (DoT 2020a). The DoT real time system data from Two Rocks is shown in Figure 4.12 (DoT 2020b).

The measured wave conditions from the DoT real time system offshore of Jurien Bay at the peak of the storm showed wave heights around 7.5m with a mean wave period of approximately 11s (H_s=7.5m, T_m=11s). The peak significant wave height through the event of 8.2m was measured at 1:56pm on 25 May 2020 (DoT2020a). This is the highest significant wave height on record at Jurien Bay.

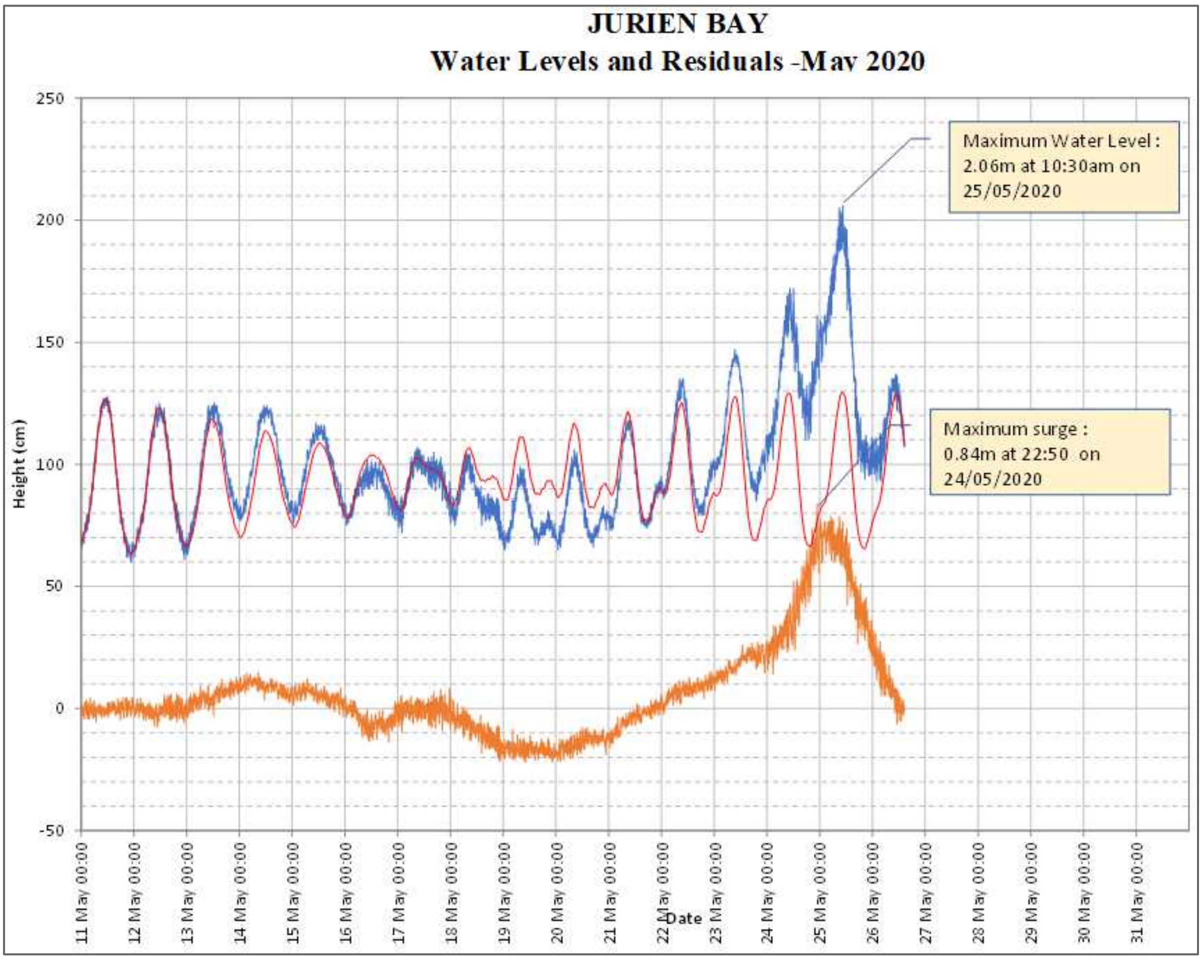


Figure 4.11: Analysis of the Jurien Bay tide gauge data through peak of TC Mangga in May 2020 showing the measured water level, predicted water level and residual (DoT 2020a).

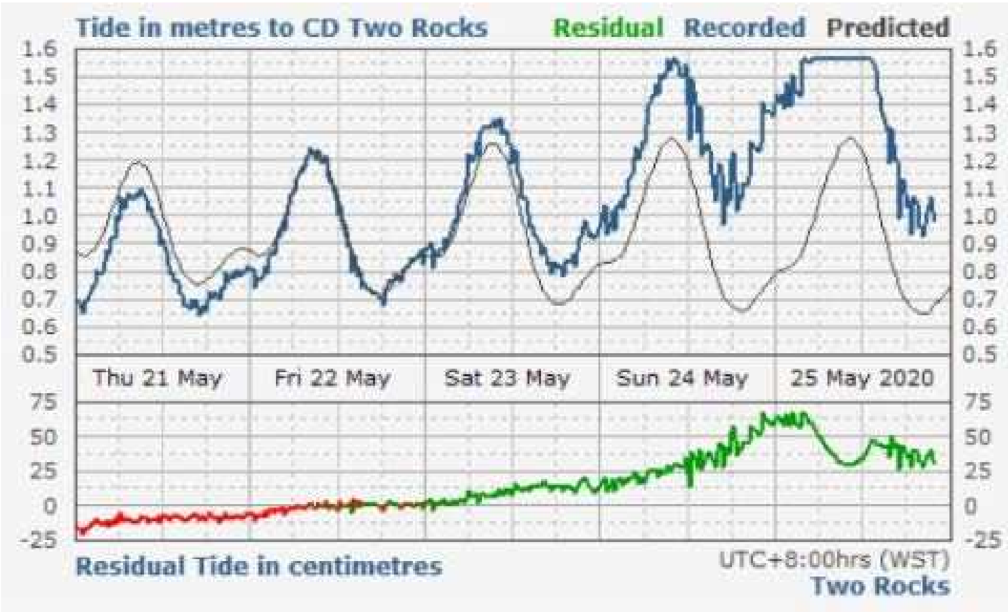


Figure 4.12: Measured tide gauge data at Two Rocks through TC Mangga in May 2020 (DoT 2020b).

For the study area, the TC Mangga event impacted the shorelines through Gingin bringing elevated water levels and large waves. High water levels and localised erosion occurred through Lancelin with images from Grace Darling Park shown in Figure 4.13. Elevated water levels along the Lancelin shoreline are shown in Figure 4.14 for locations at the jetty and Edward Island Point track.

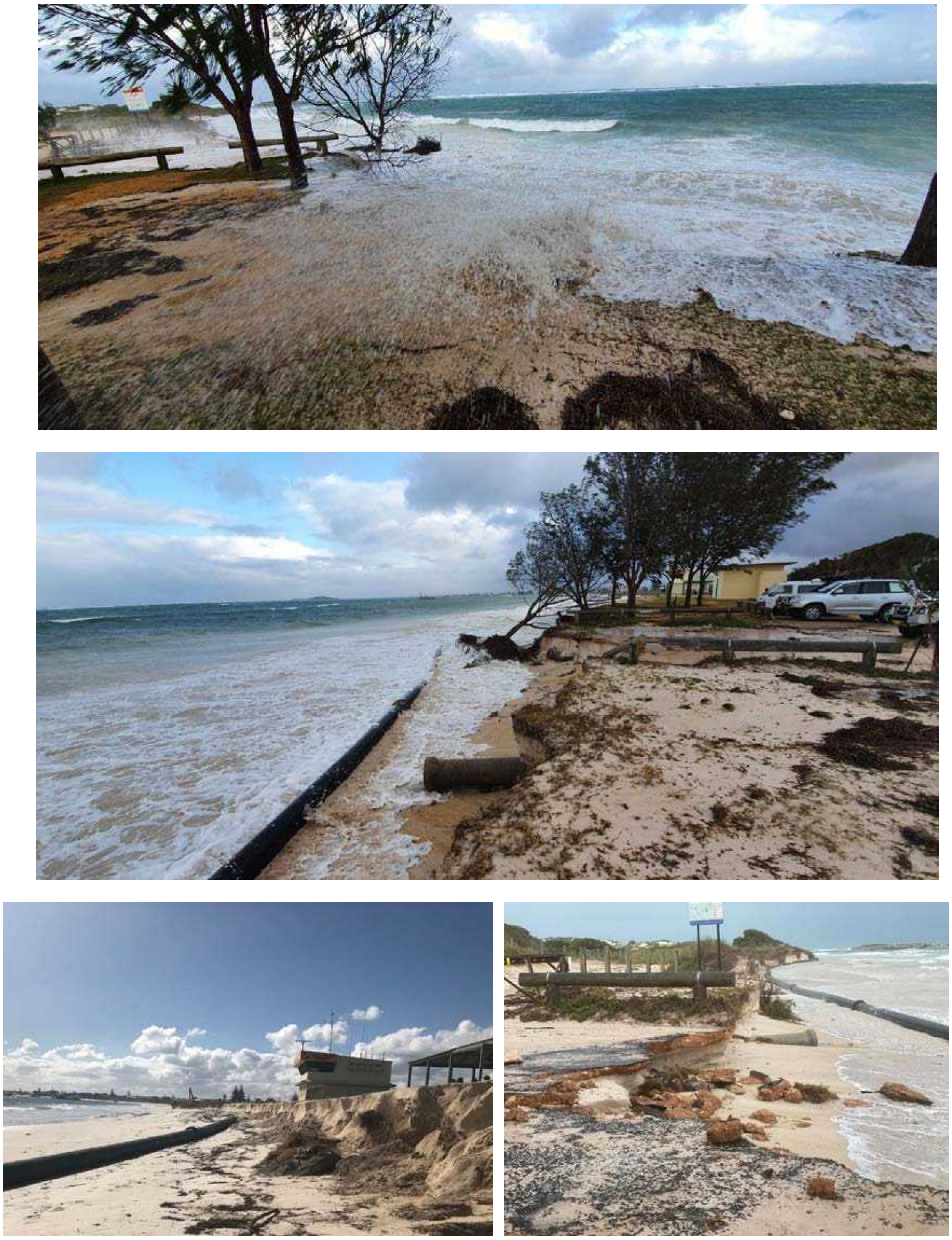


Figure 4.13: Upper image and middle Image: Grace Darling Park, elevated water levels through peak of storm, 25 May 2020. Lower image: post storm showing erosion scarp at Grace Darling Park and Edward Island Track. Images provided by Shire of Gingin and Lancelin Facebook Site

Figure 4.14: Images from Lancelin during TC Mangga storm showing elevated water levels at the jetty (upper image), Hopkins Street Track (centre Image) and Edward Island Track (Lower Image). Source. Images provided by Shire of Gingin and Lancelin Facebook Site

5. Design Event Selection

In developing a 'design' storm for coastal inundation along the Gingin study sites consideration of the following three datasets has been undertaken:

1. DoT design storm reference based on TC Ned (Seashore Engineering, 2020);
2. Baird's 10,000 yr cyclone track data set (Taylor et al, 2018); and
3. Hybrid storm event based on data from the JRA-55 model

5.1 Department of Transport Design Storm Events

Figure 2.2 and Figure 2.3 present the design storm tracks for a 500-yr ARI inundation event (based on historical event TC Ned) prepared for the DoT and presented in Seashore Engineering (2020). Appendix A.1 presents the track parameters for those events as defined in Seashore Engineering (2020). Both of those storm events have been modelled with the coupled hydrodynamic and wave model presented in the previous sections.

Seashore Engineering (2020), nor earlier documents including Seashore Engineering (2018) describe the specific derivation of the design cyclone tracks for the 500-year inundation track from the original TC Ned track. Table 5.2 presents a summary of the TC Ned track data available from the Bureau of Meteorology, the 500yr ARI DoT inundation track data presented in Appendix A, and the 500yr ARI event from the Baird Monte Carlo data base (see Section 5.2). It is noted that approaching the coast between the Gingin study area and the Perth northern suburbs, TC Ned experienced extra-tropical transition and intensified compared to early track positions further north. The assumed extra-tropical transition in the 500yr ARI event tracks are critical to the intensity and scale of those design events.

5.2 Baird Monte Carlo Cyclone Track Model

Baird's Monte Carlo data set (Taylor et al, 2018) for Australia representing a 10,000-year climatology of cyclone tracks has been analysed to identify synthetic storm events that generate storm surges with return periods between 100 and 500 years ARI.

Baird's Monte Carlo cyclone track model extend the historical record with simulated events using a stochastic-based modelling approach. Such approaches have been applied in the USA and Australian context for several years, e.g., Vickery et al (2000a, 2000b; James and Mason 1999).

Baird Australia's Monte Carlo cyclone track model covering the Australian cyclone region (90 °E to 160 °E, 10 °S to 40 °S) is based on the Bureau of Meteorology historical best track database using cyclone tracks recorded in the post-satellite era (1960/61 to 2014/15 seasons). The operation and validation of this model has been presented in Burston et al (2015) and Taylor et al (2018). The validation shows good agreement between the Monte Carlo model and the historical climatology over the northeast Indian Ocean (Figure 5.1).

Further, the incidence of tropical cyclone landfall along Western Australia coastline in the Monte Carlo model verifies well against the historical climatology. In the context of this study, the study area is near the boundary of Sectors 5 and 6 in Figure 5.2. The modelled landfall crossing in Sector 5 agrees well with the historical best track data set whilst for Sector 6 the median modelled landfall frequency is lower than the historical data set but the historical data landfall is within the 95% confidence interval model.

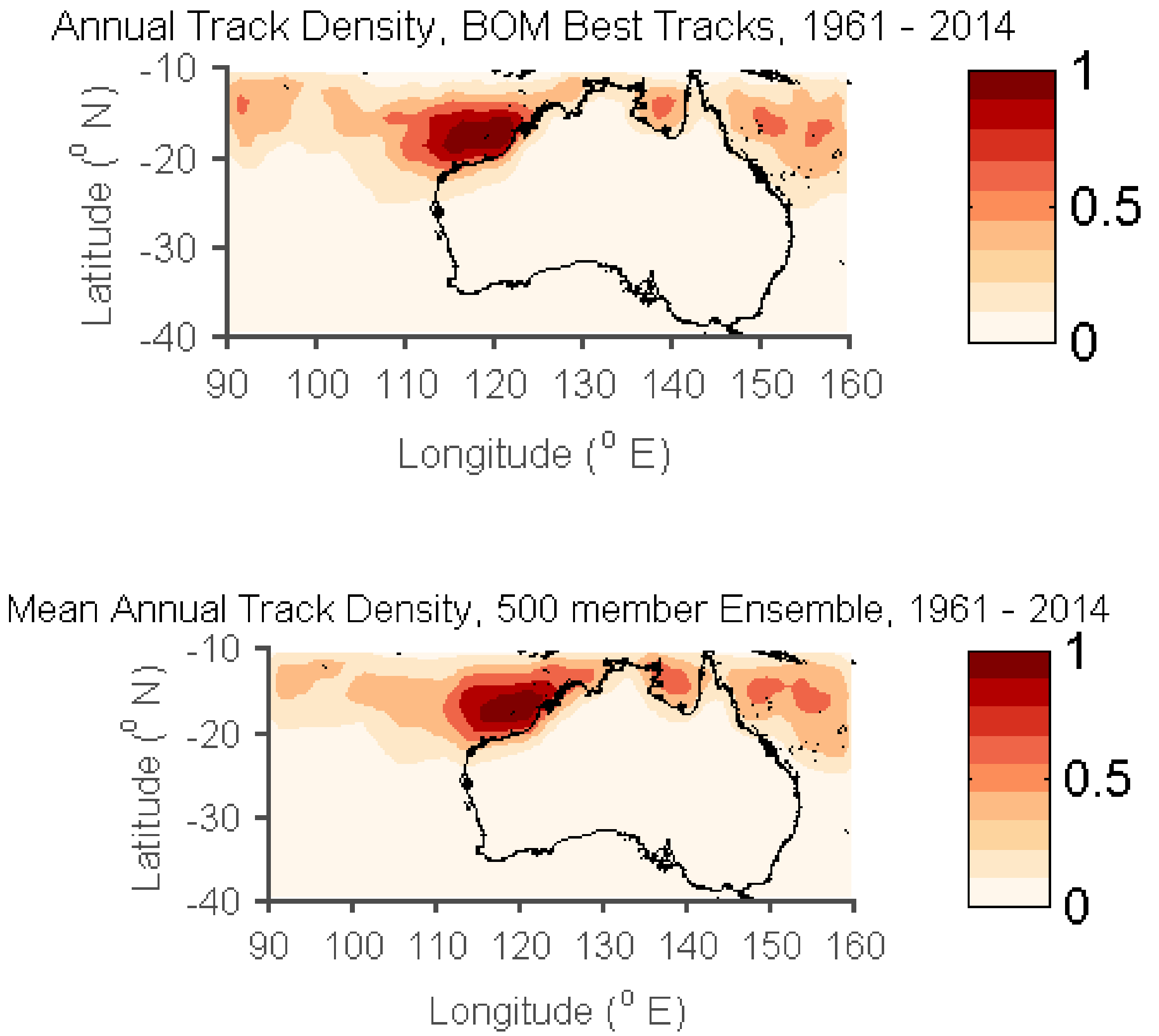


Figure 5.1: Comparison of (upper) measured and (lower) mean modelled track density of tropical cyclones in the Australian region.

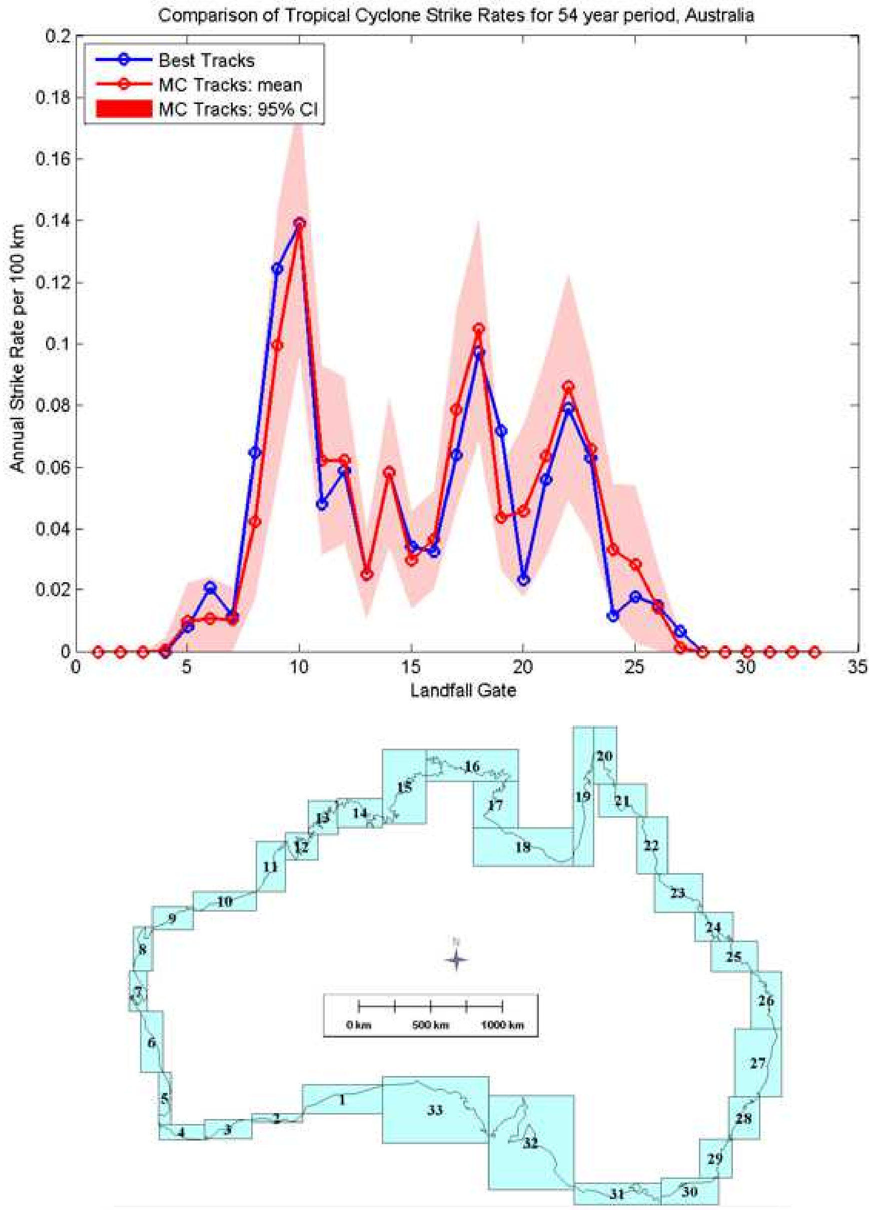


Figure 5.2: (Upper) Comparison of landfall incidence along the Australian coastline: measured (blue) BOM best track dataset: 1960/61 – 2014/2015 and modelled (red) 500-member ensemble of the Monte Carlo track model for a corresponding time period. (Lower) Coastal crossing 'gates'.

Focusing on the largest storm surge events in the study area, the Monte Carlo data set had a higher frequency of coast 'parallel' cyclones that generated large storm surges between Guilderton and Lancelin. A design cyclone track was selected based on modelled storm surge at the four focus areas of this study (Lancelin, Ledge Point, Seabird and Guilderton) and examining the track parameters for all events within 150 km of the coastline in the study area. This criterion identified approximately 400 unique storm tracks over a 10,000 year period representing a frequency of a cyclone event every 25-years on average with an intensity of Category 1 or higher. It should be noted, the event frequency in the Monte Carlo data set was not used to directly assign design cyclone tracks. To select a representative design cyclone event, the Monte Carlo data set was analysed in three steps:

1. The step first involved reviewing the cyclone tracks of the top 20 storm surge events in the data base as presented in Figure 5.3. The track analysis indicated that coast parallel tracks dominated the top 20 events in the database (≈67% of tracks) and that there was a particular event which had a coast parallel track that was positioned off the coastline to result in the maximum wind speeds being generated near the coastline along the length of the Gingin study area. This event (MC ID 67197, see red line Figure 5.3) had a return period of between 500 and 1000 years ARI based on the Monte Carlo data set with a central pressure near Lancelin of 958 hPa. The scale parameters of the storm included a Radius to Maximum Wind (RMW) of 33 km, and a radius to gales (R34) of ≈200 km.

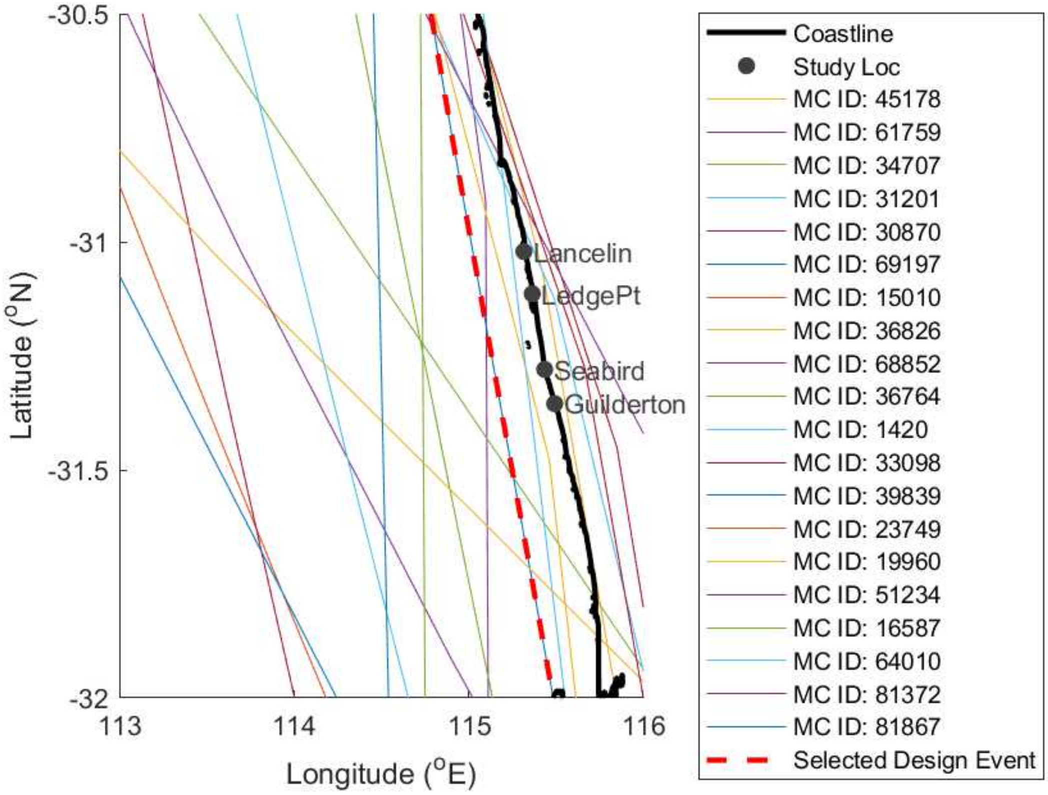


Figure 5.3: Top 20 Monte Carlo (Taylor et al, 2018) storm surge events for the Gingin study area with the selected design event (red dashed line)

2. The second step in the cyclone selection was to analyse the central pressure distribution for all Monte Carlo cyclones within 150 km of the study area and complete an Extreme Value Analysis for relatively frequent (20 to 50 yrs ARI) and extreme events (>= 100 yrs ARI) and compare the Monte Carlo data set with the post-satellite era Bureau of Meteorology track data (1970 to 2019). The post-satellite era Bureau of Meteorology track data had limited track events within 150 km of the study area, and as a result the analysis region for historical data was expanded to within 250 km.
3. The third step was to select scale parameters for the design Monte Carlo track including Radius to Maximum Winds (RMW), radius to gales (R34) and Radius to Outer Closed Isobar (ROCI). The Monte Carlo data set was analysed for all events within 150 km of the study area and 75th=percentile (25% probability of exceedance values were selected for all scale parameters based on events that were of similar central to the specific design event. The scale parameters for the design cyclones is presented in Table 5.2.

The design track selected is MC69197 shown in Figure 5.4 and this was adopted for the 20, 100 and 500-years ARI events.

Table 5.1: Comparison of historical (BoM Best Track) and Monte Carlo cyclone minimum central pressure near the study area (bold values indicate central pressure adopted for design events – see Table 5.2)

ARI (yr)	BoM Best Track (1970-2019): 250 km of study area (n=12)	Monte Carlo Data Set (10000 yr): 150 km of study area
10	995	1000
20	992	**994**
50	987	990
100	985	**985**
500	`N/A	**967**

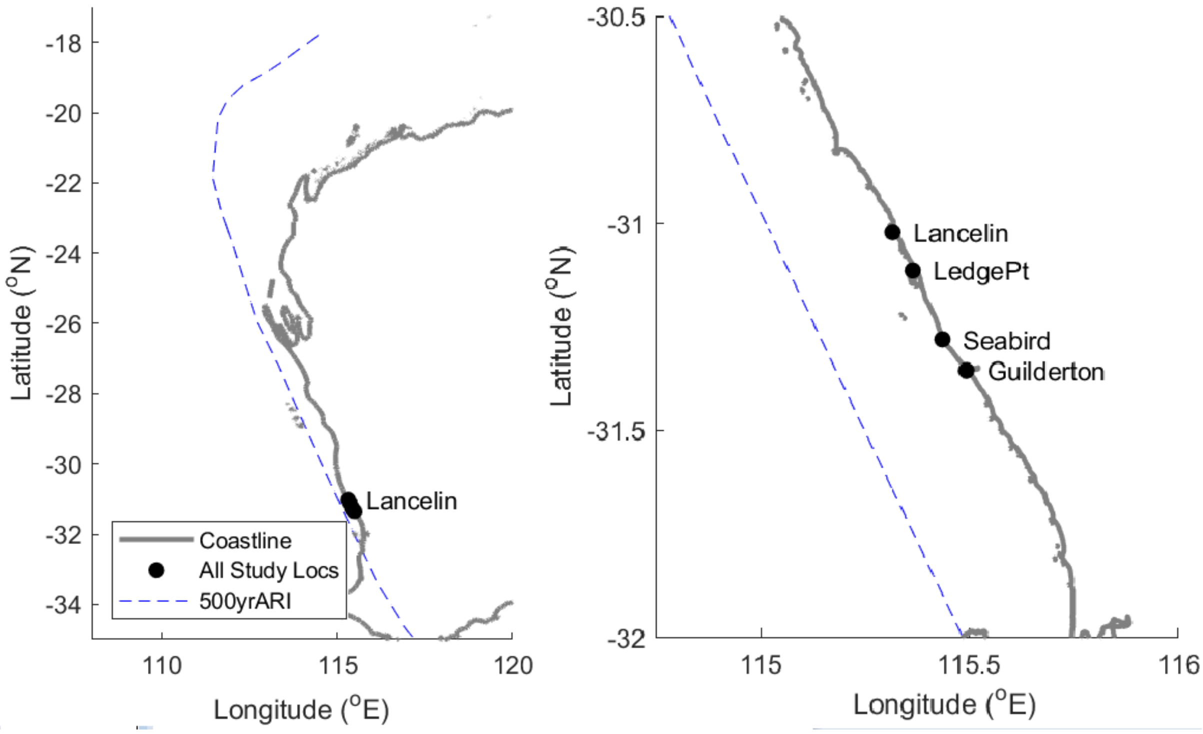


Figure 5.4: Baird MC Database – 500-yr ARI Inundation Event (MC69197)

The intensity and track parameters of the synthetic cyclone track (MC69197) are presented in Table 5.2. For reference the DoT design track based on a 'Worst Case' TC Ned is also presented (Seashore 2020). There is good agreement for the 500-year ARI event between the Baird synthetic event, and the DoT design inundation track for central present and peak wind speed, excluding forward speed asymmetry. Baird synthetic event is a relatively tight radius cyclone which has a storm scale that it is appropriate to include forward speed asymmetry in the calculation of Maximum Sustained Wind.

In Table 5.2, the Baird MC event (69197) has a MSW which includes forward speed asymmetry based on the McConochie (2004) model whereas the DoT design inundation track does not add forward speed asymmetry based on Loridan *et al* (2013) which estimated that 67% of transitioning tropical cyclones did not exhibit a forward speed asymmetry as normally defined for a tropical cyclone (i.e. forward right quadrant for southern hemisphere – see Section 2.2.1)

The DoT track has a very large radius to maximum winds whereas the Baird track has the eye passing close to all the study locations (see Figure 5.4).

Table 5.2: Summary of design cyclone intensity and scale parameters – Baird MC and Seashore Engineering (2020) track.

ARI (yr)	Reference Event	CP (hPa)[c]	MSW (m/s)[c]	Fwd. Spd. (m/s)[c]	RMW (km)[c]	R34 (km)[c]	ROCI (km)[c]	Min. Dist. Study Site (km)[c]
20	69197	994	31.6[a]	13.6	44.7	140	350	28
100	69197	985	38.6[a]	13.6	44.2	155	400	28
500	69197	968	46.6[a]	13.6	43.9	198	500	28
500	Seashore 'Worst Case' TC Ned	972.8	36.7[b]	20.0	180	630	N/A	180
-	TC Ned	1001[d]	23.2[b, d]	20.0[d]	N/A[d]	N/A[d]	500[d]	≈70[d]

a. Including forward speed asymmetry.

b. Forward speed asymmetry not added to event undergoing extra tropical transition.

c. Abbreviations: CP = Central Pressure, MSW = Maximum Sustained Wind speed, Fwd Spd. = Forward Track speed, RMW = Radius to Maximum Wind speed (from eye location), R34 = Radius to Gale Force wind speed (from eye location), ROCI = Radius to Outer Closed Isobar (from eye location).

d. Tropical Cyclone Database (BoM, 2019). Reference at time 21:00 31/03/1989 UTC. Position: Longitude 114.8, Latitude -31.5. Noted as event undergoing extratropical transition and developing intensity from earlier track positions.

5.2.1 Consideration of TC Alby as a Design Event

Consideration has been given to modelling a shifted TC Alby as a potential design event. The historical track of TC Alby is presented in Figure 5.5. TC Alby tracked approximately 480 km west of the study area and had a central pressure at a latitude of -31°S of 963 hPa. This resulted in a maximum sustained wind speed of approximately 43 m/s. TC Alby was undergoing extra-tropical transition at the time it tracked offshore of the study area. TC Alby was able to maintain its intensity as it tracked south of the tropics in part due to its offshore track. The design cyclones presented in Seashore Engineering (2020) have cyclones losing intensity events track closer to the coastline.

Based on Baird's previous modelling of TC Alby, it is not considered to be a realistic event to track shift close to the study site without also assuming a significant reduction in cyclone intensity. The 'Worst Case' TC Ned is also presented (Seashore 2020) as presented in Figure 2.2 and Figure 2.3 are more appropriate for the study area. However, as noted in Sections 2.2.2.1 and 4.2, a parametric wind field model is not well suited to modelling the spatial wind field for a transitioning tropical cyclone event but the data that is provided in Seashore Engineering (2020) requires a parametric wind model to be adopted.

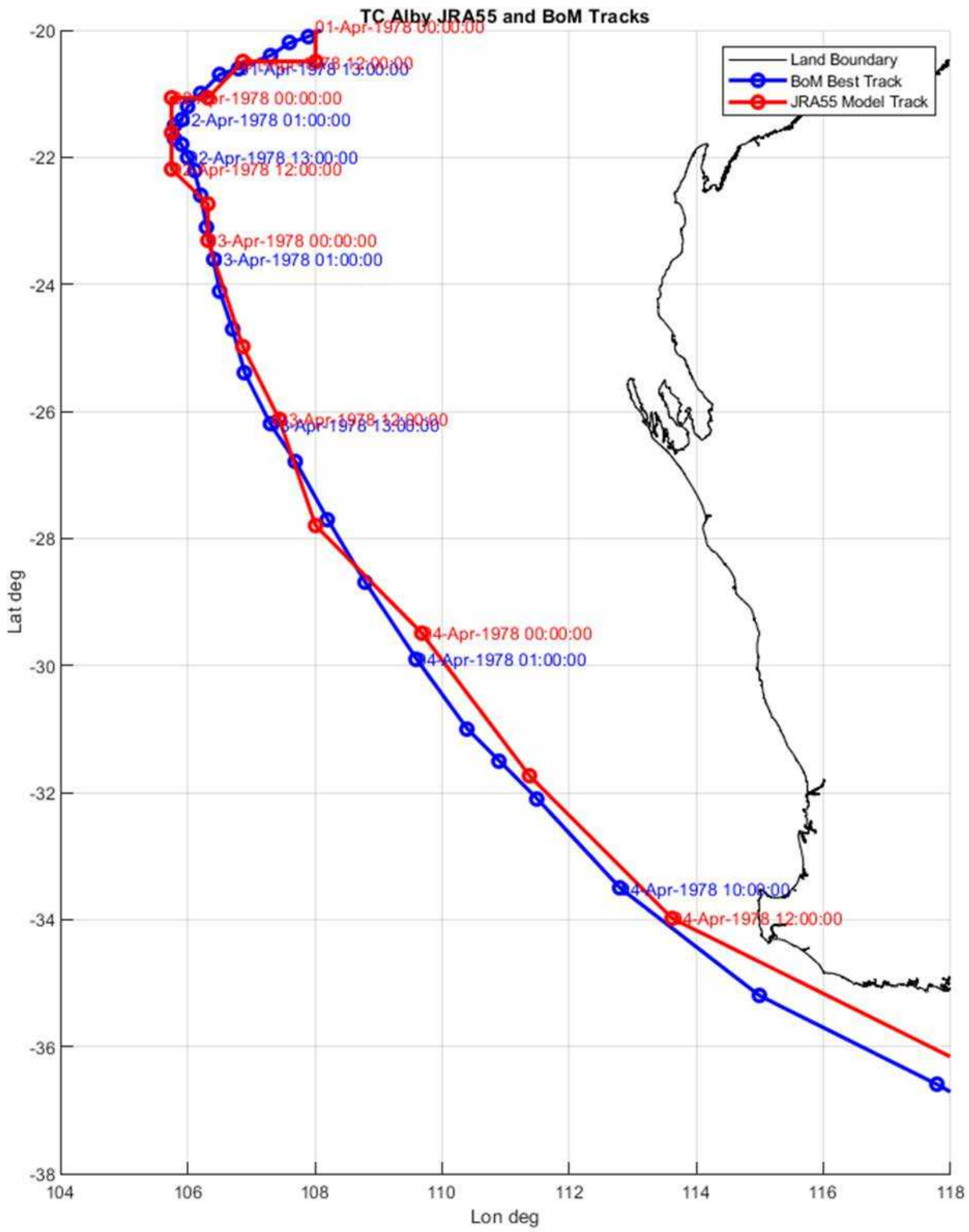


Figure 5.5: Comparisons of the TC Alby historical BoM track and the synthetic JRA-55 track

5.3 Final Recommendations for Design Events

Baird recommended the four events presented in Table 5.2 for the Gingin study area be modelled to define the design water level for the 20-year ARI, 100-year ARI and 500-year ARI. It was determined the 500-year ARI event which generates the largest total water level from the Baird (MC69197) and DoT Design Track (Seashore 2020) would be adopted as the 500-year ARI design water level for the study area. The DoT Design Track generated the largest storm surge from those two scenarios.

The events were simulated for present day and future periods across the 100-year planning period adopting sea level rise projections based on DoT recommendations:

- Current (year 2020);
- 2040 with +0.10m sea level rise allowance;
- 2070 with +0.35m sea level rise allowance; and
- 2120 with +0.90m sea level rise allowance.

In total 12 scenarios were established for design water levels across the study site for the present day and future planning periods (3 design cases, 4 ocean levels).

5.4 Concurrent Tide and Non-cyclonic Water Level in Design Events

For the design event simulations, Baird adopted the following tide and residual water level allowances in the design event modelling:

- Tide concurrent with peak surge: MHHW (see Table 3.1); and
- Residual water level (added to MSL): +0.3 m based on Figure 2.4 and Table 2.2.

5.5 Guilderton – Joint Occurrence of Ocean Inundation and catchment Flooding from the Moore River

5.5.1 Moore river Peak Level at Guilderton

Based on the literature review (DoE 2002) and Baird's analysis of the water levels in the lower Moore River, the river level around Guilderton peaks in the early autumn (April, May). River levels reached their highest point in May in the DoE 2002 study, with the bar breached for the first time in April and then breached more frequently through the winter period at lower levels. It is possible that under future sea level rise scenarios the stability of the bar may be affected, however this has not been investigated in the current study.

The breaching of the bar provides a control mechanism for limiting flood inundation at Guilderton from the Moore River during extreme catchment-based runoff. The measured data from DoE (2002) showed a peak level of approximately 2.0 m AHD prior to the breaching of the bar, with lower peaks thereafter. This control mechanism at the bar safeguards Guilderton from this type of flooding event. Photos supplied by The DWER for a major flooding event breaching the bar in 1995 are shown in Figure 5.6.

Figure 5.6: Moore River Mouth Guilderton - Large Flood Event in 1995 (DWER)

5.5.2 Joint Occurrence of Moore River Catchment Based Flood and Ocean Flooding

Joint occurrence of catchment peak water level from Moore River and ocean peak water level in cyclone events is not expected to be a critical consideration for peak inundation levels in Guilderton. It is expected that the upstream size of the Moore River catchment will delay the timing of peak catchment-based flows to Guilderton during extreme events.

Of greater relevance, the natural land levels around Moore River at Guilderton rise sharply as shown in Figure 5.7. Development is set well above the river, with house development at a minimum of 5 m AHD but generally at levels higher than 10 m AHD. This level is well above any potential inundation threat from the river or ocean even under sea level rise projections. The lowest section of the riverbank where infrastructure is located is around the Caravan Park and car park, which are located at between 3 m AHD and 5 m AHD as shown in Figure 5.7. This elevation level is above the extreme ocean levels in historical cyclone cases (Appendix B) and the peak water levels of the Moore River in the measured data (DoE 2002) however may be within the extreme flood range for the Moore River.

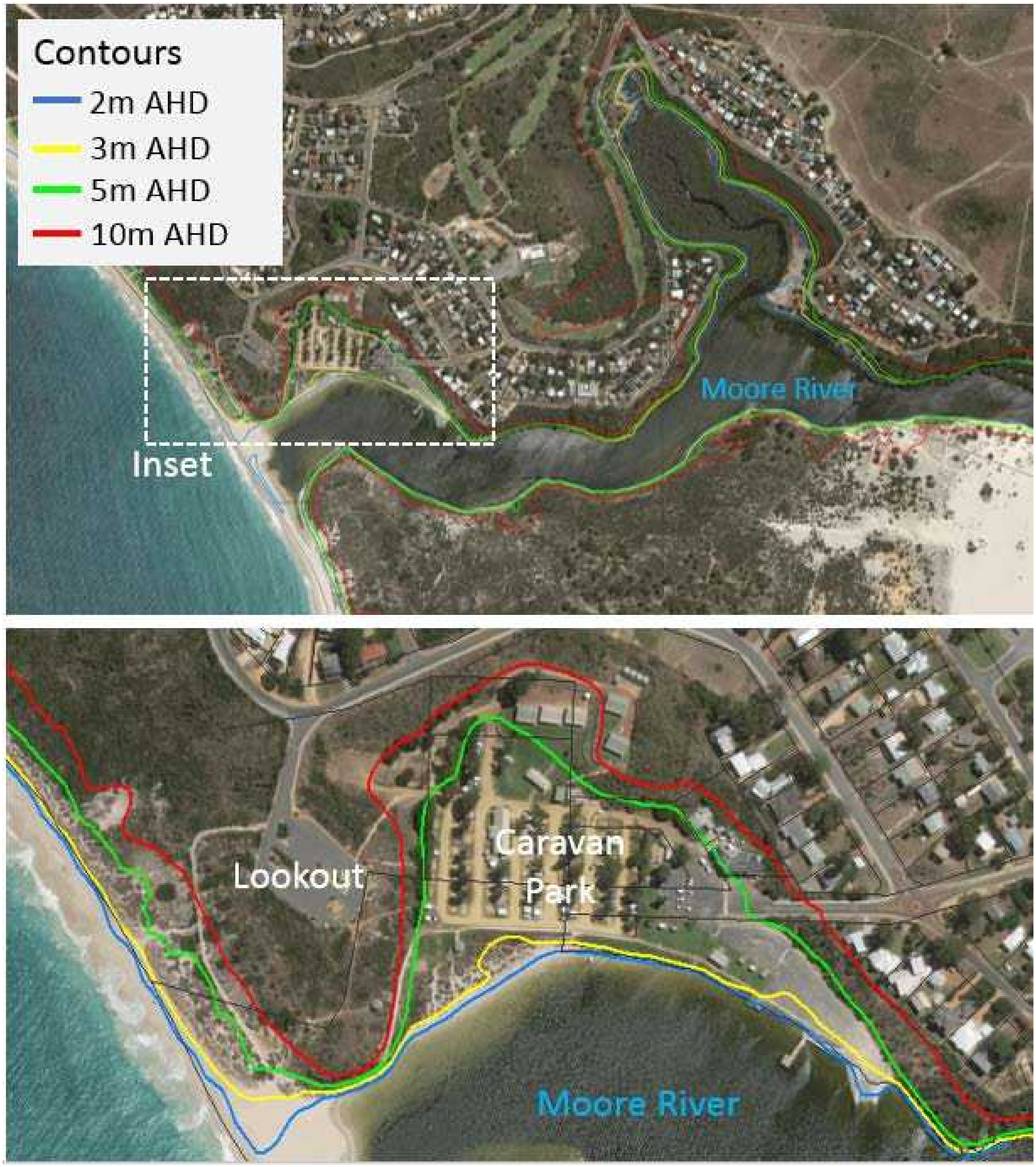


Figure 5.7: Guilderton Elevation Levels around Moore River based on LiDAR (2016)

6. Design Water Levels

6.1 Analysis of Measured Data – Extreme Value Analysis

The measured water level from the tide gauges at Jurien Bay and Lancelin were analysed using standard extreme value analysis (EVA) methods to extrapolate the expected design water levels for return periods of 2, 5, 10, 20, 50, 100, 200 and 500 years with a 95% confidence interval. The EVA provides a reference against the modelled outcomes for the extreme design cyclone cases.

For Jurien Bay and Lancelin the water level records were filtered with a 72-hour period, and a threshold of 0.88m to 0.77m respectively to obtain ~20 peak events over the 20 to 30 year data record period. Extreme design values were obtained using three extreme distributions; Weibull, Gumble and Generalised EVA.

Results are summarised in Table 6.1 for Jurien Bay and Table 6.2 for Lancelin. It is noted that EVA extrapolation above the 50yr ARI return period is provided for reference but should be treated with caution due to the limited duration of the measured data record.

Table 6.1: Extreme Value Analysis on Jurien Bay Measured Water level Data Record (1991 - 2020)

Return Period ARI	Design WL (m AHD)	Lower Bound (m AHD)	Upper Bound (m AHD)
2	0.82	0.79	0.84
5	0.88	0.82	0.93
10	0.92	0.84	1.00
20	0.97	0.86	1.09
50	1.04	0.88	1.21
100[1]	1.10	0.89	1.31
200[1]	1.15	0.90	1.41
500[1]	1.23	0.91	1.55

Note 1. ARI provided for reference but should be treated with caution due to the 30-year duration of measured data record.

Table 6.2: Extreme Value Analysis on Lancelin Measured Water level Data Record (1993-1997, 2003-2012)

Return Period ARI	Design WL (m AHD)	Lower Bound (m AHD)	Upper Bound (m AHD)
2	0.67	0.65	0.69
5	0.77	0.73	0.82
10	0.84	0.75	0.94
20	0.92	0.77	1.06
50	1.01	0.77	1.24
100[1]	1.07	0.77	1.38
200[1]	1.14	0.76	1.52
500[1]	1.23	0.74	1.72

Note 1. ARI provided for reference but should be treated with caution due to the limited duration of the measured data

6.2 Design Cyclone Model Outcomes

The recommended design cases were assessed in the model system with the peak water levels from the model cases summarised in Table 6.3 for the four towns of the study area. It is noted:

- The peak water levels are generally consistent across the four towns with up to 0.2m variation at each respective ARI;
- For the synthetic track cases at 20yr ARI, 100yr ARI and 500yr ARI Lancelin shows the highest water levels comparatively and Ledge Point the lowest.
- For the Seashore design 500yr ARI case, Lancelin shows the highest water levels comparatively and Seabird the lowest;
- The modelled 20yr ARI water level for Lancelin in Table 6.3 is slightly above the 95% confidence level of the EVA results at Lancelin in Table 6.2 calculated from the 13 years of measured data; and
- A comparison of the peak water levels from the 500yr ARI synthetic track MC 69197 and the DoT design 500yr ARI track (Seashore 2020) shows the DoT design 500yr ARI case produces a higher peak water level. As stated in Section 5.3, the adopted design case for the 500yr ARI event is based on the most severe of these two approaches.

Table 6.3: Summary of design cyclone outcomes. Peak modelled water level across the four towns in the Gingin study area.

ARI (yr)	Reference Event	Lancelin (m AHD)	Ledge Point (m AHD)	Seabird (m AHD)	Guilderton (m AHD)
20	69197	1.3	1.2	1.3	1.3
100	69197	1.5	1.3	1.4	1.4
500	69197	1.8	1.6	1.7	1.7
500	Seashore ‘Worst Case’ TC Ned	2.0	1.9	1.7	1.8

6.3 Nearshore Wave Setup

The effect of wave action on nearshore water levels has been included in the numerical modelling. Wave setup is generated within the coupled Delft-FM model as a result of radiation stress gradients from the wave field being added to the hydrodynamic model. However, Delft-FM does not represent the shoreline wave setup at fine detail and for lower period wave conditions the modelled wave setup from Delft-FM model will underestimate the total wave setup observed at the shoreline. Baird (2020a) identified that the radiation stress model in Delft-FM may overestimate nearshore wave setup for very long period storm swell conditions (i.e. $T_p \approx 15s$) as was observed in TC Alby at Busselton (see Baird, 2020) and for the large scale storm event in the DoT design track (Seashore 2020) adopted in this study. assessment as follows:

- For the cases assessed using the synthetic design cyclone track (MC69197) additional shoreline wave setup was added to the modelled water levels through the peak of the respective events as the nearshore wave periods were in the range of 7 to 10 s (T_p). Additional wave setup was estimated using the Nielsen and Hanslow (1991) wave setup distributions with inputs from the modelled cases (Hs, Tp) and beach slope; and
- For the adopted 500yr ARI design water level based on the DoT design track (Seashore 2020) the scale and intensity of the event in the model resulted in very long period nearshore waves ($T_p \approx 17s$) and the Delft-FM modelled wave setup was assessed as suitably conservative and no additional shoreline wave setup was added.

It is noted that the Nielsen and Hanslow (1991) wave setup model is most applicable for an open coast sandy beach and does not account for the full complexity of the wave setup on a shoreline with complex nearshore bathymetry, including outer reefs and rock outcrops as occurs in the study area. However, it is important to note that in the approach adopted in this study, Delft3-FM model provides a wave setup solution for the water level inside the outer breakpoint (i.e. inside the outer reef) and that the Nielsen and Hanslow (1991) wave setup models applied to the synthetic design cyclone track to provide a solution to the additional setup that occurs close to the shoreline from the final shoreline wave breaking. Baird has obtained reasonable comparisons of Nielsen and Hanslow (1991) wave setup and run-up model based on post-event survey and shoreline inspection data at a number sites including Port Hedland Spoilbank (TC Veronica March 2019, Baird Australia 2020), Collaroy-Narrabeen (June 2016, Burston et al 2016) and Busselton (TC Alby April 1978, Baird Australia 2020b).

6.4 Climate Change and Impacts on Cyclone Intensity and Frequency

The frequency of storms with tropical cyclone strength winds offshore of Gingin is very low and as a result there is considerable uncertainty in the long-term cyclone climatology of the region. For a storm like TC Alby or TC Ned whose intensity and storm scale was influenced by the combination of a rapidly moving cold front interacting with a transitioning tropical cyclone is an example of two discrete storm systems, each with a relatively low probability of occurrence occurring at the same time resulting in this being a rare combination of storm conditions.

In addition to uncertainty in historical climatology, climate change may alter cyclone climatology. There are no definitive projections of the impacts of climate change on the cyclone climatology of the Gingin region. The latest consensus literature, for example Knutson et al (2019) state medium to high confidence in the following changes to global cyclone climatology due to climate change:-

- Increase in precipitation with a median increase of 14%;
- Increase in global average event intensity with average peak intensity increasing ≈ 5%;
- An increase in proportion of events that reach severe intensity (CAT 4 and 5).

Knutson et al (2019) reports low confidence in the following:

- Increase in poleward extent of tropical cyclone events;
- An overall decrease in cyclone frequency; and

- An increase in overall number of severe cyclone events (CAT 4 and 5).

Continuing sea level rise is the most definitive climate change impact on coastal inundation along the Gingin study area. There is a high degree of confidence that sea levels will continue to rise in the future, likely at an increasing rate. In accordance with SPP2.6, sea level rise for future planning horizons is included for coastal inundation level in future planning periods but no changes in cyclone climatology have been considered. Sea level rise projections are summarised in Table 3.2.

6.5 Final Design Water Levels

The final design water levels represent the peak water level during the respective cyclone events and include near shore wave setup. Based on the model outcomes, the peak level is experienced for a period of 2 hours or less.

The final design levels have been adjusted to Australian Height Datum (AHD) based on the conversion of model results (the model datum is in mean sea level). It is noted that a common adjustment of MSL to AHD of -0.07m has been applied for the whole Gingin study area based on the Two Rocks Marina data presented in Table 3.1 to overcome the conversion anomaly at Lancelin (refer end Section 3.1.1). This represents a conservative approach.

The final design water levels are shown in Table 6.4 for Lancelin. Water level is presented for 3 locations along the Lancelin shoreline – north, mid and south. The northern shoreline is more exposed to the design storms and modelled peak water levels are generally higher. The applicable shoreline sections are shown in Figure 6.1.

Table 6.4: Lancelin Final Design Water Levels (Datum m AHD)

Return Period	20yr ARI			100yr ARI			500yr ARI		
Timeframe	North	Mid	South	North	Mid	South	North	Mid	South
2020	1.3	1.2	1.2	1.5	1.3	1.3	2.0	2.0	1.8
2040	1.4	1.3	1.3	1.6	1.4	1.4	2.1	2.1	1.9
2070	1.7	1.5	1.5	1.9	1.7	1.6	2.3	2.3	2.2
2120	2.2	2.1	2.1	2.4	2.2	2.2	2.9	2.9	2.7

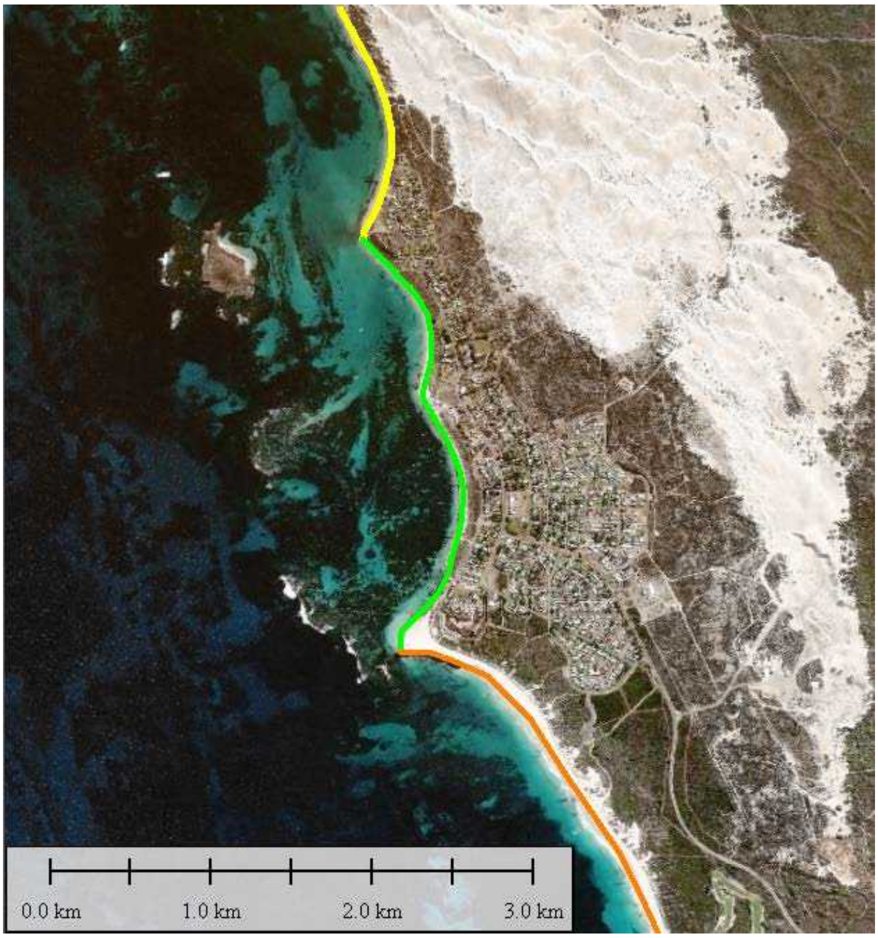


Figure 6.1: Lancelin Shoreline Sections for Design Water Level. North (Yellow), Mid (Green) and South (Orange)

The final design water levels are shown in Table 6.5 for Ledge Point. Water level is presented for 2 shoreline sections - north and south. The applicable shoreline sections are shown in Figure 6.2.

Table 6.5: Ledge Point Final Design Water Levels (Datum m AHD)

Return Period	20yr ARI		100yr ARI		500yrARI	
Timeframe	North	South	North	South	North	South
2020	1.2	1.1	1.3	1.2	1.9	1.8
2040	1.3	1.2	1.4	1.3	2.0	1.9
2070	1.5	1.5	1.7	1.6	2.2	2.1
2120	2.1	2.0	2.2	2.1	2.8	2.7

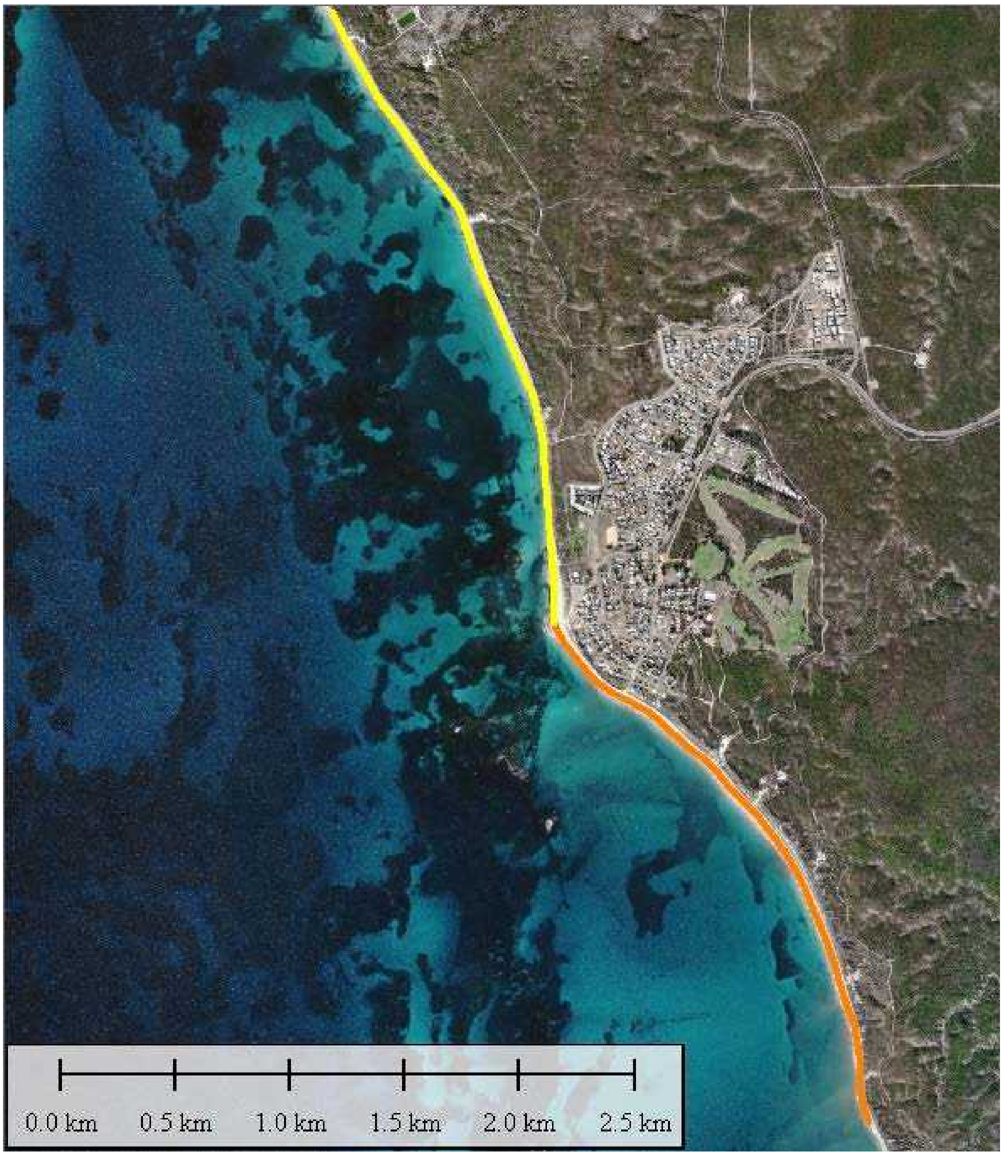


Figure 6.2: Ledge Point Shoreline Sections for Design Water Level. North (Yellow) and South (Orange)

The final design water levels are shown in Table 6.6 for Seabird and Table 6.7 for Guilderton. Modelled water level is generally consistent along the shoreline in these two locations in the design cyclone events.

Table 6.6: Seabird Final Design Water Levels (Datum mAHD)

Return Period	20yr ARI	100yr ARI	500yr ARI
2020	1.3	1.4	1.7
2040	1.4	1.5	1.8
2070	1.7	1.8	2.0
2120	2.2	2.3	2.6

Table 6.7: Guilderton Final Design Water Levels (Datum mAHD)

Return Period	20yr ARI	100yr ARI	500yr ARI
2020	1.3	1.4	1.8
2040	1.4	1.5	1.9
2070	1.7	1.8	2.1
2120	2.2	2.3	2.7

6.6 Guilderton Inundation Level Based on Influence of Catchment based flooding from Moore River

It is noted that that the design water levels from ocean based extreme events for Guilderton in Table 6.7 at all return periods for the present to 2070 are lower than the peak river level from lower Moore River reported in the measured data (DoE 2002). Based on the reported data from the lower Moore River the river level will reach approximately 2.0m AHD at Guilderton before the bar breaks (DoE 2002).

For the design case reported in Table 6.7 at planning year 2120 with 0.9m sea level rise, the design water level at the 500yr ARI is 2.7m AHD and in this scenario it is assumed the bar would be breached and the offshore water level transferred into the lower Moore River to Guilderton through the peak of the event.

7. Inundation Mapping

The design water levels presented in the previous section have been used to produce spatial mapping of the coastal inundation extents for the four towns of the study area. This mapping represents the S4 inundation component under State Coastal Planning Policy SPP2.6.

The inundation mapping is presented in Appendix C, incorporating the following:

1. The inundation depth in the maps has been derived from a ‘bathtub mapping’ approach which applies the peak ocean level determined from the design cases at each of the towns (Table 6.4 to Table 6.7) over the high resolution LiDAR data.
2. Hydro-connectivity between inland flooded areas and the ocean has been established to ensure isolated pockets of inundation at low points inland are not shown in the map.
3. The requirement of SPP2.6 to assess the peak still water level in the design events against the dune profile areas to identify where potential dune breaching occurs in extreme events has been incorporated in the mapping approach.
4. The projected coastal erosion of the topography of each coastal town in future planning periods (coastal setback lines) and the influence on the extent of coastal inundation is considered

The above coastal processes and techniques that have been applied in the development of the spatial mapping are outlined in detail in this section.

7.1 Flood Map Layout Format

To allow for appropriate resolution in the mapping the flood mapping series in Appendix C.1 has been presented in a 3-map layout for Lancelin (Figure 7.1), 2-map layout for Seabird and Ledge Point and for Guilderton is shown on one map as presented in Appendices C.2, C.3 and C.4 respectively.

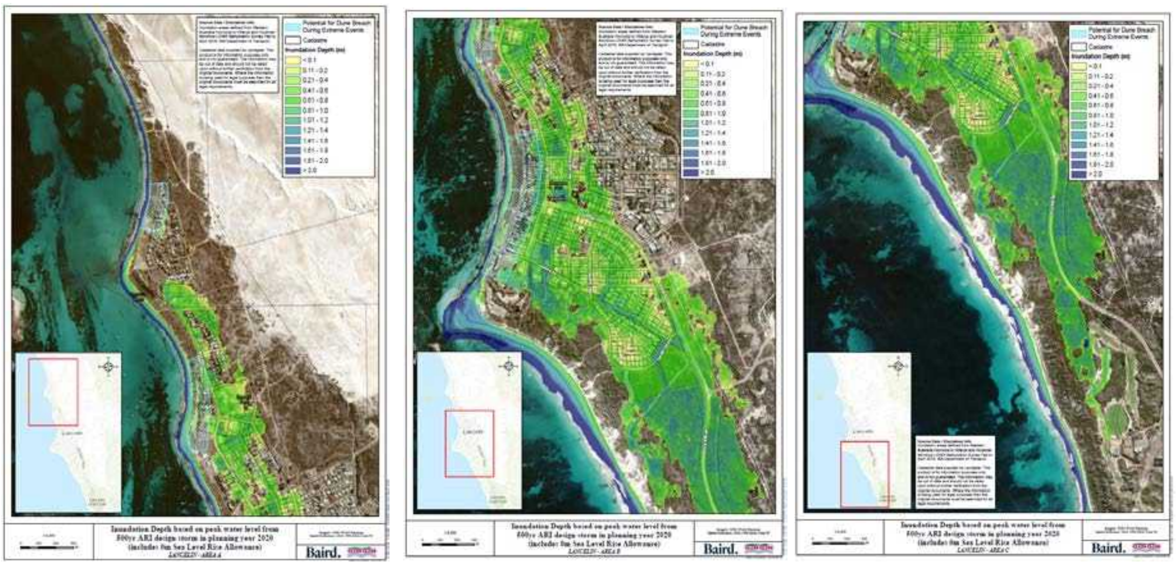


Figure 7.1: Example Map Series for Lancelin. 500yr ARI case at planning year 2020. Left to right the maps show the north, central and southern region of the Lancelin area (Full mapping is in Appendix C).

Flood depth is shown on the mapping sets in increments of 0.1m. The cadastre information from Landgate has been overlaid to provide reference to development areas and individual land parcels.

Inundation risk is highest for Lancelin, where the foredune provides a barrier that protects the lower lying inland areas from ocean-based flooding during extreme events. The stability of the foredune in severe storm events when subjected to elevated water level and large waves was assessed, to determine if there was potential for dune breaching which could lead to flooding of the inland areas (Section 7.2).

The mapping is presented for Lancelin for the three ARI design events (20yr, 100yr and 500yr) at 4 planning periods (2020, 2040, 2070, 2120). Inundation of inland areas occurs from planning year 2070 for the 20yr ARI and 100yr ARI event and from planning year 2020 for the 500yr ARI event (discussed in more detail in next section).

For Ledge Point, Seabird and Guilderton only the 500yr ARI case in the planning year 2120 is presented in Appendix C mapping. For these locations, the peak water level in the design events is contained in the foreshore areas, even under sea level rise scenarios.

7.2 Dune Stability Analysis

For the Lancelin shoreline where a foredune area protects the lower lying areas landward (Figure 7.2), the stability of the dune under elevated water levels and extreme waves is a key consideration. The foredune elevation ranges from 2m AHD to as high as 10m AHD offering natural protection to the low-lying inland areas which are at 1.0m AHD to 1.5m AHD.

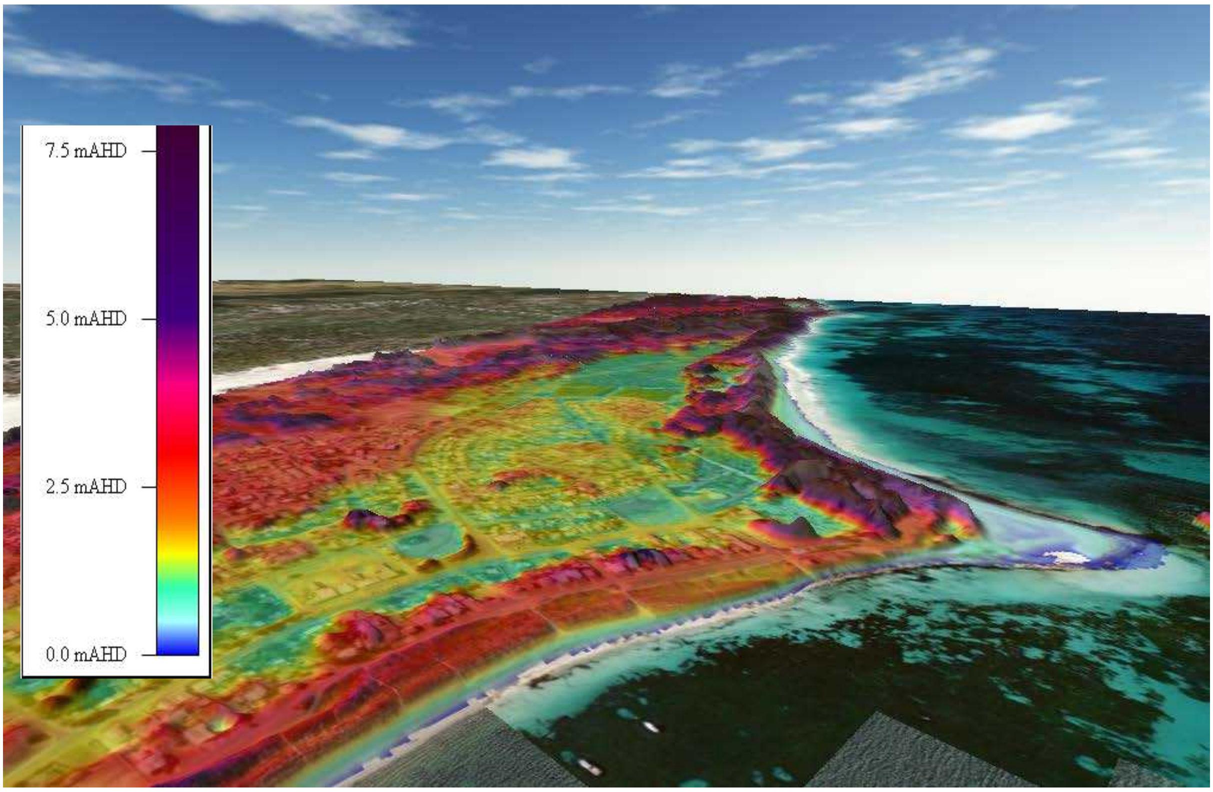


Figure 7.2: View looking south over Lancelin showing height of foredune in relation to areas landward (LiDAR imagery 3D render). The foredune elevation ranges from 2m AHD to 10m AHD offering natural protection to the low-lying inland areas which are at 1.0m AHD to 1.5m AHD.

7.2.1 Dune Stability under SPP2.6

An important consideration for the determination of inundation areas (S4 component) under the guidelines of SPP2.6, relates to the ability of the barrier dune to be maintained in extreme events under the combined process of elevated water levels and large waves. Where a continuous barrier dune is present in the shoreline areas, the capacity of the dune to provide protection from inundation should be assessed based on the cross-sectional area of the dune above the reference datum taken as the expected peak steady water level in the design storm.

A cross sectional area less than 100 m^2/m above the reference datum is assumed to be completely removed during storm activity. Under such conditions the storm inundation extent (S4) is calculated assuming the dune is removed, and the dune breach can convey flows inland. If the cross-sectional area is greater than the 100 m^2/m above the reference datum, the general dune structure is maintained through the storm event and provide a barrier against flooding for inland areas.

7.2.2 Dune Stability – Lancelin Transect Analysis

For Lancelin, the design water levels in Table 6.4 are adopted as the likely peak steady water level in each respective design event. The levels were assessed against the elevation of the foredune area to determine if the dune will be maintained in the respective design events or would be breached consistent with the approach outlined in SPP2.6 (Section 7.2.1).

To assess the dune stability, elevation profiles located at 20m to 50m intervals along the lowest lying sections of the Lancelin coast were assessed in detail using the LiDAR data. The locations for the detailed analysis are indicated in Figure 7.3. Areas outside of these transect regions are sections where there is extensive height and / or volume in the natural dune system that will not be breached in the design events.

Figure 7.3: Lancelin – Analysis transects along the coast to examine dune system capacity to be maintained in extreme events.

The analysis has been applied in the 12 design cases for Lancelin (4 planning periods, 3 return periods) to determine where dune breach may occur and result in flow paths for inland flooding. The analysis showed the dune system will not breach until the design water level reaches or exceeds 1.5m AHD in the lower two sections of transects, whilst the level of 2.0m and above would breach the northern section.

The key design events where breaching occurs is summarised in Table 7.1. In summary:

- dune breach would commence at the 2070 timeframe under assumed sea level rise for the mid-sections and at 2120 for the north section at design storms equivalent to the 20yr ARI and 100yr ARI; and
- Under the 500yr ARI water level dune breach occurs in all scenarios (present day and all future time periods).

Table 7.1: Lancelin Dune Breach Summary

	20yr ARI		100yr ARI		500yr ARI	
Timeframe	North	Mid	North	Mid	North	Mid
2020	No	No	No	No	Breach	Breach
2040	No	No	No	No	Breach	Breach
2070	No	Breach	No	Breach	Breach	Breach
2120	Breach	Breach	Breach	Breach	Breach	Breach

The breaching of the dune at the critical water levels in Table 7.1 has been incorporated into the mapping cases in Appendix C.1 with the key dune breach areas marked on the map (refer example in Figure 7.10). In summary:

- The stability of the foredune in severe storm events when subjected to elevated water level and large waves was assessed, to determine if there was potential for dune breaching which could lead to flooding of the inland areas.
  - For the section of coast north from Grace Darling Park, there is the potential for dune breaching of the foredune in severe events. The dune system is estimated to be able to withstand the 20yr ARI event and the 100yr ARI event in the present day (2020). Under future sea level rise scenarios for the 2070 planning period (+0.4m) and beyond, breaching of the foredune may occur. A storm event of 500yr ARI magnitude is estimated to breach the dune system in the present day and all future planning periods.
  - For the section of coast south of Grace Darling Park, the dune system is significant and breaching of the dune would not occur in any of the extreme events, including under future sea level rise scenarios.
- For Ledge Point, Seabird and Guilderton the developed areas are not at risk of inundation, with the natural topography set well above the extreme design water levels, including under future sea level rise scenarios.

7.3 Wave Runup

7.3.1 Wave Runup Calculations for Lancelin

The process of wave runup is discussed in Section 2.2.5. Wave runup and setup is the maximum vertical extent of wave uprush on a beach which increases with increasing wave height, wave period and beach slope. Waves that occur during cyclones can reach areas not usually reached and can carry immense power that also lead to coastal erosion and breaching of dunes.

The wave runup levels at the shoreline for Lancelin have been calculated from the design extreme model cases based on the Nielsen and Hanslow (1991) method with inputs from the modelled cases (Hs, Tp). The processes are shown in Figure 7.4 with the Lancelin shoreline analysis adopting a beach slope of 1:5 which is representative of a shoreline profile as it develops toward an eroded beach scarp at which point property and structures may then limit the landward movement of the shoreline.

Baird has obtained reasonable comparisons of Nielsen and Hanslow (1991) wave setup and run-up model based on post-event survey and shoreline inspection data at a number sites including Port Hedland Spoilbank (TC Veronica March 2019, Baird Australia 2020), Collaroy-Narrabeen (June 2016, Burston et al 2016) and Busselton (TC Alby April 1978, Baird Australia 2020b). In particular, following the June 2016 storm that impacted on Collaroy-Narrabeen (NSW), the Nielsen and Hanslow (1991) had good agreement with surveyed wave run-up levels behind a steep dune scarp.

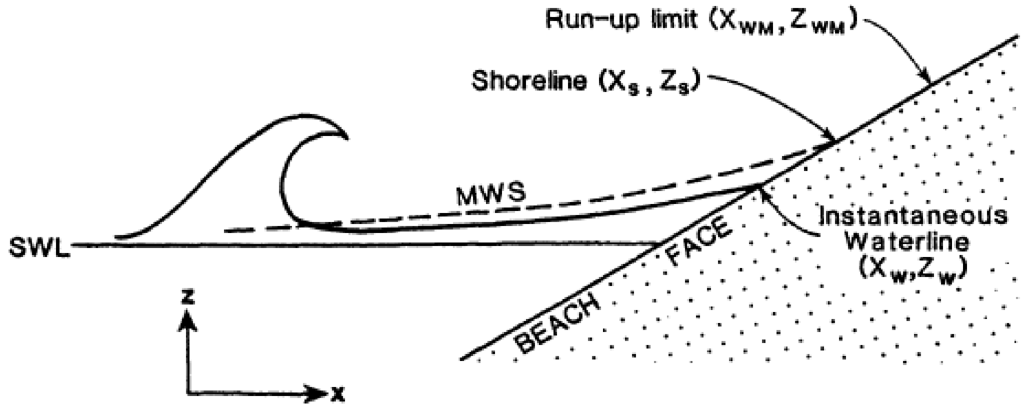


Figure 7.4: Figure showing shoreline processes of wave runup and setup under extreme wave conditions - still water level (SWL), mean water surface (MWS) and runup limit (Nielson and Hanslow 1991)

Calculated wave runup levels for Lancelin are summarised in Table 7.2 for the design cases. The wave runup levels are notably higher for the 500yr ARI case compared with the lower ARI events due to the modelled wave period for this case which had a peak period of 17s at the peak of the storm (T_p=17s).

Table 7.2: Lancelin Wave Runup Level (Datum m AHD)

Return Period	20yr ARI			100yr ARI			500yr ARI		
Timeframe	North	Mid	South	North	Mid	South	North	Mid	South
2020	2.8	2.5	3.1	3.3	3.2	3.6	7.5	6.4	7.2
2040	2.9	2.6	3.2	3.4	3.3	3.7	7.6	6.5	7.3
2070	3.2	2.8	3.5	3.7	3.5	3.9	7.8	6.7	7.6
2120	3.7	3.4	4.0	4.2	4.1	4.5	8.4	7.3	8.1

7.3.2 Calculated Wave Runup Level for Ledge Point, Seabird and Guilderton

For the three towns south of Lancelin, the natural land elevation rises steeply from the foreshore area. The crest of the foredune is at a natural elevation level well above the design water levels in the extreme events. The elevation is shown for Seabird and Ledge Point in Figure 7.5 and for Guilderton in Figure 5.7.

At these towns, the risk of inundation is not like Lancelin where a foredune protects lower lying inland areas. Even for the most extreme 500yr ARI design case in the planning year 2120 with 0.9m sea level rise the peak water level is contained within the foreshore areas. The top of the foredune where development is seen in the foreshore areas based on the LiDAR data is at:

- Approximately 6m AHD at Ledge Point;
- Approximately 8m AHD at Seabird; and
- >20m AHD at Guilderton.

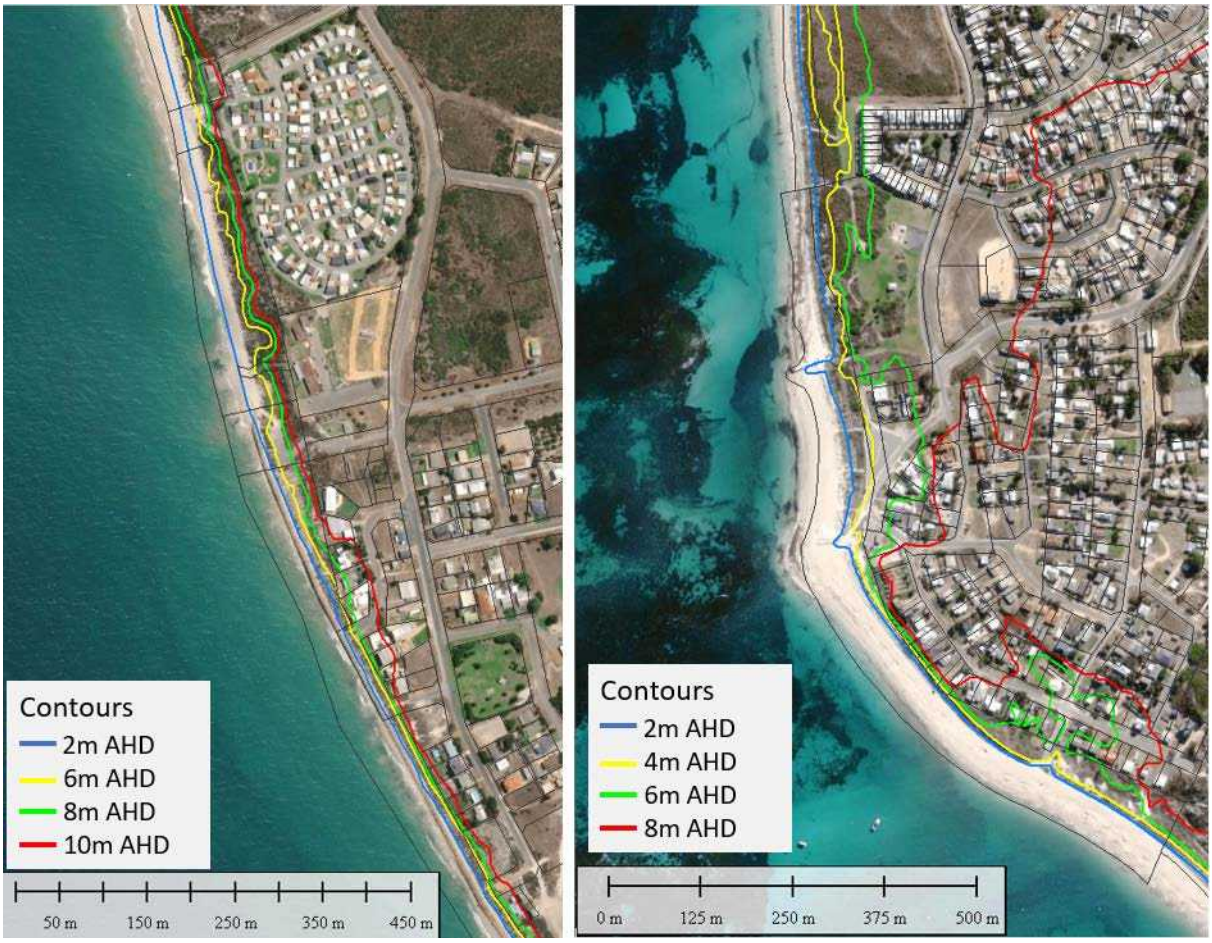


Figure 7.5: Elevation contours adjacent the foredune for the towns of Seabird (left) and Ledge Point (right) calculated based on 2016 LiDAR (DoT 2016). The contours show the natural land elevation rises steeply from the foreshore.

The wave runup calculations for Ledge Point, Seabird and Guilderton are summarised in Table 7.3, Table 7.4 and Table 7.5 respectively. The wave runup level gives an indication of the level at which wave processes during extreme events could impact the developed areas adjacent the foredune due to wave action through wave runup, over wash and sea spray.

For Ledge Point the wave runup level when compared against the LiDAR data indicates there would be some minor influence from wave runup process to the development in the foreshore areas in the south under an extreme 500yr ARI event in future planning periods (potential over wash, sea spray). At Seabird and Guilderton the foredune would be at a level to contain projected wave runup influence.

Table 7.3: Ledge Point Wave Runup Level (Datum m AHD)

Return Period	20yr ARI		100yr ARI		500yrARI	
Timeframe	North	South	North	South	North	South
2020	2.8	2.7	3.2	3.1	7.1	6.7
2040	2.9	2.8	3.3	3.2	7.2	6.8
2070	3.2	3.0	3.6	3.4	7.5	7.1
2120	3.7	3.6	4.1	4.0	8.0	7.6

Table 7.4: Seabird Wave Runup Level (Datum m AHD)

Return Period	20yr ARI	100yr ARI	500yr ARI
2020	2.6	3.0	6.9
2040	2.7	3.1	7.0
2070	3.0	3.3	7.3
2120	3.5	3.9	7.8

Table 7.5: Guilderton Wave Runup Level (Datum m AHD)

Return Period	20yr ARI	100yr ARI	500yr ARI
2020	3.0	3.3	7.7
2040	3.1	3.4	7.8
2070	3.4	3.6	8.1
2120	3.9	4.2	8.6

7.4 Coastal Processes Setback Lines

The coastal processes allowances (setback lines) for the towns of Lancelin, Ledge Point and Seabird have been calculated for the Shire (as reported in MRA 2015b, MRA 2016a and MRA 2016b). The Gingin CHRMAP report has adopted the coastal setback lines for assessment of coastal hazard risk from erosion in future planning periods. The coastal processes lines (setback lines) represent the horizontal distance from the foreshore area over which coastal processes may be active.

To incorporate the projected setback lines and the way in which they influence the extent of coastal inundation in this current study Baird have plotted the lines for the three towns in Figure 7.6, Figure 7.7 and Figure 7.8. It is important to note that the lines do not represent the shoreline position in future planning periods, rather the area over which the coastal processes have been calculated to potentially act based on the guidelines of SPP2.6. The setback distance represents the combined allowance impacts from erosion under a severe storm (S1), historical rate of shoreline change (S2) and an allowance based on sea level rise (S3). An uncertainty allowance of 0.2m a year is also included in the calculations. In many cases the

S3 component is dominant in the setback representing up to 90m of the setback allowance over the 100-years planning period.

For Lancelin, the coastal processes in future planning periods is incorporated into the method by which the dune stability calculation is undertaken (refer Section 7.2.2). The impact of sea level rise over time is included in the still water level that underpins the analysis. The inundation mapping presented for Lancelin in Appendix C reflects the effect of sea level rise on dune capacity but it is noted that it does not recognise potential for changes to the dune features as a result of landward shift of the coastal processes' setback line in future planning periods. There is considerable uncertainty over how the future shoreline evolution will occur over the 50year and 100-year planning period and a more detailed CHRMAP based approach that can include the consideration of the landform and potential adaptation approaches to provide resilience against erosion in future planning periods should be undertaken.

For the town of Ledge Point the setback lines in Figure 7.7 show a landward progression of approximately 100m between the 2030 and 2110 period. The majority of this 100m horizontal distance is composed of the allowance for sea level rise over the period (S3 component) and uncertainty allowance. The projected coastal erosion setback lines have not been considered in the presentation of the design water level in the inundation plots in Appendix C. There is considerable uncertainty over how the sea level rise would affect this section of coast and impact the process of erosion over the 50-year and 100-year planning period. To assume the coast moves back to the position of the setback line in each respective planning period due to erosion is considered unlikely and of limited value in presenting impacts for this inundation study. The consideration of likely and unlikely scenarios for erosion of the shoreline and hence future inundation could be further considered in a CHRMAP based approach that can include the consideration of the landform changes and potential adaptation approaches to provide resilience against erosion in future planning periods.

For the town of Seabird the setback lines in Figure 7.8 show similar landward progression to the Ledge Point case. The northern section of the map shows there is approximately 140m movement of the coastal processes setback line between the 2030 and 2110 period whilst in the south the distance is approximately 10m horizontal distance over this 80-year period in recognition of the presence of rock in the foreshore. As for Ledge Point, the projected coastal erosion setback lines have not been taken into account in the presentation of the design water level in the inundation plots in Appendix C. There is considerable uncertainty over how the future shoreline evolution will occur over the 50year and 100-year planning period and a more detailed CHRMAP based approach that can include the consideration of the landform and potential adaptation approaches to provide resilience against erosion in future planning periods should be undertaken. Additionally the Seabird seawall would need to be included in this analysis of shoreline stability in future planning periods as it is not included in the setback line calculations that are shown in Figure 7.8.

Finally, for Guilderton the setback lines have not been calculated in previous studies for the Shire. The scale and extent of the foredune would be expected to provide sufficient area over which coastal processes could be contained in the 100years planning period and have no effect on the overall inundation areas presented in Appendix C.

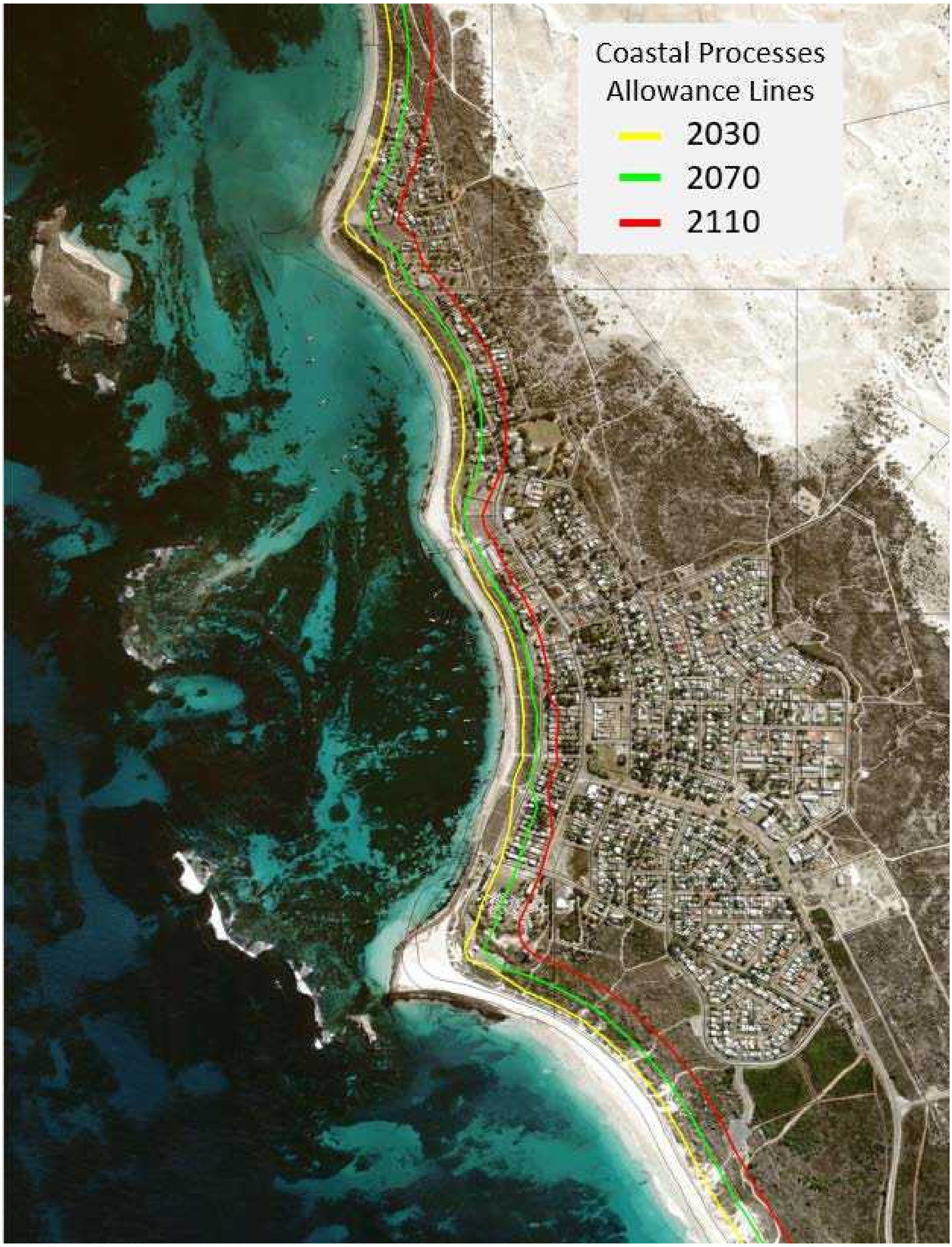


Figure 7.6: Coastal Processes Allowance for Lancelin for the planning years 2030, 2070 and 2110 (based on MRA 2016b)

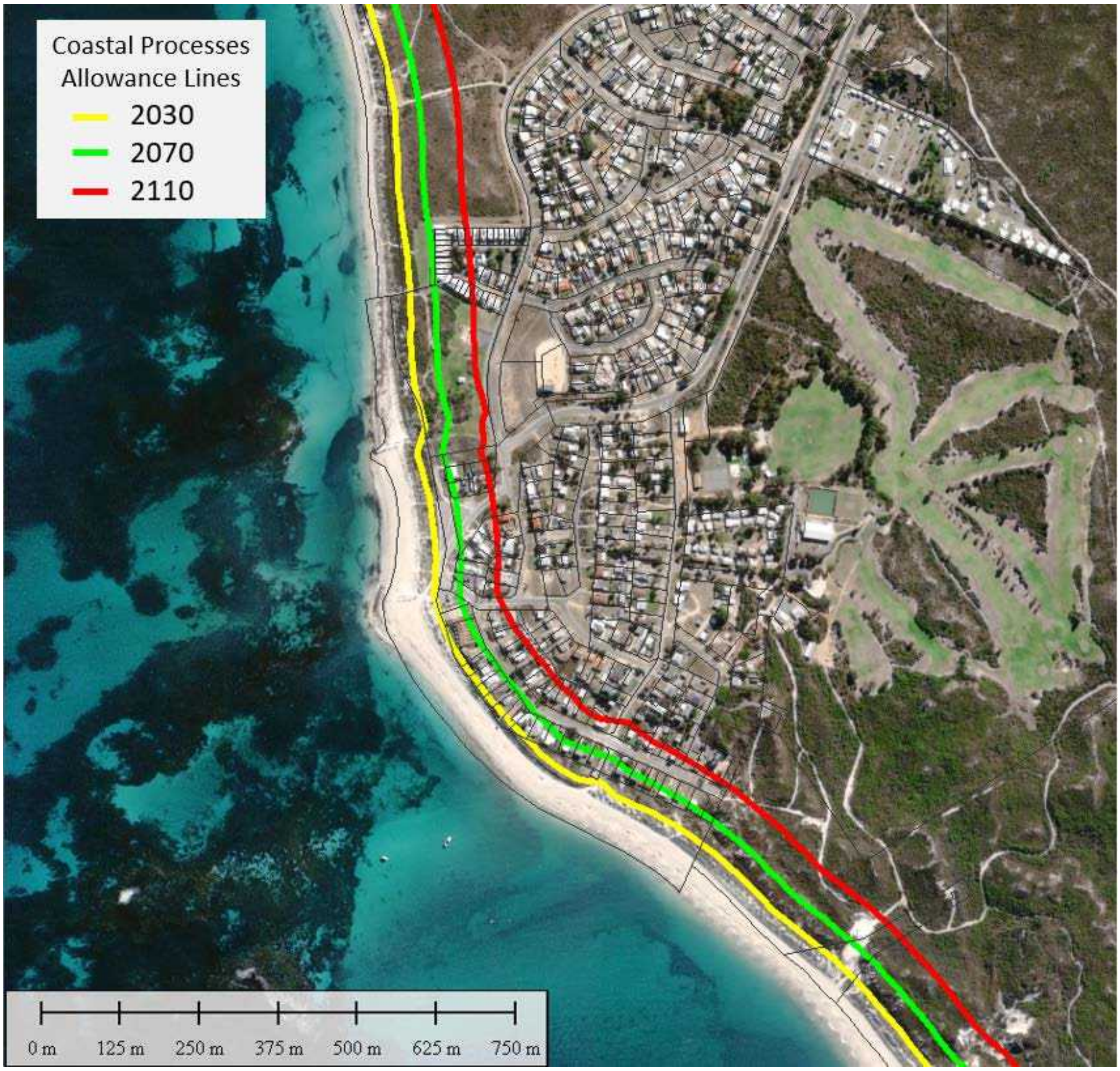


Figure 7.7: Coastal Processes Allowance for Ledge Point for the planning years 2030, 2070 and 2110 (based on MRA 2016b)

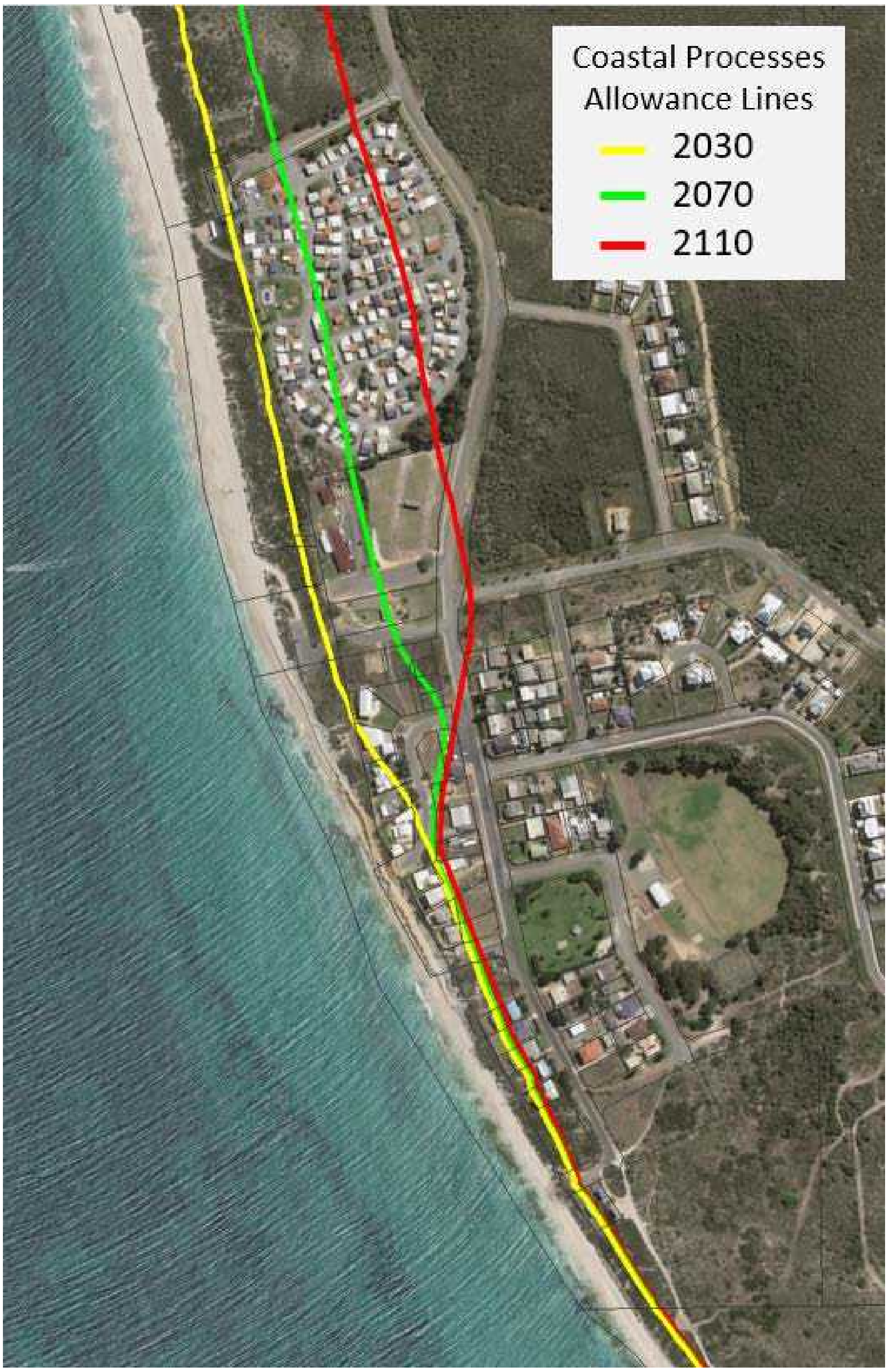


Figure 7.8: Coastal Processes Allowance for Seabird for the planning years 2030, 2070 and 2110 (based on MRA 2015b)

7.5 Bathtub Mapping Approach

The mapping of inundation areas for the design cases in Appendix C is shown as flood depth. The depth has been determined by applying the final design water levels from Section 6.5 to the land surface which is defined by high resolution LiDAR captured in 2016 (DoT 2016).

It is noted that finished floor levels of properties in the coastal areas are not considered in the inundation mapping. The accuracy of the inundation mapping in Appendix C is considered applicable at the coastal compartment scale that CHRMAP adopts (refer Figure 7.9). It is recommended that the flood assessment be refined for detailed site-specific adaptation assessments and planning policy requirements that will follow the CHRMAP study.

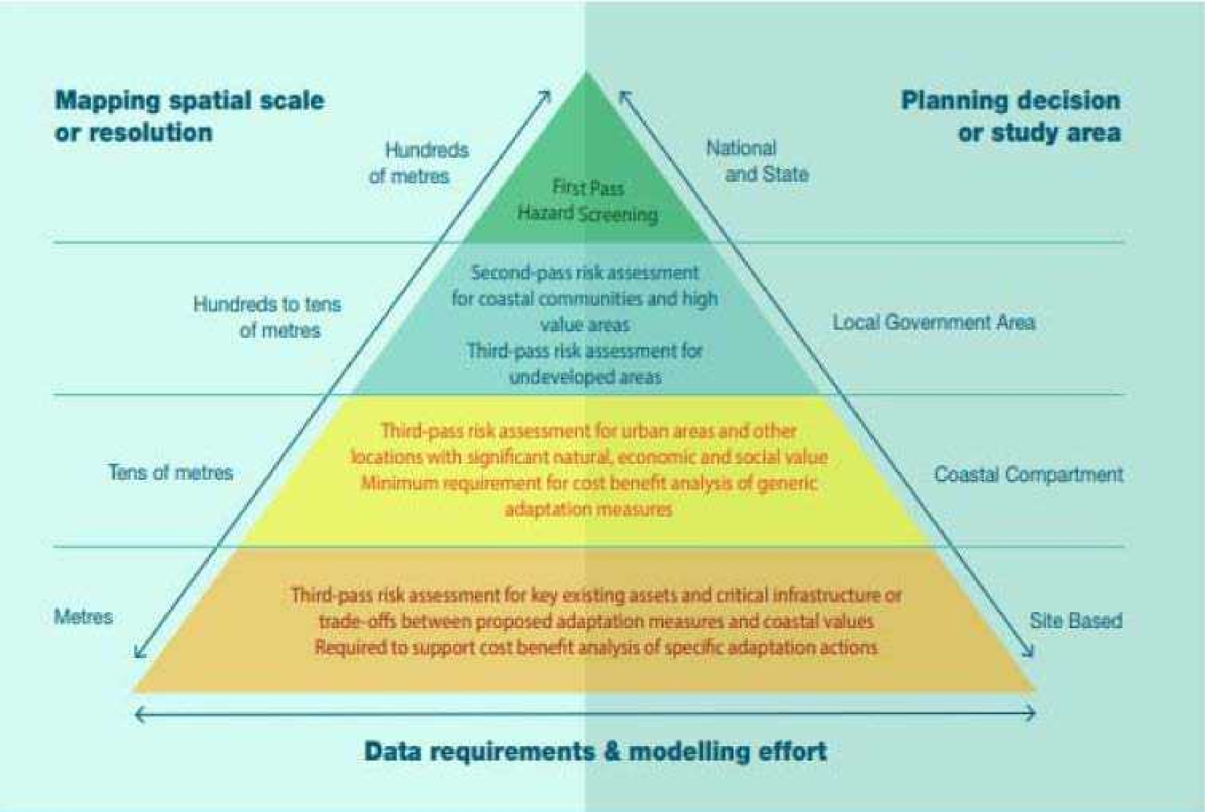


Figure 7.9: Coastal hazard mapping scale and level of data and modelling effort (Barnes 2017 adapted from Eliot 2013)

7.6 Hydro-connectivity

To improve the spatial mapping from a simple ‘bathtub’ flooding approach, all inundated areas have been incorporated a ‘hydro-connectivity’ algorithm. Hydro-connectivity ensures that the flooded areas inland connect to the offshore ocean region. This mechanism overcomes the limitation of the bathtub method where isolated inland pockets of inundation will occur, and this provided a more robust product when presenting results to the community and later developing adaptation approaches for the inland areas which would incorrectly show as flooded under the bathtub approach.

For the shoreline areas of Lancelin where dune stability may be compromised under peak storm levels and wave runup as outlined in Section 7.2 a note on the inundation mapping has been added to indicate

‘Potential for Dune Breach During Extreme Events’. This ensures the mapping shows a connection point from the ocean to flooded areas inland in circumstances where the dune is considered to have been breached under the conditions specified in SPP2.6. an example is shown in Figure 7.10.

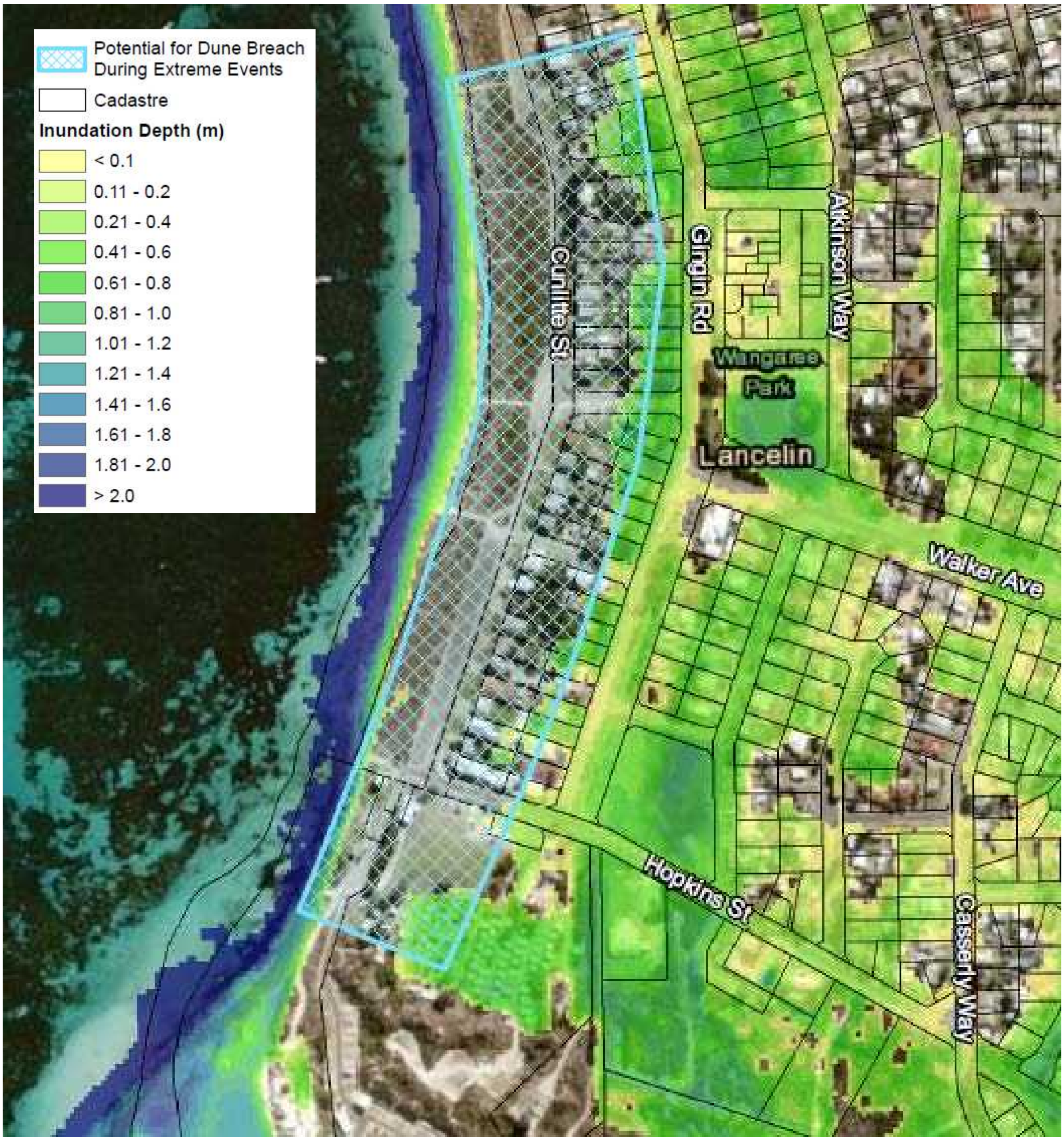


Figure 7.10: Example of dune breach area indicated on Lancelin Mapping (excerpt from 100yr ARI design storm in planning year 2070. Refer Appendix C.1)

8. Tsunami Modelling

To assess and quantify the hazard associated with tsunami within the study area, Baird has utilised Geoscience Australia's 2018 Australian Probabilistic Tsunami Hazard Assessment (PTHA, Geoscience Australia, 2018). The PTHA models the frequency with which tsunamis of any given size occur around the entire Australian coast, due to subduction earthquakes in the Indian and Pacific Oceans. Tsunami generated from sources other than subduction zones are not included in the hazard assessment. The focus on subduction zones in the southeast Indian and Pacific Oceans is justified because these are known to have produced major historical tsunami and are considered the most likely source of future events (BoM, 2010).

One such event that was observed to impact on the West Australian coast was the 2004 Sumatra–Andaman (Boxing Day) event. This event was not available from the PTHA database and there exist a number of hypothesised rupture inversions that describe the fault displacement for the event, however these are not well validated (pers. Comm. G Davies, Geoscience Australia). The challenge with the 2004 Boxing Day event is that there were no DART (Deep-ocean Assessment and Reporting of Tsunamis) buoys deployed at that time to measure the event in deep water, thus inference of the correct fault rupture characteristics cannot be accurately made.

To overcome this, Baird has collaborated with Geoscience Australia who have identified a set of 'most probable' rupture inversions and modelled each specifically for this study and provided timeseries data at the 3000m water depth contour to allow coupling with Baird's Delft-FM hydrodynamic model of the study area. Coupling the Geoscience Australia model with the Delft-FM hydrodynamic model of the coastal shelf needs to occur in deepwater where friction is not a significant influence on the tsunami propagation. This is because the Geoscience Australia model (also used for PTHA event simulations) does not include friction and is relatively coarse resolution (1-arcmin), thereby making it unsuitable for describing tsunami propagation over the shelf and into shallow water.

The Delft-FM model was run for 72hours from the earthquake rupture time, allowing a suitable simulation duration for any late arrival or nearshore resonance to be captured in the model, should they occur. The resulting nearshore tsunami signal has been compared to available tide gauge data at Lancelin, Jurien Bay and Geraldton, to benchmark the performance of the 2004 event hindcast. Figure 8.1 provides timeseries comparisons for the best performing inversion provided by Geoscience Australia against the Lancelin tide gauge with peak residual water levels summarised in Table 8.1 at locations where measured data was available at Geraldton, Jurien Bay and Lancelin.

Table 8.1: Peak Residual Water Level during the 2004 Boxing Day Tsunami

	Lancelin	Jurien Bay	Geraldton
Measured Tides (peak residual water level)	0.46	0.63	1.33
Modelled Tsunami (peak water level)	0.54	1.10	1.31

The comparison presented herein demonstrate close agreement at Geraldton and Lancelin in terms of peak water level and frequency of the largest waves during the event. The model result at Jurien Bay overestimates compared to the measured data, and the source of this is thought to be due to the bathymetric schematisation of the coastline at that site in the model, which is located within an enclosed marina location (given the close comparisons at other sites).

It is noted that no further calibration or validation has been completed for tsunami at this study site. As demonstrated at Geraldton by Geoscience Australia (2010) numerical model validation of tsunami is extremely difficult and highly dependent on the correct description of the initial rupture dimension at the tsunami source. Such a study would require considerable effort outside the scope of this study. However, the comparisons presented herein provide a degree of confidence that if the inversion rupture is well described, the Delft-FM hydrodynamic model applied in this study reasonably replicates the nearshore propagation and inshore response of the tsunami.

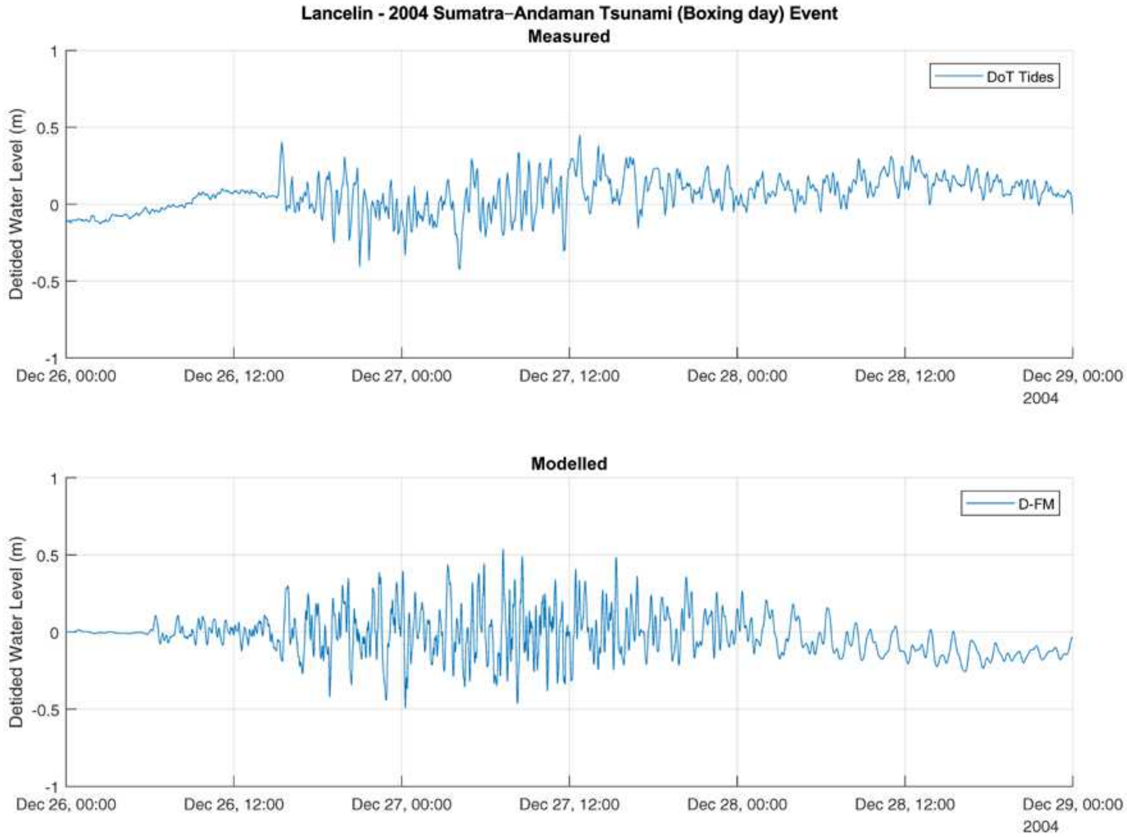


Figure 8.1: Comparison of Measured and Modelled Water Level residuals during the Boxing Day Tsunami (26th December 2004).

To define the 500-years ARI tsunami event for the study area, the publicly accessible PTHA database, consisting of modelled output from hundreds of thousands earthquake-tsunami scenarios around Australia, was interrogated to derive deepwater boundary conditions for the hydrodynamic model of the study area. The PTHA allows for the determination of average recurrence interval (ARI) levels in deep water and the identification of specific events that contribute to each ARI. From the available events at the 500 years ARI level offshore of the site, a 9.3 Mw (Mw - seismic magnitude scale) event from the Sunda arc was identified as being the most probable contributor at that hazard level. As done for the Boxing Day tsunami, water level timeseries form the PTHA model were extracted in deepwater (3000m depth contour) and applied directly to the Delft-FM model boundary.

The peak modelled water level results from the 500-years ARI tsunami event is summarised for the four towns in Table 8.2.

Table 8.2: Tsunami event at 500yr ARI – Modelled Water Level (Datum m AHD)

Return Period	500yr ARI Modelled Tsunami – Peak Water Level			
Timeframe	Lancelin	Ledge Point	Seabird	Guilderton
2020	1.9	2.1	2.1	2.2
2040	2.0	2.2	2.2	2.3
2070	2.3	2.5	2.5	2.6
2120	2.8	3.0	3.0	3.1

The results in Table 8.2 show the peak water level is comparable (within 0.1m) with the design water levels from the modelled 500yr ARI cyclone event for the Lancelin and Ledge Point locations (refer Table 6.4 and Table 6.5). At Seabird and Guilderton the peak modelled water level for the design 500yr ARI Tsunami is 0.4m to 0.5m higher than the 500yr ARI cyclone event (refer Table 6.6 and Table 6.7). Given the natural elevation of the shoreline areas at Seabird and Guilderton this additional 0.4m to 0.5m level can be accommodated in the foreshore areas. In conclusion the inundation risk to Lancelin, Ledge Point, Seabird and Guilderton from the 500yr ARI Tsunami is considered equivalent to the 500yr ARI cyclone case.

The peak water level from the 500yr ARI Tsunami event is significantly higher than for the Boxing Day Tsunami case. This is explained by the nature of the Boxing day event in which the orientation of the fault rupture was directed at Africa, whilst for the design event adopted for the Gingin coast the orientation of the fault rupture is specifically directed offshore of the Western Australia’s coast.

9. Conclusion

Baird Australia (Baird) have undertaken a Coastal Inundation Study (CIS) for the Shire of Gingin to identify potential areas subject to coastal inundation risk which will inform future planning of coastal areas. The study focus is along the coastal region of the Shire of Gingin which is located approximately 70km north of Perth in Western Australia. There are four key towns of interest in this study at Lancelin, Ledge Point, Seabird and Guilderton.

A literature review and data gathering exercise is summarised in Section 2 along with a detailed explanation of the key coastal inundation processes important for the study. Measured data sources are outlined in Section 3 that have been utilised in the study delivery.

The hydrodynamic model system is presented in Section 4. Baird's established and validated numerical model of the West Australian coast was used as a baseline for this study. This hydrodynamic model system has been applied for a number of similar studies in Western Australia and was developed by Baird using the Deltares numerical model *Delft3D Flexible Mesh Suite* (Delft-FM). The Delft-FM modelling suite has been developed to offer a fully integrated modelling framework for a multi-disciplinary approach in coastal, river and estuarine areas (Deltares 2020) and has been applied in similar studies by Baird to determine waves, water levels and currents in extreme cyclonic conditions. The numerical model applied in this study is comprised of a dynamically coupled hydrodynamic model and wave model driven by a wind model developed by Baird (*Cycwind*). Model validation against predicted tides was shown to have excellent agreement at port locations through the study region. The model was used to simulate four key historical cyclone cases with comparison to available measured data and predicted tides, providing a basis for understanding magnitude of storm surge in extreme cyclone events and demonstrating model performance within the limitations of the hindcast wind fields for some historical events. The design storm for the Gingin coast is an ex-tropical cyclone which transitions south and interacts with frontal systems coming through the southern Indian Ocean, that increases the intensity and scale of the storm system. These events are rare in the historical record and occur typically in the latter part of the cyclone season (February to May). The four historical events that were simulated were TC Alby (1978), TC Ned (1989), TC Bianca (2011) and TC Iggy (2012). The TC Mangga event occurred in May 2020 at the conclusion of the study and a discussion is presented in Section 0.

In developing a 'design' storm for coastal inundation along the Gingin study sites consideration was given to the DoT design storm based on TC Ned (Seashore Engineering, 2020), a synthetic track from Baird's 10,000 yr cyclone track data set (Taylor et al, 2018) and a hybrid storm event based on data from the JRA-55 model. The process is outlined in Section 5 with the outcome that design cases at the 20yr-ARI and 100yr-ARI were defined by the Baird track (MC69197) and the DoT Design Track (Seashore 2020) was adopted as the 500-year ARI design case as it generated the largest storm surge when compared to the Baird Track (approximately 0.2 m higher water levels). Approaching the coast between the Gingin study area and the Perth northern suburbs, TC Ned experienced extra-tropical transition and intensified compared to early track positions further north. The assumed extra-tropical transition in the 500yr ARI event tracks are critical to the intensity and scale of the Seashore design event.

The events were simulated for present day and future periods across the 100-year planning period adopting sea level rise projections based on DoT recommendations. The final water levels are summarised in Table 9.1. The final design water levels represent the peak water level during the respective cyclone events and include near shore wave setup. Based on the model outcomes, the peak level is experienced for a period of 2 hours or less.

Wave runup levels were calculated for the study area and are summarised in Section 7. The wave runup levels have been calculated from the design extreme model cases based on the Nielsen and Hanslow (1991) method with inputs from the modelled cases (Hs, Tp).

Table 9.1: Summary of design cyclone outcomes. Peak modelled water level across the four towns in the Gingin study area.

ARI (yr)	Reference Event	Lancelin (m AHD)	Ledge Point (m AHD)	Seabird (m AHD)	Guilderton (m AHD)
20	69197	1.3	1.2	1.3	1.3
100	69197	1.5	1.3	1.4	1.4
500	DoT Design (Seashore 2020)	2.0	1.9	1.7	1.8

The design water levels were used to produce spatial mapping of the coastal inundation extents for the four towns of the study area. This mapping represents the S4 inundation component under State Coastal Planning Policy SPP2.6. The inundation mapping process is outlined in Section 7 with final mapping presented in Appendix C.

The inundation mapping uses a ‘bathtub mapping’ approach which applies the peak ocean level determined from the design cases at each of the towns (Table 9.1) over the high resolution LiDAR data (DoT 2016). The mapping approach includes consideration of hydro-connectivity between inland flooded areas and the ocean. The requirement of SPP2.6 to examine dune stability at Lancelin to identify where potential dune breaching occurs in extreme events has been incorporated. Discussion of the influence of coastal erosion processes on the inundation extents calculated at each coastal town in future planning periods is included in Section 7.

- Inundation risk is highest for Lancelin, where the foredune provides a barrier that protects the lower lying inland areas from ocean-based flooding during extreme events.
  - For the section of coast north from Grace Darling Park, there is the potential for dune breaching of the foredune in severe events. The dune system is estimated to be able to withstand the 20yr ARI event and the 100yr ARI event in the present day (2020). Under future sea level rise scenarios for the 2070 planning period (+0.4m) and beyond, breaching of the foredune may occur. A storm event of 500yr ARI magnitude is estimated to breach the dune system in the present day and all future planning periods.
  - For the section of coast south of Grace Darling Park, the dune system is significant and breaching of the dune would not occur in any of the extreme events, including under future sea level rise scenarios.
- For Ledge Point, Seabird and Guilderton the developed areas are not at risk of inundation, with the natural topography set well above the extreme design water levels, including under future sea level rise scenarios.
- The foreshore areas at all study locations are susceptible to the impacts of wave run-up in design storm cases, which may result in overtopping of dunes and foreshore structures.

In Section 8 assessment of the hazard associated with tsunami within the study area is presented using Geoscience Australia’s 2018 Australian Probabilistic Tsunami Hazard Assessment (PTHA, Geoscience Australia, 2018). Baird applied its hydrodynamic model to model a validation case of the 2006 Boxing day Tsunami, with the model showing good agreement to measured peak water level during the event captured at tide gauges in Geraldton and Lancelin. A 500 yr ARI tsunami event for the Gingin study area was examined in the model with peak water level results summarised for the four towns in Table 9.2. The results show the peak water level from tsunami is comparable (within 0.1m) with the design water levels from the modelled 500yr ARI cyclone event for the Lancelin and Ledge Point locations and for Seabird and Guilderton the peak modelled water level for the design 500yr ARI Tsunami is 0.4m to 0.5m higher than the 500yr ARI cyclone event.

Table 9.2: Tsunami event at 500yr ARI – Modelled Water Level (Datum m AHD)

Return Period	500yr ARI Modelled Tsunami – Peak Water Level			
Timeframe	Lancelin	Ledge Point	Seabird	Guilderton
2020	1.9	2.1	2.1	2.2
2040	2.0	2.2	2.2	2.3
2070	2.3	2.5	2.5	2.6
2120	2.8	3.0	3.0	3.1

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Appendix A

Department of Transport Storm Tracks for 500yr ARI

Design Inundation Events

A.1 Seashore Engineering (2020) Design Cyclone Tracks based on TC Ned

Table A.1: Design Track for Lancelin

Lancelin	Longitude	115.3273			Latitude	31.01469		
	Original Storm				500-yr ARI storm			
	TC Ned (Mar 1988)				Rmax	200	km	
Date / Time	Long	Lat	CP	Rmax	Long	Lat	CP	Rmax
3/25/1989 6:00	119.8	17.4	1003		120.2	18.4	1002.1	54
3/25/1989 12:00	119.1	17.1	1001		119.5	18.1	1000.0	54
3/25/1989 18:00	118.1	16.8	999		118.5	17.8	997.8	54
3/26/1989 0:00	116.9	16.9	997		117.3	17.9	995.6	54
3/26/1989 6:00	115.8	17.1	995		116.2	18.1	993.4	54
3/26/1989 12:00	115.3	17.2	992		115.7	18.2	990.2	54
3/26/1989 18:00	114.6	17.4	989		115.0	18.4	986.9	54
3/27/1989 0:00	113.8	17.8	986		114.2	18.8	983.7	54
3/27/1989 6:00	113	18.1	982		113.4	19.1	979.3	54
3/27/1989 12:00	112.2	18.3	977		112.6	19.3	973.9	54
3/27/1989 18:00	111	18.8	967		111.4	19.8	963.0	54
3/28/1989 0:00	110.2	19	954		110.6	20.0	948.9	54
3/28/1989 6:00	109.6	19.6	948		110.0	20.6	942.4	54
3/28/1989 12:00	109.2	20.1	945		109.6	21.1	939.1	54
3/28/1989 18:00	109.1	20.4	942		109.5	21.4	935.9	54
3/29/1989 0:00	109.1	20.7	941		109.5	21.7	934.8	54
3/29/1989 6:00	109	21	945		109.4	22.0	937.0	54
3/29/1989 12:00	109	21.5	954		109.4	22.5	941.3	54
3/29/1989 18:00	109	22	964		109.4	23.0	942.4	54
3/30/1989 0:00	108.9	22.4	972		109.3	23.4	942.4	54
3/30/1989 6:00	108.5	23.2	984		108.9	24.2	945.7	54
3/30/1989 12:00	108.4	24	989		108.8	25.0	950.0	61
3/30/1989 18:00	108.5	25	992		108.9	26.0	953.3	68
3/31/1989 0:00	108.7	26.1	994		109.1	27.1	958.7	75
3/31/1989 6:00	109.2	27.2	996		109.6	28.2	961.9	90
3/31/1989 9:00	109.8	27.9	997		110.2	28.9	961.9	100
3/31/1989 12:00	110.5	28.5	998		110.9	29.5	964.1	110
3/31/1989 15:00	110.6	29.2	999		112.0	30.2	967.4	120
3/31/1989 18:00	113	30.2	1000		113.4	31.2	967.4	140
3/31/1989 21:00	114.8	31.5	1001		115.2	32.5	972.8	180
4/1/1989 0:00	116.6	32.7	1002		117.0	33.7	972.8	230
4/1/1989 3:00	118.6	33.8	1002		119.0	34.8	975.0	250
4/1/1989 6:00	120.8	34.5	1003		121.2	35.5	978.2	270

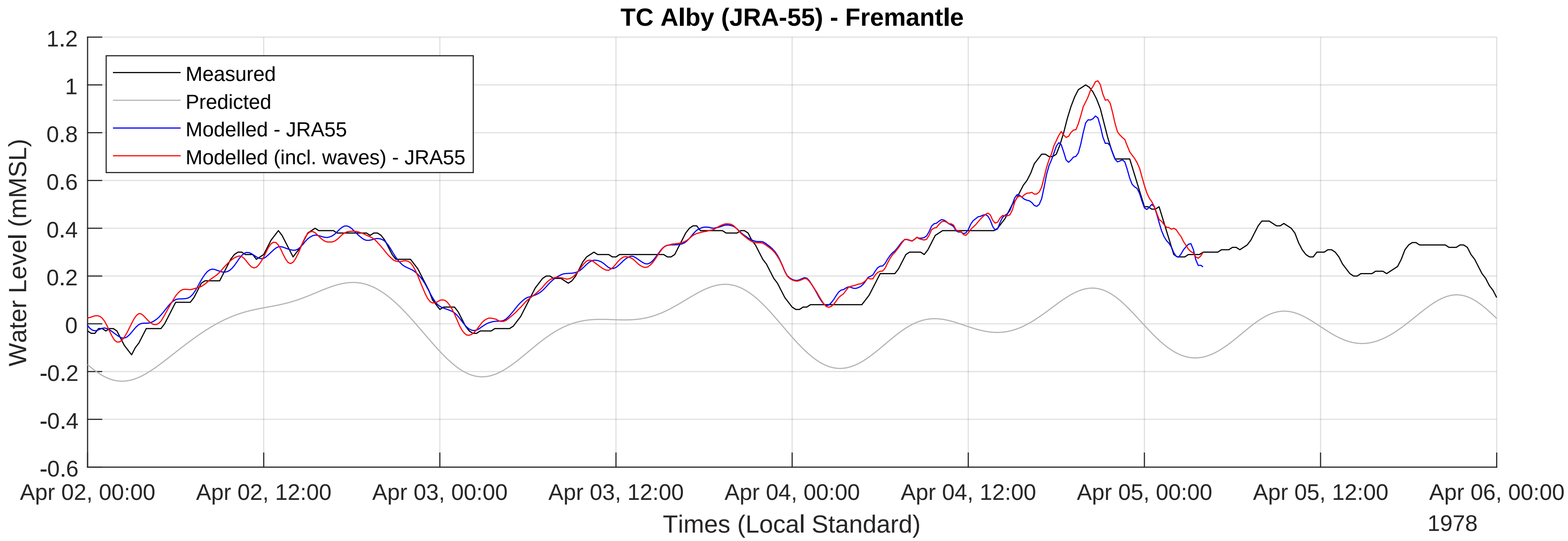
Table A.2: Design Track for Seabird

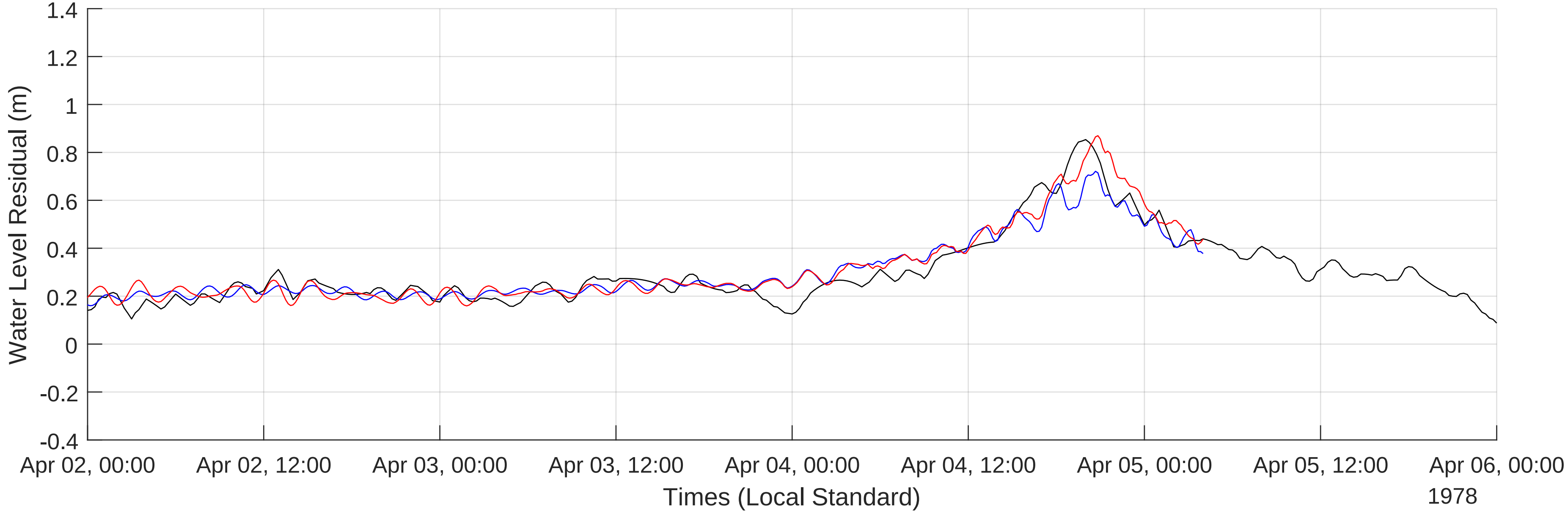
Seabird	Longitude	115.4464			Latitude	31.27694		
	Original Storm				500-yr ARI storm			
	TC Ned (Mar 1988)							
Date / Time	Long	Lat	CP	Rmax	Long	Lat	CP	Rmax
3/25/1989 6:00	119.8	17.4	1003		120.0	18.4	1002.1	54
3/25/1989 12:00	119.1	17.1	1001		119.3	18.1	1000.0	54
3/25/1989 18:00	118.1	16.8	999		118.3	17.8	997.8	54
3/26/1989 0:00	116.9	16.9	997		117.1	17.9	995.6	54
3/26/1989 6:00	115.8	17.1	995		116.0	18.1	993.4	54
3/26/1989 12:00	115.3	17.2	992		115.5	18.2	990.2	54
3/26/1989 18:00	114.6	17.4	989		114.8	18.4	986.9	54
3/27/1989 0:00	113.8	17.8	986		114.0	18.8	983.7	54
3/27/1989 6:00	113	18.1	982		113.2	19.1	979.3	54
3/27/1989 12:00	112.2	18.3	977		112.4	19.3	973.9	54
3/27/1989 18:00	111	18.8	967		111.2	19.8	963.0	54
3/28/1989 0:00	110.2	19	954		110.4	20.0	948.9	54
3/28/1989 6:00	109.6	19.6	948		109.8	20.6	942.4	54
3/28/1989 12:00	109.2	20.1	945		109.4	21.1	939.1	54
3/28/1989 18:00	109.1	20.4	942		109.3	21.4	935.9	54
3/29/1989 0:00	109.1	20.7	941		109.3	21.7	934.8	54
3/29/1989 6:00	109	21	945		109.2	22.0	937.0	54
3/29/1989 12:00	109	21.5	954		109.2	22.5	941.3	54
3/29/1989 18:00	109	22	964		109.2	23.0	942.4	54
3/30/1989 0:00	108.9	22.4	972		109.1	23.4	942.4	54
3/30/1989 6:00	108.5	23.2	984		108.7	24.2	945.7	54
3/30/1989 12:00	108.4	24	989		108.6	25.0	950.0	61
3/30/1989 18:00	108.5	25	992		108.7	26.0	953.3	68
3/31/1989 0:00	108.7	26.1	994		108.9	27.1	958.7	75
3/31/1989 6:00	109.2	27.2	996		109.4	28.2	961.9	90
3/31/1989 9:00	109.8	27.9	997		110.0	28.9	961.9	100
3/31/1989 12:00	110.5	28.5	998		110.7	29.5	964.1	110
3/31/1989 15:00	110.6	29.2	999		111.8	30.2	967.4	120
3/31/1989 18:00	113	30.2	1000		113.2	31.2	967.4	140
3/31/1989 21:00	114.8	31.5	1001		115.0	32.5	972.8	180
4/1/1989 0:00	116.6	32.7	1002		116.8	33.7	972.8	230
4/1/1989 3:00	118.6	33.8	1002		118.8	34.8	975.0	250
4/1/1989 6:00	120.8	34.5	1003		121.0	35.5	978.2	270

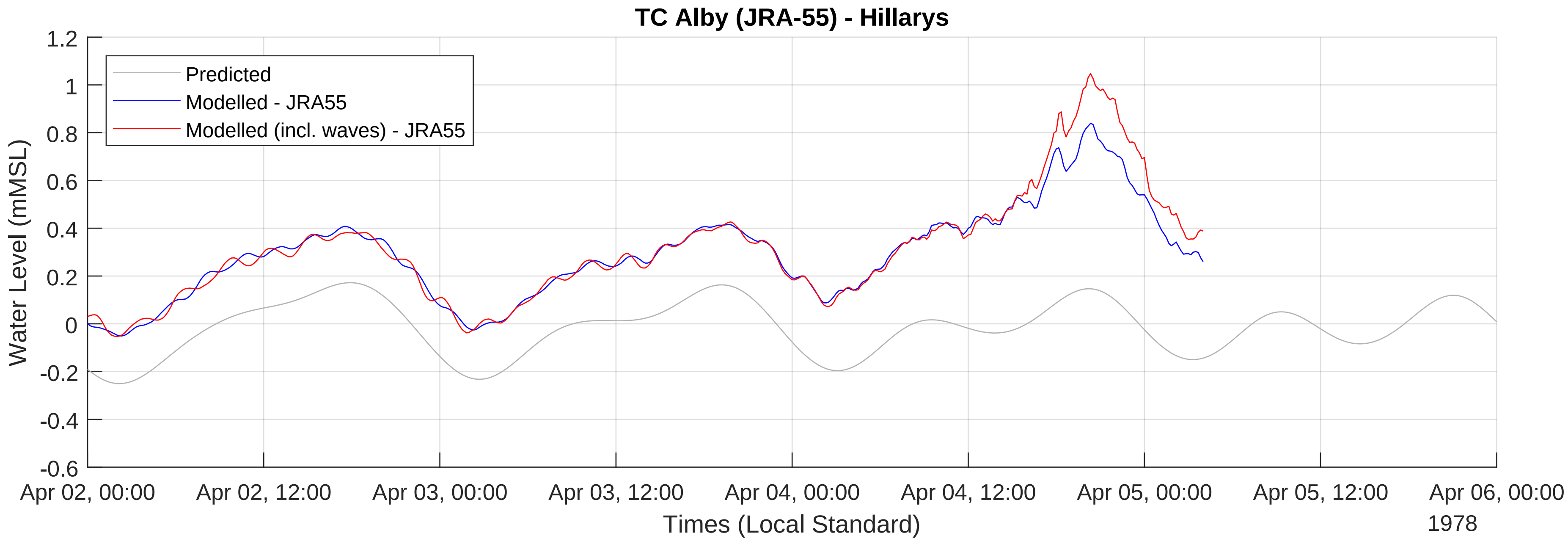
Appendix B

Hydrodynamic Model Storm Event Validation

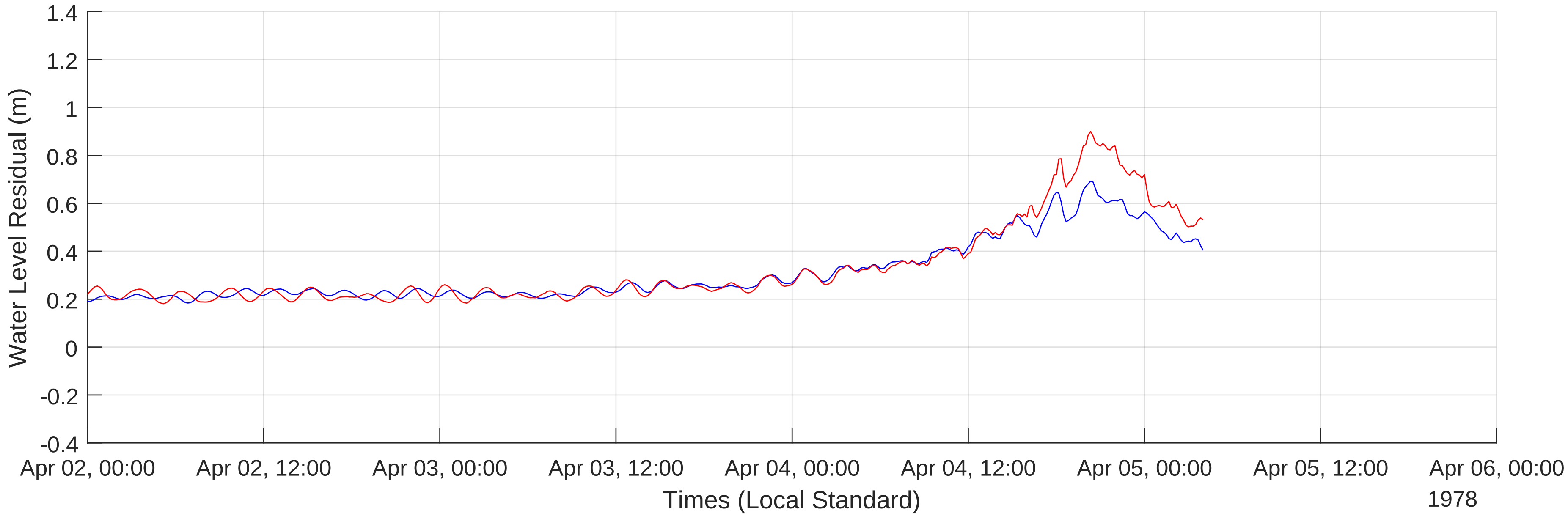
B.1 TC Alby (1978)


TC Alby (JRA-55) - Fremantle
Measured
Predicted
Modelled - JRA55
Modelled (incl. waves) - JRA55
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Apr 02, 00:00
Apr 02, 12:00
Apr 03, 00:00
Apr 03, 12:00
Apr 04, 00:00
Apr 04, 12:00
Apr 05, 00:00
Apr 05, 12:00
Apr 06, 00:00
1978
Times (Local Standard)


Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Apr 02, 00:00
Apr 02, 12:00
Apr 03, 00:00
Apr 03, 12:00
Apr 04, 00:00
Apr 04, 12:00
Apr 05, 00:00
Apr 05, 12:00
Apr 06, 00:00
1978
Times (Local Standard)

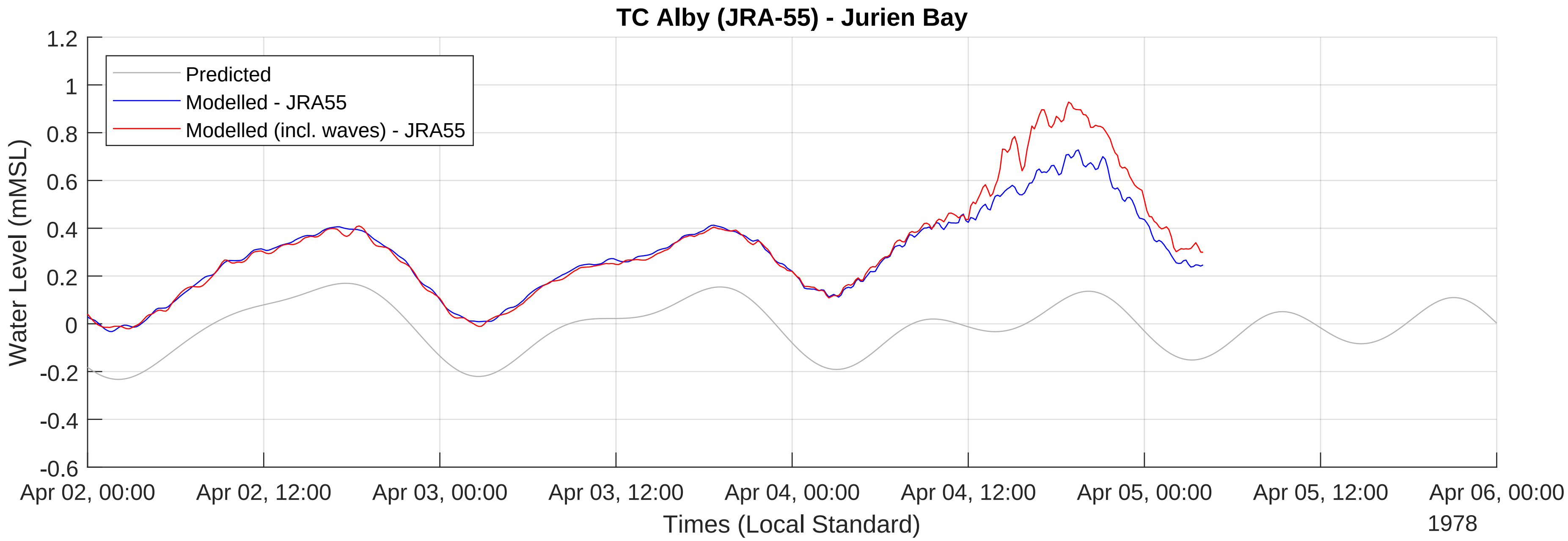


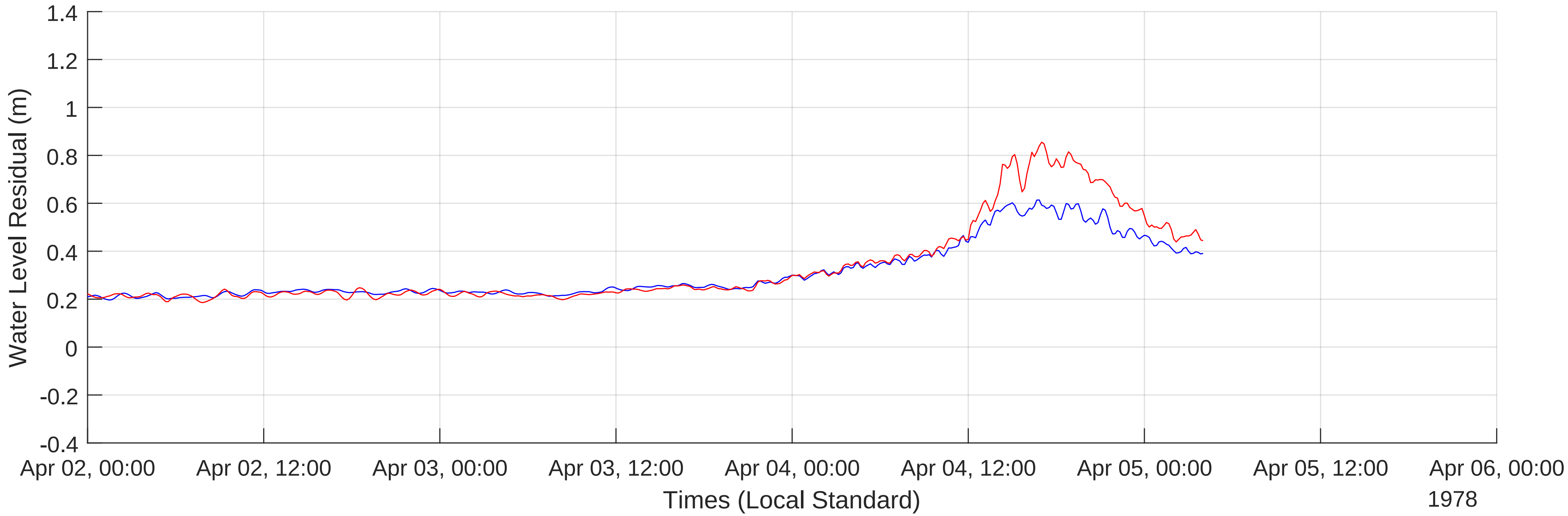
TC Alby (JRA-55) - Hillarys
Predicted
Modelled - JRA55
Modelled (incl. waves) - JRA55
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Apr 02, 00:00
Apr 02, 12:00
Apr 03, 00:00
Apr 03, 12:00
Apr 04, 00:00
Apr 04, 12:00
Apr 05, 00:00
Apr 05, 12:00
Apr 06, 00:00
1978
Times (Local Standard)

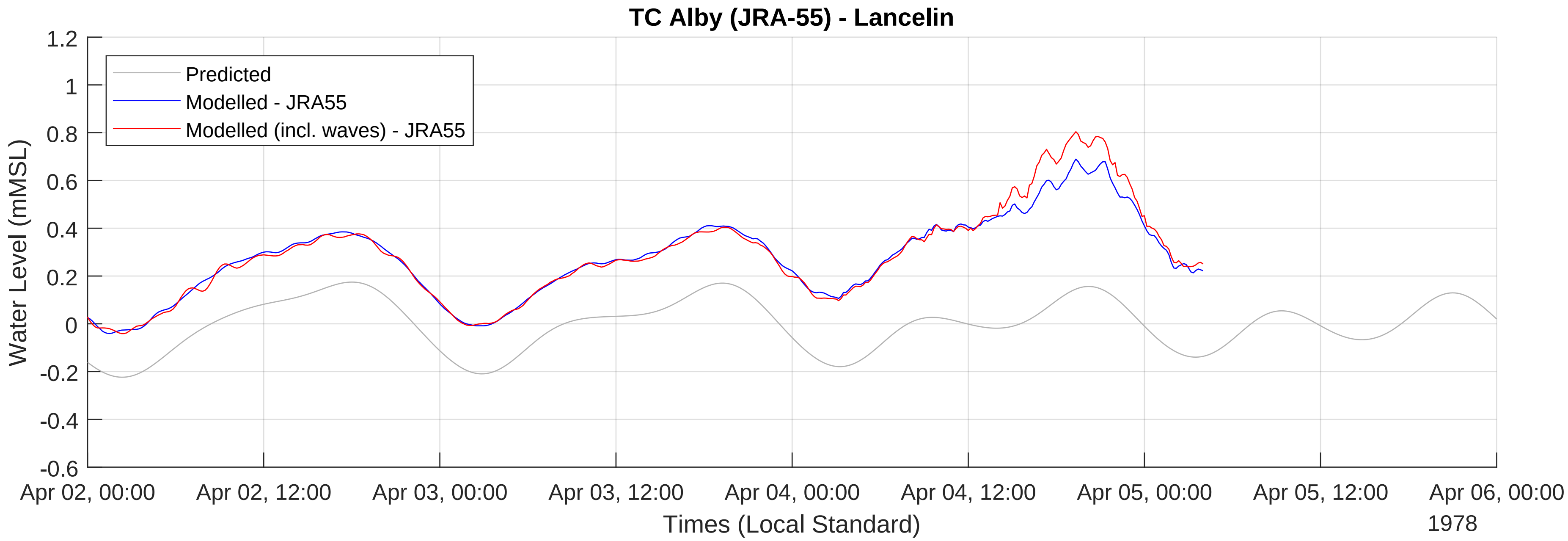


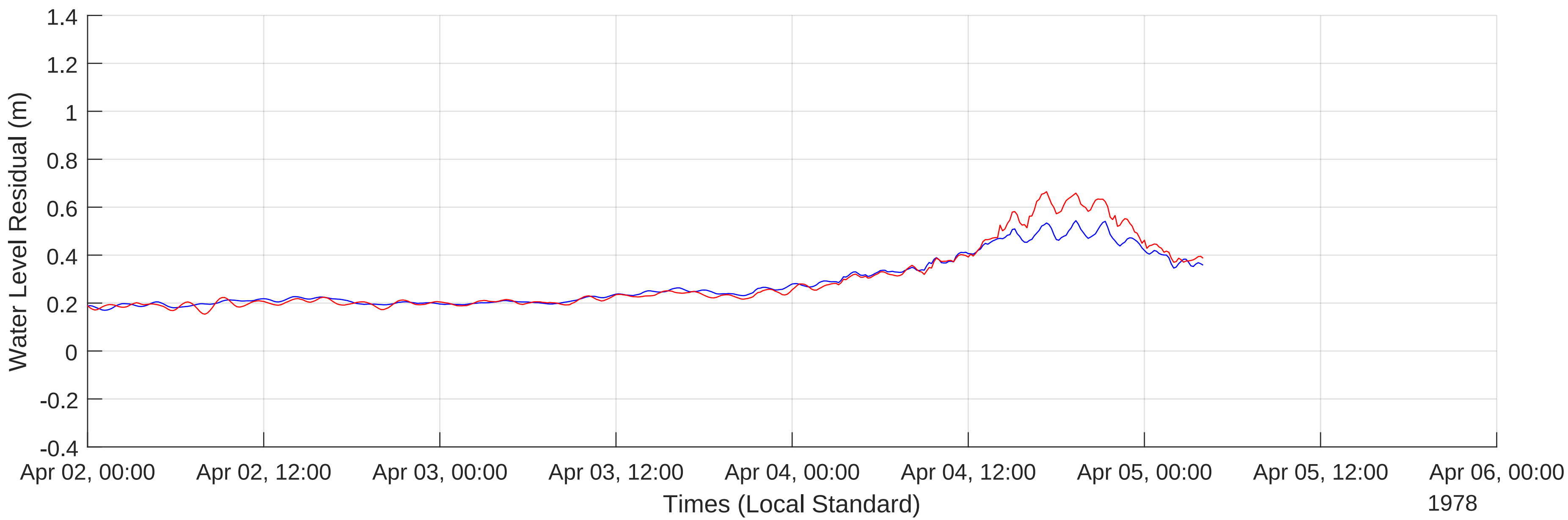
Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Apr 02, 00:00
Apr 02, 12:00
Apr 03, 00:00
Apr 03, 12:00
Apr 04, 00:00
Apr 04, 12:00
Apr 05, 00:00
Apr 05, 12:00
Apr 06, 00:00
1978
Times (Local Standard)

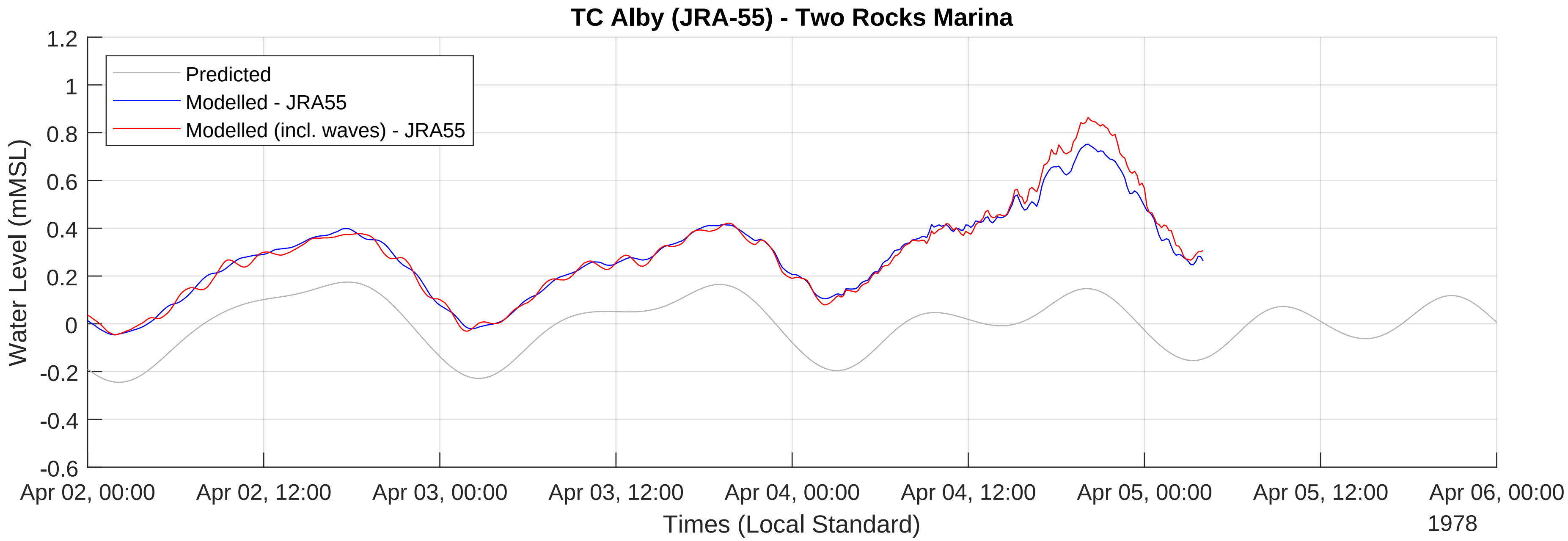
Baird.

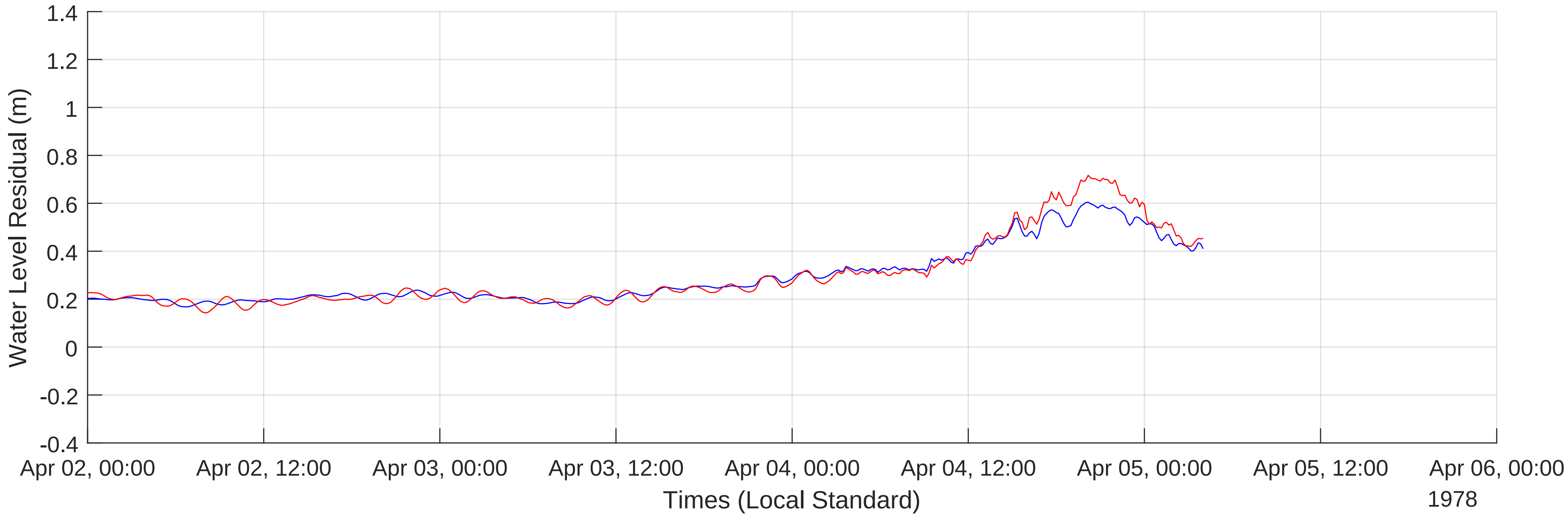

TC Alby (JRA-55) - Jurien Bay
Predicted
Modelled - JRA55
Modelled (incl. waves) - JRA55
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Apr 02, 00:00
Apr 02, 12:00
Apr 03, 00:00
Apr 03, 12:00
Apr 04, 00:00
Apr 04, 12:00
Apr 05, 00:00
Apr 05, 12:00
Apr 06, 00:00
1978
Times (Local Standard)


Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Apr 02, 00:00
Apr 02, 12:00
Apr 03, 00:00
Apr 03, 12:00
Apr 04, 00:00
Apr 04, 12:00
Apr 05, 00:00
Apr 05, 12:00
Apr 06, 00:00
1978
Times (Local Standard)

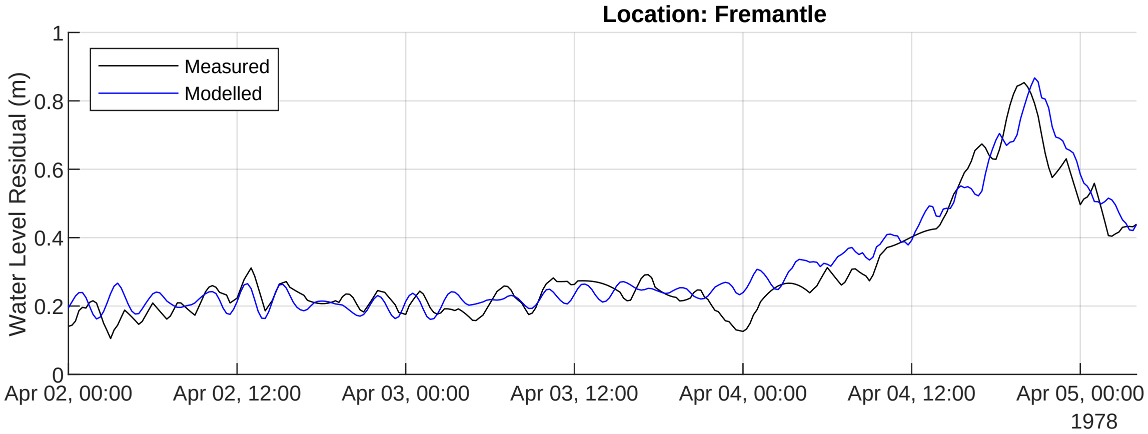

TC Alby (JRA-55) - Lancelin
Predicted
Modelled - JRA55
Modelled (incl. waves) - JRA55
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Apr 02, 00:00
Apr 02, 12:00
Apr 03, 00:00
Apr 03, 12:00
Apr 04, 00:00
Apr 04, 12:00
Apr 05, 00:00
Apr 05, 12:00
Apr 06, 00:00
1978
Times (Local Standard)

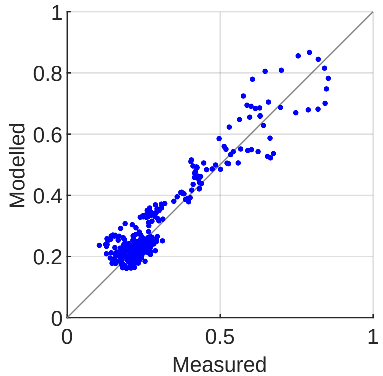

Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Apr 02, 00:00
Apr 02, 12:00
Apr 03, 00:00
Apr 03, 12:00
Apr 04, 00:00
Apr 04, 12:00
Apr 05, 00:00
Apr 05, 12:00
Apr 06, 00:00
1978
Times (Local Standard)


TC Alby (JRA-55) - Two Rocks Marina
Predicted
Modelled - JRA55
Modelled (incl. waves) - JRA55
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Apr 02, 00:00
Apr 02, 12:00
Apr 03, 00:00
Apr 03, 12:00
Apr 04, 00:00
Apr 04, 12:00
Apr 05, 00:00
Apr 05, 12:00
Apr 06, 00:00
1978
Times (Local Standard)


Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Apr 02, 00:00
Apr 02, 12:00
Apr 03, 00:00
Apr 03, 12:00
Apr 04, 00:00
Apr 04, 12:00
Apr 05, 00:00
Apr 05, 12:00
Apr 06, 00:00
1978
Times (Local Standard)

Baird.





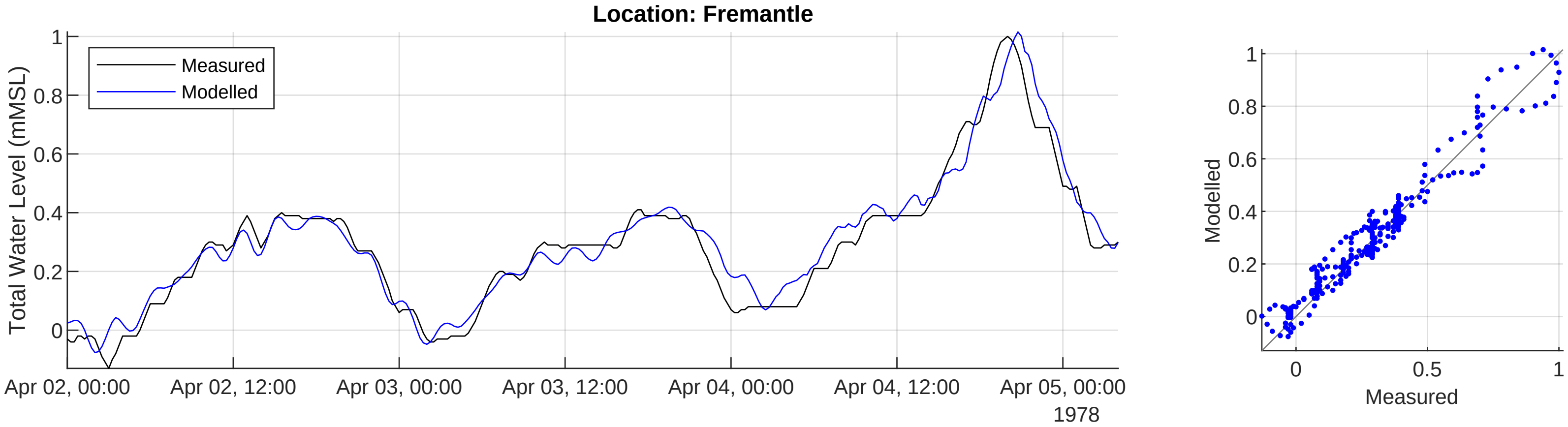
Water Level Residual (m)

Scatter: 0.180

Bias: 0.014

Skill: 0.971

RMS error: 0.054



Total Water Level (mMSL)

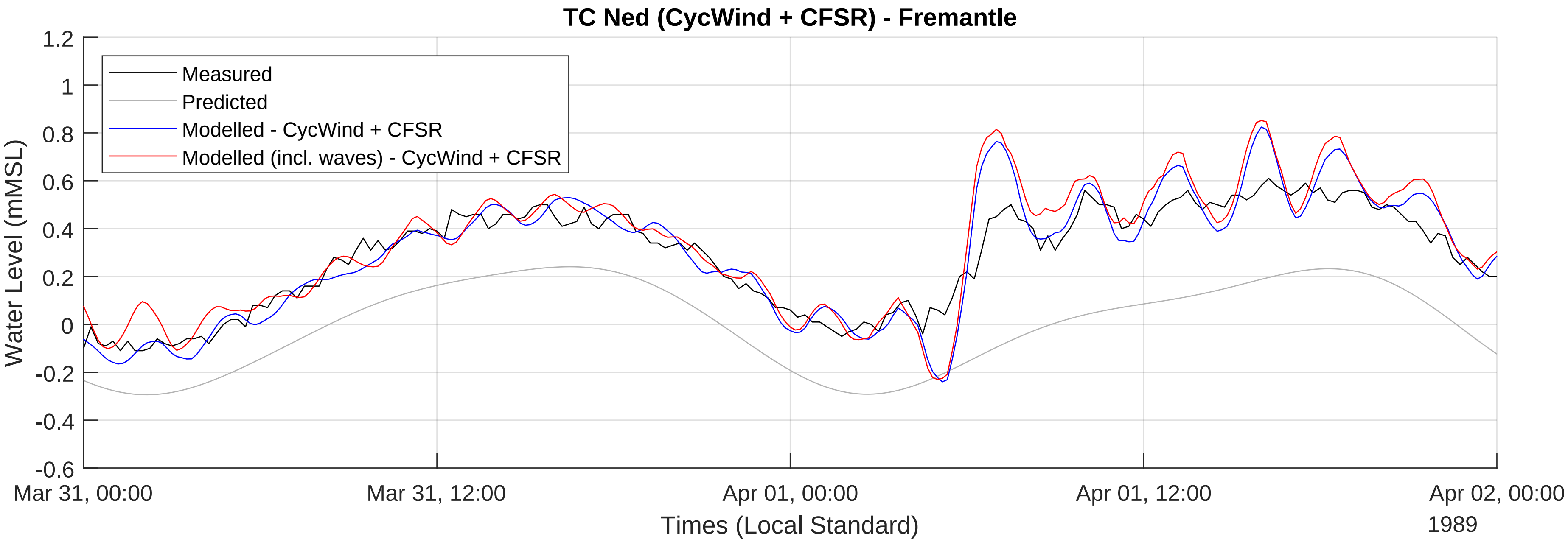
Scatter: 0.131

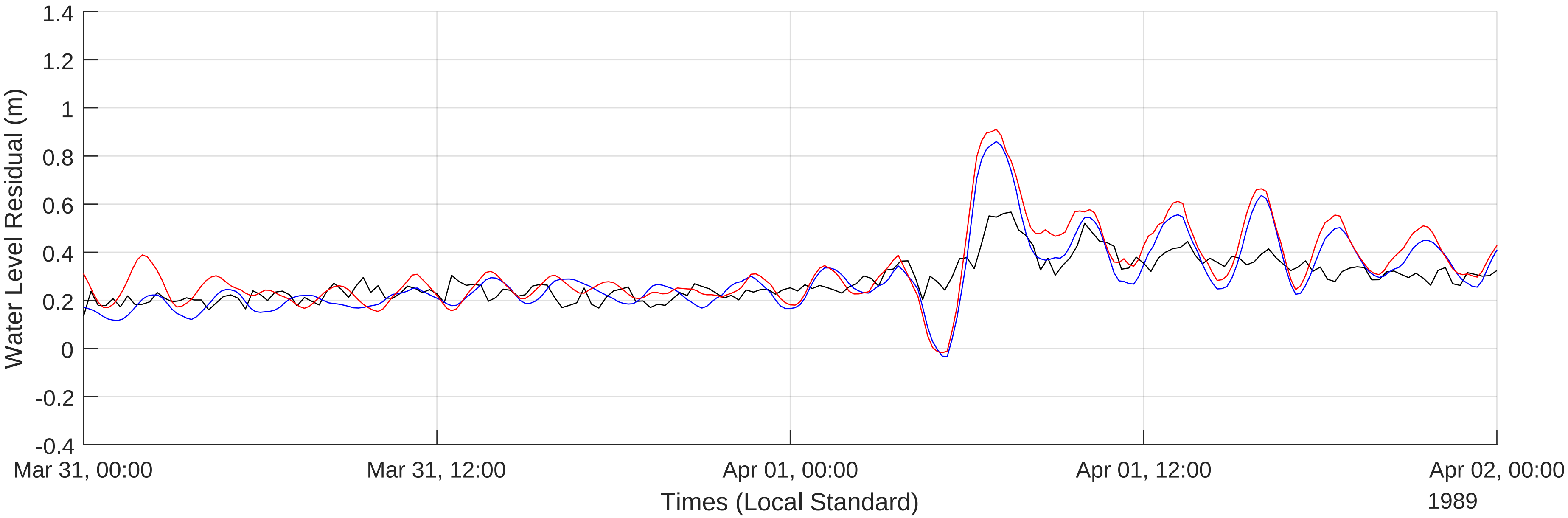
Bias: 0.014

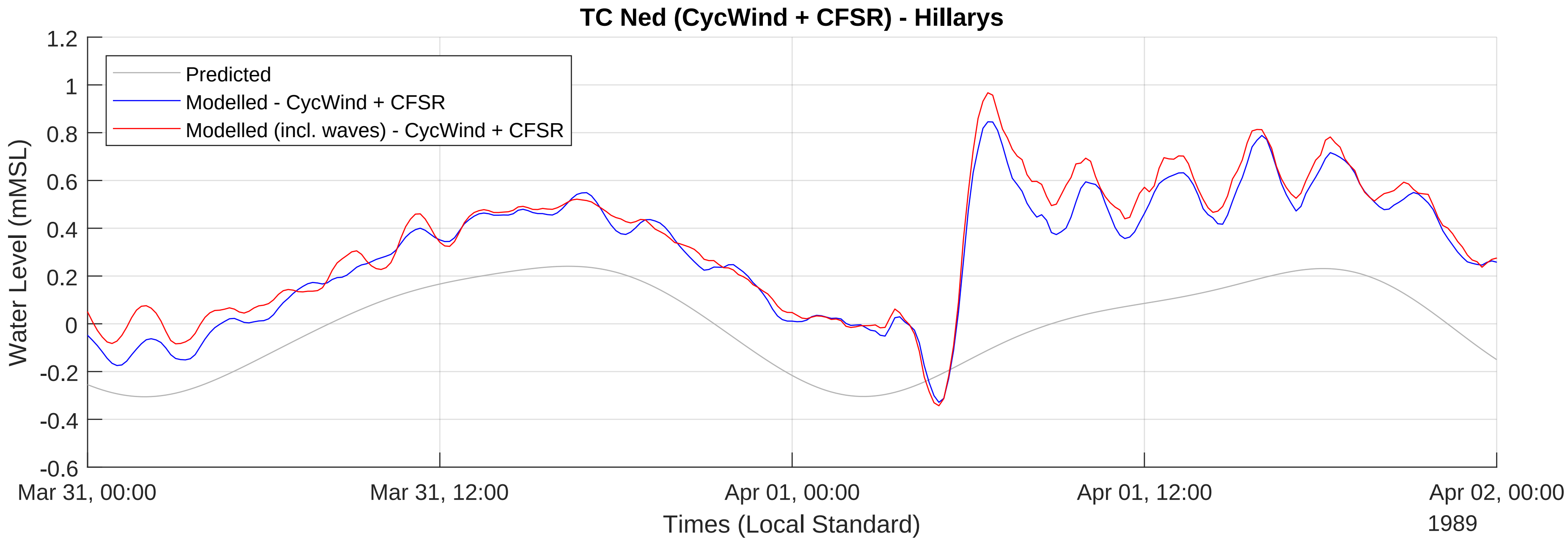
Skill: 0.985

RMS error: 0.054

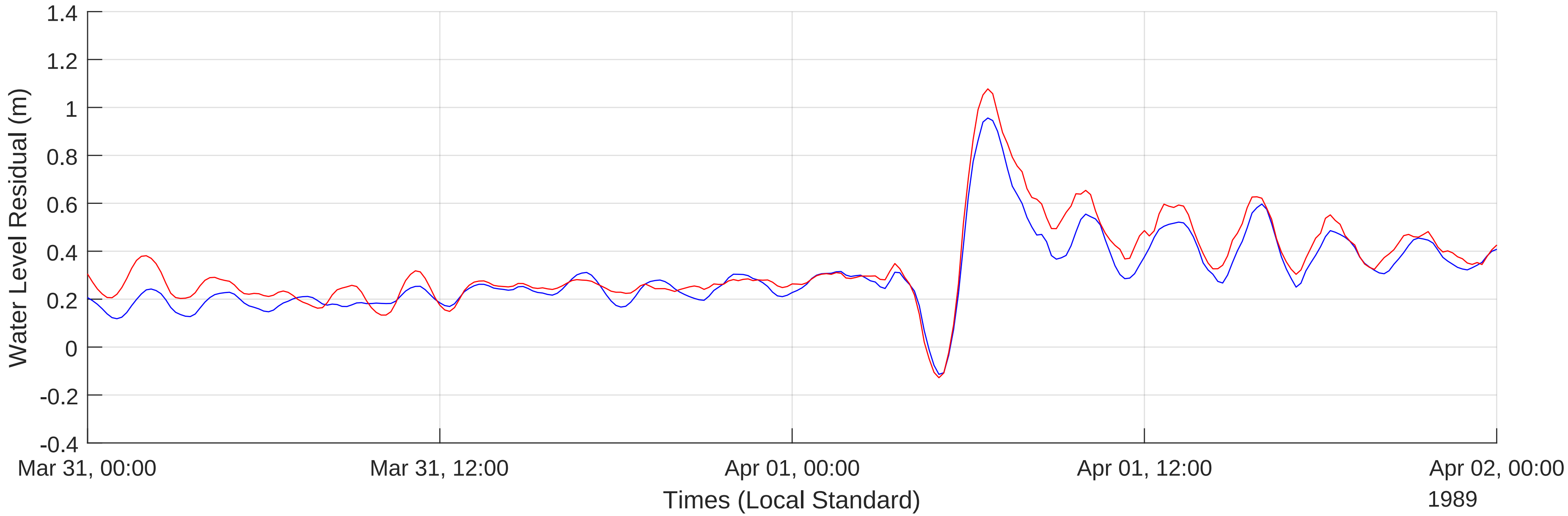
B.2 TC Ned (1989)


TC Ned (CycWind + CFSR) - Fremantle
Measured
Predicted
Modelled - CycWind + CFSR
Modelled (incl. waves) - CycWind + CFSR
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)

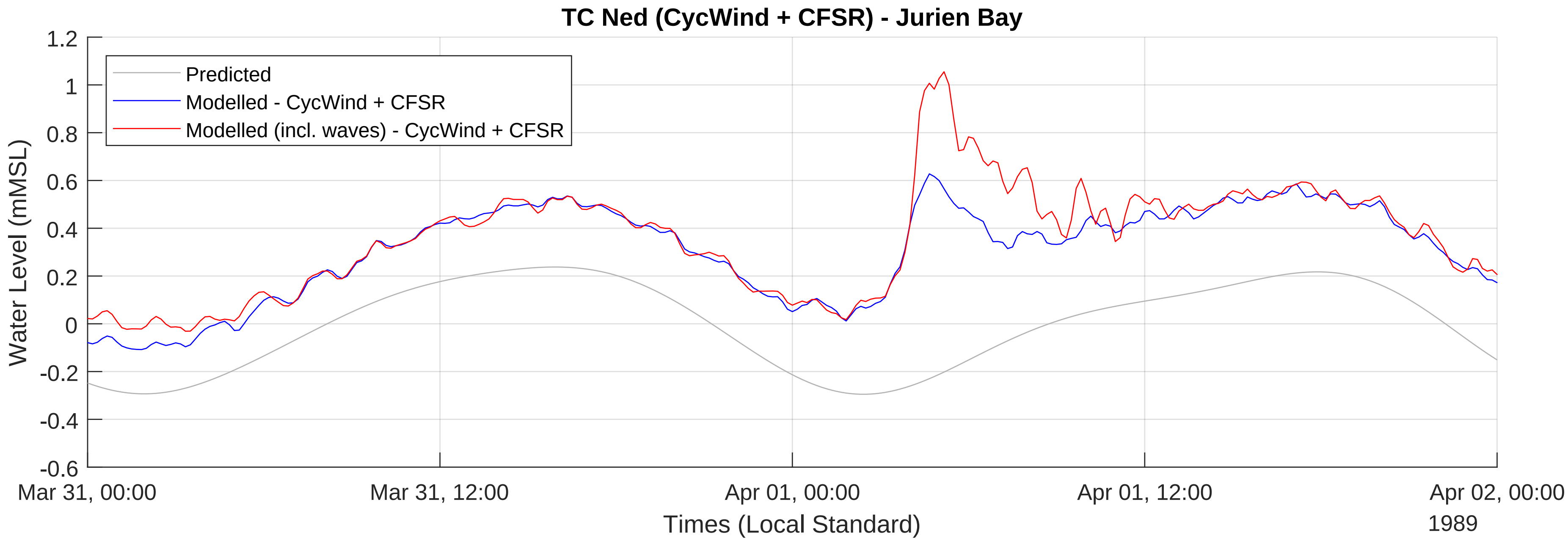

Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)

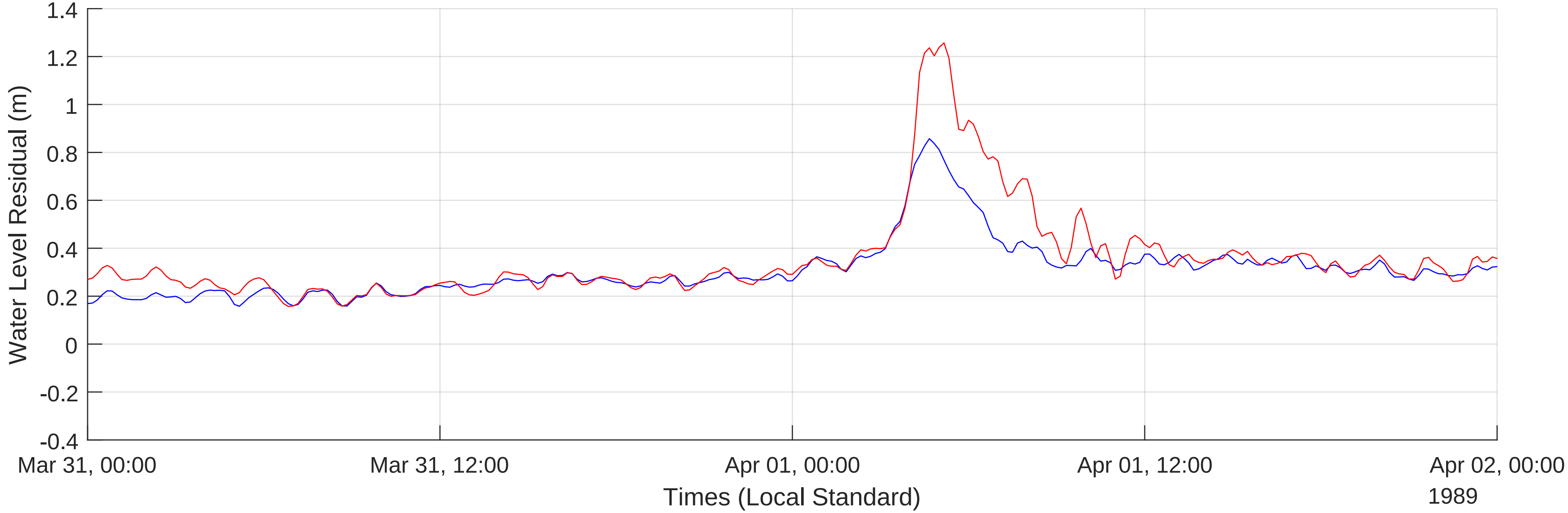


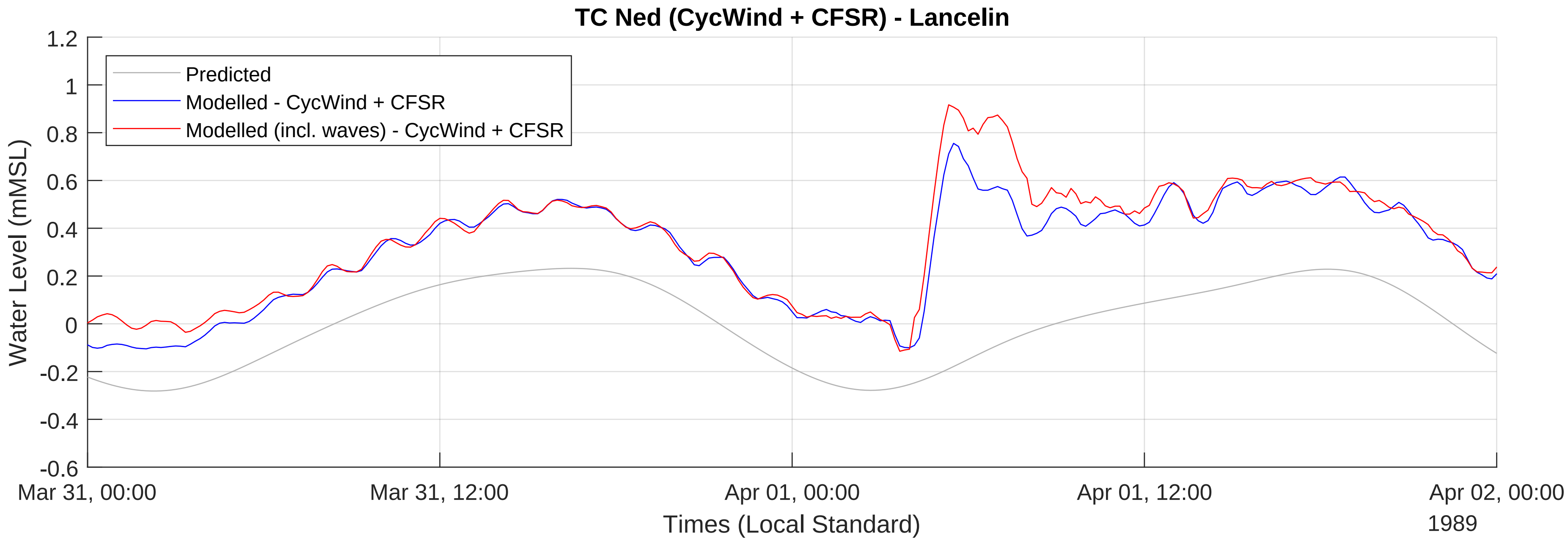
TC Ned (CycWind + CFSR) - Hillarys
Predicted
Modelled - CycWind + CFSR
Modelled (incl. waves) - CycWind + CFSR
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)



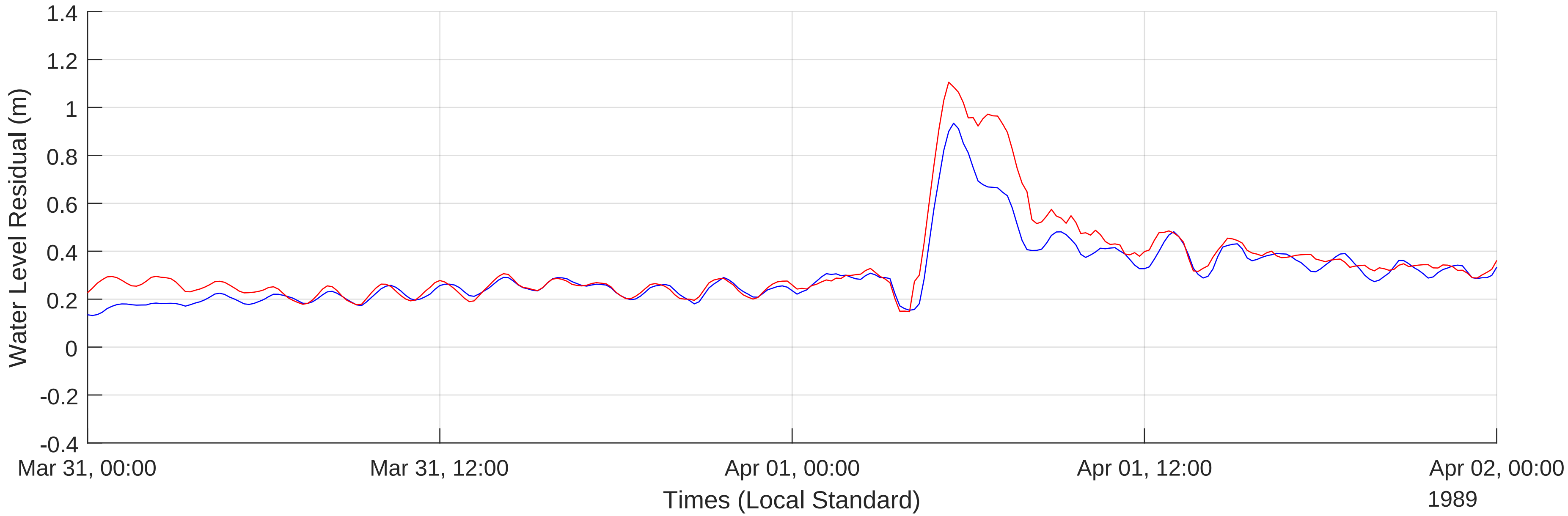
Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)


TC Ned (CycWind + CFSR) - Jurien Bay
Predicted
Modelled - CycWind + CFSR
Modelled (incl. waves) - CycWind + CFSR
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)

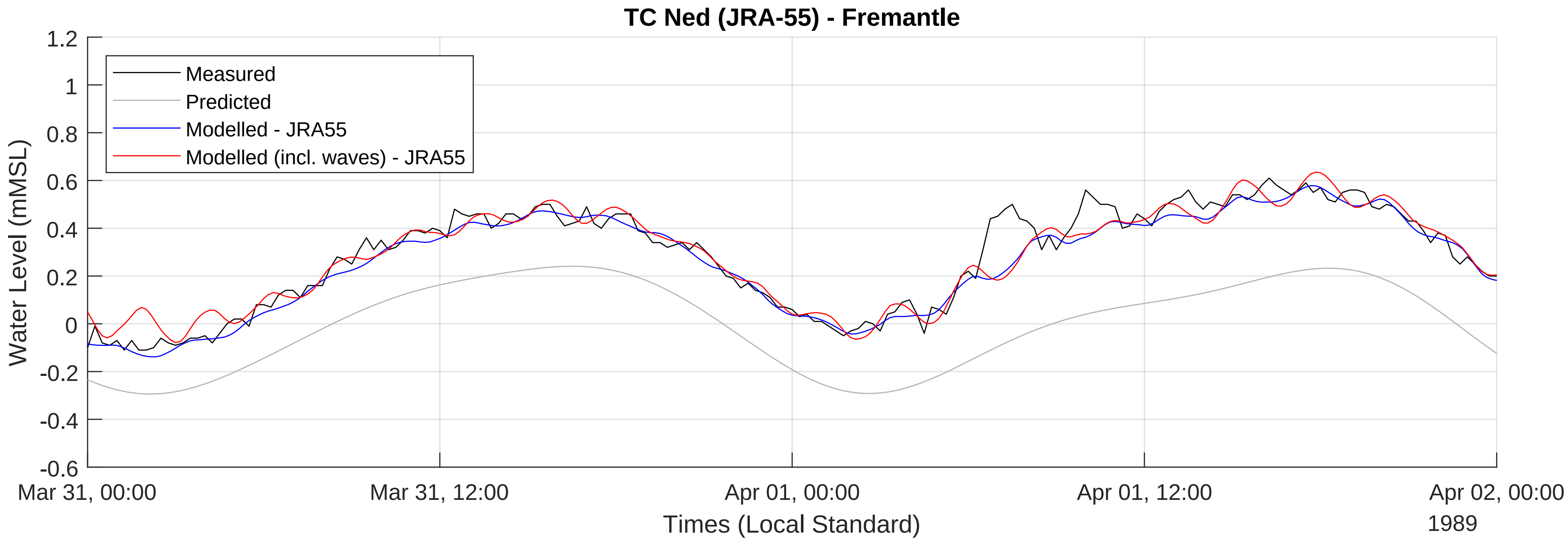

Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)



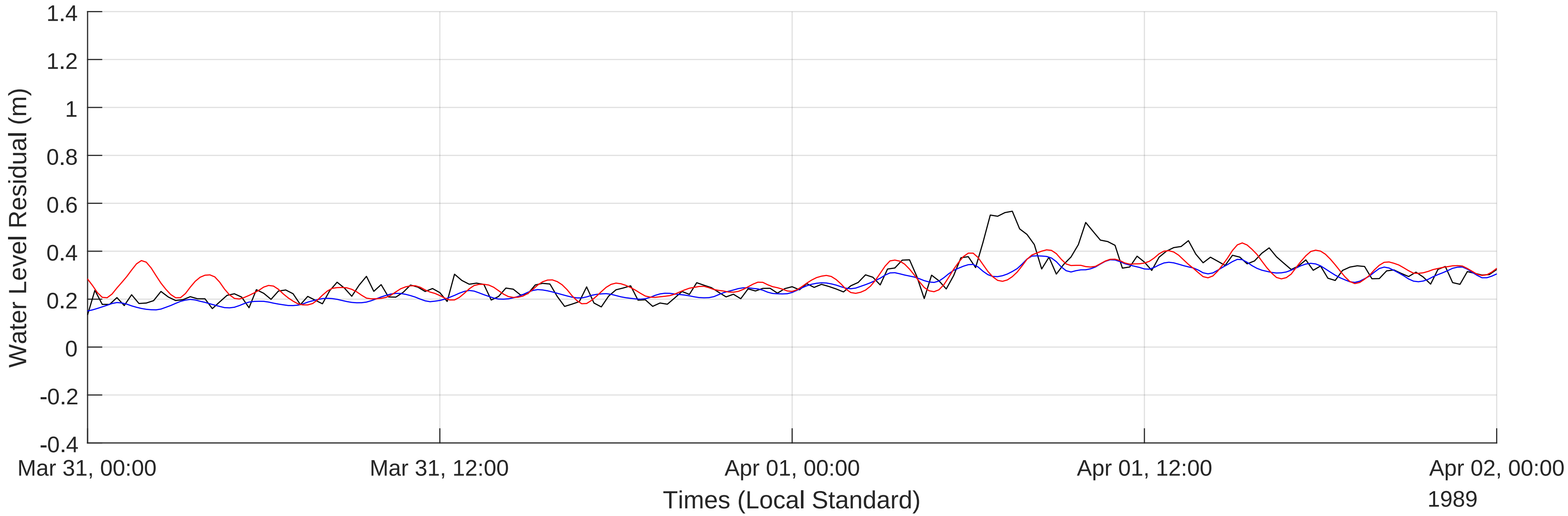
TC Ned (CycWind + CFSR) - Lancelin
Predicted
Modelled - CycWind + CFSR
Modelled (incl. waves) - CycWind + CFSR
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)



Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)

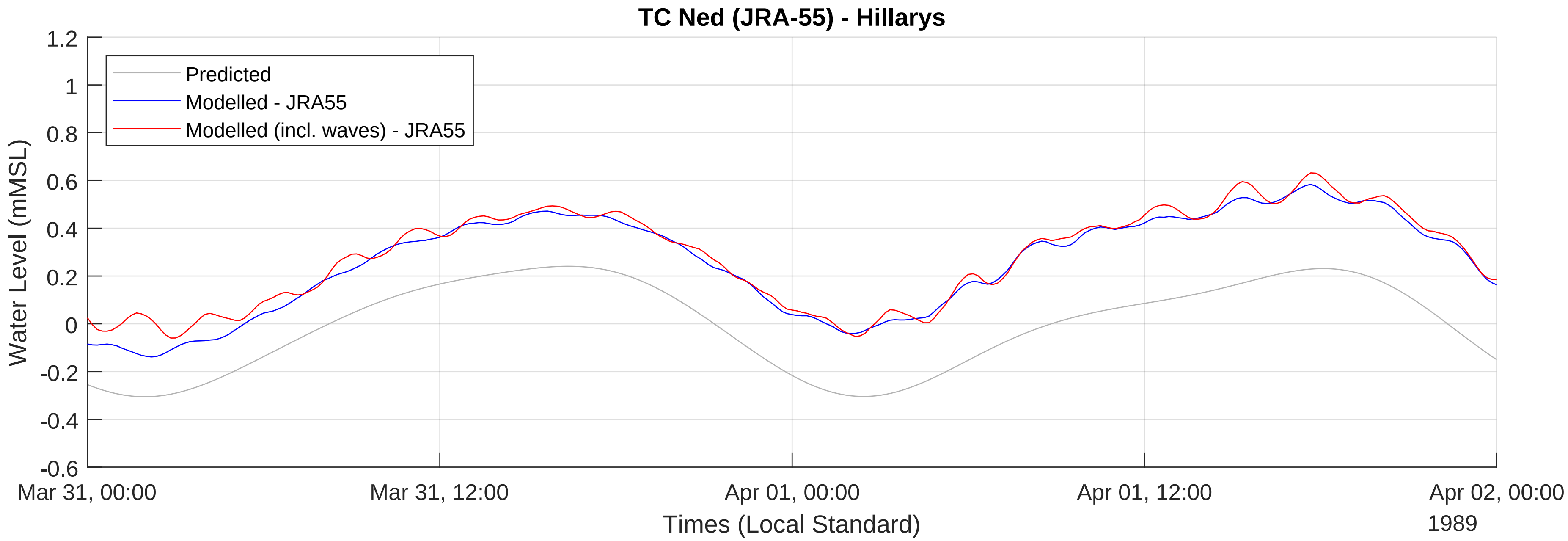


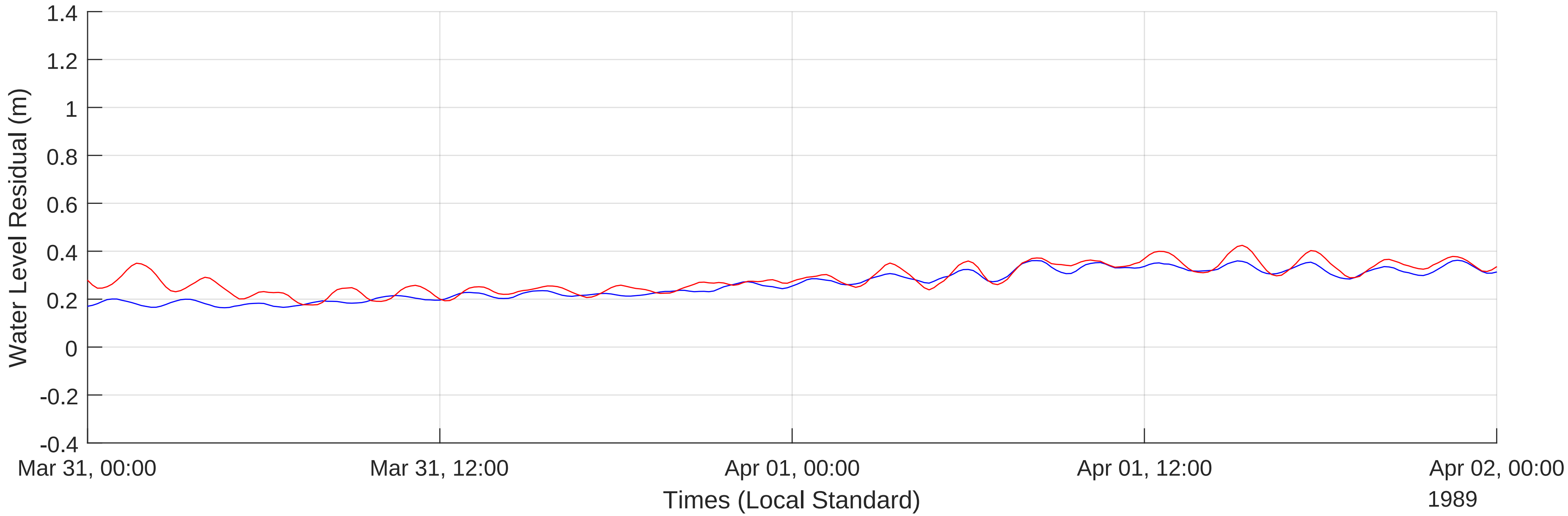
TC Ned (JRA-55) - Fremantle
Measured
Predicted
Modelled - JRA55
Modelled (incl. waves) - JRA55
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)

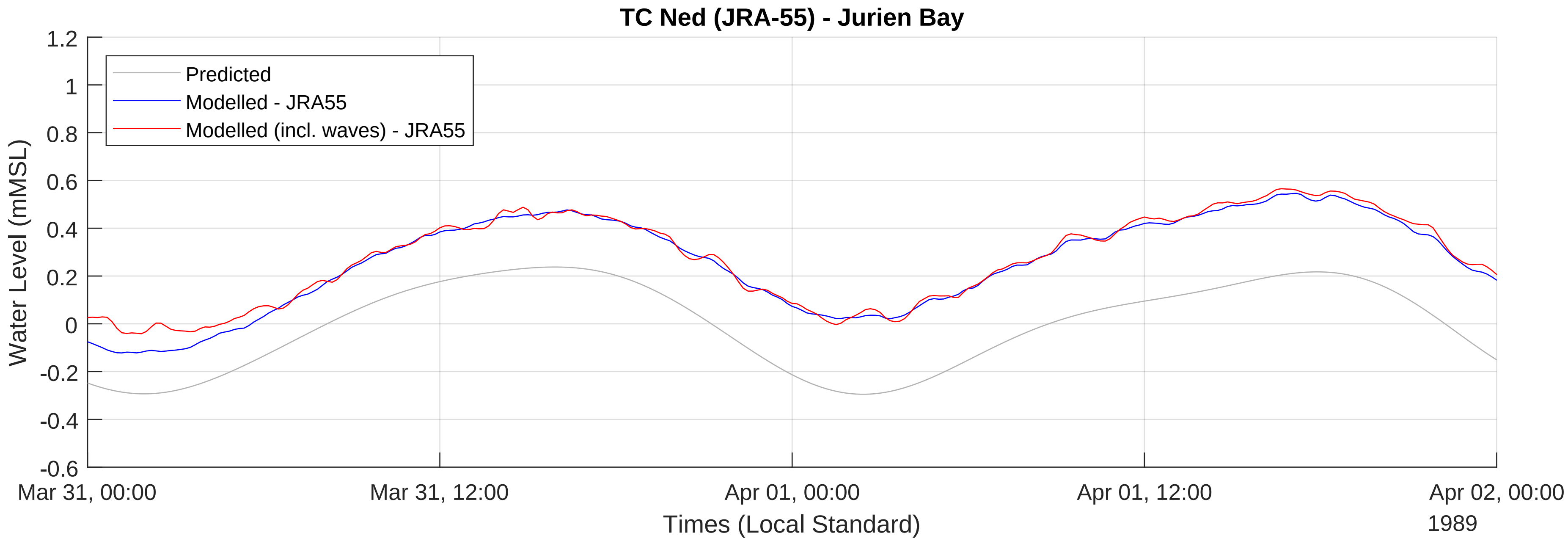


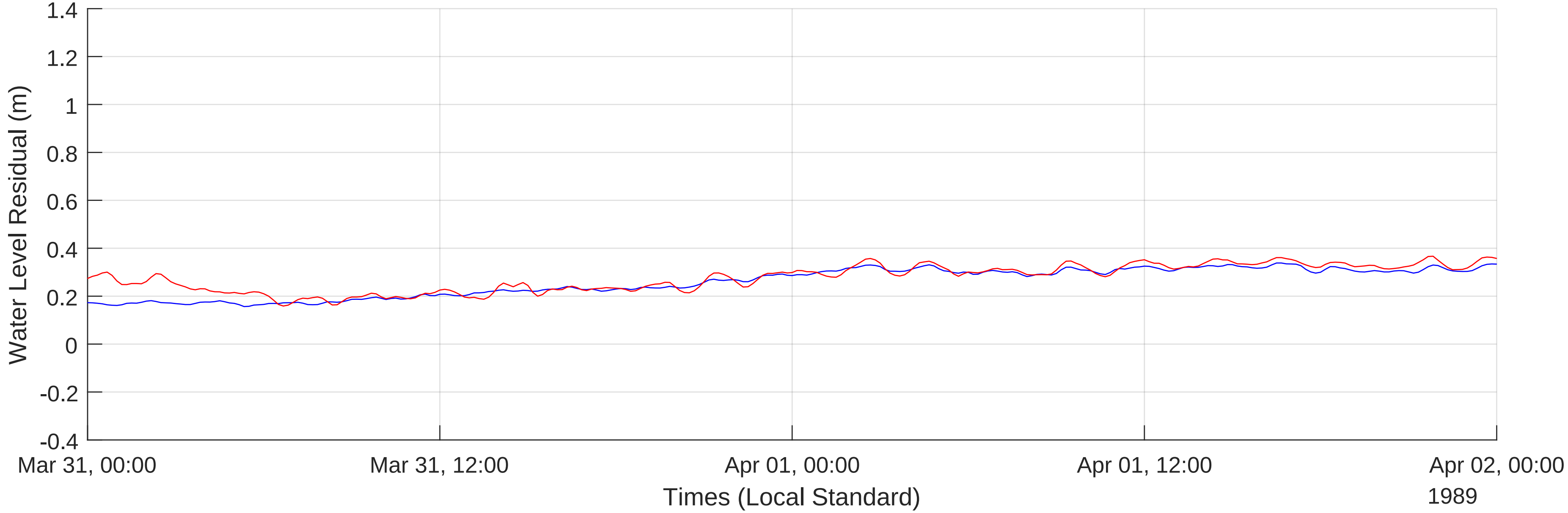
Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)

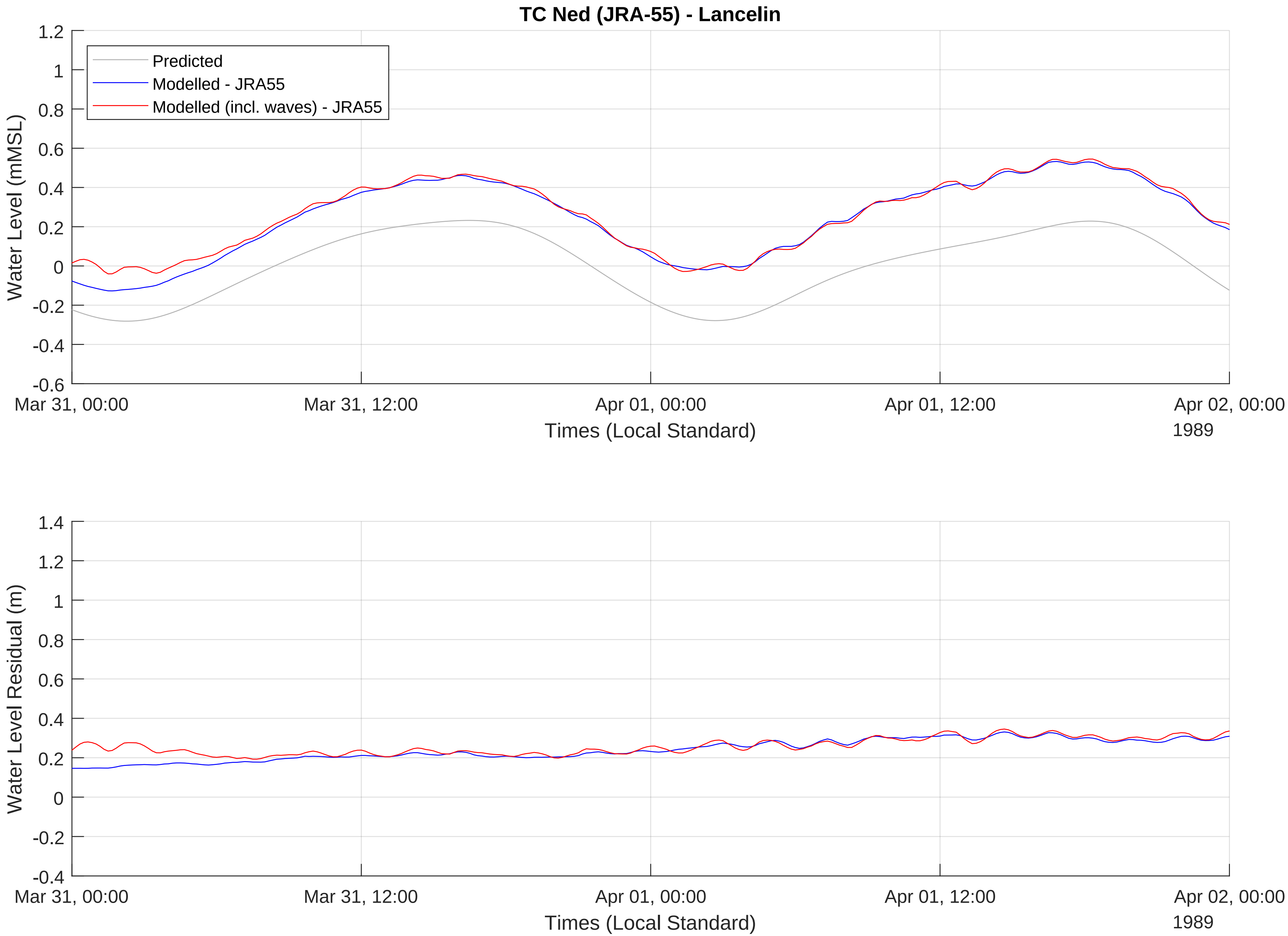
TC Ned (JRA-55) - Hillarys

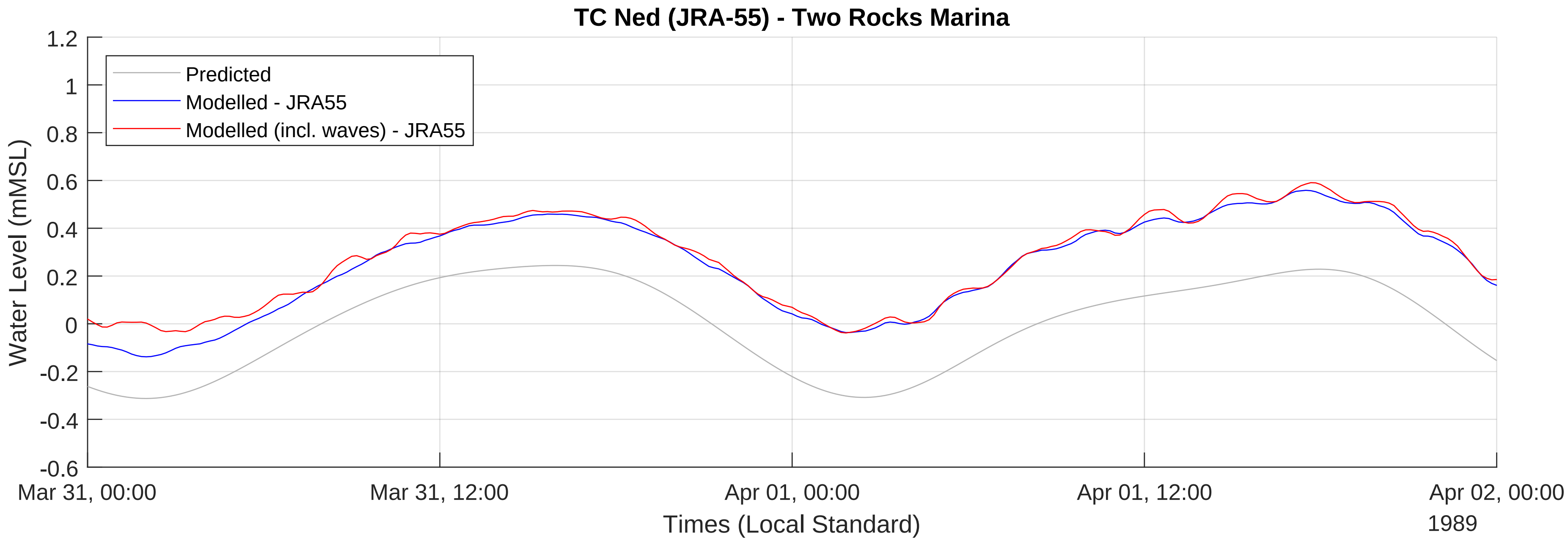


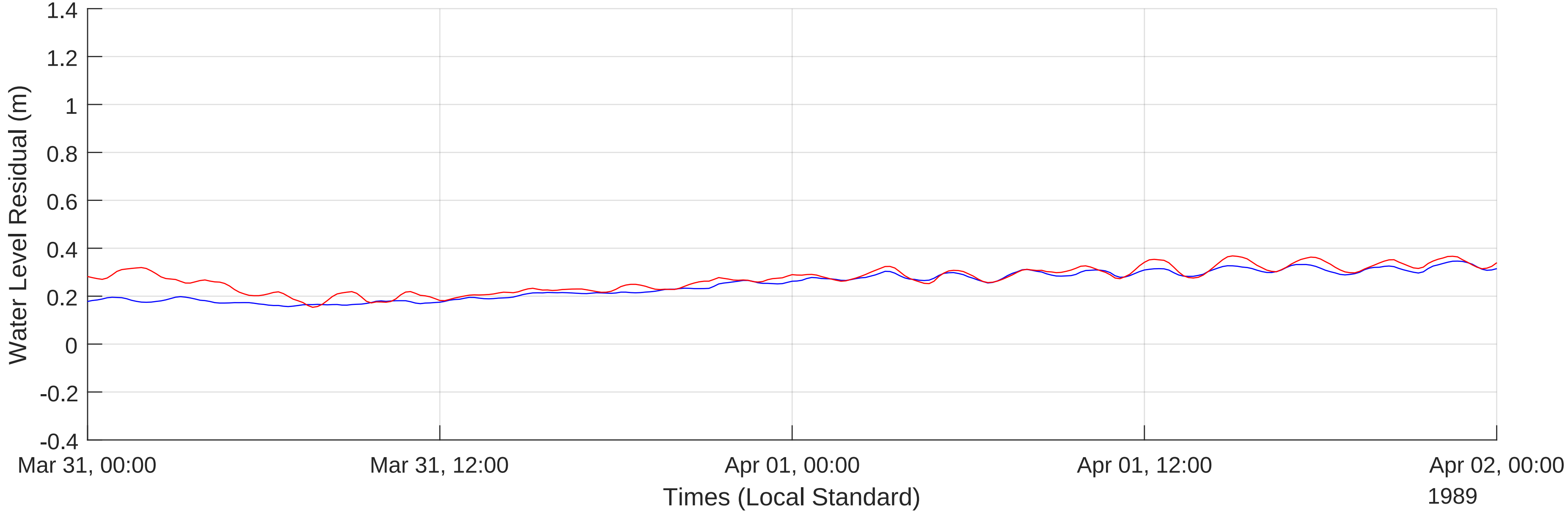



TC Ned (JRA-55) - Jurien Bay
Predicted
Modelled - JRA55
Modelled (incl. waves) - JRA55
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)

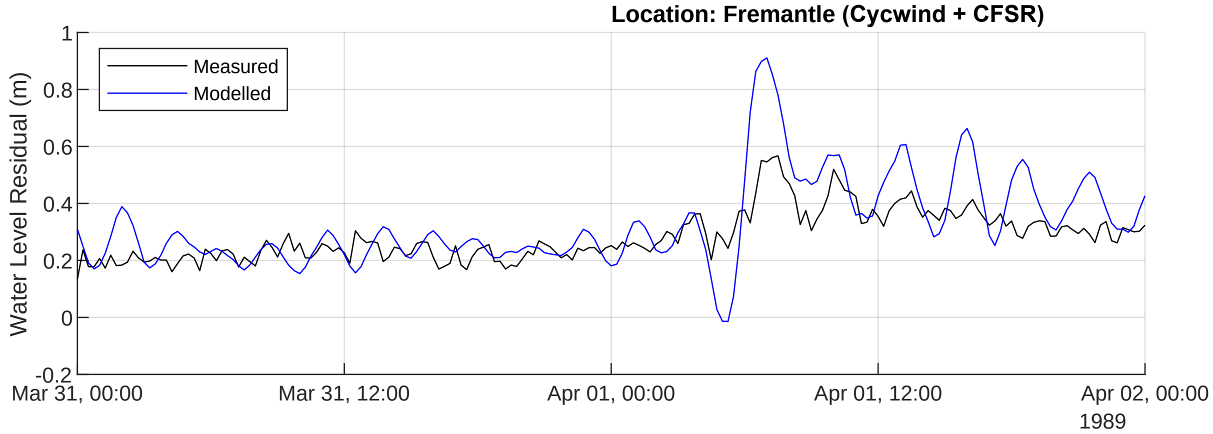

Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)

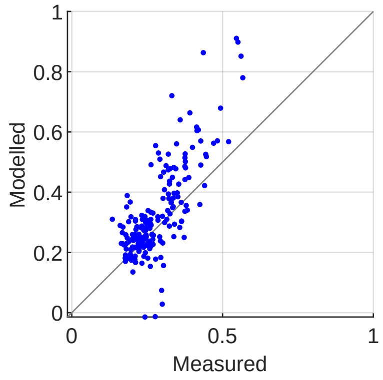

TC Ned (JRA-55) - Lancelin
Predicted
Modelled - JRA55
Modelled (incl. waves) - JRA55
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)
Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)


TC Ned (JRA-55) - Two Rocks Marina
Predicted
Modelled - JRA55
Modelled (incl. waves) - JRA55
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)


Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Mar 31, 00:00
Mar 31, 12:00
Apr 01, 00:00
Apr 01, 12:00
Apr 02, 00:00
1989
Times (Local Standard)

Baird.





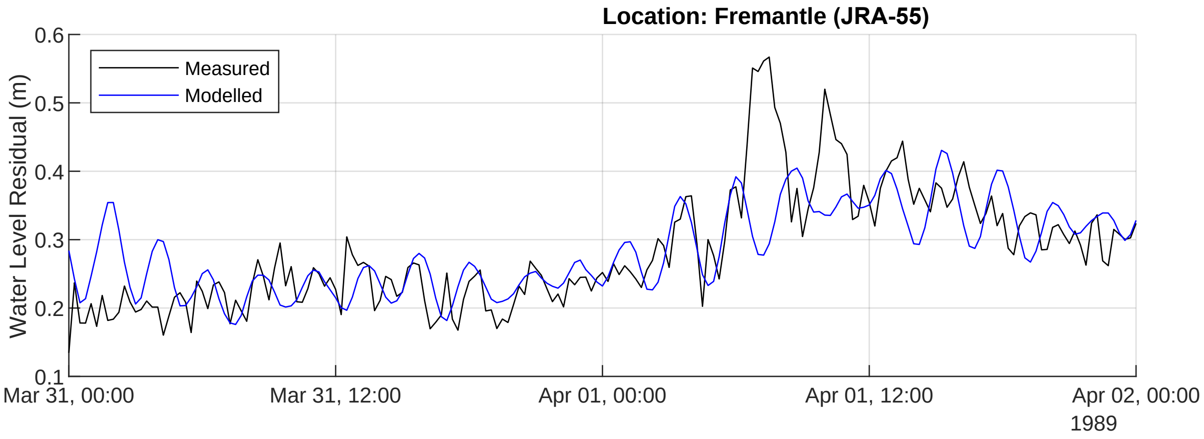
Water Level Residual (m)

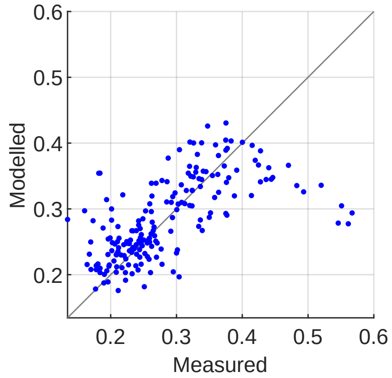
Scatter: 0.403

Bias: 0.046

Skill: 0.759

RMS error: 0.114





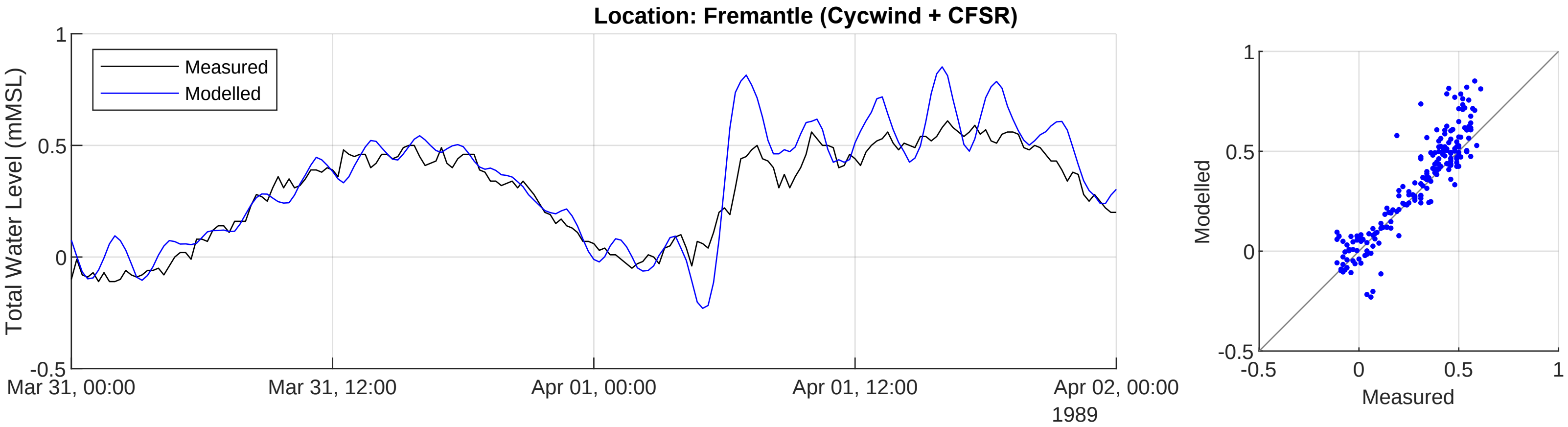
Water Level Residual (m)

Scatter: 0.233

Bias: 0.000

Skill: 0.755

RMS error: 0.066



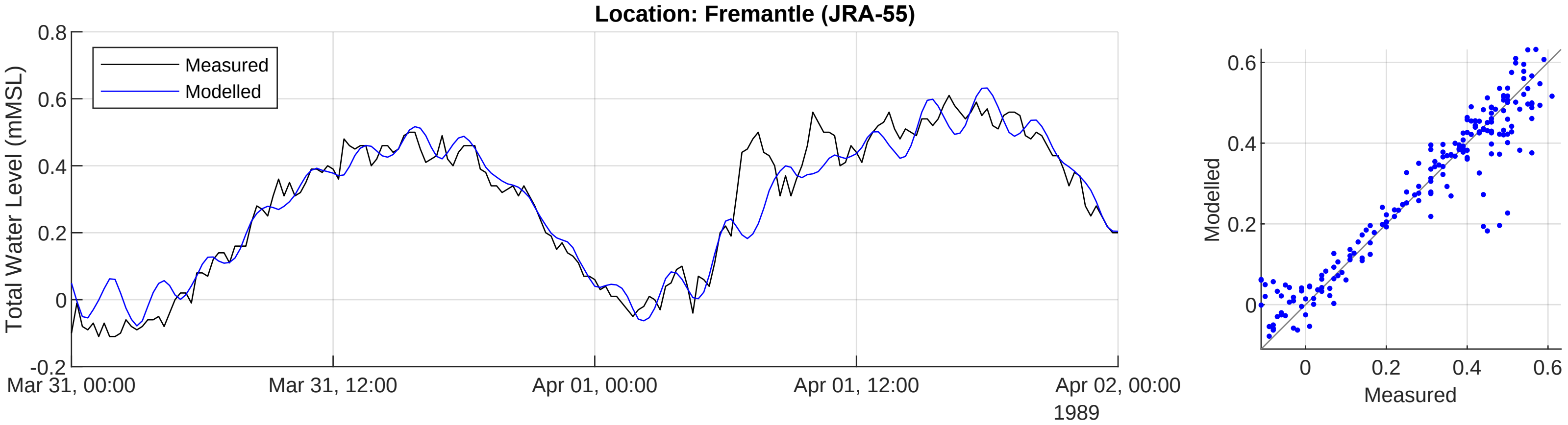
Total Water Level (mMSL)

Scatter: 0.287

Bias: 0.046

Skill: 0.938

RMS error: 0.114



Total Water Level (mMSL)

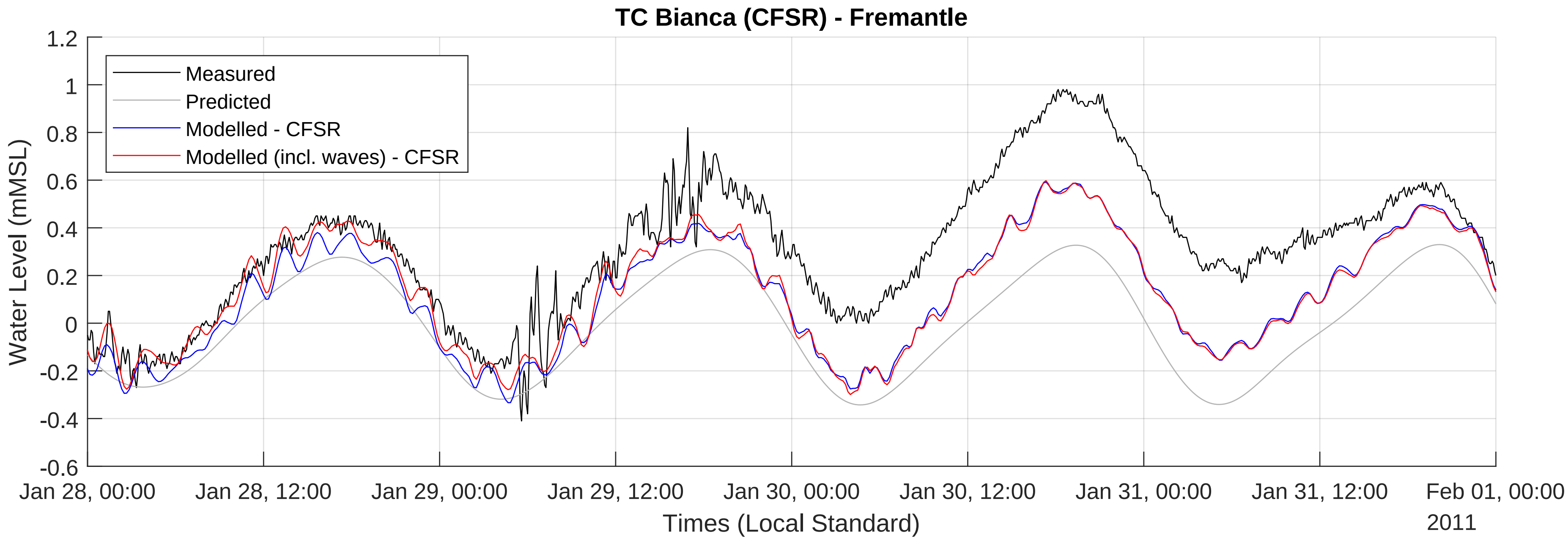
Scatter: 0.166

Bias: 0.000

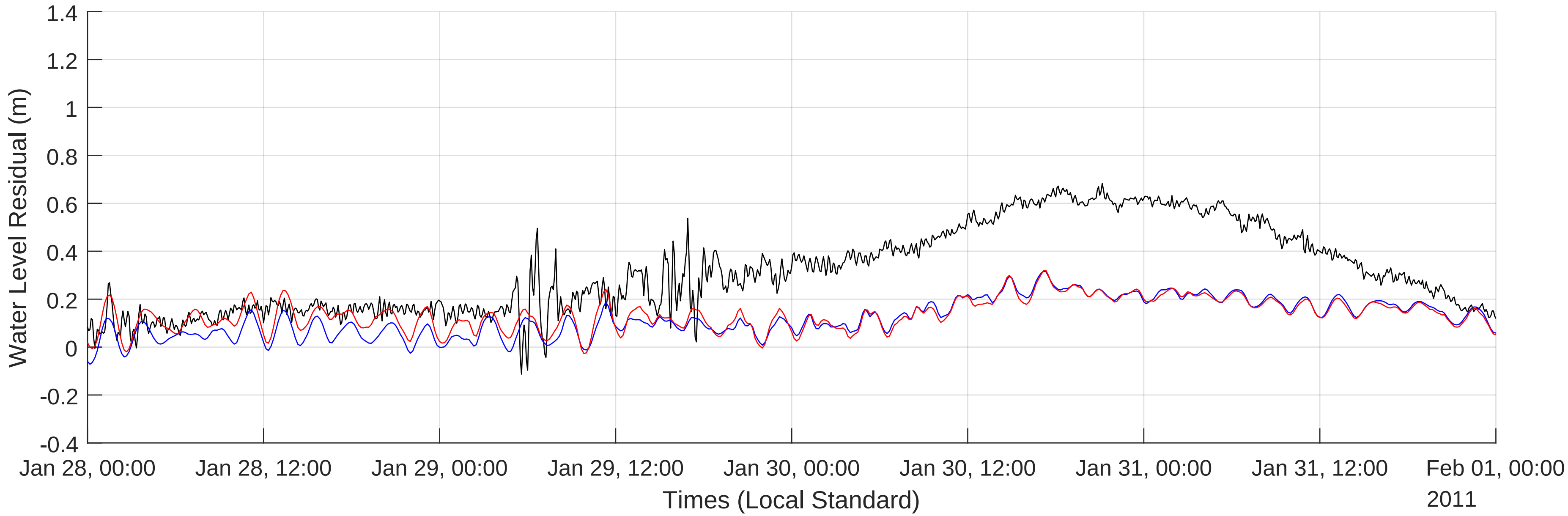
Skill: 0.973

RMS error: 0.066

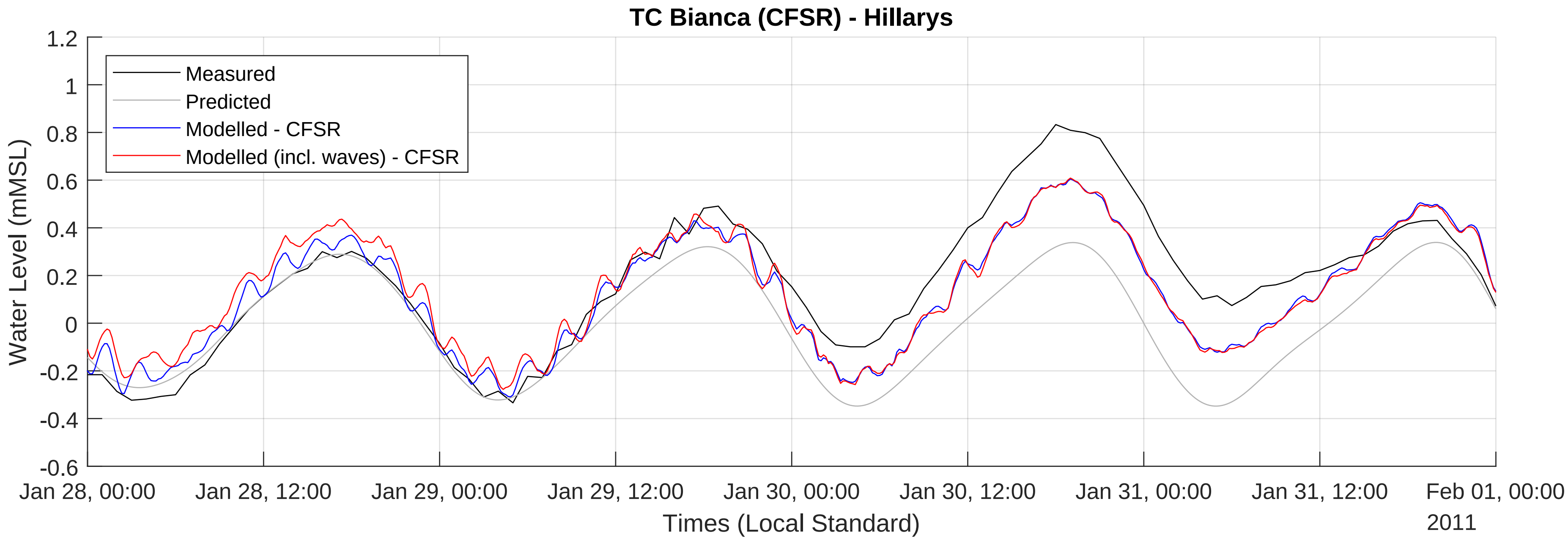
B.3 TC Bianca (2011)



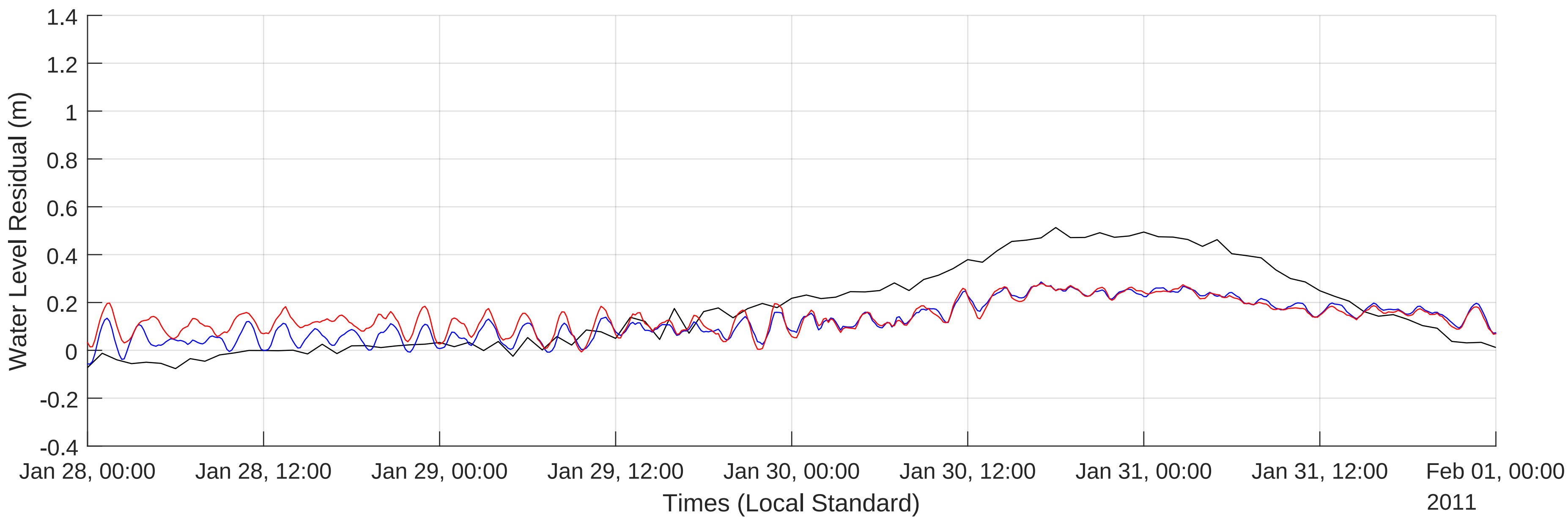
TC Bianca (CFSR) - Fremantle
Measured
Predicted
Modelled - CFSR
Modelled (incl. waves) - CFSR
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Jan 28, 00:00
Jan 28, 12:00
Jan 29, 00:00
Jan 29, 12:00
Jan 30, 00:00
Jan 30, 12:00
Jan 31, 00:00
Jan 31, 12:00
Feb 01, 00:00
2011
Times (Local Standard)



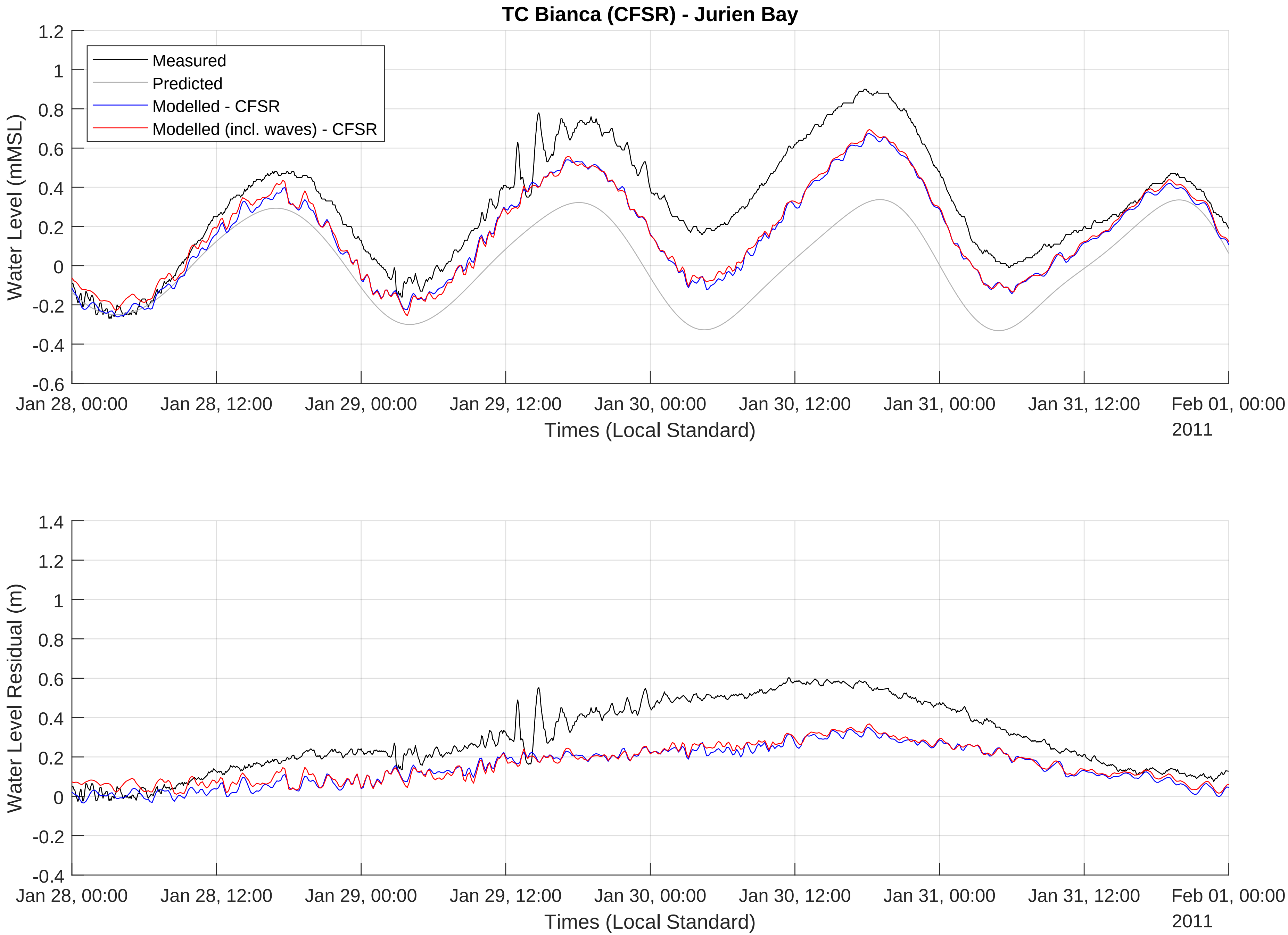
Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Jan 28, 00:00
Jan 28, 12:00
Jan 29, 00:00
Jan 29, 12:00
Jan 30, 00:00
Jan 30, 12:00
Jan 31, 00:00
Jan 31, 12:00
Feb 01, 00:00
2011
Times (Local Standard)



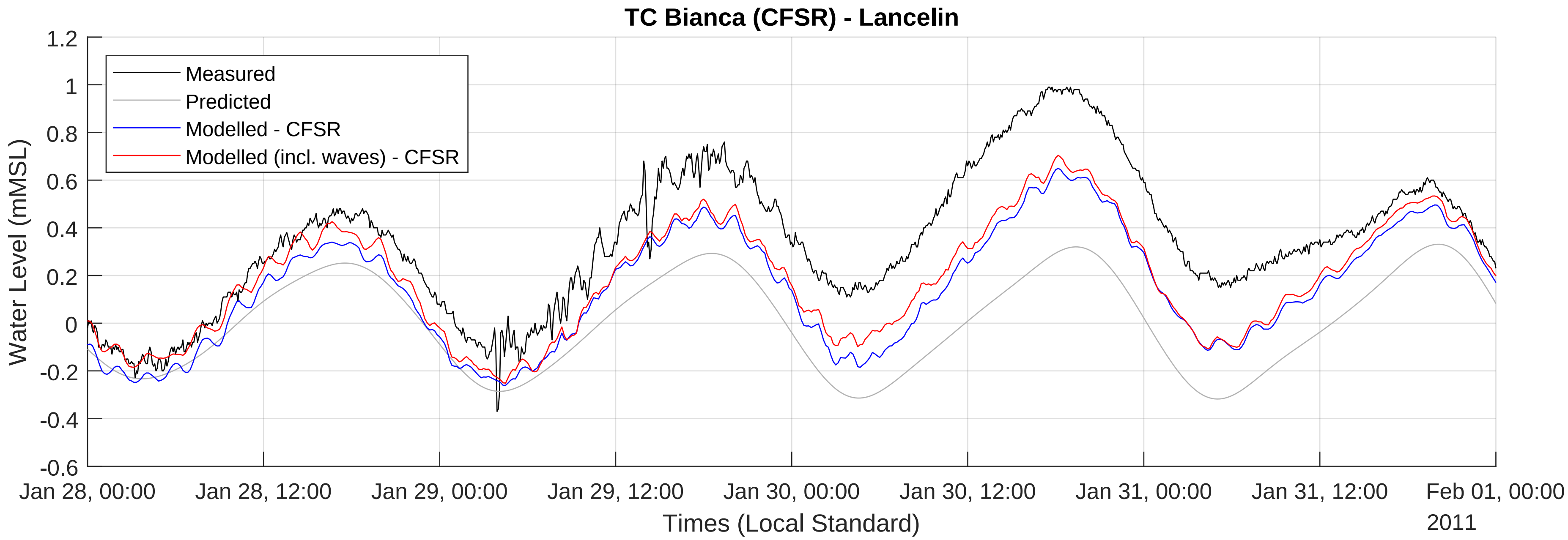
TC Bianca (CFSR) - Hillarys
Measured
Predicted
Modelled - CFSR
Modelled (incl. waves) - CFSR
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Jan 28, 00:00
Jan 28, 12:00
Jan 29, 00:00
Jan 29, 12:00
Jan 30, 00:00
Jan 30, 12:00
Jan 31, 00:00
Jan 31, 12:00
Feb 01, 00:00
2011
Times (Local Standard)

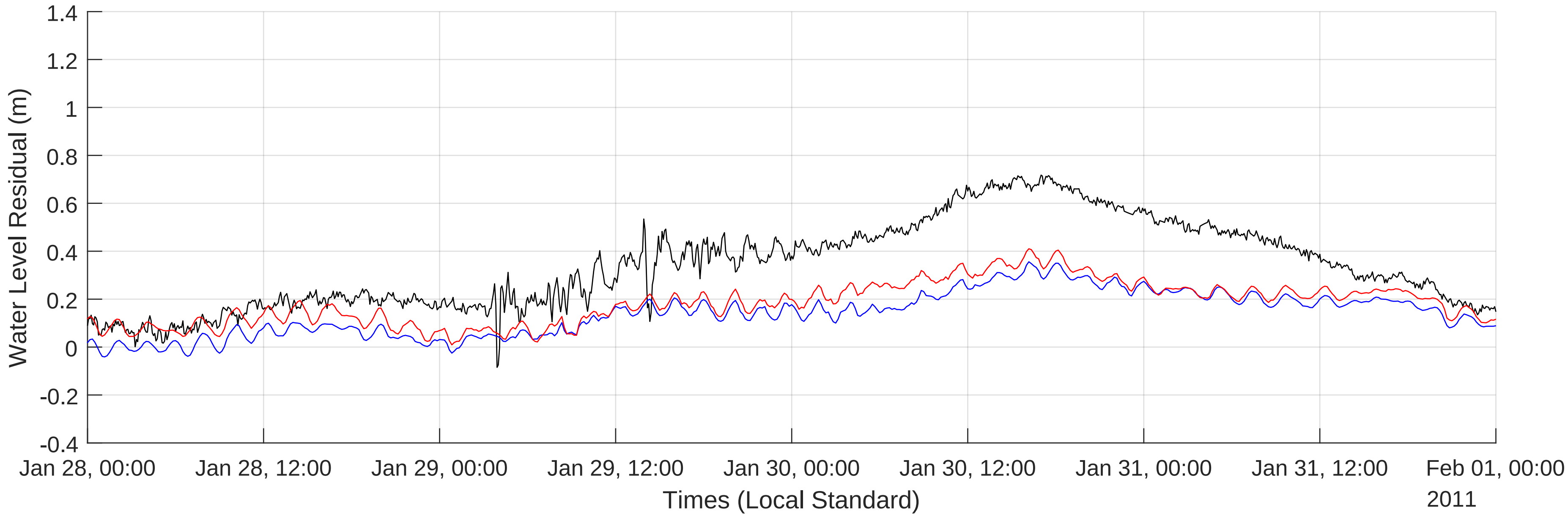


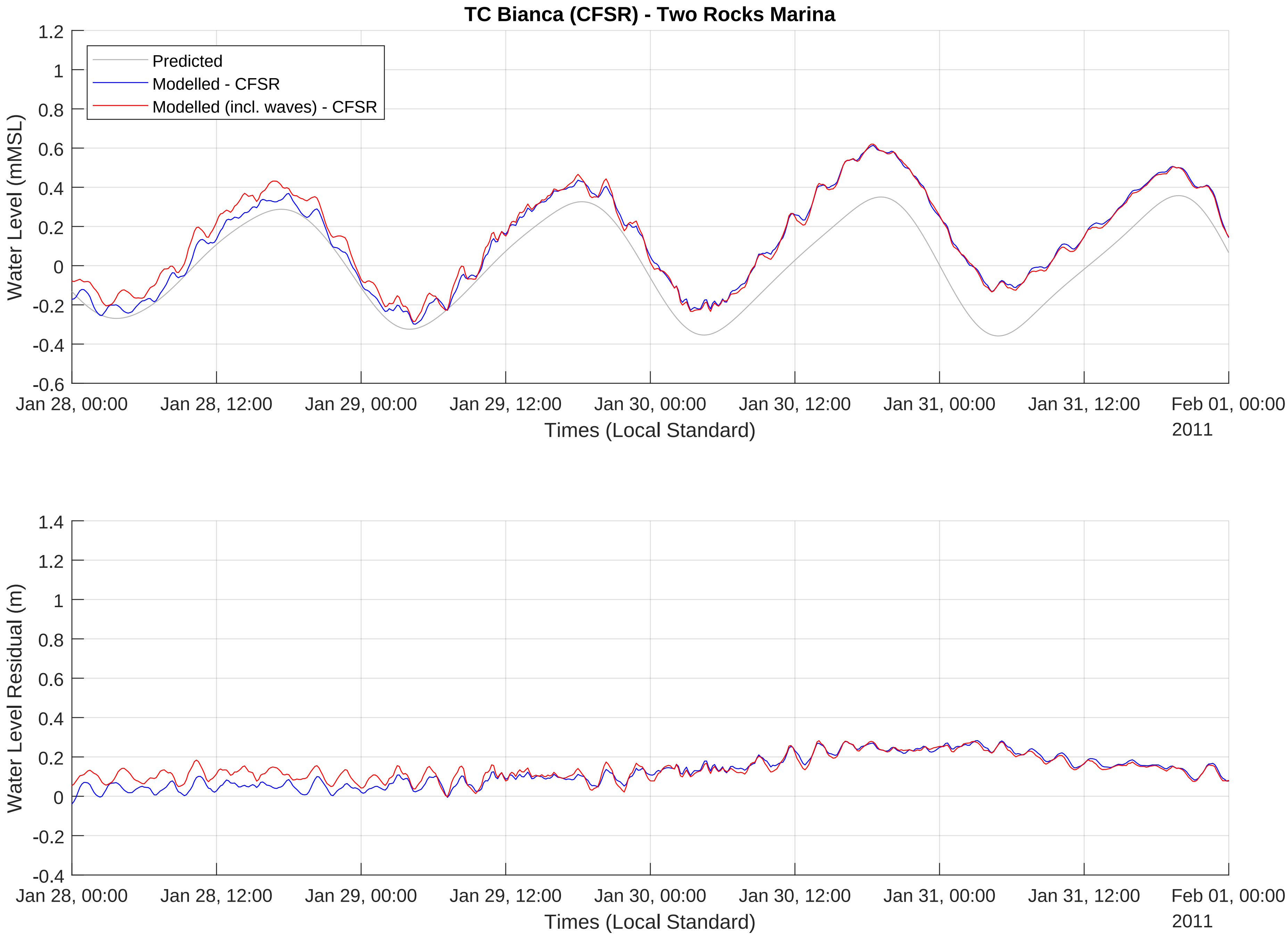
Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Jan 28, 00:00
Jan 28, 12:00
Jan 29, 00:00
Jan 29, 12:00
Jan 30, 00:00
Jan 30, 12:00
Jan 31, 00:00
Jan 31, 12:00
Feb 01, 00:00
2011
Times (Local Standard)

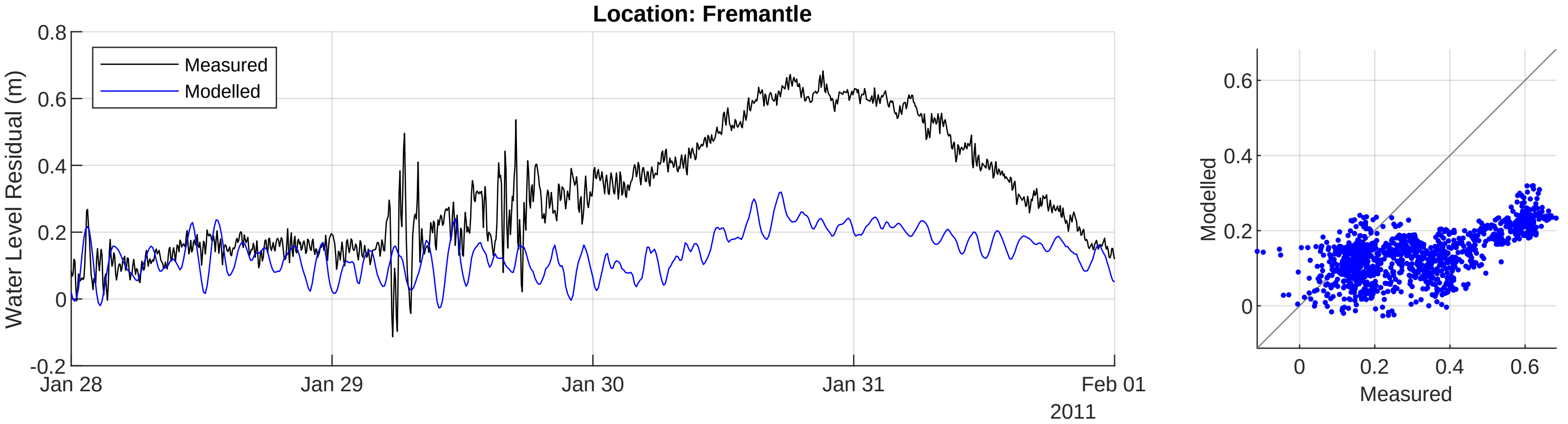


13288.101 | Apr-2020
.\Figures\TC_Coupled\WL_and_Residual_TS_TC_Bianca_CFSR_Jurien Bay.pdf


TC Bianca (CFSR) - Lancelin
Measured
Predicted
Modelled - CFSR
Modelled (incl. waves) - CFSR
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Jan 28, 00:00
Jan 28, 12:00
Jan 29, 00:00
Jan 29, 12:00
Jan 30, 00:00
Jan 30, 12:00
Jan 31, 00:00
Jan 31, 12:00
Feb 01, 00:00
2011
Times (Local Standard)


Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Jan 28, 00:00
Jan 28, 12:00
Jan 29, 00:00
Jan 29, 12:00
Jan 30, 00:00
Jan 30, 12:00
Jan 31, 00:00
Jan 31, 12:00
Feb 01, 00:00
2011
Times (Local Standard)


TC Bianca (CFSR) - Two Rocks Marina
Predicted
Modelled - CFSR
Modelled (incl. waves) - CFSR
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Jan 28, 00:00
Jan 28, 12:00
Jan 29, 00:00
Jan 29, 12:00
Jan 30, 00:00
Jan 30, 12:00
Jan 31, 00:00
Jan 31, 12:00
Feb 01, 00:00
2011
Times (Local Standard)
Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Jan 28, 00:00
Jan 28, 12:00
Jan 29, 00:00
Jan 29, 12:00
Jan 30, 00:00
Jan 30, 12:00
Jan 31, 00:00
Jan 31, 12:00
Feb 01, 00:00
2011
Times (Local Standard)



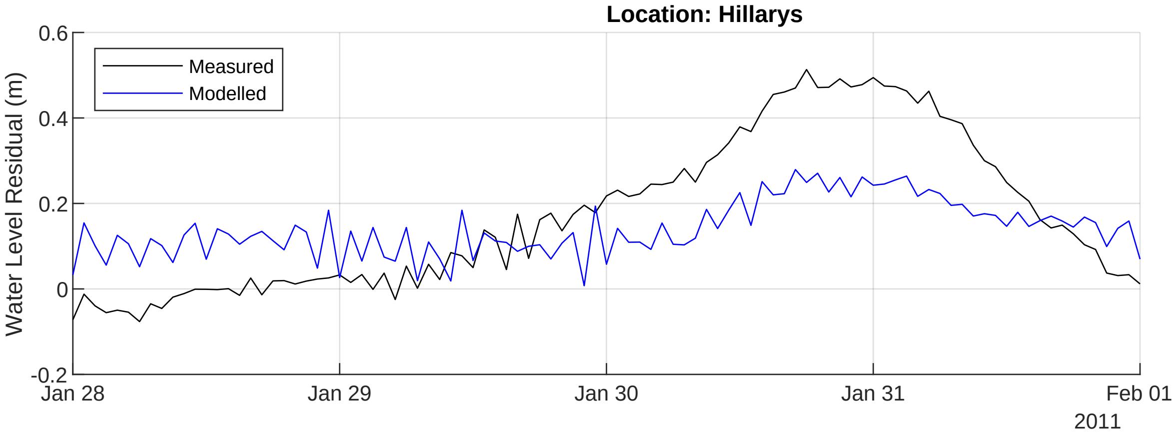
Water Level Residual (m)

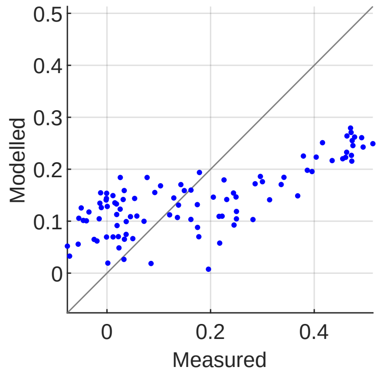
Scatter: 0.538

Bias: -0.178

Skill: 0.351

RMS error: 0.231





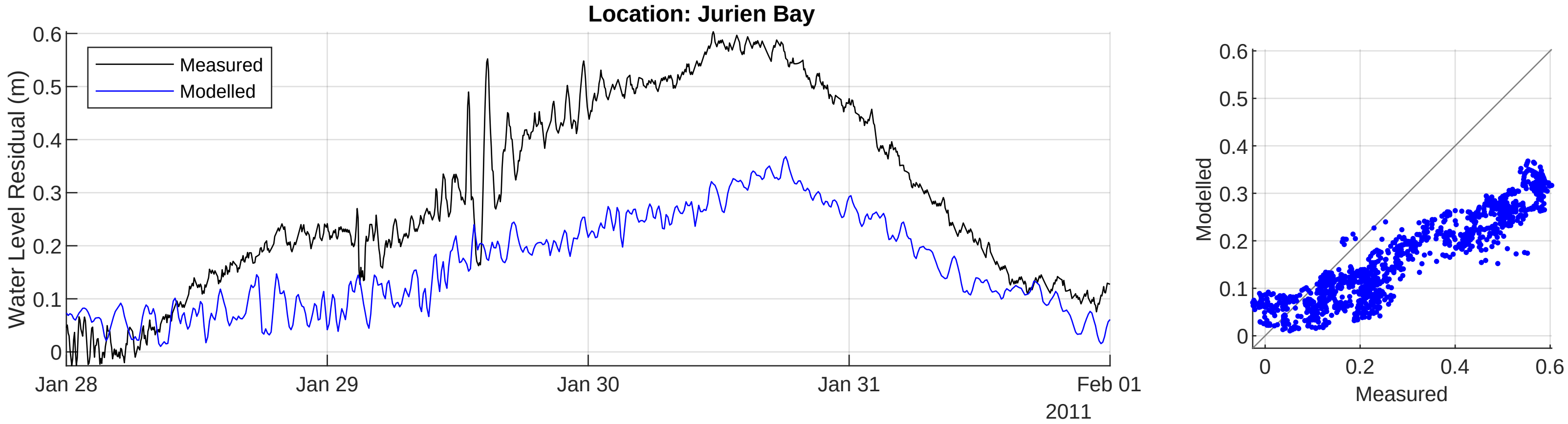
Water Level Residual (m)

Scatter: 0.560

Bias: -0.031

Skill: 0.643

RMS error: 0.139



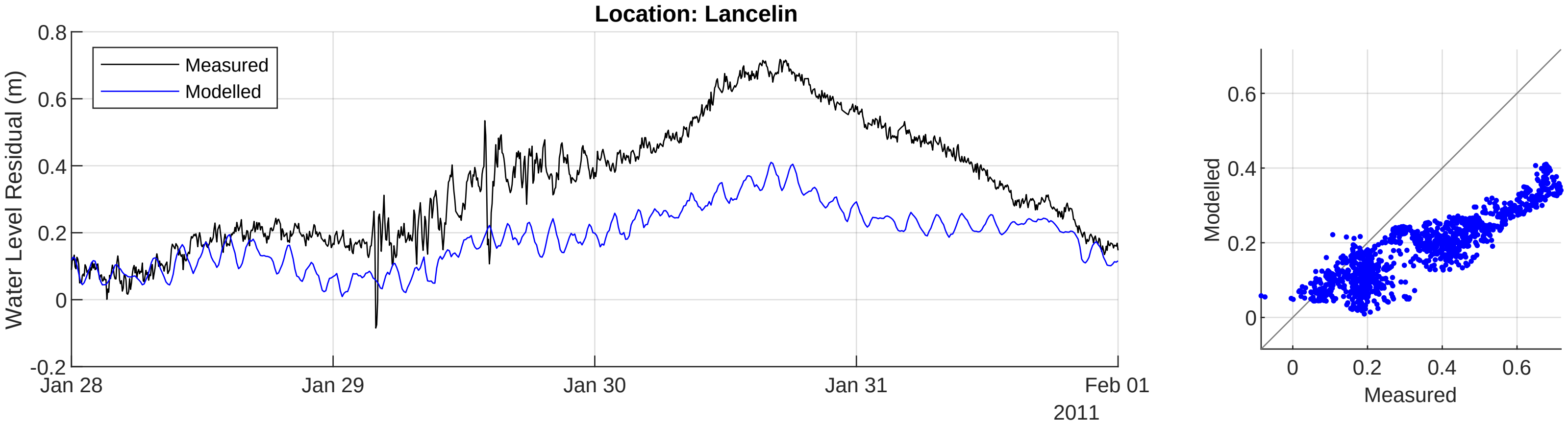
Water Level Residual (m)

Scatter: 0.512

Bias: -0.132

Skill: 0.688

RMS error: 0.165



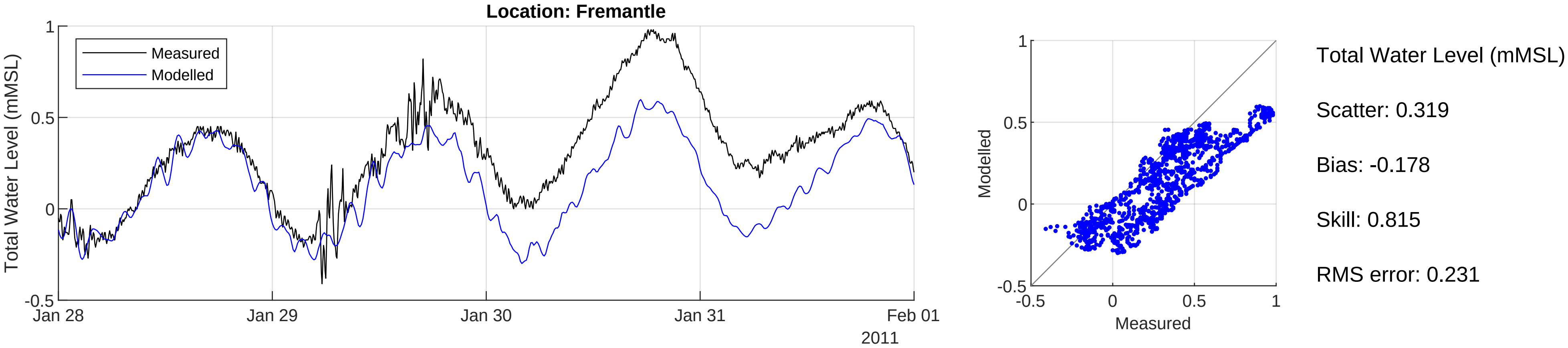
Water Level Residual (m)

Scatter: 0.454

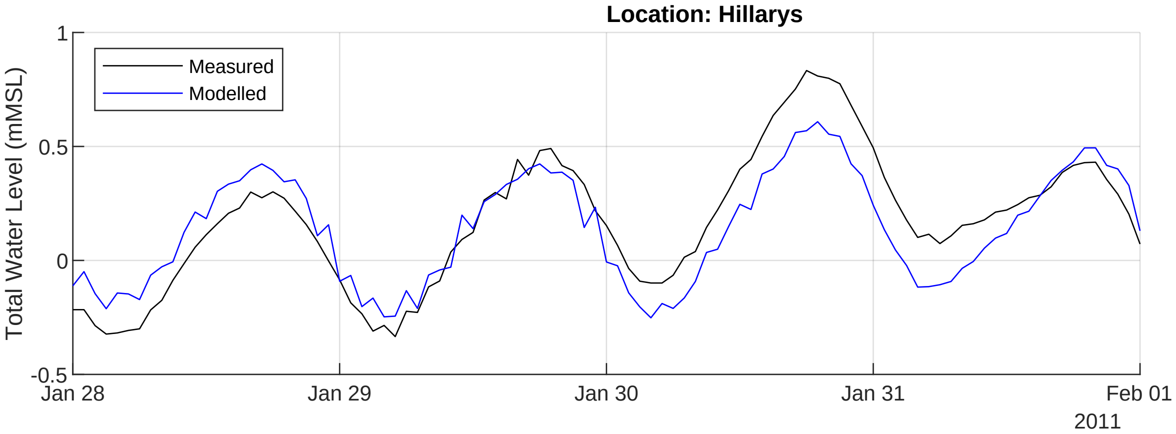
Bias: -0.159

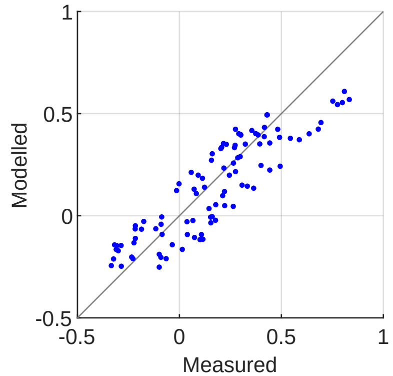
Skill: 0.601

RMS error: 0.194



Location: Fremantle
Measured
Modelled
Total Water Level (mMSL)
1
0.5
0
-0.5
Jan 28
Jan 29
Jan 30
Jan 31
Feb 01
2011
Modelled
Measured
-0.5
0
0.5
1
Total Water Level (mMSL)
Scatter: 0.319
Bias: -0.178
Skill: 0.815
RMS error: 0.231





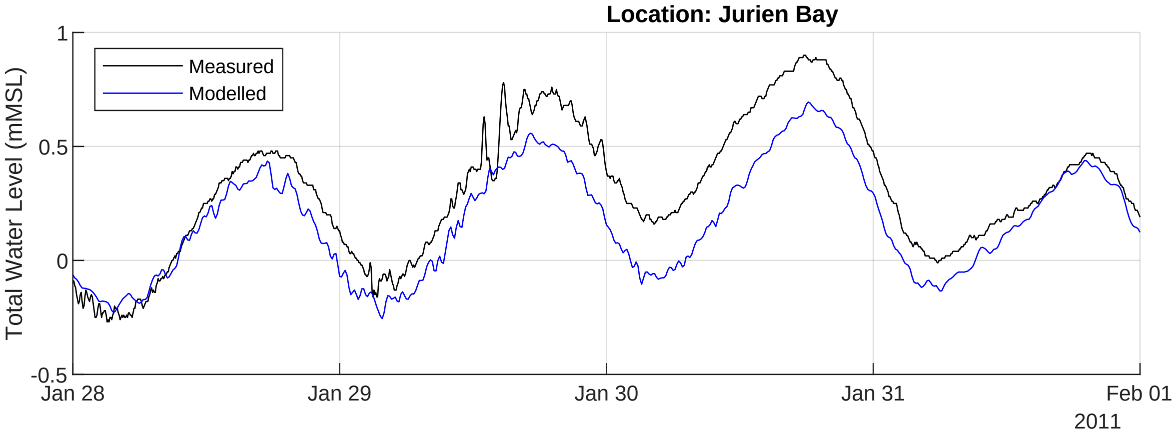
Total Water Level (mMSL)

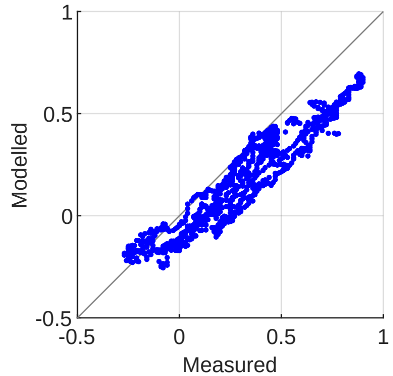
Scatter: 0.274

Bias: -0.031

Skill: 0.926

RMS error: 0.139





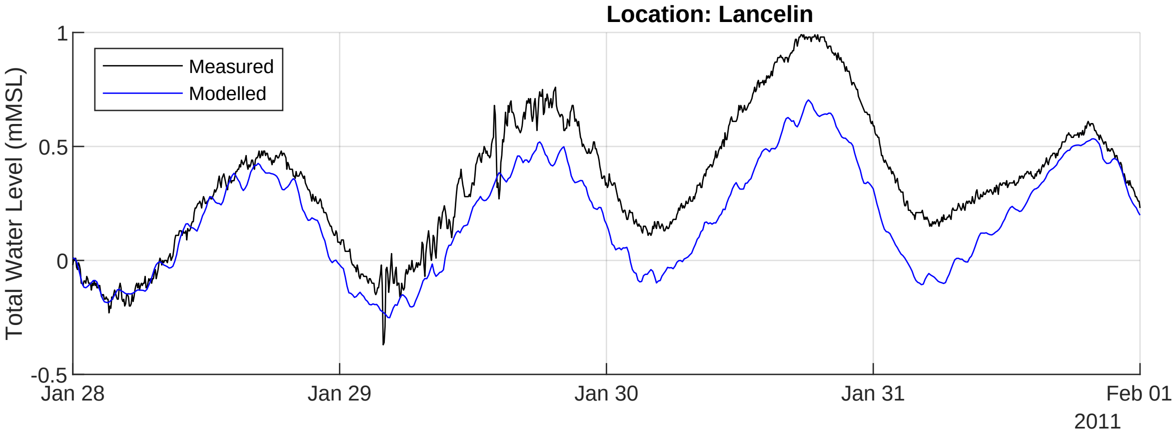
Total Water Level (mMSL)

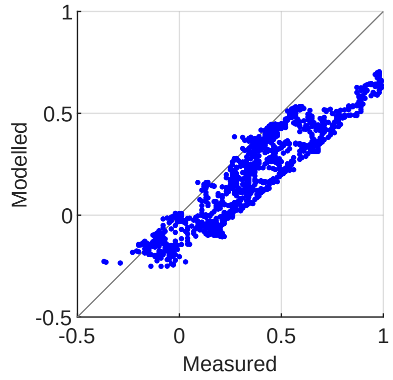
Scatter: 0.285

Bias: -0.132

Skill: 0.906

RMS error: 0.165





Total Water Level (mMSL)

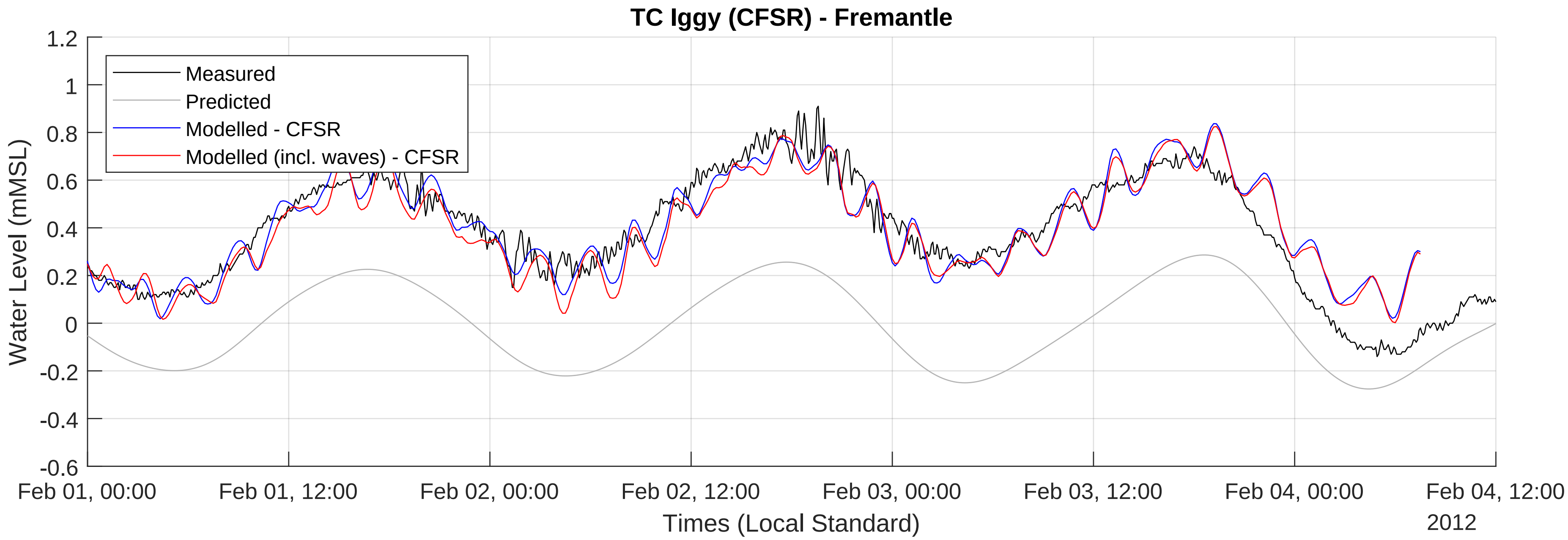
Scatter: 0.270

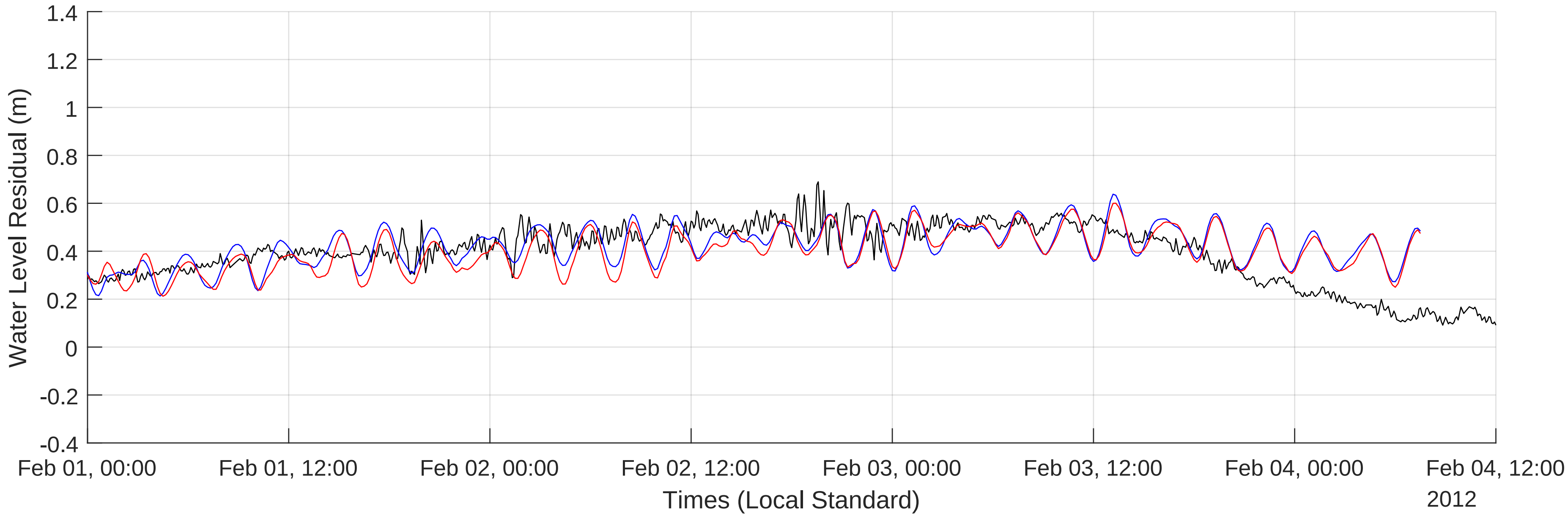
Bias: -0.159

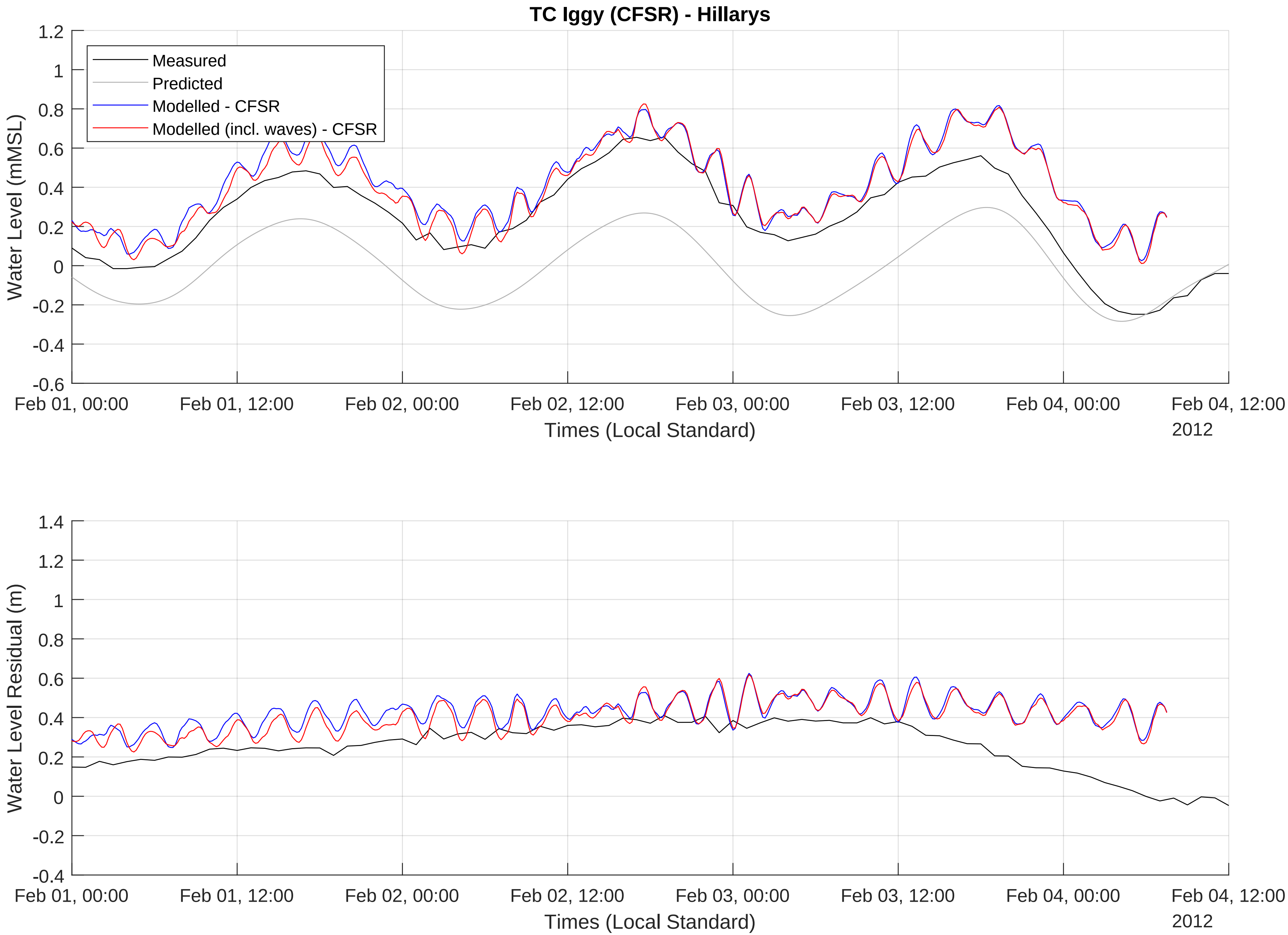
Skill: 0.872

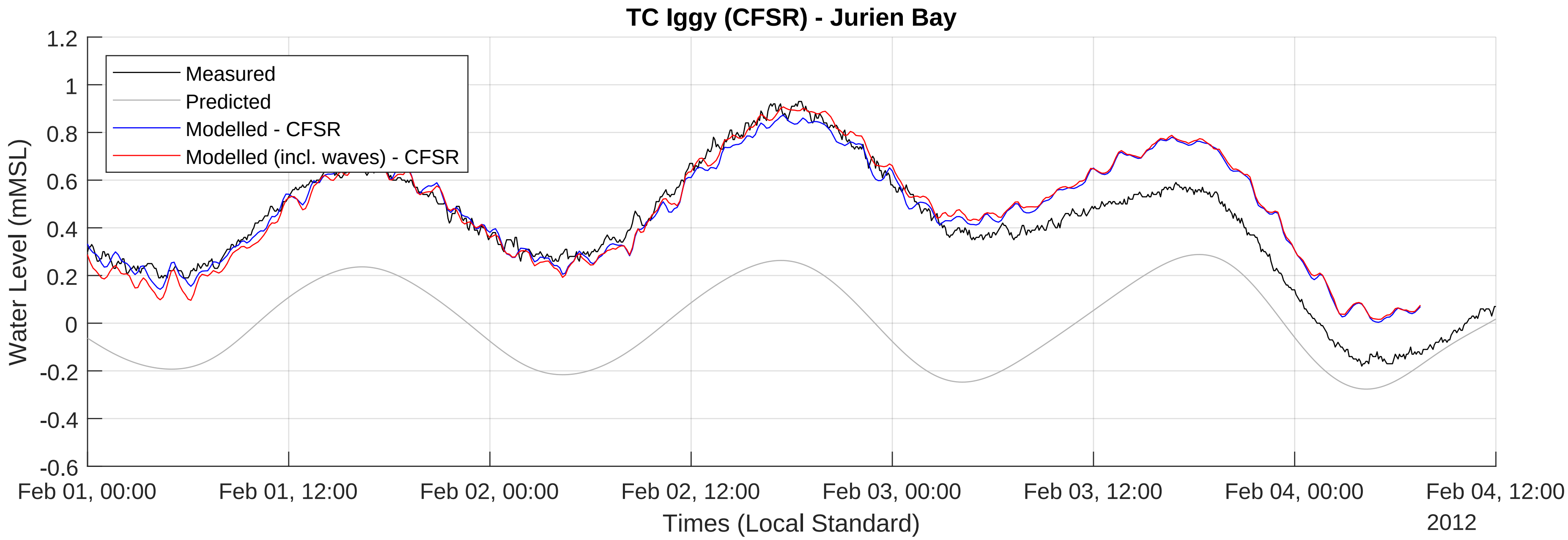
RMS error: 0.194

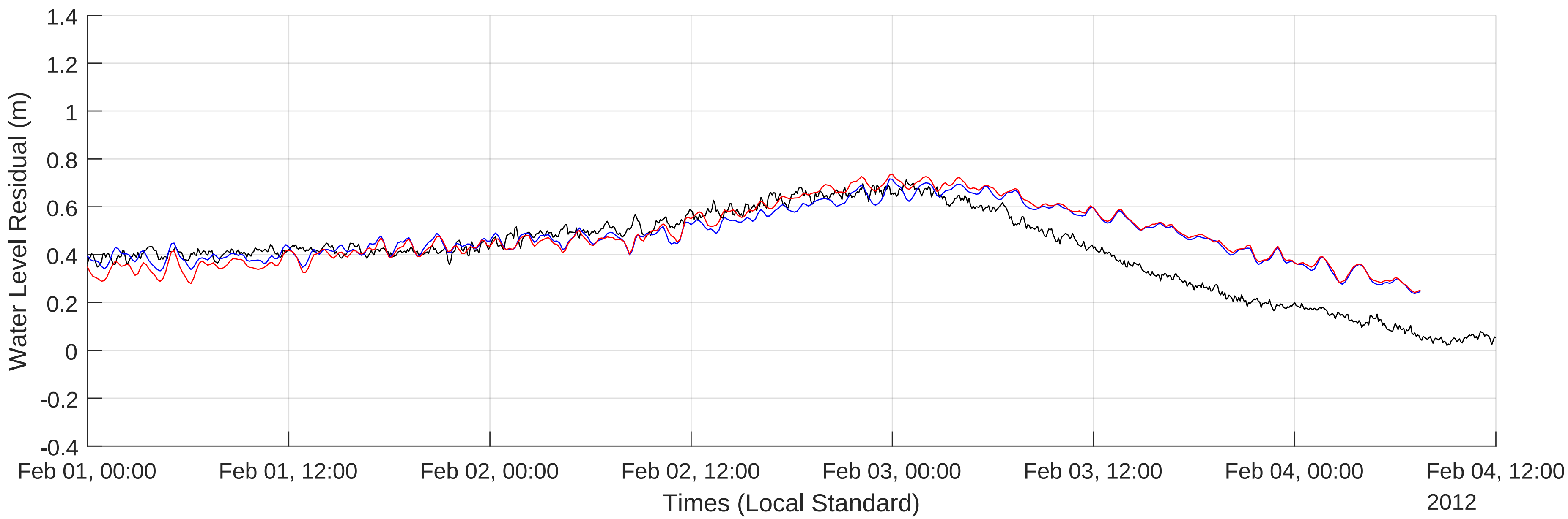
B.4 TC Iggy (2012)


TC Iggy (CFSR) - Fremantle
Measured
Predicted
Modelled - CFSR
Modelled (incl. waves) - CFSR
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Feb 01, 00:00
Feb 01, 12:00
Feb 02, 00:00
Feb 02, 12:00
Feb 03, 00:00
Feb 03, 12:00
Feb 04, 00:00
Feb 04, 12:00
2012
Times (Local Standard)

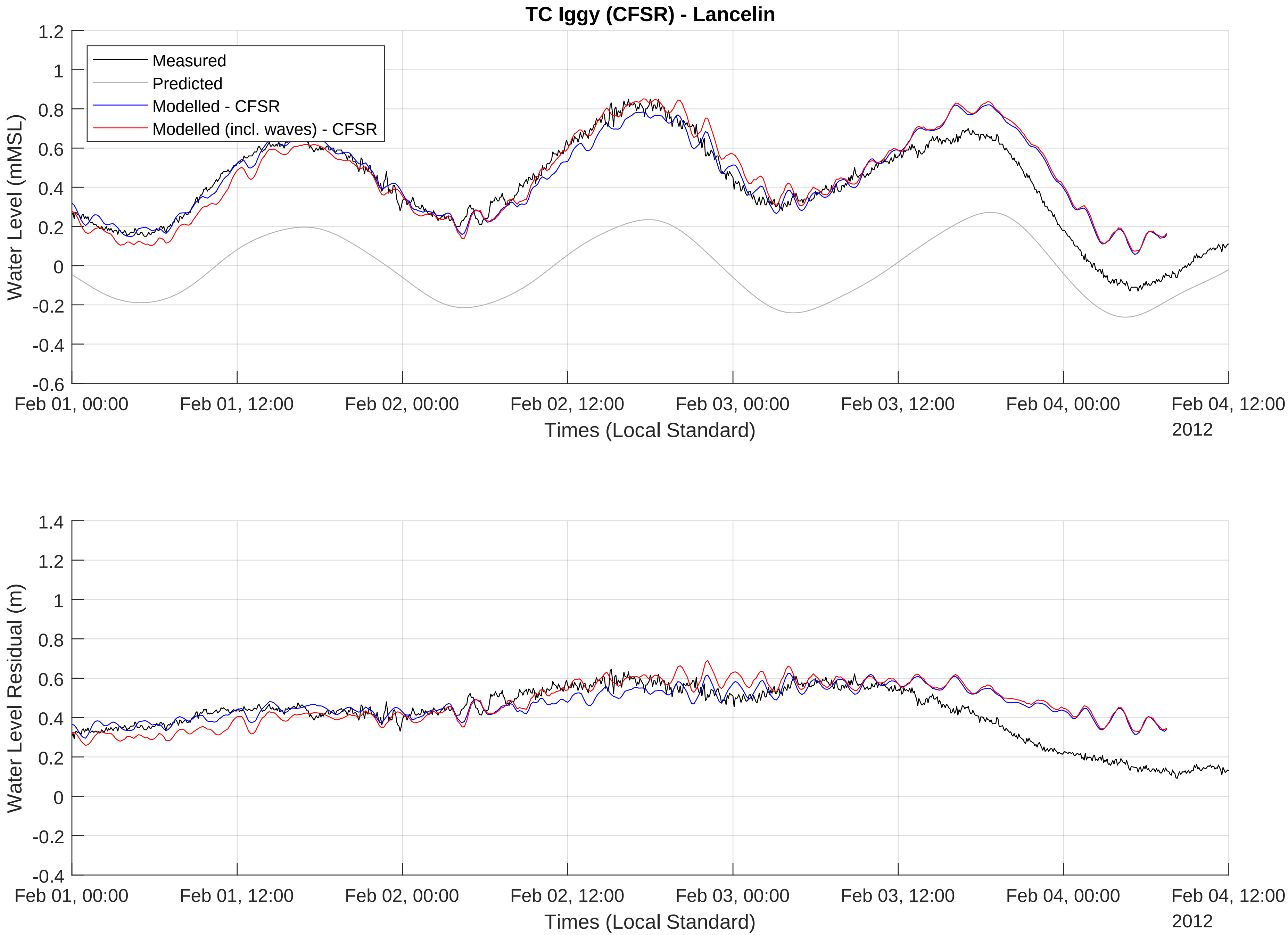

Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Feb 01, 00:00
Feb 01, 12:00
Feb 02, 00:00
Feb 02, 12:00
Feb 03, 00:00
Feb 03, 12:00
Feb 04, 00:00
Feb 04, 12:00
2012
Times (Local Standard)


TC Iggy (CFSR) - Hillarys
Measured
Predicted
Modelled - CFSR
Modelled (incl. waves) - CFSR
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Feb 01, 00:00
Feb 01, 12:00
Feb 02, 00:00
Feb 02, 12:00
Feb 03, 00:00
Feb 03, 12:00
Feb 04, 00:00
Feb 04, 12:00
2012
Times (Local Standard)
Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Feb 01, 00:00
Feb 01, 12:00
Feb 02, 00:00
Feb 02, 12:00
Feb 03, 00:00
Feb 03, 12:00
Feb 04, 00:00
Feb 04, 12:00
2012
Times (Local Standard)

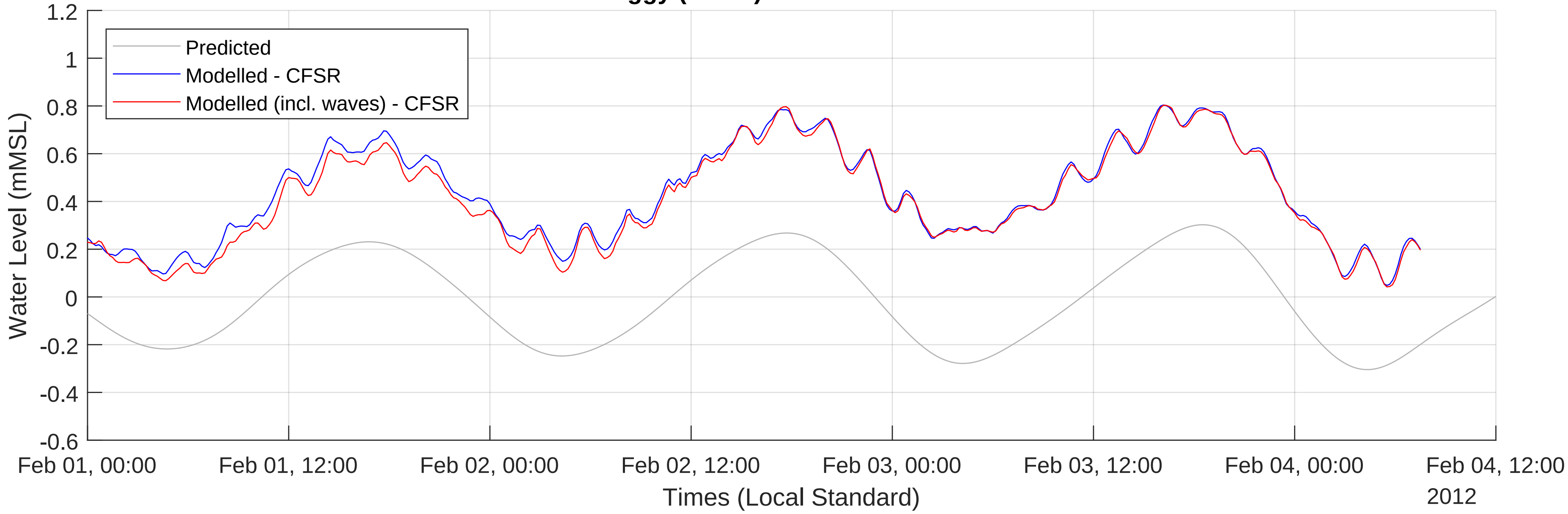

TC Iggy (CFSR) - Jurien Bay
Measured
Predicted
Modelled - CFSR
Modelled (incl. waves) - CFSR
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Feb 01, 00:00
Feb 01, 12:00
Feb 02, 00:00
Feb 02, 12:00
Feb 03, 00:00
Feb 03, 12:00
Feb 04, 00:00
Feb 04, 12:00
2012
Times (Local Standard)

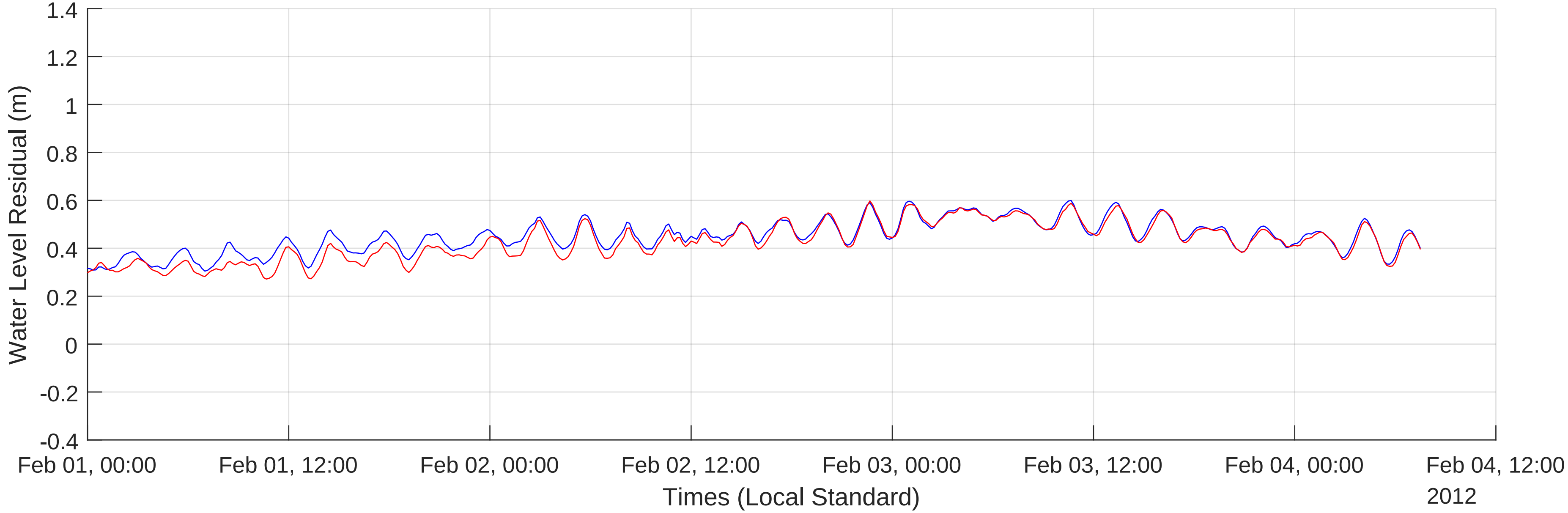

Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Feb 01, 00:00
Feb 01, 12:00
Feb 02, 00:00
Feb 02, 12:00
Feb 03, 00:00
Feb 03, 12:00
Feb 04, 00:00
Feb 04, 12:00
2012
Times (Local Standard)

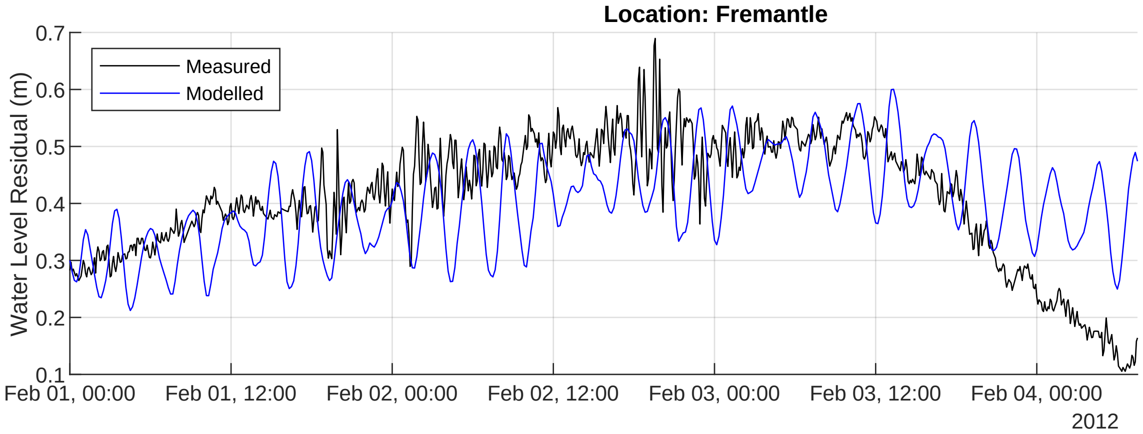
Baird.

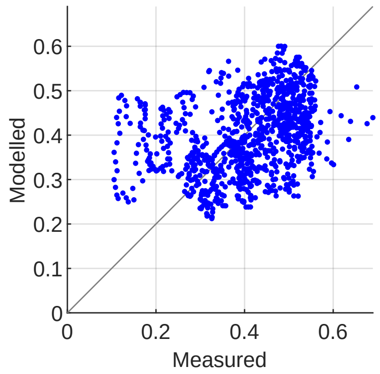

TC Iggy (CFSR) - Lancelin
Measured
Predicted
Modelled - CFSR
Modelled (incl. waves) - CFSR
Water Level (mMSL)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Feb 01, 00:00
Feb 01, 12:00
Feb 02, 00:00
Feb 02, 12:00
Feb 03, 00:00
Feb 03, 12:00
Feb 04, 00:00
Feb 04, 12:00
2012
Times (Local Standard)
Water Level Residual (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
Feb 01, 00:00
Feb 01, 12:00
Feb 02, 00:00
Feb 02, 12:00
Feb 03, 00:00
Feb 03, 12:00
Feb 04, 00:00
Feb 04, 12:00
2012
Times (Local Standard)

TC Iggy (CFSR) - Two Rocks Marina









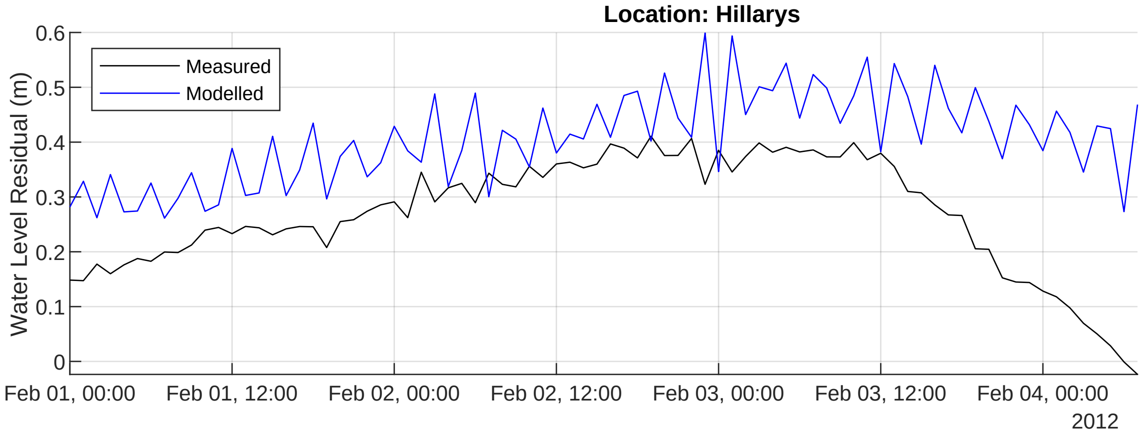
Water Level Residual (m)

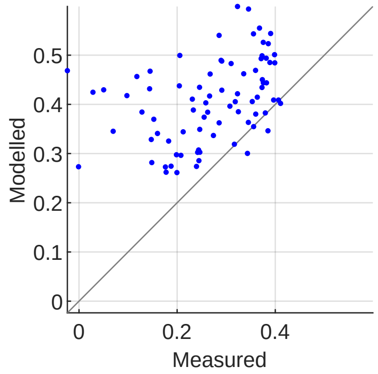
Scatter: 0.274

Bias: -0.008

Skill: 0.512

RMS error: 0.112





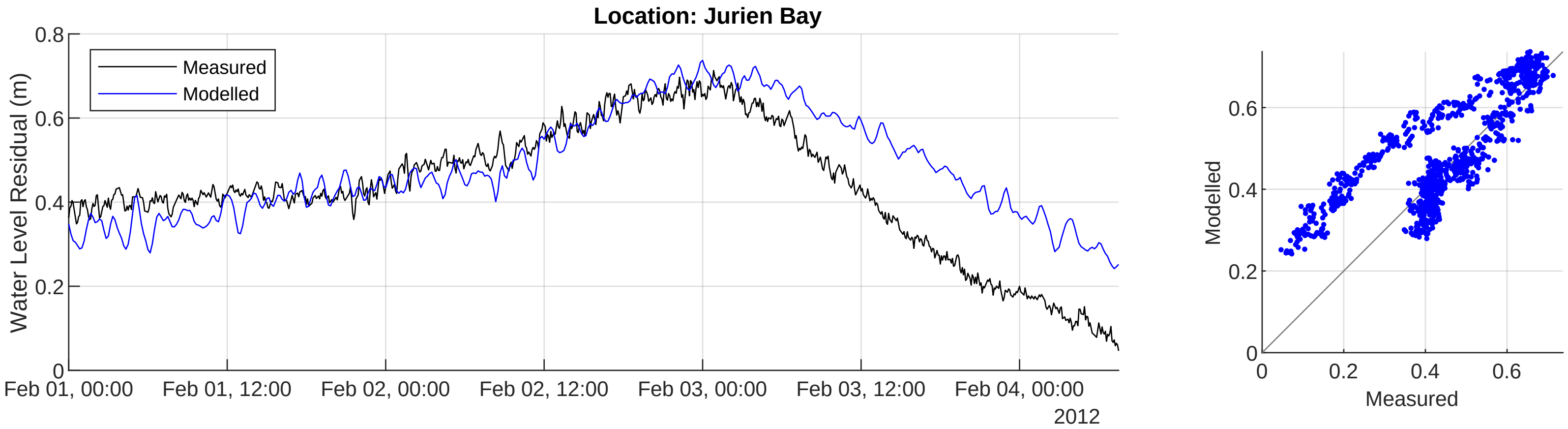
Water Level Residual (m)

Scatter: 0.587

Bias: 0.137

Skill: 0.316

RMS error: 0.172



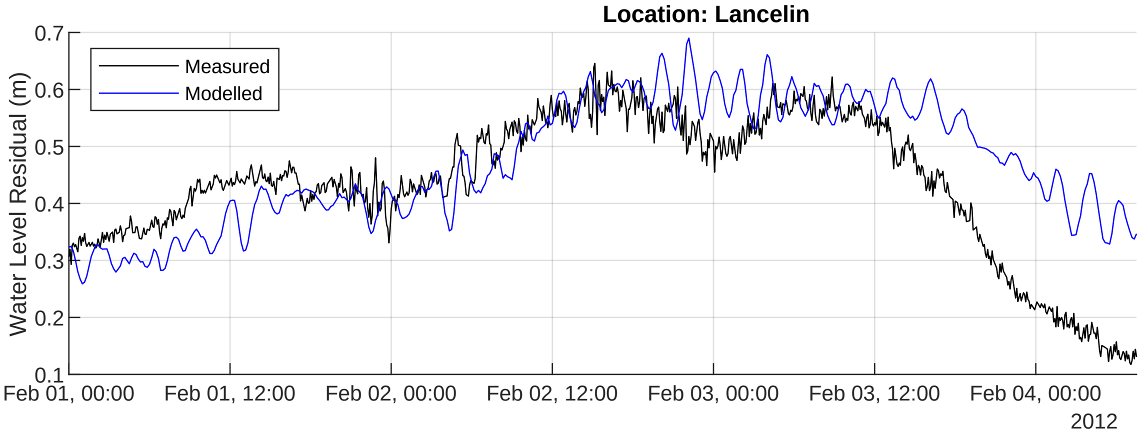
Water Level Residual (m)

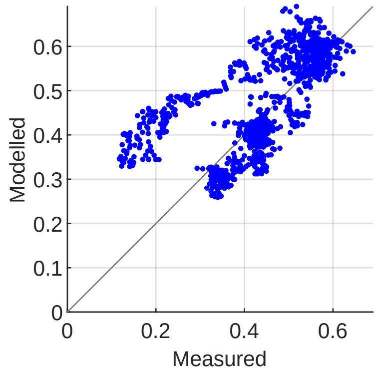
Scatter: 0.251

Bias: 0.047

Skill: 0.836

RMS error: 0.109





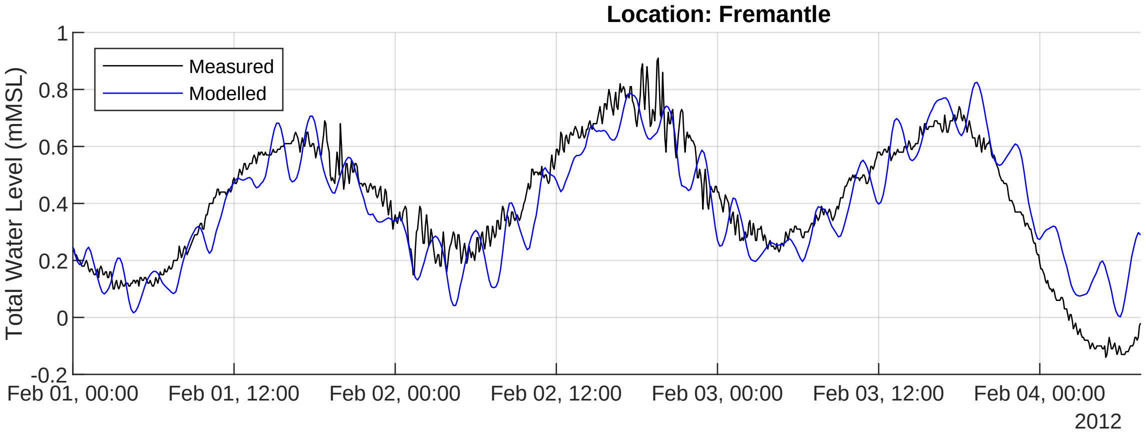
Water Level Residual (m)

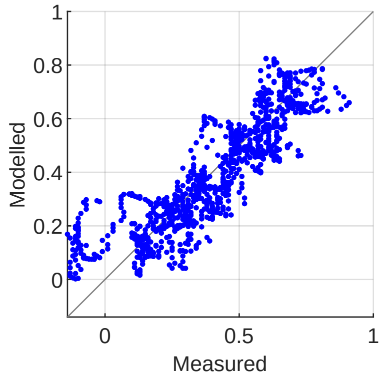
Scatter: 0.241

Bias: 0.037

Skill: 0.753

RMS error: 0.105





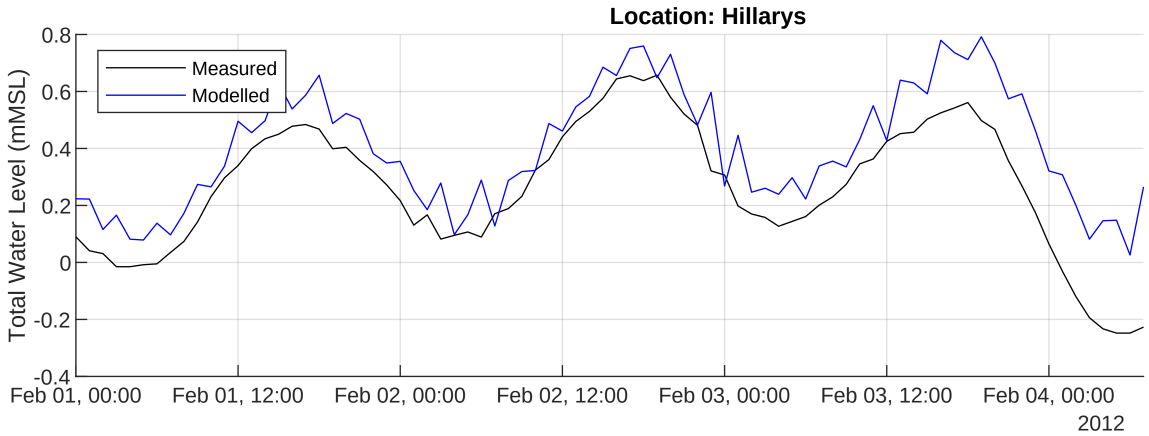
Total Water Level (mMSL)

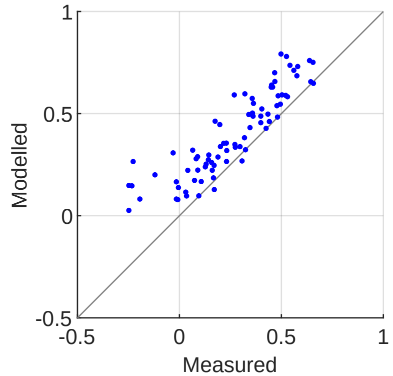
Scatter: 0.208

Bias: -0.008

Skill: 0.928

RMS error: 0.112





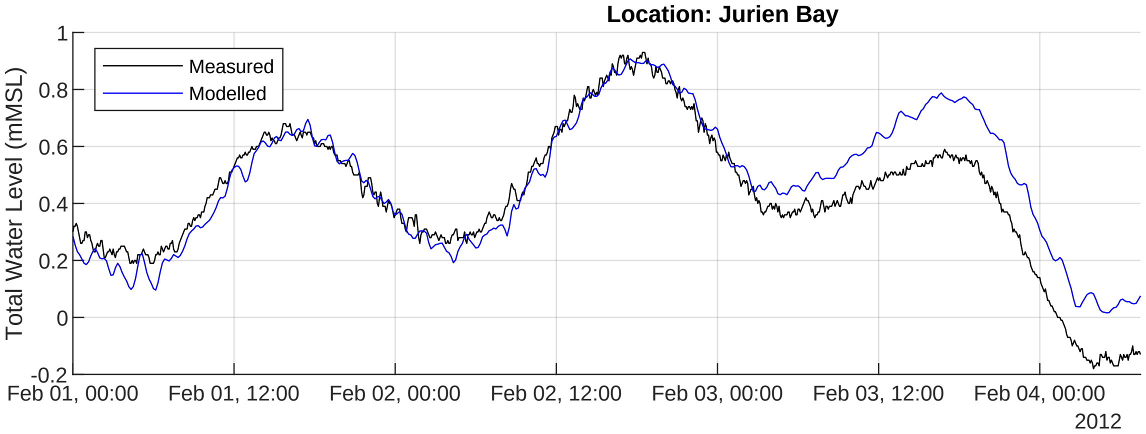
Total Water Level (mMSL)

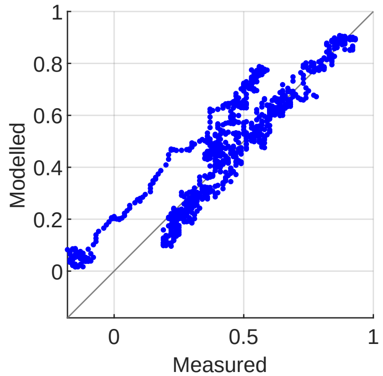
Scatter: 0.337

Bias: 0.137

Skill: 0.848

RMS error: 0.172





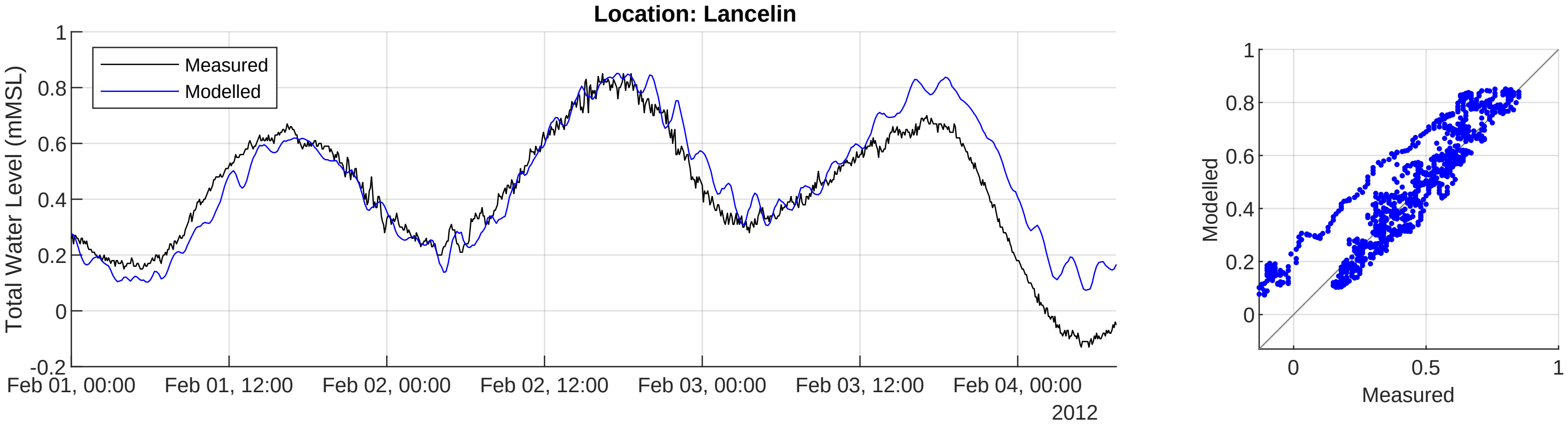
Total Water Level (mMSL)

Scatter: 0.179

Bias: 0.047

Skill: 0.946

RMS error: 0.109



Total Water Level (mMSL)

Scatter: 0.190

Bias: 0.037

Skill: 0.943

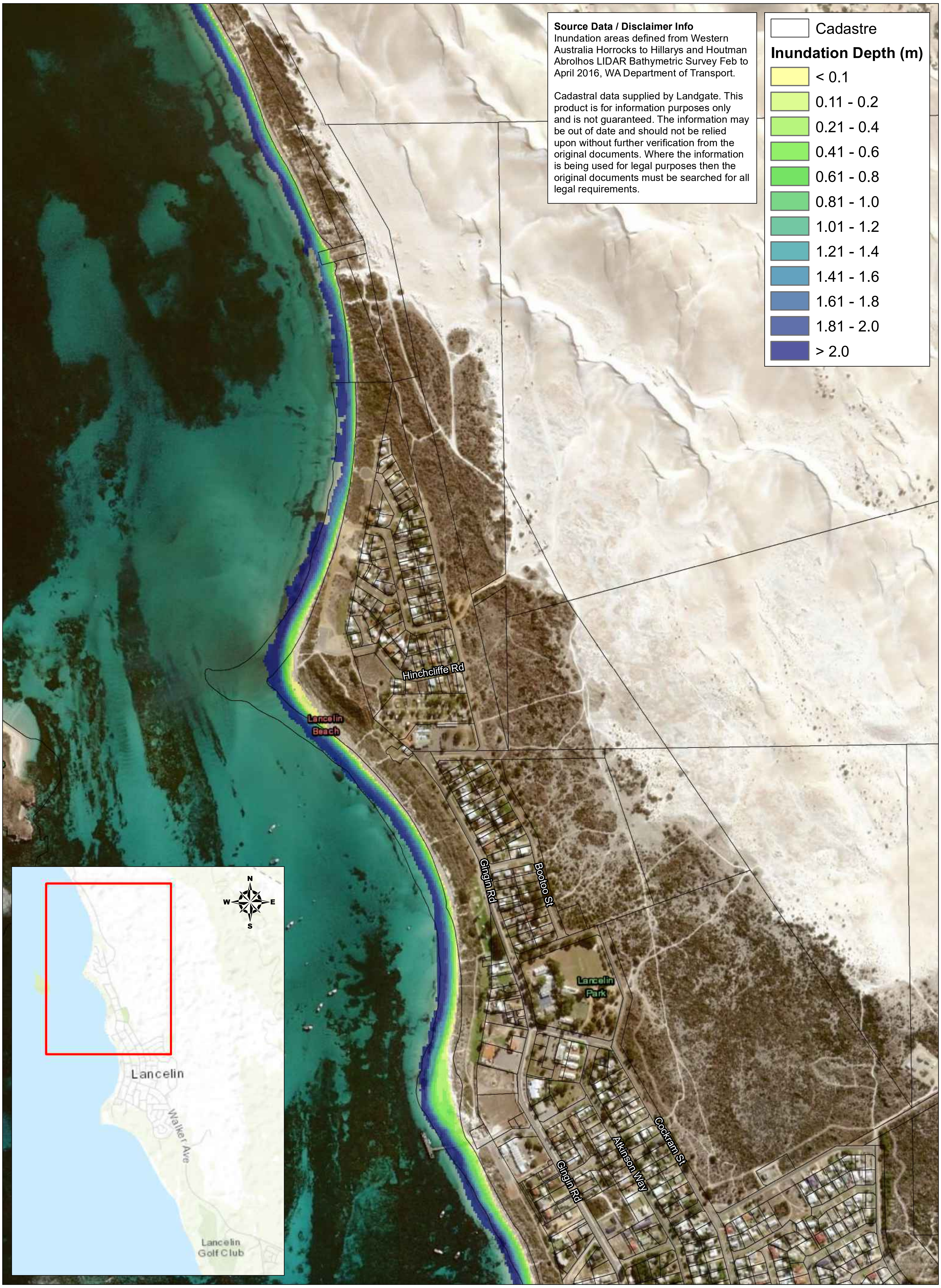
RMS error: 0.105

Appendix C

Inundation Mapping for Study Areas

C.1 Lancelin Inundation Mapping

Mapping Cases presented for the 20yrARI, 100yrARI and 500yr ARI events at planning years 2020, 2040, 2070 and 2120.



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 20yr ARI design storm in planning year 2020 (includes 0m Sea Level Rise Allowance)

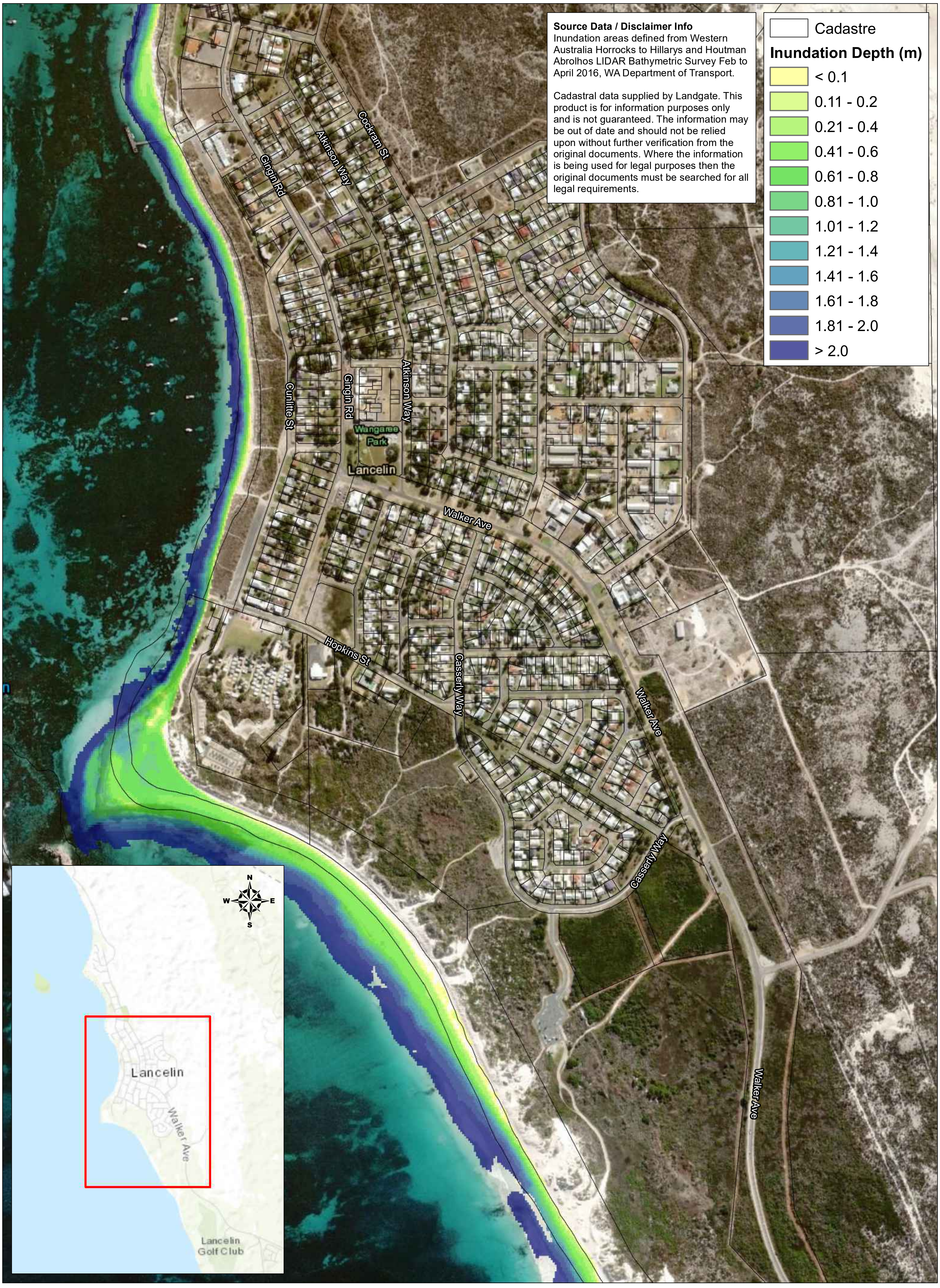
LANCELIN - AREA A

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 20yrARI Depth 2020_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

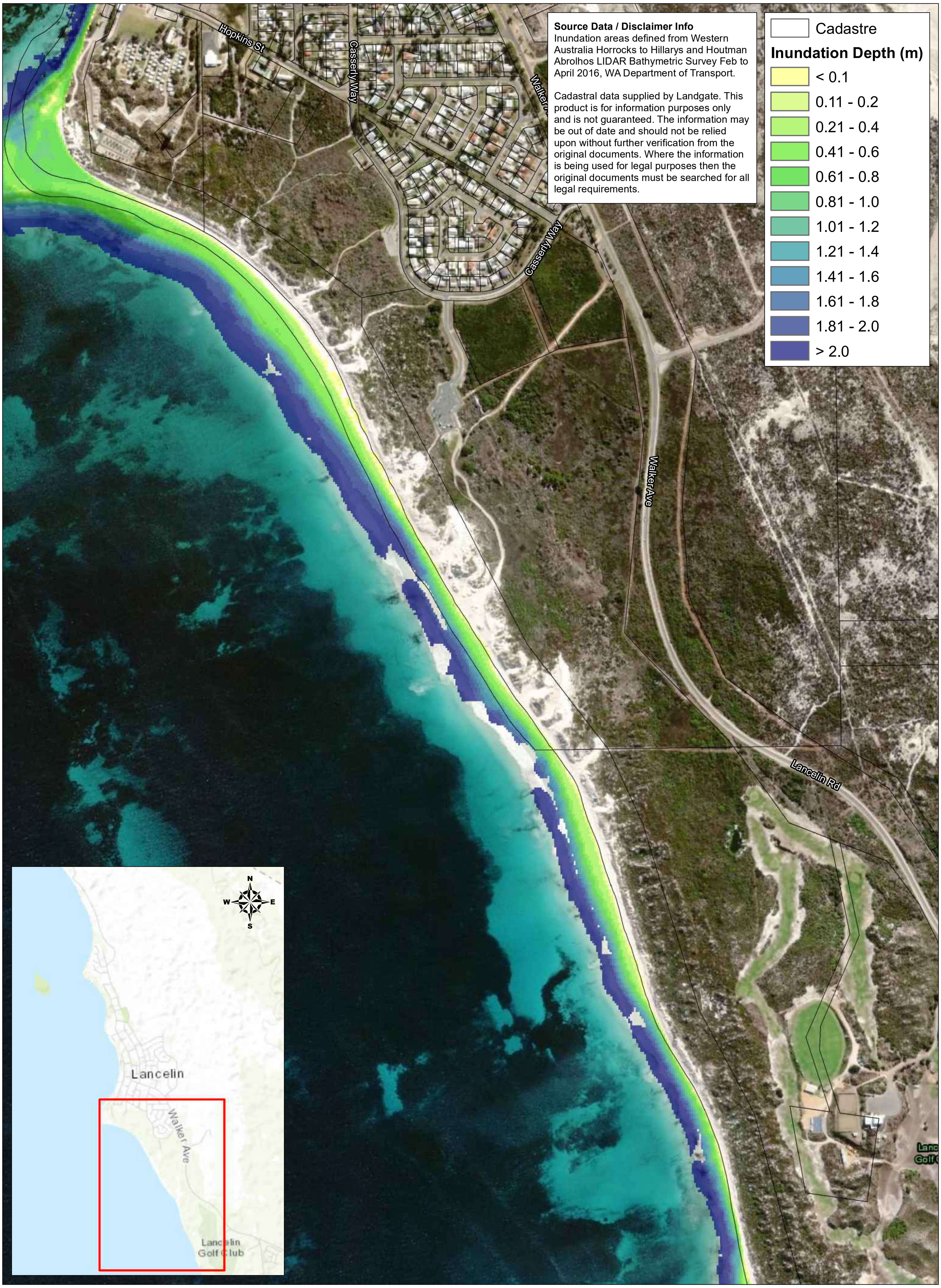
Inundation Depth based on peak water level from 20yr ARI design storm in planning year 2020 (includes 0m Sea Level Rise Allowance)

LANCELIN - AREA B

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

13288 Gingin - Lancelin - 20yrARI Depth 2020_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 20yr ARI design storm in planning year 2020 (includes 0m Sea Level Rise Allowance)

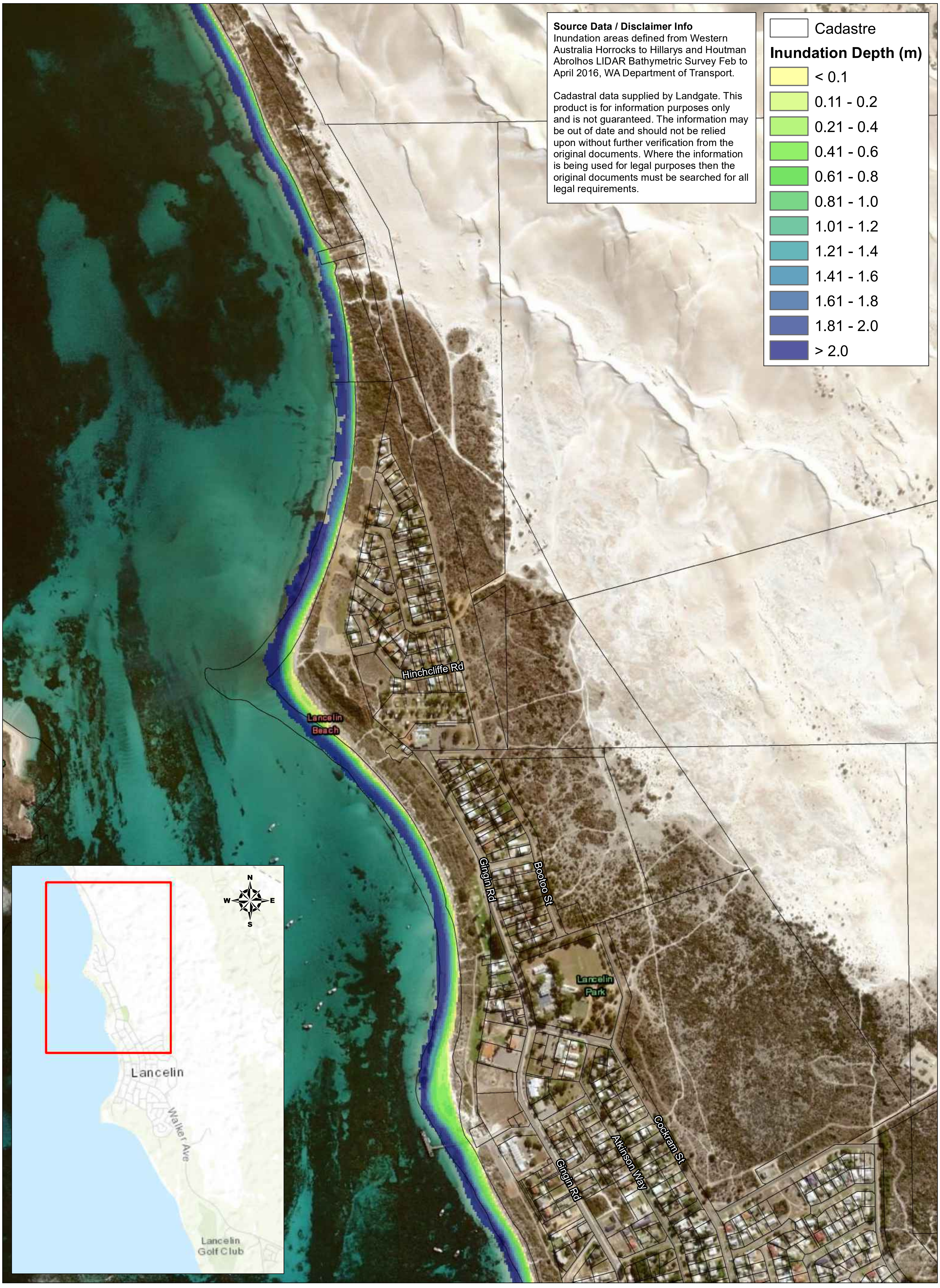
LANCELIN - AREA C

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 20yrARI Depth 2020_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 20yr ARI design storm in planning year 2040 (includes 0.1m Sea Level Rise Allowance)

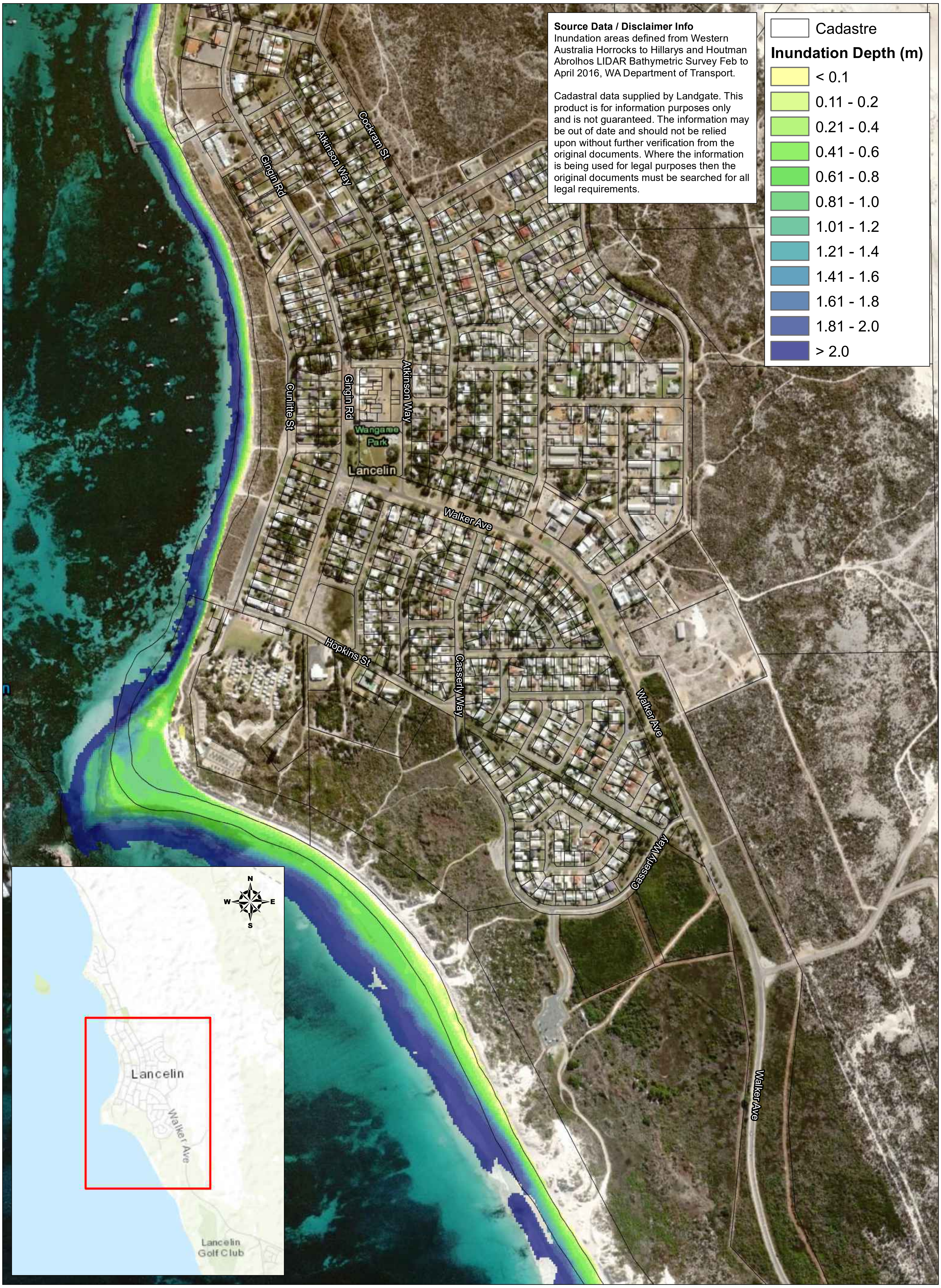
LANCELIN - AREA A

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 20yrARI Depth 2040_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 20yr ARI design storm in planning year 2040 (includes 0.1m Sea Level Rise Allowance)

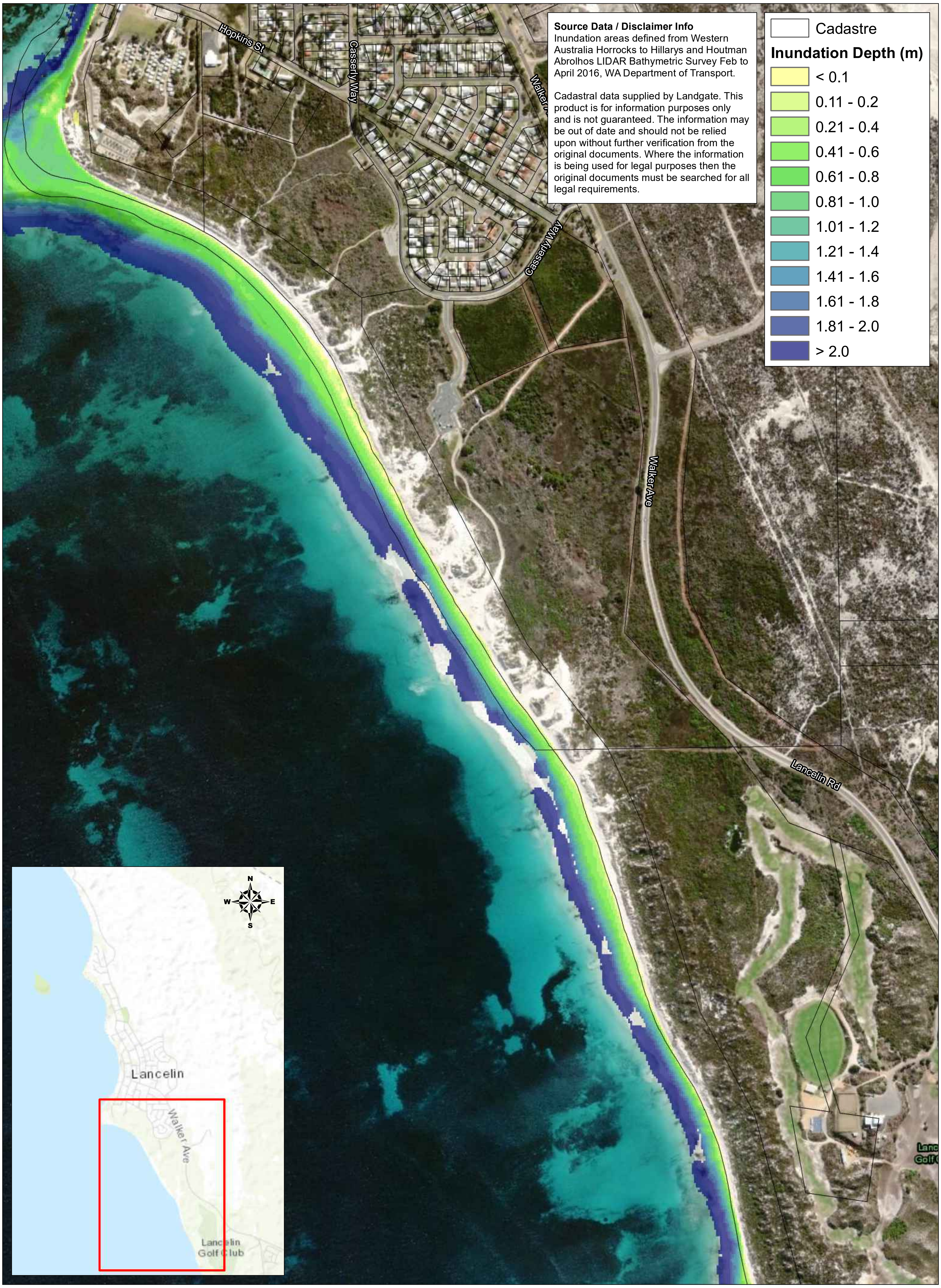
LANCELIN - AREA B

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 20yrARI Depth 2040_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 20yr ARI design storm in planning year 2040 (includes 0.1m Sea Level Rise Allowance)

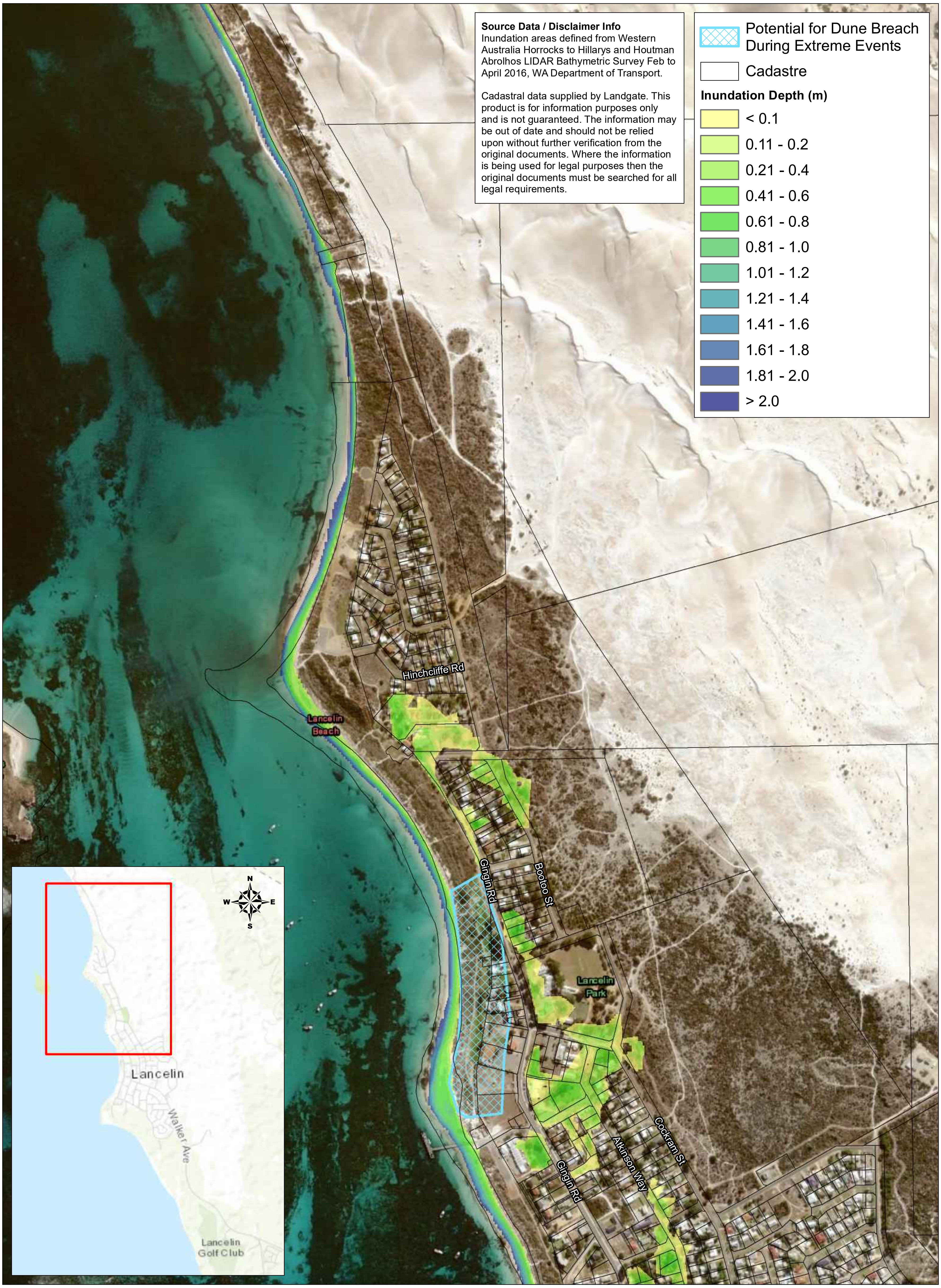
LANCELIN - AREA C

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 20yrARI Depth 2040_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 20yr ARI design storm in planning year 2070 (includes 0.35m Sea Level Rise Allowance)

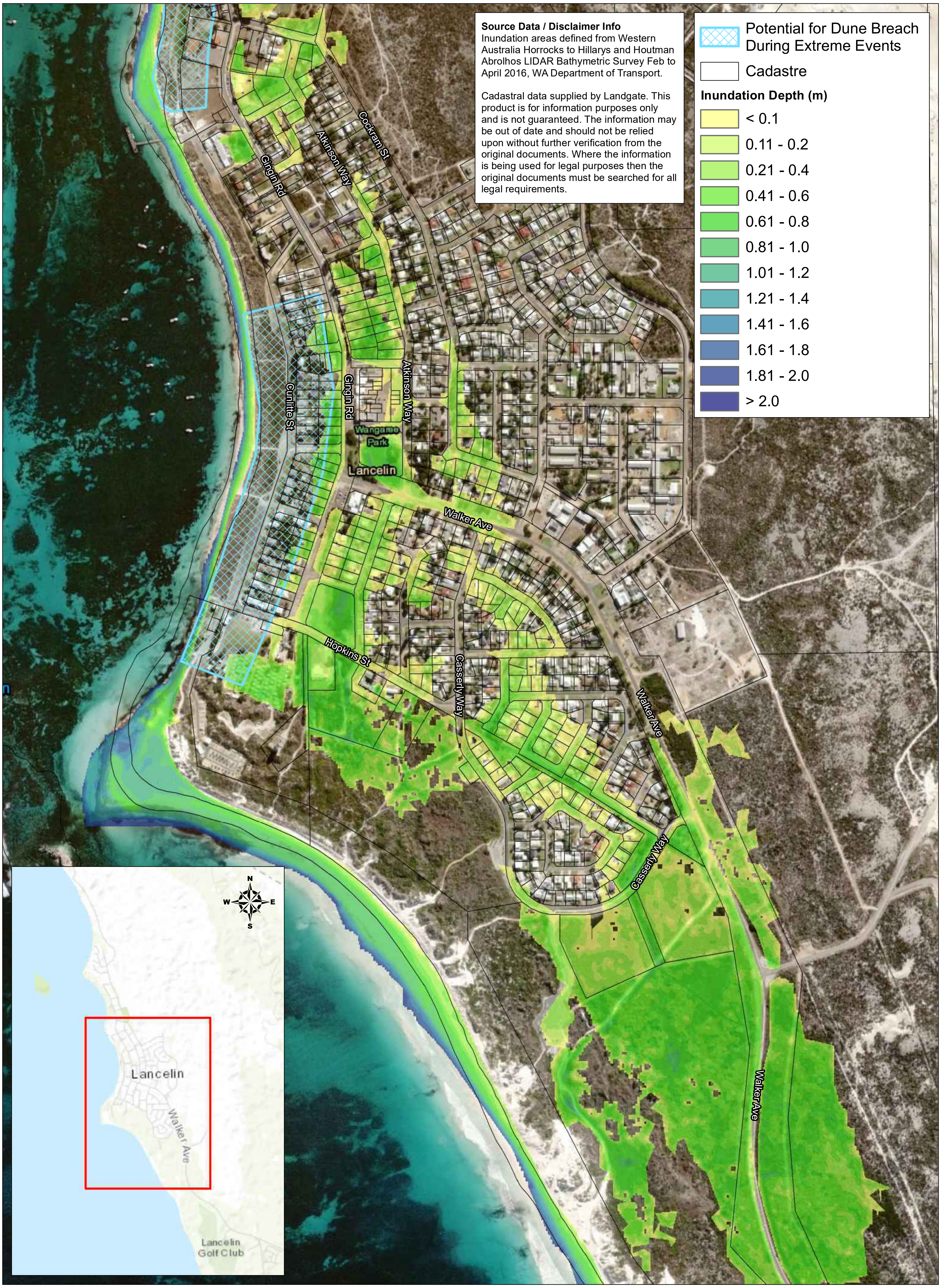
LANCELIN - AREA A

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 20yrARI Depth 2070_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 20yr ARI design storm in planning year 2070 (includes 0.35m Sea Level Rise Allowance)

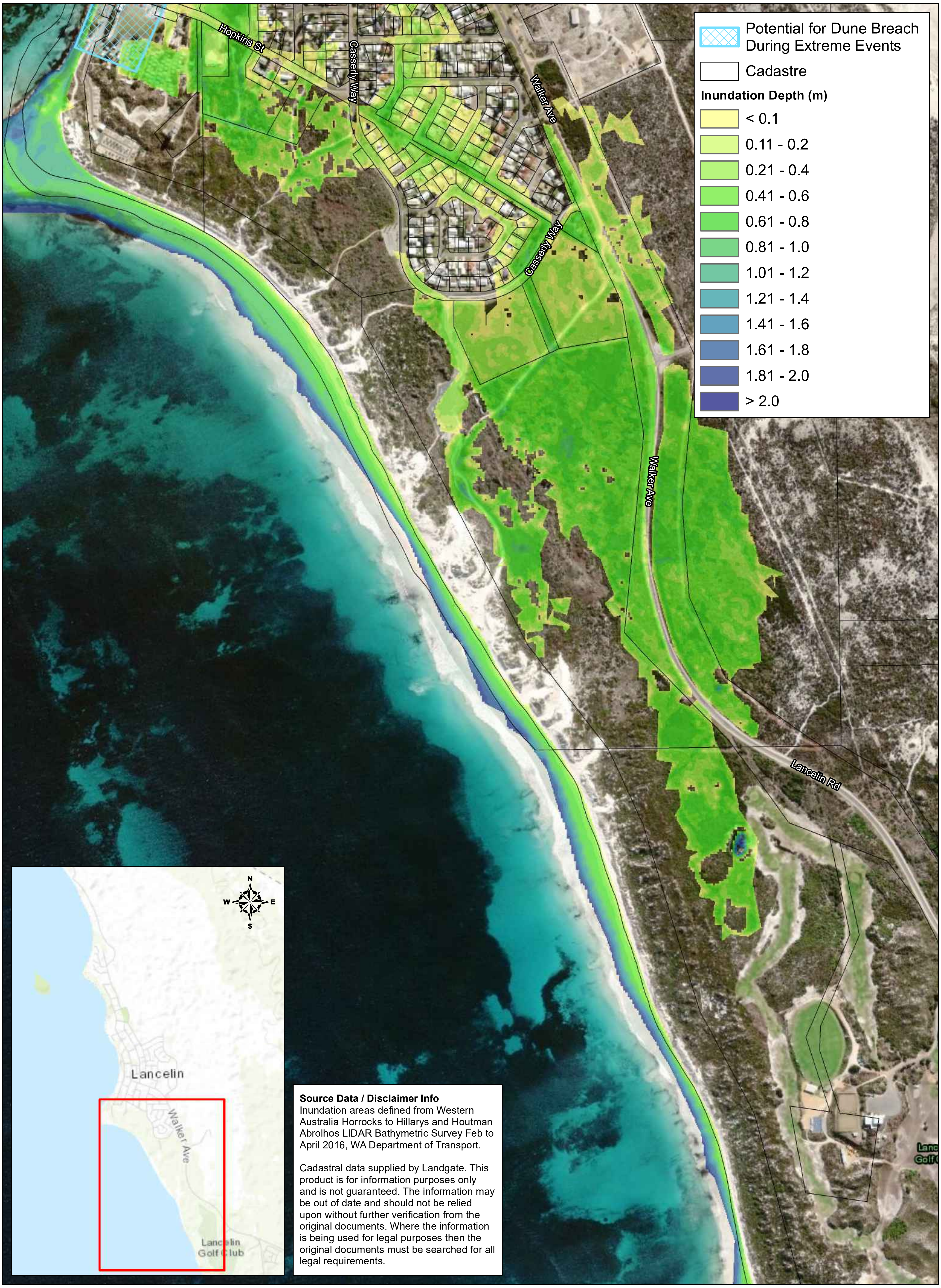
LANCELIN - AREA B

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 20yrARI Depth 2070_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 20yr ARI design storm in planning year 2070 (includes 0.35m Sea Level Rise Allowance)

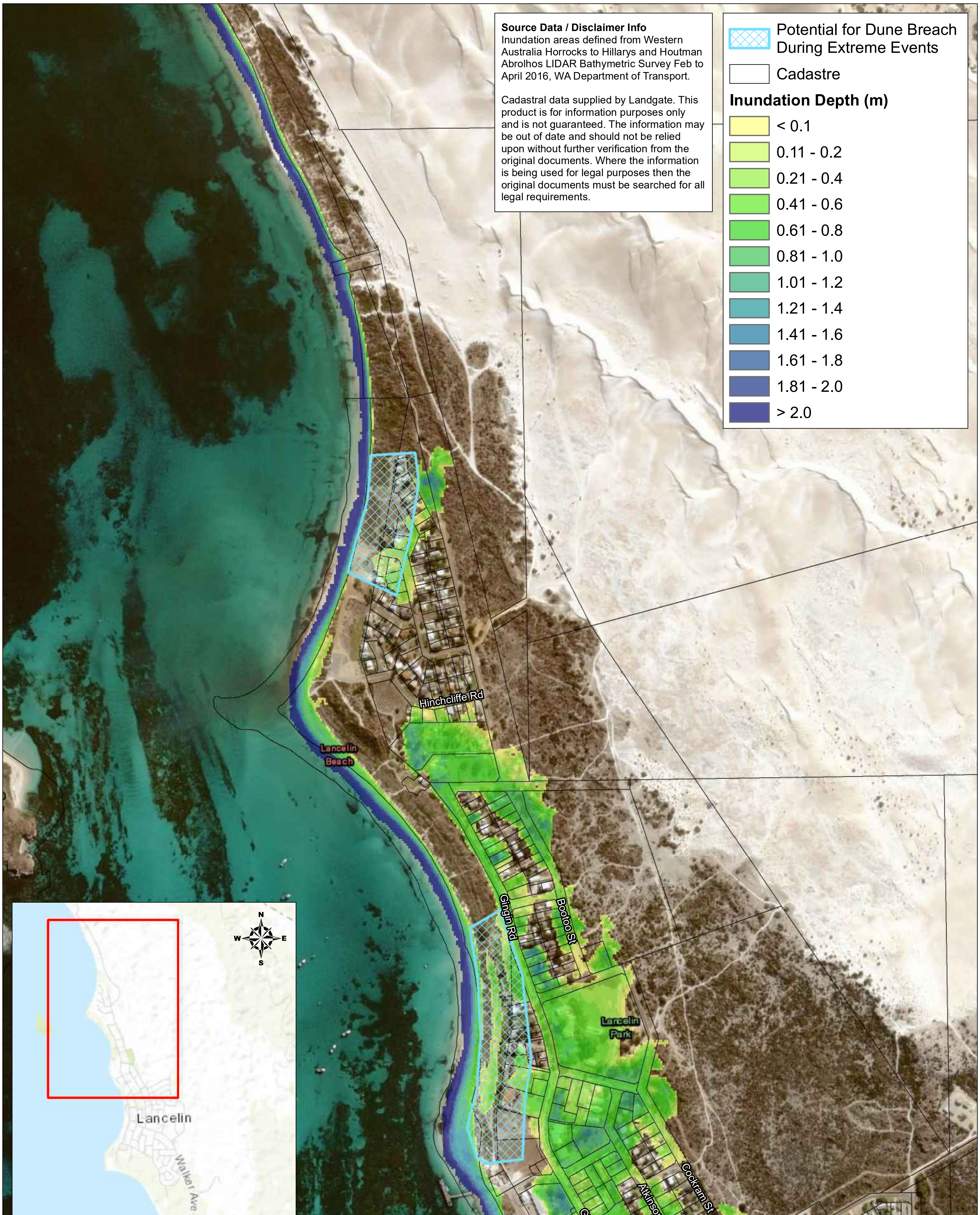
LANCELIN - AREA C

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 20yrARI Depth 2070_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 20yr ARI design storm in planning year 2120 (includes 0.9m Sea Level Rise Allowance)

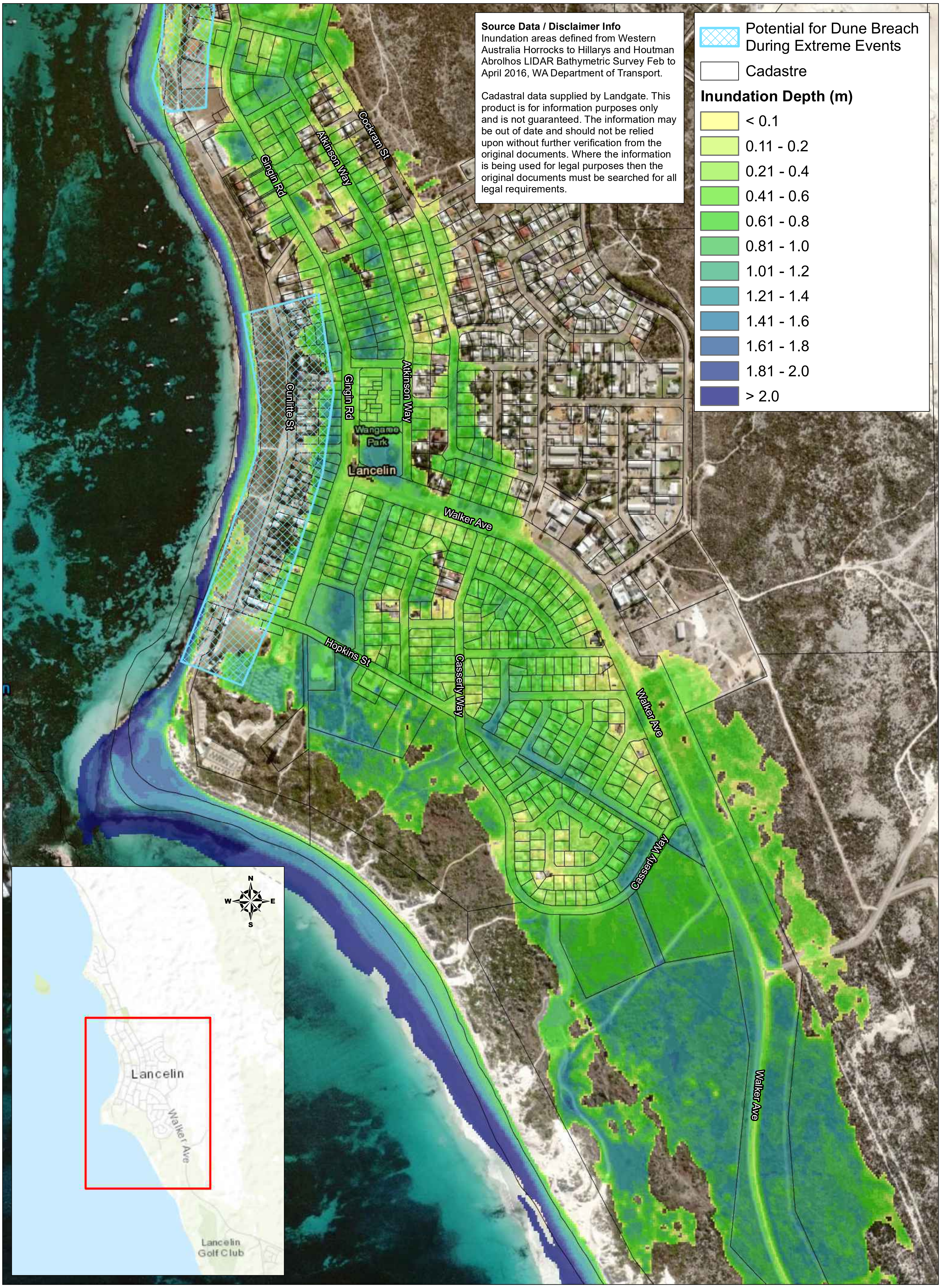
LANCELIN - AREA A

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 20yrARI Depth 2120_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 20yr ARI design storm in planning year 2120 (includes 0.9m Sea Level Rise Allowance)

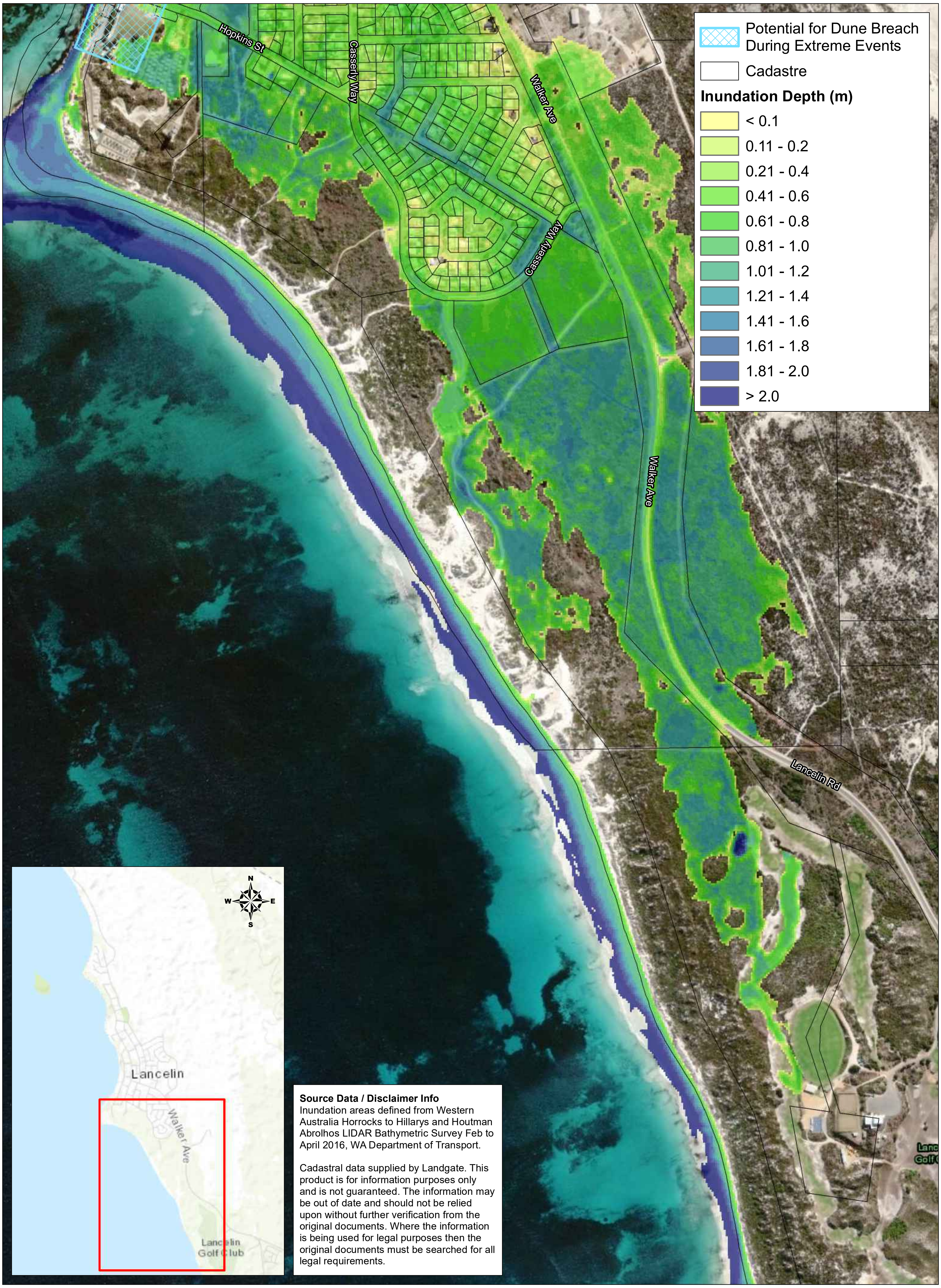
LANCELIN - AREA B

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 20yrARI Depth 2120_Rev02.mxd

Map Published: 2020-06-19



Source Data / Disclaimer Info
Inundation areas defined from Western Australia Horrocks to Hillarys and Houtman Abrolhos LIDAR Bathymetric Survey Feb to April 2016, WA Department of Transport.

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1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 20yr ARI design storm in planning year 2120 (includes 0.9m Sea Level Rise Allowance)

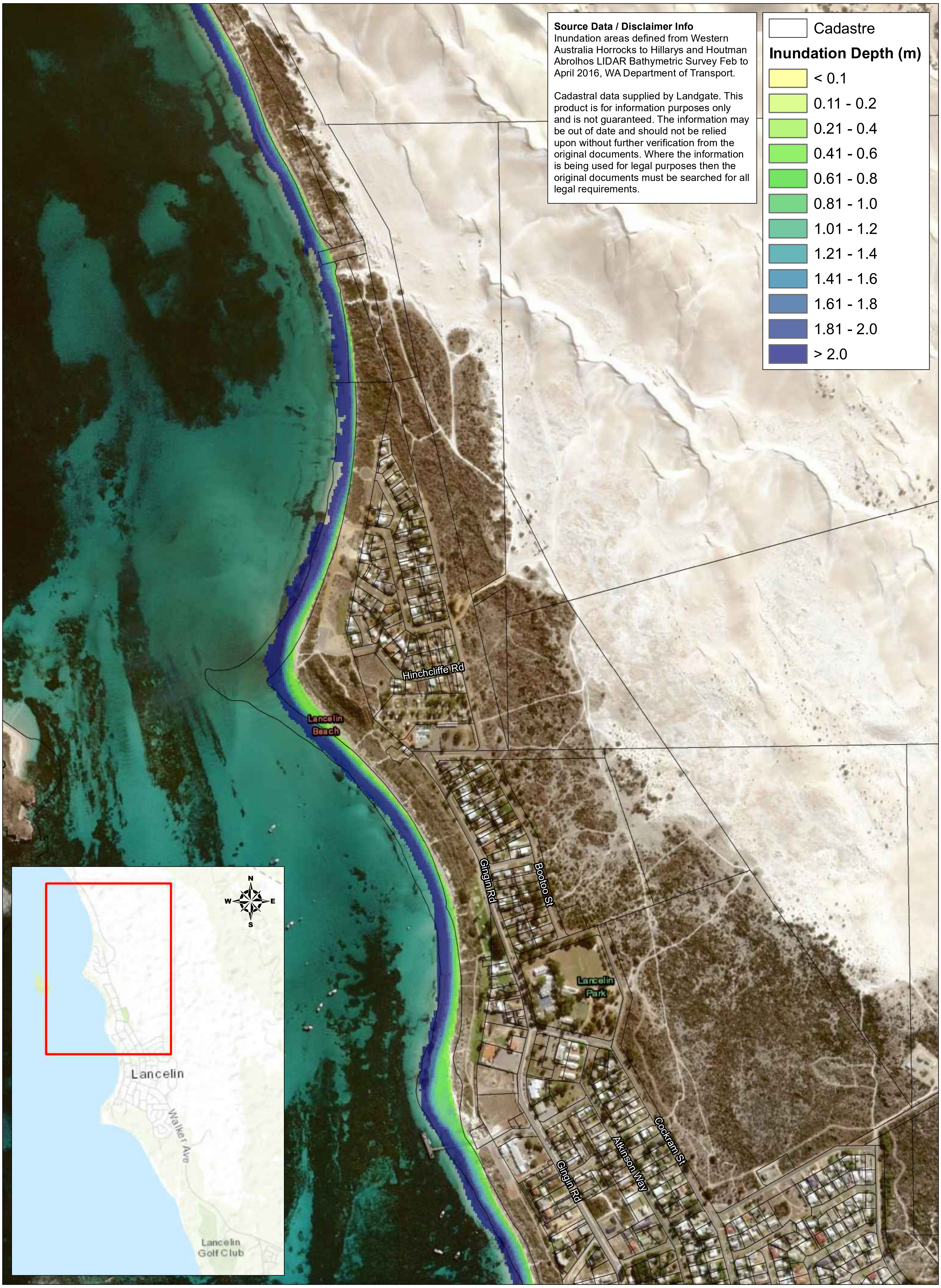
LANCELIN - AREA C

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 20yrARI Depth 2120_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 100yr ARI design storm in planning year 2020 (includes 0m Sea Level Rise Allowance)

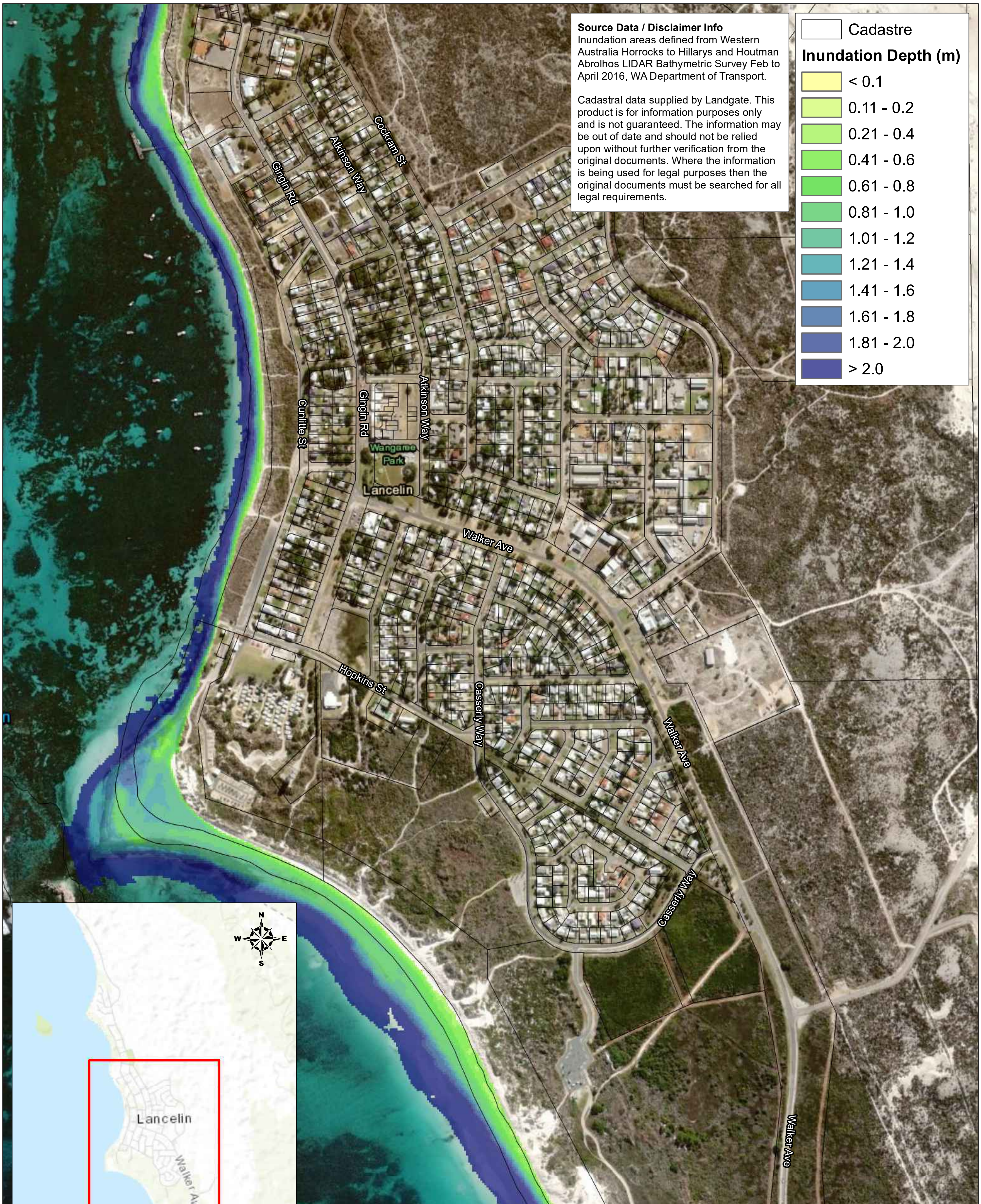
LANCELIN - AREA A

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

Map Published: 2020-06-19

13288 Gingin - Lancelin - 100yrARI Depth 2020_Rev02.mxd



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0 100 200 300 m

Inundation Depth based on peak water level from 100yr ARI design storm in planning year 2020 (includes 0m Sea Level Rise Allowance)

LANCELIN - AREA B

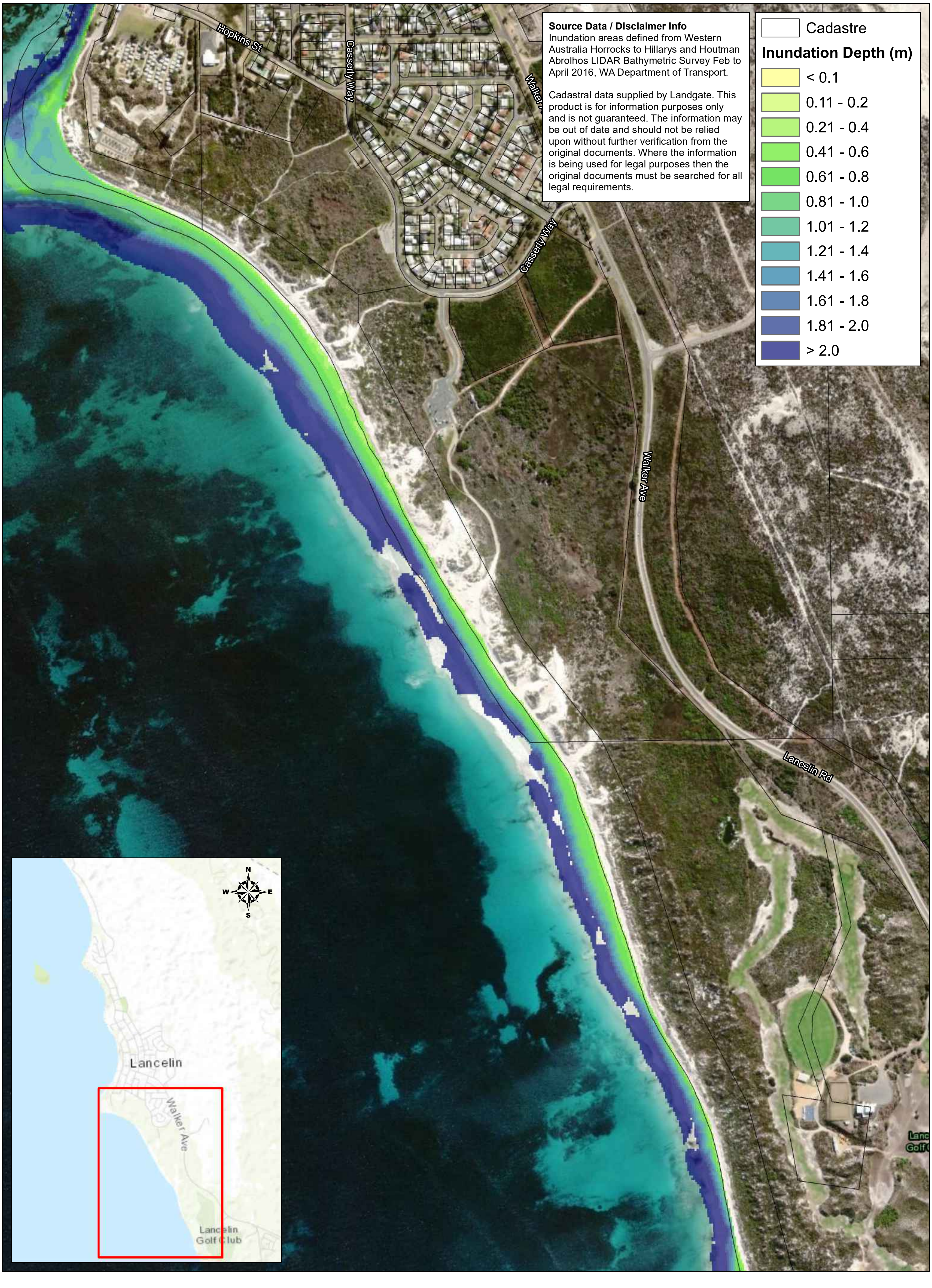
Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird.

GINGIN

Map Published: 2020-06-19

13288 Gingin - Lancelin - 100yrARI Depth 2020_Rev02.mxd



Inundation Depth based on peak water level from 100yr ARI design storm in planning year 2020 (includes 0m Sea Level Rise Allowance)

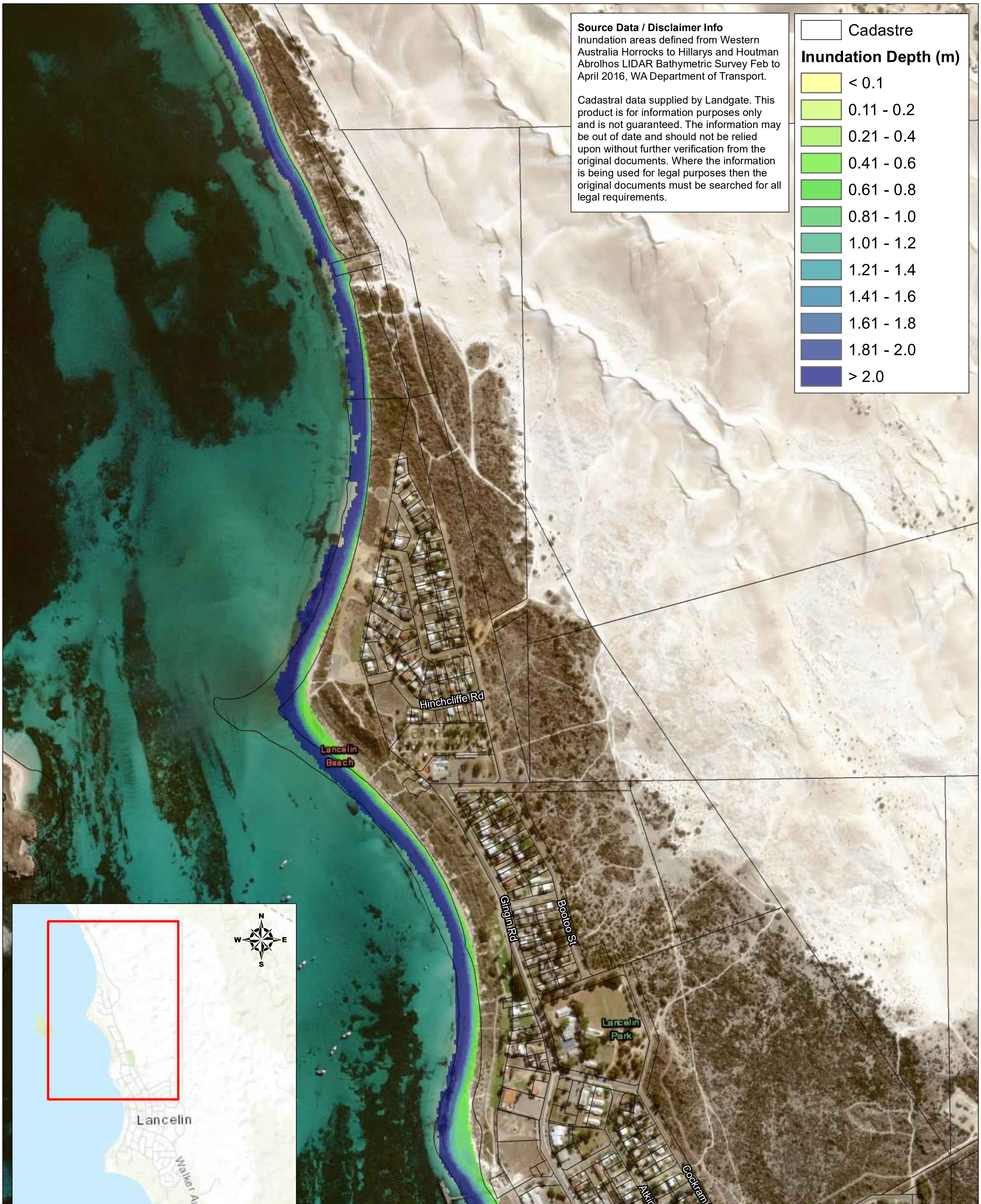
LANCELIN - AREA C

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 100yrARI Depth 2020_Rev02.mxd

Map Published: 2020-06-19



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0 100 200 300 m

Inundation Depth based on peak water level from 100yr ARI design storm in planning year 2040 (includes 0.1m Sea Level Rise Allowance)

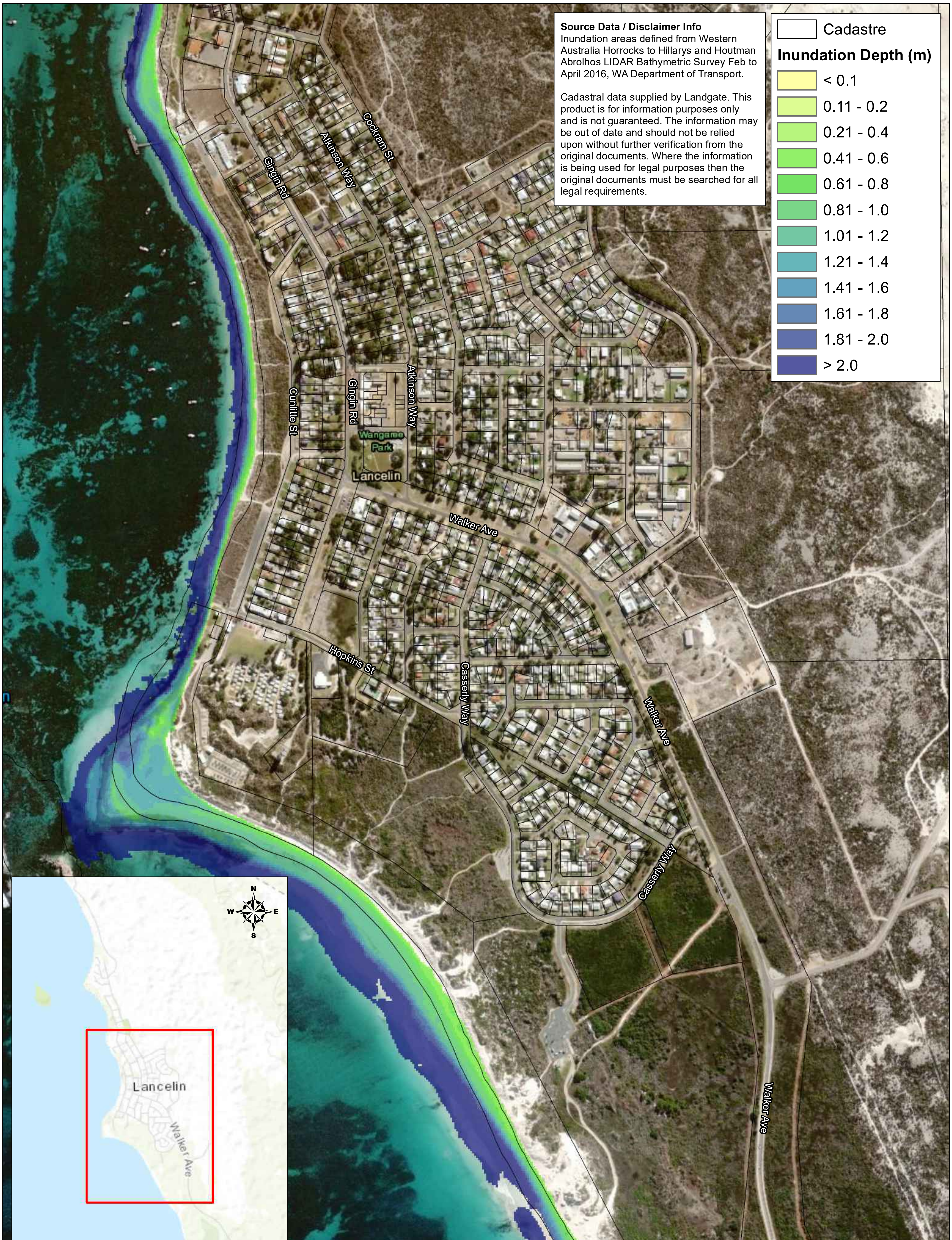
LANCELIN - AREA A

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 100yrARI Depth 2040_Rev02.mxd

Map Published: 2020-06-19



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0 100 200 300 m

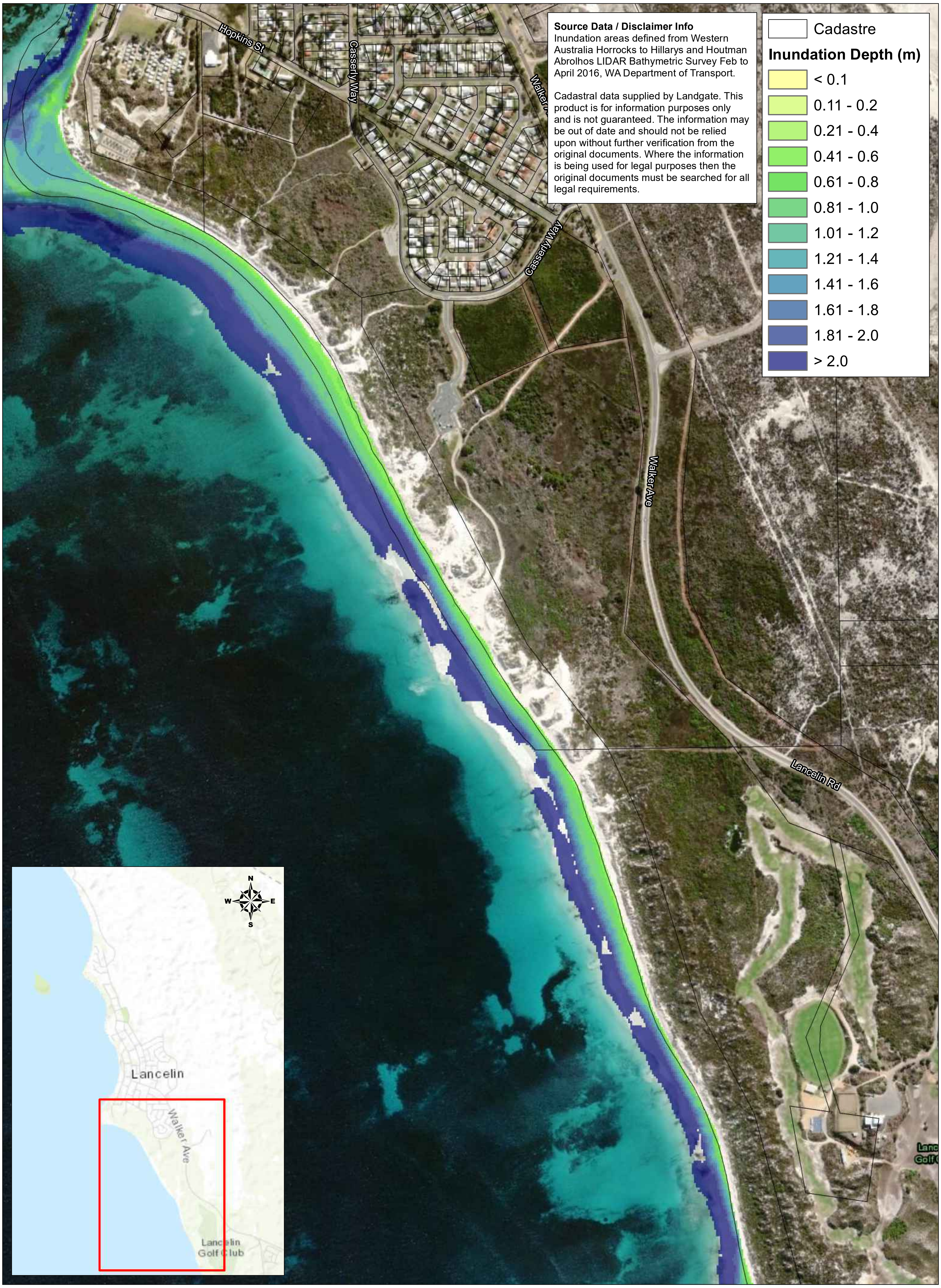
Inundation Depth based on peak water level from 100yr ARI design storm in planning year 2040 (includes 0.1m Sea Level Rise Allowance)

LANCELIN - AREA B

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

13288 Gingin - Lancelin - 100yrARI Depth 2040_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 100yr ARI design storm in planning year 2040 (includes 0.1m Sea Level Rise Allowance)

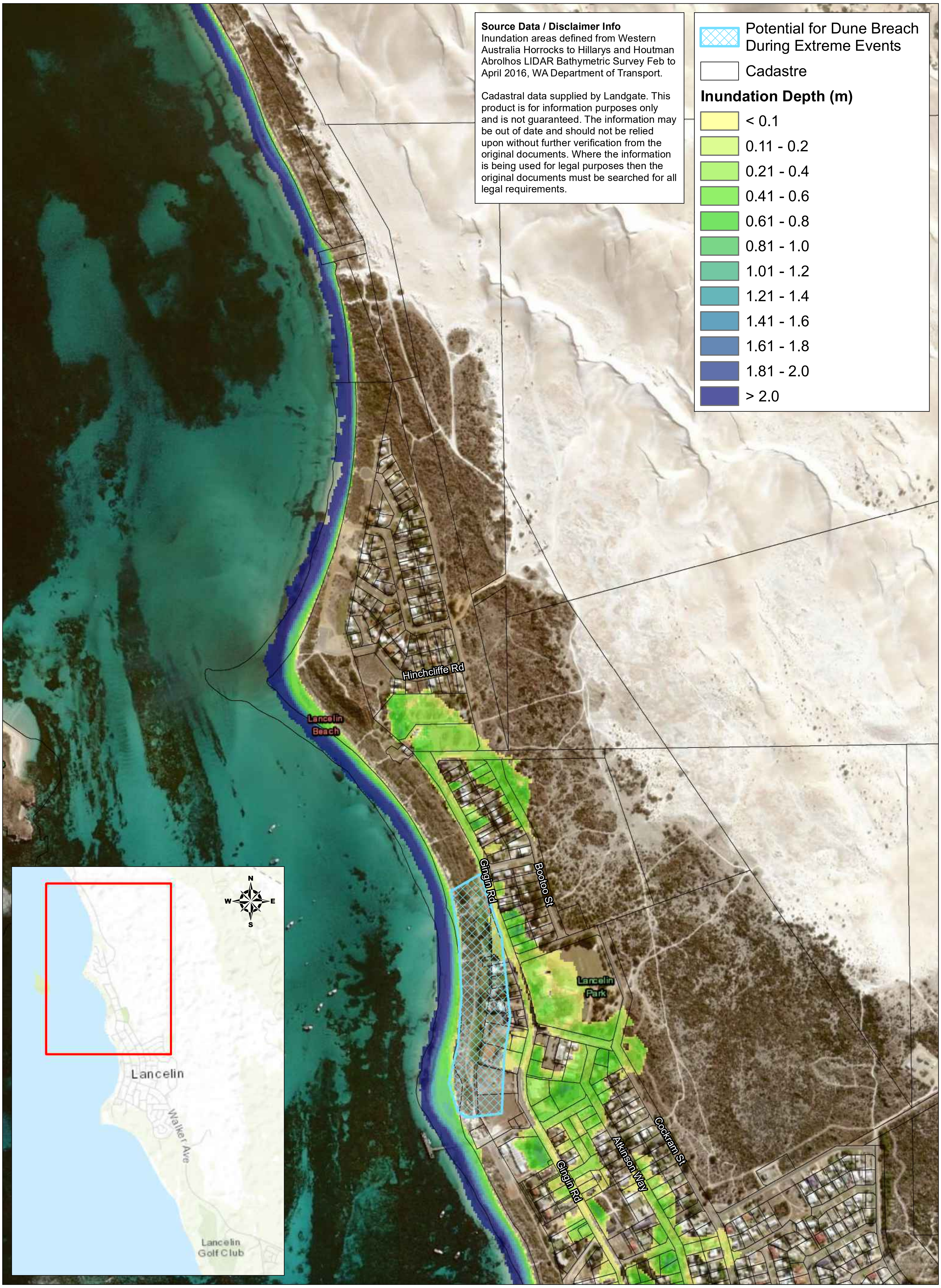
LANCELIN - AREA C

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 100yrARI Depth 2040_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 100yr ARI design storm in planning year 2070 (includes 0.35m Sea Level Rise Allowance)

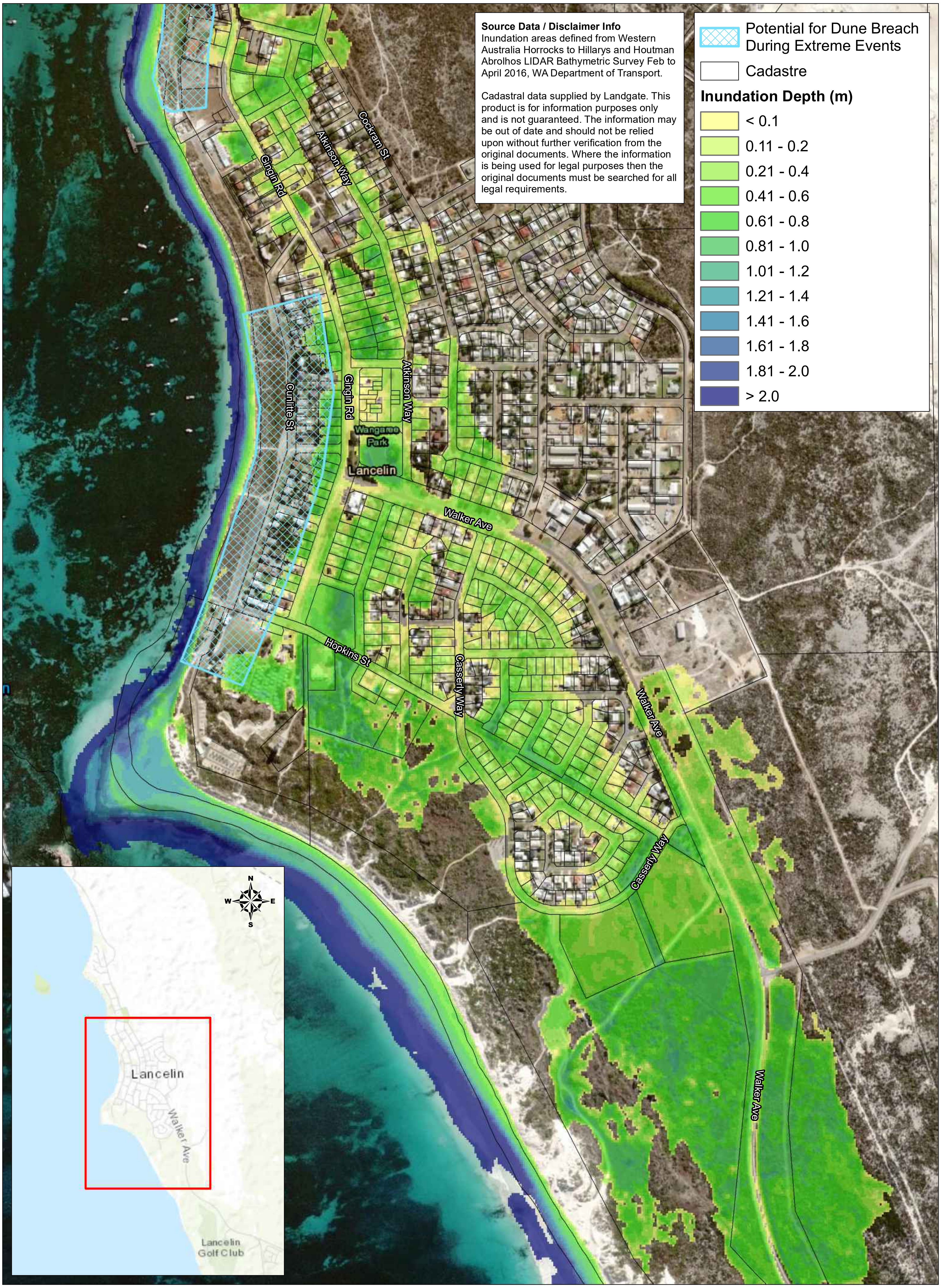
LANCELIN - AREA A

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 100yrARI Depth 2070_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 100yr ARI design storm in planning year 2070 (includes 0.35m Sea Level Rise Allowance)

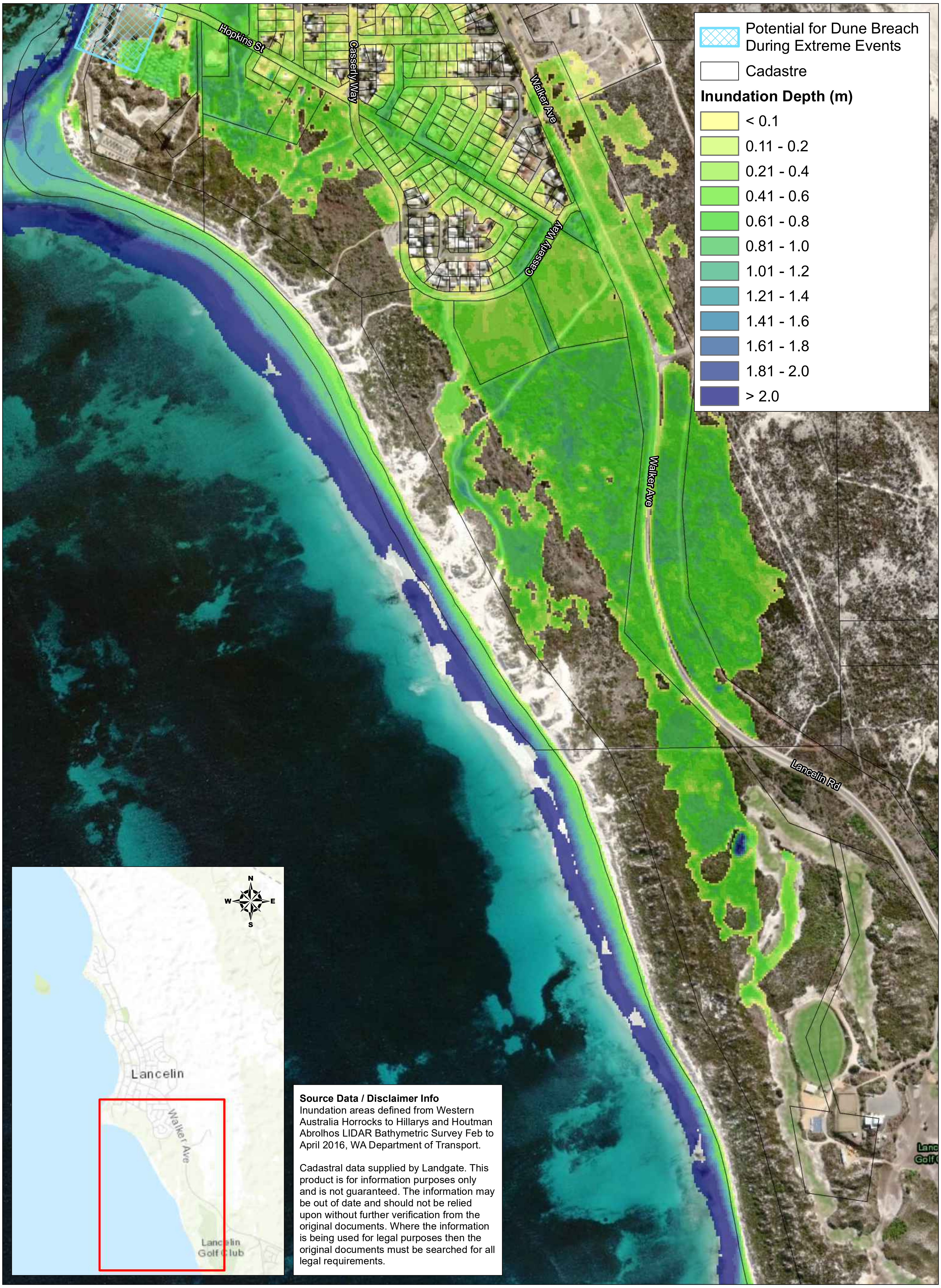
LANCELIN - AREA B

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 100yrARI Depth 2070_Rev02.mxd

Map Published: 2020-06-19



Source Data / Disclaimer Info
Inundation areas defined from Western Australia Horrocks to Hillarys and Houtman Abrolhos LIDAR Bathymetric Survey Feb to April 2016, WA Department of Transport.

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1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 100yr ARI design storm in planning year 2070 (includes 0.35m Sea Level Rise Allowance)

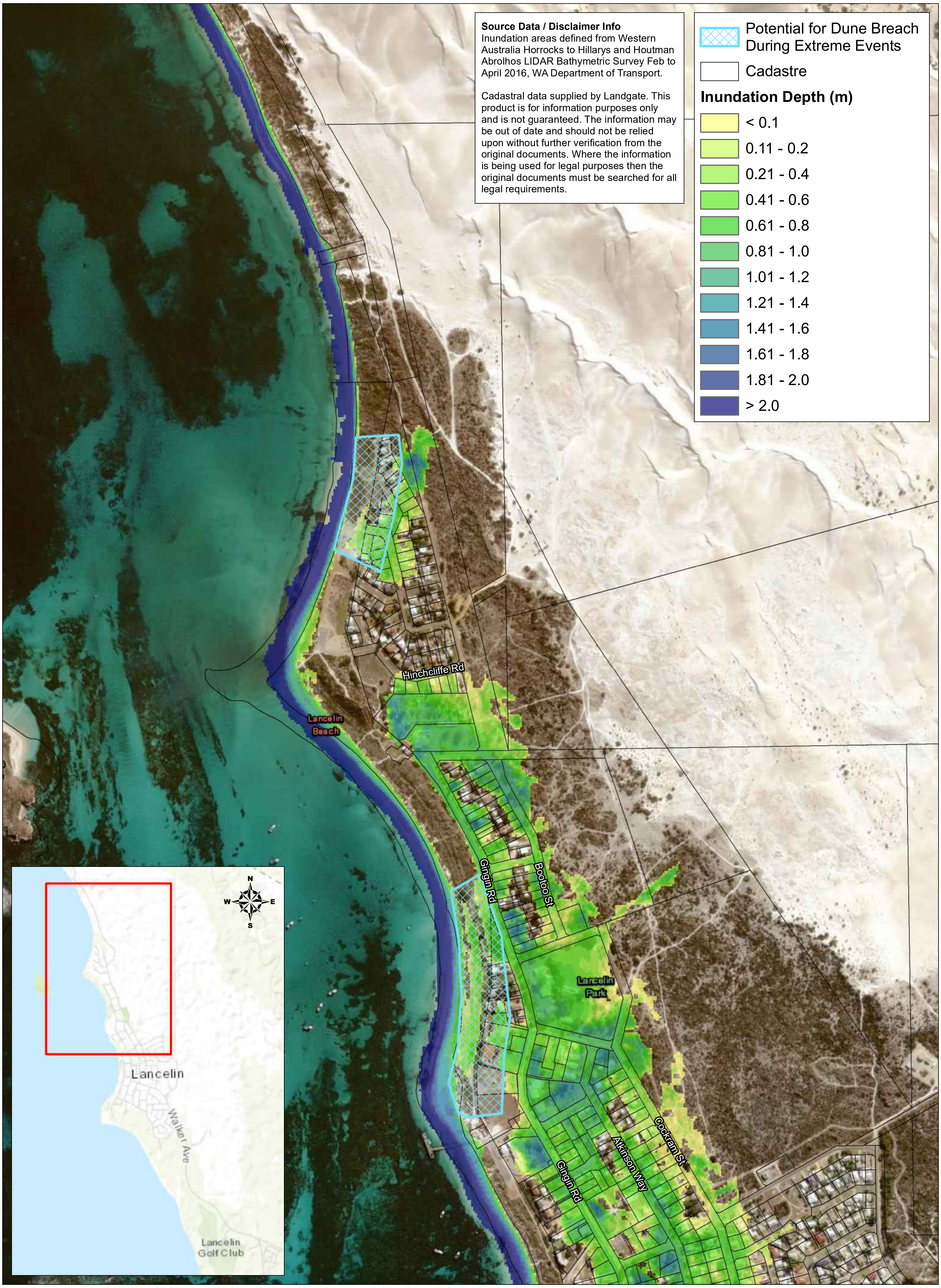
LANCELIN - AREA C

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 100yrARI Depth 2070_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 100yr ARI design storm in planning year 2120 (includes 0.9m Sea Level Rise Allowance)

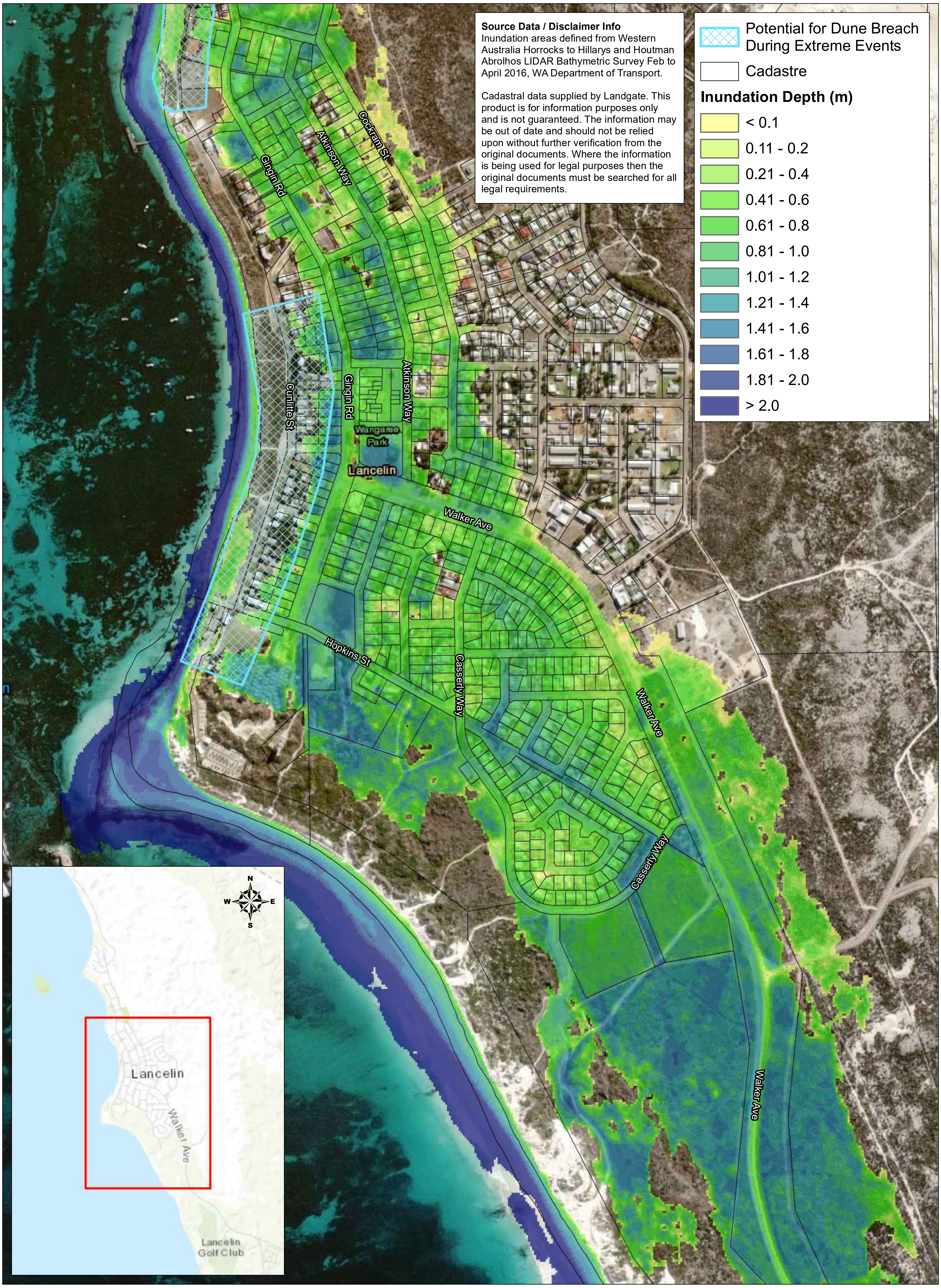
LANCELIN - AREA A

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 100yrARI Depth 2120_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 100yr ARI design storm in planning year 2120 (includes 0.9m Sea Level Rise Allowance)

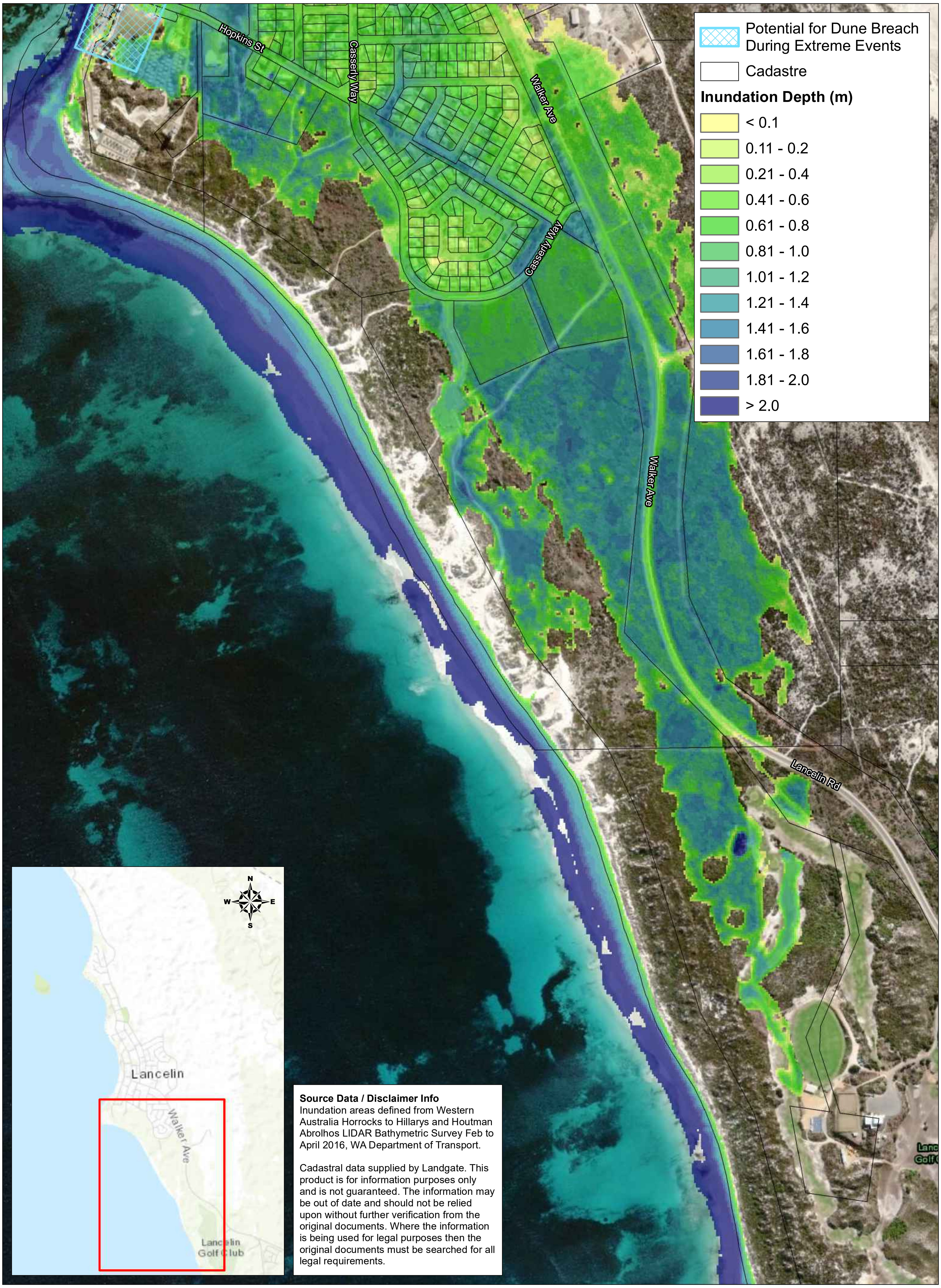
LANCELIN - AREA B

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 100yrARI Depth 2120_Rev02.mxd

Map Published: 2020-06-19



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1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 100yr ARI design storm in planning year 2120 (includes 0.9m Sea Level Rise Allowance)

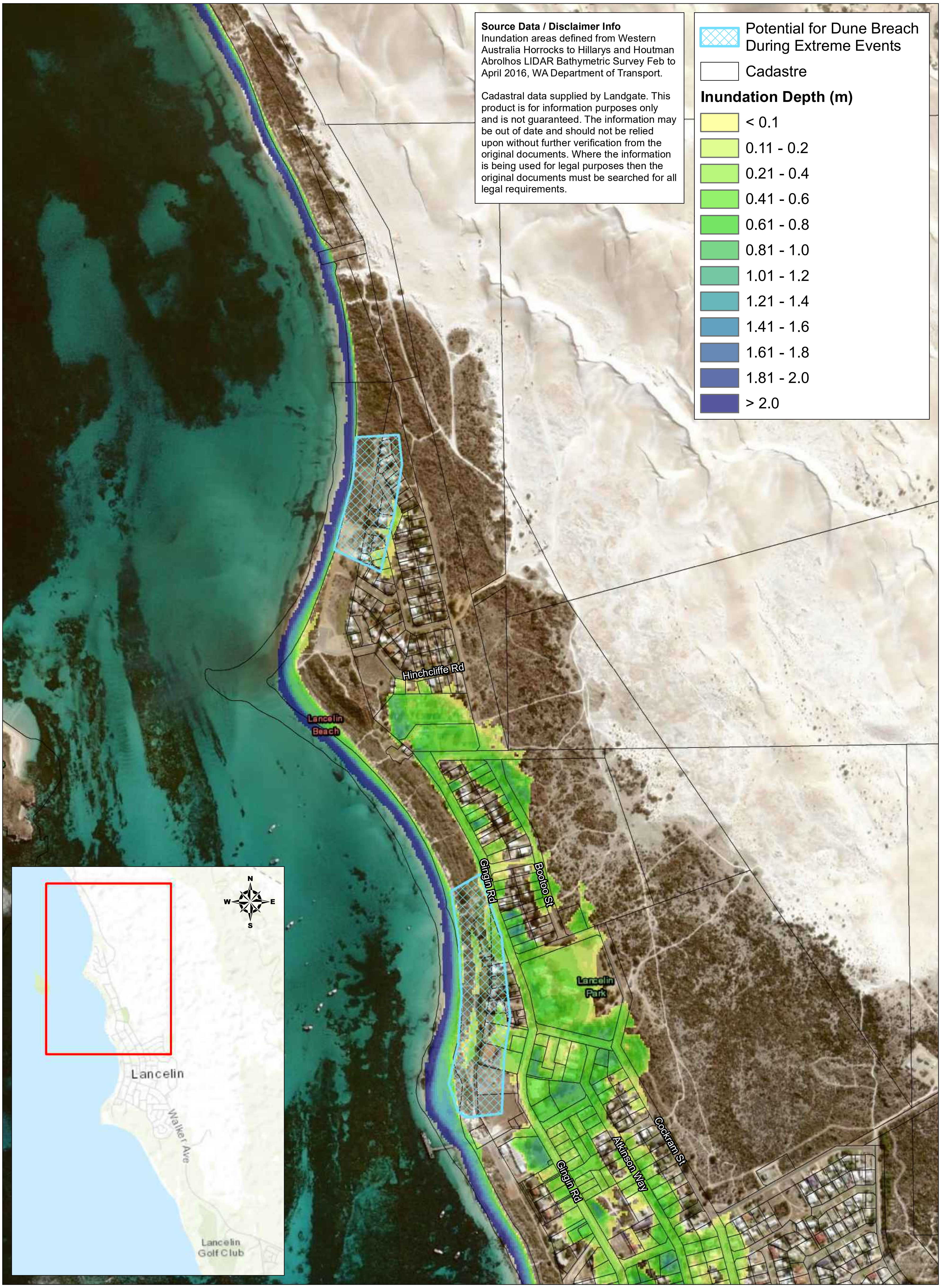
LANCELIN - AREA C

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 100yrARI Depth 2120_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 500yr ARI design storm in planning year 2020 (includes 0m Sea Level Rise Allowance)

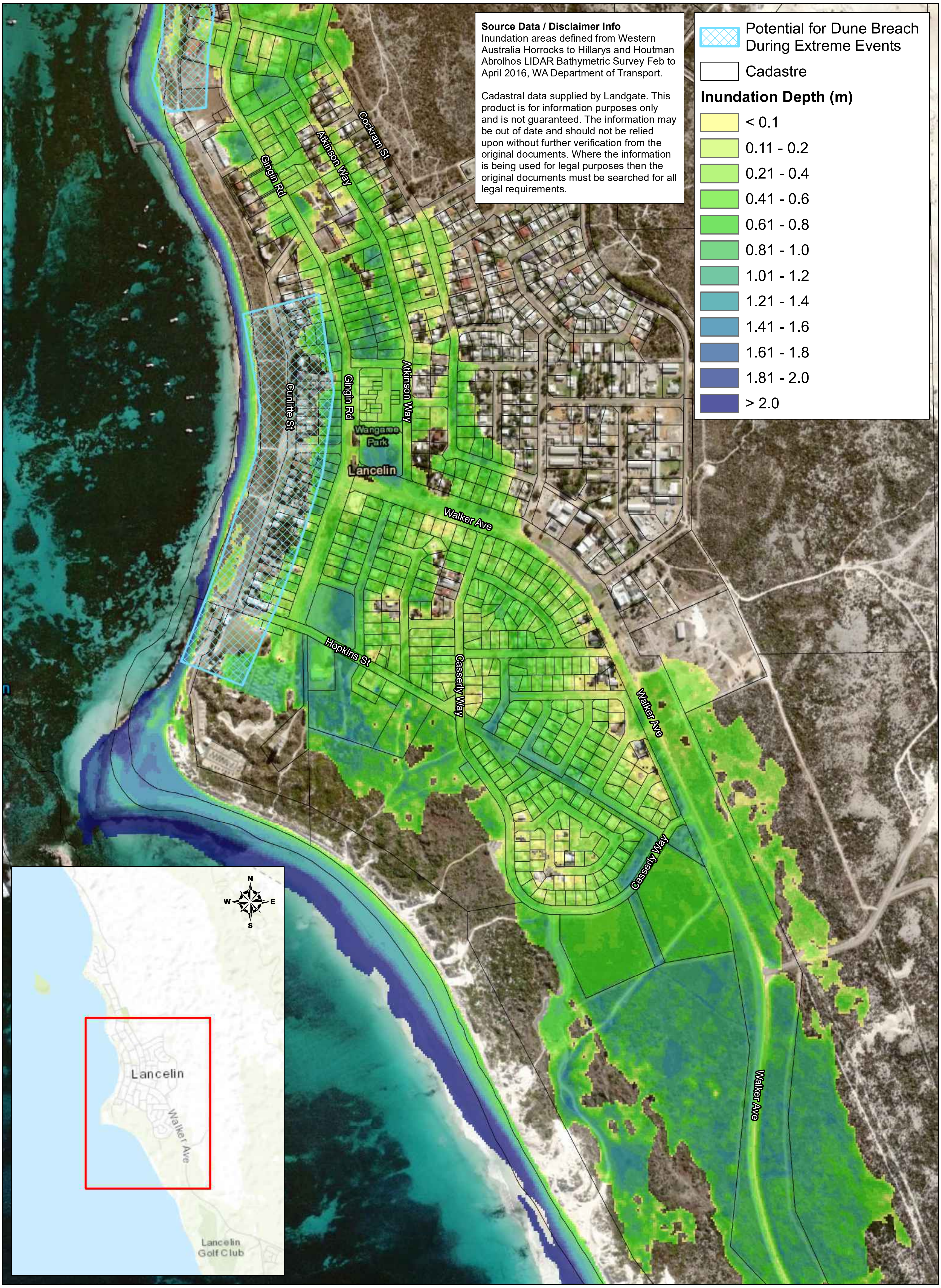
LANCELIN - AREA A

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 500yrARI Depth 2020_Rev02.mxd

Map Published: 2020-06-19



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0 100 200 300 m

Inundation Depth based on peak water level from 500yr ARI design storm in planning year 2020 (includes 0m Sea Level Rise Allowance)

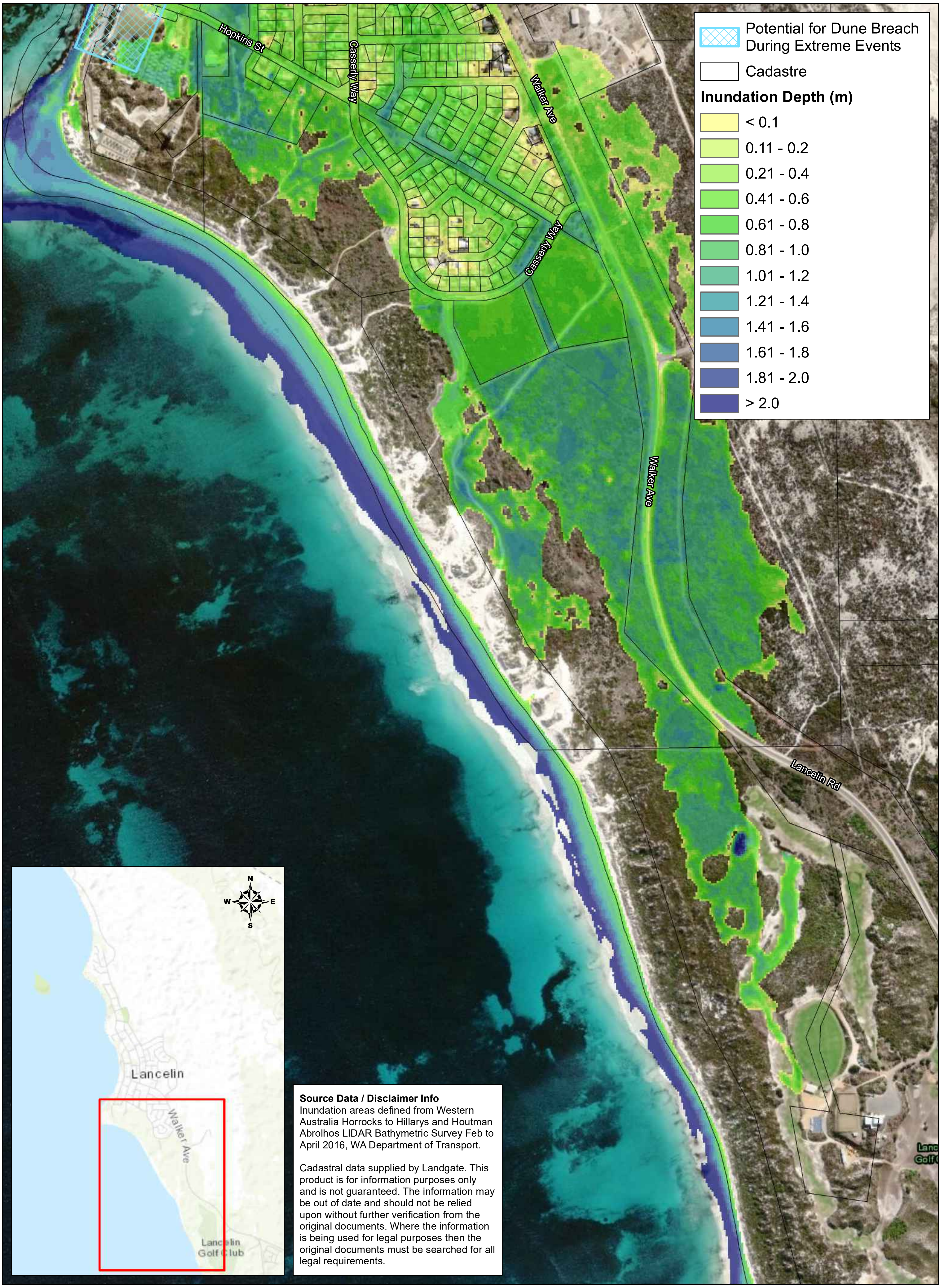
LANCELIN - AREA B

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 500yrARI Depth 2020_Rev02.mxd

Map Published: 2020-06-19



Source Data / Disclaimer Info
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1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 500yr ARI design storm in planning year 2020 (includes 0m Sea Level Rise Allowance)

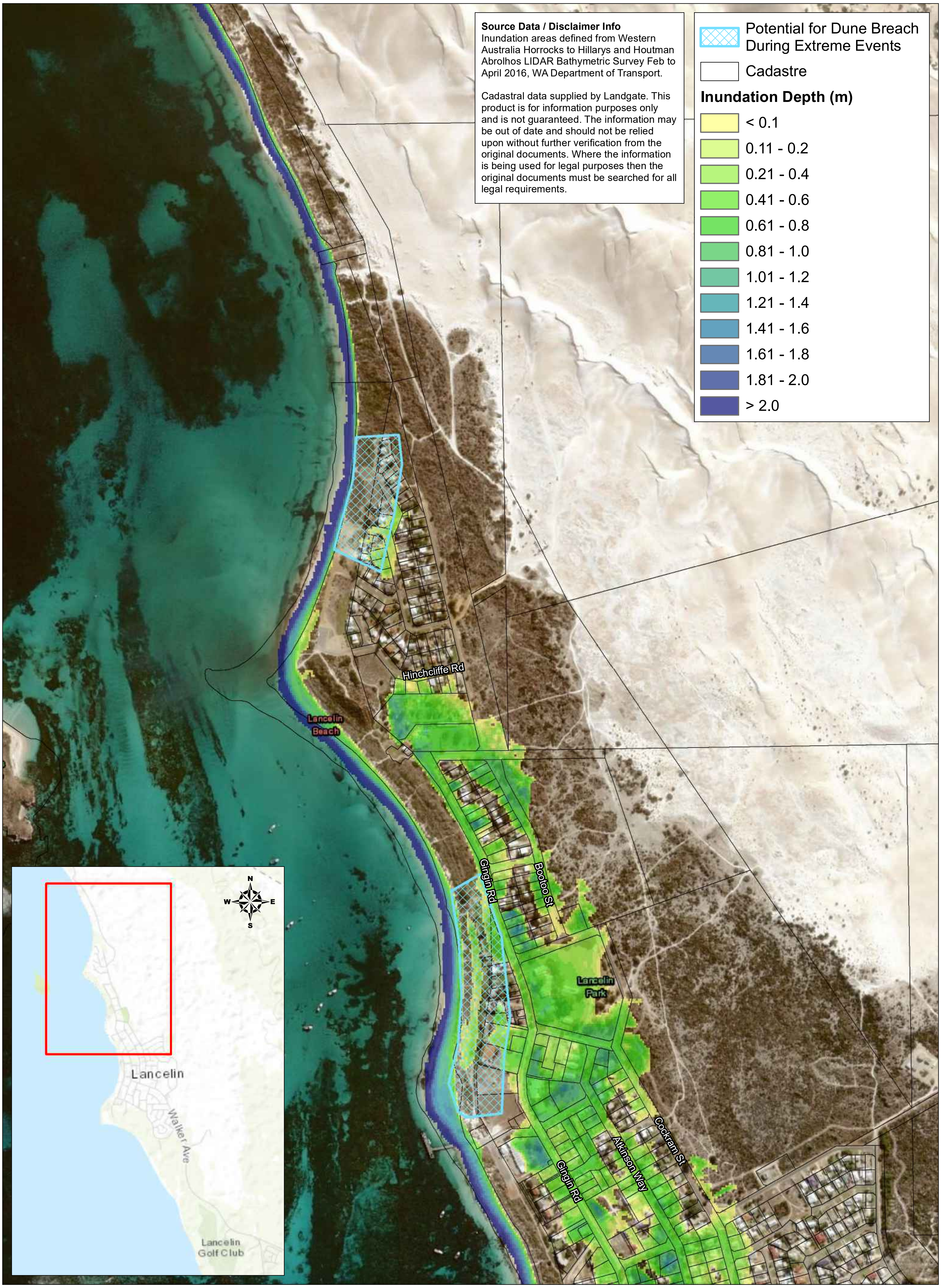
LANCELIN - AREA C

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 500yrARI Depth 2020_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 500yr ARI design storm in planning year 2040 (includes 0.1m Sea Level Rise Allowance)

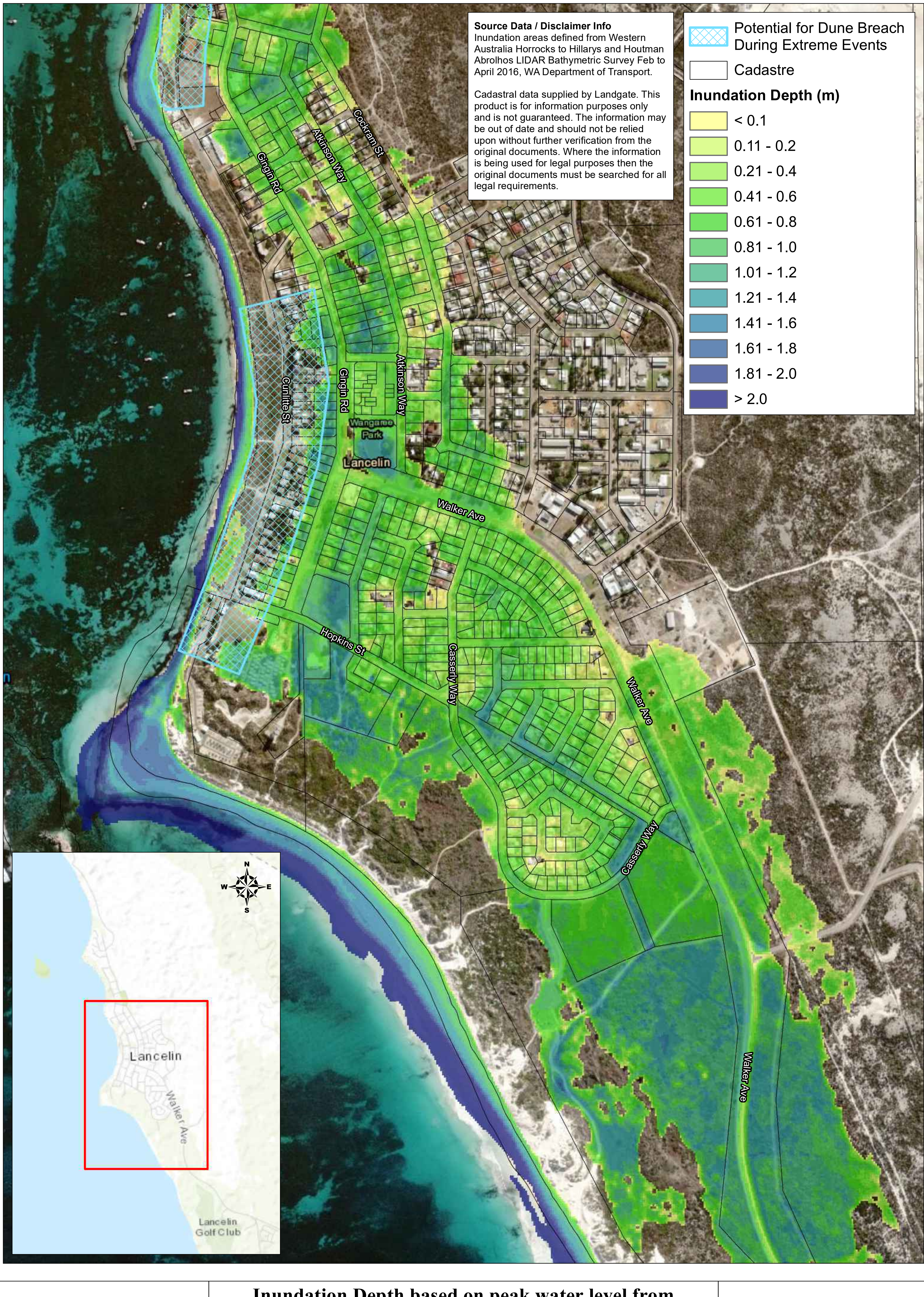
LANCELIN - AREA A

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 500yrARI Depth 2040_Rev02.mxd

Map Published: 2020-06-19



Inundation Depth based on peak water level from 500yr ARI design storm in planning year 2040 (includes 0.1m Sea Level Rise Allowance)

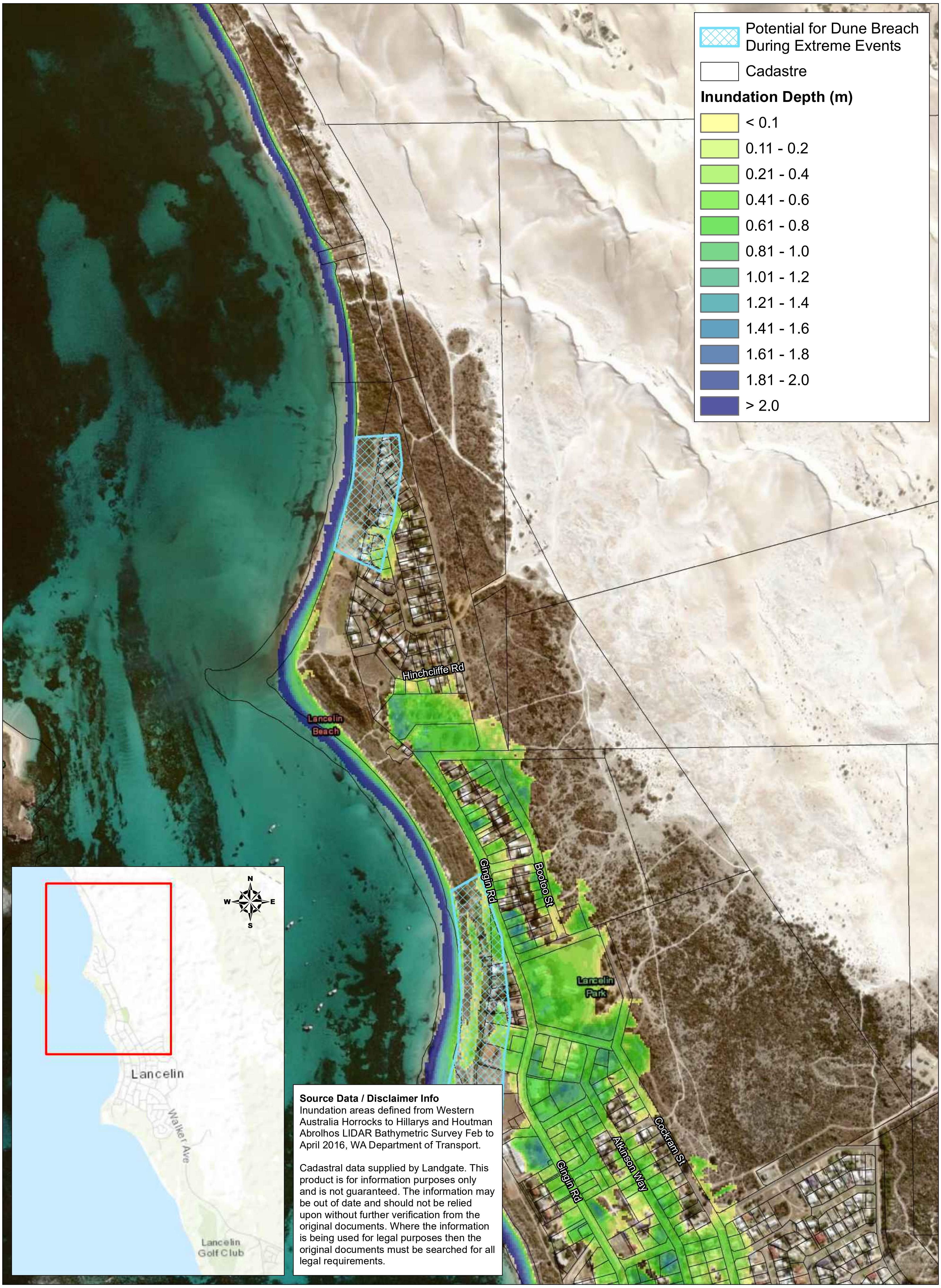
LANCELIN - AREA B

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 500yrARI Depth 2040_Rev02.mxd

Map Published: 2020-06-19



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1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 500yr ARI design storm in planning year 2040 (includes 0.1m Sea Level Rise Allowance)

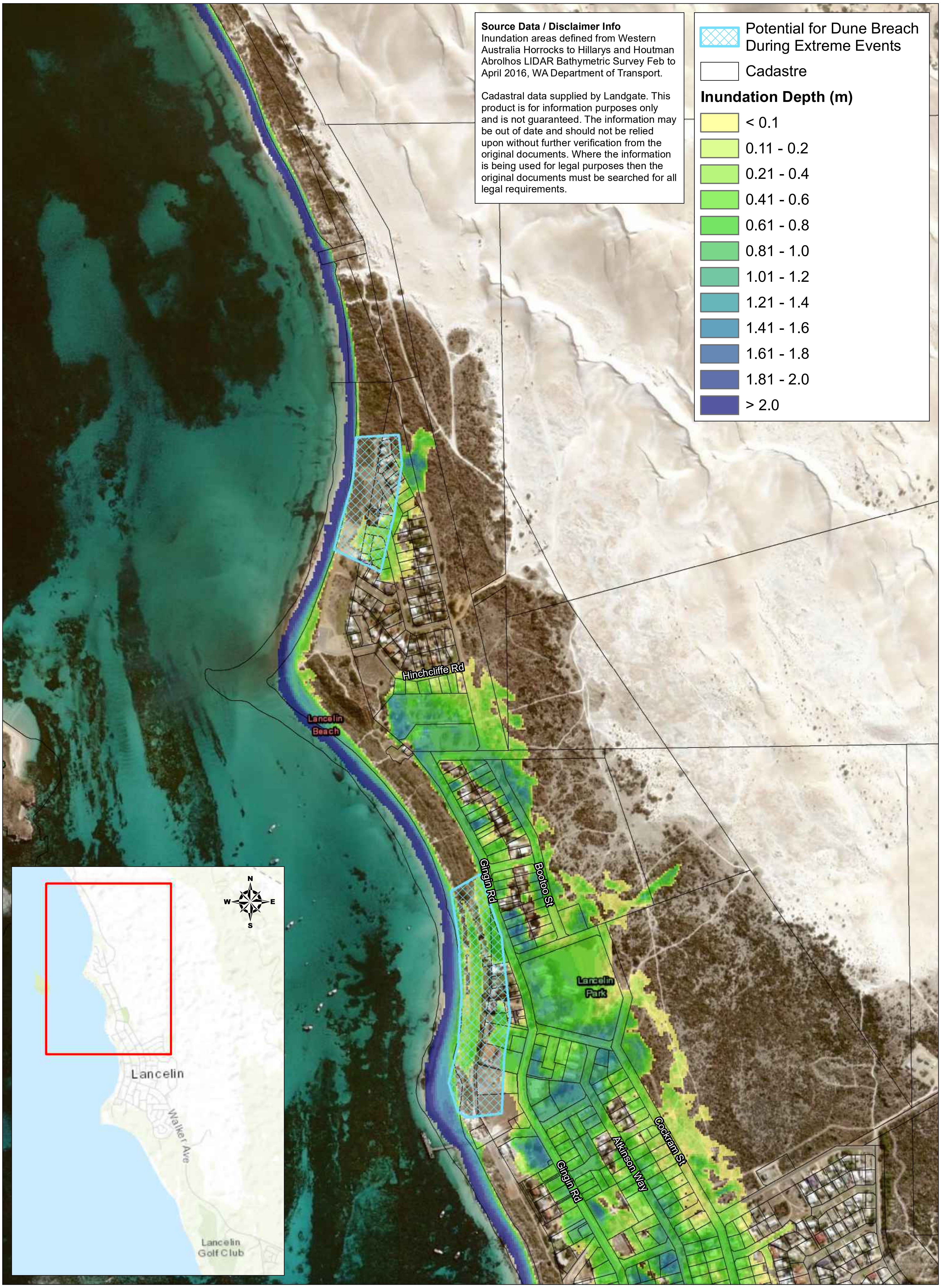
LANCELIN - AREA C

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 500yrARI Depth 2040_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 500yr ARI design storm in planning year 2070 (includes 0.35m Sea Level Rise Allowance)

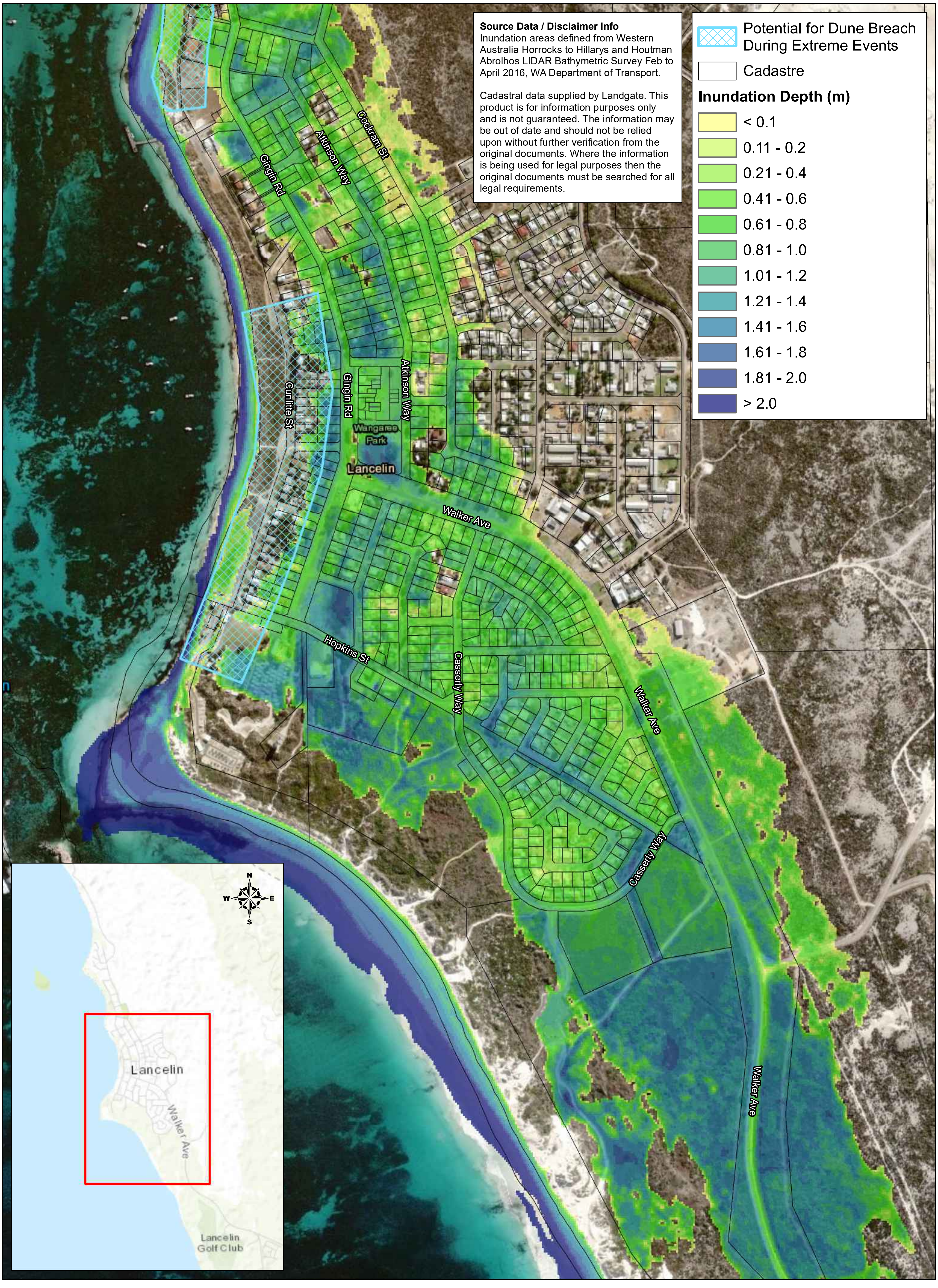
LANCELIN - AREA A

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 500yrARI Depth 2070_Rev02.mxd

Map Published: 2020-06-19



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0 100 200 300 m

Inundation Depth based on peak water level from 500yr ARI design storm in planning year 2070 (includes 0.35m Sea Level Rise Allowance)

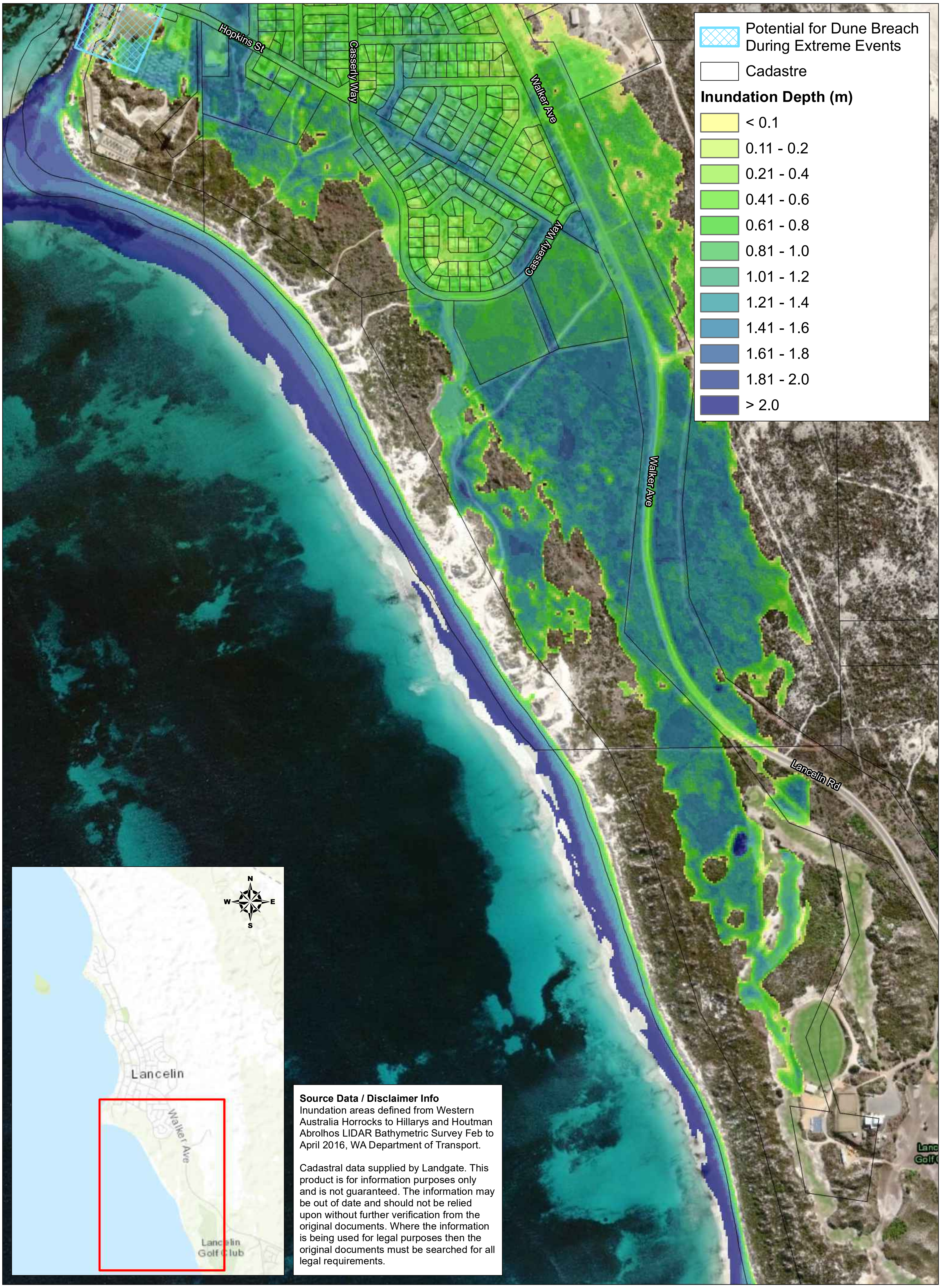
LANCELIN - AREA B

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 500yrARI Depth 2070_Rev02.mxd

Map Published: 2020-06-19



Source Data / Disclaimer Info
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1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 500yr ARI design storm in planning year 2070 (includes 0.35m Sea Level Rise Allowance)

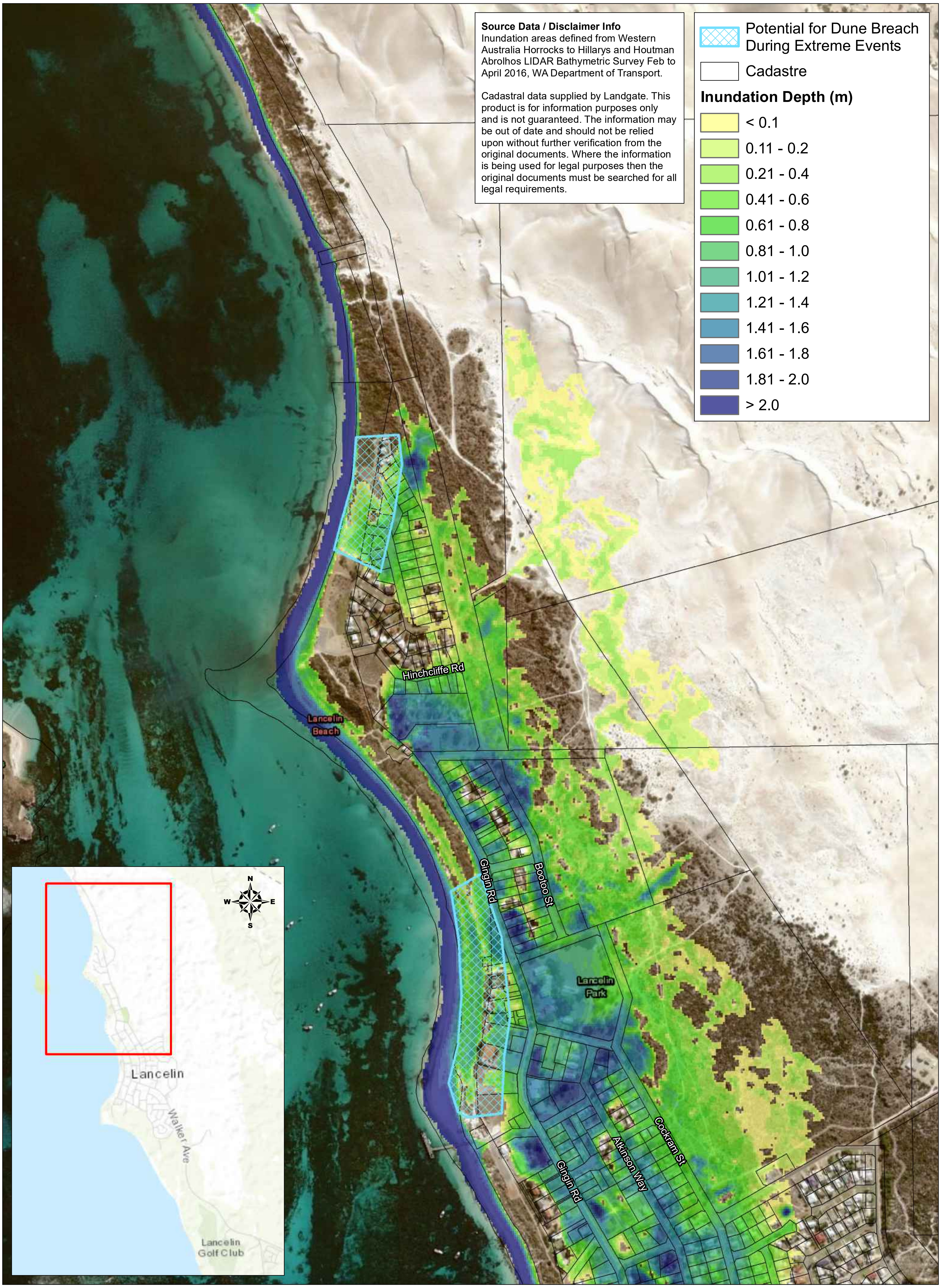
LANCELIN - AREA C

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 500yrARI Depth 2070_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 500yr ARI design storm in planning year 2120 (includes 0.9m Sea Level Rise Allowance)

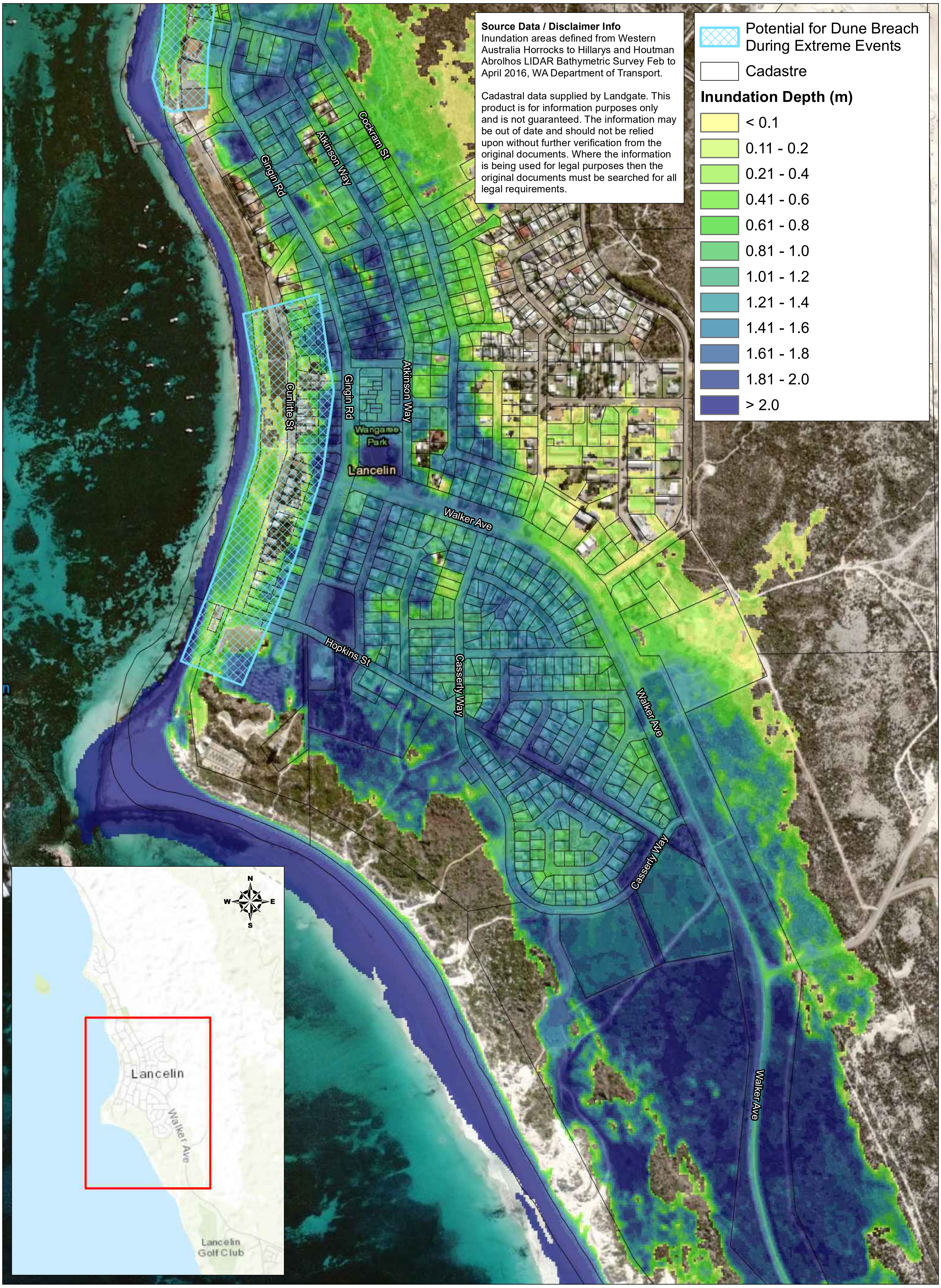
LANCELIN - AREA A

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 500yrARI Depth 2120_Rev02.mxd

Map Published: 2020-06-19



1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 500yr ARI design storm in planning year 2120 (includes 0.9m Sea Level Rise Allowance)

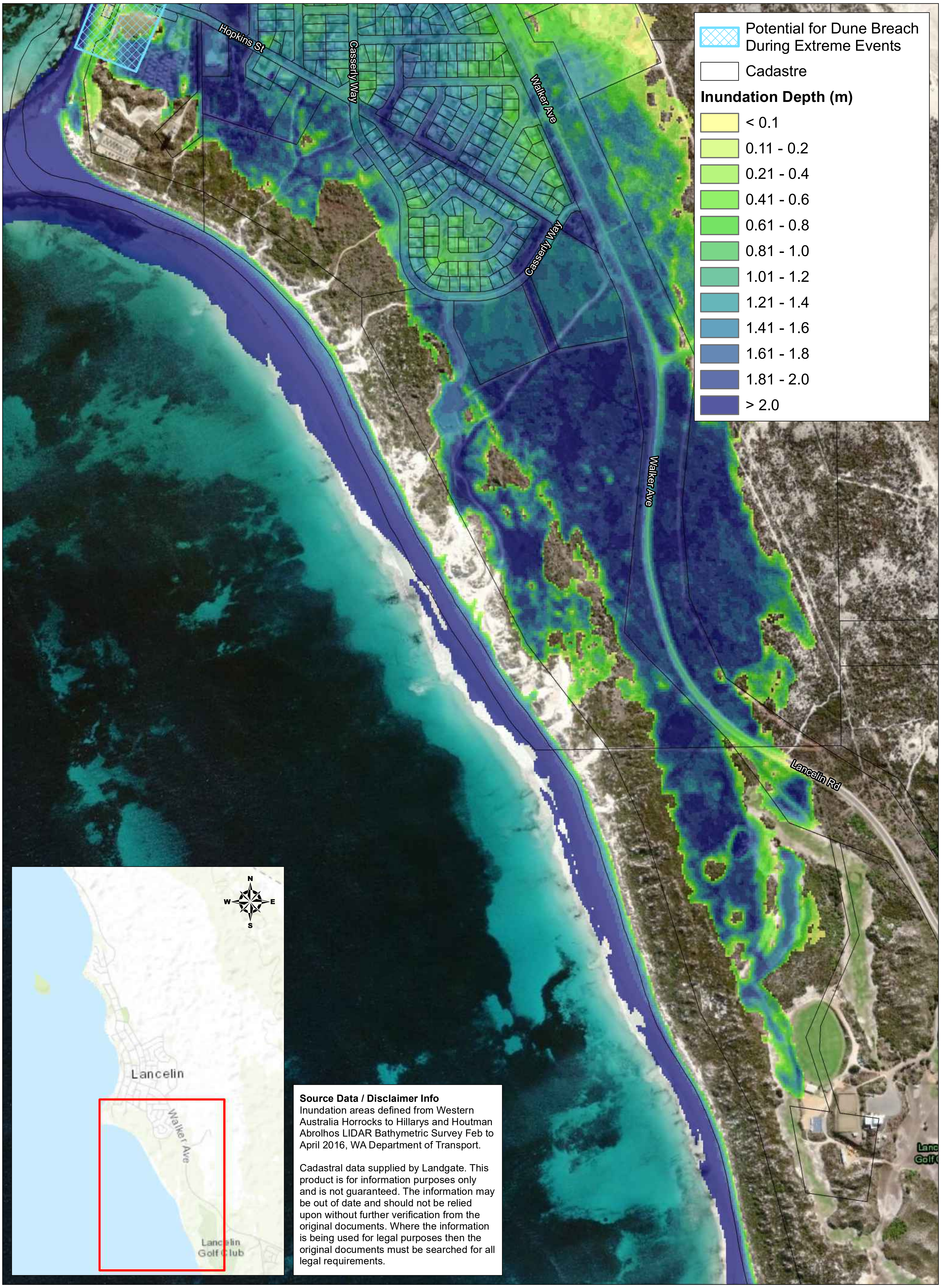
LANCELIN - AREA B

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Lancelin - 500yrARI Depth 2120_Rev02.mxd

Map Published: 2020-06-19



Source Data / Disclaimer Info
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1:8,000

0 100 200 300 m

Inundation Depth based on peak water level from 500yr ARI design storm in planning year 2120 (includes 0.9m Sea Level Rise Allowance)

LANCELIN - AREA C

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

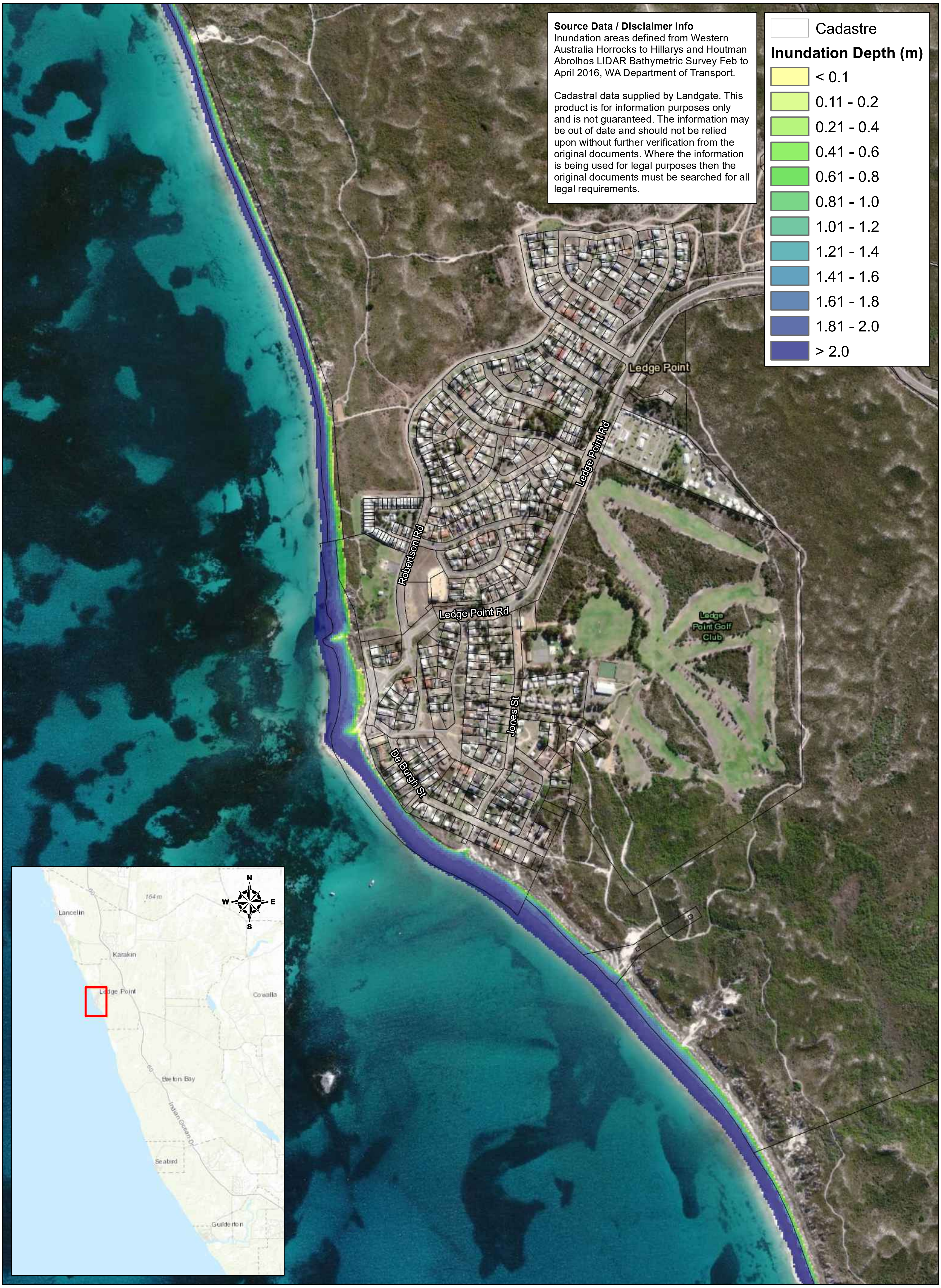
Baird. GINGIN

13288 Gingin - Lancelin - 500yrARI Depth 2120_Rev02.mxd

Map Published: 2020-06-19

C.2 Ledge Point Inundation Mapping

Mapping Cases presented for the 500yr ARI events at planning year 2120.



1:9,000

0 100 200 300 m

Inundation Depth based on peak water level from 500yr ARI design storm in planning year 2120 (includes 0.9m Sea Level Rise Allowance)

LEDGE POINT

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

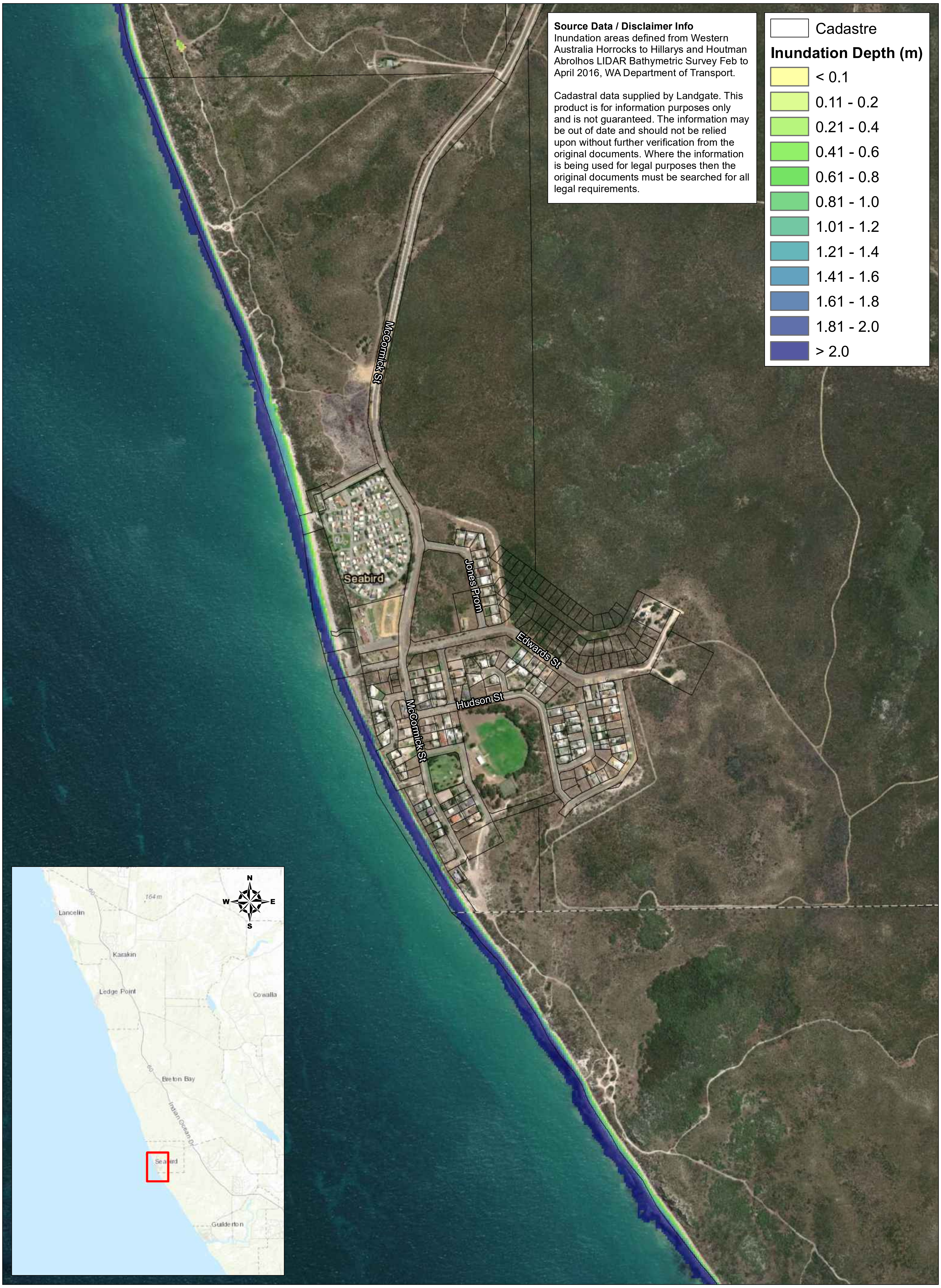
Baird. GINGIN

13288 Gingin - Ledge Point - 500yrARI Depth 2120_Rev01.mxd

Map Published: 2020-04-30

C.3 Seabird Inundation Mapping

Mapping Cases presented for the 500yr ARI events at planning year 2120.



1:9,000

0 100 200 300 m

Inundation Depth based on peak water level from 500yr ARI design storm in planning year 2120 (includes 0.9m Sea Level Rise Allowance)

SEABIRD

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

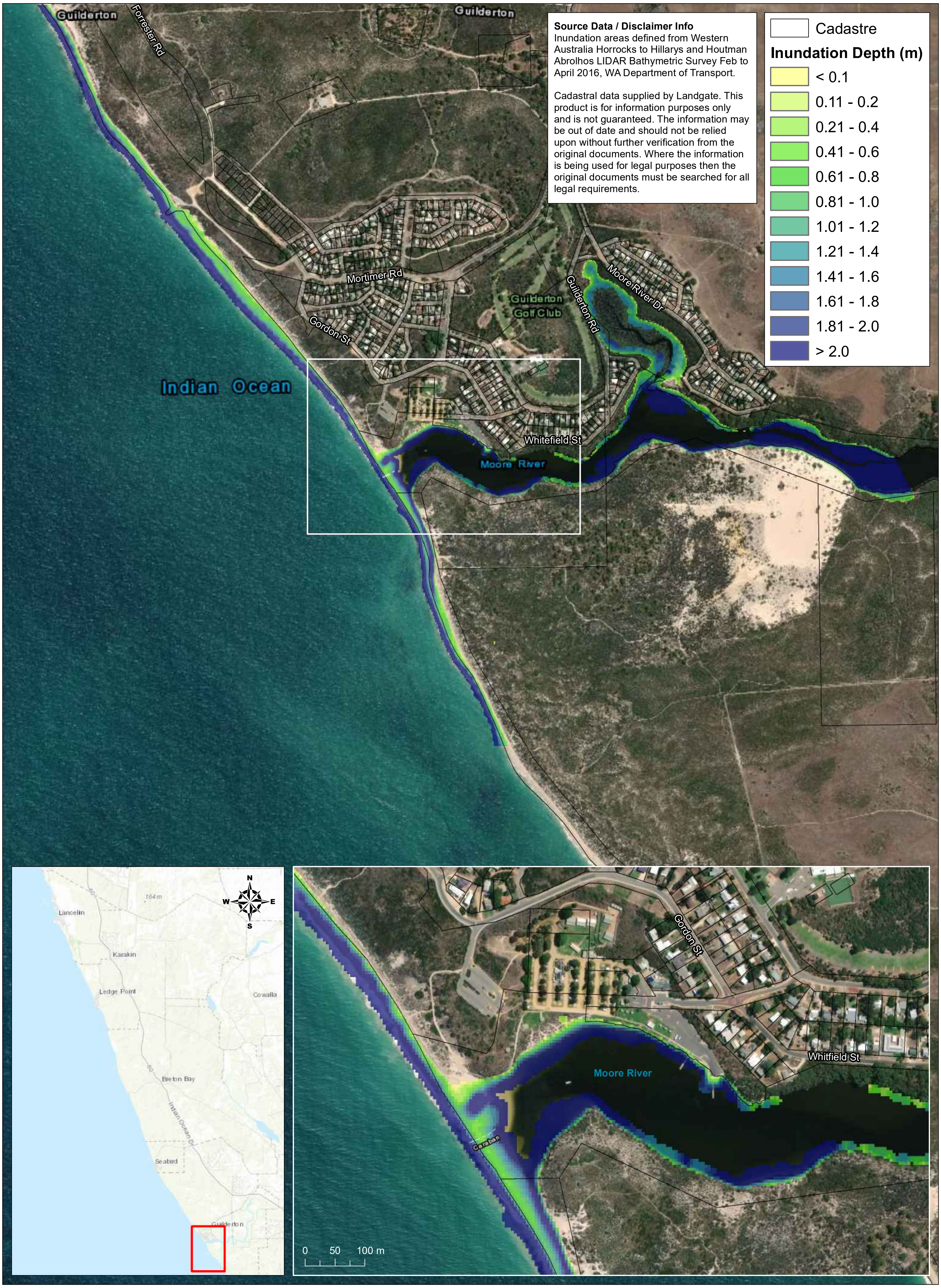
Baird. GINGIN

13288 Gingin - Seabird - 500yrARI Depth 2120_Rev01.mxd

Map Published: 2020-04-30

C.4 Guilderton Inundation Mapping

Mapping Cases presented for the 500yr ARI events at planning year 2120.



1:14,000

0 150 300 450 m

Inundation Depth based on peak water level from 500yr ARI design storm in planning year 2120 (includes 0.9m Sea Level Rise Allowance)

GUILDERTON

Imagery: ESRI World Basemap
Spatial Reference: GDA 1994 MGA Zone 50

Baird. GINGIN

13288 Gingin - Guilderton - 500yrARI Depth 2120_Rev01.mxd

Map Published: 2020-04-30