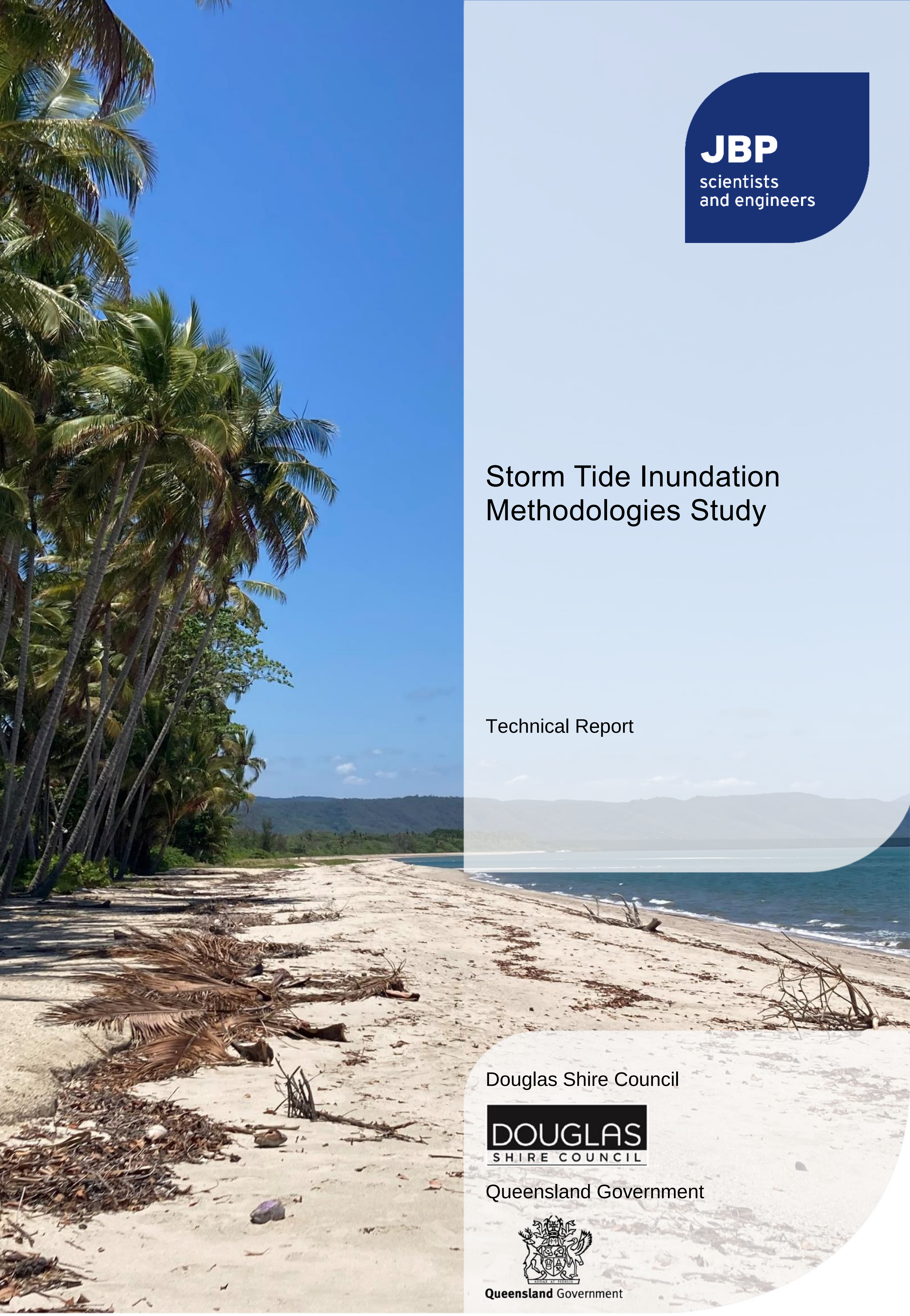

Storm Tide Inundation Methodologies Study

Technical Report

Douglas Shire Council

Queensland Government

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Revision History

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P02 / 04 Dec 2020		JE, PH
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Contract

This report describes work commissioned by Mr Paul Hoye, on behalf of the Douglas Shire Council, by a letter dated 16 July 2020. Douglas Shire Council's representatives for the contract were Paul Hoye and Jenny Elphinstone. Clare Yang, Michael Thomson, Ellie Vahidi and Daniel Rodger of JBP carried out this work.

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The Storm Tide Inundation Methodologies Study (the Study) is an initiative of the Queensland Government. Jeremy Benn Pacific (JBP) and Douglas Shire Council acknowledge the significant funding contribution of the Queensland Government, without which the Study could not have proceeded. The Study provides greater certainty for the Douglas Shire community and increases its understanding and resilience to storm tide inundation. The Study identified the significance of coastal vegetation to reduce the impact of storm tide inundation. The mapping of current and future storm tide levels will increase the community's awareness and understanding of this coastal hazard and will support better preparedness and landuse planning.

Disclaimer

Jeremy Benn Pacific ("JBP") has prepared this report for the sole use of Douglas Shire Council (the “Client”) and its appointed agents in accordance with the Agreement under which our services were performed.

JBP has no liability regarding the use of this report except to the Client. No other warranty, expressed or implied, is made as to the professional advice included in this report or any other services provided by JBP.

The conclusions and recommendations contained in this report are based upon information provided by others and upon the assumption that all relevant information has been provided by those parties from whom it has been requested and that such information is accurate. Information obtained by JBP has not been independently verified by JBP, unless otherwise stated in the report.

The methodology adopted and the sources of information used by JBP in providing its services are outlined in this report. The work described in this report was undertaken between July 2020 to March 2021 and is based on the conditions encountered and the information available during this period of time. The scope of this report and the services are accordingly factually limited by these circumstances.

Certain statements made in the report that are not historical facts may constitute estimates, projections or other forward-looking statements, and even though they are based on reasonable assumptions as of the date of the report, such forward-looking statements by their nature involve risks and uncertainties that could cause actual results to differ materially from the results predicted. JBP specifically does not guarantee or warrant any estimate or projections contained in this report.

Executive Summary

JBP were commissioned by Douglas Shire Council (DSC) to investigate new approaches to map storm tide inundation for the Queensland coastline. The project has reviewed a range of Australian and international approaches to simulate the combined effect of tides, storm surges and waves over different shorelines and vegetation types to produce a best practise approach for the Douglas coastline, which can also be applied for other Queensland regions.

The Douglas Shire coastline experiences a range of hydrodynamic, wave, and morphologic processes that influence the depth and extent of storm tide inundation. An assessment of the Douglas shoreline identified four typical shoreline types that will influence nearshore wave and overtopping processes, which include (i) natural beach and dunes, (ii), wetlands, marshlands and estuaries, (iii) rocky outcrops, cliffs and hard structures, and (iv) mangroves. A four-step process has been proposed to produce storm tide maps over these shorelines. This includes an initial step to undertake a storm tide study, which would assess climatology, cyclones and offshore wave characteristics using existing best-practise methods such as the QLD Blue Book. Storm tide inundation would then be simulated through three additional steps:

1. Assessment of shoreline types, e.g. (i) natural beach and dunes, (ii), wetlands, marshlands and estuaries, (iii) rocky outcrops, cliffs and hard structures, and (iv) mangroves.
2. Undertake a nearshore assessment using different modelling methodologies for coastal and vegetation types
    a. XBeach for natural beach and dune systems,
    b. Hydrodynamic modelling for wetlands, marshlands and estuaries
    c. Artificial Neural Network for rocky outcrops, cliffs and hard structures
    d. XBeach for Mangroves
3. Undertake hydrodynamic modelling to simulate tides, storm tide, setup and nearshore/overtopping processes over the foreshore.

This process was followed for the Douglas Coastline, with the peak coastal inundation depth and water levels mapped for each community. The peak inundation depth for many locations was attributed to the volume of overtopped water, rather than the storm tide level. In these areas the site location and elevation was a key factor, with the storm tide depth varying due to its proximity to dunes, the slope of the land, and function of nearby drainage infrastructure. This meant that the inundation level can vary throughout a community, based on local conditions. Storm tide inundation maps have been developed at a lot-specific level, for multiple return periods and planning horizons. The table below shows present day, 1% Annual Exceedance Probability (AEP) storm tide levels, including an additional 0.25m for minimum building pad levels and additional 0.5m freeboard for finished flood levels.

Table E-1: Present day storm tide level range for key communities, including 0.5m freeboard

Locality	Storm tide level range (present day, 1% AEP), mAHD	Finished floor level (storm tide for present day, 1% AEP, plus 0.5m), mAHD	Storm tide level range (2100 0.8m SLR, 1% AEP), mAHD	Finished floor level (storm tide for 2100 0.8m SLR, 1% AEP, plus 0.5m), mAHD	Pad level for 2100 0.8m SLR, 1% AEP
Wangetti	0.65 - 2.14	1.15 - 2.64	2.16 - 3.02	**2.66 - 3.52**	2.41 - 3.27
Oak Beach	2.01 - 3.73	2.51 - 4.23	2.40 - 3.79	**2.90 - 4.29**	2.65 - 4.04
Port Douglas	1.21 - 3.06	1.71 - 3.56	2.66 - 3.08	**3.16 - 3.58**	2.91 - 3.33
Cooya Beach	2.13 - 2.64	2.63 - 3.14	2.85 - 3.94	**3.35 - 4.44**	3.10 - 4.19
Newell Beach	1.53 - 4.00	2.03 - 4.50	2.34 - 4.08	**2.84 - 4.58**	2.59 - 4.33
Wonga Beach	1.56 - 3.10	2.06 - 3.60	1.95 - 3.38	**2.45 - 3.88**	2.20 - 3.63
Thorton Beach	1.61 - 2.03	1.11 - 2.53	2.48 - 2.95	**2.98 - 3.45**	2.73 - 3.20
Degarra	1.04 - 1.77	1.54 - 2.27	1.28 - 2.62	**1.78 - 3.12**	1.53 - 2.87

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Abbreviations

AEP................................ Average Exceedance Probability

ANN .... Artificial Neural Network

CRSTIS.......................... Cairns Regional Storm Tide Inundation Study

CHAS............................. Coastal Hazard Adaptation Strategy

DEM............................... Digital Elevation Model

DES................................ Department of Environment and Science

DFL .... Defined Flood Level

DSC .... Douglas Shire Council

DSTE .... Design Storm Tide Elevation

EA .... Environmental Agency

GIS................................. Geographic Information Systems

HAT................................ Highest Astronomical Tide

HFL .... Habitable Floor Level

LGA................................ Local Government Area

MSQ............................... Maritime Safety Queensland

QLUMP .... Queensland Land Use Management Plan

QWMIP .... Queensland Water Monitoring Information Portal

SEPA .... Scottish Environmental Protection Agency

SWAN .... Simulating WAves Nearshore

TWL .... Total Water Level

1 Introduction

JBP were commissioned by Douglas Shire Council (DSC) to undertake new storm tide mapping throughout the DSC Local Government Area (LGA). The project has reviewed a range of Australian and international approaches to simulate the combined effect of tides, storm surges and waves over different shorelines and vegetation types to produce a best practise approach for the Douglas coastline. The research undertaken and modelling methodology developed within this project is available for other Councils to use to support improved storm tide mapping.

The Douglas Shire region has an area of approximately 2,400 square kilometres and shares a 70km coastal boundary with the Great Barrier Reef World Heritage Area. The coastline has an array of coastal landforms and physical attributes, ranging from sandy beaches, vegetated dunes, mangroves, cliffs and rocky outcrops. A number of areas, communities and transport routes are located along the foreshore, which are impacted by coastal processes. Detailed climatology, storm surge and wave modelling has been undertaken in previous studies, although did not consider foreshore processes, coastal vegetation, or the flowpaths that any overtopped water would take during an extreme storm. This project now considered these processes in detail.

Douglas Council has completed a Coastal Hazard Adaption Strategy (CHAS) through the Queensland Government-funded QCoast 2100 program. This Strategy included the Douglas Resilient Coast Strategic Plan, where Council committed to 35 priority actions to reduce the impacts of coastal hazards on communities and natural assets. A better understanding of the impact of storm tide and riverine flood inundation is one of the priority actions. In order to meet this action, this study has:

- Classified the Douglas shoreline into different shoreline types and vegetation zones.
- Analysed different Australian and international methodologies to map storm tides over the different shoreline categories.
- Evaluated the best approaches for large-scale application, which can be developed into a new guideline to support other coastal councils.
- Applied the new methodology to undertake revised shire-wide storm tide mapping.

In addition to this introduction section, the report contains the following chapters:

- **Section 2:** Coastal processes, hazards and available data
- **Section 3:** Storm tide inundation methodologies
- **Section 4:** Douglas Storm Tide Inundation Modelling
- **Section 5:** Allowances for freeboard
- **Section 6:** Summary and Recommendations
- **Appendix A:** Storm Tide Mapping

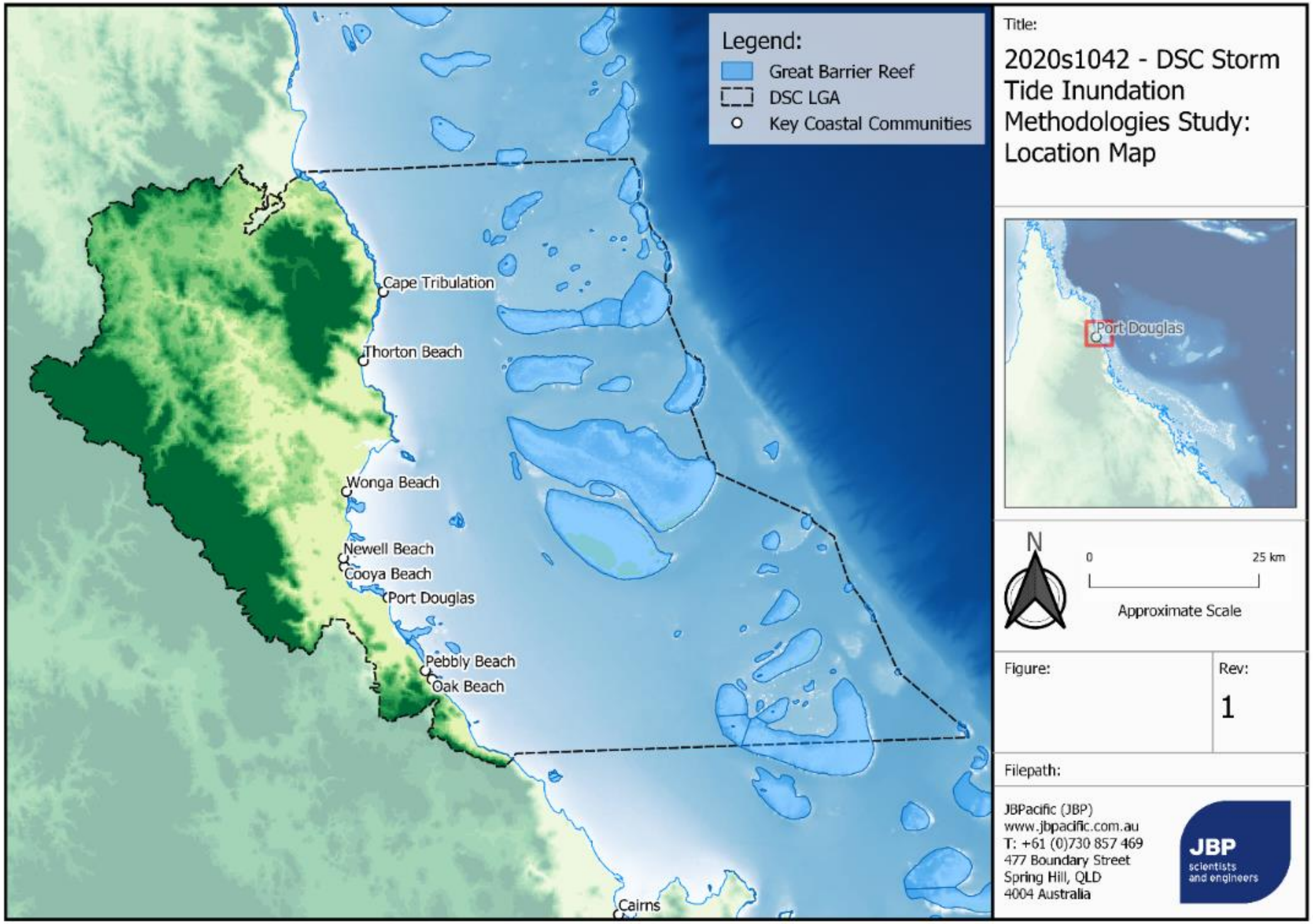

Figure 1-1:Douglas Shire Council Local Government Area

2 Coastal processes, hazards and available data

Before undertaking any studies involving coastal modelling, it is first important to consider the underlying coastal processes affecting the site. The Douglas Shire coastline experiences a range of hydrodynamic, waves, and morphologic processes that are linked through dependant and independent variables. This includes the underlying astronomical tide, the passage of local storms and cyclones, the interaction of storm surges along the open coastline, the local wave climate, any sheltering provided by nearshore reefs, and the role of nearshore and dune vegetation. A range of these coastal processes are shown in Figure 2-1.

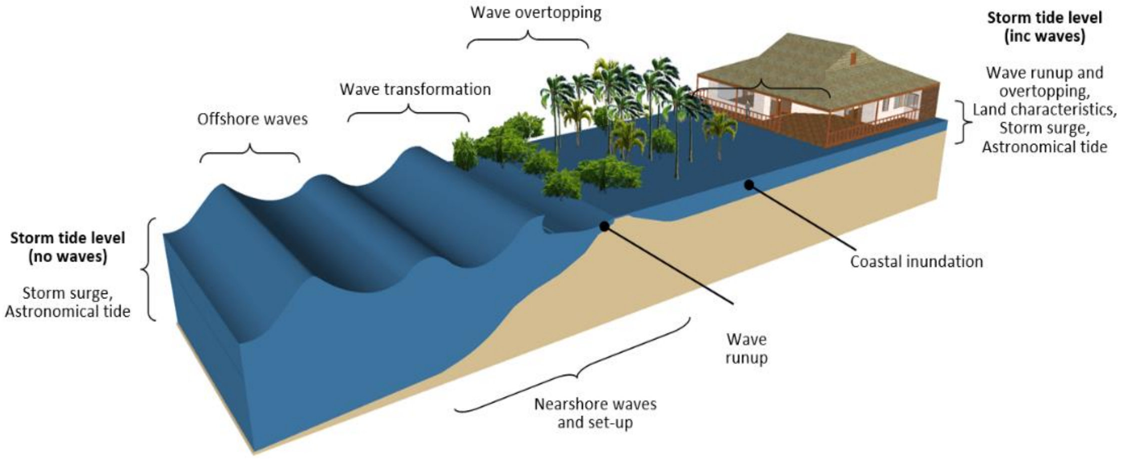

Figure 2-1:Drivers of coastal risk

The way in which different coastal processes interact will determine the tidal and wave conditions experienced at any location. As shown in Figure 2-1, these may include the following:

- Astronomical tide: This is the regular periodic variation in water levels due to the gravitational effects of the moon and sun, which can be predicted with generally very high accuracy at any point in time (past and present) if sufficient measurements are available. The highest expected tide level at any location is termed the Highest Astronomical Tide (HAT) and occurs once each 18.6 year period, although, at some sites, high tide levels similar to HAT may occur several times per year and the level of HAT is often exceeded by the combination of a high tide and a non-astronomical weather-related event.
- Storm surge: This is the combined result of the severe atmospheric pressure gradients and wind shear stress of the storm acting on the underlying ocean. The storm surge is a long period “wave” capable of sustaining above-normal water levels over several hours or even days. The wave travels with and ahead of the storm and may be amplified as it progresses into shallow waters or is confined by coastal features. The magnitude of the surge is affected by several factors such as storm intensity, size, speed and angle of approach to the coast and the coastal bathymetry.
- Wave setup: As waves break, they create a localised effect to increase the sea level, known as breaking wave setup. It predominately occurs at a sloping beach or structure and becomes less significant within river mouths or protected low-lying mangrove or swampy lands.
- Nearshore waves and wave runup: If broken waves reach the shoreline any residual energy may intermittently run up and down the beach face, known as wave runup. This may cause localised impacts as waves can reach elevations higher than the underlying storm tide level. The vertical elevation the waves may reach will be dependent on the slope of the shoreline, the porosity, vegetation and the coastal (wave and sea) conditions.

2.1 Available data

A range of studies and datasets are available at a regional scale throughout the Douglas region. These provide information on coastal hazards, planning controls, bathymetric and topographic data, and vegetation types.

2.1.1 Datums

All vertical elevations has been measured from the Australian Height Datum (AHD), which normally approximates mean sea level within a range of several centimetres.

2.1.2 Return Periods

The annual exceedance probability (AEP) of a storm event is a measure of the event severity. The AEP is the probability that a given storm tide event will be exceeded in one year. Therefore a 1% AEP event is more severe (and less likely) than a 5% AEP event.

2.1.3 Coastal Hazard Adaptation Strategy (CHAS) and Resilient Coast Strategic Plan

Council has completed a Coastal Hazard Adaption Strategy (CHAS) through the Queensland Government funded QCoast 2100 program. On the 28 May 2019, Council formally adopted a Resilient Coast Strategic Plan[1], committing the organisation to 35 priority actions identified through the CHAS to reduce the impacts of coastal hazards on communities and natural assets. A better understanding of the impact of storm tide and riverine flood inundation is one of the priority actions.

2.1.4 Douglas Planning Scheme 2018

The Douglas Council Planning Scheme[2] was approved in 2018 under the Sustainable Planning Act 2009. As required by the then State Planning Policy, the Planning Scheme includes an overlay for storm tide inundation extents based on regional mapping prepared by the Department of Environment and Science (DES). For development trigger by the flood and storm tide hazard overlay code the Client relies on the Cairns Region Storm Tide Inundation Study (2013) prepared by BMT WBM and reissued on 12 December 2017

2.1.5 Cairns Region Storm Tide Inundation Study (CRSTIS) (WBM BMT 2013)

Storm tide mapping is currently available throughout most of the coastal zone based on the Cairns Regional Storm Tide Inundation Study (CRSTIS). Whilst prepared in 2012, the CRSTIS currently serves as the primary source of wave and storm tide data for the region. The CRSTIS contains detailed offshore cyclone modelling, wave modelling and wave runup calculations to produce an estimate of storm tide elevation under future climate change conditions. Wave setup and runup levels have been estimated based on an assumed beach slope of 1:10 and empirical equations following Stockdon (2006)[3]. For situations where the dune is overtopped by storm tide and wave runup, this estimate is acknowledged to be too large and hence wave runup height will be overestimated. Coastal inundation mapping was achieved through a 'bathtub mapping' approach, which did not consider local conditions, vegetation types, topography, or different beach slopes. This adds a level of uncertainty within the CRSTIS outputs and maps, in particular for planning purposes. Whilst these maps have been used within the DSC Planning Scheme, any ambiguity in mapping and the defined coastal storm tide levels presents a risk to Council. CRSTIS storm tide estimates are shown in Table 2-1.

2.1.6 Storm tide modelling for Degarra (JBPacific 2019).

This investigation was undertaken by JBPacific to support DSC disaster risk management at Degarra, located to the north of the Daintree River. The study was undertaken to fill gaps within the CRSTIS, which extends north to Cape Tribulation. The study has investigated the potential impacts of a Severe Tropical Cyclone hitting the area. A credible severe cyclone scenario was identified by Queensland Fire and Emergency Services (QFES) to be similar to Tropical Cyclone (TC) Ita in 2014 (which was Category 3 at landfall), however landing north of Degarra at a high tide. This scenario was tested within a new Delft3D cyclone model, and the storm tide extents added to the CRSTIS for Council planning.

1 Resilient Coast Strategic Plan, 2019-2029, DSC

2 Douglas Shire Planning Scheme 2018 Version 1.0 - Part 8: Overlays, DSC

3 Stockdon, H.F., et al. (2006). Empirical parameterization of setup, swash, and runup, Coastal Engineering 53, 573-588.

Table 2-1:Present day and 2100 (0.8m Sea Level Rise) storm tide levels including wave setup and runup for a 1%AEP event (CRSTIS: Tables 4-4, 5-2)[4]

1% AEP Storm Tide including Wave Effects (mAHD)		
Location	**Present Day**	**2100 (0.8m Sea Level Rise)**
Bramston Beach	2.69	3.58
Cairns North Beach	3.15	4.04
Trinity Beach	2.98	3.86
Oak Beach	2.96	3.85
Port Douglas	2.95	3.87
Wonga Beach	3.03	4.04
Thornton Beach	2.78	3.74

2.1.7 Bathymetry and Topographic data

A combination of several topographic and bathymetric datasets are available for this project

- Topographic Data: Elevation data above mean sea level is available through the QLD 5m Light Detection and Ranging (LiDAR) Digital Elevation Model (DEM). The 5m LiDAR DEM has been sourced from more than 200 individual LiDAR surveys conducted between 2001 and 2015[5]. For larger areas where the 5m dataset is not available, the 30m Great Barrier Reef (GBR) topographic data has been used.
- Additional 1m LiDAR tiles have been sourced from the Department of Natural Resources, Mines and Energy (DNRME) for areas where higher-resolution is required. This includes the beach profile and areas around structures. This 1m data has been captured using LiDAR technology over sections of the coastal area from the Cook Shire to Whitsunday Regional Council since 2009. It is regularly updated and spans over 10 Local Government Areas and includes several offshore islands[6].
- Bathymetric Data: Offshore bathymetry was obtained between the coastline to the outer GBR by the DeepReef 30m dataset[7]. The GBR30 bathymetric dataset was developed in collaboration between James Cook University, Geoscience Australia, and the Australian Hydrographic Office to compile all available digital bathymetry data to develop regional-scale, 30m resolution grids. This contains deep-water multibeam surveys, airborne lidar bathymetry and chart data, all edited as point clouds to remove noise, and merged into a consistent WGS84 horizontal datum, and an approximate mean sea level vertical datum.

2.1.8 Vegetation and ground cover

The Douglas Shire coastline is an area of significant coastal biodiversity. It contains estuaries, mangrove forest, wetlands, rivers, and coral reefs, each able to influence the extent and depth of coastal flooding. Ground cover has been mapped from the Queensland Land Use Mapping Program (QLUMP)

2.1.9 Satellite derived land cover assessment

The Douglas Shire area contains some of the most unique vegetated zones in Australia, including dense tropical rainforest, mangroves, and agricultural pasture. Therefore, a novel approach has been used to classify spatially distinct areas of vegetation cover in the Douglas LGA. The European Space Agency's Sentinel-2 Satellite imagery was used to classify areas of distinct vegetation cover. The Sentinel-2 satellite delivers spectral bands for blue (B2), green (B3), red (B4), and near-infrared (B8) channels with a 10-meter resolution. Vegetation absorbs solar radiation (or light) during

4 BMT WBM Pty Ltd (January 2013) Cairns Region Storm Tide Inundation Study

5 Geoscience Australia 2015. Digital Elevation Model (DEM) of Australia derived from LiDAR 5 Metre Grid. Geoscience Australia, Canberra. http://pid.geoscience.gov.au/dataset/ga/89644

6 Department of Natural Resources, Mines and Energy (2016) Available via: https://www.business.qld.gov.au/running-business/support-assistance/mapping-data-imagery/imagery/airborne-lidar-data

7 Beaman, R.J. (2018) "100/30 m-resolution bathymetry grids for the Great Barrier Reef", SSSI Hydrography Commission Seminar, March 2018. Surveying and Spatial Sciences Institute (SSSI), Canberra, Australia.

photosynthesis, typically in the visible red (B4) range, and reflects light in the near-infrared (B8) range. This means that high photosynthetic activity (i.e. from healthy, green, leafy trees) leads to less light being reflected in the red region and large reflectance in the near-infrared. The ratio of red to infrared allows for a clear separation of vegetation from other natural objects. An image pixel with high reflectance in the near-infrared region is likely to be denser than its surroundings.

The most common vegetation index used in agriculture is the Normalized Difference Vegetation Index' (NDVI), which is calculated for aerial images from:

$$NDVI = (B8 - B4)/(B8 + B4)$$

Pixels of NDVI value > 0.7 suggest the presence of dense canopy, lower positive values (> 0.3) may indicate weeds or otherwise generally unhealthy vegetation with bare soils and urban areas exhibiting even lower positive NDVI values between 0 and 0.2. Very low positive (< 0.1) or even slightly negative value pixels typically suggest water features. For the purpose of this study an NDVI of >0.7 was used to identify dense canopy and NDVI <0 to identify water bodies in the study region. Soils including sand along the coastal stretch of the study region was identified using a value between 0 and 0.15. The adopted NDVI bins are summarized in Table 1 below and example output is shown in Figure 4. Figure 2-2 shows an example of the spatial distribution of roughness as classified by NDVI.

Table 2-2:Adopted NDVI bins for classifying areas of roughness

Roughness Class	NDVI bin
Water Body	<= 0.0
Sand/ Bare Soil	0.0 - 0.15
Agriculture / Crop	0.15 - 0.5
Low – Moderate Vegetation	0.5 - 0.7
Dense Vegetation	>0.7

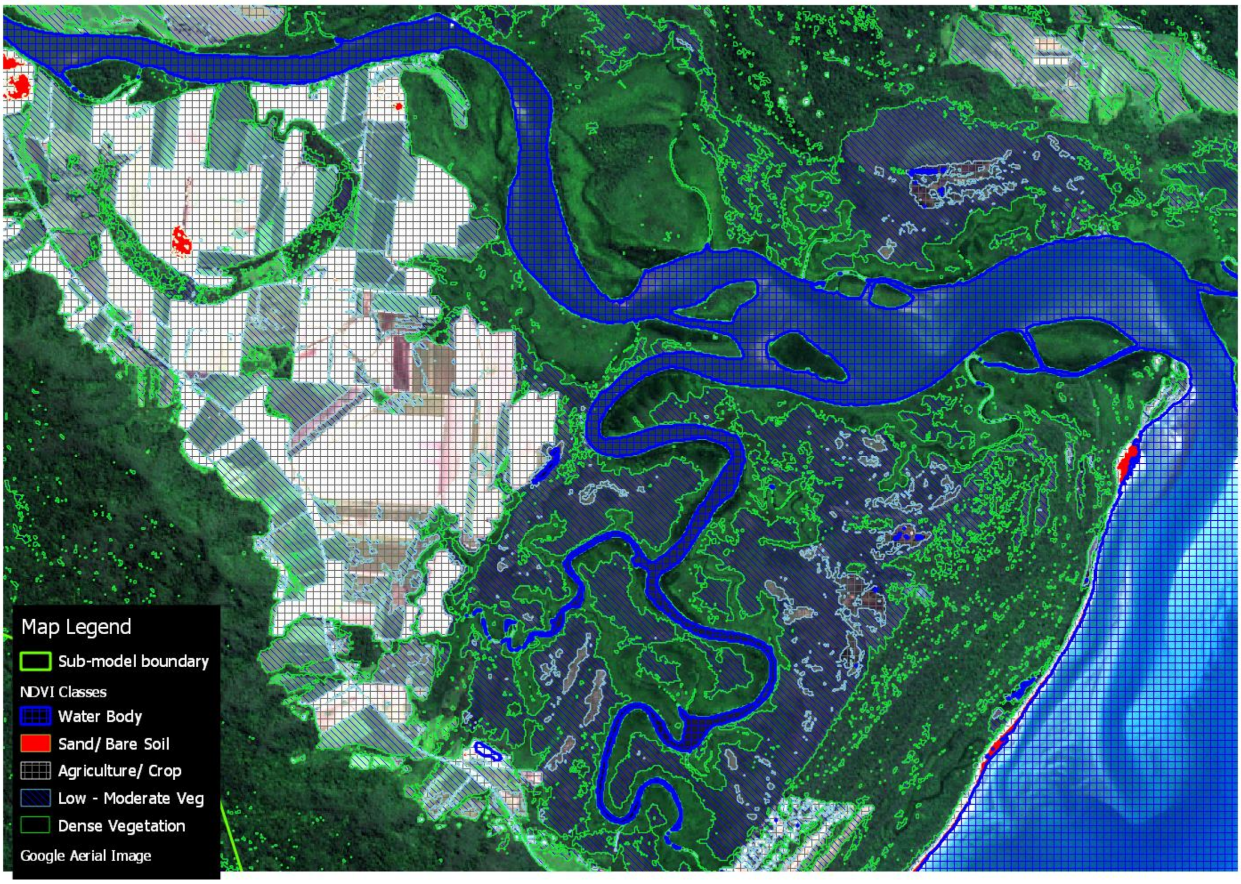

Figure 2-2:Example of NDVI coverage classes on the Daintree River

3 Storm tide inundation methodologies

Storm tide maps are widely used for land use planning, engineering, and disaster risk management. However, there is not a single approach used to simulate all processes, shoreline types, and vegetation types, which results in a range of methodologies having been developed in Australia and Internationally.

The extent and depth of coastal inundation arising from storm tides and extreme wave conditions will be influenced by nearshore vegetation, beach topography, dune vegetation, and the elevation of the coastal plain. A detailed assessment of the Douglas shoreline was undertaken to categorise typical shoreline types that will influence nearshore wave and overtopping processes. Through site inspections, review of Council reports and aerial imagery, four key shoreline types have been identified:

1. Natural beach and dunes
2. Wetlands and Marshlands, including estuaries
3. Rocky outcrops, cliffs and hard structures
4. Mangroves

Beach and dune

Wetlands and Marshlands

Rocky outcrops, cliffs and hard structures

Mangroves

Figure 3-1:Key shoreline types requiring coastal inundation modelling

A range of Australian and international wave, runup, overtopping and storm tide modelling approaches have been reviewed and the most applicable methods for each shoreline type. These are summarised in the following sub-sections, which includes a review of the following:

- Existing methods to simulate cyclones, extreme sea levels and nearshore waves
- Existing methods to estimate areas of potential inundation (bath-tub mapping)
- New methods:
    - New methods to simulate nearshore wave effects at beaches and dunes
    - New methods to simulate wave overtopping at structures
    - New methods to simulate vegetation
    - New methods to simulate hydrodynamics

3.1 Existing methods to simulate cyclones, extreme sea levels and nearshore waves

Storm tide mapping can only be as good as the nearshore water level data being used. Typically, storm tide maps use nearshore storm tide levels and wave conditions, which are estimated through a range of separate assessments. This can include the development of numerical tide models, calculation of non-cyclonic water levels, completion of a climatology assessment, modelling of a cyclone event set, statistical analysis, and estimation of local wave effects such as wave setup. The development of these assessments is currently outside the scope of this project, which assumes nearshore conditions are readily available.

3.2 Existing methods to estimate areas of potential inundation (bath-tub mapping)

In Australia, a widely used approach for creating large-scale coastal flood maps is to use a GIS-based or "bathtub" approach[8]. This method overlays a peak water level, typically the combination of the astronomical tide, storm surge, and any wave runup/setup components, on a DEM to create a flood surface. Depth maps are created from a simple subtraction of the DEM from the overlaying flood level. This method is limited as it does not allow for latency of flow along water courses and assumes a steady-state water level, rather than an episodic tidal event.

An improvement on this method is the use of a two-part projection mapping approach (see Figure 3-2) such as that used in the CRSTIS. All locations along the open coastline are considered to be at risk of inundation up to the storm tide plus wave runup level, which is then reduced back to the storm tide only level far from the coastline. This mapping is split into three zones:

- Open coast: Areas located along the open coastline are likely to be affected by storm tide, including wave effects. In these locations the peak water level may be the result of waves occurring at the peak storm tide level and running up and over the frontal dune.
- Overtopping interpolation zone: All areas within a nominal distance (e.g. 200 m) of the coastline may be subject to overtopped water flowing away from the beach. In these areas located behind the frontal dune, the use of peak wave runup levels would overestimate the inundation level. A 200 m interpolation zone can be applied to transition between the 'storm tide plus wave' level to the 'storm tide only' level.
- Storm tide only: Any area positioned beyond 200 m of the coast or within estuaries is mapped by storm tide levels only.

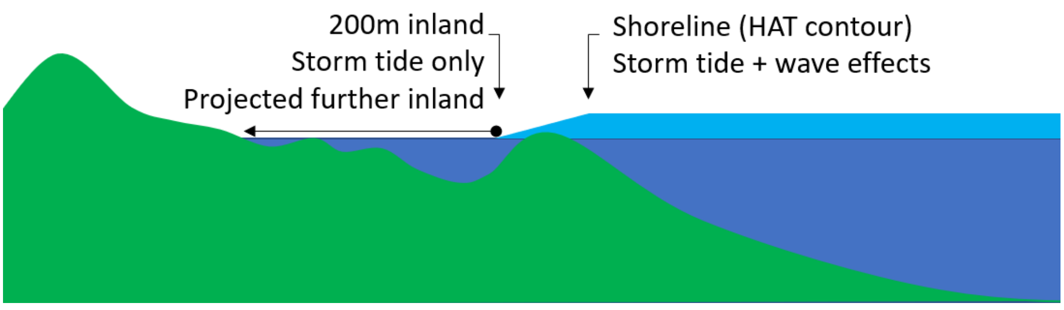

Figure 3-2:Schematic of the two-part projection modelling approach.

This bathtub method of coastal flood mapping is recognised as conservative for several reasons. The combined water levels from tide, surge, wave-setup and wave runup level is unrealistic, as this combination cannot be sustained for a significant duration in the event of a storm. This method also assumes that the peak water level conditions have sufficient time and volume to extend to the furthest reaches of any low-lying system, and that any overtopped water has sufficient volume to fill all lower-lying land up to the given water level. The approach does not consider the influence of nearshore vegetation, beach topography, dune vegetation, and the coastal zone, or how water flows once it passes behind the dunes. In order to replicate these processes, more complex approaches must be considered.

8 DES. 2018. A guide to 'good practice' storm tide inundation mapping and modelling. Department of Environment and Science. Queensland Government, Brisbane.

3.3 New methods to simulate nearshore wave effects at beaches and dunes

The challenges with storm tide mapping along open coast beaches and sand dunes is that inundation will be affected by the combined processes of tides, storm surges, wave setup and wave runup. This is further complicated by the effect of nearshore waves; which are affected by processes such as shoaling, breaking, wave setup and wave runup. Different numerical models are available to simulate these processes, with varying levels of detail.

3.3.1 Phase averaged, spectral wave model

A spectral wave model can simulate the growth, decay and transformation of waves throughout the coastal zone, including wave setup. It can be run in 1D over a defined cross section or 2D over a wide area. Using a spectral wave model to calculate nearshore wave height and wave setup is considered an improved approach to empirical equations. Examples include the SWAN (Simulating WAves Nearshore) wave model and MIKE SW.

This study has used SWAN, is a third-generation spectral wave model, developed at Delft University of Technology[9]. The SWAN physics engine accounts for wave generation by wing and propagation in time and space, shoaling, refraction due to current and depth, frequency shifting due to currents and non-stationary depth.

A spectral wave model is considered the most applicable approach to simulate wave setup at open coastlines in a coastal inundation study.

3.3.2 XBeach

XBeach is an open-source numerical model that has been increasingly used in recent years for the purpose of wave runup and overtopping assessment (Roelvink et al, 2010)[10]. It can be run to simulate groups of waves, or 'surfbeat' in phase-averaged mode, or in a phase-resolving (non-hydrostatic) modes to capture both incident and infragravity wave components.

The model is establishing itself as an industry-standard tool for modelling coastal wave and sediment processes. It performs especially well for cross-shore dominated coastal processes, where it can estimate the effect of the underlying nearshore bathymetry and dunes on wave breaking, runup and overwash/breaching processes. XBeach is documented to have been used in coastal inundation studies in Australia, UK, Canada, Fiji, USA, South America, Netherlands, and Vietnam. In addition to wave setup estimation, XBeach includes the effects of vegetation (e.g. mangroves) and hard structures (e.g. seawalls). When running in non-hydrostatic mode, XBeach resolves individual waves to output impulsive discharge from wave run up and overtopping. Typical run times for a 1 hour modelled timeframe are between 10 to 15 minutes when applying this mode to a 1D model.

A wide range of outputs can be extracted from the model, which include the peak wave runup level or and volume of overtopped water during a storm. This may be used in conjunction with a 2D hydrodynamic model to map coastal inundation behind sand dunes (See Section 3.6)

XBeach is considered the most applicable approach to simulate overtopping at sandy or vegetated dunes in a coastal inundation study.

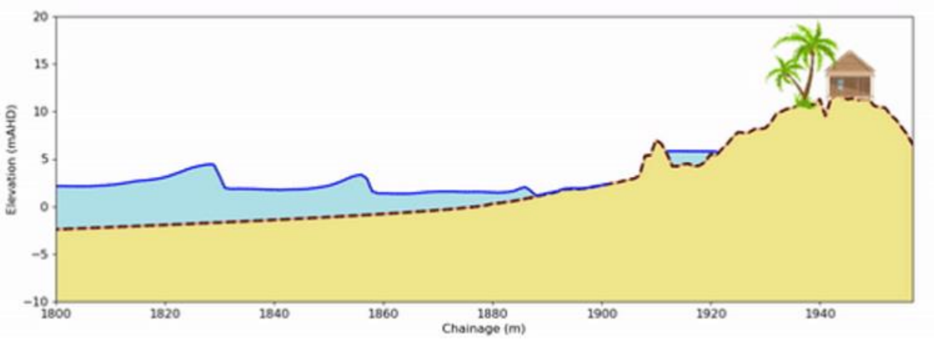

Figure 3-3:Modelling non-hydrostatic (phase-resolving) wave conditions in a 1D XBeach model, overtopping for wave runup collects behind the dune

9 Delft Univeristy of Technology (2020) Available via: http://swanmodel.sourceforge.net/

10 Roelvink, D., Reniers, A., Van Dongeren, A., Van Thiel de Vries, J., Lescinski, J. and McCall, R. 2010. XBeach model description and manual. Delft University of Technology, User Manual, Delft, The Netherlands

3.4 New methods to simulate wave overtopping at structures

The complexity of the physical processes leading to wave overtopping introduces a high degree of uncertainty into its quantification. As a result, the overtopping caused by individual waves is not typically calculated; instead the average overtopping rate for a particular sea-state is estimated using empirical or physical models. An example of an empirical model is the Artificial Neural Network (ANN) tool, developed as part of the EurOtop II manual. This empirical-based model is described as the most suitable methodology for evaluating wave overtopping for composite defences such as seawall structures and armour.

The ANN was developed by the European CLASH (Crest Level Assessment of Coastal Structures) programme, to calculate the wave overtopping discharge rates at defence sections. EurOtop uses a large database of results from physical modelling tests to derive a solution based on complex defence profiles. Overtopping estimates are produced based on a dataset of actual physical model tests which are linked to 22 input parameters to “fit” the design case to data from over 13,000 wave overtopping tests. These input parameters define the seawall structure’s geometry and surface characteristics and are summarised by crest height, slopes, berm conditions, armour size, and hydraulic parameters. These include, but are not limited to: crest height (Rc); armour height (Ac); armour width (Gc); berm elevation (hb); berm width (B); upper slope (αu); lower slope (αd); and roughness (γf)[11] (see Figure 3-4).

Whilst based on physical testing, as with all calculation approaches, the ANN tool has limitations. Estimates are given based on a limited dataset of small-scale physical model tests, undertaken around the world, which are affected by model and scale effects, the accuracy of measurement equipment and wave generation techniques. There is also the potential for limited data for particular defences, for example overtopping across wide structures, as few model tests are available within the database. As a result, it is important that the results of the Neural Network are used with a degree of engineering judgement and caution.

The ANN is considered the most applicable approach to simulate overtopping at structures in a coastal inundation study.

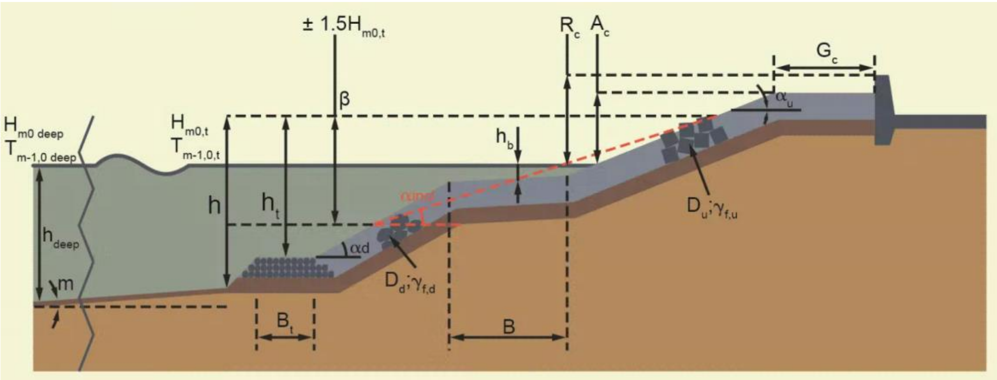

Figure 3-4:Input parameters for estimating overtopping volumes with the EurOtop ANN (EurOtop 2018)

3.5 New methods to simulate vegetation

3.5.1 Shoreline vegetation

The effects of shoreline vegetation on coastal flood processes is an emerging area of research in coastal engineering. At the Deltares Laboratory in the Netherlands, full scale physical modelling has been conducted of semi-submerged willow trees in the 300m Delta wave flume. Waves were forced through a 40m willow "forest" and the reduction of wave runup and overtopping was compared against a control case. Test results show a reduction in wave runup of around 15%, dependent on wave conditions and water levels. The volume of overtopping was also observed to be reduced by 60% with the inclusion of vegetation for wave heights between 0.5m and 1.5m and periods of around

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11 EurOtop, 2018. Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application. Van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P. and Zanuttigh, B., www.overtopping-manual.com.

3 to 6 seconds[12]. Similar laboratory wave flume experiments have been used to extend the XBeach numerical model to include the dampening effects on waves from semi-submerged vegetation. This was accomplished by incorporating approaches for wave dissipation by vegetation developed by Mendez and Losada (2004)[13] as well as Suzuki et al (2011)[14]. With these inclusions, XBeach was able to successfully reproduce the dampening effects observed in laboratory experiments conducted by Kansy (1999) [15] on submerged seagrass. The model has since been updated to allow for the inclusion of varying types of plant species, including mangroves, that can be uniformly or non-uniformly distributed throughout the model.

XBeach is considered the most applicable approach to simulate coastal vegetation in a coastal inundation study.

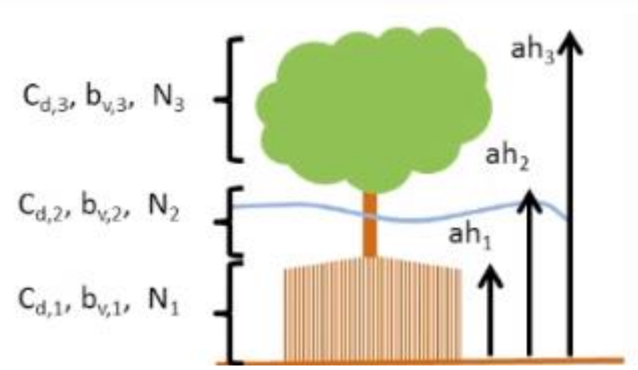


Figure 3-5:Parameterisation of mangrove trees in XBeach (Roelvink et al (2010))

3.5.2 Modelling mangroves

The XBeach model includes options for simulating submerged and semi-submerged vegetation. This is an important inclusion for the XBeach model as overwhelming evidence suggests that mangroves can reduce the height of wind and swell waves over relatively short cross-shore distances. Field measurements of wave-height reduction vary from 26% to 45% over 100 meters of mangroves, to as much as 50 and 100% over 500 meters of mangroves, according to data collected by Mazda et al. (2006) and Quartel et al. (2007), respectively. Figure 3-6 shows the reduction in height of small waves propagating through 100m of dense mangrove from tests conducted by Bao (2011)[16] at four study sites in Vietnam. The average reduction in wave height is around 60% across 100m.

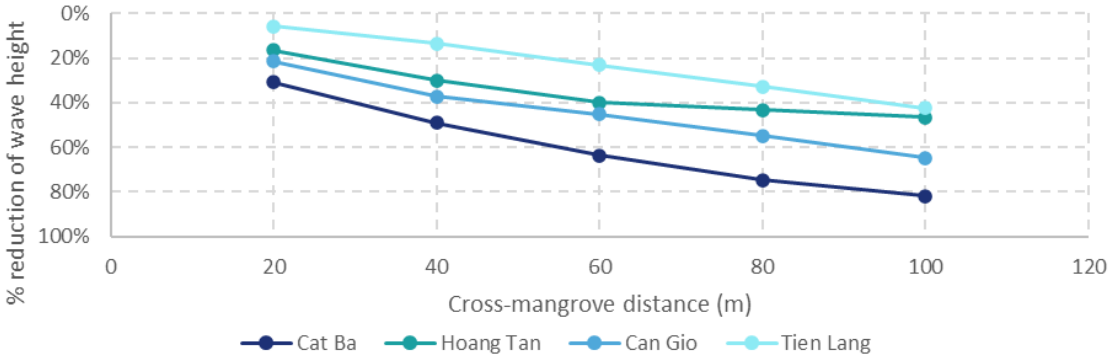


Figure 3-6:Wave dissipation through 100m of mangrove forest at four sites in Vietnam, adapted from Bao et al (2011).

12 Çete C. (2019). Quantifying the effect of woody vegetation on the wave loads on a dike using remote sensing. Delft University of Technology. Available at: https://repository.tudelft.nl

13 Mendez, F.M., Losada, I.J. (2004). An empirical model to estimate the propagation of random breaking and nonbreaking waves over vegetation fields. Coastal Engineering 51,103–118

14 Suzuki, T., Zijlema, M., Burger, B., Meijer, M.C., Narayan, S. (2011). Wave dissipation by vegetation with layer schematization in SWAN. Coastasl Engineering 59, 64-71

15 Kansy S. (1999) Interaction between Ocean Waves and Kelp including Wave Breaking. Diploma Thesis, Technical University Braunschweig, Germany.

16 Bao T. (2011) Effects of mangrove forest structures on wave attenuation in coastal Vietnam. Oceanologia, 53 (3) pp. 807–818.

These studies showed that wave height decreases exponentially with distance through the mangrove forest. The research also showed that mangrove plants with aerial roots will reduce waves in shallow water more rapidly than those without. At greater water depths, waves may pass above aerial roots, however low branches can perform a similar dissipative function. Tree species, age, and size also have an important role in wave reduction, as well as the slope of the shore and the height of incoming waves[17].

XBeach is considered the most applicable approach to simulate the effects of waves through mangroves in a coastal inundation study.

3.6 New methods to simulate hydrodynamics

Complex, large scale inundation modelling is typically undertaken using two-dimensional modelling. This type of model applies hydraulic calculations over a computational topographic grid to simulate how a storm surge will propagate along the coastline, up rivers, estuaries or into harbours. Models can be forced using a tidal water level boundary, either as a timeseries or based on harmonic constituents, with inflow boundaries used to represent additional water flowing over dunes or overtopping structures.

There is a wide range of numerical modelling software available for marine, coastal and estuarine modelling. Common models include Delft3D (Deltares), MIKE21 (DHI) or TUFLOW (BMT Group[18]), which include combined 1D and 2D modelling. These models are based on similar mathematical concepts, and most can adopt a structured or unstructured grid. Structured grids can include rectilinear or curvilinear cells and typically adopt a finite difference solution scheme, while unstructured grids use a finite volume solution scheme and allow different shaped computational cells. Some models will allow direct coupling to a wave model, e.g. Simulating WAves Nearshore (SWAN), where wave forces can be transferred into the hydrodynamic model to compute the wave-induced water levels and currents. Alternatively, wave setup values can be applied directly to the tidal water level boundary if calculated externally, however will result in a simplification of wave setup processes.

A 2D hydraulic model such as TUFLOW, coupled with overtopping inputs from SWAN, the ANN or XBeach is considered the most applicable approach to simulate the combined effects of tides, surges, setup and overtopping in a coastal inundation study. Further consideration has been given to its representation of vegetation through bed roughness.

Challenges to accurately simulating tidal hydrodynamics includes the specification of model friction, which is represented through a bed roughness. Coastal and marine habitats, particularly around heavily vegetated mangroves, can change tidal and storm surge hydrodynamics[19]. The dissipative effects of these areas can be incorporated as zones of varying roughness, specified as a Chezy coefficient or Manning's 'n' value. For the latter, typical 'n' values range from 0.01 to represent smooth concrete channels with no obstructions to above 0.15 in streams with a large amounts of large woody debris and vegetation that impedes flow[20]. Various publications exist that can be used to select appropriate 'n' values for different vegetation types, with a selection shown below.

- Open water, seabed and reefs[21,22]:
  - Open water: 0.02
  - Estuary bed: 0.015
  - Reefs: 0.05
- Straight channels[23]:

17 McIvor, A.L., Möller, I., Spencer, T. and Spalding. M. (2012) Reduction of wind and swell waves by mangroves. Natural Coastal Protection Series: Report 1. Cambridge Coastal Research Unit Working Paper 40. Published by The Nature Conservancy and Wetlands International. 27 pages. ISSN 2050- 7941. URL: http://www.naturalcoastalprotection.org/documents/reduction-of-wind-and-swell-wavesby-mangrove

18 https://www.TUFLOW.com/TUFLOW.aspx

19 Losada, I.J., M. Beck, P. Menéndez, A. Espejo, S. Torres, P. Díaz-Simal, F. Fernández, S. Abad, N. Ripoll, J. García, S. Narayan, D. Trespalacios. 2017. Valuation of the Coastal Protection Services of Mangroves in the Philippines. World Bank, Washington, DC.

20 An Australian handbook of stream roughness coefficients, Land and Water Australia. 2009.

21 Zhang et al (2012). The role of mangroves in attenuating storm surges. Estuarine, Coastal and Shelf Science. 102-103. pp 11-23

22 Mattocks, C. and Forbes, C. (2008) A real-time, event-triggered storm surge forecasting system for the state of North Carolina. Ocean Modelling 25(3-4), 95-119

23 Brisbane City Council (2003) Appendix C of the Natural Channel Design Guidelines (BCC, 2003)

- Bed n = 0.02
  - Banks n = 0.06
  - Bankfull n = 0.024
- Vegetation and natural channels (Australian Rainfall and Runoff, and QLD DES "good practice" storm tide inundation mapping):
  - Clean, regular vegetated section: n = 0.03
  - Channel with some stones and weeds: n = 0.035
  - Nearshore including trees n = 0.04
  - Relatively dense vegetation n = 0.05
  - Some rocks and/or brushwood: n = 0.05
  - Dense vegetation n = 0.07
  - Very rocky or with standing timber: n = 0.1
- Estuarine coastal systems (World Bank WAVES report[24]):
  - Mangrove n = 0.15

Representing dense coastal vegetation such as mangroves has been the subject of ongoing research. This includes laboratory and in-field testing, the latter including work on the reduction of storm surges by mangroves in the Gulf of Mexico, which shows 1km of propagation through mangroves can reduce the storm surge by between 10-30% (see Figure 3-7).

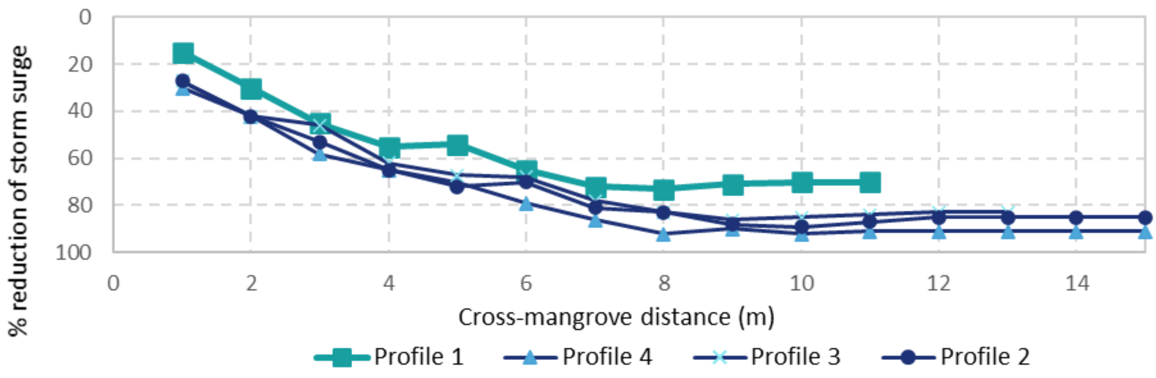


Figure 3-7:Storm surge dissipation through mangrove forests for profiles in the United States gulf, adapted from Zhang et al (2012).

For this study, vegetation roughness has been split into two categories based on new NDVI vegetation mapping (described in Section 2.1.9). Figure 3-8 shows the coverage of dense vegetation sourced from the NDVI mapping compared to QLUMP.

- Dense vegetation/mangrove: Manning's 'n' of 0.15
- Low to medium vegetation: Manning's 'n' of 0.06

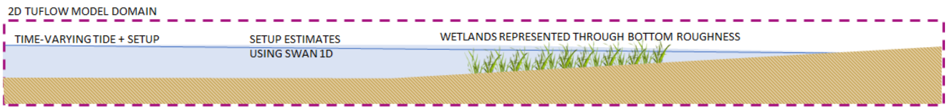
24 World Bank. 2016. Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs. M. W. Beck and G-M. Lange, editors. Wealth Accounting and the Valuation of Ecosystem Services Partnership (WAVES), World Bank, Washington, DC. Accessed on 21 Nov 2020 from:
https://www.nature.org/content/dam/tnc/nature/en/documents/Technical_Rept_WAVES_Coastal_2-11-16_web_1.pdf

Figure 3-8:Comparison of vegetation calculated from aerial imagery NDVI mapping

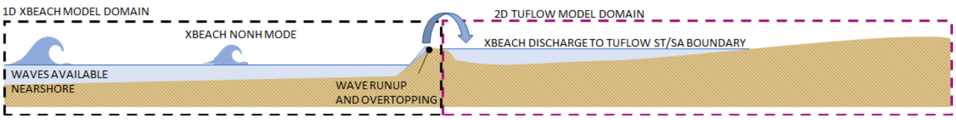
3.7 Combined process

Based on the Australian and international literature review, a four-step process is proposed to produce storm tide maps. This includes an initial step to undertake a storm tide study, including climatology, cyclone modelling and offshore wave modelling. This would be subject to existing best-practise methods, including those outlined in the QLD Blue Book[25], which have not been described in this report. This project focusses on Steps two to four, as shown below.

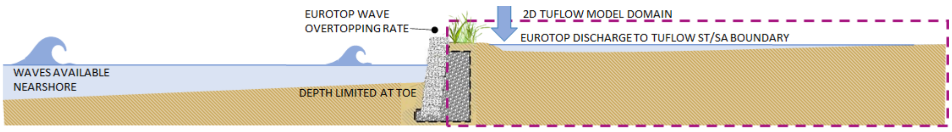
1. Undertake a storm tide study following relevant best practise guidance to estimate nearshore storm tide level and wave conditions
    - This project has adopted the outputs of the CRSTIS
2. Assessment of shoreline types
    - This project has identified:
        i. wetlands, marshlands, and estuaries
        ii. natural beach and dune systems,
        iii. rocky outcrops, cliffs, and hard structures XBeach for mangroves
        iv. mangroves
3. Undertake a nearshore assessment using different modelling methodologies for coastal and vegetation types
    - This project has used four approaches (see Figure 3-9):
        i. Hydrodynamic modelling for wetlands, marshlands and estuaries



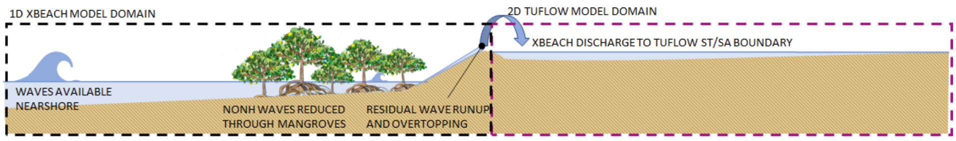
        ii. XBeach for natural beach and dune systems



        iii. ANN for rocky outcrops, cliffs and hard structures



        iv. XBeach for mangroves



4. Use a hydrodynamic model to simulate tides, storm tide, setup and nearshore/overtopping processes.
    - This project has used a TUFLOW hydrodynamic model

25 QLD Government (2001) Queensland Climate Change and Community Vulnerability to Tropical Cyclones, Oceans Hazard Assessment

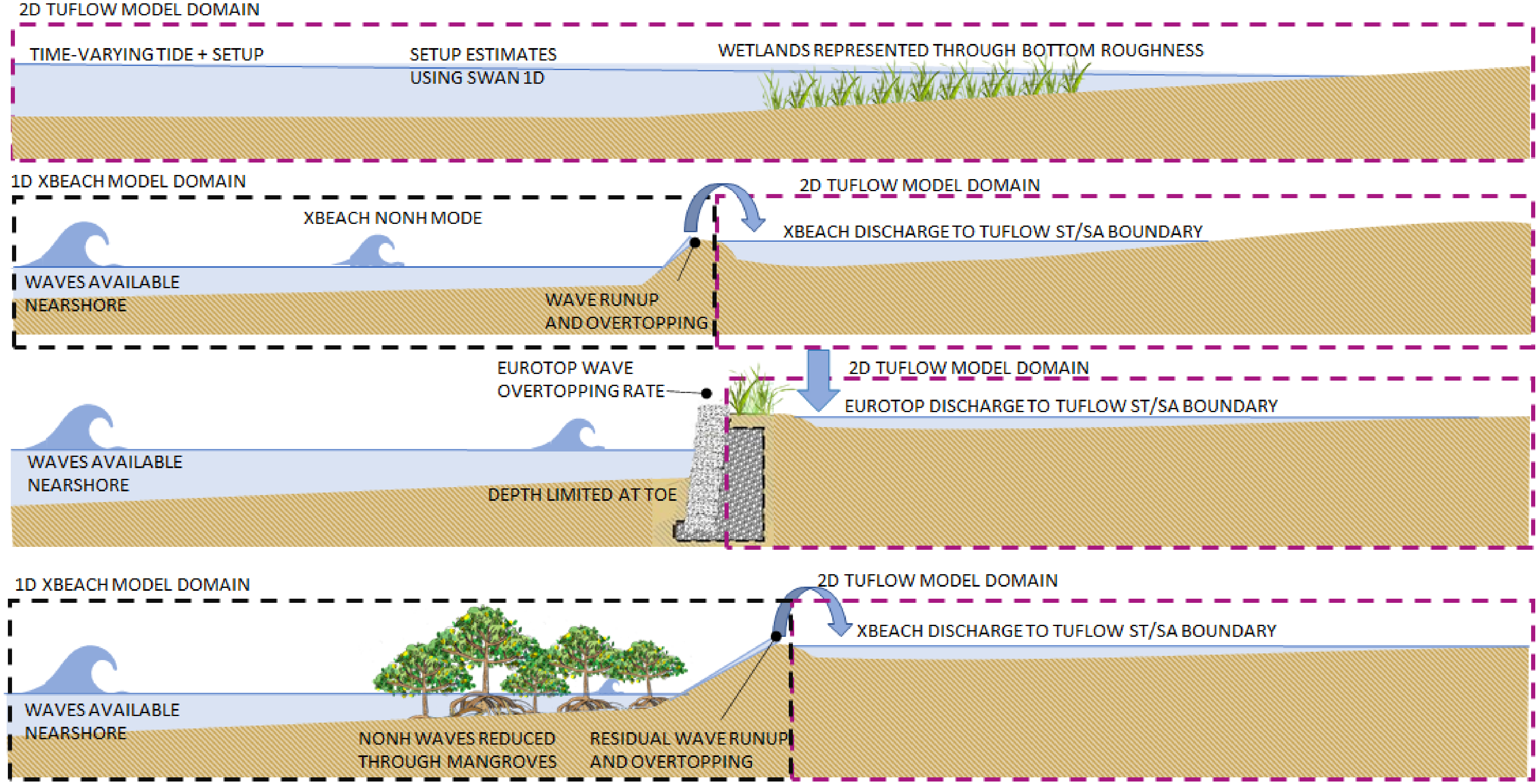


Figure 3-9:Schematic for nearshore modelling

4 Douglas Storm Tide Inundation Modelling

4.1 Introduction

Nearshore storm tide levels and wave estimates for the Douglas Coastline have been adopted from previous analysis undertaken within the CRSTIS. These have been subject to new high detail modelling to understand how coastline types and vegetation can influence the elevation and extend of inundation. This has used the following steps:

1. XBeach modelling for natural beach and dune systems,
2. Hydrodynamic modelling for wetlands, marshlands and estuaries
3. ANN for rocky outcrops, cliffs and hard structures
4. XBeach for Mangroves
5. A combined TUFLOW hydrodynamic model for community-scale mapping

4.2 Hydrodynamic modelling for wetlands, marshlands and estuaries

4.2.1 Approach

As a tide propagates along a coastline and into estuaries, it will be influenced by the local geomorphology, friction, dissipation, and other non-linear interactions. A conceptual model of the coastal zone has been developed to consider the key processes.

- Hydrodynamics: The Douglas LGA experiences a diurnal (two per day) macro-tidal range, with a spring tidal range of around 1.8m. As these tides propagate towards the shoreline they will induce local currents, sweep around headlands, and propagate within estuaries up to, and beyond, the tidal limit. Any model will need to represent these time- and spatially varying tidal conditions.
- Dissipation through estuaries and vegetation: Much of the Douglas coastline is heavily vegetated mangroves, wetlands and marshlands. These will dampen the tidal signal, particularly for estuaries such as the Mowbray River, as it propagates in from the coastline. Any model will need to include spatially varying roughness to represent vegetation.
- Wave conditions: Waves arriving at the shoreline are subject to shoaling, breaking, run up and overtopping. Any overtopped water will continue to flow into low-lying areas or back to the coastline and may worsen coastal inundation. Any model will need to include the ability to input overtopped water along the dune crest.
- Changing dune morphology: Sandy dunes will evolve throughout a storm as they are impacted by waves and high-water levels. Whilst it is an important process, it has not been considered within this study.

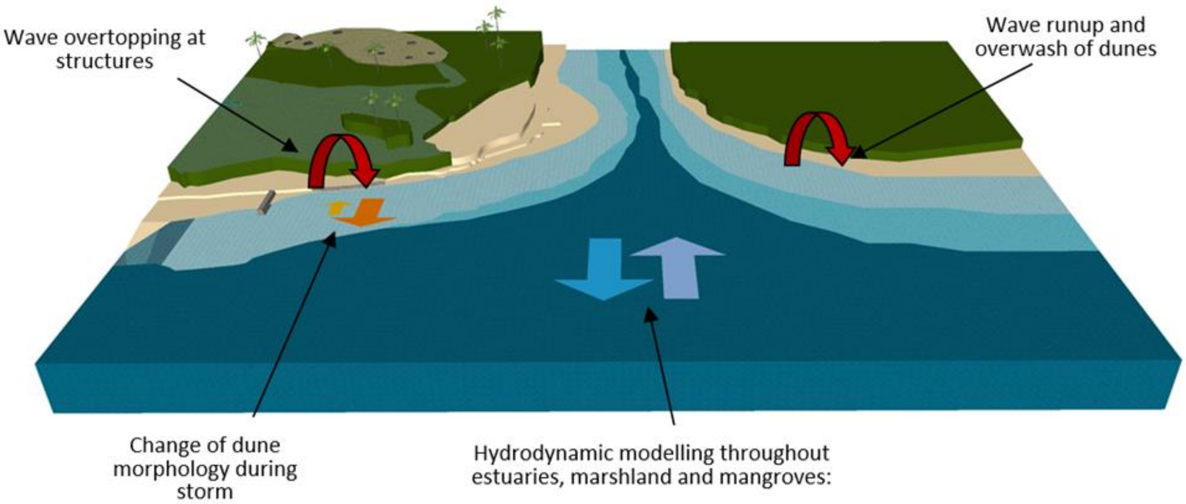


Figure 2-1:Coastal processes occurring along the Douglas coastline

4.2.2 Model selection

The TUFLOW numerical model was selected to represent these processes. TUFLOW is an industry standard 1D/2D hydrodynamic software package used for computer simulation of inundation. It has been selected to simulate tide conditions, being forced using spatially varying offshore tidal boundaries, including an allowance for storm surges, and additional inputs for wave runup and overtopping.

Several hydrodynamic model domains have been established throughout the Douglas coastline. Each positioned to allow tidal propagation through the nearshore zone, over mangroves and marsh land, through estuaries, and over the coastal floodplain. A schematisation of a typical model setup is shown in Figure 4-1. The tidal boundary has been positioned at the -5mAHD depth contour, and the model extends upstream inland of the maximum tidal and storm surge limits. The model has been forced with an astronomic tidal signal, with a storm surge added and aligned with a high tide level. The shape of the storm surge has been based on Cooktown gauge records during Tropical Cyclone Ita, with the peak surge adjusted to match the design storm tide levels predicted within the CRSTIS. An additional allowance was then added to represent wave setup. This wave setup has been recalculated within a separate 1D SWAN model for each coastal community. It has been calculated for each AEP and applied as a constant increase to the storm tide timeseries at the boundary during the storm. Each model uses a base gridsize of 30m, with the resolution increased around key communities. Where available, tide gauge data has been used to calibrate models, such as in the Mossman River.

Figure 4-1:Conceptual model sketch, showing the key processes to be replicated within the numerical model

4.2.3 Topography, bathymetry and channel design

Elevation data has been based on the QLD 5m LiDAR DEM topography and 30m GBR bathymetry, for the open coastline, as described in Section 2.1.7. However, topographic and bathymetric data does not extend within major river channels. In these areas nominal channel dimensions have been used, where the channel banks are based on LiDAR data, and the inner channel defined as having a 1:5 slope with a uniform depth of 2m below the lowest DEM level, which typically represents the water surface at the time of survey. This results in an approximately trapezoidal cross-channel profile.

4.2.4 Model roughness

Roughness layers are applied to the hydrodynamic model grid for varying spatial types (e.g. urban areas, wetlands, agricultural pasture). A roughness value ascribed to each layer is used in model computations to determine the rate of horizontal flow velocity over the grid. This characteristic is one of the key differences between the modelling approach to storm tide mapping and the projection or 'bathtub' approach. Where projection mapping assumes all points below a specified level are inundated, the modelling approach considers flood latency due to roughness and can reduce the extent of the flood map.

Model roughness has applied a Mannings 'n; value, based on the parameters described in Section 3.6. This includes the use of two roughness values for relatively dense of sparse mangroves, based on new NDVI vegetation analysis (Section 2.1.9). Roughness zones have been based on a combination of QLUMP and NDVI. The adopted roughness values are shown in Table 4-1.

Table 4-1:Model roughness

Vegetation class	Mannings 'n;
Dense vegetation/mangrove	0.06-0.15
Other minimal use	0.120
Residential and farm infrastructure	0.040
Grazing native vegetation	0.035
Managed vegetation	0.030
River channel	0.030
Open water	0.030
Sandy beach	0.025

4.2.5 Model calibration

No significant storm surges have occurred within the Douglas coastline to allow a detailed calibration of the extreme sea levels. The most recent significant cyclone event is considered to be TC Ita, which made landfall at Cook Town around 12:00pm on April 11th, 2014. However, due to the cyclone track passing behind the LGA before re-emerging south of Cairns, Port Douglas was spared from a significant surge.

In order to calibrate hydrodynamics, the model has been calibrated against the Mossman tide gauge over consecutive high tide cycles during November 2019, and validated against data from May 2020. Only the Mossman river gauge has been used for calibration due to the paucity of tidal-influenced river gauges in the Douglas LGA.

- Tidal calibration: Water level records from the Mossman River gauge (QWMIP)[26] were extracted for November 2019. This gauge is located approximately 5.5km upriver from the Mossman river mouth and regular tidal signal is present in the gauge record. A series of high tides from 23rd to 25th November 2019 was chosen for calibration. Model boundary conditions have been sourced from Mossman storm surge gauge (MSQ)[27] and applied at the offshore model boundary. The recorded and observed tide levels are shown in Figure 4-2, which shows a satisfactory agreement at peak tide levels. The average error over the series of high tide water levels was 0.029m for this calibration event. The differences in tidal signal during mid and low tides is considered to be due to riverine baseflow adding to low-tide water levels. No baseflow has been included within the TUFLOW model, which aims to represent the peak tides.
- Validation: The model was re-run as a validation exercise in May 2020. The tide signal from the Port Douglas Tide Gauge (MSQ) has been used as the offshore boundary

26 https://water-monitoring.information.qld.gov.au/
27 https://www.qld.gov.au/environment/coasts-waterways/beach/storm/storm-sites/mossman

conditions, and the upstream tide signal at the Mossman River gauge compared. The results are shown in Figure 4-3, which produced a mean high tide error of 0.004m.

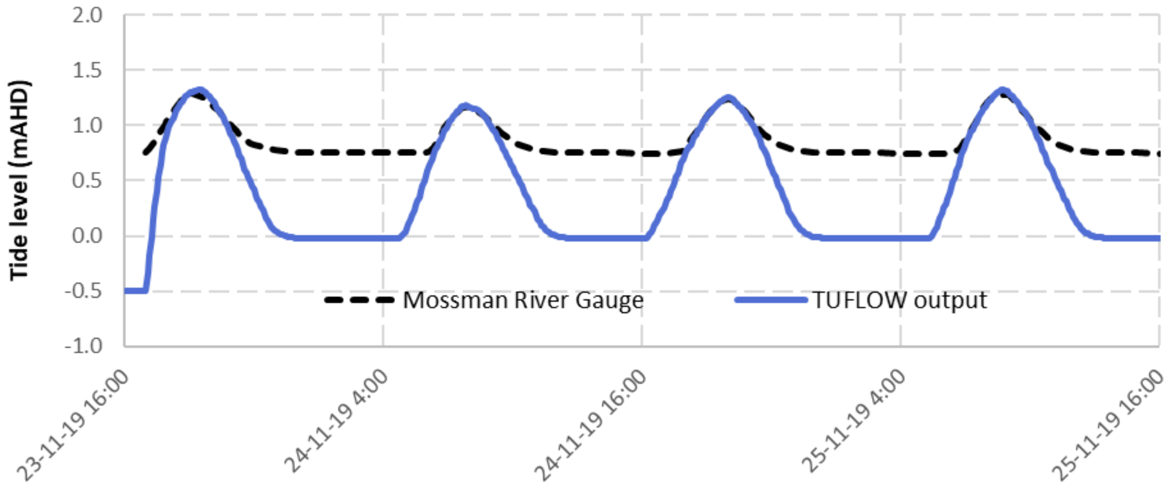


Figure 4-2:Observed and simulated tidal signal during Nov 2019 calibration

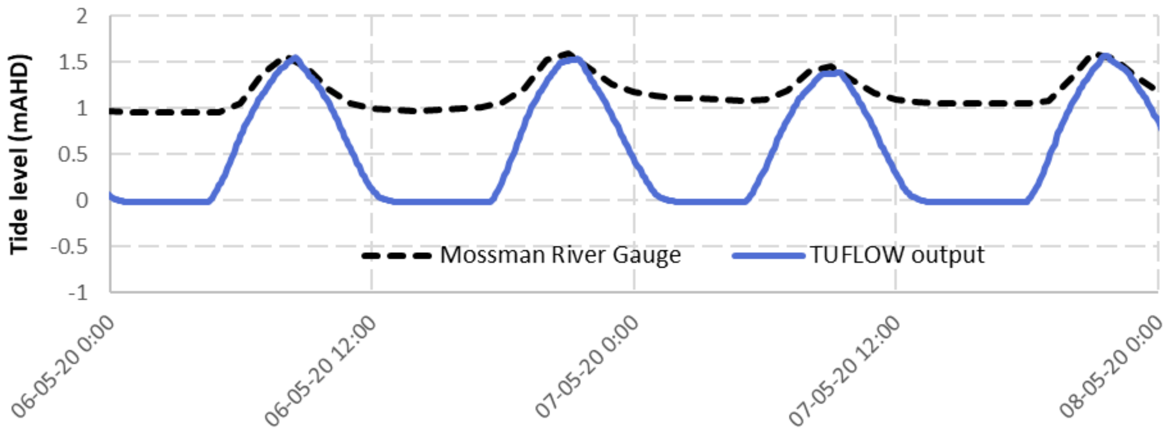


Figure 4-3:Observed and simulated tidal signal during May 2020 validation

4.2.6 Choice of sub-models

The Douglas Shire LGA domain has been divided in to seven distinct models to reduce computational demand (Figure 4-4). The sub-model domains are adjoined by adjacent headlands. Representative output points from the CRSTIS have been used for input tide and wave conditions in each sub-model.

4.3 Boundary conditions

Each of the seven model domains have been configured as shown in Figure 3-2, which include:

- Dynamic offshore tidal signal
- A storm surge profile representing TC Ita, which is scaled to achieve the peak water level estimated within the CRSTIS. These are shown in Table 4-2 and Table 4-3.
- An additional allowance for wave setup, which is described in Section 4.4.1.

- Additional wave inputs calculated using XBeach or the ANN, described in Section 4.5 to Section 4.6.
- Additional influence of waves propagating through mangroves, described in Section 4.7.

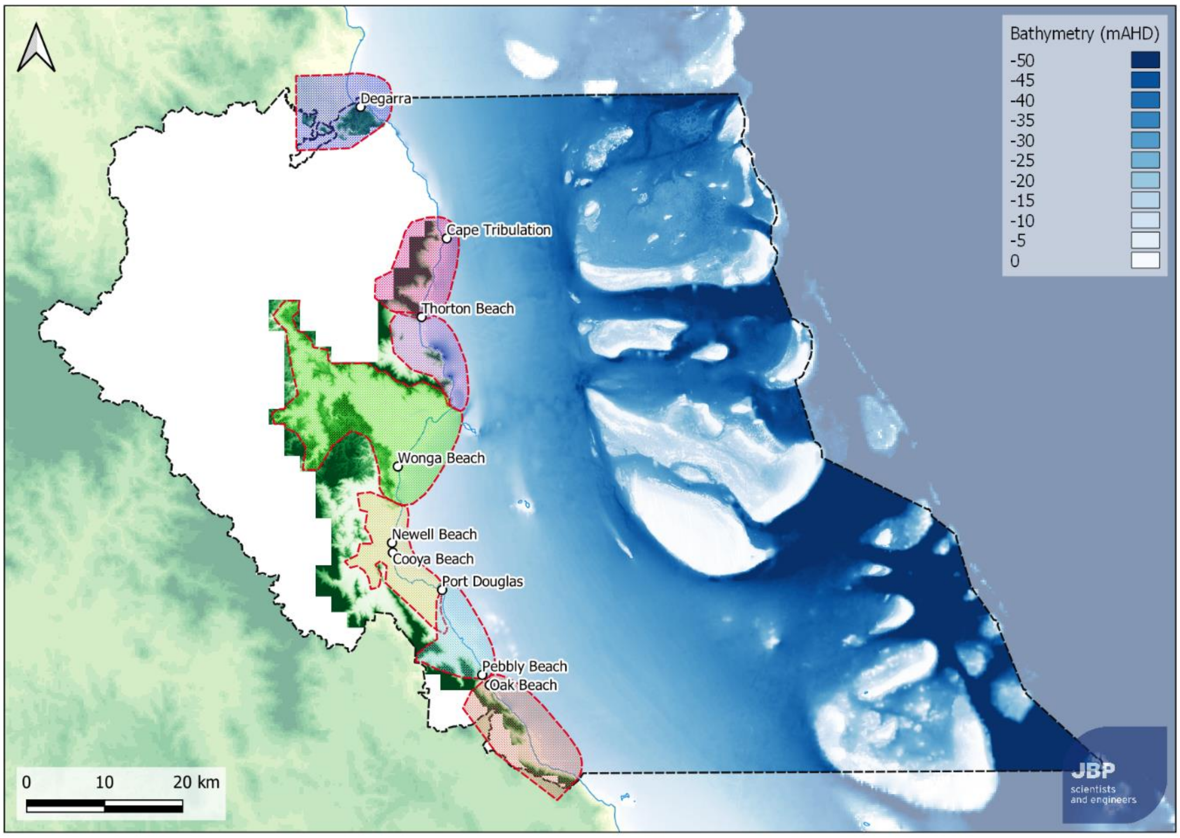


Figure 4-4:Division of Douglas Shire LGA into seven distinct sub-models, with coverage of 5m LiDAR topography data and 30m GBR bathymetry

4.3.1 Present day conditions

Storm tide levels and wave conditions have been sourced from the CRSTIS. The CRTIS provides tabulated results for around 400 output points at 500m spacing along the Cairns and Douglas Council coastlines. Points at the key communities of Oak Beach, Pebbly Beach, Port Douglas, Cooya Beach, Newell Beach, Wonga Beach, Thornton Beach, Cape Tribulation and Degarra have been selected from dataset, and are shown in Table 4-2 for present day. These have been applied to the entire offshore boundary in each model.

4.3.2 Future design conditions

Design storm surge and tide conditions for the 2100 planning horizon have been taken from the CRSTIS. Tabulated data for future scenarios is not provided in the CRSTIS Appendix. However, results for 1% AEP storm tide and storm tide with wave effects at the key communities of Oak Beach, Port Douglas, Wonga Beach, and Thornton Beach are provided in Tables 5-1 and 5-2 of the same report. Two climate change scenarios are presented for sea level rise of 0.8m and 1.1m. For both scenarios a 10% increase in modelled cyclone intensity has been applied. For the purposes of the current study, only the 0.8m SLR scenario has been considered, which aligns with State Government guidance. Table 4-3 shows the 2100 offshore conditions used for modelling as taken for the CRSTIS.

The CRSTIS only provides 2100 results for the 1%AEP scenario, therefore the storm tide and storm tide plus surge levels for other AEPs have been estimated from the increase of the 1%AEP present-day to 2100 levels. As no climate change results are provided in the CRSTIS for the communities of Pebbly Beach, Cooya Beach, Newell Beach, Cape Tribulation, and Degarra, the modelling conditions have been calculated from an average increase of the other four. Future wave conditions have been sourced from the model outputs provided by BMT, the wave results did not change in the revised version of the CRSTIS, therefore the future wave conditions have been adopted.

Table 4-2:Present day wave height, wave period, and storm tide for key communities taken from the CRSTIS

		Oak Beach	Pebbly Beach	Port Douglas	Cooya Beach	Newell Beach
	CRSTIS ID	217	221	248	267	273
	X-coord	342596	341832	336495	331474	330323
	Y-coord	8164327	8165968	8175330	8181105	8183540
Significant Wave Height (m)	2% AEP	2.66	3.13	2.72	2.57	2.62
	1% AEP	2.74	3.28	2.81	2.64	2.68
	0.5% AEP	2.80	3.37	2.89	2.68	2.73
Design Wave Period (s)	2% AEP	6.28	6.81	6.35	6.17	6.23
	1% AEP	6.37	6.97	6.45	6.26	6.31
	0.5% AEP	6.44	7.07	6.55	6.31	6.36
Storm Tide (surge plus tide) (mAHD)	2% AEP	1.66	1.66	1.65	1.68	1.68
	1% AEP	1.84	1.85	1.82	1.92	1.93
	0.5% AEP	2.09	2.08	2.06	2.25	2.28

		Wonga Beach	Thornton Beach	Cape Tribulation	Degarra
	CRSTIS ID	291	343	364	388
	X-coord	331061	333556	336413	326670
	Y-coord	8192249	8210945	8220830	8239466
Significant Wave Height (m)	2% AEP	2.80	2.71	3.47	2.83
	1% AEP	2.93	3.07	4.05	3.30
	0.5% AEP	3.01	3.26	4.56	3.67
Design Wave Period (s)	2% AEP	6.44	6.34	7.17	6.47
	1% AEP	6.59	6.75	7.75	7.00
	0.5% AEP	6.68	6.95	8.22	7.38
Storm Tide (surge plus tide) (mAHD)	2% AEP	1.66	1.60	1.57	1.55
	1% AEP	1.87	1.71	1.67	1.62
	0.5% AEP	2.18	1.91	1.77	1.68

Table 4-3:Future 2100 wave conditions and storm tide for key communities taken from the CRSTIS

		Oak Beach	Pebbly Beach*	Port Douglas	Cooya Beach*	Newell Beach*
	CRSTIS ID	217	221	248	267	273
	X-coord	342596	341832	336495	331474	330323
	Y-coord	8164327	8165968	8175330	8181105	8183540
Significant Wave Height (m)	2% AEP	2.69	3.19	2.76	2.60	2.64
	1% AEP	2.77	3.32	2.85	2.66	2.70
	0.5% AEP	2.82	3.40	2.91	2.70	2.74
Design Wave Period (s)	2% AEP	6.31	6.87	6.39	6.21	6.26
	1% AEP	6.40	7.02	6.50	6.28	6.33
	0.5% AEP	6.46	7.10	6.57	6.33	6.38
Storm Tide (surge plus tide) (mAHD)	2% AEP**	2.44	2.47	2.45	2.50	2.50
	1% AEP	2.71	2.75	2.70	2.85	2.87
	0.5% AEP**	3.08	3.09	3.06	3.34	3.39

		Wonga Beach	Thornton Beach	Cape Tribulation*	Degarra*
	CRSTIS ID	291	343	364	388
	X-coord	331061	333556	336413	326670
	Y-coord	8192249	8210945	8220830	8239466
Significant Wave Height (m)	2% AEP	2.86	2.86	3.68	2.98
	1% AEP	2.96	3.15	4.26	3.45
	0.5% AEP	3.04	3.33	4.77	3.83
Design Wave Period (s)	2% AEP	6.51	6.51	7.39	6.65
	1% AEP	6.63	6.84	7.94	7.16
	0.5% AEP	6.71	7.03	8.41	7.53
Storm Tide (surge plus tide) (mAHD)	2% AEP**	2.49	2.39	2.33	2.30
	1% AEP	2.80	2.55	2.48	2.41
	0.5% AEP**	3.26	2.85	2.63	2.50

*Storm tide estimated from average increase of other communities

**Storm tide estimated from increase of 1%AEP from present-day to 2100, for each community

4.4 Derivation of storm surge profiles

Storm surge profiles have been based the residual surge recorded at the Cooktown tidal gauge for Tropical Cyclone Ita in 2014. Recorded water level data has been extracted from the MSQ data, and combined with astronomical tide generated using the Utide python tool. Utide is an astronomical tide reconstruction tool that estimates tidal harmonics from an input recorded water level series[28]. The residual storm surge has been calculated as the anomaly from astronomical tides, as shown in Figure 4-5.

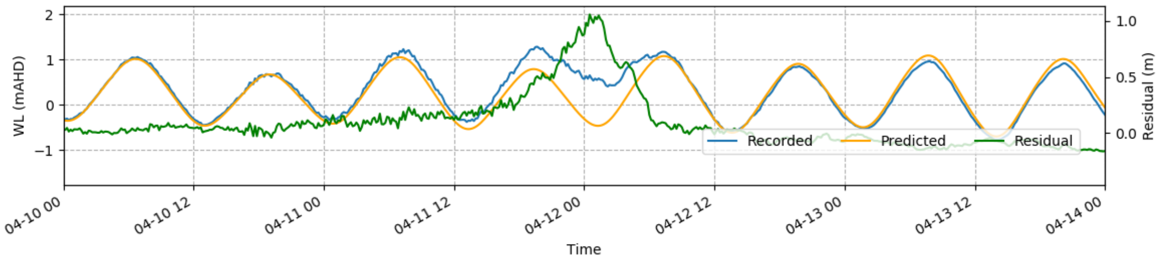


Figure 4-5:TC Ita storm surge at Cooktown tide gauge.

The residual surge series has been smoothed and normalised to establish a "unit" storm surge profile and added to a HAT tide event timeseries to achieve the CRSTIS storm tide only level for each AEP and location. In this way, the modelled storm tide levels from the CRSTIS can be simulated as a periodic tidal event. Figure 4-6 shows the HAT and unit surge profile, and the combined 1% AEP storm tide event.

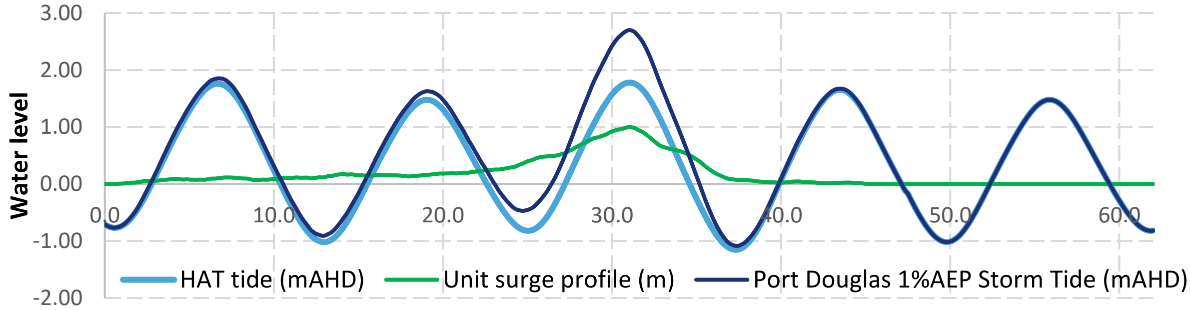


Figure 4-6:Overlay of unit hydrograph, HAT tide signal, and combined to form 1% AEP storm tide event at Port Douglas

4.4.1 Modelling increase storm tide due to wave effects

Wave setup is an increase in elevation of the nearshore water level due to breaking waves. Waves approaching the shore convey energy and momentum in the direction of the wave. As these waves reach the surfzone, their energy is dissipated as breaking, however their momentum is not dissipated but rather transferred to the water column. This results in a sloping water surface toward the shoreline. For regular waves, this results in a "static" setup condition where the level of wave setup remains constant with unchanging storm tide and wave conditions[29]. Additionally, wave runup is the back-and-forth oscillation of the waterline along the shore due to incoming waves. The level of wave runup fluctuates on the timescale of incoming wave periods (i.e. around 6-10 seconds).

In the CRSTIS wave setup and runup were calculated using a mixed approach. The SWAN (Simulating WAves Nearshore) wave energy model was used to calculate wave setup. For wave runup, the empirical approach developed by Stockdon et al (2006) was originally used to determine the level exceeded by 2% of runup events over a constant 1:10 sloped beach, with both setup and runup combined as "wave effects" withing CRSTIS storm tide results.

For this new study, wave setup, runup and overtopping were each recalculated. Wave setup has been recalculated using a 1D SWAN wave energy model. SWAN is a third-generation wave model

28 Codiga, D.L., 2011. Unified Tidal Analysis and Prediction Using the UTide Matlab Functions. Technical Report 2011-01. Graduate School of Oceanography, University of Rhode Island, Narragansett, RI. 59pp. ftp://www.po.gso.uri.edu/pub/downloads/codiga/pubs/2011Codiga-UTide-Report.pdf

29 Dean, R. G., and Walton, T. L., 2009. Wave set-up. In Kim, Y. C. (ed.), Handbook of Coastal and Ocean Engineering. Singapore: World Scientific, pp. 1–23

which has been applied as a 1D coastal transect, applying the offshore wave and water level conditions from the CRSTIS. Each transect has been developed using a combination of 5m LiDAR topography, bathymetric chart data and 30m GBR bathymetry. A new wave setup model has been developed for each TUFLOW hydrodynamic model. The resulting setup values varies due to the wave, hydraulic conditions and bathymetry. Setup has varied for each coastal community, return period and planning horizon, and added back into the to CRSTIS storm tide estimates. These have been used as the water level boundaries within each TUFLOW model, as shown in Table 4-4 and Table 4-5 for present day and 2100 scenarios respectively.

Table 4-4:Present day storm tide plus wave setup for key communities

		Oak Beach	Pebbly Beach	Port Douglas	Cooya Beach	Newell Beach
Design Storm Tide plus Wave Setup (mAHD)	CRSTIS ID	217	221	248	267	273
	X-coord	342596	341832	336495	331474	330323
	Y-coord	8164327	8165968	8175330	8181105	8183540
	2% AEP	1.82	1.92	1.81	1.82	1.88
	1% AEP	2.05	2.15	2.00	2.07	2.13
	0.5% AEP	2.28	2.37	2.23	2.43	2.48

		Wonga Beach	Thornton Beach	Cape Tribulation	Degarra
Design Storm Tide plus Wave Setup (mAHD)	CRSTIS ID	291	343	364	388
	X-coord	331061	333556	336413	326670
	Y-coord	8192249	8210945	8220830	8239466
	2% AEP	1.79	1.83	1.74	1.64
	1% AEP	2.02	1.97	1.89	1.73
	0.5% AEP	2.35	2.21	2.03	1.80

Table 4-5:2100 storm tide plus wave setup for key communities

		Oak Beach	Pebbly Beach	Port Douglas	Cooya Beach	Newell Beach
Design Storm Tide plus Wave Setup (mAHD)	CRSTIS ID	217	221	248	267	273
	X-coord	342596	341832	336495	331474	330323
	Y-coord	8164327	8165968	8175330	8181105	8183540
	2% AEP	2.67	2.75	2.63	2.70	2.71
	1% AEP	2.94	3.04	2.90	3.03	3.07
	0.5% AEP	3.34	3.36	3.28	3.51	3.56

		Wonga Beach	Thornton Beach	Cape Tribulation	Degarra
Design Storm Tide plus Wave Setup (mAHD)	CRSTIS ID	291	343	364	388
	X-coord	331061	333556	336413	326670
	Y-coord	8192249	8210945	8220830	8239466
	2% AEP	2.64	2.59	2.55	2.41
	1% AEP	2.94	2.77	2.76	2.54
	0.5% AEP	3.38	3.05	2.90	2.62

4.5 XBeach modelling for natural beach and dune systems

4.5.1 Approach

The Douglas sand dunes are relatively low lying, with storm tide levels and wave overwash potentially occurring during an extreme event. To account for these effects, wave runup has been simulated over low lying dunes fronting key communities. This has been applied as a 1D model at Oak Beach, Port Douglas, Cooya Beach, Newell Beach and Wonga Beach. Wave boundary conditions have been sourced from the nearest CRSTIS output point for 2%, 1%, and 0.5% AEP events for present day and 2100 scenarios. These input wave conditions have been input at a shore-normal orientation for each cross-shore transect, which extends offshore to a depth equal to the CRSTIS output point. For the purposes of this study, the effects of erosion and morphological change have not been included in the model, nor have the effects of wind on wave-forcing.

The XBeach "surfbeat" (phase-averaging) mode has been applied. Bathymetry in all models has been sourced from the GBR 30m Bathymetry dataset. Beach and dune topography has been sourced from the 5m LiDAR. The model has applied a varying computational grid, from 3m (offshore) to 1m (onshore). This achieves the required model resolution in the nearshore zone whilst optimising model run times by increasing offshore grid spacing to the ideal 20-25 cells per wavelength. Models were run for all return period and planning horizons, with a simulation time of three-hours to cover the peak tide and surge levels.

4.5.2 Modelling wave runup

A virtual wave runup gauge has been applied in the model to record the fluctuations in water level at the beach face. The critical wave runup level has been classified as the height exceeded by 2% of the incident waves, or $R_{2\%}$. For each beach profile and AEP event the "find peaks" method has been applied within XBeach, with the minimum distance between peaks set to seven seconds, and the minimum prominence (height above adjacent low points) set to 0.02m. Figure 4-7 shows an example of the raw output runup signal with extracted peaks and base tidal signal. Where the peak runup has not exceeded the crest of the frontal dune, the $R_{2\%}$ has been calculated and shown in Table 4-6. Sensitivity analysis has been conducted on the influence of dune crest height on wave runup level, which results showing it is a highly critical parameter.

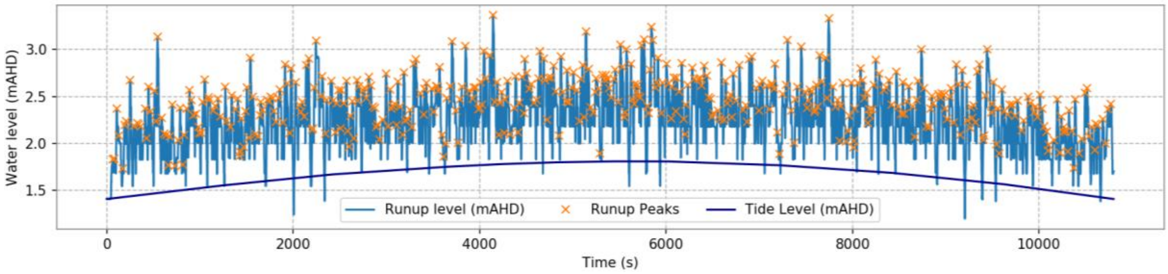


Figure 4-7:XBeach runup signal for a present day 1% AEP event at Port Douglas, with peaks identified and base storm tide signal

Table 4-6:Present day and 2100 $R_{2\%}$ runup heights for the frontal dune at key communities.

		Oak Beach	Port Douglas	Cooya Beach	Newell Beach	Wonga Beach
Present Day $R_{2\%}$ (mAHD)	2% AEP	3.17	3.08	3.07	3.09	2.81
	1% AEP	3.55	3.26	3.16	3.33	3.11
	0.5% AEP	3.55	3.61	3.46	3.59	3.31
2100 $R_{2\%}$ (mAHD)	2% AEP	3.86	3.91	3.69	3.76	3.32
	1% AEP	4.19	4.31	4.08	4.13	3.32
	0.5% AEP	4.49	4.71	4.11	4.61	3.56

4.5.3 Modelling wave overtopping

Where wave runup exceeds the dune crest level, dune overwash will occur. The XBeach and TUFLOW models have been coupled to simulate the flow paths of this overtopped water at the key communities of Oak Beach, Port Douglas, Cooya Beach, Newell Beach and Wonga Beach.

The overtopping results from each beach profile has been used to estimate the overwash volume. Overtopping has been extracted as it passes over the peak dune crest level, and saved as a discharge timeseries (q_x). This results in a roughly periodic discharge signal as individual waves break over the dunes, as shown in Figure 4-8. A low pass filter has been used to smooth out the rate of individual waves, however the total volume of overtopped water conserved throughout the storm. This volume of wave overwash has been applied as a time-averaged discharge into the TUFLOW model, rather than the impulsive signal.

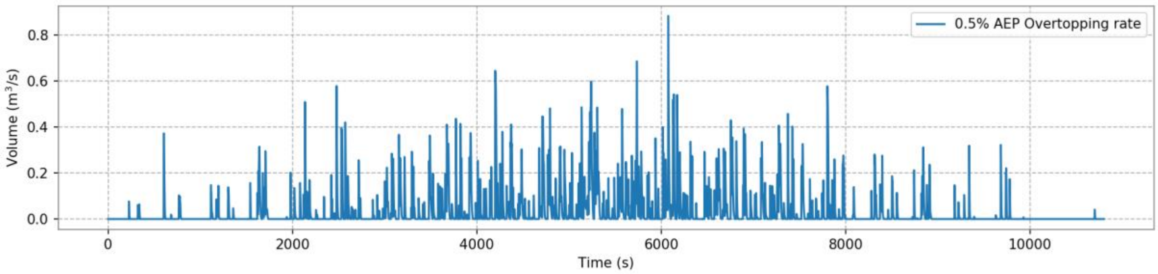


Figure 4-8:Impulsive XBeach wave overtopping signal for 2100 0.5% AEP event at Port Douglas.

4.5.4 Notes on removal of tide only discharge

For the 2100 future storm tide scenarios at Newell and Wonga beach, the dune crest was shown to be overtopped by the storm tide alone (i.e. without waves). As overtopping from tide is already considered in the TUFLOW model, the tide-only inflow rate has been removed from the XBeach discharge results, to avoid double-counting this volume.

The rate of discharge ($m^3/s/m$) from overtopping has been applied in the TUFLOW model as an ST boundary along the landward sloping side of the frontal dune at each key community. The TUFLOW model applies this rate to each grid cell along the inflow boundary. Table 4-7 shows the cumulative discharge volumes per linear meter of dune applied during a 3-hour storm period for the key coastal communities of Oak Beach, Port Douglas, Cooya Beach, Newell Beach and Wonga Beach.

Table 4-7:Present day and 2100 cumulative wave overtopping volumes for key communities, per linear meter of dune.

		Oak Beach	Port Douglas	Cooya Beach	Newell Beach	Wonga Beach
Present Day (m^3/m)	2% AEP	0.0	0.0	0.0	257.7	185.3
	1% AEP	0.3	0.0	0.0	613.1	539.8
	0.5% AEP	14.0	0.0	0.0	1056.0	1078.9
2100 (m^3/m)	2% AEP	121.0	0.7	0.0	1288.7	1277.7
	1% AEP	375.2	30.3	1.4	1611.1	2152.0
	0.5% AEP	865.7	370.9	90.6	2171.7	4302.9

4.5.5 Overtopping validation

Maximum water levels for each AEP have been extracted from TUFLOW output grids along the 1D cross-section at Wonga Beach. Table 4-8 shows the results of XBeach wave runup compared with the maximum water level recorded on the profile in TUFLOW. Across all AEPs and planning horizons the overtopping in the coupled XBeach/TUFLOW underpredicts the expected XBeach wave runup level. This can be accounted for by the lack of momentum given to the discharged volume in TUFLOW. The underprediction ranges from -0.03 to -0.27m. This is considered a trade-off between having the full spatial representation and mapping from a 2D simulation, versus having a 1D simulation for each community. These differences may be accounted for through a freeboard level for any development.

Table 4-8:Comparison of 1D XBeach runup levels and max water level in TUFLOW

		XBeach runup level (mAHD)	TUFLOW water level (mAHD)	Difference (m)	% error
Present Day (m^3/m)	2% AEP	2.81	2.78	-0.03	-1%
	1% AEP	3.11	2.92	-0.19	-6%
	0.5% AEP	3.31	3.06	-0.25	-8%
2100 (m^3/m)	2% AEP	3.32	3.10	-0.22	-7%
	1% AEP	3.32	3.26	-0.06	-2%
	0.5% AEP	3.56	3.29	-0.27	-8%

4.6 Modelling wave overtopping with EurOtop ANN

4.6.1 Background

The EurOtop ANN (Artificial Neural Network) is an empirical model which uses laboratory wave overtopping results to estimate wave overtopping rates. Hard structures are input using 22 input conditions, which are used to fit the structure to the library of laboratory results. These conditions parameterise the structure dimensions and materials as well as incoming wave and water level conditions. The rock wall at Rex Smeal Park in Port Douglas has been modelled in the ANN. The defence cross-section has been created from 1m LiDAR, using the following key parameters:

- Structure slope: 1 : 2.22
- Crest level: 3.12 mAHD
- Rock size (D_{50}): 0.5m (Figure 4-9)

Wave and storm tide conditions have been sourced from the CRSTIS. Waves have been depth limited at the toe of the structure. Table 4-9 shows the cumulative discharge volumes estimated by the ANN per linear meter of rockwall during a 3-hour storm period. The model conditions for this structure fit the test data well, with an average confidence margin of 2%. Only present-day conditions have been considered for wave overtopping of the Rex Smeal Park rock wall will be submerged by the storm tide in the 2100 planning horizon.

Table 4-9:Present day cumulative wave overtopping volumes for Rex Smeal Park rockwall

Present day return period	Peak overtopping rate (L/s/m)	Total overtopping volume (m^3)
2% AEP	1.67	18.0
1% AEP	8.17	88.2
0.5% AEP	49.20	531.4

Figure 4-9:Site image from Rock wall structure at Rex Smeal Park, showing typical slope and approximate rock size distribution.

4.7 Modelling mangroves in XBeach

4.7.1 Background

Coastal mangrove forests can significantly reduce incoming wave height and overtopping volumes. The complex matrix of mangrove roots and branches has a dissipative effect on incoming wave energy. The XBeach model include the effects of wave dampening through submerged and semi-submerged vegetation and has been used to model wave overtopping of natural beaches fronted by mangroves. XBeach treats vegetation as a field of inflexible cylinders and allows inputs for density (N), height (ah), diameter (b_v), and drag coefficient (C_d) of vegetation. Vegetation fields can be modelled as vertical sections (i.e. roots, trunk, branches) with different parameters applied to each. Overtopping with dune-fronting mangroves has been modelled or the southern end of Bougainvillea Street at Cooya Beach. The mangrove forest has been modelled as a root, trunk, branch system and applied as a 100m segment along a 1D beach profile at Bougainvillea St. Table 4-10 shows the vegetation parameters used in modelling. The recommend parameters for mangroves have been used.

Table 4-10:Vegetation parameters used to simulate mangrove forest in XBeach

Section	Height (m)	Drag	Diameter (m)	Density (#/m)
Roots	0.5	2	0.05	100
Trunk	0.8	1	0.15	5
Branches	1.3	2	0.1	50

Table 4-11 shows the results of cumulative overtopping volumes calculated by XBeach during all present-day scenarios. For the purposes of this study, only present-day wave scenarios have been modelled. 2100 storm tide levels are projected to exceed the dune crest in this location, with tidal flow through mangroves incorporated in the base TUFLOW model.

Table 4-11:Present day cumulative wave overtopping volumes for Bougainvillea St., with and without mangroves

Bougainvillea St. South, Cooya Beach		With mangrove	w/o mangrove	% reduction
Present Day (m^3/m)	2% AEP	0.0	103.6	100%
	1% AEP	9.5	330.9	97%
	0.5% AEP	150.3	819.5	82%

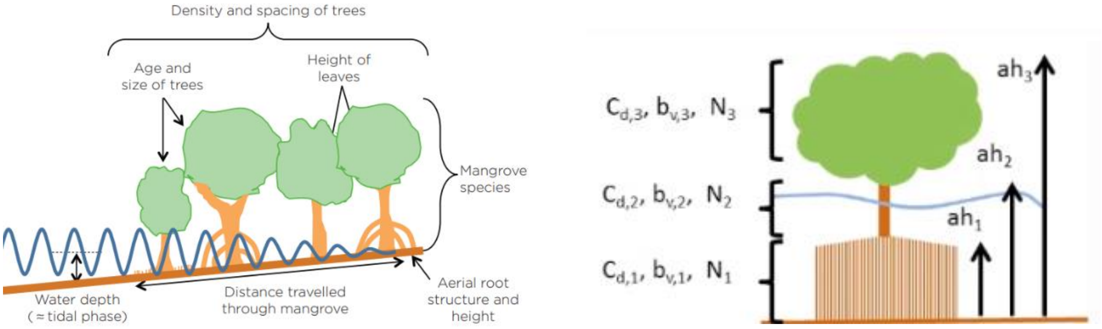


Figure 4-10:The effects of mangrove forest characteristics on wave dissipation, World Bank (2016)[30] and mangrove parameterisation (Roelvink et al. 2009)[31].

Figure 4-11:Example of mangroves on a natural beach

30 World Bank. (2016). Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs. M. W. Beck and G-M. Lange, editors. Wealth Accounting and the Valuation of Ecosystem Services Partnership (WAVES), World Bank, Washington, DC.

31 Roelvink, D., Reniers, A., Van Dongeren, A., Van Thiel de Vries, J., Lescinski, J. and McCall, R. 2010. XBeach model description and manual. Delft University of Technology, User Manual, Delft, The Netherlands

4.7.2 Sensitivity analysis

Sensitivity analysis has been conducted on the input vegetation parameters by ranging section height, diameter, drag and density. For each case, the reduction of wave height through the 100m mangrove section was recorded. This analysis showed that the model is not overly sensitive to changes of the vegetation parameters. The most influential parameter was stem density however this parameter only affected the reduction of average wave height by approximately 2%.

Additional analysis was conducted on the effect of mangrove field width on wave reduction in the model. As expected, a wider forest with further reduce wave height through the mangrove field, as shown in Figure 4-12.

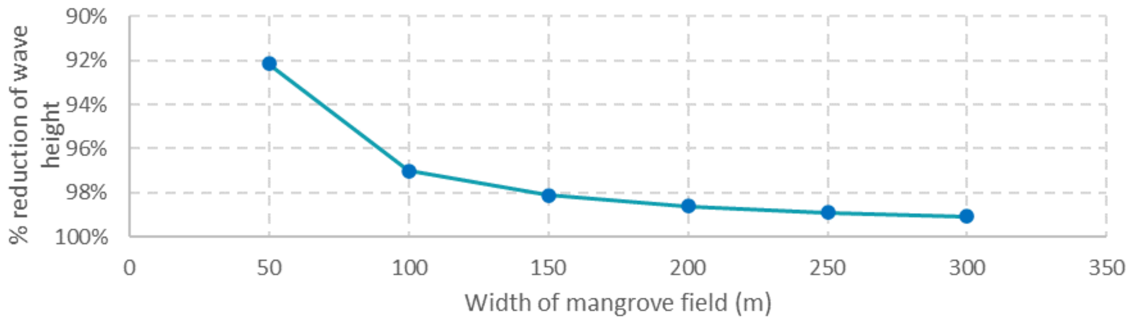


Figure 4-12: Sensitivity of wave height reduction to mangrove field width in the XBeach model.

4.8 A combined hydrodynamic model for community-scale mapping

Seven modelling domains were created, using a combination of tide and storm surge modelling, wave setup allowances, wave inputs for a range of shoreline types (dunes, structures and mangroves). These were used to simulate the following scenarios:

- 2% AEP, 1% AEP and 0.5% AEP
- Present day and 2100 planning horizons.

The peak inundation depth was extracted for each community and are presented in Appendix A.

5 Allowance for freeboard

Freeboard provisions are used to manage the risks associated with uncertainty in flood and storm tide inundation estimations. Best practice flood risk management suggests freeboard be estimated in studies where uncertainty in the estimates of flood levels can arise from storm surges in coastal waters and where the future climate has the potential to significantly increase risk.

Freeboard is the additional height above the Defined Flood Level (DFL), as determined by the appropriate authority, to account for uncertainties due to wave action and localised hydraulic behaviour[32]. The finished floor level for habitable areas, or Habitable Floor Level (HFL), is typically established based on the DFL plus any freeboard.

In treating flood risk, best practice suggest "*there are many circumstances in which a freeboard of 0.3-0.6m may be considered acceptable. The lower freeboard is generally only considered acceptable for use in shallow water where the potential for other effects is limited."* [33] A range of freeboard provisions have been adopted by councils across Queensland, as presented in Table 5-1.

Whilst state-of-the-art modelling techniques have been applied in this study to determine storm tide levels for the Douglas Shire Council LGA, uncertainty remains within the final mapping and levels due to several factors, which include:

- Modelled storm tide levels are based on the Cairns Regional Storm Tide Inundation Study (CRSTIS), which is now approaching 10-years of age, and several aspects of this study have been flagged (e.g. the lack of non-cyclonic events) that could be improved using updated best-practice methods.
- Some processes cannot be replicated in the model, for instance momentum of overtopping waves is not conserved, only discharged volume.
- A single dune profile was used to represent each segment of coastline, which may lead to under-estimation of overtopped volumes in some sections.
- The addition of riverine flooding during a coincident rainfall event has not been included.
- The new hydrodynamic model has not been fully calibrated and validated, due to a lack of real-world storm tide events, and its performance is as yet unquantified.

A minimum building pad level and freeboard has been applied for the purpose of this study to account for these uncertainties. This includes:

- A minimum building pad level of 0.25m above the 1% AEP storm tide level.
- A minimum freeboard for finished flood levels of 0.50m above the 1% AEP storm tide level.

Table 5-1:Example freeboard allowances adopted by different Councils in QLD.

LGA	Land Use	Pad Level	Min HFL	Min Non-HFL
Brisbane City Council	Dwelling house	1%AEP	1%AEP + 500mm	1%AEP + 300mm
Moreton Bay	Residential Dwelling	-	1%AEP + 500mm	-
Townsville	Residential Dwelling	-	>1%AEP	-
Cairns	Residential Dwelling	1%AEP	1%AEP + 300mm	-
Fraser coast	Residential Dwelling	DSTE	>DSTE	-
Gold Coast	Residential Dwelling	-	1%AEP + 300mm	-

32 ABCB (2019), Construction of buildings in flood hazard areas - ABCB Standard 2012.3

33 Australian Disaster Resilience Handbook 7: Managing the Floodplain: A Guide to Best Practice in Flood Risk Management in Australia, 2013, Australian Institute for Disaster Resilience CC BY-NC

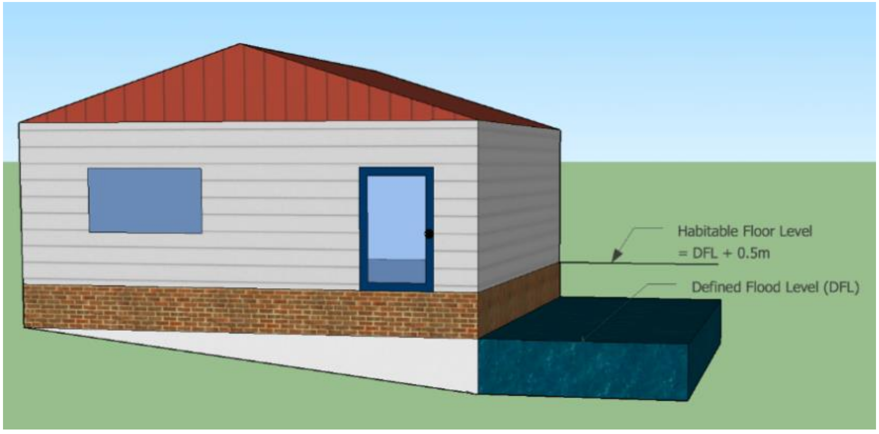


Figure 5-1:Graphic representation of defined flood level (DFL) and freeboard.

6 Summary and Recommendations

JBPacific were commissioned by Douglas Shire Council (DSC) to investigate new approaches to map storm tide inundation for the Queensland coastline. The project has reviewed a range of Australian and international approaches to simulate the combined effect of tides, storm surges and waves over different shorelines and vegetation types to produce a best practise approach for the Douglas coastline, which can also be applied for other Queensland regions. Following calculation with a detailed storm tide study, a three-step process has been proposed to produce storm tide maps:

1. Assessment of shoreline types, e.g. (i) natural beach and dunes, (ii), wetlands, marshlands and estuaries, (iii) rocky outcrops, cliffs and hard structures, and (iv) mangroves.
2. Undertake a nearshore assessment using different modelling methodologies for coastal and vegetation types
   a. XBeach for natural beach and dune systems,
   b. Hydrodynamic modelling for wetlands, marshlands and estuaries
   c. Artificial Neural Network for rocky outcrops, cliffs and hard structures
   d. XBeach for Mangroves
3. Undertake hydrodynamic modelling to simulate tides, storm tide, setup and nearshore/overtopping processes over the foreshore.

This process was followed for the Douglas Coastline, which resulted in seven large-scale hydrodynamic modelling domains created, using a combination of tide and storm surge modelling, wave setup allowances, and wave inputs which were calculated through separate XBeach and Neural Network models. The peak coastal inundation levels simulated within these integrated hydrodynamic models were compared back against detailed XBeach 1D wave runup models, which shown an underprediction in peak level of up to -0.3m. This is due to the loss of momentum when the models are coupled. This is considered a trade-off between having the full spatial representation and mapping from a 2D simulation, versus having a 1D simulation for each community. These differences have been considered within a nominal 0.5m freeboard level.

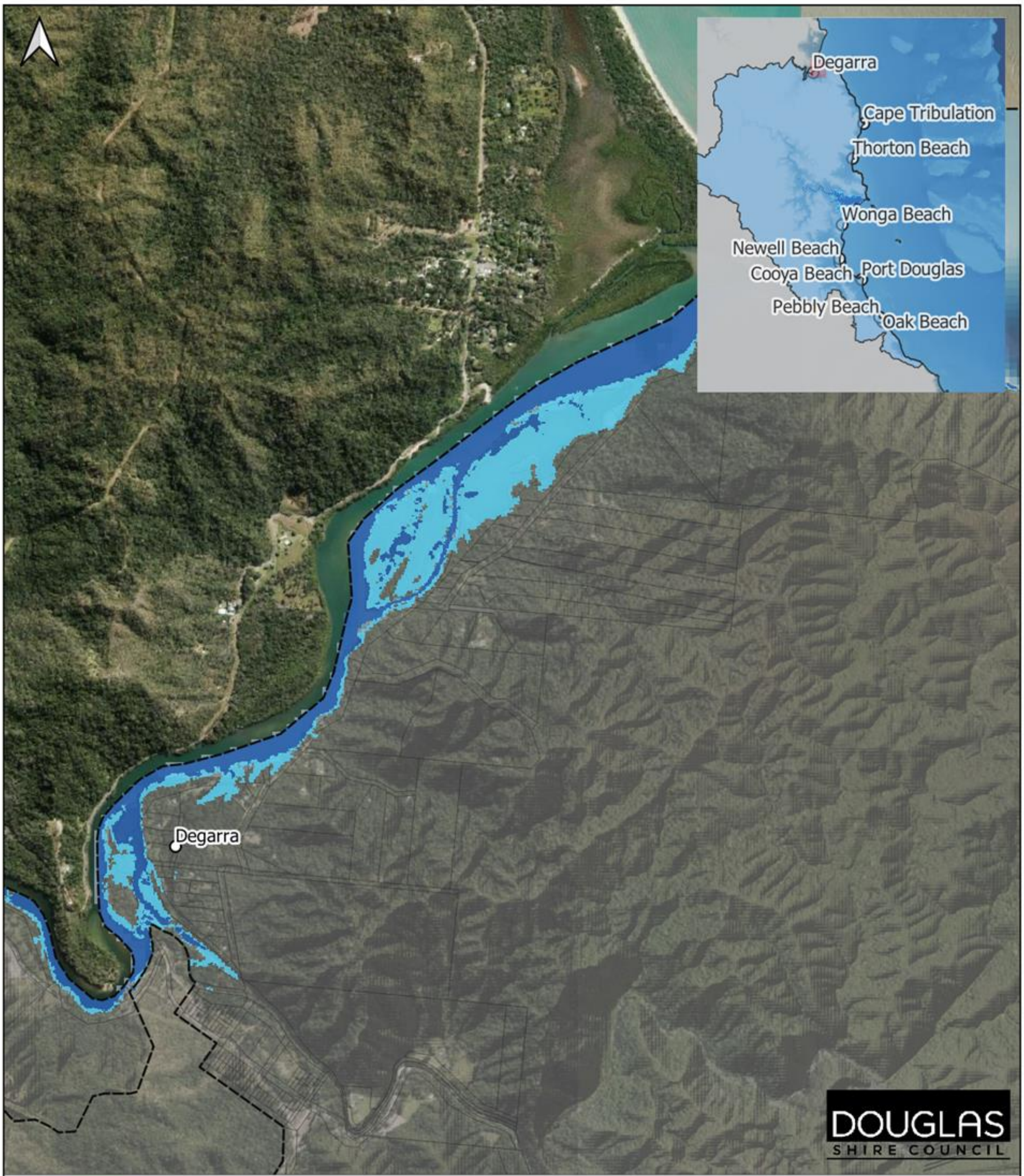
Storm tide inundation maps have been developed at a lot-specific level, for multiple return periods and planning horizons. The table below shows present day, 1% Annual Exceedance Probability (AEP) storm tide levels, including an additional 0.25m for minimum building pad levels and additional 0.5m freeboard for finished flood levels.

Table 6-1:Present day storm tide level range for key communities, including 0.5m freeboard

Locality	Storm tide level range (present day, 1% AEP), mAHD	Finished floor level (storm tide for present day, 1% AEP, plus 0.5m), mAHD	Storm tide level range (2100 0.8m SLR, 1% AEP), mAHD	Finished floor level (storm tide for 2100 0.8m SLR, 1% AEP, plus 0.5m), mAHD	Pad level for 2100 0.8m SLR, 1% AEP
Wangetti	0.65 - 2.14	1.15 - 2.64	2.16 - 3.02	**2.66 - 3.52**	2.41 - 3.27
Oak Beach	2.01 - 3.73	2.51 - 4.23	2.40 - 3.79	**2.90 - 4.29**	2.65 - 4.04
Port Douglas	1.21 - 3.06	1.71 - 3.56	2.66 - 3.08	**3.16 - 3.58**	2.91 - 3.33
Cooya Beach	2.13 - 2.64	2.63 - 3.14	2.85 - 3.94	**3.35 - 4.44**	3.10 - 4.19
Newell Beach	1.53 - 4.00	2.03 - 4.50	2.34 - 4.08	**2.84 - 4.58**	2.59 - 4.33
Wonga Beach	1.56 - 3.10	2.06 - 3.60	1.95 - 3.38	**2.45 - 3.88**	2.20 - 3.63
Thorton Beach	1.61 - 2.03	1.11 - 2.53	2.48 - 2.95	**2.98 - 3.45**	2.73 - 3.20
Degarra	1.04 - 1.77	1.54 - 2.27	1.28 - 2.62	**1.78 - 3.12**	1.53 - 2.87

7 Appendix A: 1% AEP Storm Tide Mapping

Degarra Domain Present Day 100yr Depth Map



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477 Boundary Street
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Scale
0 500 1,000 m

Date
26/11/2020

Legend

Inundation depth (m)
- Less than 1m
- Greater than 1m

Title
Storm Tide Inundation Including Wave Overtopping: Present Day 1%AEP

Project
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Client
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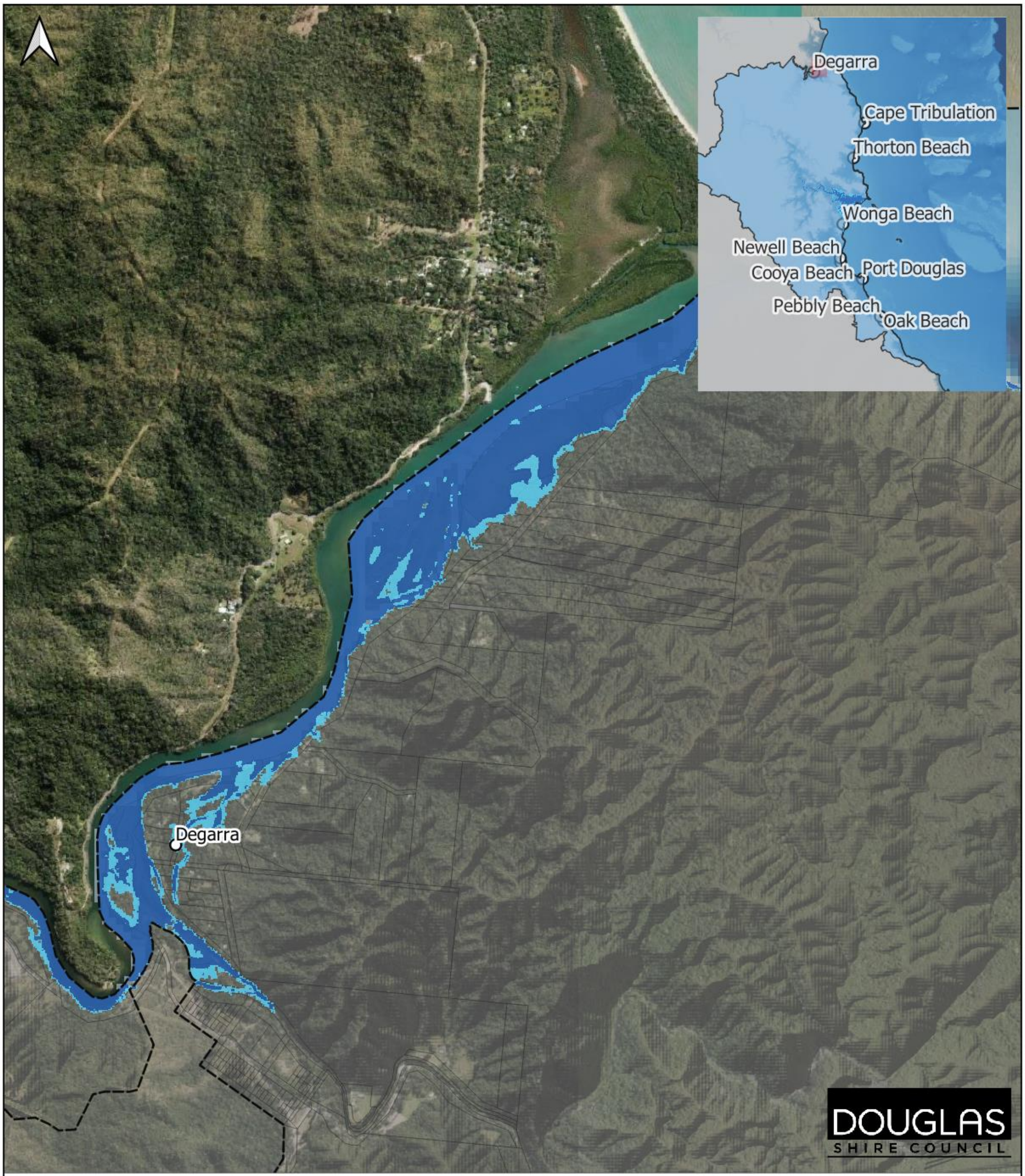
Degarra Domain Future 100yr Depth Map



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Date
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Legend

Inundation depth (m)

- Less than 1m
- Greater than 1m

Title
Storm Tide Inundation Including Wave Overtopping: Projected 2100 1%AEP 0.8m SLR

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Cape Tribulation Domain Present Day 100yr Depth Map

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Scale

0 400 800 m

Date
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Legend

Inundation depth (m)
- Less than 1m
- Greater than 1m

Title
Storm Tide Inundation Including Wave Overtopping: Present Day 1%AEP

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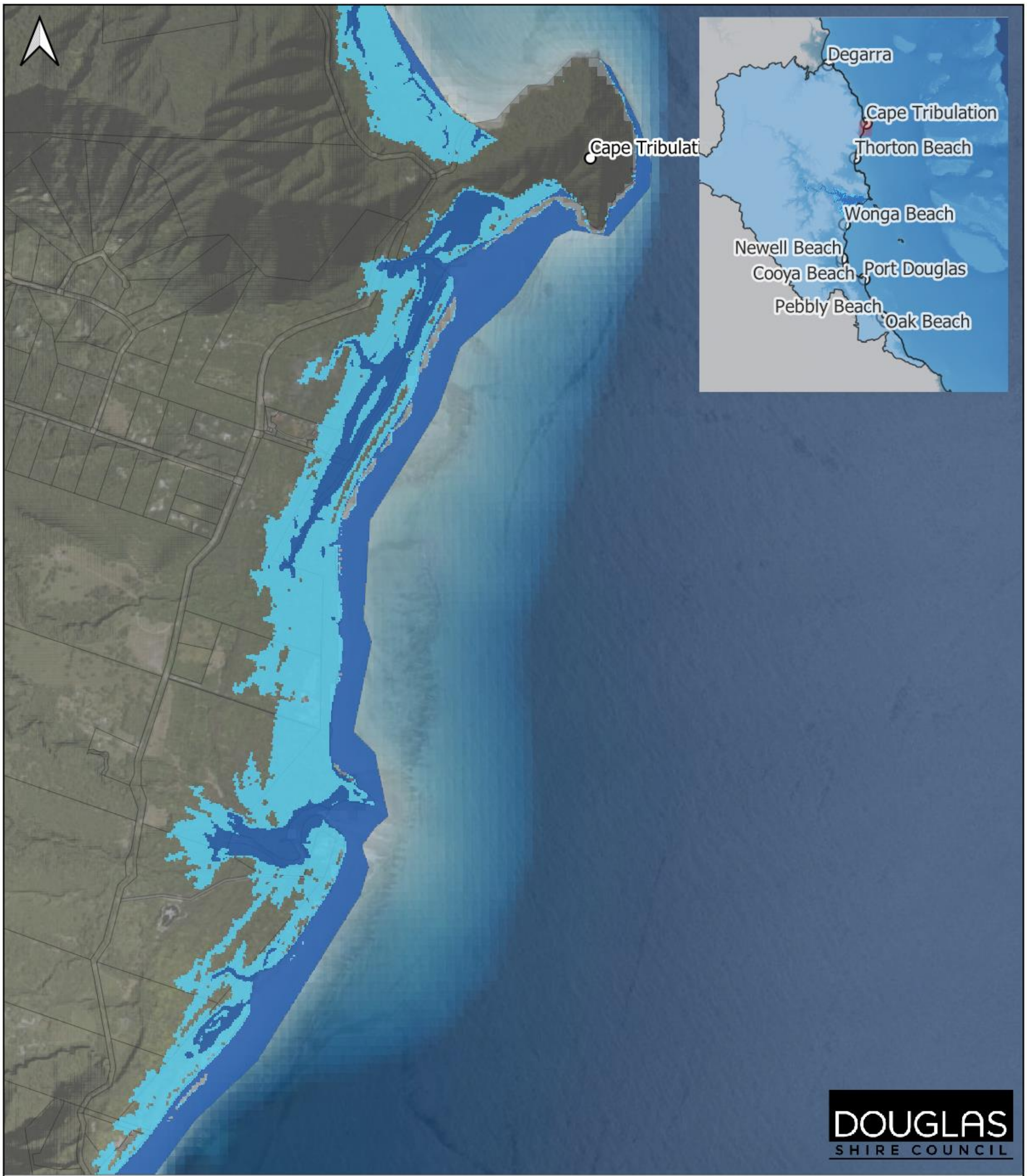
Cape Tribulation Domain Future 100yr Depth Map



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Legend
Inundation depth (m)
Less than 1m
Greater than 1m

Title
Storm Tide Inundation Including Wave Overtopping: Projected 2100 1%AEP 0.8m SLR

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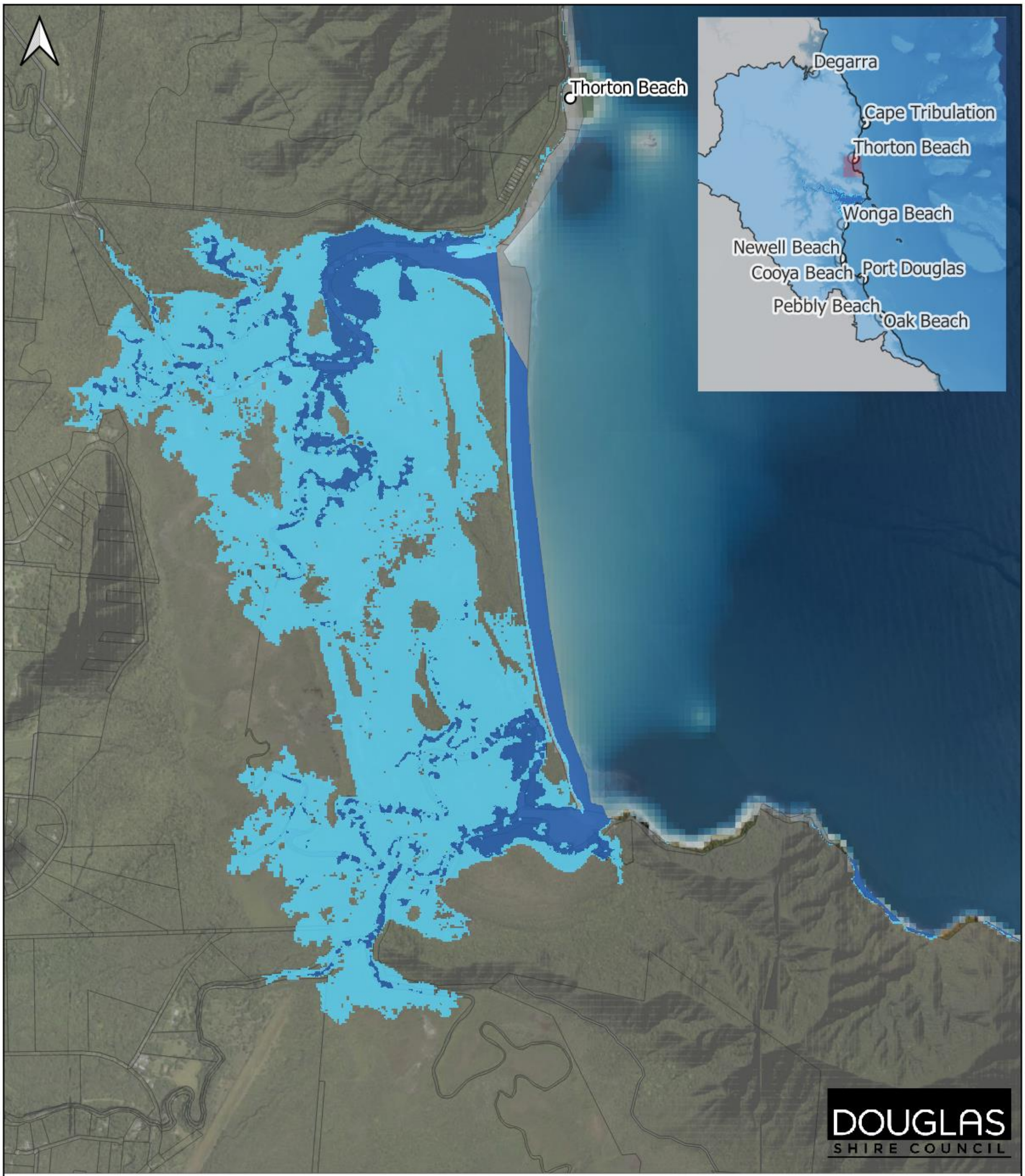
Thornton Domain Present Day 100yr Depth Map



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Scale

0 600 1,200 m

Date
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Legend

Inundation depth (m)

- Less than 1m
- Greater than 1m

Title
Storm Tide Inundation Including Wave Overtopping: Present Day 1%AEP

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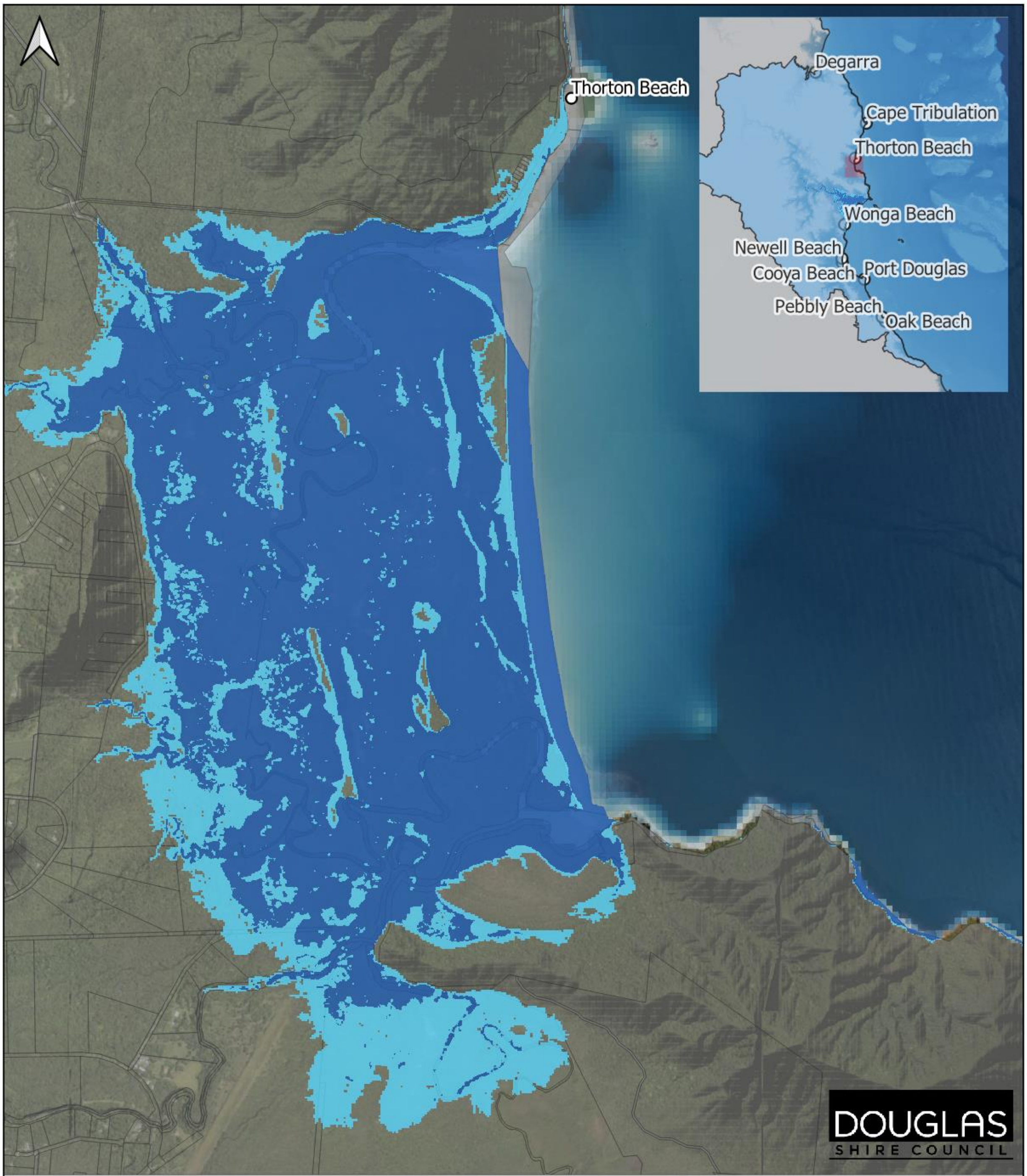
Thornton Domain Future 100yr Depth Map



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Scale

0 600 1,200 m

Date
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Legend

Inundation depth (m)

- Less than 1m
- Greater than 1m

Title

Storm Tide Inundation Including Wave Overtopping: Projected 2100 1%AEP 0.8m SLR

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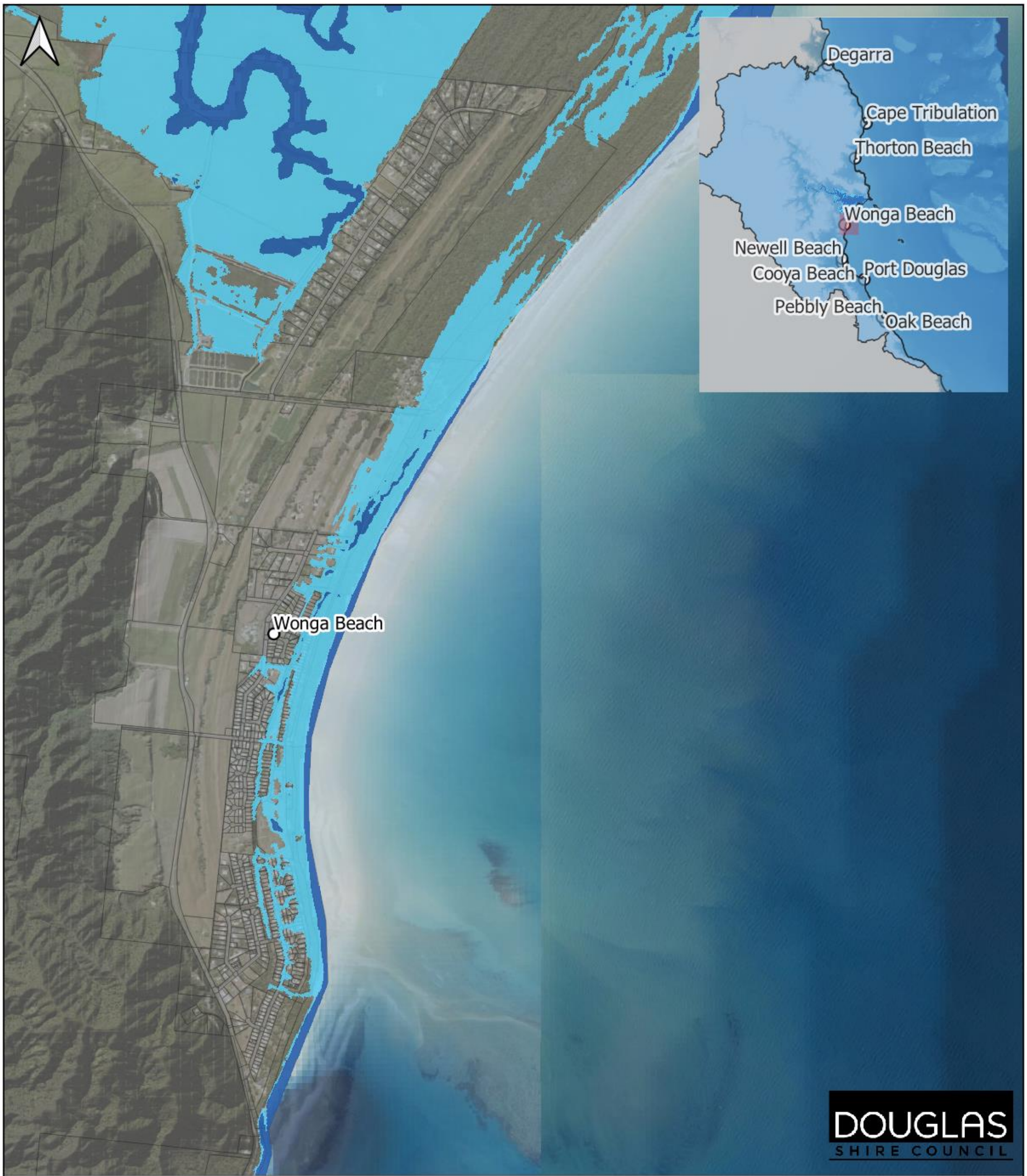
Wonga Domain Present Day 100yr Depth Map



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0 600 1,200 m

Date
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Legend

Inundation depth (m)

- Less than 1m
- Greater than 1m

Title
Storm Tide Inundation Including Wave Overtopping: Present Day 1%AEP

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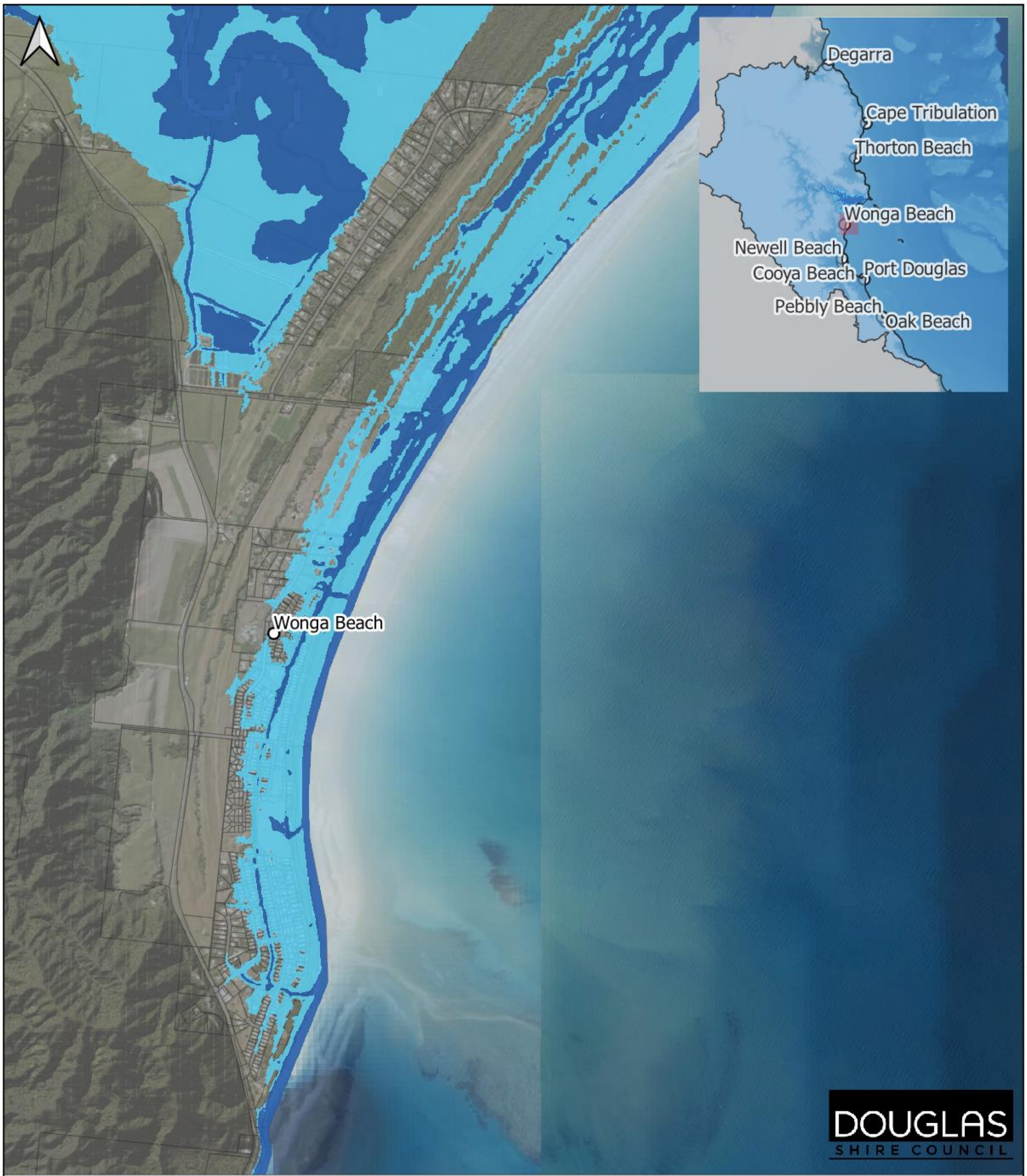
Wonga Domain Future 100yr Depth Map



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Legend

Inundation depth (m)

- Less than 1m
- Greater than 1m

Title
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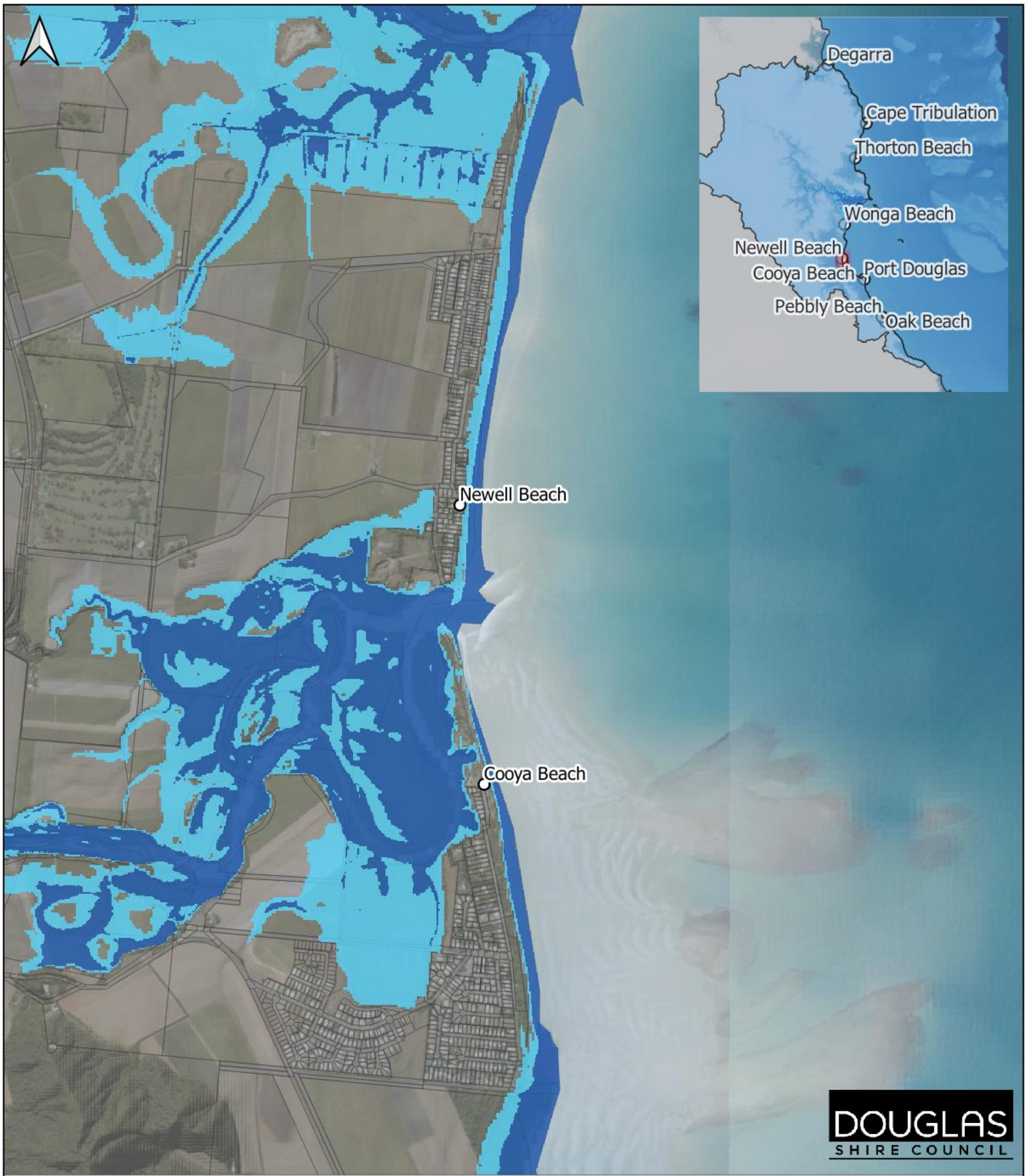
Cooya/Newell Beach Domain Present Day 100yr Depth Map



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Inundation depth (m)

Less than 1m

Greater than 1m

Title
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Cooya/Newell Beach Domain Future 100yr Depth Map

Port Douglas/Pebbly Beach Domain Present Day 100yr Depth Map

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Legend
Inundation depth (m)
- Less than 1m
- Greater than 1m

Title
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Port Douglas/Pebbly Beach Domain Future 100yr Depth Map

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Legend

Inundation depth (m)

- Less than 1m
- Greater than 1m

Title
Storm Tide Inundation Including Wave Overtopping: Projected 2100 1%AEP 0.8m SLR

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Oak Beach Domain Present Day 100yr Depth Map

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Inundation depth (m)

- Less than 1m
- Greater than 1m

Title
Storm Tide Inundation Including Wave Overtopping: Present Day 1%AEP

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Oak Beach Domain Future 100yr Depth Map

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