CLIENTS | PEOPLE | PERFORMANCE

Townsville and Thuringowa City Councils

Townsville-Thuringowa Storm Tide Study

Final Report

Part B – Detailed Report

April 2007

INFRASTRUCTURE | MINING & INDUSTRY | DEFENCE | PROPERTY & BUILDINGS | ENVIRONMENT

Contents

Table Index

Figure Index

Appendices

Executive Summary

Aims

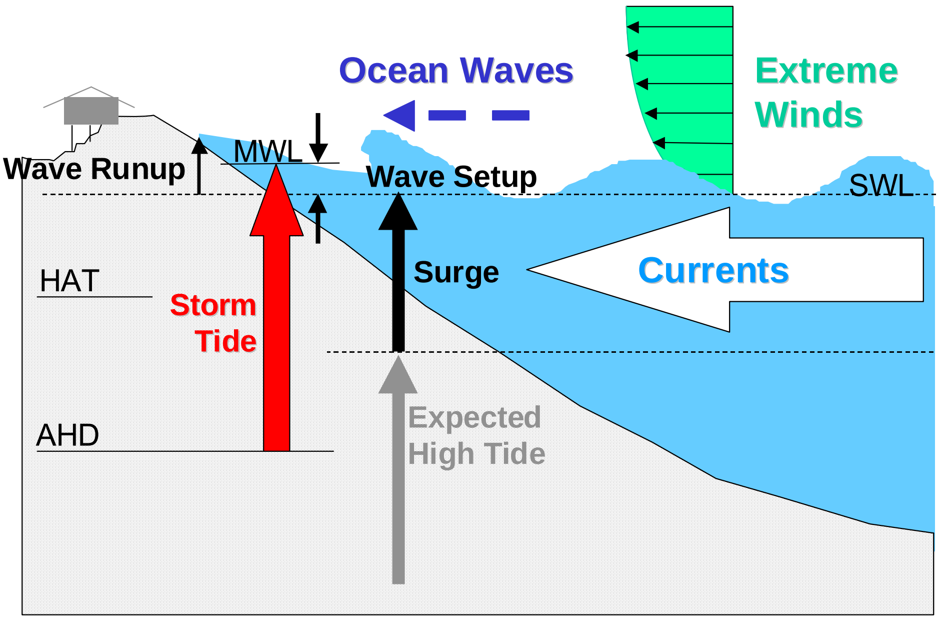
The Townsville-Thuringowa Storm Tide Study has been completed under the auspices of the Federal Government's Natural Disaster Risk Mitigation Program (NDRMP). The aim of this program is to minimise / reduce future costs associated with the occurrence of natural diasters through better planning processes.

For this study, the primary focus has been on the determination of inundation associated with a range of statistical storm tide events, and the levels of risk and exposure associated with predicted inundation.

In addition, the study was charged with developing a storm tide warning system (SEAtide), suitable for use by the Bureau of Meteorology (BoM) in managing storm tide threats in the Townsville/Thuringowa region.

Components of Storm Tide

Storm tide estimates comprise several elements, these being tide, surge, and wave setup, as illustrated below. An advantage offered by this study is that each component can be provided at each location, separately, or added together as storm tide. In addition, wave height predictions can be extracted from the model results. Localised wave runup has not been considered.



Methodology

A comprehensive analysis technique was applied, resulting in the prediction of storm tides associated with four recurrence intervals (50 years, 100 years, 500 years, and a 10,000 year event, which has been equated to the maximum likely storm tide event).

The methodology is in keeping with the Queensland Climate Change investigations, a report sponsored by the Bureau of Meteorology in Queensland and various State Government departments.

In keeping with this method, a series of mathematical models has been applied, resulting in the generation of calibrated wind, surge and hydrodynamic models. Results from these runs have been input into a parametric model, which was then run in a Monte-Carlo simulation, with 50,000 years of cyclones and storm tides simulated.

With respect to inland inundation, two prediction methods were utilised. Estimates of storm tide (with and without wave setup) were determined at 560m intervals along the coastline for each of the four design recurrence intervals. For the purposes of comparison, the values without wave setup were then extrapolated inland using GIS procedures.

Hydrodynamic modelling (Delft package) was then used to simulate the inland flow / penetration of the storm tide, with wind stress and friction effects accounted for. These model runs do not include wave setup, which applies only at points on the coast where the land height exceeds the predicted surge height. The DELFT model runs tend to provide higher levels inland, where low-lying land extends well inland, and where there are no hills or barriers to wind.

A comparison of predicted levels (extrapolated open coast without setup and DELFT overland flow method) was then made, with the higher of the two predictions adopted at all locations.

Data

Significant data resources were required to enable the completion of this project. These include a database of historical cyclones, offshore bathymetric (sea-floor) data, tidal data, topographic and cadastral data (provided by each Council), and knowledge of the location and details of key infrastructure.

Tropical Cyclone Climatology

This study has considered all available records with respect to cyclones passing within 500 km of Townsville, with reference to data dating back to the 1900s. However, given the lack of reliability of some of this data, statistical information has focussed on cyclones occurring since 1959/1960. During this time, some 45 cyclones have passed within 500 km, an average of 1.8 cyclones per season. The number of cyclones per season has varied from zero to five.

In assessing the climatology, consideration has been given to recorded intensities, probable maximum intensity, parameters such as radius to maximum winds, and the forward speed of cyclones.

Model Development

The model development process, referenced above in brief, uses four different modelling packages, three of which address the simulation of cyclonic winds and pressure, hydrodynamics (tides), and waves. A statistical model is then applied to generate the estimates of storm tide along the coastline.

The various models have been developed using a system of nested grids. The largest of these grids, which provides data as to the sea-bed and hence water depth, extends almost 800 km off-shore, and almost 1400 km along the coastline. The smallest grid is 30 km x 35 km, with a grid size of 55 m. The model development process is discussed in detail in Chapter 5 of the report. However, key features of this process include:

- Calibration to Cyclone Althea (1971)
- Verification against Cyclone Aivu (1989)
- Completion of sensitivity analysis model runs
- Modelling of over 350 theoretically possible cyclones, approaching on a number of different tracks.
- Simulation of a synthetic 50,000 year period (90,000 cyclones) using a statistical model.

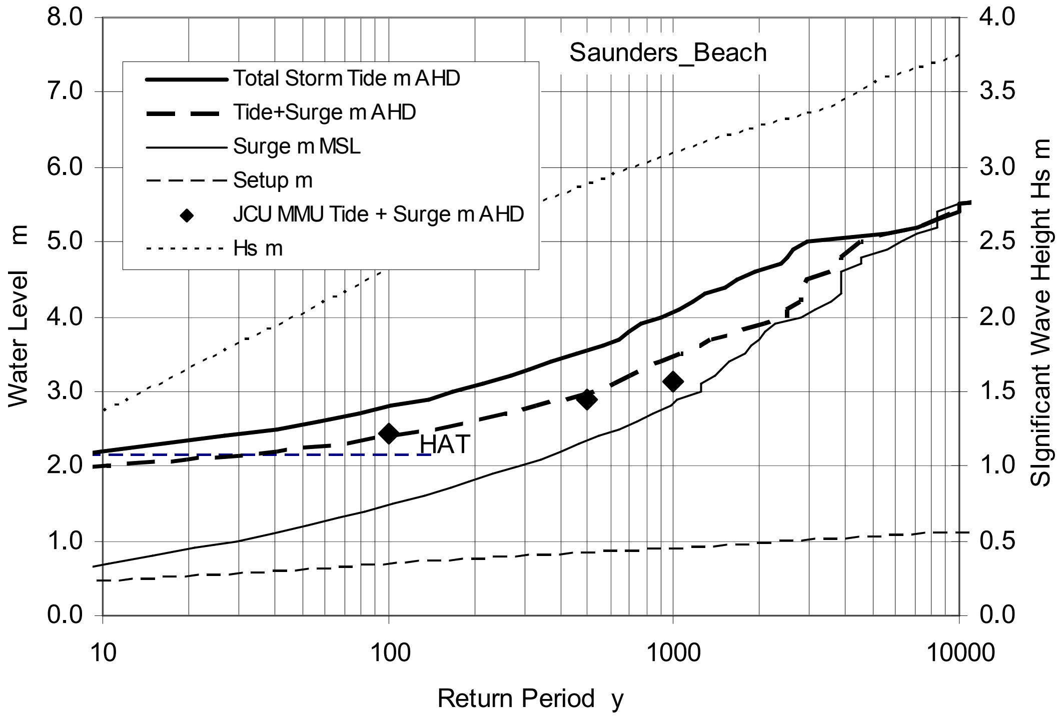
Storm Tide Levels

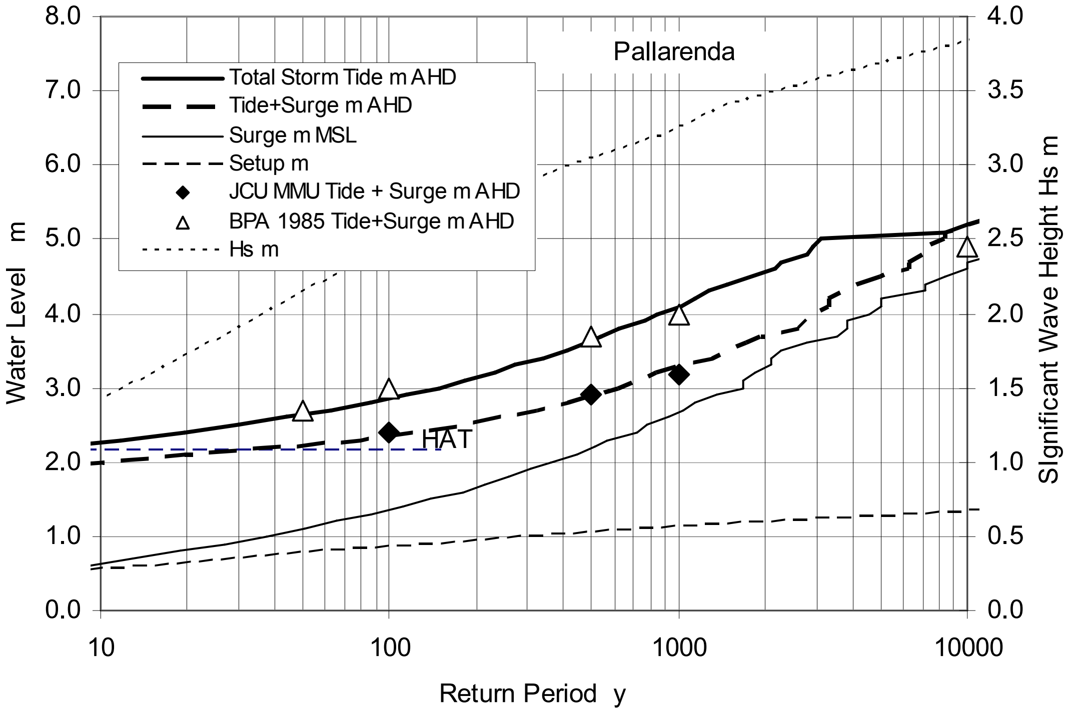
Storm tide levels have been estimated along the Townsville-Thuringowa coastline, extending inland to the maximum extent of inundation. A sample of the results in tabular form is presented below. Storm tide levels are presented relative to Australian Height Datum (AHD) and are inclusive of wave setup.

	Estimated Return Period of Total Storm Tide Level				
Site	**50 y**	**100 y**	**500 y**	**1000 y**	**10000 y**
Crystal_Creek	2.8	3.1	4.0	4.1	7.3
Balgal	2.7	3.0	4.0	4.5	6.2
Rollingstone	2.6	2.9	3.8	4.4	6.0
Mystic_Sands	2.7	3.0	4.0	4.7	6.2
Surveyors Creek	2.7	3.0	3.5	3.8	6.0
Toolakea	2.6	2.8	3.1	3.4	5.3
Bushland_Beach	2.6	2.9	3.6	4.0	5.3
Bohle_River	2.2	2.3	2.8	3.2	4.8
Pallarenda	2.6	2.9	3.6	4.1	5.2
Kissing_Point	2.7	2.9	3.8	4.3	5.5
North_Ward	2.7	3.0	3.9	4.4	5.4
Nelly_Bay	2.5	2.7	3.3	3.7	5.0

The figures below provide an illustration of the relative magnitude of each of the individual components of storm tide. Examples are presented for Pallarenda and Saunders Beach.

The figures also provide comparisons with previous JCU and BPA studies for estimated surge plus tide levels (not including wave setup). The present surge plus tide results are consistent with latest JCU estimates, and both are of the order of 0.5 m lower than BPA studies done in 1985. In many locations, this means that the present total storm tide levels (including wave setup) are similar to the 1985 studies estimates without allowance for wave setup.





Mapping

A comprehensive set of maps has been produced for each of the nominated events. These have been produced in several formats, illustrating inundation extent, water surface level and water depths at all locations within the affected area. Maps have been organised into a series of grids, with 8 maps covering the Townsville area, and 10 for Thuringowa. On a comparative basis, the 50 and 100yr events show little difference in the extent of inundation, whereas the 10,000 yr event demonstrates significant inundation. This is most evident along the Thuringowa coastline, where modelling suggests that several metres of water may be added inland as waters are funnelled into valleys.

Overall, the areas most affected by inundation include the Bohle River floodplain and Town Common, areas to the south of Ross River, and to a lesser extent, several of the beachside communities of Thuringowa (Ollera Ck, north of Balgal, Bluewater Ck). Significant low-lying areas between Toomulla and Toolakea (i.e. Leichardt Ck and Christmas Ck) are also affected.

Greenhouse Effect

Greenhouse effects have been considered in terms of higher sea levels, warmer air and sea temperatures, the resultant impact on the likely maximum intensity of cyclones, and the potential increase in the incidence of cyclones.

Vulnerability

The vulnerability assessment has been based on application of a review of the predicted and mapped storm tide levels, and the implications for critical infrastructure, as identified in consultation with Townsville and Thuringowa Councils. Tables have been produced for each area, summarising property and population at of death risk for the range of storm tide events considered.

Thuringowa Properties and Population at Risk from Storm Tide Inundation

Study Area	50 yr ARI		100 yr ARI		500 yr ARI		10,000 yr ARI	
	P I	PAR	P I	PAR	P I	PAR	P I	PAR
Mutarnee	0	0	0	0	0	0	0	0
Rollingstone	9	25	14	39	14	39	310	868
Clement	0	0	0	0	0	0	89	250
Bluewater	1	3	8	22	35	98	184	515
Yabulu	3	9	9	25	32	90	254	711
Mount Low	1	3	2	6	9	25	845	2366
Total	**14**	**40**	**33**	**92**	**90**	**252**	**1682**	**4710**

Note: **P I** denotes number of properties inundated.

PAR denotes population at risk.

Townsville Property and Population at Risk from Storm Tide Inundation

Study Area	50 yr ARI		100 yr ARI		500 yr ARI		10,000 yr ARI	
	P I	PAR*	P I	PAR*	P I	PAR*	P I	PAR*
Annandale	0	0	1	3	1	3	495	1386
Arcadia	0	0	0	0	1	3	57	160
Belgian Gardens	0	0	1	3	47	132	212	594
Bohle	0	0	0	0	0	0	4	11
Cluden	0	0	1	3	1	3	107	300
Cungulla	0	0	19	53	23	64	245	686
Currajong	0	0	0	0	18	50	883	2472
Garbutt	0	0	0	0	6	17	687	1924
Gulliver	0	0	0	0	0	0	199	557
Hermit Park	6	17	9	25	121	339	1073	3004

Study Area	50 yr ARI		100 yr ARI		500 yr ARI		10,000 yr ARI	
	P I	PAR*	P I	PAR*	P I	PAR*	P I	PAR*
Horseshoe Bay	0	0	0	0	0	0	14	39
Hyde Park	1	3	1	3	113	316	452	1266
Mount Louisa	0	0	0	0	0	0	8	22
Mt St John	1	3	1	3	1	3	2	6
Mundingburra	0	0	0	0	0	0	358	1002
Mysterton	0	0	0	0	4	11	308	862
Nelly Bay	3	8	4	11	5	14	34	95
North Ward	0	0	0	0	42	118	233	652
Oonoonba	0	0	13	36	206	577	437	1224
Pallarenda	0	0	0	0	0	0	292	818
Picnic Bay	0	0	0	0	1	3	24	67
Pimlico	0	0	0	0	67	188	694	1943
Railway Estate	2	6	131	367	1000	2800	1087	3044
Rosslea	0	0	0	0	0	0	336	941
Rowes Bay	0	0	0	0	4	11	101	283
South Townsville	0	0	46	129	320	896	623	1744
Townsville City	0	0	0	0	6	17	14	39
West End	2	8	3	8	38	106	436	1221
West Point	0	0	0	0	0	0	7	20
Wulguru	0	0	0	0	0	0	76	213
Total	**15**	**45**	**230**	**644**	**2048**	**5734**	**10196**	**28549**

It must be stressed that predictions for the 10,000 year event have a much greater band of uncertainty than those for the smaller events, and should be treated as broad estimates only.

In addition, a review of the Disaster Management Plan has been undertaken. Typically, the only items affected by the results of this study are evacuation routes, as evacuation centres appear to be outside inundation zones.

SEAtide Warning System

As part of this study, a storm tide warning system, known as SEAtide, has been developed. SEAtide has been provided to the Queensland Regional Office of the Bureau of Meteorology, which agreed to trial the system during the 2005/2006 cyclone season. The system allows predictions of storm tide at the coast, based on an estimation of the location, track and characteristics of the cyclone.

For predictions of inundation away from the coast (i.e. inland penetration of storm tide), it will also be necessary to reference the water surface maps produced as part of this study, noting that in some cases, levels may increase.

1. Introduction

This study is concerned with the understanding, assessment and management of the risk posed by tropical cyclone storm tide to population, housing and infrastructure in the Townsville - Thuringowa region. It provides essential information that can be used to mitigate the effects of extreme storm tide through the planning process and also delivers emergency response maps and a real-time warning capability for emergency management.

1.1 Background

The study region is located within a very active zone of tropical cyclone occurrence and accordingly has a long history of encounters with severe tropical cyclones. Amongst the earliest recorded impacts of storm tide in Queensland is the 1884 event at nearby Bowen, and the infamous *Sigma* cyclone of 1896, named after one of the many vessels that sank at Townsville during the cyclone's passage (Holthouse 1971).

Many lesser events followed in the ensuing years but it was *Althea* in December 1971 that "*raised our collective conscience to the storm tide threat in Queensland*" (Harper 1999) with a 2.9 m storm surge arriving close to low tide that still managed to reach about 0.5 m above the Highest Astronomical Tide (HAT). While the major damage to Townsville was from wind, the loss of The Strand seawall and many vessels highlighted the reality that a major storm tide disaster had luckily been avoided through pure chance. Memories of the 5.4 m AHD storm tide that inundated Mackay in 2 m of seawater in 1918 were invoked and spurred Government research initiatives through James Cook University to improve knowledge of these potentially deadly events in this region (e.g. Sobey *et al.* 1977).

As a result of this impetus, the first statistically based storm tide estimates for the Townsville area were subsequently published by the Beach Protection Authority (e.g. Harper 1985) and have been widely adopted for planning purposes since that time. In 2000, updated methodologies were applied through the Queensland Climate Change initiative (e.g. as reported in Harper 2004) and led to new surge plus tide estimates being published for much of the east coast of Queensland (Hardy *et al.* 2004).

This study builds on the collective knowledge gained since 1971 and provides the most detailed assessment yet undertaken of storm tide risks for the Townsville and Thuringowa City Local Government Areas.

1.2 Aims and Objectives

The purpose of the study is to quantify the likelihood of coastal areas within the cities of Townsville and Thuringowa being inundated by a storm tide arising from tropical cyclones, and to map these results, such that town planning and emergency planning issues can be more accurately addressed than in the past.

In addition, the brief called for the provision of a real-time warning system to assist emergency managers.

In accordance with the scope of work, the methodology closely follows the recommendations set out in the recent Government-sponsored Queensland Climate Change investigations (e.g. Harper 2001, 2004). In particular, the so-called “hybrid” modelling philosophy has been implemented, whereby a range of numerical, analytical and statistical models are constructed to provide a basis for the estimation of storm tide risks and the extrapolation of their impacts to very low probabilities (very high return periods).

The study analyses are necessarily based on “present climate” but, in conformance with the Scope of Work, some commentary on making allowance for possible enhanced-greenhouse effects is included in Chapter 7, leading to the identification of additional areas of concern.

With knowledge of the probability of specific water elevations being equalled or exceeded, **long term planning** can be adopted to mitigate against the more adverse impacts. **Emergency response planning** can also utilise this information to ensure adequate resources will be allocated to those areas most likely to be affected.

The study outcomes are provided in a number of forms, principally a series of maps and tables showing:

- storm tide elevation that corresponds to a specific return period risk;
- areas subject to inundation by storm tide and a MapInfo database containing all predictions; and
- probability of equalling or exceeding specific depths of inundation.

These provide an essential input to long term planning whilst also allowing a relative ranking of risks for emergency response. Additionally, a real-time warning system is provided, based on the models that have been developed for the planning-targeted outcomes.

1.3 Definitions

The total seawater level experienced at a coastal, ocean or estuarine site during the passage of a severe tropical cyclone will be made up of relative contributions from a number of different effects, as depicted in Figure 1-1**.** The combined or total water level is then termed the ***storm tide***, which is an absolute vertical level, referenced in this report to ***Australian Height Datum*** **(AHD)**. Potential ***open coast inundation depths*** however, are referenced relative to the local Highest Astronomical Tide level (HAT), which is reasonably constant throughout the region. Local inundation depths are indicated via mapping in situations where overland flooding is described.

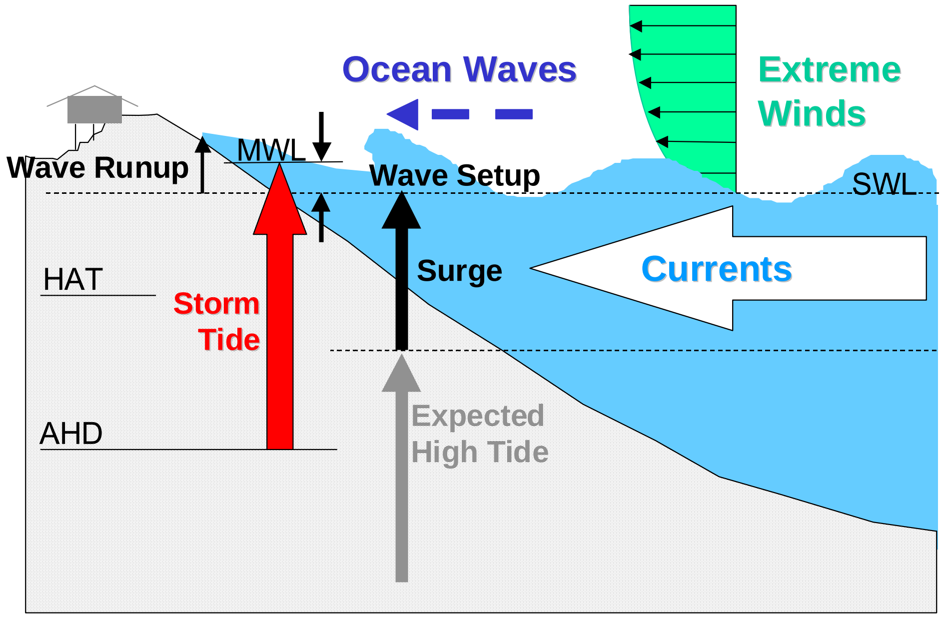


Figure 1-1: Water level components of an extreme storm tide (after Harper 2001)

1.3.1 Components of a Storm Tide

It is important to understand the different water level components that can comprise the total storm tide. These effects can vary throughout any given region depending on the local conditions. With reference to Figure 1-1:

(a) The 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 y period, although at some sites tide levels similar to HAT may occur several times per year. The tidal variation across the region is not significant but has been accounted for in this investigation.

(b) Storm Surge

This is the combined result of the severe atmospheric pressure gradients and wind shear stress of the tropical cyclone acting on the underlying ocean. The storm surge is a long period “wave” capable of sustaining above-normal water levels over a number of hours. 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. Typically the length of coastline that is severely affected by a tropical cyclone storm surge is of the order of 100 km either side of the track although some influences may extend many hundreds of kilometres. The magnitude of the surge is affected by many factors such as storm intensity, size, speed and angle of approach to the coast and the coastal bathymetry.

(c) Breaking Wave Setup

Severe wind fields also create abnormally high sea conditions and extreme waves may propagate large distances from the centre of a cyclone as ocean swell. These waves experience little or no attenuation in deepwater regions and an offshore storm can impact several hundred kilometres of coastline. As the waves enter shallower waters they refract and steepen under the action of shoaling until their stored energy is dissipated by wave breaking either offshore or at a beach or reef. After breaking, a portion of the wave's kinetic energy is converted into potential energy, which, through the continuous action of many waves, is capable of sustaining shoreward water levels that are above the still-water level (SWL) further offshore.

This increase in still-water level immediately after wave breaking occurs on a beach is known as ***breaking wave setup*** and applies to most natural beaches and reefs. Wave setup is only associated with the rapid energy losses occurring during breaking and does not occur in river mouths, swampy lands or areas that suffer inundation to the extent that waves do not immediately break but rather are degraded more gradually through frictional or diffractive effects. Accordingly the modelling here assumes that wave setup contributions cease when the tide plus surge level exceeds a nominal open coast dune crest elevation.

(d) Still water level (SWL) and mean water level (MWL)

The storm surge, mainly caused by the interaction of the extreme wind-driven currents and the coastline, raises coastal water levels above the normally expected tide over a large area, producing the so-called still water level or SWL. This is the highest water level at a point on the shoreline if wave action is smoothed out.

Meanwhile, the extreme-wind generated ocean waves, combinations of swell and local seas, are driven before the strong winds and ride upon the SWL. As part of the process of wave breaking, a portion of their energy can then be transferred into potential energy as vertical wave setup, yielding a higher mean water level (MWL) at the beach face. As previously mentioned, this effect is not always active and not always effective as it depends upon local beach and dune geometry.

(e) Overland inundation and wave penetration

When normally dry land becomes inundated during a severe storm tide episode, the sea begins to quickly flood inland as an intermittent "wave front", driven by the initial momentum of the surge, products of wave setup and the local surface wind stress. This flow then reacts to the local ground contours and the encountered hydraulic roughness due to either natural vegetation or housing and other infrastructure. It will continue inland until a dynamic balance is reached between the applied hydraulic gradients, wind stress and the land surface resistance or until it becomes constrained by elevation and creates a ponding effect. As the storm surge abates or the tide reduces, an ebb flow is created. This is commonly responsible for much of the observed scouring after such events.

(f) Specific effects not considered in this study

The present study focuses on the estimation of storm tide depth and extent of possible inundation and hence does not explicitly address the velocity of the encroaching storm tide flow.

Further, as the new “stillwater” surface gradually reforms behind the propagating front, the exact extent to which individual unbroken or partially reformed ocean waves might further penetrate into a coastal region will be very site specific. In the assessment of nearshore damage, some account of these possible effects is included empirically but no wave modelling over land has been undertaken.

Finally, while much of the wave energy at the open coast prior to inundation occurring can be converted into setup, there remains some residual energy in the form of individual waves that will generate ***runup*** and may cause localised impacts and erosion at elevations above that of the nominated storm tide level.

These effects can only be estimated with specific information about the land-sea interface, which may be changing in time as the storm tide increases in height. This would include the slope of the shoreline, the porosity, vegetation and the incident wave height and period. It is recommended that specific fine scale analyses for this effect should always be carried out where a particular facility may be threatened.

There remain other related phenomena that are not addressed here but which can also have an affect on the local water level. These may include long period shelf waves that temporarily change the predicted tidal elevation, unsteady surf beat in specific high energy wave environments, and stormwater and/or river runoff. It is recommended that suitably qualified practitioners consider these effects on a case by case basis.

1.3.2 Return Period Concepts

The present study reports its findings in terms of statistical *Return Periods*. It is important to understand that a return period (or average recurrence interval or ARI) is simply the expected average elapsed time in years between equalling *or exceeding* a specified event level. This concept does not guarantee that the nominated event’s return period number of years will have elapsed before such an event occurs again. In fact, the probability of experiencing the “n” year return period event within any consecutive period of “n” years is approximately 64%, i.e. more likely than not. For example, the 100 year and 1000 year event could both occur in the same year or one might occur twice in the same year, etc.

Appendix F provides further guidance on interpreting return period results given in this study.

1.4 Study Area

The coastal areas in the following localities were subject to storm tide risk assessment:

- A coastal strip extending from Crystal Creek (Thuringowa) south to Cleveland Palms (Townsville);

- Magnetic Island; and
- Cungulla.

According to the LGA planning schemes, the coastal zone of the study area includes land in the following nine categories:

- Low-density residential;
- urban residential;
- rural protection;
- rural;
- industrial;
- commercial;
- particular development;
- open space; and
- public purpose.

1.5 Study Team and Ackowledgments

This report represents a collaborative effort between GHD Pty Ltd and Systems Engineering Australia Pty.

Key components of the study were performed by Dr Bruce Harper, Director, (Systems Engineering Pty Ltd) and Dr Ivan Botev, Study Manager, Waterways Group (GHD Pty Ltd) under the direction of Ross Fryar, Waterways Group (GHD Pty Ltd).

GHD Pty Ltd and Systems Engineering Australia Pty Ltd wish to acknowledge contributions to the present study by the Marine Modelling Unit (MMU) within the School of Engineering at James Cook University in Townsville (now at the Australian Maritime College in Launceston). Associate Professor Tom Hardy kindly permitted use of the base bathymetry for the "A" and "B" resolution numerical hydrodynamic grids for the Townsville region. These grids had been earlier developed by the MMU for use by the Bureau of Meteorology. Mr Luciano Mason of the MMU also provided digital tidal constituent data for the Townsville region derived from MMU numerical tidal modelling of the Great Barrier Reef precincts.

2. Methodology Overview

2.1 Philosophy

Extreme storm tide levels caused by tropical cyclones cannot be estimated solely on the basis of historically measured water levels (Harper 2001). This is because the available record of tropical cyclones affecting any single location on the coast is quite small, the resulting storm surge response is often complex and very site specific, and the final storm tide is dependent on the relative phasing with the astronomical tide. Hence, measured storm tide data alone is typically inadequate for extrapolation to very low probabilities of occurrence. The analysis of ancient coastal sediment records may in time prove useful in augmenting more direct analyses. This field, termed paleotempestology, is however not considered sufficiently reliable at this point in time.

To overcome this problem, it is necessary to formulate a statistical model of the coastal region that will attempt to re-create the observed region-wide tropical cyclone climatology and numerically generate long sequences of potential storm tide scenarios. The statistical model must be supported by a series of deterministic hydrodynamic models that will describe the effect that an individual cyclone has on the coastal region, i.e. the relationship between the wind speed and atmospheric pressure patterns and the resulting storm surge and wave setup for a given cyclone scenario. This is then combined with a tidal description of the region that recreates the known tidal characteristics. When the effect of a single cyclone can be adequately described, the statistical model is used to generate many thousands of possible situations and the resulting statistics are used to determine the probability of storm tide levels throughout the study area.

Importantly, the accuracy of the model predictions is checked against historical data on a case by case basis where possible, or compared with long term measurements of wind speed at airports in the region, which are typically less subject to localised effects.

To provide more specific information during extreme inundation events a series of detailed overland flow scenarios can then be modelled at high spatial and temporal resolution and the results used to produce maps of the extent and depth of possible flooding. This information can then be used to assess the potential impacts on infrastructure and the community and assist in long term planning to mitigate those effects.

To complete the armoury against the threat of extreme storm tide, a real-time warning system has been developed to provide tactical support for emergency managers. Because the greatest uncertainty in estimating the storm tide is caused by uncertainty in the cyclone parameters themselves, it is critical that the warning system itself is also statistically based. Using this philosophy, the warning system is fully consistent with all the other aspects of the analyses.

2.2 Methodology

The adopted methodology utilises a number of sophisticated numerical models, some addressing the deterministic (cause and effect) elements of the problem and others addressing the probabilistic (chance) aspects. Each has been done to a comparable level of detail and together, demonstrate a good degree of accuracy against historical datasets.

Figure 2-1 provides an overall conceptual view of the study methodology, which is based firstly on the availability of data to describe the tropical cyclone threat to the region, data to describe the coastal geography, historical storm tide data for calibration and for defining the regional tide characteristics. Data on regional winds is also used for model validation and finally, the coastal infrastructure assets must be identified. Chapter 3 discusses the study data in more detail.

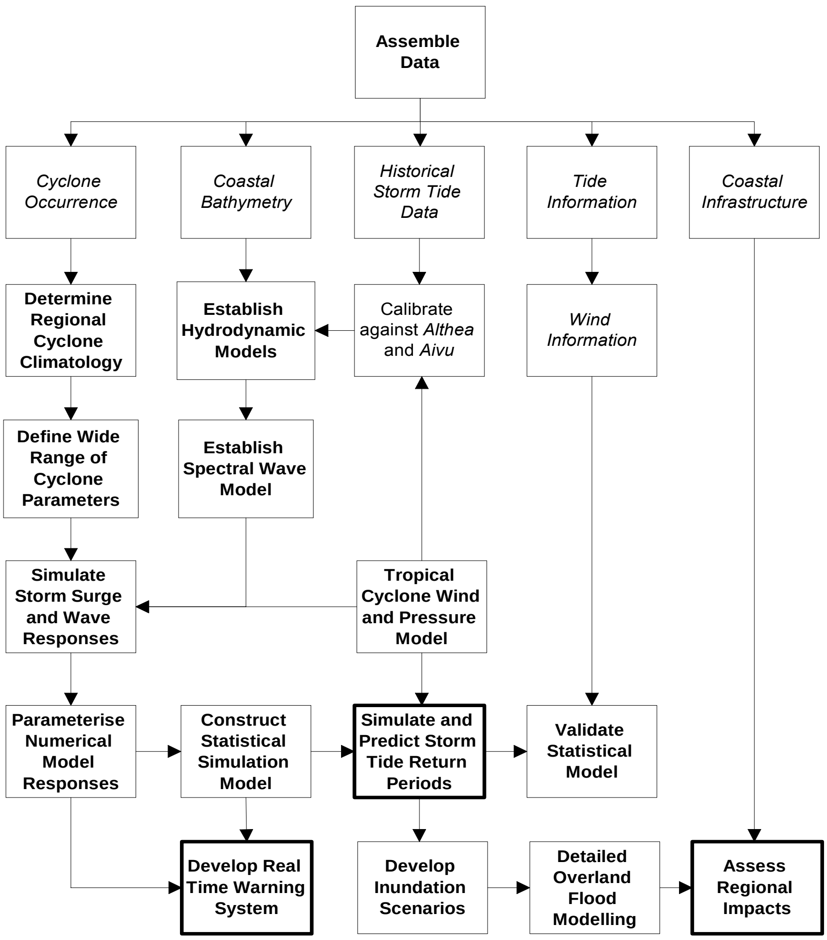


Figure 2-1 An overview of the study methodology

A climatological risk assessment of the threat from tropical cyclones in the region is then undertaken to obtain statistical descriptions that can be extrapolated to return periods of interest. This includes statistics describing the expected variation in cyclone frequency, intensity, path and size within the region. Chapter 4 discusses the detailed analyses that have been required.

In parallel with the development of the cyclone climatology, numerical models that can estimate the impacts of tropical cyclones on the underlying ocean are established. A numerical hydrodynamic model is used to estimate the strength of the wind driven currents and resulting storm surge, while a spectral wave model is used to estimate wave heights and periods, which contribute the breaking wave setup water level component. The models are constructed based on regional bathymetry data, comprising several nested numerical grids to resolve the near-shore islands, capes and bays. Details are given in Chapter 5 and 6.

The numerical storm surge and wave models are driven by a tropical cyclone wind and pressure field model (described in Appendix B) that generates the complex winds produced by a moving tropical cyclone, according to a set of parameters supplied to it. For example, the set of parameters that approximate tropical cyclone *Althea,* which impacted Townsville in 1971, was used as part of the verification of the storm surge model. Additionally, a detailed recreation of the storm tide produced by cyclone *Aivu* in 1989 has been undertaken (refer Appendix A) that provides additional confidence in the wind and surge model accuracy.

A much wider set of parameters was then used to simulate the effects of many hundreds of possible cyclones in the Townsville-Thuringowa region. These parameters were chosen based on the identified range of values from the known long-term climatology of the region.

When the results of simulating the wide range of possible cyclones is obtained, the resulting storm surge and wave heights are parameterised (simplified) into a form that is amenable to statistical modelling. This enables the otherwise very computationally intensive numerical surge and wave model results to be re-generated and interpolated very efficiently to enable a simulation of many thousands of years of possible cyclone events. The accuracy of this parameterisation is checked to ensure it is consistent with the other analysis assumptions.

After the parametric surge and wave models are established and tested, the statistical model is built by combining them with the climatology description. At this point, the local astronomical tide is included and also the wave height and period is converted to breaking wave setup so that the overall height of the combined storm tide (tide + surge + setup) can be determined at any **open coast location** in the study area during the passage of a *synthetic* cyclone. The probability of water level exceedance can then be obtained by simulating an extended period of possible tropical cyclones affecting the region (50,000 years has been used) and accumulating the resulting time history of the tide, the surge and the wave setup at each coastal location.

In this context, the model is not used to predict the future, but rather to estimate what the past experience up until this date might have been if 50,000 years of measurements had been available. A very long period is simulated simply to enable very low probabilities to be reliably estimated. For example, simulating 50,000 years provides 50 estimates of the 1,000 year return period water level and 5 estimates of the 10,000 year water level, upon which the average levels for those return periods will be based. While there will be a single highest value produced during the simulation it's nominal return period of 50,000 years will have a very high variability associated with it. Accordingly, confidence in the accuracy of the prediction diminishes as the return period increases.

The statistical model is then verified by comparing its probability predictions against other data wherever possible. Clearly this is not possible in the case of the storm tide itself, but the tide statistics can be checked against their known probability of exceedance and also the predicted wind speeds (which are separately accumulated by the model) are compared with the available long-term regional wind records. Other checks are also done to ensure that the linear superposition of tide, surge and setup is a reasonable approximation to the real situation where there may be some interaction between these events.

Next, the predicted exceedance of coastal water levels generated from the statistical modelling process for each point of interest is subjected to extreme value analysis. The results are interpolated and mapped to define the 50, 100, 500 and 10,000 year storm tide elevations. Additionally, the Probable Maximum Flood or PMF called for in the Scope of Work is defined here by the nominal 10,000 year return period estimate (PMF being a term used in inland-based flood studies).

The possible effects of prolonged ENSO (El Nino Southern Oscillation) bias and greenhouse-induced climate change are considered in a subsequent step, whereby possible future climate scenarios are simulated and those results compared with the estimates for "present climate" (refer Chapter 7).

The analysis to this point considers the open coast storm tide levels that are applicable at the shoreline. However, during extreme events inundation of the coastal margins occurs and the ocean floods inland under the action of the momentum of the sea and also the continued surface forcing of the extreme winds.

Hence detailed numerical modelling of the overland flooding process is then undertaken for a selection of representative extreme events that correspond to the open coast return periods of interest. The development of the flood wave depends on the duration and scale of the event. Its final extent then forms the basis of inundation mapping and is used to assess the impacts on infrastructure and the community.

Finally, a real-time warning system has been constructed as a subset of the statistical simulation model with a graphical user interface to facilitate its use as a tactical emergency management tool. This product relies on information that would be provided by the Bureau of Meteorology and is designed to be used by experienced personnel who would be in direct communication with Bureau officers under arrangements that could potentially be put in place by the Queensland Tropical Cyclone Coordination Committee. Details of the warning module and its operation are provided in a separate report (SEA 2005) and Chapter 9.

3. Project Data

Data acquisition and integration are key elements in the storm tide modelling and impact assessment processes. Key data includes regional tropical cyclone climatology, offshore bathymetry, definition of the coastline, tide, land elevation (topography) and existing infrastructure within the study area.

Data on bathymetry, coastline and land elevation are introduced below whilst the characteristics of the tide are discussed in Section 3.2.

3.1 Bathymetry and Coastline

The bathymetry (geometry of the sea bed) in the near-shore region is based on available Aus series navigational charts:

- Aus 256, Cleveland Bay And Approaches, Scale 1:50,000;
- Aus 257, Townsville Harbour and Ross River Entrance, Scale 1:7,500.

The charts have been supplemented with the following digital sets:

- Thirty arc second grid data for the region obtained from the Australian Geological Survey Organization (AGSO); and
- Gridded data provided by the Marine Modelling Unit at James Cook University in Townsville corresponding to the A2, B5, C13 and C12 domains (p 278, Section 11, Harper 2001).

The Aus series navigational charts have been digitised and exported as scattered data (XYZ triplets shown in Appendix G) into a raster based GIS package from which the bathymetry of the models has been obtained.

Coastline information has been extracted from navigational charts and supplemented with data from the Queensland Spatial Information Directory (QSID).

3.2 Tidal Data

Tidal data necessary for the operation of the hydrodynamic (deterministic) modelling system adopted for the project consisted of:

- Tidal constituents for the Port of Townsville (Australian Tide Tables, 2005);
- Tidal predictions for the 50, 100, 500 and 10,000 y events at the Port of Townsville which were obtained using the above constituents and the IOS method (Foreman, M.G.G., 1996);
- Tidal constituents at the open sea boundary of the A02 grid (A2 domain) obtained from a 5-minute global tidal model operated by NTC.

Figure 3-1 provides an example of the predicted tide for the 3564 year.

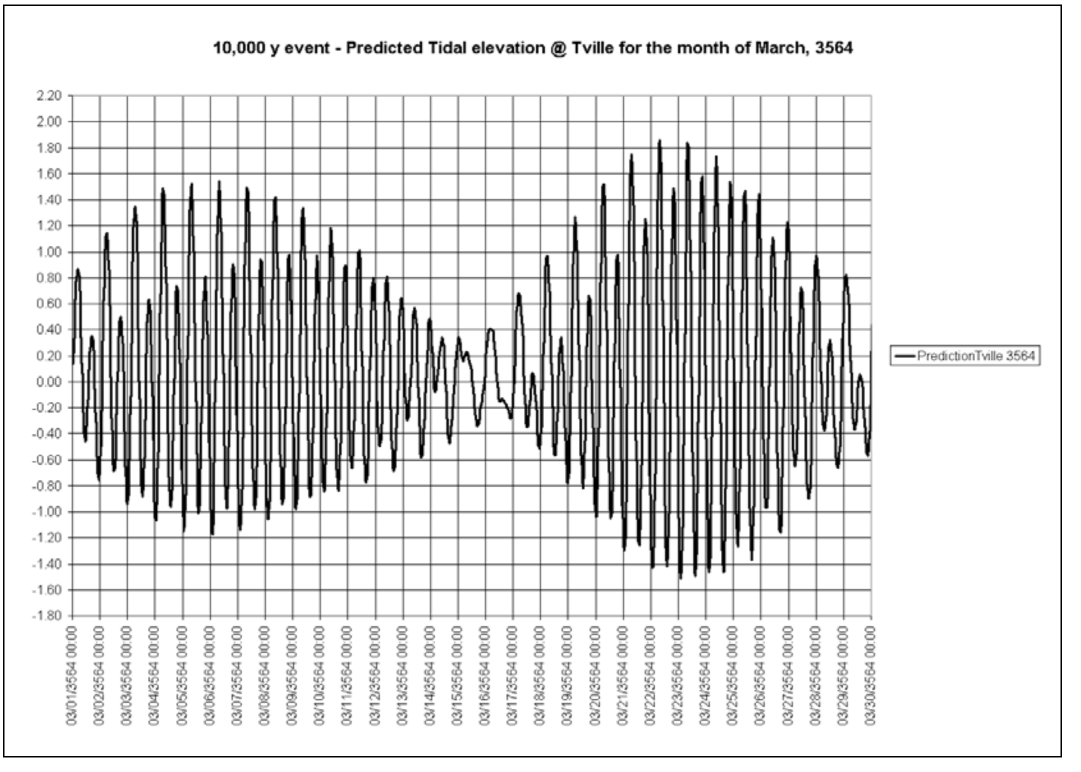


Figure 3-1 Predicted tidal elevation at the Port of Townsville for the month of March, 3564 used for inundation mapping purposes associated with the 10,000 y event

3.3 Land Elevation Data

Accurate delineation of the zones of potential flooding resulting from storm tide entails the availability of high-resolution digital topographic (land elevation) data in addition to reliable bathymetric and coastline information.

High – resolution land elevation data (1.0 m grid spacing) were obtained from the Land Information Unit - Townsville City Council and the GIS Information Services Unit at Thuringowa City Council.

3.4 Infrastructure

Data on community infrastructure potentially at risk from storm tide events has been collated. The following infrastructure has been considered:

- Water supply and sewerage infrastructure;
- Transport infrastructure;
- Power and telecommunications infrastructure; and
- Critical community infrastructure such as hospitals and emergency services.

Data pertaining to this infrastructure has been collected from:

- A review of Townsville and Thuringowa GIS databases;
- Review of as-constructed information held by Council departments responsible for infrastructure collation/collection;
- Review of existing infrastructure plans held by GHD; and
- Discussions with key infrastructure stakeholders including Townsville and Thuringowa Councils, Ergon Energy, Telstra, Department of Main Roads, and the Department of Emergency Services.

4. Regional Tropical Cyclone Climatology

4.1 Tropical Cyclones

The tropical cyclone is a large scale and potentially very intense tropical low-pressure weather system that affects the Queensland region typically between November and April (Harper 2001). In Australia, such systems are upgraded to *severe* tropical cyclone status (referred to as *hurricanes* or *typhoons* in some countries) when average, or sustained, surface wind speeds exceed 120 km/hr. The accompanying shorter-period destructive wind gusts are often 50 per cent higher than the sustained winds. In the southern hemisphere, tropical cyclone winds circulate clockwise around the centre, as seen in the spiral cloud patterns of the satellite image in Figure 4-1.

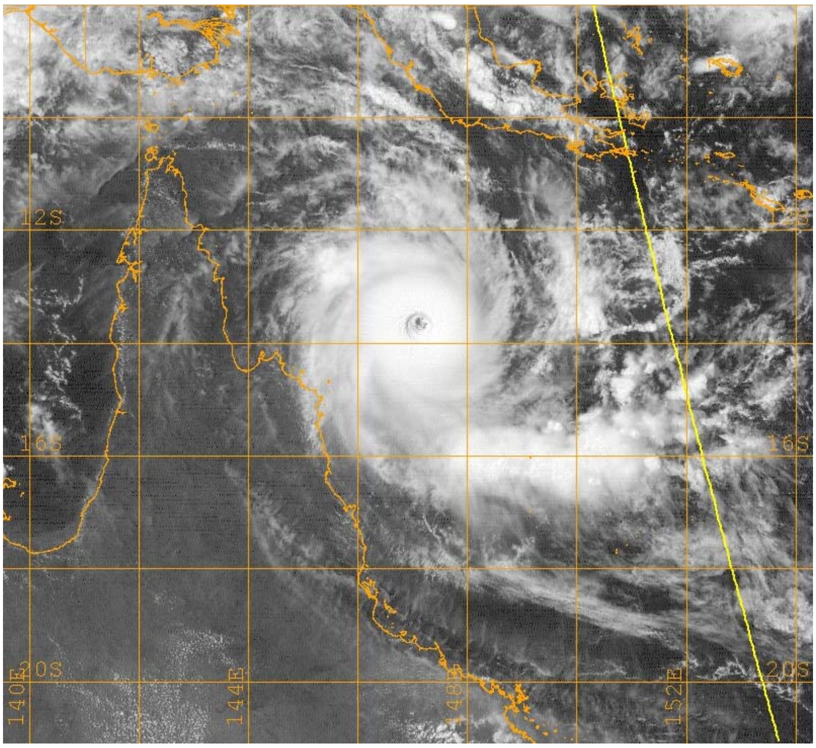


Figure 4-1 Category 5 tropical cyclone *Ingrid* approaching the North Queensland coast in March 2005. (US Navy processed image)

There are three components of a tropical cyclone that combine to make up the total cyclone hazard - strong winds, intense rainfall and induced ocean effects, including extreme waves, currents, storm surge and resulting storm tide. The destructive force of cyclones is usually expressed in terms of the strongest wind gusts likely to be experienced. Maximum wind gust is related to the central pressure and structure of the system, whilst extreme waves and storm surge, are linked more closely to the combination of the *mean* surface winds, central pressure and regional bathymetry.

The Australian Bureau of Meteorology uses the five-category system shown in Table 4-1 for classifying tropical cyclone intensity in Australia. Severe cyclones are those of Category 3 and above.

Table 4-1 Australian tropical cyclone category scale

Category	Maximum Wind Gust (km/hr)	Potential Damage
1	<125	minor
2	125-170	moderate
3	170-225	major
4	225-280	devastating
5	>280	extreme

The main structural features of a severe tropical cyclone at the earth's surface are the eye, the eye wall and the spiral rainbands. The eye is the area at the centre of the cyclone at which the surface atmospheric pressure is lowest. It is typically 20 to 50 km in diameter, skies are often clear and winds are light. The eye wall is an area of cumulonimbus clouds, which swirls around the eye. Small scale tornado-like vortices of even more extreme winds may also occur associated with the eye wall and outer rain bands. The rain bands spiral inwards towards the eye and can extend over 1000 km or more in diameter. The heaviest rainfall and the strongest winds, however, are usually associated with the eye wall.

For any given central pressure, the spatial size of individual tropical cyclones can vary enormously. Generally, smaller cyclones occur at lower latitudes and larger cyclones at higher latitudes but there are many exceptions. Large cyclones can have impacts far from their track, especially on waves and storm tide. For example, *David* crossed the coast near Yeppoon in 1976 and caused significant coastal impacts in south eastern Queensland; *Justin* in 1997 offshore Cairns caused increased water levels along the entire east coast.

Cyclonic winds circulate clockwise in the Southern Hemisphere and the wind field within a moving cyclone is generally asymmetric so that winds are typically stronger to the left of the direction of motion of the system (the "track"). This is because on the left-hand side the direction of cyclone movement and circulation tends to act together; on the right-hand side, they are opposed. During a coast crossing in the Southern Hemisphere, the cyclonic wind direction is onshore to the left of the eye (seen from the cyclone) and offshore to the right.

Given specifically favourable conditions, tropical cyclones can continue to intensify until they are efficiently utilising all of the available energy from the immediate atmospheric and oceanic sources. This maximum potential intensity (MPI) is a function of the climatology of regional sea surface temperature (SST) and atmospheric temperature and humidity profiles. When applying a thermodynamic MPI model for the Queensland coast (Holland 1997ab), indicative values for the MPI increase northwards from about 940 hPa near Brisbane to 880 hPa for regions north of Townsville. Thankfully, it is rare for any cyclone to reach its MPI because environmental conditions often act to limit intensities in the Queensland region. The present study however, makes allowance for this extreme condition.

4.2 Dataset Description

The study has considered all available records of tropical cyclones from official Bureau of Meteorology records (National Climate Centre) as well as local Queensland Regional Office records in Brisbane. However, only those cyclones that entered within a 500 km radius of Townsville have been included in the statistical analyses. The choice of a 500 km radius is based on capturing all events that would have been capable of directly affecting the Townsville - Thuringowa area within a 24 hour period and provides a sufficient sample of the statistical population to enable reasonably reliable estimates to be made of intensity, frequency of occurrence and track. The complete cyclone data set since the early 1900s shows a fluctuation in recorded occurrences of tropical cyclones that is due not just to the natural variability of these large-scale storms, but also the often poor detection rate prior to the introduction of satellites in the late 1950's and early 1960's (Holland 1981). In order to ensure a stable and reliable statistical series for model extrapolation purposes, only data since 1959/60 onwards is used in the present study. This provides a total of 45 cyclone seasons up until 2003/2004, the latest year available from the Bureau. Appendix J summarises the tropical cyclone dataset used in this study.

The Bureau tropical cyclone data set consists of a series of estimated positions of the centre of each cyclone, together with the estimated central pressure (hPa), at an interval of typically 6 hours. Little or no information about the size of the cyclone is normally available (except in recent years), and hence the radius to maximum winds is a parameter that has to be further estimated. Some editing of the official Bureau data sets has been undertaken to remove duplicate storm records, correct known errors and make other adjustments based on advice from the Severe Weather Section at the Queensland Regional Office in Brisbane (Jeff Callaghan, personal communication).

4.3 Analysis and Interpretation

A total of 80 cyclones have occurred within the 45 season record and within the 500 km study region, averaging 1.78 cyclones per season. The time history of the frequency of cyclone occurrence is shown in Figure 4-2, showing a fluctuation about a 5 year average value of between 1 to 3 storms per year. Some years indicate zero storms within the 500 km radius while the maximum number during this time has been 5 storms in one season, which has occurred on two occasions: 1975/76 and 1977/78.

The variability in cyclone occurrences over a 3 to 5 year span is now known to be strongly associated with the so-called El Niño - Southern Oscillation (ENSO) phenomenon (Basher and Zheng, 2000). ENSO refers to a quasi-biennial oscillation of the sea surface temperatures (SST) in the eastern tropical Pacific Ocean. During a so-called El Niño period, the SST is warmer than normal in the east and rainfall and tropical cyclone activity in northern Australia tends to decrease. In the reverse situation, called La Niña, the SST in the eastern Pacific is cooler than normal and rainfall and tropical cyclone activity increases along the east coast of Australia.

The Southern Oscillation Index (SOI) is a measure of the strength of the ENSO episodes, derived from surface pressure data at Darwin and Tahiti. The SOI is also plotted on Figure 4-2, where it can be seen that a generally persistently negative SOI (El Niño) has been associated with a decrease in cyclone occurrences over the past 20 years in the Townsville region. Since 1959 though, the number of El Niño - La Niña cycles is approximately equal, although the strengths have varied (Pielke and Landsea 1999). This suggests that the long-term average frequency of occurrence of 1.78 storms per season for the statistical region is reasonably reliable. However, it should be noted that ENSO fluctuations specifically alter the true likelihood of storm tide risk in any particular year of exposure. Some researchers (e.g. Power *et al.* 1999) suggested that the trends of the past 10 to 15 years may have started reversing and that the western Pacific could be entering a period of prolonged La Niña activity in the new millennia, but recent years have seen only mild La Niña or near neutral conditions persisting. Section 7.1 further considers the effect of ENSO on storm tide estimates.

The corresponding time history of minimum storm central pressures is shown in Figure 4-3, illustrating the great variety possible in intensities. The 5 year average line in this case has been significantly shifted downwards around 1989 due to a re-classification here of *Aivu* from a Category 3 to a Category 5 storm (refer Appendix A), making it potentially the most intense ever in this region.

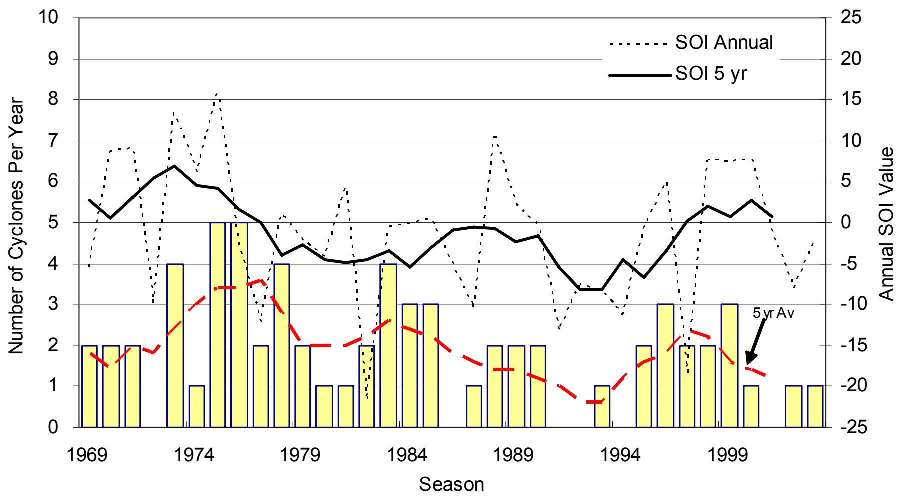


Figure 4-2 Time history of cyclone occurrence within 500 km of Townsville

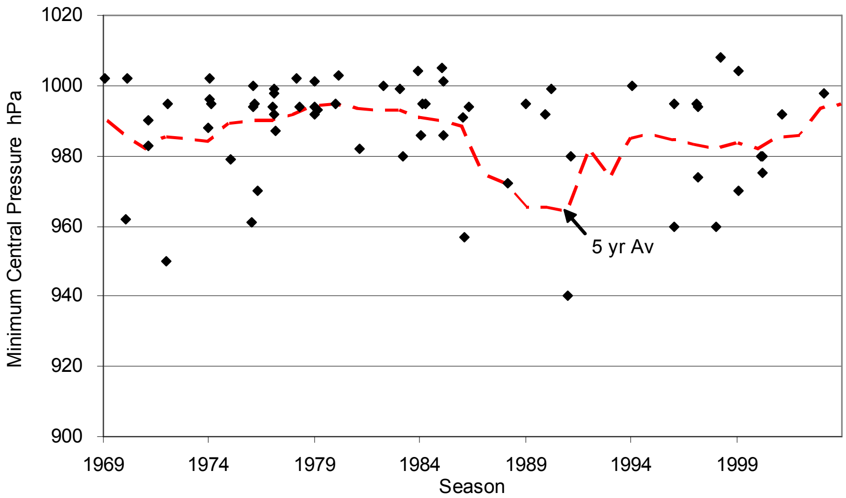
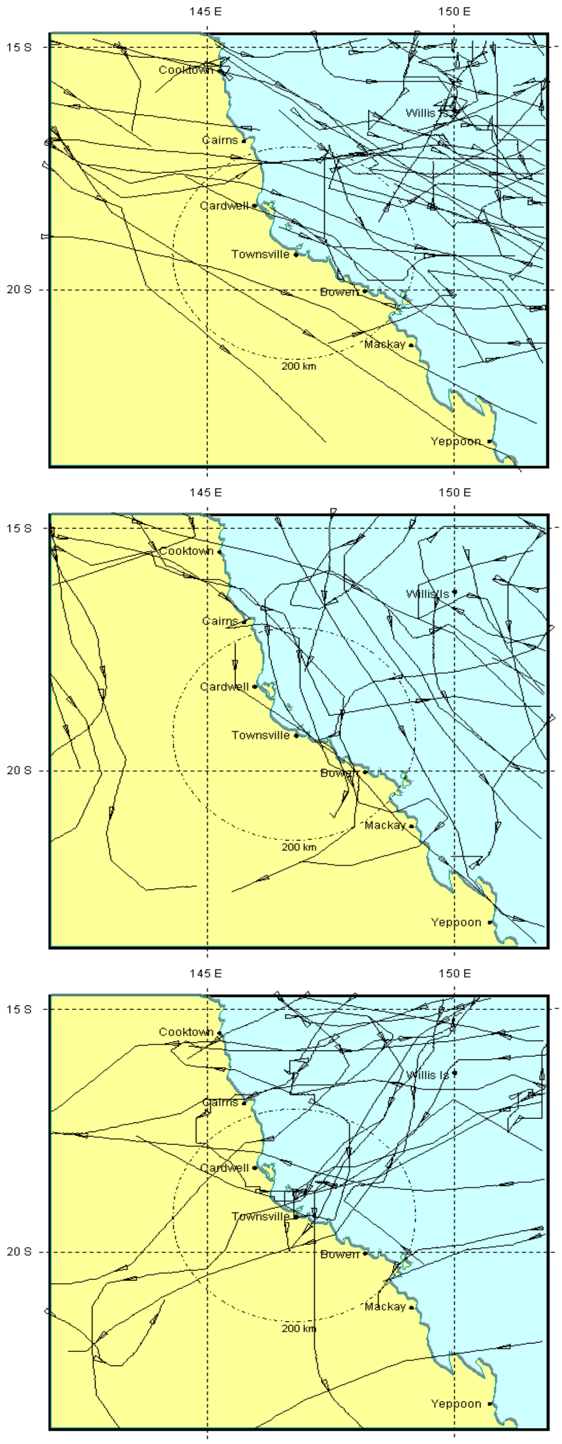


Figure 4-3 Time history of cyclone intensity within 500 km of Townsville

The tracks of tropical cyclones often appear random and chaotic but a more cohesive structure can be seen when the storms are grouped into what are believed to be common statistical populations. The present study assumes three basic track classes exist in this region, being offshore moving, parallel to coast and onshore moving. The 80 storm sample is split into these classes as shown in Figure 4-4. The over-land examples of the offshore class in this region are predominantly decayed Gulf of Carpentaria storms moving eastwards while the over-sea examples are relatively weak near-coast developing systems.

The parallel class are concentrated about 200 to 400 km offshore but also contain examples of oblique coast-crossing events and some over-land storms. The onshore class is by far the most intense and suggests a concentration in the vicinity of Townsville-Bowen, although statistical tests cannot identify a specific spatial trend because of the limited data.

The most significant parameter affecting regional storm tide is the intensity of the tropical cyclone winds. This is typically indirectly represented by the central pressure of the cyclone but also depends in part on other scale parameters (refer Appendix B). The estimated minimum central pressure for each of the 80 storms is then statistically analysed using Extreme Value Theory (Benjamin and Cornell, 1970) to obtain the likelihood of particularly intense storms occurring anywhere within the 500 km radius region. The statistical analyses are undertaken firstly for each separate track class and then combined into a single regional prediction, summarised graphically in Figure 4-5 in terms of return period and the cyclone category based on the approximate central pressure equivalents of Table 4-1. It can be shown that the most intense cyclones are contributed mainly by the onshore class, which typically represent fully mature storms in favourable steering currents. On this basis, the 100 year return period cyclone intensity in this region is predicted to be approximately 921 hPa.



Offshore

Parallel

Onshore

Figure 4-4 Cyclone tracks capable of affecting the Townsville-Thuringowa Region classified into offshore (42%), parallel (29%) and onshore (29%) populations.

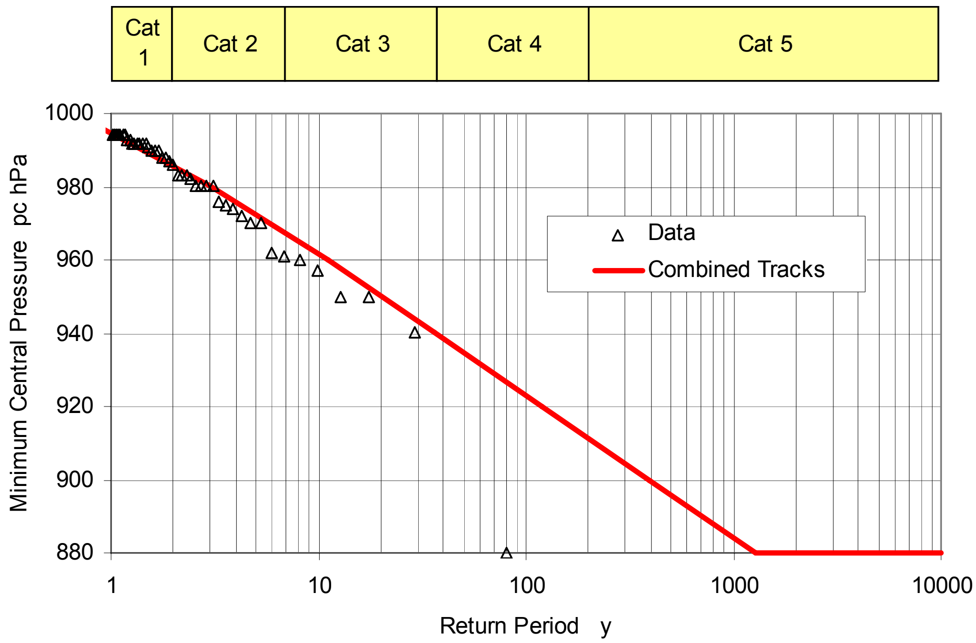


Figure 4-5 Extreme value analysis of cyclone intensity within 500 km of Townsville

Coupled with this theoretical (normally unbounded) analysis there needs to be a consideration of the maximum potential intensity (MPI) that might be sustained in any region. This is a function of a number of physical parameters but principally the sea surface temperature and the upper atmosphere profile (Holland 1997b). For the Townsville region the MPI is assessed as 880 hPa (Holland 1997a) – equivalent to the revised *Aivu*. Based on the present analysis, this MPI has a return period of approximately 1000 years anywhere within 500 km of Townsville.

Many other storm parameters are also extracted during the analysis phase. For example, the variation in forward speed, which adds to the strength of the cyclonic winds, the duration of storms, track bearing and the tendency for a proportion of storms to weaken (fill) as they move closer to the coast are based directly on the recorded data set. The spatial distribution of coast crossings relative to Townsville has been assumed to be equally distributed. All of the above statistical estimates of tropical cyclone behaviour and strength have been assembled for use by the statistical storm tide model and used as a “template” to allow the generation of many thousands of synthetic storm events. Table 4-2 summarises the key model parameters for the 500 km radius statistical region used for this study. The ambient pressure for all cyclones is set at 1007 hPa.

Table 4-2 Key statistical climatology parameters for the Townsville region

Parameter Name	Variable	Units	Offshore	Parallel	Onshore
Ambient Pressure	p_n	hPa	1007	1007	1007
% This Track			42.5	28.7	28.7
Av. No. Per Year			0.42	0.51	0.51
Gumbel Intensity	*U*	hPa	996.12	995.90	988.63
Parameters	α		0.14576	0.16281	0.05973
Max Potential Intensity	MPI	hPa	950	880	880
Overland Decay	*Fd*	km	1e5	100	100
Radius to Max Wind	mean	km	40	30	30
	std dev	km	10	10	10
Wind Peakedness	mean	-	1.25	1.50	1.5
	std dev	-	0.25	0.25	0.25

5. Numerical Model Development and Testing

5.1 Introduction

This section describes the detailed development of the necessary wind, storm surge, wave and statistical models, as well as addressing related aspects such as tidal effects. A range of modelling software has been applied, as required for each stage of the project. The key modelling packages consist of:

- Tropical Cyclone Wind and Pressure Model;
- Delft3D – FLOW module (for hydrodynamics);
- ADFA1 – Spectral Wave Model; and
- SATSIM – Surge and Tide Simulation Model.

5.2 Computational Grids

The selection of numerical modelling domains (i.e., size and resolution) follows from the recommendations and arguments presented in Harper (2001), which are summarized as follows:

- Ensure adequate resolution of the principal ocean environment scales involved in storm tide modelling – ocean, coastal, bay and beach.
- Beware the conflict of scales and resolution. Resolve these by adopting a combination of large parent grids (e.g., 2000 km offshore coverage) and refined, nested regional grids.
- Parent grid(s) should have sufficient spatial definition to warrant the adequate resolution of the wind field and provide global-scale forcing of the storm tide.
- The extent of the parent grids depends upon the location of the open boundaries, which can be difficult to model, because information on hydrodynamic forces outside of the model domain may not be available. The best solution is to place any open boundaries as far as possible from the area of interest and to include as much of the forcing directly within the model domain.
- Nested grids (with a resolution of the order of few hundred meters) must preserve the ability to model very fine local scales (bathymetry, wave setup) in the vicinity of specific communities at risk.
- The temporal scale should be able to resolve the tropical cyclone wind while the system of grids should operate at time steps compliant with the Courant time limit

Based on the above selection rationale, a system of three nested transitions involving four types of grid (A, B, C and D) has been adopted for both the validation and operational stages of the numerical hydrodynamic and spectral wave modelling.

Figure 5-1 to Figure 5-3 present the selected grids. Grids A2, B5 and C5 have been used for operational modelling of the open coast Townsville – Thuringowa region and for validation of tropical cyclone *Althea*. Grids A2, B5 and C6 have been used to validate tropical cyclone *Aivu*, which made landfall south of Home Hill. Overland grids D5 and D6 have been used for detailed inundation scenario flow modelling in Thuringowa and Townsville urban areas. The A, B and C grids were kindly supplied in original form for use in this project by the James Cook University Marine Modelling Unit, based on their work undertaken for the Queensland Climate Change project. Additional detailing was carried out here on the C5 grid to improve nearshore elevations and coastline definitions in the vicinity of The Strand and Townsville Harbour.

Table 5-1 Computational Domain Parameters

Grid	Resolution		Extent (grid cells)		Dimensions (km)	
	'arc	km	Alongshore	Offshore	Alongshore	Offshore
A2	7.5	13.9	101	57	1390	778
B5	1.5	2.8	161	65	448	179
C5	0.3	0.56	77	281	42	156
C6	0.3	0.56	79	243	43	135
D51	0.03	0.055	920	242	51	14
D52	0.03	0.055	620	520	35	29

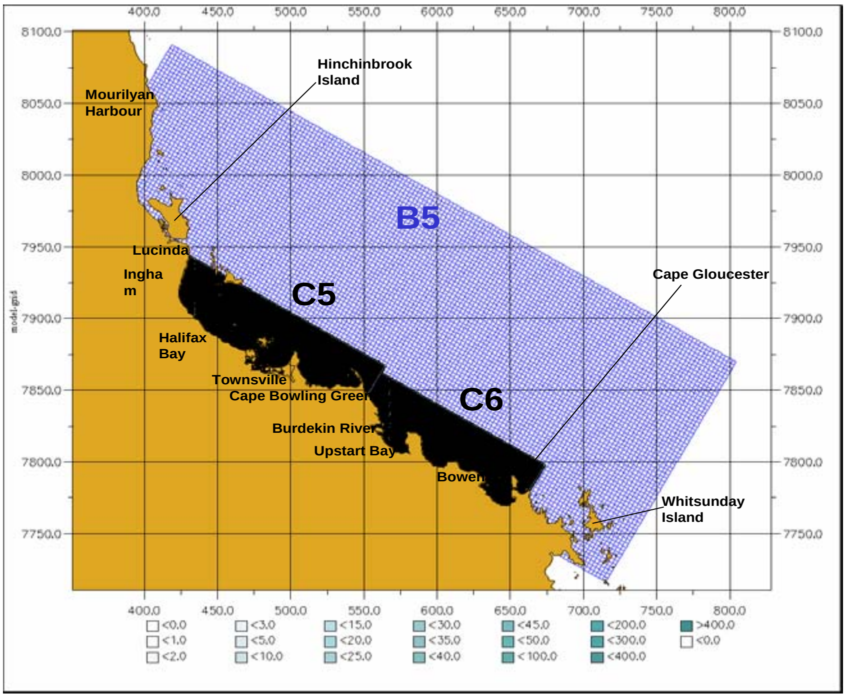


Figure 5-1: Computational domains B5, C5 and C6

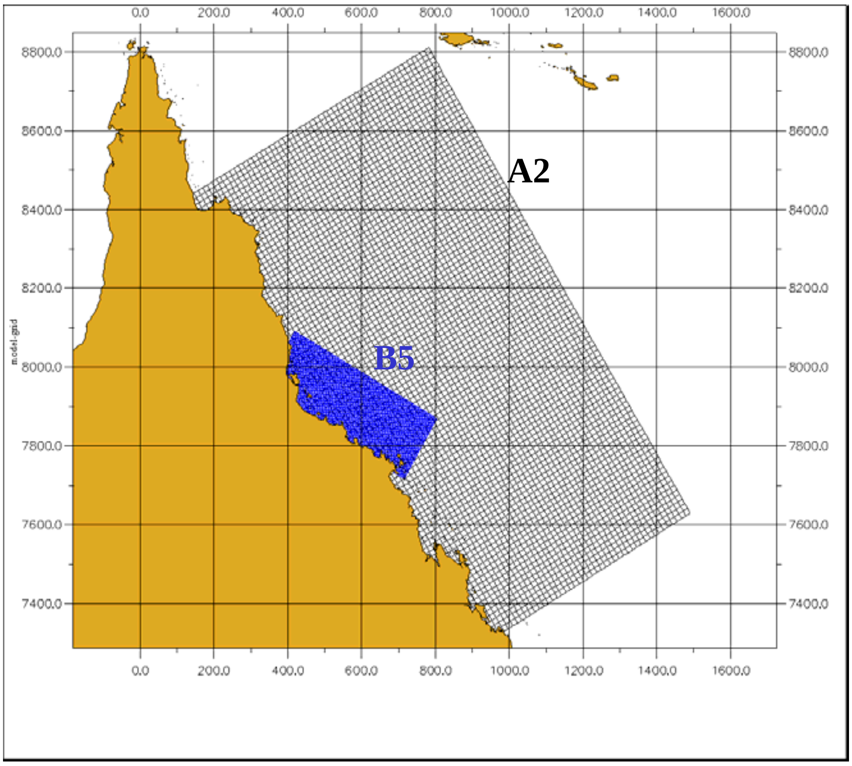


Figure 5-2 Computational domains A2 and B5

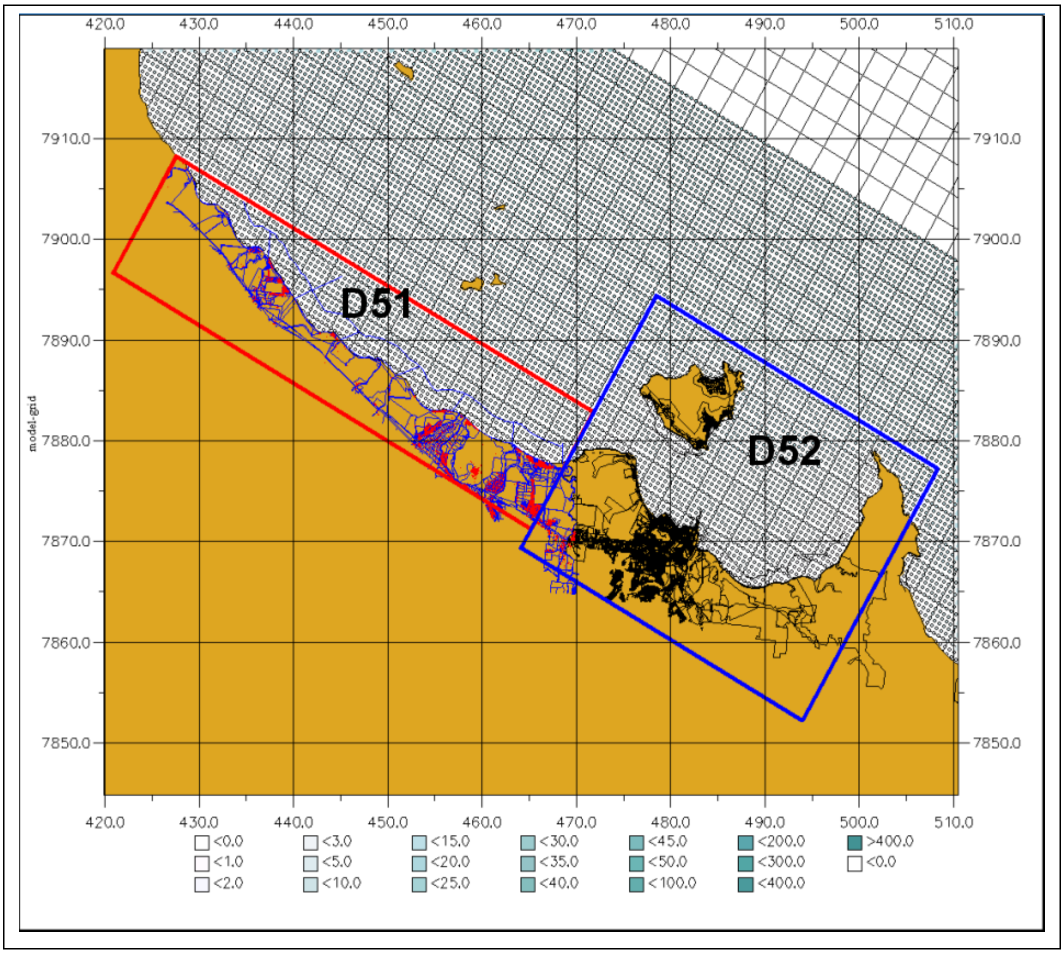


Figure 5-3: Computational domains D51 and D52 for overland flow scenarios

The D51 and D52 grids were constructed here based on considerations associated with:

- the correct representation of the topographic relief and the variability of the terrain;
- the accuracy in depicting linear features such as channels and streams;
- existing watershed boundaries and the connectivity between the various flow (flooding) paths;
- practical issues such as run time for each scenario and software capabilities.

5.3 Tropical Cyclone Wind and Pressure Model

The details of this model are presented in Appendix B and are based on Harper and Holland (1999). The model has been used extensively throughout Australia and internationally to represent the broad scale wind and pressure fields of a mature tropical cyclone. It relies on a series of parameters to describe a tropical cyclone when it is over an open ocean environment, namely:

- the central Mean Sea Level pressure p_c
- the surrounding, or ambient, pressure p_n
- the radius to maximum winds R
- the windfield peakedness factor B
- the storm track (speed V_{fm} and direction θ_{fm})

The SEA implementation used in this study also accounts for the effect of storm attenuation when the eye crosses the coast.

The model generates estimates of the 10 minute average wind speed and direction at a height of 10 m above the ocean surface for supply to the hydrodynamic models for storm surge and waves. It also estimates the 3 sec wind gust for comparison with long term wind records at Townsville Airport. The MSL pressure is also supplied to the hydrodynamic model as it has an influence on the generation of the storm surge.

5.3.1 Example of Wind and Pressure Modelling

Figure 5-4 shows an example of the wind field generated by the model for a (very severe) 907 hPa Category 5 storm on a bearing of 210˚ approximately 3 hours before its landfall near Rollingstone. The radius to maximum winds in this case is 25 km, windfield peakedness is 1.3 and the forward speed is 4 m/s. The eye at this time is crossing Palm Island, and the peak mean wind speed of 46 m/s is located towards the left rear of the storm centre. The clockwise circulation and track asymmetry can be clearly seen as discussed in Section 4.1. Townsville is experiencing peak winds of about 33 m/s at this time, similar to the highest winds during *Althea*.

The peak 3 sec wind gust from such a storm is estimated to be about 65 m/s or 234 km/hr.

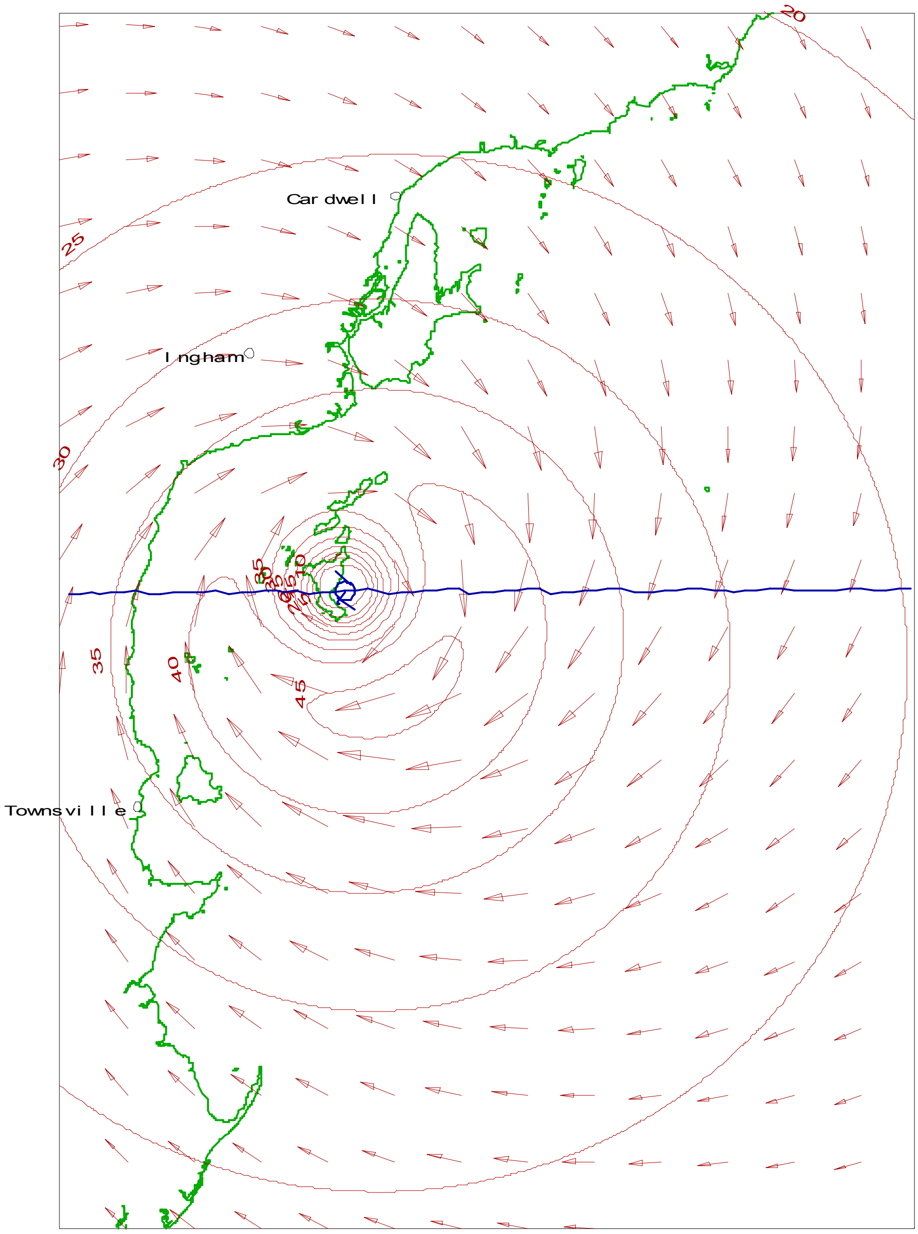


Figure 5-4 Example tropical cyclone wind field pattern

5.4 Hydrodynamic Model

Hydrodynamic (storm surge) modelling has been carried out using the FLOW module of the Delft3D suite of models developed by Delft Hydraulics (The Netherlands). The model has been forced by space and time varying wind and atmospheric pressure fields applied at the free surface of the ocean and operated in two-dimensional, depth-integrated mode.

The selection of the FLOW module is based on:

- A long history of successful storm surge modelling applications (most recently in Vietnam (2001), Andhra Pradesh, India (2001), Russia (1999) and South China SEA (1998)); and
- An exceptionally robust overland flooding (wetting and drying) mechanism allowing stable dynamic simulations with wide stage fluctuations even in the presence of “stranded” or isolated wet areas.

The simulation of overland flooding (based on the mechanism of wetting and drying of intertidal flats) is considered an essential advantage of the module owing to the implementation of the critically important concept of moving boundaries. Models that do not implement the moving boundary concept have trouble accounting properly for volume during the wetting process.

The algorithm for re-activation of land and tidal flats is based on a user-defined threshold depth above which a grid cell is considered wet. The algorithm is particularly efficient when combined with the Alternative Direction Implicit (ADI) finite-difference method implemented in FLOW. In particular, the approach does not require that computational cells be kept artificially “active” throughout the simulation, resulting in faster run times and lower storage requirements.

Both, the re-activation algorithm and the ADI finite difference method are nowadays widely accepted as the de facto standard technique for the treatment of overland flooding.

5.4.1 Example of Storm Surge Modelling

The complexity and dynamics of the modelled nearshore surge-only response is illustrated through a sequence of four panels shown in Figure 5-5. Arranged from top to bottom in clockwise direction, the patterns depict the storm surge pattern prior, during and after landfall of the cyclone whose instantaneous wind field was shown in Figure 5-4.

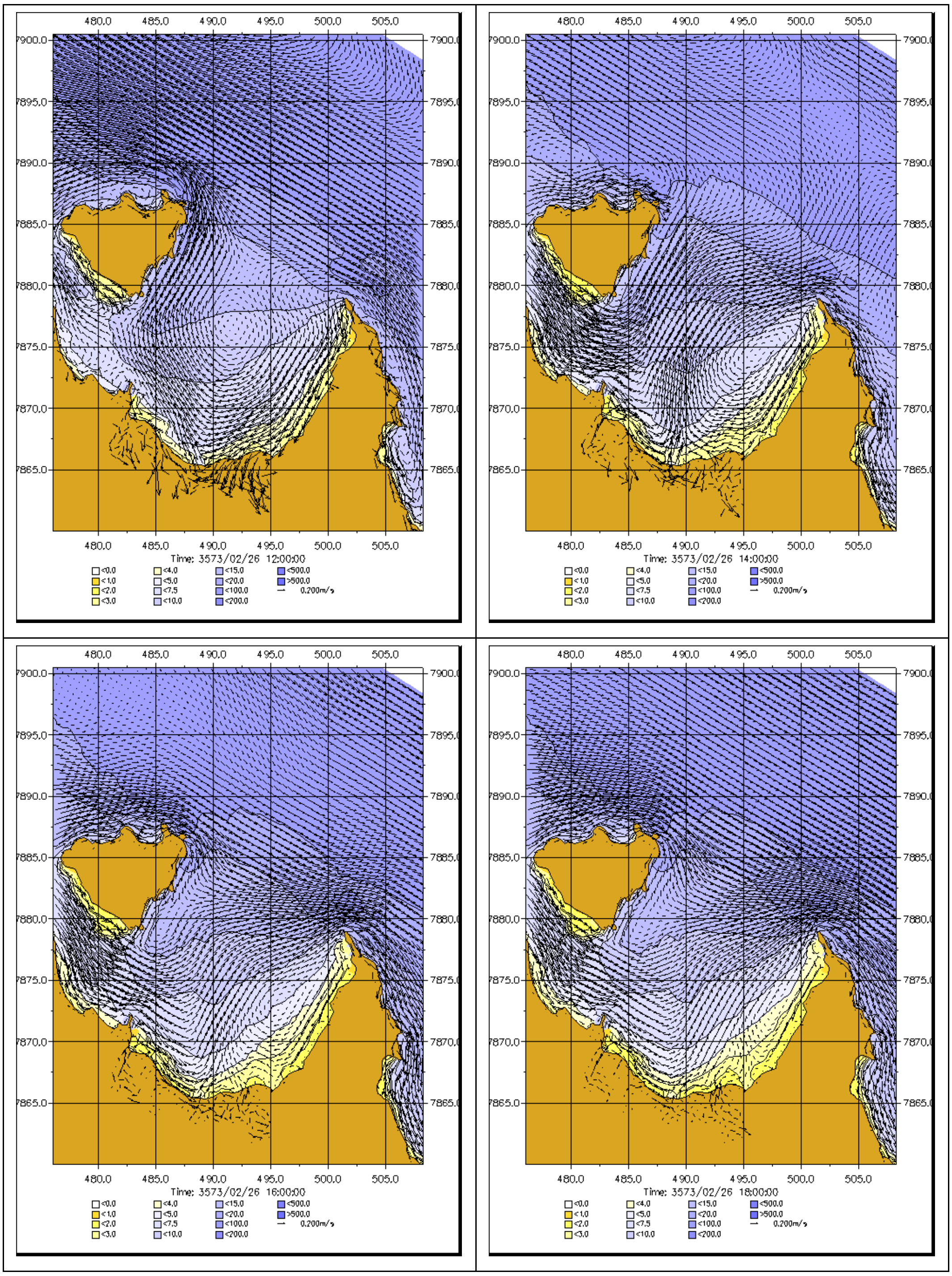


Figure 5-5 Example output from the hydrodynamic model

5.4.2 Assumptions

For storm surge predictions, i.e., in cases where the hydrodynamic model supplied the storm surge component of water elevation to the surge and tide simulation analysis undertaken by the SATSIM model, the hydrodynamic model was established to operate without simultaneous tidal forcing, except for specific scenario testing. Although the tides throughout the Great Barrier Reef region are known to be complex (e.g. Bode and Mason 1992) and can be very difficult to model accurately, the interaction between storm surge and astronomical tide is typically weak. This means that a model that assumes the sea is initially set to Mean Sea Level (MSL) and subsequently adds the predicted tide to the modelled storm surge gives almost exactly the same result as a model that makes the sea level vary with the tide while it calculates the storm surge. However, a series of special tests were subsequently done at varying mean water level to estimate the likely additional effect of tide interaction in the region (refer Section 5.8.2 for details), which was found to be small.

For modelling of overland inundation, the hydrodynamic model was operated with simultaneous tidal forcing as explained in Section 6.6.2.

The Townsville – Thuringowa area is adjacent to the Great Barrier Reef and, while care is needed when modelling in and around reef passages, no special consideration has been made of the reef formations for this study, other than the broad scale shallowing of the waters. This is considered to have a negligible impact on the nearshore surge estimates since the majority of the storm surge generation is confined to the continental shelf landwards of the reef margin.

5.4.3 Verification against Cyclone *Althea*

Details of tropical cyclone *Althea* and its resulting 2.9 m recorded storm surge, as described in Harper (2001) and Harper *et al.* (2001), were used to reconstruct the storm. With an intensity of 950 hPa, *Althea*-like storms have an estimated return period of about 20 years anywhere within the 500 km radius of Townsville. However, the probability of producing another 2.9 m storm surge is much lower, depending also on the particular track, size and speed etc.

Previous modelling by James Cook University (Harper 2001) had shown that the *Althea* storm tide could be accurately recreated without simultaneous modelling of the astronomical tide. This is in spite of the peak surge having occurred close to low tide, when maximum surge-tide non-linear interaction might be expected. Accordingly, the calibration check was also done at Mean Sea Level (MSL), neglecting the tidal component.

Results of the calibration check are shown in Figure 5-6 and Figure 5-7 demonstrating a good agreement between the measured surge component at the Townsville Harbour tide gauge and the Delft3D model combined with the Harper and Holland wind and pressure model. The predicted storm surge levels (2.8 m range) are within a 3.5% margin of error with respect to the magnitude of the peak storm surge (2.89 m) recorded at the Townsville tide gauge. The accuracy of the prediction is comparable to the accuracy achieved in reconstructing the wind and pressure fields (3.5% for peak wind speeds and bias within 5% for the majority of anemometers available).

On this basis the hydrodynamic model has been demonstrated to provide very accurate storm surge estimates in the region, even without specialised Great Barrier Reef modelling or simultaneous inclusion of the astronomical tide.

It is worth noting that the quality of the calibration results was significantly improved after changes were made to the configuration of Townsville harbour reflecting more closely the existing conditions in 1971 (i.e., without the Western Breakwater). The 1971 harbour configuration left the monitoring stations more exposed to the effect of the storm tide producing higher water levels.

Further confidence in the combined modelling capability is illustrated in Appendix A, where a detailed reconstruction of cyclone *Aivu* in 1989 shows very favourable comparisons with the available data.

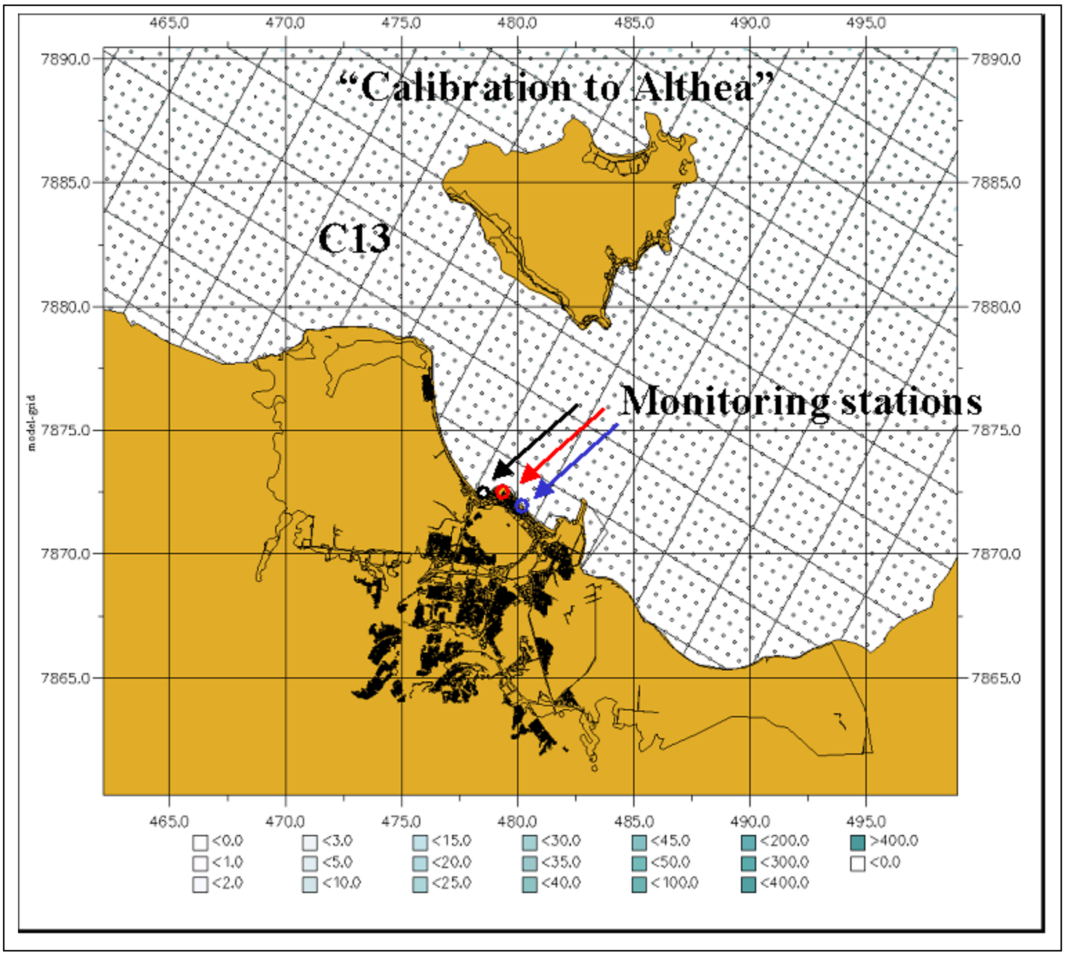


Figure 5-6: Monitoring stations for verification of Cyclone Althea

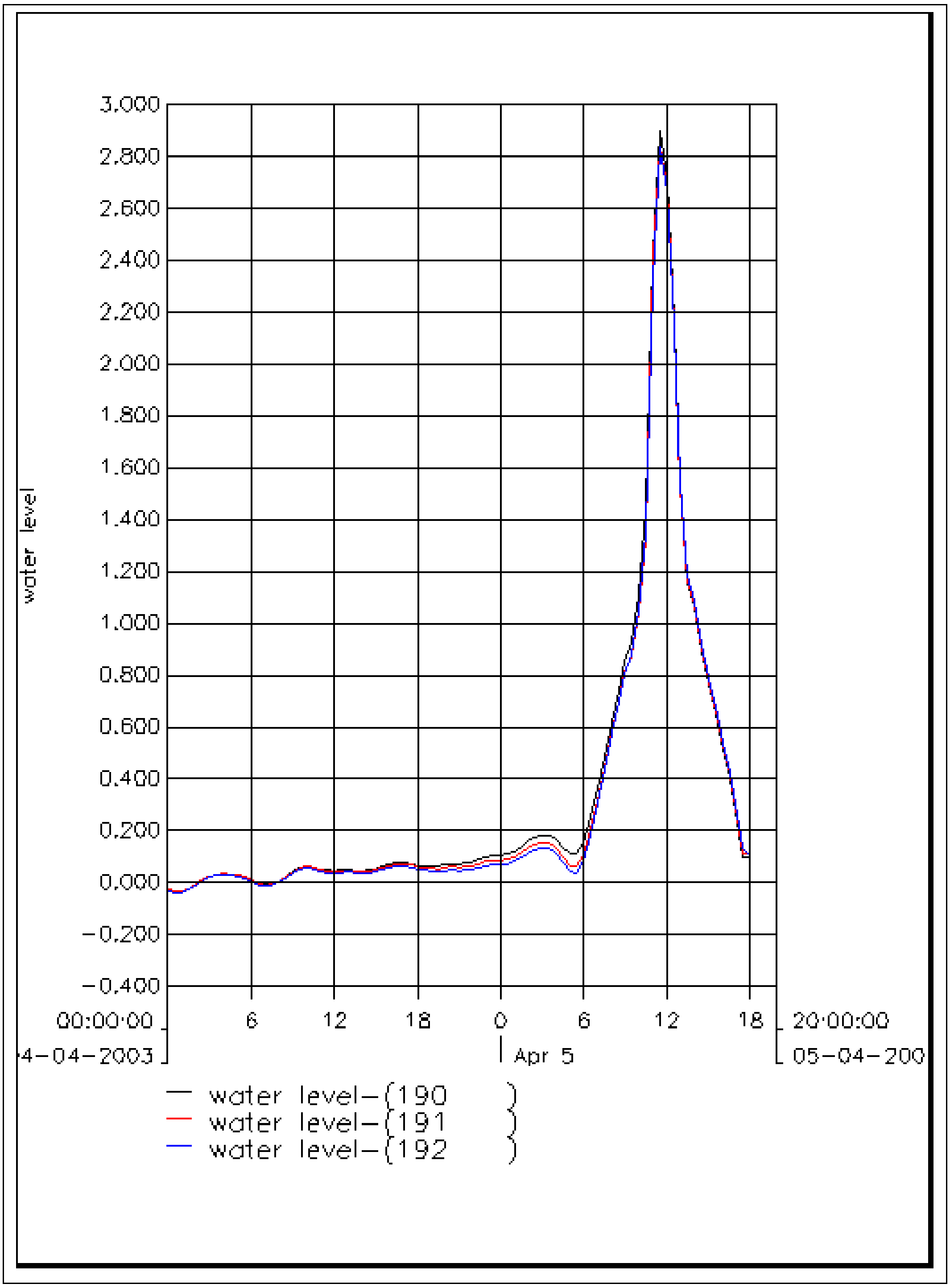


Figure 5-7: Time histories of storm surge elevation at monitoring stations shown in Figure 5-6

5.4.4 Sensitivity Analysis

In line with the methodology adopted in Harper (2001), the sensitivity of the hydrodynamic modelling has been tested with respect to:

- grid resolution;
- extent of the numerical grids;
- numerical time-steps for storm surge and overland modelling;
- effect of the Great Barrier Reef;
- duration of the initial 12 h build up period required to reduce numerical transient effects for storm surge analysis; and
- duration of the initial build up period required to reduce numerical transient effects for overland inundation modelling.

The sensitivity analysis resulted in the adoption of:

- 1 min time step for the A, B and C type grids;
- 0.2 min time step for the D51 and D52 grids;
- a 12 h build-up period for storm surge analysis excluding the effects of the tides;
- a build-up period for overland flow and inundation modelling of 7 days due to the inclusion of the effects of the tides;
- the upwind approach for determining water levels at cell surfaces leading to the enhanced discharge throughout the cell face; and
- nesting of the D-class grids into the C grid in offshore areas extending well beyond the surf zone.

Some of the sensitivity tests were performed as part of previous studies undertaken by GHD and SEA, i.e., Storm Tide Modelling Study of The Whitsunday Coast and Resort Islands, November 2003, and were repeated for continuity purposes. These include tests assessing the effect of the Great Barrier Reef, the use of 1 min time step for storm surge modelling on the A, B and C type grids, the duration of the initial 12 h build up period required to reduce numerical transient effects for storm surge analysis, etc.

A second series of tests specific to the present study were also undertaken. These included tests on the effect of the ramp of wind for both storm surge and inundation (overland) modelling, the adoption of the upwind technique in determining water levels, tests with respect to the grid-cell size and extent of the D-class grids and the corresponding time step, etc.

Based on the sensitivity tests, the following key conclusions were reached:

- the effect of the Great Barrier Reef can be safely neglected;
- the numerical solution is very sensitive to the size of the grid cells indicating that a significant improvement in hindcast accuracy could be further achieved by refining the grids. Although the latter is highly desirable, the results presented in Section 5.4.3 indicate that a practical (reasonable) limit to hindcast accuracy had been already achieved. Therefore, for the sake of maintaining practical run times, a final grid resolution of 566 m was adopted for the purpose of storm surge modelling;

◗ a build-up period of a few days is generally necessary for overland modelling because of the inclusion of the tides in the modelling process; a maximum period of 7 days was adopted for all events (100y, 500y, 10,000y) included in the analysis;

Two sets of results from the sensitivity analysis are presented in Figure 5-8.

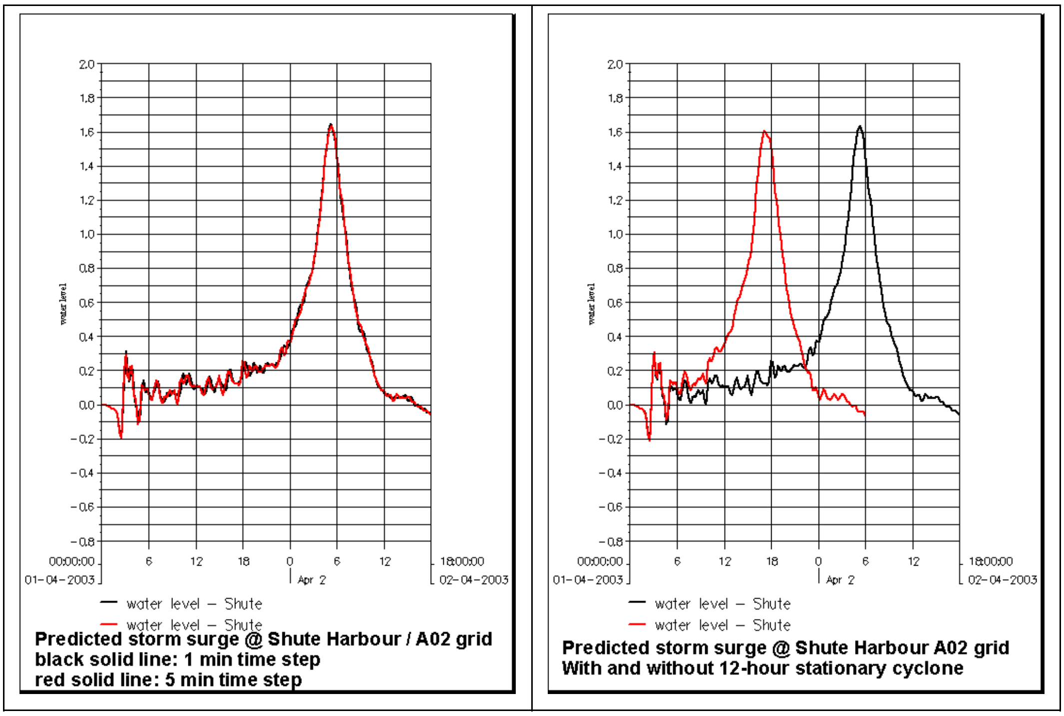


Figure 5-8: Results from the sensitivity analysis. Left: The effect of time step resolution, Right: The effect of a 12 hour initial build-up (stationary cyclone)

5.5 Spectral Wave Model

In order to provide estimates of the breaking wave setup component of the total storm tide, a numerical spectral wave model of the Townsville Thuringowa Region was also established. The ADFA1 model (refer Appendix D) was originally developed at James Cook University in the 1980s by Dr Ian Young, and later at the Australian Defence Force Academy in Canberra (ADFA). It is a so-called 2nd-generation spectral wave model that has been widely applied throughout Australia, especially on the North West Shelf, with great success in reproducing the measured waves from tropical cyclones (e.g. Harper *et al.* 1993).

5.5.1 Computational Grids

The numerical wave model was constructed using the same base bathymetry as the hydrodynamic model and at the same nested grid resolutions. To ensure accurate representation of wave development fetches between the islands and the Great Barrier Reef, the detailed reef description from the JCU-supplied bathymetry was also used. All wave modelling was conducted at Mean Sea Level, which is considered reasonable for the present purposes. To ensure a reasonable representation of the incident wave conditions responsible for breaking wave setup, the C grid modelling was conducted with a minimum nearshore depth of 3 m.

5.5.2 Verification

There is no site-specific wave data readily available for the immediate area during tropical cyclone conditions that is suitable for verifying the operation of the wave model. However, as detailed elsewhere in the report, wave modelling was undertaken for cyclone *Althea as* part of the verification of the operation of the parametric wave model and as evident in Appendix A, the model performs very well in regard to reproducing measured regional wave data during cyclone *Aivu*.

5.5.3 Example of Wave Modelling

Figure 5-9 presents the same example cyclone as Figure 5-4 but this time showing the complex pattern of wave heights, periods and directions that are expected across the region. The contours show the significant wave height in metres, with the peak of almost 8 m occurring to the north of Magnetic Island. Wave heights beneath the eye are generally below 2 m and the shielding effect of the islands and the Great Barrier Reef can be seen where wave height shadows are created. The vectors show the direction of the wave energy and their length is proportional to the wave period. Maximum single wave heights would be about twice the height of the significant wave heights.

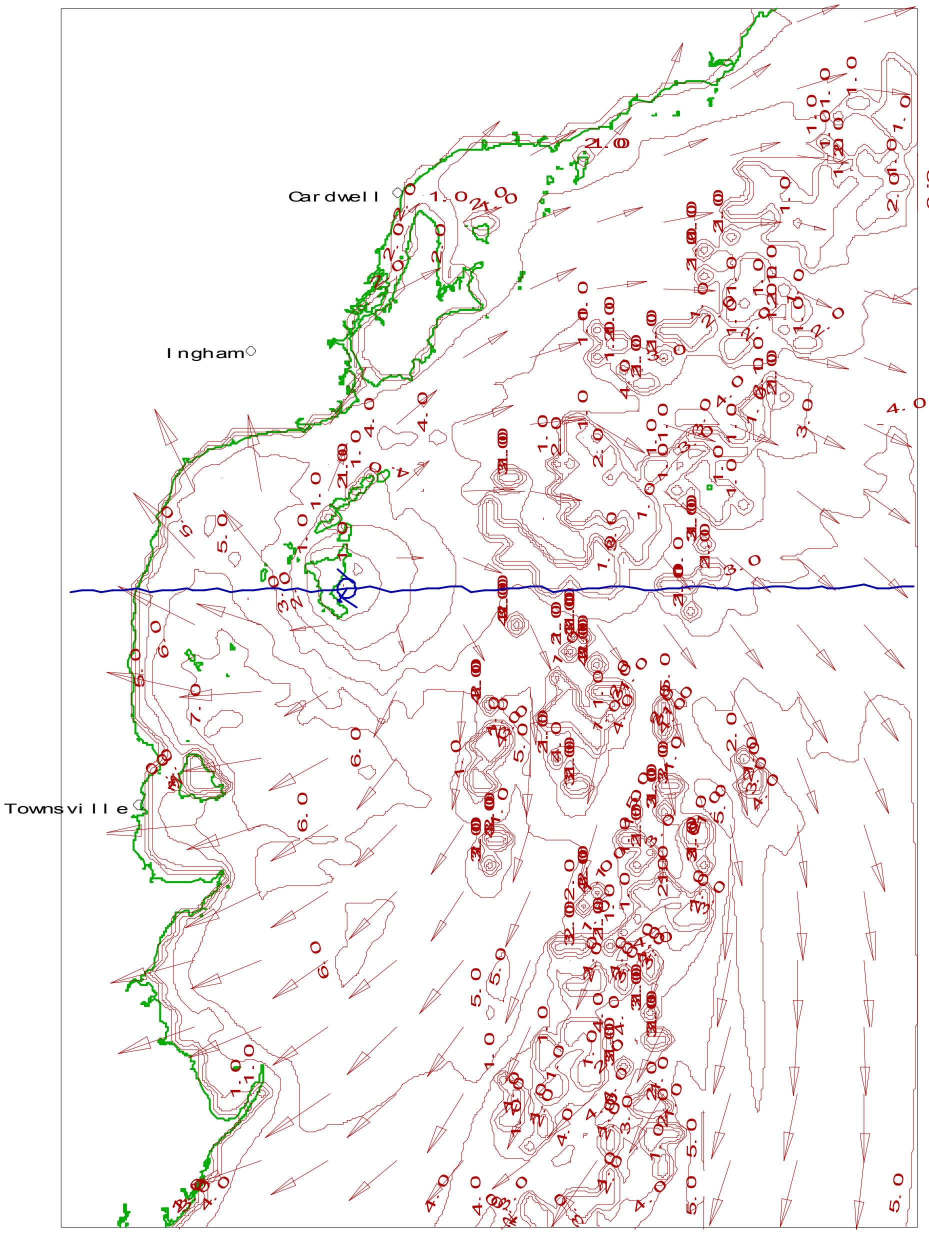


Figure 5-9 Example tropical cyclone wave height pattern

5.6 Establishment of the Open Coast Parametric Models

Parametric surge and wave models were developed to summarise the complex results from the fully numerical hydrodynamic and spectral wave models and to express their output in a form that can be readily assimilated by the statistical model and also form the basis of the real-time probabilistic warning system.

5.6.1 Cyclone Parameter Selection for Full Scale Modelling

The climatology assessment from Chapter 4 identified the principal cyclone parameter values likely to apply to the Townsville - Thuringowa region. These form the basis of a series of conceptual straight-line and constant speed synthetic cyclone tracks, which when modelled systematically by the fully numerical models, provide a response function for surge and waves that can be readily interpolated to provide output at any coastal location.

Figure 5-10 shows the distribution of cyclone tracks that were chosen to ensure adequate spatial coverage of the region was achieved. These comprised 3 sets of tracks, chosen to represent the best coverage of the likely storm surge response:

- 130° - parallel to the coast;
- 270° - oblique crossing; and
- 210° - perpendicular crossing.

Each of the conceptual cyclones is described by the same set of parameters as presented in Section 5.3, except that the pressure difference Δp is introduced to specify the storm intensity:

$\Delta p = p_n - p_c$

A total of 324 individual simulations were then used to form the "base" storm response, using the range of parameters as summarised in Table 5-2 and Table 5-4.These comprised three values for intensity, two radii, a fixed *B*, two forward speeds and three angles of approach.

Table 5-2 Base storm parameter set

Parameter	Unit	Description	Range of Values
Δp	hPa	Pressure Difference (intensity)	50, 75 and 100
R	km	Radius	25 and 45
B	-	Wind Peakedness	1.3
V_{fm}	m/s	Velocity of forward motion	4 and 8
θ_{fm}	Bearing °	Angle of approach	130, 210 and 270

Table 5-3 provides a summary of all cyclone tracks considered, with nine tracks per bearing.

Table 5-3 Adopted Cyclone Tracks

Track Bearing (deg)		
270˚	210˚	130˚
Coastal Crossing Distance X (km)		
190	200	75
150	150	50
125	125	25
100	100	0
75	75	-25
50	50	-50
25	0	-75
0	-50	-100
-50	-150	-150

Notes:

1. Refer Figure 5-10 for location of all tracks.
2. 0 km track defined by numbering of individual points.
3. 0 km track is that which would cause the maximum surge for Townsville and southern Thuringowa.

The coastal crossing distance shown here is measured from Cape Bowling Green, this being a convenient exposed reference location. Figure 5-10 shows the distribution of the cyclone tracks that were modelled based on this convention, which is detailed in Appendix E. The "offshore" class of cyclones is not included at this point because their surge response will be relatively small, but in the statistical modelling their characteristics are assumed to be similar to the 130° case.

Each of the 324 combinations of intensity, speed, direction, size and location were simulated by the hydrodynamic model and the spectral wave model. Each simulation then considered an elapsed real time of 30 h, with the start of the cyclone being 18 h before "landfall" and continuing until 12 h afterwards. In the case of the parallel-moving storms, "landfall" is the time of closest approach to the reference location. Figure 5-10 shows the landfall-relative timing for the track passing through the reference location. Each model cyclone also underwent an additional initial 12 h build up period, with the storm held stationary, to reduce numerical transient effects.

In addition to the base set of storms, a series of 27 special sensitivity tests **(**Figure 5-4) were also undertaken to explore the surge and wave response at the upper and lower limits of some of the parameter ranges and to check linearity and scaling assumptions. These were done with a selected range of fixed values for the other parameters.

Table 5-4 Additional sensitivity testing

Parameter	Unit	Values Tested
Δp	hPa	10, 25, 125
R	km	15, 65
B	-	0.7, 1.0, 1.6, 1.9, 2.1, 2.4
V_{fm}	m/s	2, 8, 10
θ_{fm}	degree	170

Finally, since all the preceding simulations were conducted at Mean Sea Level (MSL), a special set of sensitivity tests was undertaken at +1.2 m and -1.2 m, representative of approximately the Mean High Water Springs (MHWS) and Mean Low Water Springs (MLWS) tidal condition in the region. These results were used to devise a surge-tide interaction function for the model (refer Section 5.8.2).

Overall, a total of 355 detailed numerical hydrodynamic and spectral wave model runs were undertaken, each utilising the three nested grid systems and providing time history output of water elevation, wave height, period and direction each 10 minutes at 377 coastal locations in the region from Ingham south to Bowling Green Bay.

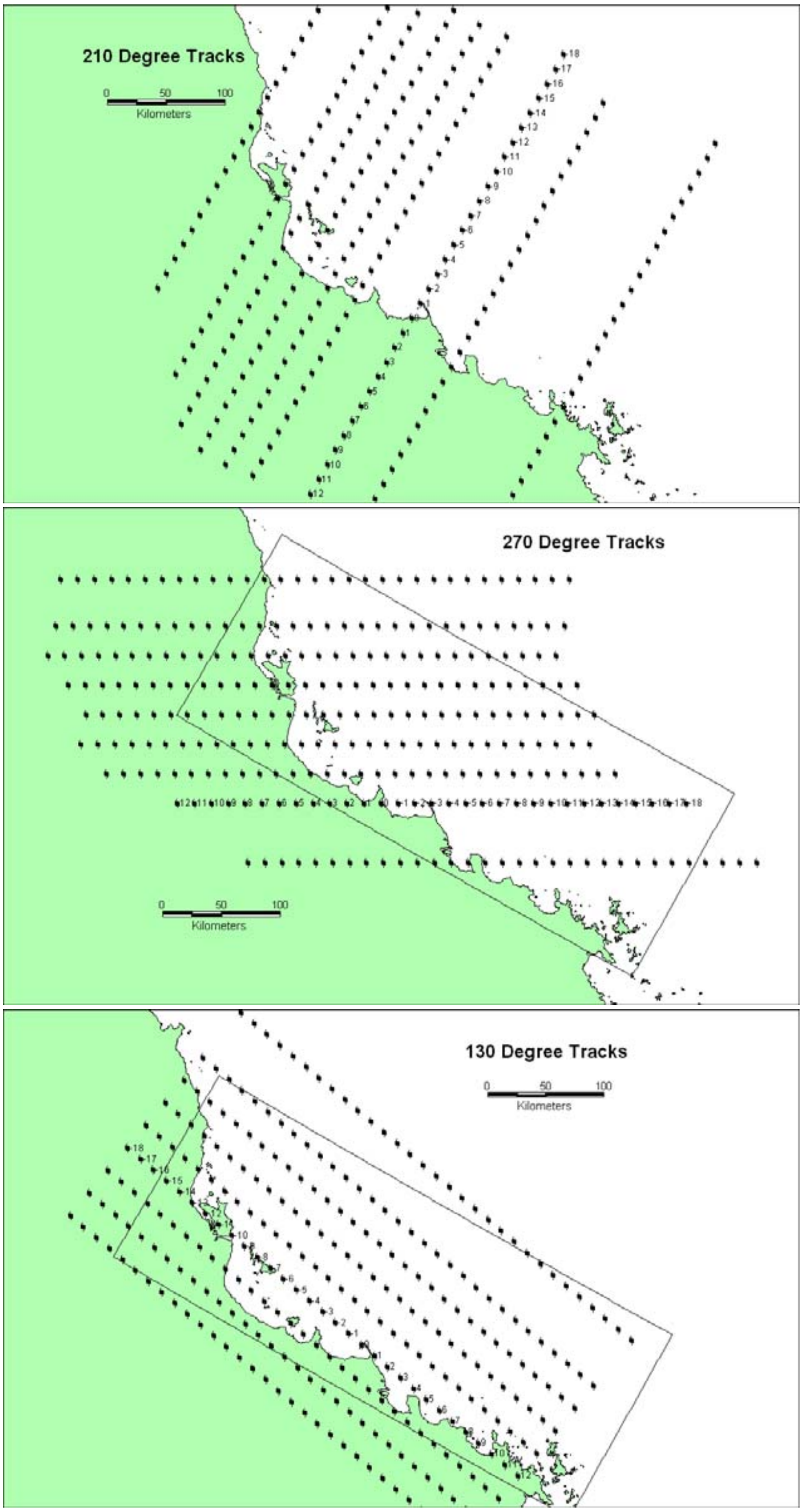


Figure 5-10 Synthetic tropical cyclone tracks chosen for modelling

5.7 Processing of the Numerical Model Results

Each of the above full scale numerical model simulations were processed according to a method developed by SEA (2002), which combines the output in such a way as to extract the underlying regional and local storm surge and wave responses. The method, which is an enhanced form of earlier analyses undertaken for the Beach Protection Authority (Harper and M^{c}Monagle 1985), is simple in concept but complex to illustrate. Essentially, all of the model output for each track direction is condensed into a series of characteristic alongshore and offshore spatial profiles and a time history profile, all of which are scaled according to the intensity of the cyclone, its size and speed. Multiple track directions can be added as necessary to complete the description of the regional response. Additionally, each specific location is allocated a local response function that describes any localised changes in surge or wave height behaviour (including time differences) peculiar to that location. The method allows the rapid recreation of a storm surge or wave height response at any of the coastal locations based on a set of supplied storm parameters.

The parametric model is optimised for highest accuracy at the time of the predicted peak condition (surge or wave height) and typically reproduces the numerical model results to within about 5% for surge and within 0.5 m for wave height and within 2 s for peak spectral wave period.

5.7.1 Example Parametric Model Results

Examples of the parametric storm surge model performance are shown in Figure 5-11 for the cyclone illustrated in Figure 5-4. Each graph provides a comparison showing the predicted time history of water level at selected locations in the region as given by the full Delft3d model and by the simplified parametric model. The time axis is hours relative to the time of landfall. The agreement between the full numeric solution and the parametric model can be seen to be quite excellent.

The equivalent comparisons between the parametric wave model and the ADFA1 spectral wave model are shown in Figure 5-12. In this case the comparisons are less favourable, especially at Saunders Beach (difference of approximately 0.25 m) during the wave build-up period but the peak condition is reasonably well matched. Because wave heights can change rapidly over small distances and within narrow passages it is generally more difficult to parameterise the wave response. Generally though, the model performs quite well for the purpose of predicting indicative wave setup components and there is no evidence of any systematic bias.

By way of illustrating some basic outcomes from the storm surge modelling, a simplified regional estimator of maximum storm surge magnitude is provided in Table 5-5 and Figure 5-13. These have been prepared using the *SEAtide* (Section 9) prediction model developed here based on the parametric model of storm surge. The results are based on a series of increasingly more intense storms at right angles to the coast having average speed 4 m/s, radius of 30 km and peakedness of 1.0. The landfall points chosen were 30 km north of (a) Townsville and (b) Bluewater and the results, which were similar, were then averaged.

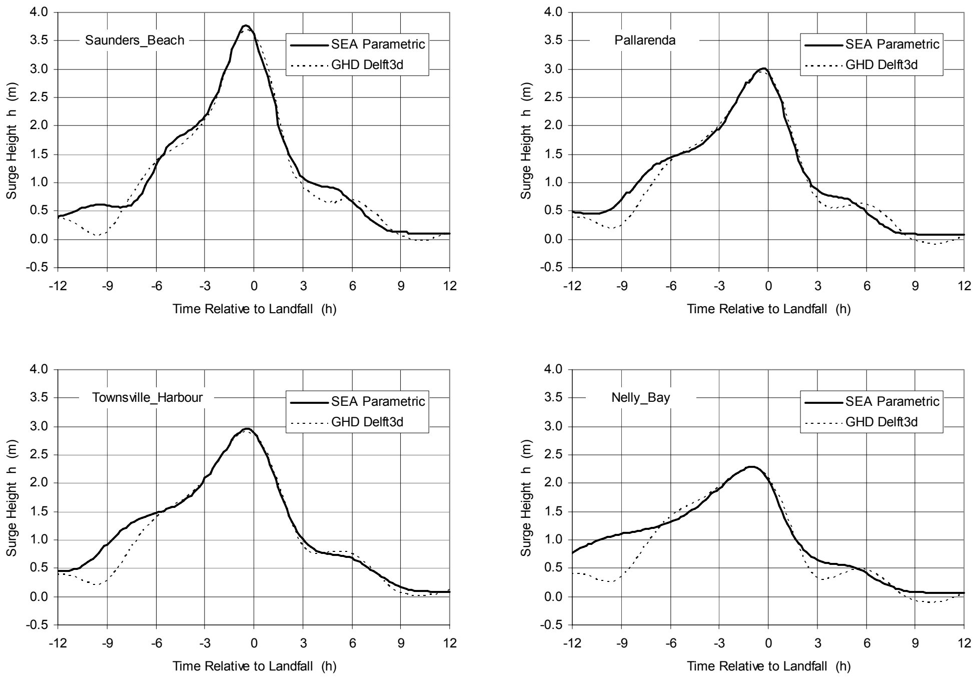


Figure 5-11 Example of parametric storm surge model performance

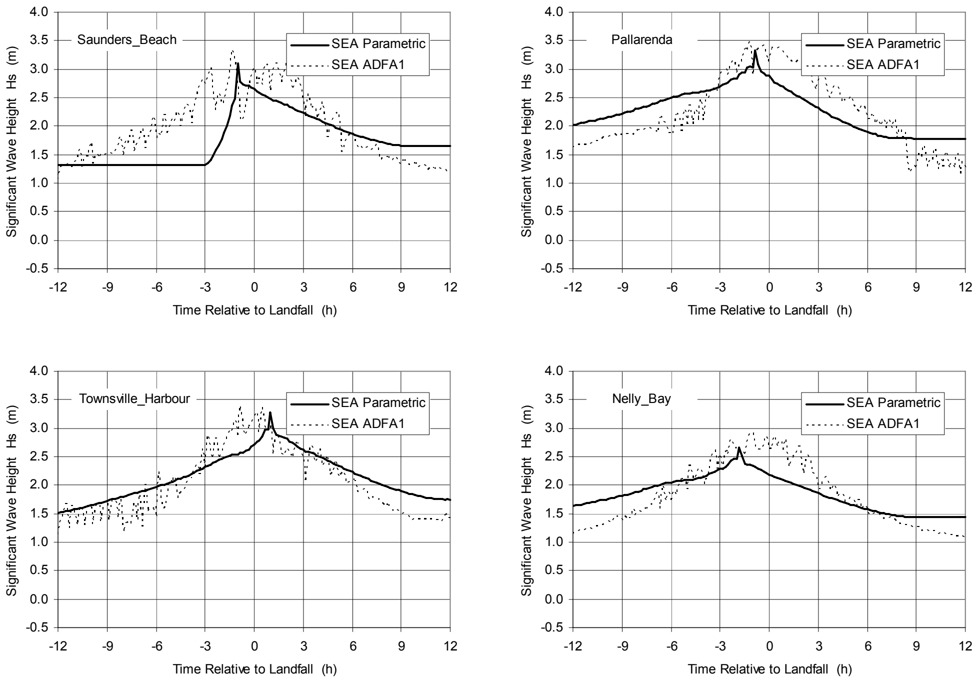


Figure 5-12 Example of parametric wave model performance

Note that these are estimates using "average" storm parameter values and specific parameter combinations can lead to significantly different values. For example, the fast moving TC *Althea* produced a 2.9 m surge magnitude but was only 950 hPa (Cat 3.7). These results provide an indication of possible surge magnitudes but for accurate forecasting, the *SEAtide* predictive model should be used directly with the full set of estimated storm parameters.

Table 5-5 Regional peak storm surge magnitude estimates

Cyclone	**Central**	**Average Peak**
Category	Pressure	Surge Magnitude
	hPa	m
1	995	0.6
2	985	0.9
3	970	1.4
4	940	2.1
5	915	3.3
6[1]	875	4.9

[1] Note that "Category 6" here is simply a means of allowing consistent extrapolation past the open-ended Australian Category 5 scale. There is no "official" Category 6.

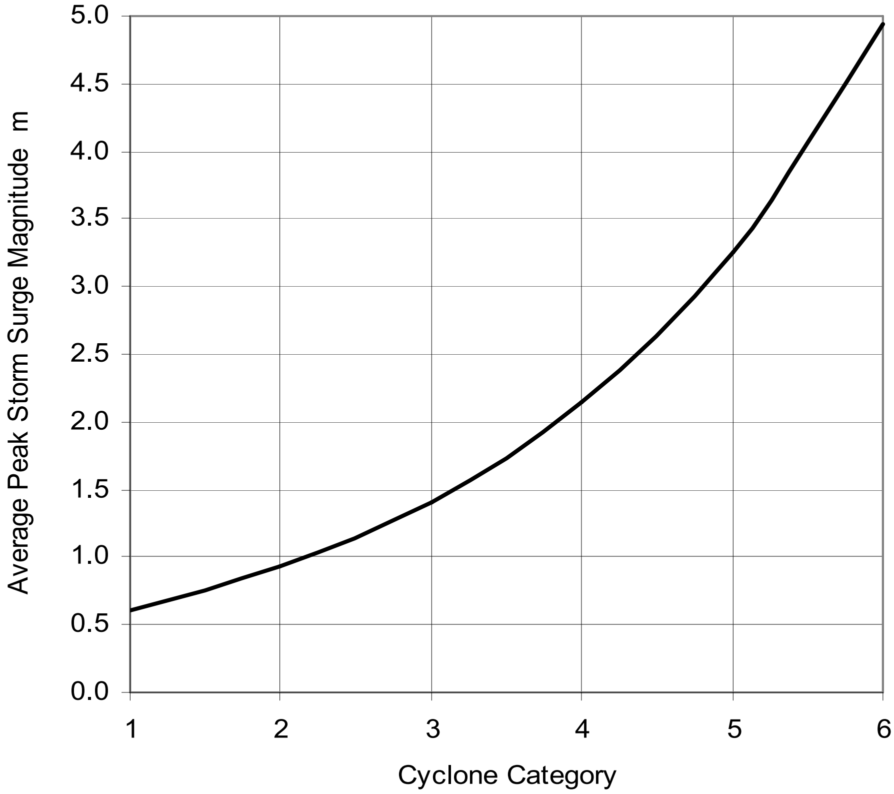


Figure 5-13 Regional peak storm surge magnitude estimator

5.8 Statistical Simulation Modelling

The detailed operation of the statistical simulation model SATSIM (Surge and Tide Simulation) is described in Appendix E. In summary, the model generates an artificial history of tropical cyclones based on the climatology described in Chapter 4. The model maintains a clock that calculates the occurrence of the next event based on random number sequences and then allocates the necessary parameters, randomly sampled from the climatology distributions. Each cyclone's predicted wind, surge and wave response at each of the sites of interest is then generated by the parametric models, interpolating as necessary between the available modelled scenarios. The wave height and period estimate is converted into a breaking wave setup height before being added to the surge and both are superimposed on the background astronomical tide for that date in time. This is repeated for 50,000 years of synthetic cyclones and the exceedance statistics of the combined total water level at each site then forms the basis of the probabilistic storm tide level predictions.

5.8.1 Astronomical Tide Effects

Astronomical tides in the Townsville-Thuringowa region are mixed diurnal and semi-diurnal with a marked diurnal inequality (a significant difference between heights of consecutive high or low tides). The Standard Port for the region is Townsville Harbour, where accurate values of the tidal constituents have been obtained from Queensland Transport and the tidal planes are given in the Tide Tables (QDOT 1998) as:

Table 5-6 Tidal planes at Townsville

Tidal Plane		m AHD
Highest Astronomical Tide	HAT	2.15
Mean High Water Springs	MWHS	1.21
Mean Sea Level	MSL	0.10
Mean Low Water Springs	MLWS	-1.13
Lowest Astronomical Tide	LAT	-1.86

There is little official guidance on tidal planes along the adjacent coastline considered in the study but the variation is known to be relatively small. Accordingly, a simple linear interpolation of tidal planes has been undertaken between the available datums, leading to a set of "range ratios" relative to the standard port. Accordingly, the SATSIM model generates a base tidal level using the Townsville constituents and then applies the calculated range ratio to that value for each of the sites in the study region. A selection of the applied range ratios is given in Table 5-7. Tidal phase differences are small and not included as they simply represent a further random variation within the model.

Table 5-7 Tidal range ratios used for statistical modelling

Location	Ratio	Location	Ratio	Location	Ratio
Taylors Beach[2]	0.970	Shelly Beach	0.990	Florence Bay	0.960
Allingham[2]	0.970	Cape Pallarenda	0.990	Arthur Bay	0.960
Forrest Beach[2]	0.970	Pallarenda	0.998	Arcadia (Alma Bay)	0.960
Cassady Beach[2]	0.970	Rowes Bay	0.998	Nelly Bay	0.960
Bronte Beach[2]	0.970	Kissing Point	0.998	Picnic Bay	0.960
Crystal Creek	0.980	North Ward	0.998	Bolger Bay	0.960
Mutarnee	0.980	Breakwater Casino	0.998	West Point	0.960
Balgal	0.990	Townsville Harbour	1.000	Huntingfield Bay	0.960
Rollingstone	0.990	South Townsville	0.990	Wilson Bay	0.960
Mystic Sands	0.990	Ross River	0.990	Horseshoe Bay	0.960
Toomulla	0.990	Launs Beach	0.980	Radical Bay	0.960
Toolakea	0.990	Whiterock Bay	0.970	Havannah Island	0.970
Bluewater Beach	0.990	Long Beach	0.970	Cape Ferguson	0.913
Saunders Beach	0.990	Red Rock Bay	0.970	Chunda Bay	0.913
Bushland Beach	0.990	Cape Cleveland	0.960	Cungulla	0.913
Bohle River	0.990	Paradise Bay	0.940	Haughton River	0.913

5.8.2 Surge – Tide Interactions

As discussed earlier, special model tests were undertaken to determine the extent to which there might be non-linear interaction between the astronomical tide and the storm surge. If there is, the test conducted at a consistently low tide level (-1.2 m AHD) would be expected to produce a larger storm surge component than that conducted at a consistently high tide level (+1.2 m AHD). While this does not represent the actual dynamics of surge-tide interaction, it is likely that it will detect any significant level of dependency.

The results of these tests indicated that the average magnitude of surge-tide interaction across all study sites was about ±4%. This means that, on average, a cyclone of a given intensity occurring at a low tide level would produce a 4% larger storm surge than the same cyclone occurring at a high tide level. Although this average

[2] Located in Hinchinbrook Shire

change is within the error bars of many of the other assumptions made, some individual sites experienced differences as high as 10% or even more. While some of these % changes seem high, they relate to relatively low surge magnitudes in those cases. To ensure that some account of possible surge-tide interaction is made, the site-specific differences from these tests have been included in the statistical model, so that it constantly applies the differences, linearly interpolated across the tidal variation.

5.8.3 Deterministic Verification of the Statistical Simulation Model

The deterministic accuracy of the SATSIM model is illustrated with reference to Tropical Cyclone *Althea*, which impacted Townsville in December 1971. The actual storm track is shown in Figure 5-14, together with a series of straight line approximations over the last several hours before landfall.

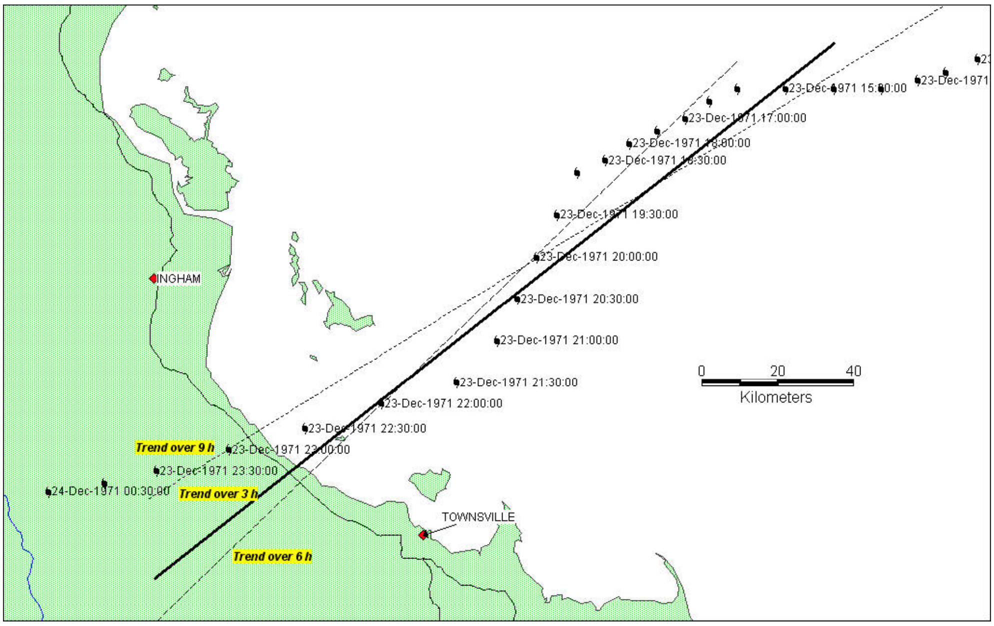


Figure 5-14 Actual track of *Althea* and various straight-line approximations

The SATSIM model is then invoked with the following parameter set (based on Harper *et al.* 2001), where *X* is this instance is measured perpendicular to the track from Townsville:

Parameter:	Landfall Time	Δp	R	B	V_{fm}	θ_{fm}	X
Unit:	UTC	hPa	km	-	m/s	°	km
Value:	24-Dec-1971 00:00	58	30	1.0	8.4	228	35

To exactly reproduce the measured surge and storm tide the above speed and direction have been taken as the averaged values over the last 4 h before landfall. Figure 5-15 then shows the simultaneous time history of wind, waves, tide, surge and setup that are predicted to occur at Townsville during the passage of the cyclone, compared with either measured data from the actual event and/or modelled data. The top graph shows the predicted variation in wind speed as the cyclone passes, compared with the measured mean V_m and gust V_3 wind speeds at the airport. The peak winds are quite well matched in each case but the model predicts a broader response than was actually experienced. These differences are due to the model assumption of a straight-line track and constant storm parameters, whereas the actual storm was more dynamic.

The middle graph shows the predicted variation in significant wave height H_s and peak spectral wave period T_p over the same time. No measurements of waves are available so the comparison here is with the ADFA1 spectral wave model prediction. The lower traces are for H_s and show SATSIM predicting a slightly lower peak wave height and also slightly lagged in time. The upper traces are for T_p and show SATSIM matches the peak condition well but does not represent the rapidly fluctuating values predicted by ADFA1[3]. These values are in broad agreement with estimates from Harper *et al.* (2001), which were based on the JCU/MMU WAMGBR spectral wave model.

The bottom graph shows the predicted tide variation on the day interacting with the predicted storm surge component (with peak of 2.82 m) to yield a surge plus tide peak level of 2.54 m AHD. This is compared with the measured tide gauge values inside the harbour, which peaked at 2.53 m AHD on a 2.89 m surge. It is assumed that the tide gauge record is unaffected by wave setup effects.

The wave setup component likely to be applicable to the adjacent beaches is calculated from the time variation of wave height and period for a nominal water depth of 3m and produces a peak value of about 1m. This component adds to the surge plus tide variation to give a predicted *total storm tide* level peaking at 3.6 m AHD. Debris levels between 5 and 6 m AHD were reported in the vicinity of the Tobruk Pool adjacent to the harbour. As noted in Harper *et al.* (2001), these levels are consistent with the likely additional effects of wave runup.

The foregoing real storm example illustrates how the statistical simulation model generates a specific storm event from just a few parameters and also illustrates the accuracy with which the prediction can be made. In the statistical mode, random numbers are used to sample the storm parameter sets from the probability distributions specified in Section 5.6. The frequency of occurrence of equalling or exceeding any water level over a simulated 50,000 year period then directly determines the statistical *return period* of that level.

[3] The wave conditions near Townsville Harbour are much complicated by the sheltering effects of Magnetic Island and the spectral model peak period is a volatile parameter that can rapidly change in such circumstances.

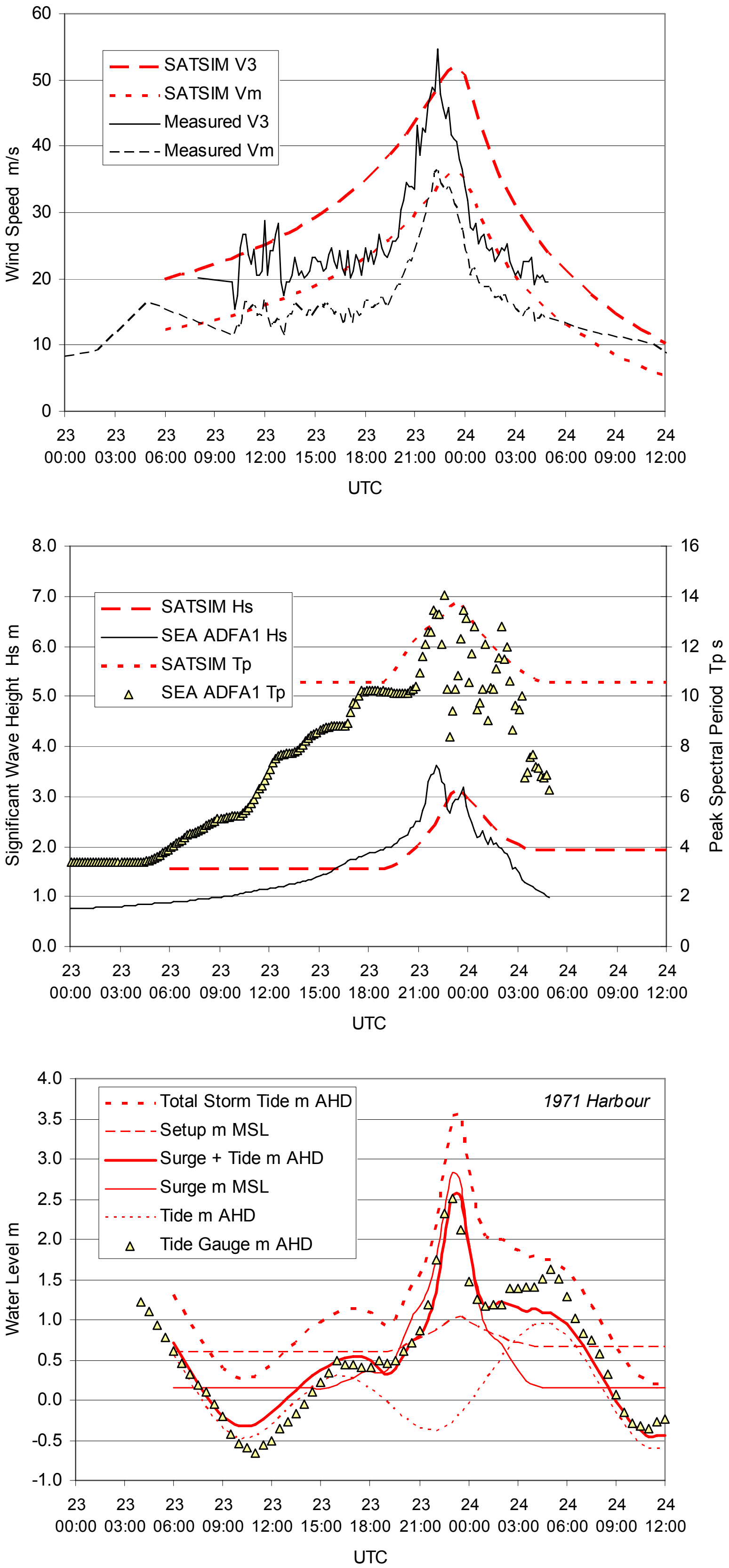


Figure 5-15 Example of the SATSIM prediction for *Althea* at Townsville

5.8.4 Statistical Verification of the Simulation Model

There is no absolute way that the statistical aspects of the model can be verified, other than ensuring that the various component parts of the model are performing correctly. The only statistical checks that can be done relate to the model's re-creation of the astronomical tide statistics and a comparison of its wind speed predictions with long term regional values.

Figure 5-16 shows the modelled statistics of highest tides at Townsville Harbour, compared with the official HAT tidal plane from the Tide Tables. Normally, HAT is associated with an 18.6 y tidal cycle, hence it should fall at around the 20 y return period value if fully sampled. However, the statistical model only samples 6 months of each year (the cyclone season from November to April) and so the apparent return period has been essentially doubled. The remaining differences are due to the use of a half-hour tidal sample, a 0.1 m discretisation level in the model statistics kernel and a reduced set of tidal constituents (the principal 37 only) being used. On this basis, the model is deemed to be correctly sampling the astronomical tide.

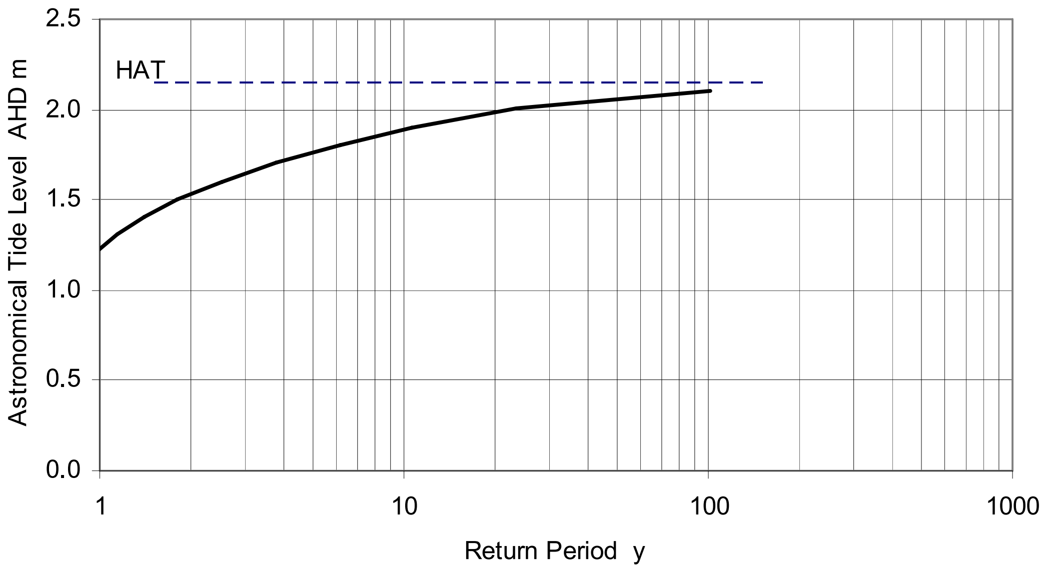


Figure 5-16 Verification of the generated HAT tidal plane at Townsville Harbour

The next test considers the model's prediction of mean and gust wind speeds at Townsville when compared with an analysis of the 62 y record from Townsville Airport. The wind data was obtained from the Bureau of Meteorology Climate Services Section and analysed to extract the peak winds occurring only during periods when a tropical cyclone was within a 300 km radius of the site. This should help filter out the effects of other severe weather such as isolated local thunderstorms. The data were also windowed over a 7 day period to ensure independent samples were obtained and are ranked here in Figure 5-17` using traditional quantile plotting techniques (Harper 1999).

The SATSIM predictions based on a 50,000 y simulation are then overplotted and show a very favourable comparison; the model generally following the trend of the data, although slightly above most observations beyond the 10 y return period. Allowing for the fact that the model is predicting over-water wind speeds away from the influence of land, this is a good verification of the model's capabilities. It is interesting to note that the highest recorded wind gust is that due to *Althea* at Townsville in 1971, which the model places about the 500 y return period. Also shown for independent verification are predictions from the JCU/MMU simulation study reported in Hardy *et al.* (2001) and McConochie *et al.* (2004) kindly provided here by Mr Jason McConochie. The JCU study considered a simulation period equivalent to 2500 y.

It will be noted that these SATSIM predicted gust wind speeds are somewhat lower than the Australian wind loading standard AS1170.2 (Standards Australia 2002), which forms the basis for structural design in this region. It is anticipated that the AS1170.2 regional wind speeds may well be revised in the coming years on the basis of the results from this and other recent tropical cyclone simulation studies (e.g. Harper 1999b, McConochie et al 2004).

Note also that the return period of a given wind speed for a single point cannot be directly compared with the return period of a specific cyclone intensity within a finite area (e.g. Figure 4-5). The wind speed return period here is the average outcome from a large number of individual cyclones, some of which will be more intense than others, at different distances of approach (e.g. north and/or south of the site or parallel to the coast), different forward speeds and the like. These results therefore correctly answer "What is the probability of a site in Townsville experiencing wind speeds greater than or equal to Category 3?" rather than "What is the probability of Townsville being hit by a Category 3 storm?". The latter question is not specifically relevant and can only be partially answered within an areal context because cyclones and cities are of finite size and the cyclone wind profile varies.

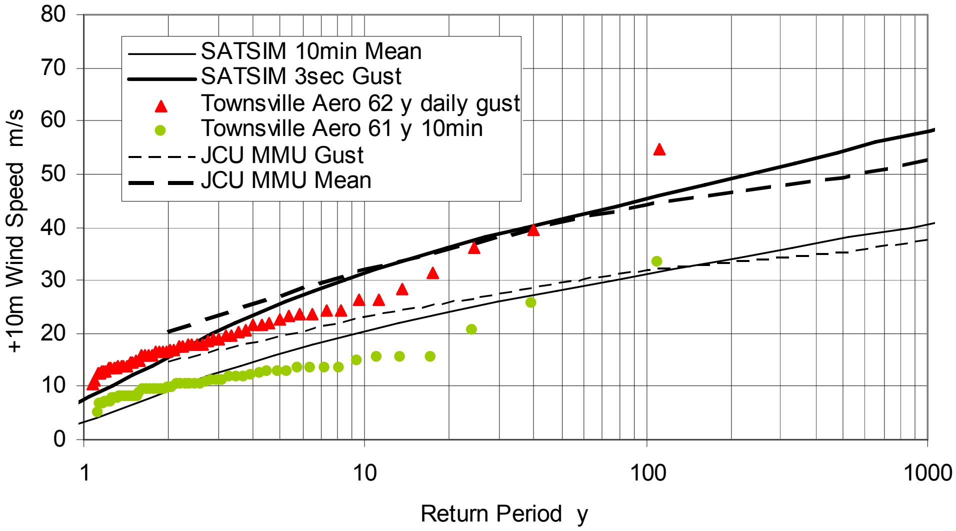


Figure 5-17 Statistical simulation model prediction of regional wind speeds

6. Results

6.1 Overview

The open coast storm tide estimates presented in this section are derived from the statistical simulation model, which uses the parametric wind, storm surge and wave models to generate 50,000 years of artificial cyclone events, each combined with the astronomical tide. This synthetic time series is then statistically analysed to determine the return period of the total storm tide levels throughout the region. These estimates are directly applicable to the open coast or beachfront.

Results from the statistical model are presented in two different formats:

- Absolute levels relative to Australian Height Datum (AHD); and
- Inundation depths relative to the local Highest Astronomical Tide (HAT).

Each of these is then provided as:

- Tabulated values for the identified localities;
- Regionally ranked summary graphs; and
- Selected site specific return period graphs.

It should be noted that the actual depth of inundation will vary in accordance with the difference between local ground level and storm tide level, both of which are referenced to AHD. The detailed inundation mapping (refer later) will provide more specific information away from the coastline. The depth of inundation to HAT will be the highest expected depth at the "shoreline" where the highest astronomical tide would normally reach. Hence, any depth relative to HAT indicates the maximum depth that seawater is expected to reach over and above the normal human experience of the highest tide level.

Detailed fine scale hydrodynamic modelling (surge plus tide only) has then been undertaken for a selection of representative "inundation" events. The choice of which events to model in detail has been based on an examination of all of the storms generated by the statistical model to determine representative surge and tide combinations. These have been separately selected on the basis of a "Thuringowa" region stretching from Bohle River north to Crystal Creek and a "Townsville" region from Cape Pallarenda south to the Cleveland Bay Purification Plant. No fine scale modelling has been undertaken at Cungulla because of the small areas involved, where a simple horizontal extension of the open coast levels is deemed acceptable.

The fine scale modelling therefore is deterministic in that it considers a single representative event affecting each region, but each event reproduces the statistically-derived water levels along the open coast for a specific return period and then applies the surface wind stress effects to the overland flow. **Breaking wave setup is considered limited to a narrow strip of coastal land and is not considered to contribute to the wide-scale inundation further inland.** Reference should also be made to Section 6.6.

6.2 Open Coast Storm Tide Levels

This chapter presents results for selected points along the coastline. The location of these points is illustrated in the two figures provided at the end of the chapter.

Storm tide levels **relative to Australian Height Datum (AHD)** (and inclusive of wave setup) are summarised below in Table 6-1, Figure 6-1 and Figure 6-2.

Table 6-1 Estimated Total Storm Tide Levels (in metres) referenced to AHD

	Estimated Return Period of Total Storm Tide Level				
Site	**50 y**	**100 y**	**500 y**	**1000 y**	**10000 y**
Crystal_Creek	2.8	3.1	4.0	4.1	7.3
Ollera Creek	2.7	3.0	3.2	3.9	6.7
Road End (Moongabulla)	2.5	2.6	3.3	3.9	6.9
Mutarnee	2.7	3.0	4.0	4.7	6.6
Balgal	2.7	3.0	4.0	4.5	6.2
Rollingstone	2.6	2.9	3.8	4.4	6.0
Mystic_Sands	2.7	3.0	4.0	4.7	6.2
Surveyors Creek	2.7	3.0	3.5	3.8	6.0
Toomulla	2.6	2.8	3.7	4.3	5.6
Leichhardt Creek	2.2	2.4	3.0	3.6	5.5
Christmas Creek	2.5	2.5	3.0	3.5	5.6
Toolakea	2.6	2.8	3.1	3.4	5.3
Bluewater_Beach	2.5	2.7	3.1	3.4	5.3
Deep/Healy Creek	2.7	3.0	3.1	3.4	5.3
Saunders_Beach	2.6	2.8	3.5	4.1	5.5
Black River	2.5	2.5	2.9	3.3	5.3
Bushland_Beach	2.6	2.9	3.6	4.0	5.3
Bohle_River	2.2	2.3	2.8	3.2	4.8
Shelly_Beach	2.9	3.1	4.0	4.4	6.5
Cape_Pallarenda	2.5	2.7	3.3	3.7	5.6
Pallarenda	2.6	2.9	3.6	4.1	5.2
Rowes_Bay	2.7	3.0	3.8	4.4	5.9
Kissing_Point	2.7	2.9	3.8	4.3	5.5

	Estimated Return Period of Total Storm Tide Level				
Site	50 y	100 y	500 y	1000 y	10000 y
North_Ward	2.7	3.0	3.9	4.4	5.4
Breakwater_Casino	2.6	2.8	3.6	4.0	5.1
Townsville_Harbour	2.6	2.9	3.5	3.6	5.4
South_Townsville	2.6	2.9	3.7	4.0	5.6
Ross_River	2.9	3.0	3.2	3.7	5.7
Florence_Bay	2.8	3.0	3.8	4.1	5.5
Arthur_Bay	2.4	2.5	3.0	3.4	5.1
Arcadia_(Alma_Bay)	2.4	2.6	3.2	3.6	5.0
Nelly_Bay	2.5	2.7	3.3	3.7	5.0
Picnic_Bay	2.5	2.7	3.4	3.8	5.8
Bolger_Bay	2.6	2.8	3.0	3.0	3.9
West_Point	2.4	2.5	3.1	3.4	4.9
Huntingfield_Bay	2.3	2.4	3.0	3.3	4.8
Wilson_Bay	2.4	2.5	3.0	3.3	4.8
Horseshoe_Bay	2.4	2.5	3.0	3.3	4.7
Radical_Bay	2.5	2.6	3.1	3.4	4.6
Cungulla	2.5	2.7	3.5	3.6	4.9

Note: Values include wave setup, which applies only at the coastline where a barrier (e.g. a sand dune) exists at a higher level.

Figure 6-1 is a graphical summary of selected values in Table 6-1, grouped by geographic proximity. As a general rule, the main differences between the sites are due to the different breaking wave setup contributions and the relationship to the estimated dune crest height.

It should be noted that Figure 6-1 **(and later Figure 6-4 Example site specific components of the total storm tide**

) are plots of raw model data, from which interpolated return period values are derived and presented in the various tables. It should also be noted that the raw statistical model predictions become more erratic at return periods greater than 1000 years (refer Section 2.2). Inclusion of the continuous model projection here is not to imply a greater accuracy than is available from the model assumptions. The single 10,000 year values presented in later tables and in some figures should be regarded as approximate only.

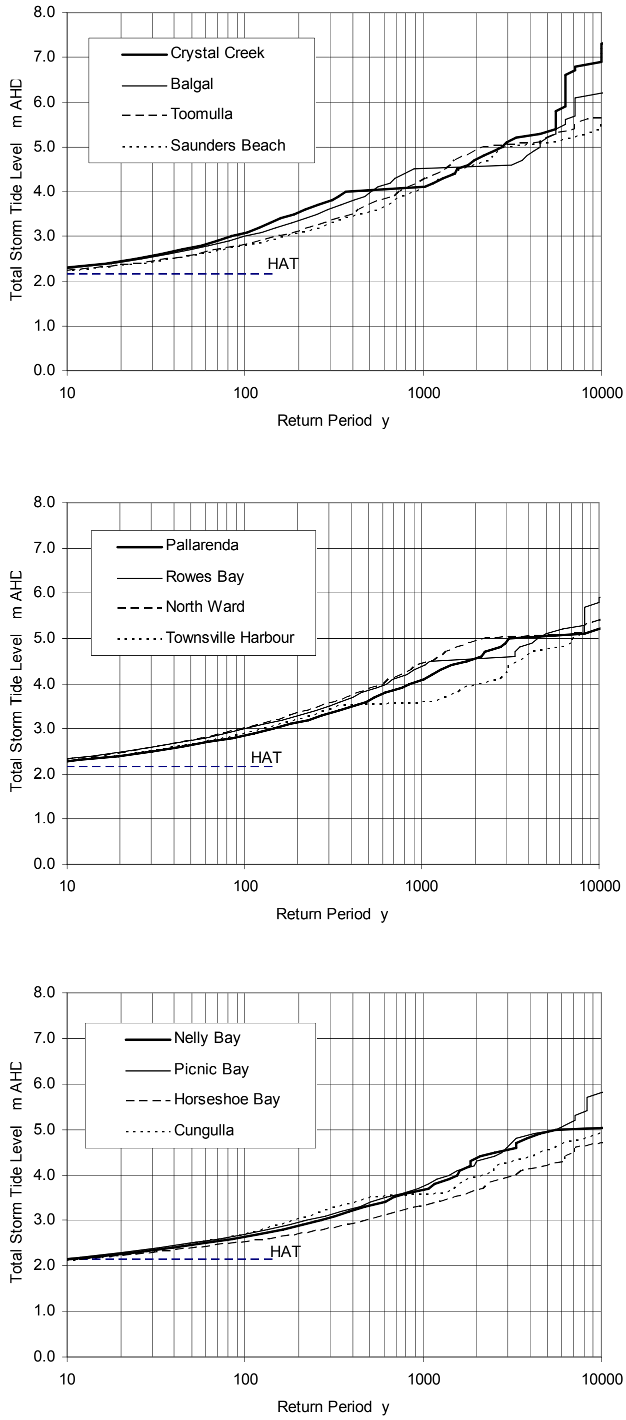


Figure 6-1 Estimated total storm tide levels for selected sites

Figure 6-4 Example site specific components of the total storm tide

(provided later) shows some detail of the relative contributions of surge and wave setup at specific sites.

Figure 6-2 illustrates the relative storm tide rankings for different sites. The order of sites is deliberately based on the 1,000 yr storm tide level, giving a smooth variation from highest to lowest ranked levels for this event. However, this process accentuates the variability in predicted levels for the 10,000 yr ARI event, where it can be seen the order of rankings is different owing to a combination of changing slope in the risk profiles beyond the 1,000 yr ARI and to the more erratic (less smooth) model predictions at the 10,000 yr ARI. Ranking on the basis of the 1000 yr event is therefore the more practical approach.

As previously mentioned, many of the differences in levels seen between nearby or adjacent sites are due to the assumed local dune crest heights, which will directly modulate the breaking wave setup estimate. The extent to which extreme values of wave setup could actually occur is difficult to assess within the present scope of work, whereby the representation of setup is necessarily simplified and ignores the real 2D situation[4]. As a result, the highest indicated storm tide levels are typically at those sites within large bays, exposed to waves and with a high dune crest elevation. Protected offshore sites with a low crest elevation have the lower estimates due to offshore attenuation of the surge and because the wave setup cannot develop above the dune crest height.

6.3 Open Coast Inundation Depths

Open coast inundation depths **relative to HAT** are summarised in Table 6-2 and Figure 6-3. These are expressed relative to the highest astronomical tide (HAT) so that it is easier for the public to relate to the additional depth of inundation that would arise over and above what they are used to. That is, they represent the additional depth of sea water over and above that associated with HAT at the open coast.

The relative ranking of storm tide inundation depths for the selection of townships is similar to that for the absolute elevations. The majority of locations have an estimated 1,000 yr return period storm tide inundation depth between 1.0 and 2.0 m above HAT, with only seven sites exceeding 2.0 m. However, about half of all the sites are estimated to exceed 3.0 m inundation at the coast at the 10,000 yr level. Note that localised wave runup would add to these levels in specific situations.

[4] The model wave setup assumptions are based on a 1D concept whereby incident waves are assumed perpendicular to the coast, the "beach" is of constant form and that the assigned "dune crest" height is constant between the modelled open coast locations. In practice, the wave directions, beach slopes and dune crests will vary and it is likely that rip currents will be established in a 2D sense that will act to reduce the wave setup in certain areas on a dynamically changing basis and that some sections of dunes will be eroded.

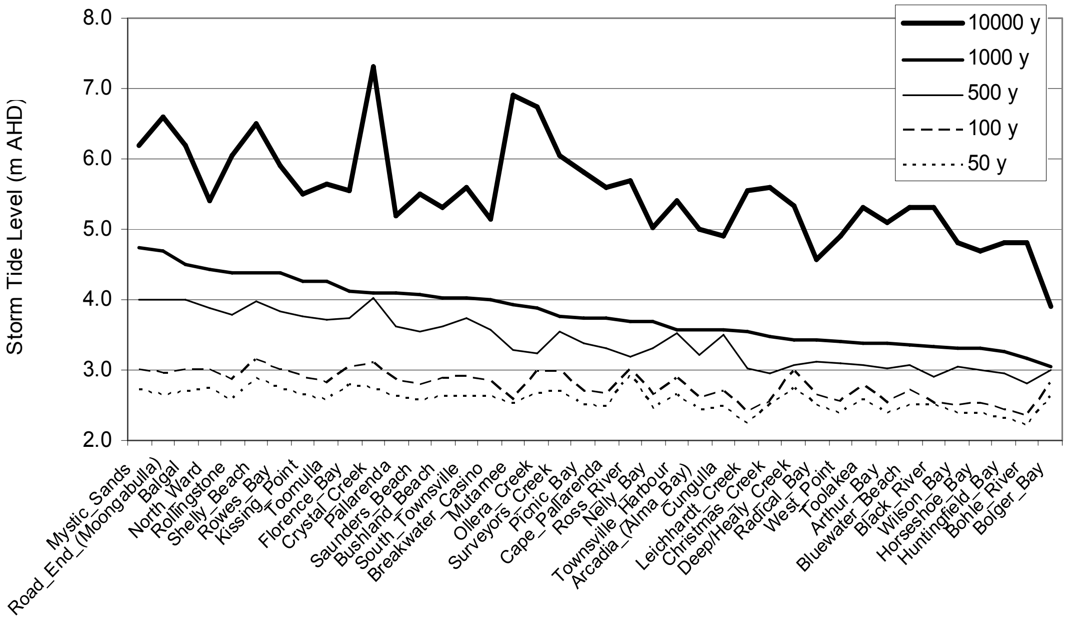


Figure 6-2 Ranking of estimated total storm tide levels

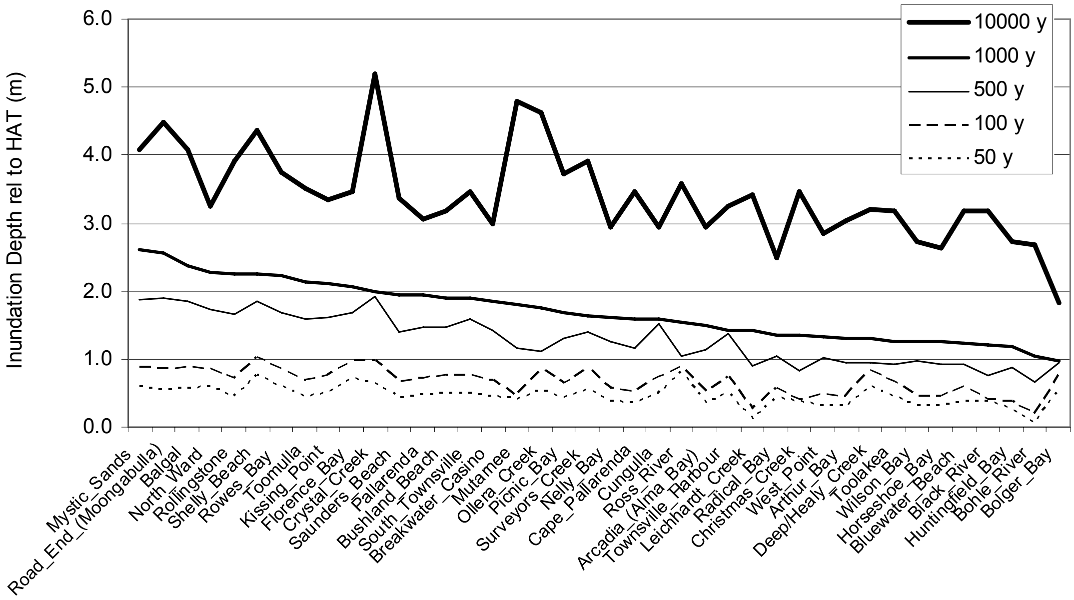


Figure 6-3 Ranking of estimated storm tide with respect to depth above HAT

Table 6-2 Estimated Storm Tide Inundation Depths above HAT for Selected Return Periods (metres)

Site	50 y	100 y	500 y	1000 y	10000 y
Crystal_Creek	0.6	1.0	1.9	2.0	5.2
Ollera Creek	0.6	0.9	1.1	1.8	4.6
Road End (Moongabulla)	0.4	0.5	1.2	1.8	4.8
Mutarnee	0.5	0.9	1.9	2.6	4.5
Balgal	0.6	0.9	1.9	2.4	4.1
Rollingstone	0.4	0.7	1.7	2.3	3.9
Mystic_Sands	0.6	0.9	1.9	2.6	4.1
Surveyors Creek	0.6	0.9	1.4	1.6	3.9
Toomulla	0.4	0.7	1.6	2.1	3.5
Leichardt Creek	0.1	0.3	0.9	1.4	3.4
Christmas Creek	0.4	0.4	0.8	1.3	3.5
Toolakea	0.4	0.7	0.9	1.3	3.2
Bluewater_Beach	0.4	0.6	0.9	1.2	3.2
Deep / Healy Creek	0.6	0.8	0.9	1.3	3.2
Saunders_Beach	0.4	0.7	1.4	1.9	3.4
Black River	0.4	0.4	0.8	1.2	3.2
Bushland_Beach	0.5	0.8	1.5	1.9	3.2
Bohle_River	0.1	0.2	0.7	1.0	2.7
Shelly_Beach	0.8	1.0	1.8	2.3	4.4
Cape_Pallarenda	0.4	0.5	1.2	1.6	3.5
Pallarenda	0.5	0.7	1.5	1.9	3.1
Rowes_Bay	0.6	0.9	1.7	2.2	3.8
Kissing_Point	0.5	0.8	1.6	2.1	3.4
North_Ward	0.6	0.9	1.7	2.3	3.3
Breakwater_Casino	0.5	0.7	1.4	1.9	3.0
Townsville_Harbour	0.5	0.7	1.4	1.4	3.3
South_Townsville	0.5	0.8	1.6	1.9	3.5

Site	50 y	100 y	500 y	1000 y	10000 y
Ross_River	0.8	0.9	1.1	1.6	3.6
Florence_Bay	0.7	1.0	1.7	2.1	3.5
Arthur_Bay	0.3	0.5	1.0	1.3	3.0
Arcadia_(Alma_Bay)	0.4	0.5	1.1	1.5	2.9
Nelly_Bay	0.4	0.6	1.3	1.6	3.0
Picnic_Bay	0.4	0.6	1.3	1.7	3.7
Bolger_Bay	0.6	0.8	0.9	1.0	1.8
West_Point	0.3	0.5	1.0	1.3	2.8
Huntingfield_Bay	0.3	0.4	0.9	1.2	2.7
Wilson_Bay	0.3	0.4	1.0	1.3	2.7
Horseshoe_Bay	0.3	0.5	0.9	1.3	2.6
Radical_Bay	0.4	0.6	1.1	1.4	2.5
Cungulla	0.5	0.7	1.5	1.6	2.9

6.4 Example Site Specific Estimates and Comparisons with other Published Values

Figure 6.4 provides some examples of the relationship between the estimated storm surge and wave setup components that add together to produce the total storm tide estimate. Also shown are the significant wave heights generated by the model, applicable to a nominal 3 m nearshore depth. Where available, comparisons are made with other published estimates for surge plus tide levels in the region. It should be noted that because of the complex relationships between each of the water level components, they do not necessarily add together linearly across return period space.

The top-left graph is for Crystal Creek, which is situated at the northern limit of Thuringowa City on an open coast within the broad expanse of Halifax Bay. This site has the highest estimated 10000 y total storm tide, which the graph shows is due to tide plus surge effects only beyond the 1000 y level. Although the breaking wave setup curve continues to rise, the model has limited its effects on the total storm tide level above the dune crest height. Also shown are the 1985 tide plus surge estimates from Harper (1985, 1999) for this stretch of coast, which reasonably match the present levels up to the 500 y ARI. The numerical modelling shows that Halifax Bay is particularly exposed to potentially large storm tide episodes.

The adjacent graph is for nearby Balgal, which shows a slightly lower tide plus surge result but wave setup is higher and the total storm tide is higher than at Crystal Creek until the dune crest is overtopped at around the 3000 y ARI. The 1985 estimates are again very close to the present tide plus surge values up until the 500 y ARI.

The remaining graphs illustrate similar behaviours with respect to the relationship between the wave setup component and the local dune crest. Comparisons with the 1985 tide plus surge values are however less favourable, with the older analyses typically showing magnitudes closer to the present total storm tide levels.

The graphs for Balgal, Saunders Beach, Pallarenda, Townsville and Horseshoe Bay additionally show estimated tide plus surge levels from the recently published JCU/MMU study (Hardy *et al.* 2004). In this case, the comparisons are very favourable out to the 500 y ARI at all sites and to 1000 y at Townsville, Pallarenda and Horseshoe Bay. Further north at Saunders Beach and Balgal, the present estimates begin to rise above the JCU/MMU estimates.

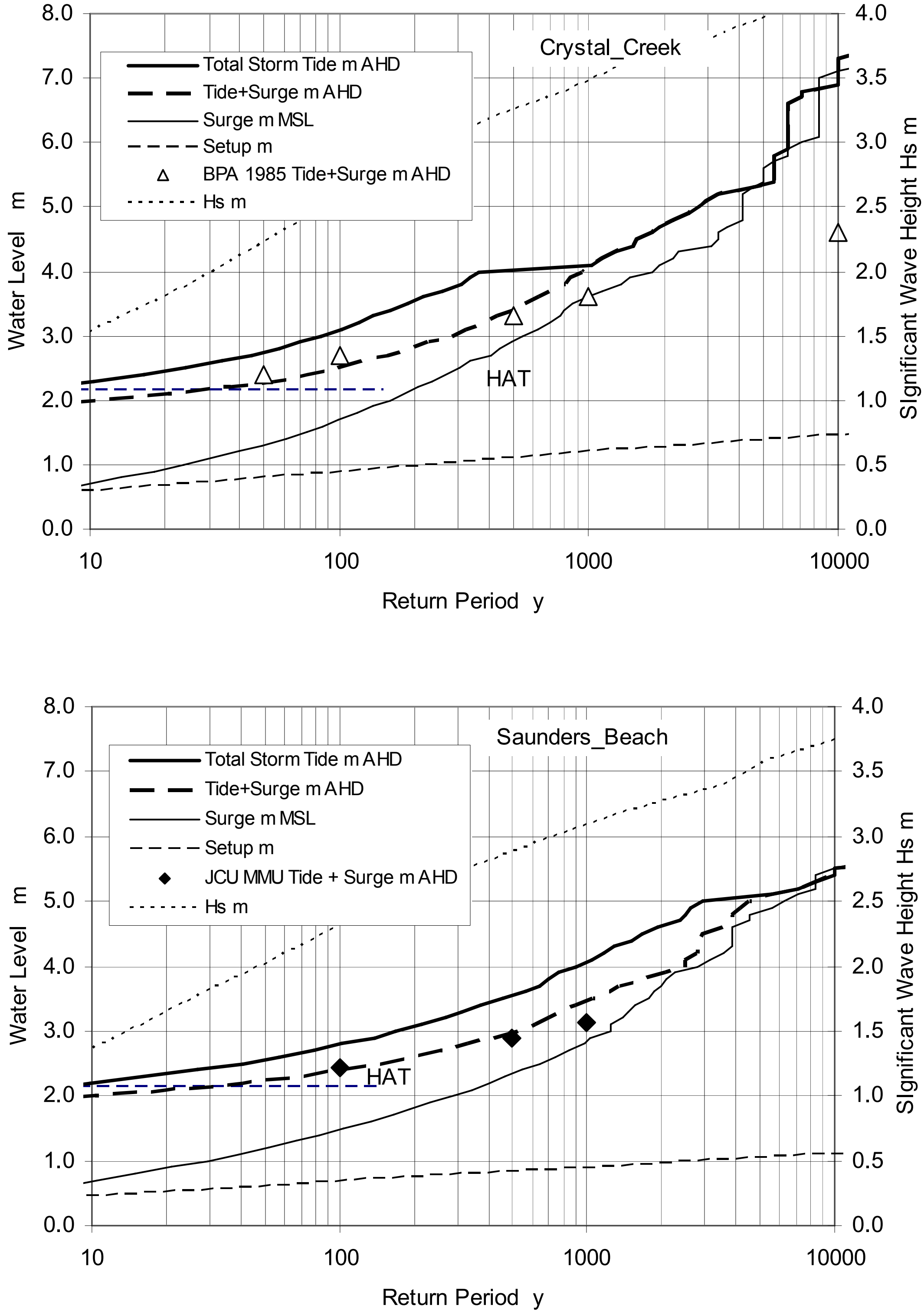
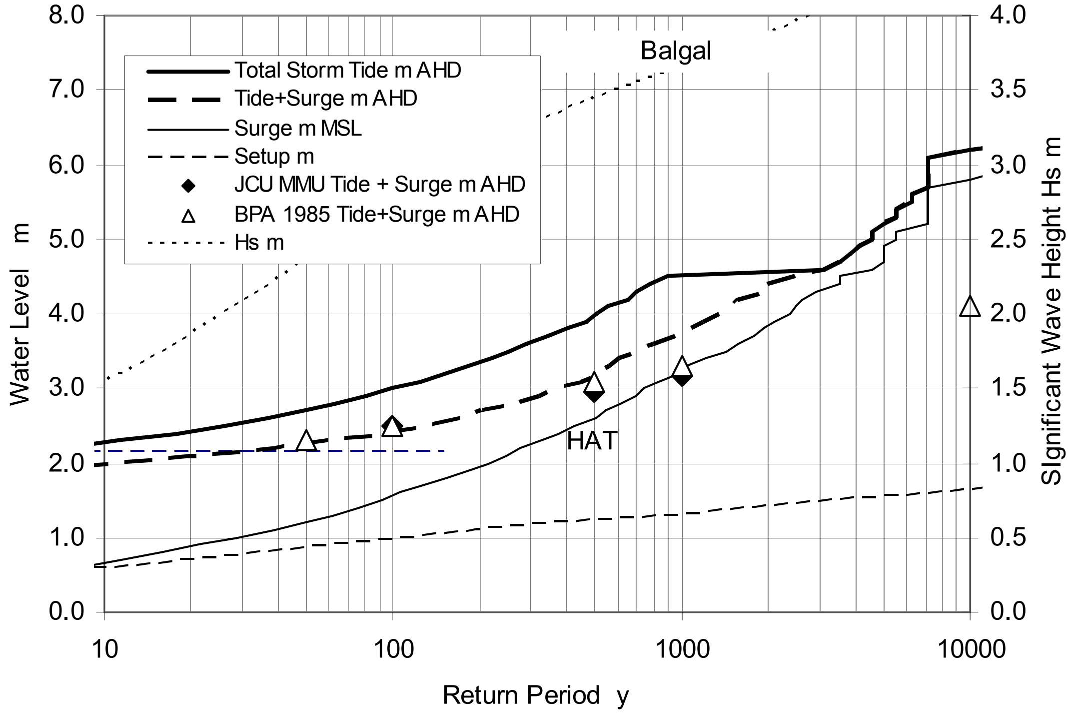


Figure 6-4 Example site specific components of the total storm tide



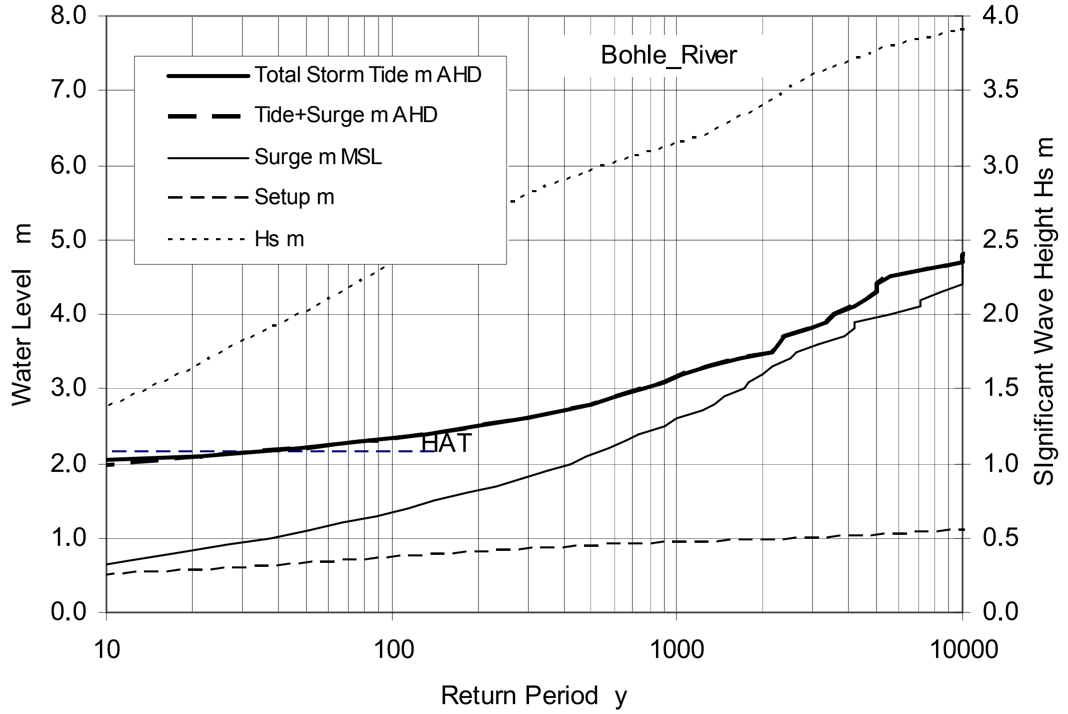
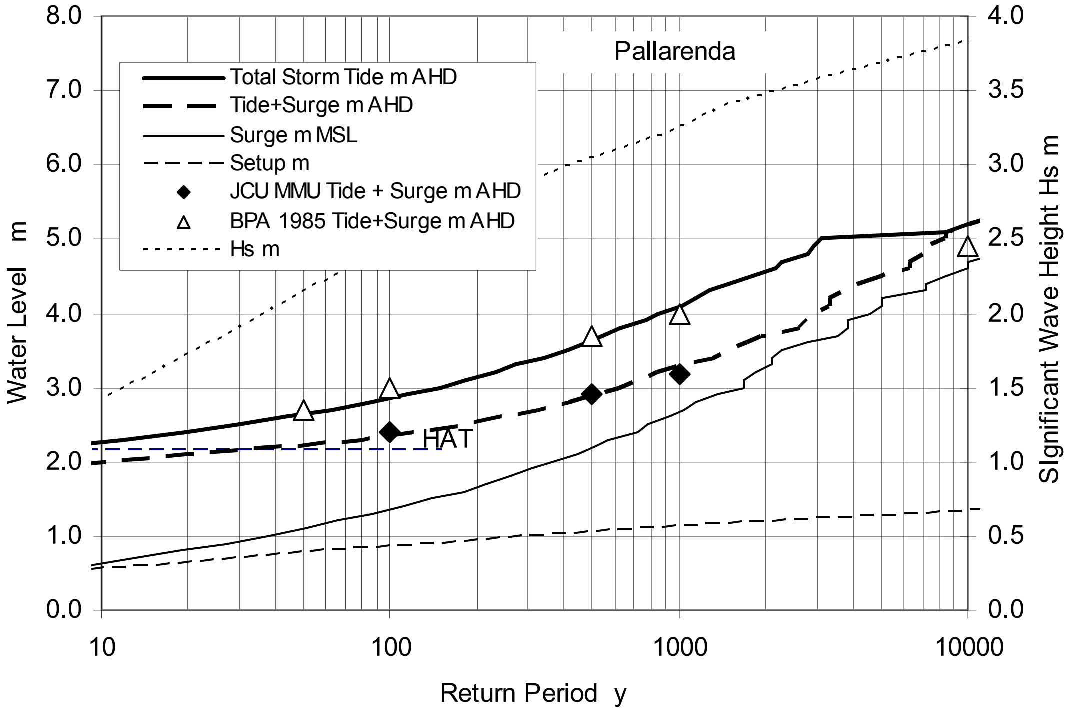


Figure 6-4 Example site specific components of the total storm tide



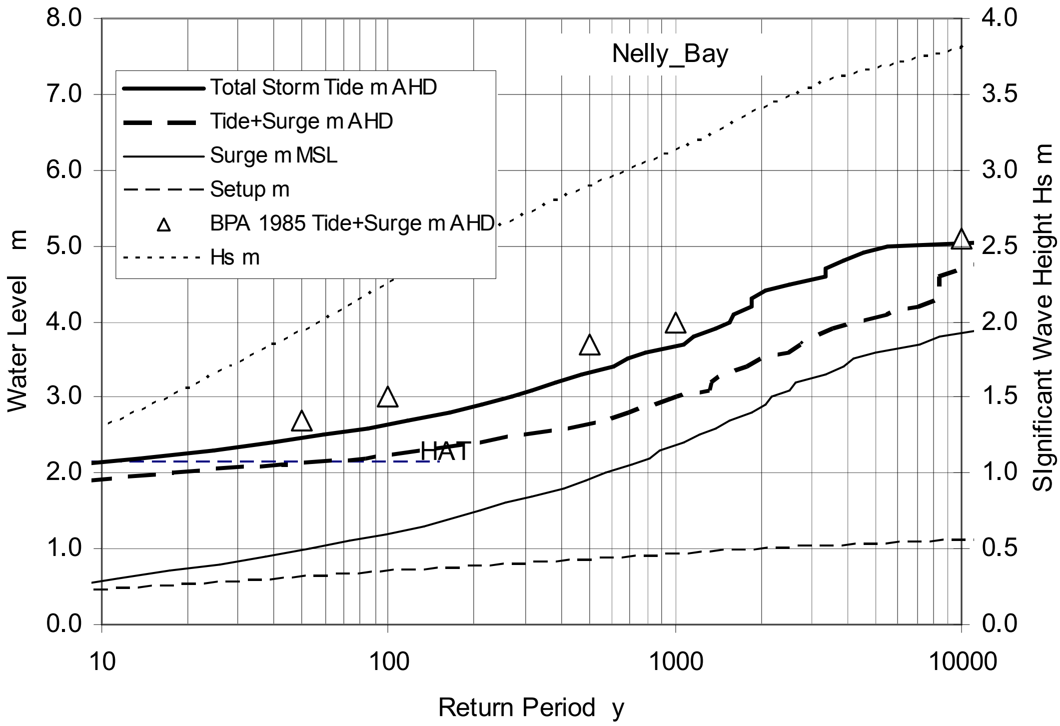
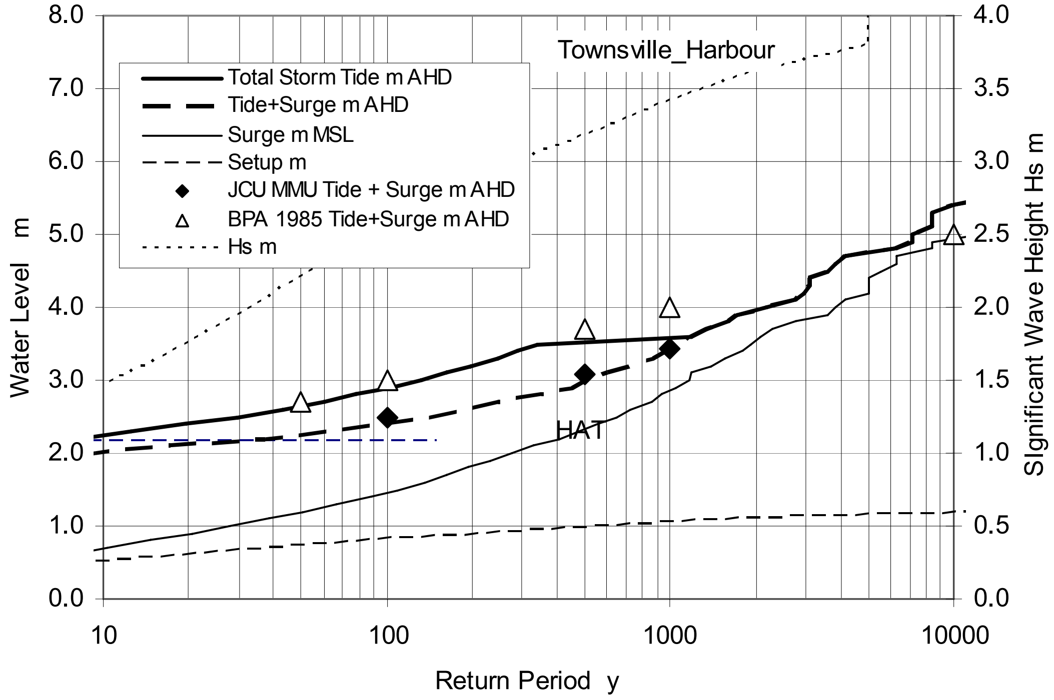


Figure 6-4 Example site specific components of the total storm tide



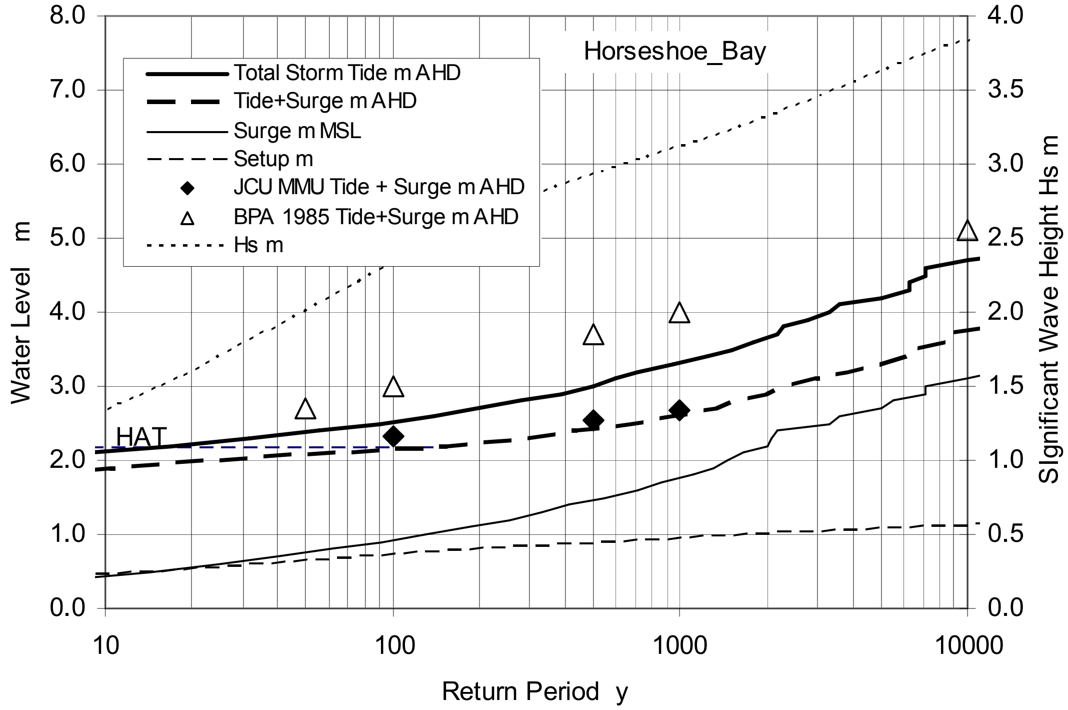
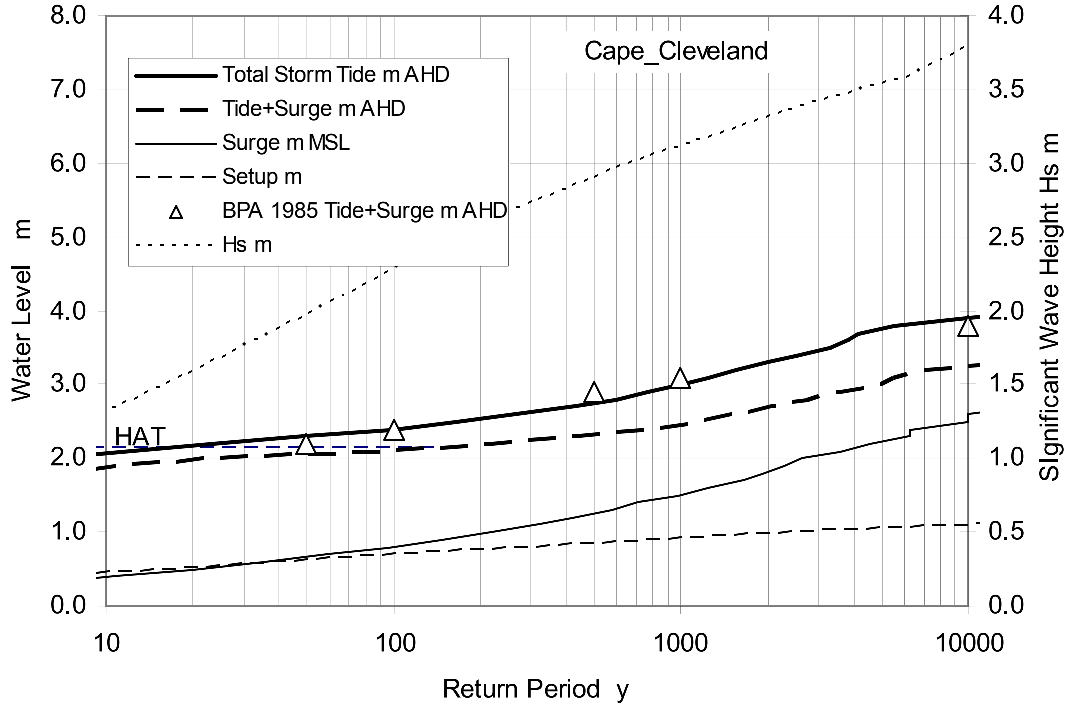


Figure 6-4 Example site specific components of the total storm tide



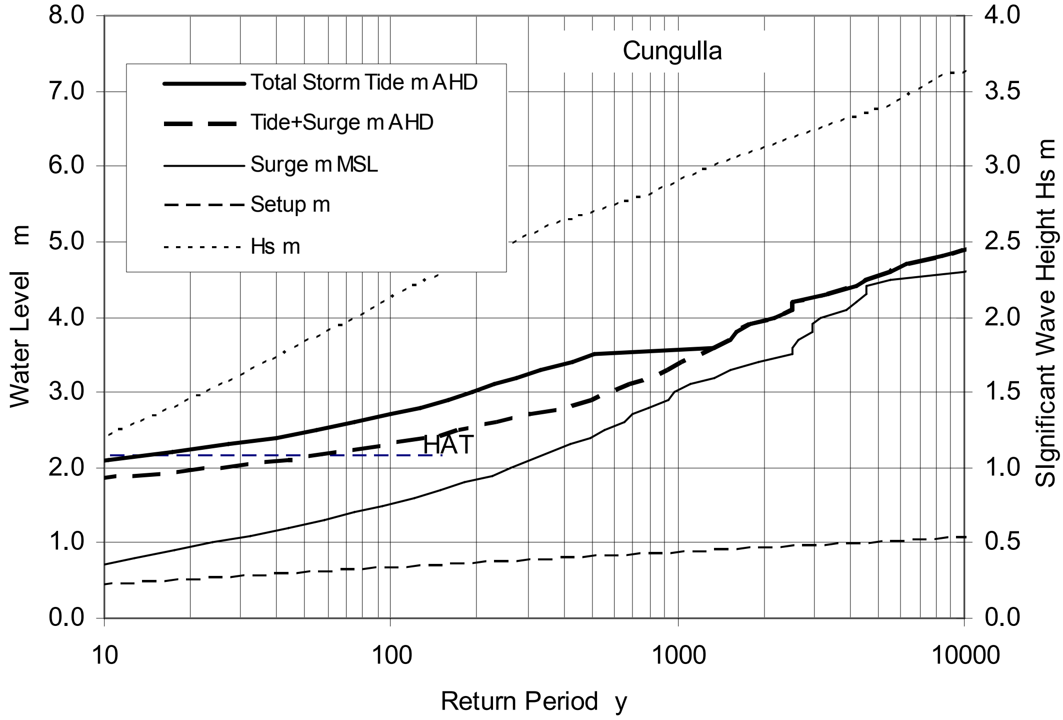


Figure 6-4 Example site specific components of the total storm tide

6.5 Saltwater Intrusion Water Level Persistence

The SATSIM model maintains statistics on the periods of time during which the predicted total storm tide levels are exceeded at each site. This information might be of benefit to emergency managers and in consideration of other effects such as the potential erosion of sandy scarps and the like, that has been outside of the present study scope.

Table 6-3 provides a summary of water level persistence for a number of selected sites in the study area that will be broadly representative of intermediate sites. The table shows the estimated time in hours that the water level equals or exceeds the indicated return period of total storm. These times are presented in terms of the probability of exceedance of those times, whereby the 50% value is the median exceedance (close to the mean or average), while the 10% value is close to the highest possible time and the 90% is close to the smallest possible time you should expect. For example, at Pallarenda under a 500 y scenario, one can expect that the level will be maintained for not less than 0.7 h, average about 1.9 h and have a 10% chance of going beyond 5 h.

Table 6-3 Duration of Saltwater Intrusion

Site	Return Period y	Time in Hours that Water Level Equals or Exceeds the Return Period Total Storm Tide Level								
		% Exceedance of Time								
		90	80	70	60	50	40	30	20	10
Crystal_Creek	50	0.3	0.7	1.1	1.4	1.8	2.2	2.8	3.7	5.4
	100	0.6	1.0	1.3	1.7	2.1	2.5	2.9	3.7	4.5
	500	0.5	0.8	1.0	1.4	1.9	2.3	2.7	3.0	4.3
	1000	0.3	0.7	1.0	1.3	1.6	1.9	2.2	2.5	3.7
Balgal	50	0.6	1.0	1.4	1.8	2.2	2.6	3.2	3.9	5.4
	100	0.6	0.9	1.3	1.7	2.1	2.5	3.0	4.0	5.0
	500	0.6	0.8	1.1	1.4	1.8	2.2	2.6	3.1	4.6
	1000	0.3	0.6	0.8	1.1	1.5	1.7	2.0	2.7	4.0
Saunders_Beach	50	0.5	0.8	1.1	1.5	1.8	2.2	2.6	3.3	4.4
	100	0.4	0.7	1.1	1.4	1.8	2.2	2.8	3.4	4.5
	500	0.6	0.9	1.2	1.4	1.8	2.2	2.7	3.3	4.7
	1000	0.5	0.7	0.9	1.2	1.5	2.0	2.5	2.9	3.8
Pallarenda	50	0.4	0.8	1.2	1.5	1.8	2.2	2.7	3.4	4.7
	100	0.5	0.9	1.3	1.6	2.0	2.4	2.9	3.4	4.6
	500	0.7	0.9	1.2	1.5	1.9	2.1	2.4	3.1	5.0
	1000	0.4	0.7	1.0	1.2	1.5	1.9	2.7	3.5	4.1
Townsville_Harbour	50	0.5	0.9	1.3	1.6	1.9	2.3	2.8	3.5	4.9
	100	0.5	0.8	1.1	1.5	1.9	2.4	2.8	3.6	4.6
	500	0.3	0.6	1.0	1.3	1.6	2.0	2.4	3.3	4.8
	1000	0.5	1.0	1.2	1.4	1.6	1.9	2.5	3.5	4.5
Nelly_Bay	50	0.4	0.9	1.2	1.5	1.9	2.2	2.6	3.3	4.6
	100	0.4	0.8	1.2	1.5	1.9	2.3	2.8	3.5	4.8
	500	0.5	0.8	1.2	1.6	1.9	2.3	2.7	3.4	4.5
	1000	0.6	0.9	1.1	1.5	1.8	2.1	2.7	3.7	6.1

6.6 Discussion

6.6.1 Wave Setup

Figure 6-5 and Figure 6-6 indicate the open coast locations that may be affected by wave setup. **The results show that the total storm tide level at the open coast is quite sensitive to the estimated wave setup component and the assumed nominal dune crest elevation.** Because wave setup can be a very localised phenomena dependent on the near and upper beach geometry, erodibility etc, the estimated levels may well be conservative. The nominal dune crest levels have been estimated within 0.5m AHD.

Hence, without a much more detailed analysis it is not possible to further quantify this effect. The more stable predictor of sustained water level along the open coast is the tide plus surge level (i.e. excluding wave setup), because of the much longer wavelength of the storm surge compared with an ocean wave.

The comparisons of tide plus surge estimates here with other published studies are quite favourable when considering the differences between the various studies. The 1985 estimates are derived from only nine simulations on a relatively coarse hydrodynamic model of 9.3 km resolution driven by a tropical cyclone model precursor to the Holland model (Harper 1977). The 1985 statistical model was also limited to a 1939 to 1979 climatology. Considering these differences it is not surprising that the 1985 estimates are higher than the present values. Interestingly though, the studies agree best at locations that are on relatively straight and open stretches of the coast.

The recent JCU/MMU study was done to a similarly detailed level to the present approach and shares basic open coast model grids and resolutions and many aspects of the wind field model. The main difference is that the JCU/MMU study considered more realistic natural storm tracks where the likely variability of storm parameters over time was captured. As a result, a parametric surge model was not developed but rather a large number of individual storms were fully modelled, albeit still at a fixed MSL. This processing overhead restricted the absolute number of storms that could be considered to about 5,000 in total, representing a synthetic time period of about 3,000 years. These storms were then recombined with randomly sampled tidal signals to produce the statistical estimates. Thus when comparing the present results, based on 50,000 years of synthetic storms, and the JCU/MMU results it is not surprising that they might differ towards the higher ARI values. It is gratifying however that the results have been shown to be very close across a wide range, thus providing a high level of confidence for planning purposes. The following section also demonstrates further similarities in respect of enhanced Greenhouse estimates.

Tables providing storm tide levels (with and without wave setup) are provided in Appendices K and L.

6.6.2 Application of Wave Setup Estimates

The role of the breaking wave setup process in contributing to the total storm tide is described in detail in Section 1.3.1. Importantly, wave setup applies only at an exposed coastline where the large incoming ocean waves are predominantly breaking directly onto a beach face, or a coastal barrier, dissipating their energy within a short distance. Wave setup will tend not to occur at river mouths, swampy low lying areas, places that are protected from the incoming waves or are located some distance inland from the coast, even if they are being flooded by the sea. All supplied detailed mapping has neglected the wave setup component because of its expected localised impacts along the open coastline, but the following advice is to assist Councils in interpreting the wave setup estimates for planning purposes.

The simulation model has employed an algorithm based on an estimate of the local "dune height" to decide when and where the wave setup will apply in the vicinity of the modelled open coastline sites. The extent to which any actual location on the open coast is affected by wave setup can then be gauged by comparing the ARI estimates for the closest adjacent modelled site in Appendix K (with wave setup) with the equivalent values from Appendix L (without wave setup). When the two levels are equal the model has decided that wave setup is not active because the land is effectively flooded immediately landwards of those sites. **Figure 6-5** and **Figure 6-6** indicate the location of the modelled nearshore sites where a wave setup component may be applicable for a specific ARI case.

At the present level of analysis it is not possible to say with certainty how far landward from the actual coastline wave setup effects might persist. Hence, when considering which levels to apply to a specific coast-exposed property from a planning perspective (i.e. those with wave setup or those without wave setup), the following protocol is suggested:

> *If the property falls within an area delineated by the shoreline (nominal high tide mark) and a 150m landward projection of that shoreline, apply the storm tide level including wave setup. Otherwise apply the storm tide level without setup as indicated on the inundation mapping.*

This protocol should result in a suitably conservative allowance for wave setup effects that is consistent with the present level of analysis. To define the areas likely to be impacted by wave setup with greater certainty, more detailed studies of breaking wave effects during storm tide events are recommended.

6.6.3 Inundation Modelling

Key factors that govern the height of the storm surge and hence the extent and intensity of overland inundation are summarised on the State Disaster Management Group website (http://www.disaster.qld.gov.au\disaster\surge.asp), with greater detail provided earlier in this report and in Harper (2001).

The key factors are:

- The intensity of the cyclone – the stronger the winds, the higher the surge;

- The speed of the cyclone – the faster the cyclone crosses the coast, the higher the surge;
- The angle at which the cyclone crosses the coast - a right angle crossing will increase the surge;
- The shape of the seafloor – the more gentle the slope, the greater the surge;
- Local features such as bays, headlands or islands can funnel the surge and amplify its height.

Following from the methodology adopted for the study, the effects of the above factors are accounted for throughout the implementation of SATSIM and mapped by extending inland the resulting SATSIM water level at the coastline until a matching terrain height is encountered. In addition to these effects, the landward increase in inundation depth caused by overland flow under the effect of cyclonic winds acting on the free water surface beyond the HAT line has also been included. The latter contribution to inundation depth has been estimated from the storm surge model as explained below.

Inundation (overland flow) modelling of inland areas was integrated into the storm surge modelling process whereby the hydrodynamic model was operated under the effects of the tide and cyclonic winds corresponding to a series of extreme events (i.e., 100y, 500y and 10000y events). This process led to the generation of time- and space-varying water elevations that were used to amend the SATSIM inundation depths with a dynamic inland component.

The forcing, the numerical grids and algorithms applied for the overland flow modelling were identical to those adopted in the coastal zone for the storm surge modelling.

With respect to the forcing, overland inundation was driven by the cyclonic winds propagating inland and water levels propagated from the coast in a one step process linking directly the dynamics in the coastal zone to the overland flooding. This ensured the correct representation of flood wave paths, arrival and recess times, water surface gradients and transfer of momentum at the coast.

The numerical grids used for the overland inundation modelling (D51 and D52) extended offshore well beyond the surf zone where nesting in the C grids was undertaken thus ensuring the capture, transformation and transfer in landward direction of the spatial and temporal structure of the storm surge build-up without potential loss of momentum.

Due to the staggered grid applied in Delft3D-FLOW, the total water depth at a velocity point for the computation of the discharge through a cell face is not uniquely defined. Usually it is determined by the arithmetic average of the depth specified in the vertices of the cell face (side) plus the average of the water levels computed in the cell centres at each side of that cell face. To improve the discrete representation of the overland flooding process, the option of determining water levels at cell faces using the upwind approach was adopted. This approach, which generally enhances the discharge throughout the cell face because the upwind water level is usually higher than the average water level, has been found to produce physically more realistic results in overland inundation studies than the one based on the arithmetic average of water levels.

For the purpose of representing the effect of winds more realistically, the overland wind-drag formulation was adjusted to account for the presence of buildings and structures in densely populated/developed areas.

6.7 Storm Tide Mapping

Mapping of the predicted storm tide levels represents one of the key deliverables of the project, with a comprehensive set of maps produced for each of the nominated events. These have been produced in several formats, illustrating:

- The extent of inundation; and
- Water depths.

Examples of each type of map are provided in Appendix H. The full set of maps is provided as a separate Appendix document for each Council in A3 format. These maps allow two key planning functions to be addressed, namely:

- A tool to facilitate managing of the ongoing development process, such that approvals are not granted in areas of unacceptable risk, and
- Better quantification of the extent of inundation for different recurrence intervals, such that the likelihood / frequency of evacuation events can be better gauged, and such that the maximum extent of inundation is better quantified.

Whilst predictions were generated on a 55m resolution grid, the results are mapped to a 10 m grid in order to more accurately represent small scale depressions and waterways.

Maps have been organised into a series of grids, with eight maps covering the Townsville area, and ten for Thuringowa. The 50 and 100 yr events show little difference in the inundation extent, whereas the 10,000 yr event demonstrates significant inundation. This is most evident along the Thuringowa coastline, where modelling suggests that several metres of water may be added inland as waters are trapped in valleys.

Overall, the areas most affected by inundation include the Bohle River floodplain and Town Common, areas to the south of Ross River, and to a lesser extent, several of the beachside communities of Thuringowa (Ollera Ck, north of Balgal, and Bluewater Ck). Significant low-lying areas between Toomulla and Toolakea (i.e. Leichardt Ck and Christmas Ck) are also affected.

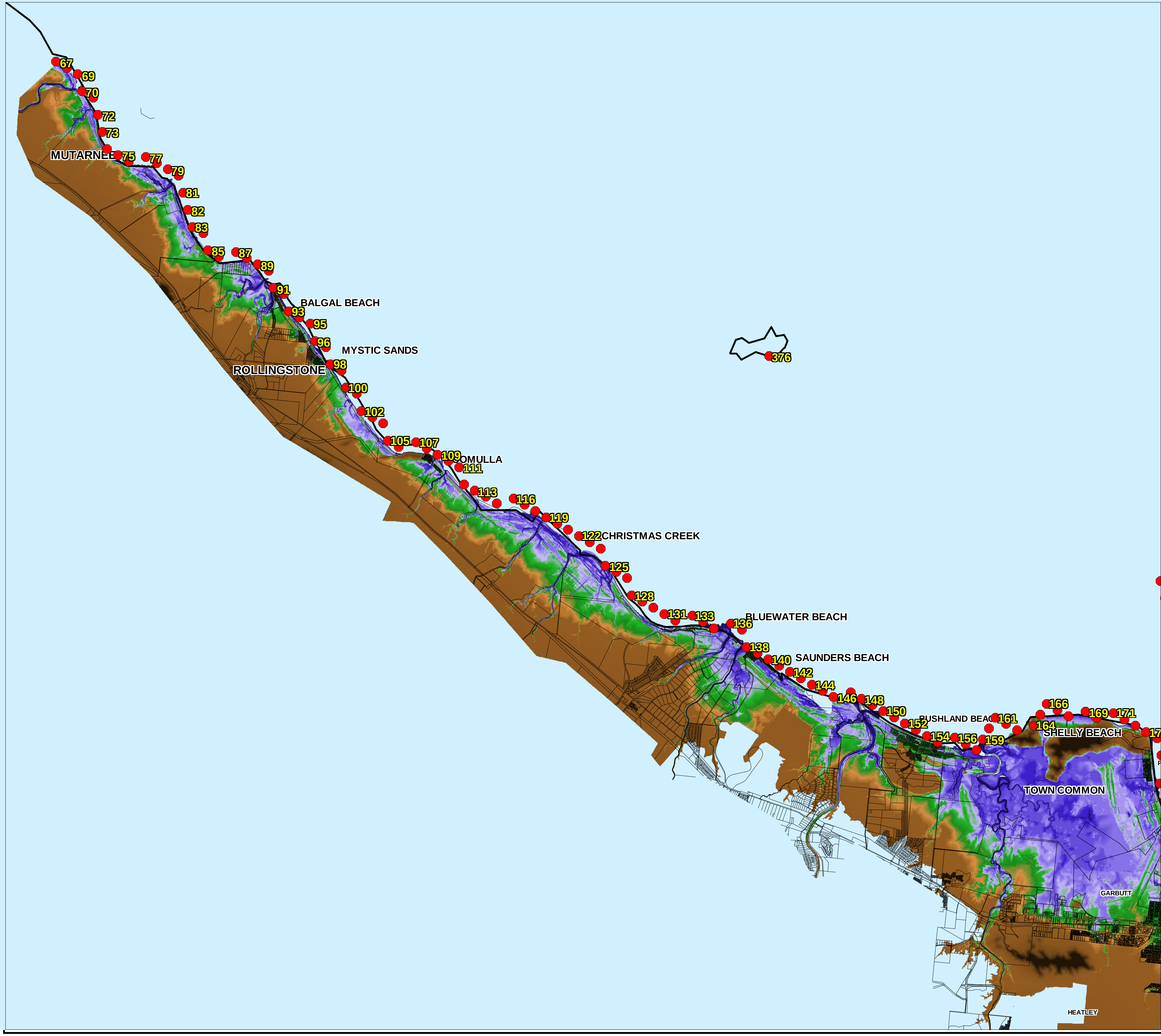
All results have also been produced in GIS format. When loaded onto Council's system, enquiries can be made as to depths or water surface at any location, for any of the four events considered. This has a practical benefit, in terms of dealing with planning considerations on an individual lot basis – i.e. the mapping can be used as a whole-of-city guide, but for detailed queries, reference can be made to the GIS database.

In terms of interpreting the results, it is important to reiterate that the 10,000 year event represents an estimate of the maximum storm tide event, and therefore retains an element of uncertainty. In particular, those areas along the Thuringowa coastline, where levels of up to 9 m AHD are predicted, should not be treated as absolute. Instead, a risk based approach should be applied, whereby those areas potentially subject to the greatest storm tide levels are provided with safe access.

TOWNSVILLE & THURINGOWA STORM TIDE STUDY

FIGURE 6.5

Thuringowa Open Coast Locations



LEGEND

- Wave Setup Data Points
- DCDB
- Coastline

North

Source Information: Topographic and DCDB Data supplied by Thuringowa and Townsville City Councils

SEA GHD MANAGEMENT ENGINEERING ENVIRONMENT

G:\41\13819\Mapinfo\Sat Sim Open Coast_Thuringowa.WOR

TOWNSVILLE & THURINGOWA STORM TIDE STUDY

FIGURE 6.6

Townsville Open Coast Locations

LEGEND

Wave Setup Data Points

DCDB

Coastline

North

Source Information: Topographic and DCDB Data Supplied by Thuringowa and Townsville City Councils

MANAGEMENT ENGINEERING ENVIRONMENT

G:\41\13819\Mapinfo\Sat Sim Open Coast_Townsville.WOR

7. Possible Impacts of ENSO and the Enhanced Greenhouse Effect

This section considers the possible impact on the storm tide estimates of both short term climate variability, as represented by the ENSO effect, and the long term effects under possible enhanced Greenhouse.

7.1 El Niño - Southern Oscillation (ENSO)

The El Niño - Southern Oscillation (ENSO), which originates in the tropical Pacific Ocean, is the strongest natural fluctuation of climate on inter-annual timescales and is also believed to influence decadal timescales (Nicholls 1992). The large scale climatic features of ENSO are known to shift the point of concentration of cyclone tracks on a seasonal basis, whereby so-called La Niña years experience an increase in tropical cyclone numbers closer to the east Australian coast. In the opposite scenario, or El Niño years, the centre of activity moves further east to the Pacific Islands region but the total number of storms each year in the South Pacific basin remains relatively constant.

The relative incidence of El Niño and La Niña episodes over the past 120 years typically suggests a chaotic system where the relative proportion of each extreme is similar. However, during the past two decades, there has been a much higher occurrence of El Niño events due to a general warming of the eastern pacific. Many climate models predict a continuation of the ENSO-like phenomenon under enhanced greenhouse conditions, with the possibility that El Niño conditions will become more prevalent.

The El Niño phase sees abnormally warm ocean temperatures off the coast of South America and along the central and eastern Pacific equatorial zone and simultaneously cooler ocean temperatures in the western Pacific and the Coral Sea. During the reverse cycle, or La Niña, ocean temperatures near the Queensland coast are typically above average. Ocean temperature is not the only factor causing cyclone variability, but it is a prime contributor, and when combined with associated shifts in large-scale zones of atmospheric convergence (Basher and Zheng 1995), the regions of tropical cyclone genesis in the South Pacific tend, as a result, to move further towards the east (El Niño) or the west (La Niña).

There are several techniques used for determining the state or strength of the ENSO condition. One of the most widely used methods is the Southern Oscillation Index (SOI), which compares differences in the mean monthly sea level pressure between Darwin and Tahiti. The SOI has been shown to be a strong indicator of rainfall and tropical cyclone activity in northern Australia and Queensland.

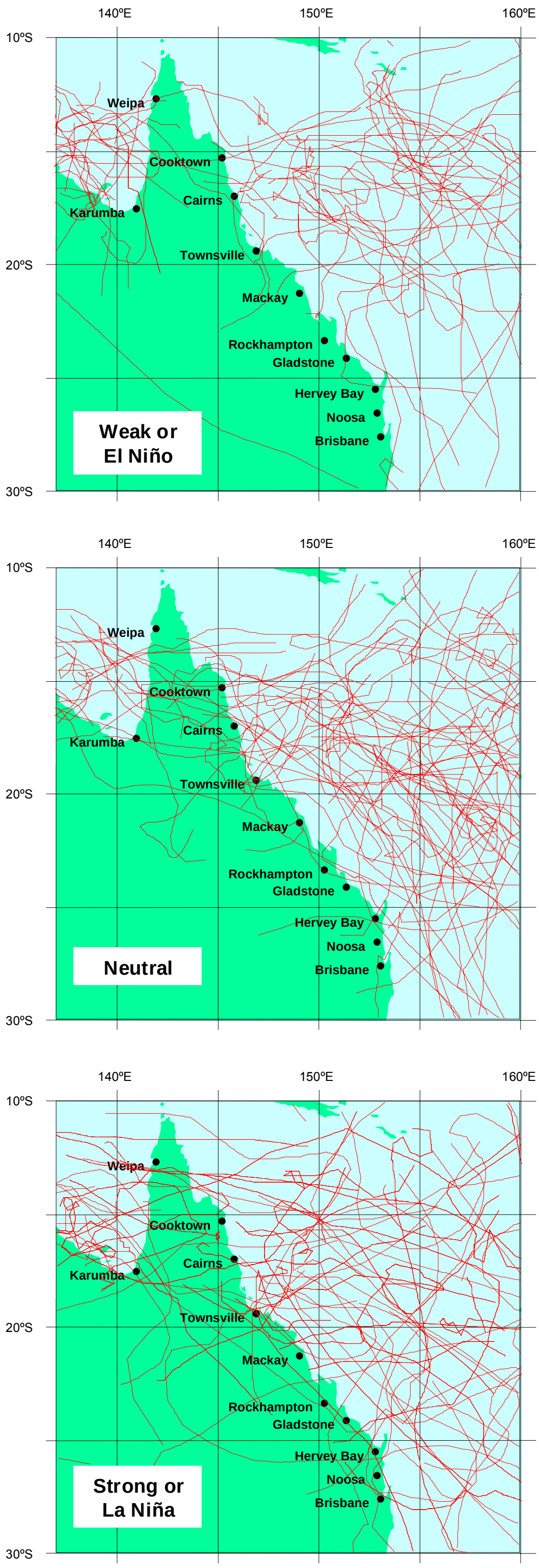


Figure 7-1 Tropical cyclone tracks grouped according to ENSO category (after Harper 2001)

A positive (strong) value indicates a La Niña condition and a negative (weak) value indicates an El Niño. Another common method of measuring the ENSO condition is to use sea surface temperature readings (SSTs) from various zones in the Pacific. These data have become routinely available from satellite as well as ships, drifting buoys and from moored buoy networks positioned along the equator. Using an accepted SST-based sequence from 1959 to 1997 (e.g. from Pielke and Landsea, 1999), Figure 7-1 shows that when the historical storm track record is separated into El Niño and La Niña periods, there is a quite noticeable effect on the tracks of tropical cyclones near the Queensland coast. During the El Niño (negative SOI) phase there are very low incidences of tropical cyclones near Brisbane, while during La Niña (the positive SOI) phases cyclone activity tends to be located further south and closer to the coast. For most of the time though, "neutral" conditions prevail, which are similar to the combined statistics. While the ENSO phenomenon appears to be somewhat random, El Niño years have outnumbered La Niña years by about a factor of three since the mid-1970s. This has been reflected along much of the east coast of Queensland by a corresponding reduction in frequency of cyclone occurrence. Exactly why this preference for El Niño episodes has persisted during this period is not entirely clear but it may be related to longer period climatic variability or even global climate change. From 1998 to early 2000, there has been a return to mild La Niña and near-neutral conditions, which have persisted to the present.

7.1.1 Representation of the ENSO Variability

The risk assessment methodology utilised here considers the recorded history of frequency, intensity and tracks of tropical cyclones within 500 km of the coast after the advent of satellite detection in 1959/60. While the occurrences of cyclones in any single year can vary considerably, as detailed in Chapter 4, the risk model uses the average occurrence rate when simulating storm tide responses. The observed inter-annual variability is assumed to merely represent a constant element of randomness in the weather patterns. However, increasingly detailed climate analyses show the presence of trends in occurrences rather than randomness alone, which suggests that there are other longer-term climate variables that might also be considered.

Because of the relatively short record of tropical cyclone data, separation of the data set into ENSO phase subsets tends to negate the statistical value. Accordingly, a simplified approach to estimate the impact of the ENSO variability is adopted here. It is assumed that the principal difference between ENSO periods relates to the relative proportion of storm track types (offshore moving, parallel and coast-crossing) and that the intensity of storms remains relatively constant according to the track class. For the present purposes, modified frequency of occurrence parameters have been derived which broadly describe the observed variation in track proportions from Figure 7-1. These are presented in summary form as Figure 7-2, where the “average” line shows the combined data set that forms the basis of the long term storm tide predictions. The “neutral” and “El Nińo” lines are closest to the average, whereas the “La Nińa” line exhibits the significant shift towards landfalling storms. These modified occurrence values have then been used in sensitivity tests in place of the long-term average track proportions to gauge the impact of "long term averages" of each of the ENSO phase periods. The true system behaviour then can be considered to vary between the ENSO extremes. This permits the current SOI and forward seasonal trend to be used to assess the impacts over the coming months or year relative to the standard case of the long term average.

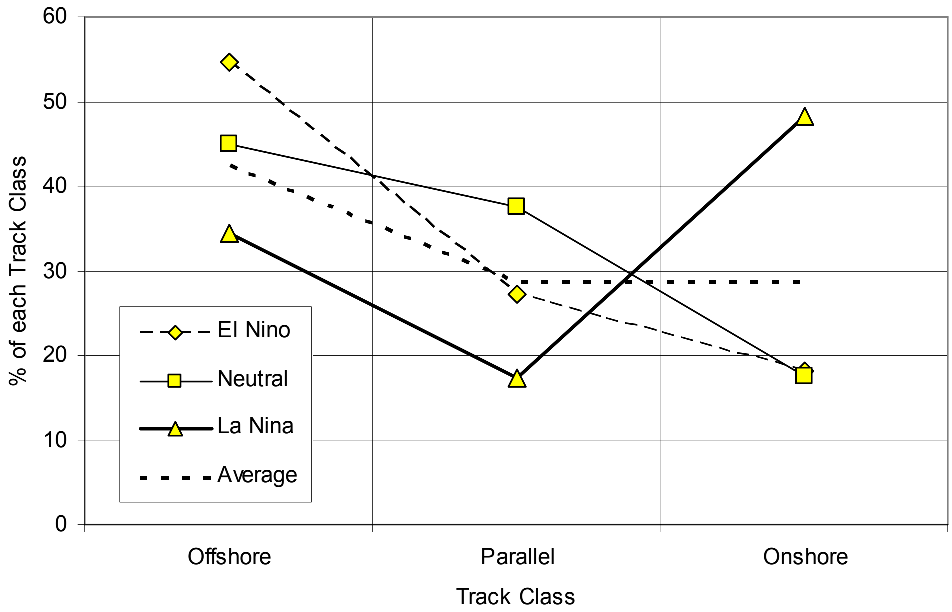


Figure 7-2 Tropical cyclone track classes according to ENSO category

7.1.2 Results of Modelling the ENSO Variability

One direct indication of the possible effects of ENSO can be seen in Figure 7-3, which shows the impact on the predicted gust wind speed at Townsville. The assumption of persistent neutral and El Níno phases causes a slight reduction in the return period curve relative to the average, while the La Nína phase causes a slight increase due to the larger proportion of landfalling storms.

Based on the assumed scenarios, the effect of ENSO therefore appears relatively small in regard to wind speed and this is reflected in the storm tide estimates also, where almost no differences are predicted below the 100 y return period level. Table 7-1 summarises the results in terms of the modelled differences averaged across all named sites in the study area. Consistent with the wind speed variation, the neutral and El Níno phases cause a slight reduction relative to the average, while the La Nína phase causes a slight increase. At the PMF level, the result is slightly less consistent but this is due to the innate model sensitivity at the 10,000 y level.

Table 7-1 Summary of estimated differences in the long term storm tide levels due to ENSO variability

ENSO	100 yr	500 yr	1000 yr	10,000 yr
Phase	m	m	m	m
El Nińo	-0.1	-0.2	-0.3	-1.0
Neutral	-0.1	-0.2	-0.3	-0.8
La Nińa	0.1	0.2	0.1	-0.4

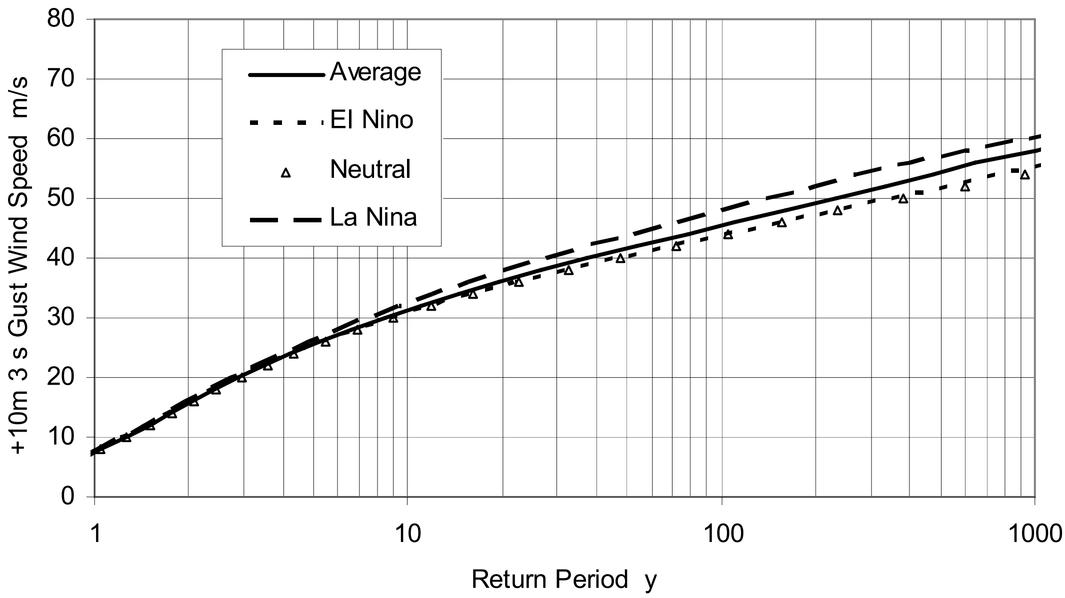


Figure 7-3 Effect of ENSO Phase on Modelled Gust Wind Speeds at Townsville

7.2 The Enhanced Greenhouse Effect

Over the past two decades there has been a growing awareness of the potential impacts that human-induced global climate change may have, and especially its possible effects on the coastal environment (NCCOE 2004). The estimated return periods for storm tide levels in the present study rely on the assumption that the natural environment, although highly variable, remains statistically static and that probability distributions for tropical cyclones and sea level are unchanging with the passage of time. However, the proven rise in atmospheric carbon dioxide levels and an increasing trend in mean air temperatures points to the possibility of the Earth being subject to an enhanced "greenhouse" effect, which means that these assumptions may be in error to some extent. Consequently, some consideration of the possible impacts of future climate change on modifying the present storm tide estimates is addressed in this section. The effect that these possible climate changes might have already had on the past historical data is not able to be quantified and is therefore neglected at this time.

7.2.1 Potential Sea Level Rise

Global sea levels are expected to rise as a consequence of enhanced greenhouse warming of the earth (IPCC 2001). The observed rate of sea level rise during the 20th century is thought to be in the range 1.0 to 2.0 mm/yr, although there are large regional differences.

The main contributions to this projected rise are, in order of decreasing contribution:

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

The official projections of global average sea level rise from 1990 to 2100 are in the range 0.09 to 0.88m (IPCC 2001; CSIRO 2001), as summarised in Table 7-2 below.

Table 7-2 Projected Rise in Global Mean Sea Level by the Year 2100

Range	**m**
Min	0.09
Central	0.48
Max	0.88

Although the year 2100 is normally quoted, it is important to note that if greenhouse gas concentrations were stabilised (even at present levels), sea level is nonetheless predicted to continue to rise for hundreds of years, e.g. refer the trends displayed in Figure 7-4. The range of projected rise in sea level is based on a number of different greenhouse gas emission scenarios that are derived from consideration of the possible socio-economic and political makeup of a future world. No probabilities are attached to the stated ranges and so the “central” estimate is often taken as the planning reference. However, to allow comparison with other recently published levels conducted by JCU/MMU (Hardy *et al.* 2004, Harper 2004), the upper level estimates at 2050 are considered and then extended to 2100 for completeness. As will be seen, it is possible to infer the central estimates of sea level rise based on these results if required for planning purposes.

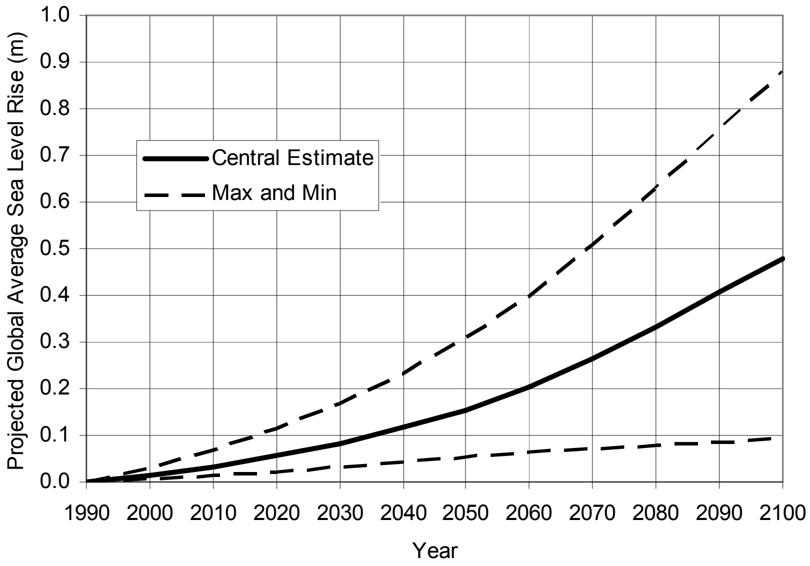


Figure 7-4 Official Projections of Global Average Sea Level Rise (after NCCOE 2004)

7.2.2 Possible Changes to Tropical Cyclones

The current IPCC (2001) view on the possible effects of climate change on tropical cyclones supports the statement by the specialist Tropical Marine Research Program sub-committee of the WMO Commission for Atmospheric Sciences (Henderson-Sellers *et al.* 1998), which provides definitive guidance on a number of specific tropical cyclone issues.[5]

The major conclusions of this assessment are as follows (NCCOE 2004):

- Long-term reliable data on tropical cyclone intensity and frequency show substantial multi-decadal variability but there is no clear evidence of any long term trends in number, intensity or location.
- Recent thermodynamic modelling attempts to estimate the maximum potential intensity (MPI) of tropical cyclones in present climate has shown good agreement with observations (e.g. Holland 1997).
- Application of MPI techniques to changed climate indicate the MPI of cyclones will remain the same or undergo a modest increase of up to 10 - 20% at the extreme end of the scale.
- The broad geographic regions of cyclone genesis and therefore also the regions affected by tropical cyclones are not expected to change significantly.
- The very modest available evidence points to an expectation of little or no change in global frequency.

[5] In spite of a series of controversial scientific papers during 2005 (e.g. Emanuel 2005, Webster et al. 2005) the 1998 WMO position was essentially reinforced at the 6th International Workshop on Tropical Cyclones (IWTC-VI), held in Costa Rica in November 2006. The updated WMO statement was made available at http://www.wmo.int/web/arep/arep-home.html in December 2006 and can also be sourced via WMO (2006).

- Regional or local frequency of occurrence may however change substantially, in either direction, because of the dependence of cyclone genesis and track on other phenomena (e.g. ENSO) that are not yet predictable.

7.2.3 Climate Change Scenarios Considered for this Study

In light of the above scientific projections, the climate change scenarios considered in this study are summarised below in Table 7-3.

Table 7-3 Enhanced Greenhouse Scenarios

Scenario Year	Increase in Frequency of Occurrence	Increase in Maximum Potential Intensity	Increase in Mean Sea Level
	%	%	m
2050	10	10	0.5
2100	10	20	0.9

In regard to these assumptions:

(a) A rise in mean sea level (MSL) will also lead to a rise in HAT and the tidal characteristics may also change slightly as a result, but this effect is ignored. Also, although AHD is based on MSL, it is assumed here that the AHD datum will remain where it is now.

(b) An increase in tropical cyclone MPI is not a straightforward concept to apply to the statistical description of individual cyclone central pressure values. The interpretation made here is that the most intense of cyclones may increase their intensity but that not all cyclones will be more intense. The way that this is applied is shown in Figure 7-5, whereby the potential % increase (relative to Δp) is blended into the present climate description used by the statistical model.

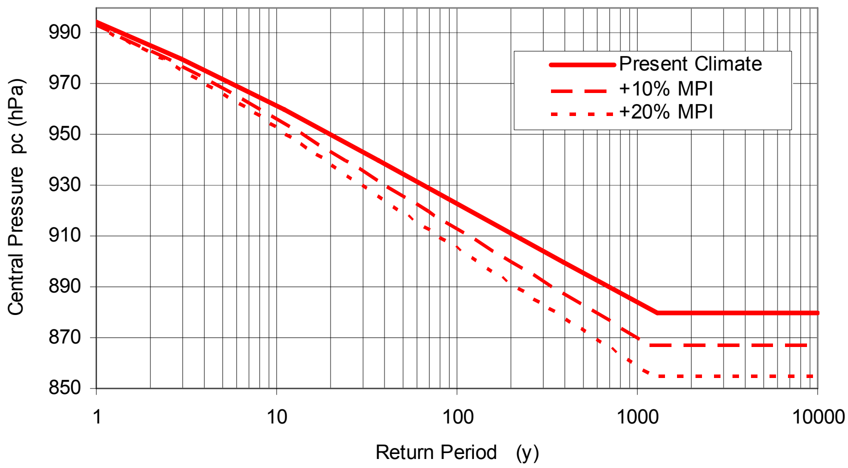


Figure 7-5 Assumed Possible Changes in the Intensity of Tropical Cyclones under Enhanced Greenhouse Conditions within 500km of Townsville

7.2.4 Results of the Climate Change Scenarios

To simplify the presentation of the potential impact of climate change, only the increases in estimated storm tide levels are provided in the following tables. The values below in Table 7-4 and Table 7-5 may then be added to those Table 6-1 to obtain an estimate of the potential storm tide probability levels relative to present day AHD by the year 2050 or 2100 respectively.

The results for 2050 show an average increase across all sites of interest of 0.5 m at both the 500 yr and 1000 yr return period and 0.7 m for the 10,000 yr. The corresponding averaged results for 2100 are increases of 1.1 m, 1.2 m and 1.9 m respectively. The increases vary partly as a result of the dune crest elevation at each site, which has the effect of limiting the breaking wave setup component differently under different scenarios. Remembering that the "max" estimate for sea level rise has been used, there is a possibility then that storm tide levels would be less than these values. The effect of the static increase in MSL has been subtracted at the base of each table to reveal an estimate of the separate combined effects of the increase in frequency of occurrence and the increased MPI. These can then be added to, for example, the "central" estimates of MSL rise if required.

However, if the projected increase in El Niño years eventuates, there is also the likelihood that the regional frequency of severe tropical cyclones crossing the coast will reduce, which could have a similar but opposite impact to a +10% MPI increase. Also, sea level rise in the Southern Hemisphere is expected to be slightly below the global average.

Table 7-4 Estimated Increase in Total Storm Tide Levels for Selected Return Periods under Enhanced Greenhouse Scenario in the Year 2050

	Estimated Return Period of Total Storm Tide Level				
	50 y	**100 y**	**500 y**	**1000 y**	**10000 y**
Site	**m AHD**	**m AHD**	**m AHD**	**m AHD**	**m AHD**
Crystal_Creek	0.4	0.4	0.1	0.6	1.0
Ollera Creek	0.3	0.1	0.6	0.6	0.5
Road End (Moongabulla)	0.1	0.3	0.6	0.6	0.5
Mutarnee	0.4	0.4	0.6	0.3	0.6
Balgal	0.4	0.4	0.5	0.1	0.9
Rollingstone	0.4	0.4	0.6	0.6	1.1
Mystic_Sands	0.4	0.4	0.7	0.3	1.2
Surveyors Creek	0.4	0.4	0.2	0.6	1.3
Toomulla	0.4	0.4	0.5	0.6	1.2
Leichhardt Creek	0.4	0.4	0.5	0.4	1.0
Christmas Creek	0.1	0.2	0.5	0.4	0.7
Toolakea	0.4	0.2	0.4	0.5	0.9
Bluewater_Beach	0.4	0.3	0.4	0.5	0.8
Deep/Healy Creek	0.3	0.1	0.4	0.5	1.1
Saunders_Beach	0.4	0.4	0.6	0.5	1.0
Black River	0.1	0.2	0.6	0.5	0.8
Bushland_Beach	0.4	0.4	0.6	0.5	0.8
Bohle_River	0.3	0.4	0.5	0.5	0.8
Shelly_Beach	0.4	0.5	0.6	0.7	0.4
Cape_Pallarenda	0.4	0.4	0.6	0.7	0.5
Pallarenda	0.4	0.4	0.6	0.7	0.5
Rowes_Bay	0.4	0.5	0.6	0.2	0.5
Kissing_Point	0.4	0.5	0.6	0.7	0.6
North_Ward	0.4	0.5	0.6	0.6	0.8
Breakwater_Casino	0.4	0.4	0.5	0.1	0.9
Townsville_Harbour	0.4	0.5	0.1	0.6	0.7

	Estimated Return Period of Total Storm Tide Level				
	50 y	100 y	500 y	1000 y	10000 y
Site	**m AHD**	**m AHD**	**m AHD**	**m AHD**	**m AHD**
South_Townsville	0.4	0.4	0.5	0.7	0.9
Ross_River	0.1	0.1	0.6	0.8	0.8
Florence_Bay	0.4	0.4	0.6	0.6	0.8
Arthur_Bay	0.4	0.4	0.6	0.6	0.5
Arcadia_(Alma_Bay)	0.4	0.4	0.5	0.6	0.1
Nelly_Bay	0.4	0.4	0.6	0.7	0.3
Picnic_Bay	0.4	0.4	0.6	0.7	0.5
Bolger_Bay	0.4	0.2	0.1	0.2	0.7
West_Point	0.4	0.4	0.5	0.5	0.1
Huntingfield_Bay	0.3	0.4	0.5	0.6	0.7
Wilson_Bay	0.4	0.4	0.4	0.6	0.9
Horseshoe_Bay	0.4	0.4	0.5	0.5	0.6
Radical_Bay	0.4	0.4	0.5	0.5	0.8
Cungulla	0.4	0.4	0.1	0.6	1.1
Average	0.3	0.4	0.5	0.5	0.7
Relative to Static 0.3m MSL Increase	0.0	0.1	0.2	0.2	0.4

Table 7-5 Estimated Increase in Total Storm Tide Levels for Selected Return Periods under Enhanced Greenhouse Scenario in the Year 2100

	Estimated Return Period of Total Storm Tide Level				
	50 y	**100 y**	**500 y**	**1000 y**	**10000 y**
Site	**m AHD**	**m AHD**	**m AHD**	**m AHD**	**m AHD**
Crystal_Creek	1.0	0.9	0.8	1.5	2.4
Ollera Creek	0.6	0.5	1.4	1.4	2.4
Road End (Moongabulla)	0.7	1.0	1.4	1.5	2.3
Mutarnee	1.0	1.1	1.0	0.7	2.5
Balgal	1.0	1.1	0.6	0.7	2.6
Rollingstone	1.0	1.1	1.2	0.8	2.8
Mystic_Sands	1.0	1.1	1.0	0.5	2.6
Surveyors Creek	0.8	0.6	1.0	1.5	2.8
Toomulla	1.0	1.1	1.3	0.8	2.6
Leichhardt Creek	1.0	1.0	1.3	1.3	2.4
Christmas Creek	0.7	0.9	1.3	1.3	2.0
Toolakea	0.6	0.6	1.2	1.3	2.1
Bluewater_Beach	0.7	0.6	1.2	1.3	1.9
Deep / Healy Creek	0.5	0.4	1.2	1.3	2.1
Saunders_Beach	1.0	1.1	1.5	1.0	1.9
Black River	0.7	0.8	1.3	1.3	1.8
Bushland_Beach	1.0	1.1	0.9	0.7	1.8
Bohle_River	0.9	1.0	1.3	1.3	2.0
Shelly_Beach	1.1	1.1	1.4	1.6	1.4
Cape_Pallarenda	1.0	1.1	1.3	1.5	1.7
Pallarenda	1.0	1.1	1.4	1.0	1.6
Rowes_Bay	1.0	1.1	0.7	0.8	1.7
Kissing_Point	1.0	1.1	1.3	0.8	1.6
North_Ward	1.0	1.1	1.2	0.7	1.8
Breakwater_Casino	1.0	1.1	0.6	0.9	1.9

	Estimated Return Period of Total Storm Tide Level				
	50 y	**100 y**	**500 y**	**1000 y**	**10000 y**
Site	**m AHD**	**m AHD**	**m AHD**	**m AHD**	**m AHD**
Townsville_Harbour	0.9	0.7	0.8	1.4	1.7
South_Townsville	1.0	1.1	0.9	1.6	1.9
Ross_River	0.4	0.5	1.4	1.7	1.8
Florence_Bay	1.0	1.1	1.3	1.4	1.5
Arthur_Bay	1.0	1.0	1.3	1.3	1.4
Arcadia_(Alma_Bay)	1.0	1.1	1.3	1.4	1.0
Nelly_Bay	1.0	1.1	1.4	1.3	1.2
Picnic_Bay	1.0	1.1	1.3	1.6	1.3
Bolger_Bay	0.4	0.3	0.6	0.9	1.7
West_Point	1.0	1.0	1.2	1.3	0.7
Huntingfield_Bay	1.0	1.0	1.2	1.4	1.5
Wilson_Bay	1.0	1.0	1.2	1.4	1.6
Horseshoe_Bay	1.0	1.0	1.2	1.3	1.5
Radical_Bay	1.0	1.0	1.2	1.3	1.5
Cungulla	1.0	0.8	0.8	1.4	2.1
Average	0.9	0.9	1.1	1.2	1.9
Relative to Static 0.9m MSL Increase	0.0	0.0	0.2	0.3	1.0

7.2.5 Comparisons with Recent JCU/MMU 2050 Surge plus Tide Estimates

As mentioned earlier, one of the reasons for choosing the “upper” MSL estimate with the 2050 scenario was to allow comparison with the recently published JCU/MMU estimates for surge + tide under Greenhouse conditions (Hardy *et al.* 2004). Note that wave setup is not included in the JCU/MMU analysis, and hence comparisons with the total storm tide estimates in Table 7-4 and Table 7-5 are not possible. However Figure 7-6 presents some selected site comparisons in the context of surge plus tide alone.

The graphs show an exact correspondence for 2050 at all sites for the 100 y return period and very close correspondence at Townsville and Pallarenda for the 500 y level. At the 1000 y level the present estimates are approximately 0.3 to 0.4 m higher across these sites. Results are also available for Horseshoe Bay, where the correspondence between the two studies (not shown) is almost exact.

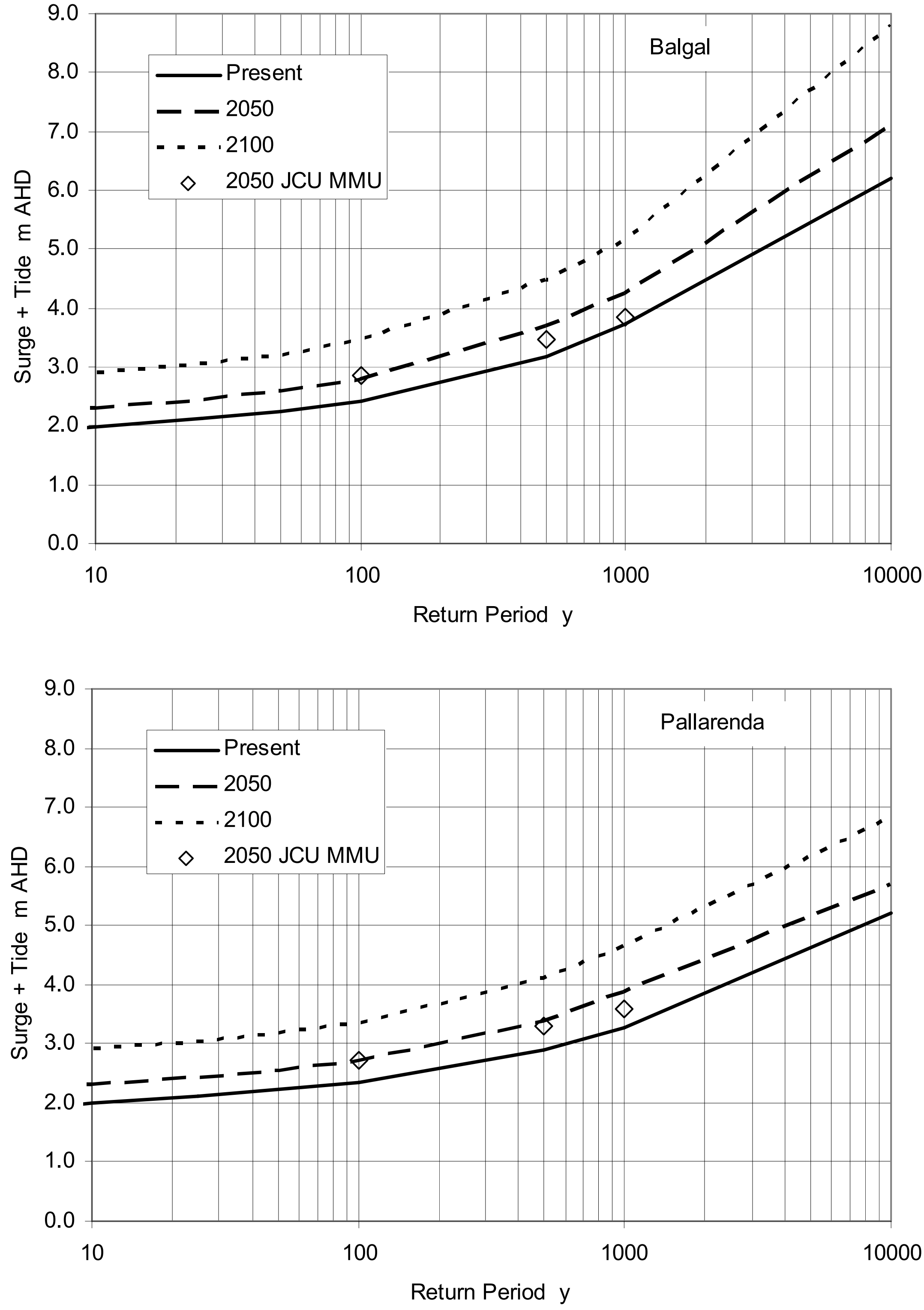
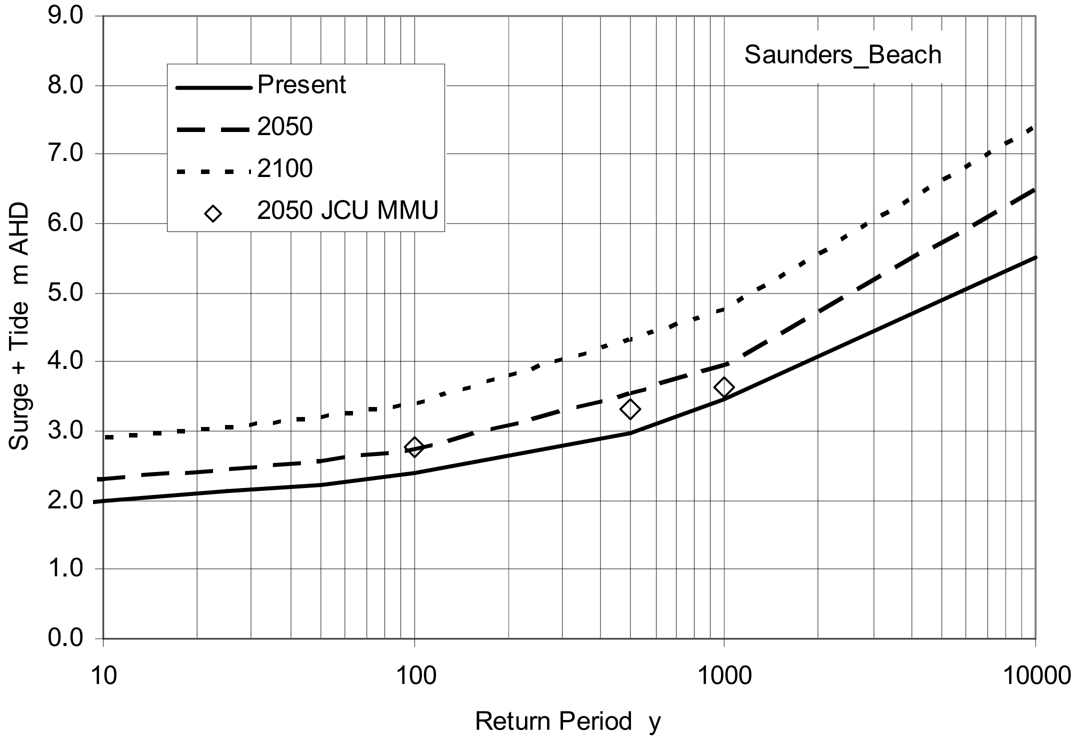


Figure 7-6 Surge plus tide only comparisons with the JCU/MMU 2050 estimates



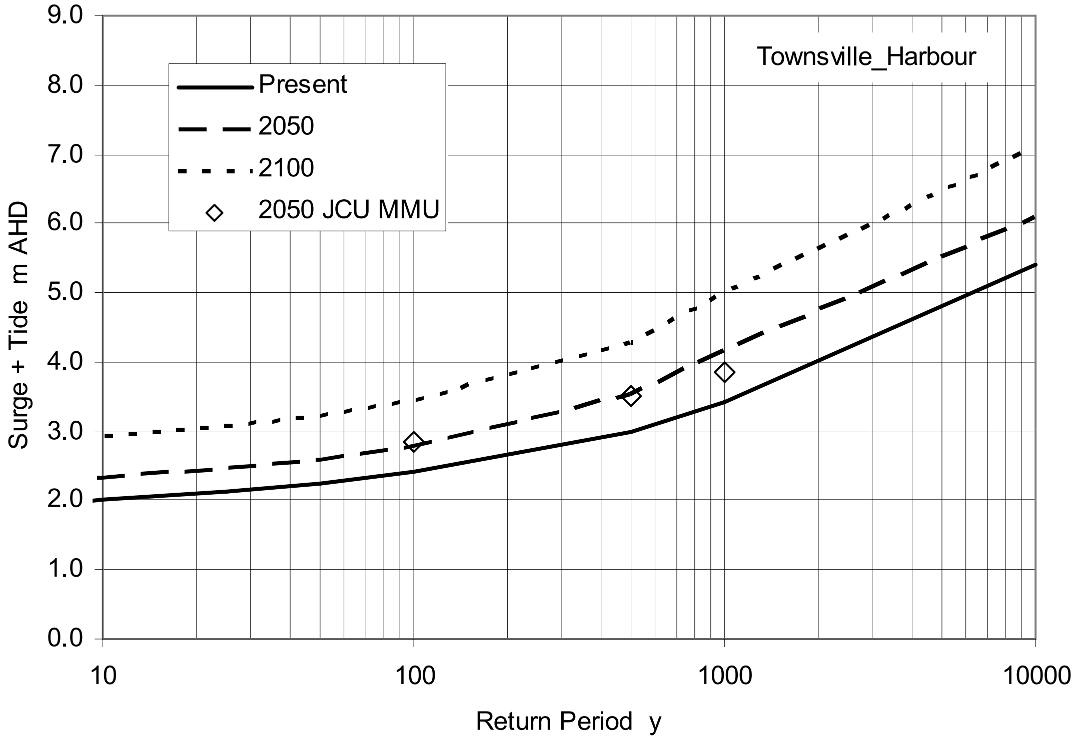


Figure 7-6 Surge plus tide only comparisons with the JCU/MMU 2050 estimates

8. Vulnerability Assessment

8.1 Population at Risk

An estimation of the potential "Population At Risk" (PAR) for each of the study sub areas within Thuringowa and Townsville has been made based on DCDB and Australian Bureau of Statistics (ABS) 2001 Census data.

The PAR has been estimated for two levels of risk, these being the total population affected by storm tide and the PAR of death or serious injury from storm tide. It has been assumed that residential properties inundated by a depth of 0.5 m or greater would expose the resident population to risk of serious injury or death.

8.1.1 City of Thuringowa

Analysis of Thuringowa PAR was conducted by visually inspecting flood inundation maps for each of the study sub areas as defined in Project Drawing 2025/2, "Cyclone Surge, Wave Impact and Inundation Study Thuringowa Sub Areas".

Table 8-1 shows the Thuringowa PAR broken down by study sub area for the 100, 500, and 10,000 yr ARI storm tide events.

Table 8-1 Thuringowa population at risk from storm tide (any inundation)

Study Area	50 yr ARI		100 yr ARI		500 yr ARI		10,000 yr ARI	
	P I	PAR*	P I	PAR*	P I	PAR*	P I	PAR*
Mutarnee	0	0	0	0	0	0	0	0
Rollingstone	9	25	14	39	14	39	310	868
Clement	0	0	0	0	0	0	89	250
Bluewater	1	3	8	22	35	98	184	515
Yabulu	3	9	9	25	32	90	254	711
Mount Low	1	3	2	6	9	25	845	2366
Thuringowa Total	14	40	33	92	90	252	1682	4710

* Assuming 2.8 persons per household (Source Australian Bureau of Statistics, 2001).

* PI = Properties Inundated.

Table 8-2 shows the Thuringowa PAR with respect to serious injury or death from storm tide.

Table 8-2 Thuringowa population at risk of death from storm tide inundation greater than 0.5 m in depth

Study Area	50 yr ARI		100 yr ARI		500 yr ARI		10,000 yr ARI	
	P I	PAR*	P I	PAR*	P I	PAR*	P I	PAR*
Mutarnee	0	0	0	0	0	0	0	0
Rollingstone	7	20	11	31	11	31	140	392
Clement	0	0	0	0	0	0	89	250
Bluewater	0	0	2	6	7	20	138	387
Yabulu	0	0	4	12	18	51	240	672
Mount Low	0	0	1	3	6	17	802	2246
Thuringowa Total	7	20	18	52	42	119	1409	3947

* Assuming 2.8 persons per household (Source Australian Bureau of Statistics, 2001).

* PI = Properties Inundated.

8.1.2 Townsville

The Townsville study area PAR analysis was completed through a GIS interrogation of the estimated flood depths and Townsville City Council's GIS database, which contained the necessary property details. Only residential properties or commercial properties likely to house people during an event were considered.

The total numbers of properties inundated for the 50, 100, 500 and 10,000 storm tides are 15, 230, 2048 and 10196 respectively. In turn this corresponds to a PAR from the nominated storm tides of 45, 644, 5734, and 28549.

Residential properties in Townsville estimated to be inundated by 0.5 m or more for the nominated storm tide events of 50, 100, 500 and 10,000 yr ARI storm tides are 0, 10, 1298 and 9352 respectively. This gives the estimated PAR of death or serious injury for Townsville as 0, 29, 3635 and 26186 respectively for the 50, 100, 500 and 10,000 yr ARI storm tides.

Table 8-3 Townsville Population at Risk from Storm Tide (any inundation)

Study Area	50 yr ARI		100 yr ARI		500 yr ARI		10,000 yr ARI	
	P I	PAR*	P I	PAR*	P I	PAR*	P I	PAR*
Annandale	0	0	1	3	1	3	495	1386
Arcadia	0	0	0	0	1	3	57	160
Belgian Gardens	0	0	1	3	47	132	212	594
Bohle	0	0	0	0	0	0	4	11
Cluden	0	0	1	3	1	3	107	300
Cungulla	0	0	19	53	23	64	245	686
Currajong	0	0	0	0	18	50	883	2472
Garbutt	0	0	0	0	6	17	687	1924
Gulliver	0	0	0	0	0	0	199	557
Hermit Park	6	17	9	25	121	339	1073	3004
Horseshoe Bay	0	0	0	0	0	0	14	39
Hyde Park	1	3	1	3	113	316	452	1266
Idalia	0	0	0	0	23	64	698	1954
Mount Louisa	0	0	0	0	0	0	8	22
Mt St John	1	3	1	3	1	3	2	6
Mundingburra	0	0	0	0	0	0	358	1002
Mysterton	0	0	0	0	4	11	308	862
Nelly Bay	3	8	4	11	5	14	34	95
North Ward	0	0	0	0	42	118	233	652
Oonoonba	0	0	13	36	206	577	437	1224
Pallarenda	0	0	0	0	0	0	292	818
Picnic Bay	0	0	0	0	1	3	24	67
Pimlico	0	0	0	0	67	188	694	1943
Railway Estate	2	6	131	367	1000	2800	1087	3044
Rosslea	0	0	0	0	0	0	336	941
Rowes Bay	0	0	0	0	4	11	101	283
South Townsville	0	0	46	129	320	896	623	1744

Townsville City	0	0	0	0	6	17	14	39
West End	2	8	3	8	38	106	436	1221
West Point	0	0	0	0	0	0	7	20
Wulguru	0	0	0	0	0	0	76	213
Townsville Total	**15**	**45**	**230**	**644**	**2048**	**5734**	**10196**	**28549**

Table 8-4 Townsville Population at Risk of Death from Storm Tide Inundation (greater than 0.5m depth)

Study Area	50 yr ARI		100 yr ARI		500 yr ARI		10,000 yr ARI	
	P I	PAR*	P I	PAR*	P I	PAR*	P I	PAR*
Annandale	0	0	0	0	1	3	231	647
Arcadia	0	0	0	0	0	0	44	123
Belgian Gardens	0	0	0	0	14	39	194	543
Bohle	0	0	0	0	0	0	4	11
Cluden	0	0	0	0	1	3	101	283
Cungulla	0	0	0	0	21	59	244	683
Currajong	0	0	0	0	6	17	793	2220
Garbutt	0	0	0	0	1	3	681	1907
Gulliver	0	0	0	0	0	0	87	244
Hermit Park	0	0	4	11	91	255	1071	2999
Horseshoe Bay	0	0	0	0	0	0	14	39
Hyde Park	0	0	1	3	46	129	452	1266
Idalia	0	0	0	0	6	17	671	1879
Mount Louisa	0	0	0	0	0	0	1	3
Mt St John	0	0	1	3	1	3	2	6
Mundingburra	0	0	0	0	0	0	240	672
Mysterton	0	0	0	0	4	11	289	809
Nelly Bay	0	0	0	0	4	11	28	78
Nome	0	0	0	0	0	0	1	3

North Ward	0	0	0	0	1	3	212	594
Oonoonba	0	0	0	0	98	274	437	1224
Pallarenda	0	0	0	0	0	0	271	759
Picnic Bay	0	0	0	0	0	0	19	53
Pimlico	0	0	0	0	33	92	669	1873
Railway Estate	0	0	2	6	769	2153	1084	3035
Rosslea	0	0	0	0	0	0	320	896
Rowes Bay	0	0	0	0	0	0	103	288
South Townsville	0	0	2	6	176	493	603	1688
Town Commom	0	0	0	0	0	0	1	3
Townsville City	0	0	0	0	3	8	14	39
West End	0	0	0	0	22	62	406	1137
West Point	0	0	0	0	0	0	5	14
Wulguru	0	0	0	0	0	0	60	168
Townsville Total	**0**	**0**	**10**	**29**	**1298**	**3635**	**9352**	**26186**

8.2 Infrastructure

Critical and community infrastructure in the Townsville-Thuringowa area at risk from storm tide events have been identified and assessed with respect to the estimated total storm tide levels. The location of key infrastructure is highlighted in Figures 8.1 and 8.2.

The following items of infrastructure have been assessed:

- Water supply and sewerage infrastructure;
- Transport infrastructure;
- Power and telecommunications infrastructure; and
- Critical community infrastructure such as hospitals and emergency services.

Critical infrastructure was identified through the following actions:

- Review of Townsville and Thuringowa GIS databases;
- Review of *as-constructed* information held by the respective Council Engineering Departments;
- Review of existing infrastructure plans held by GHD;

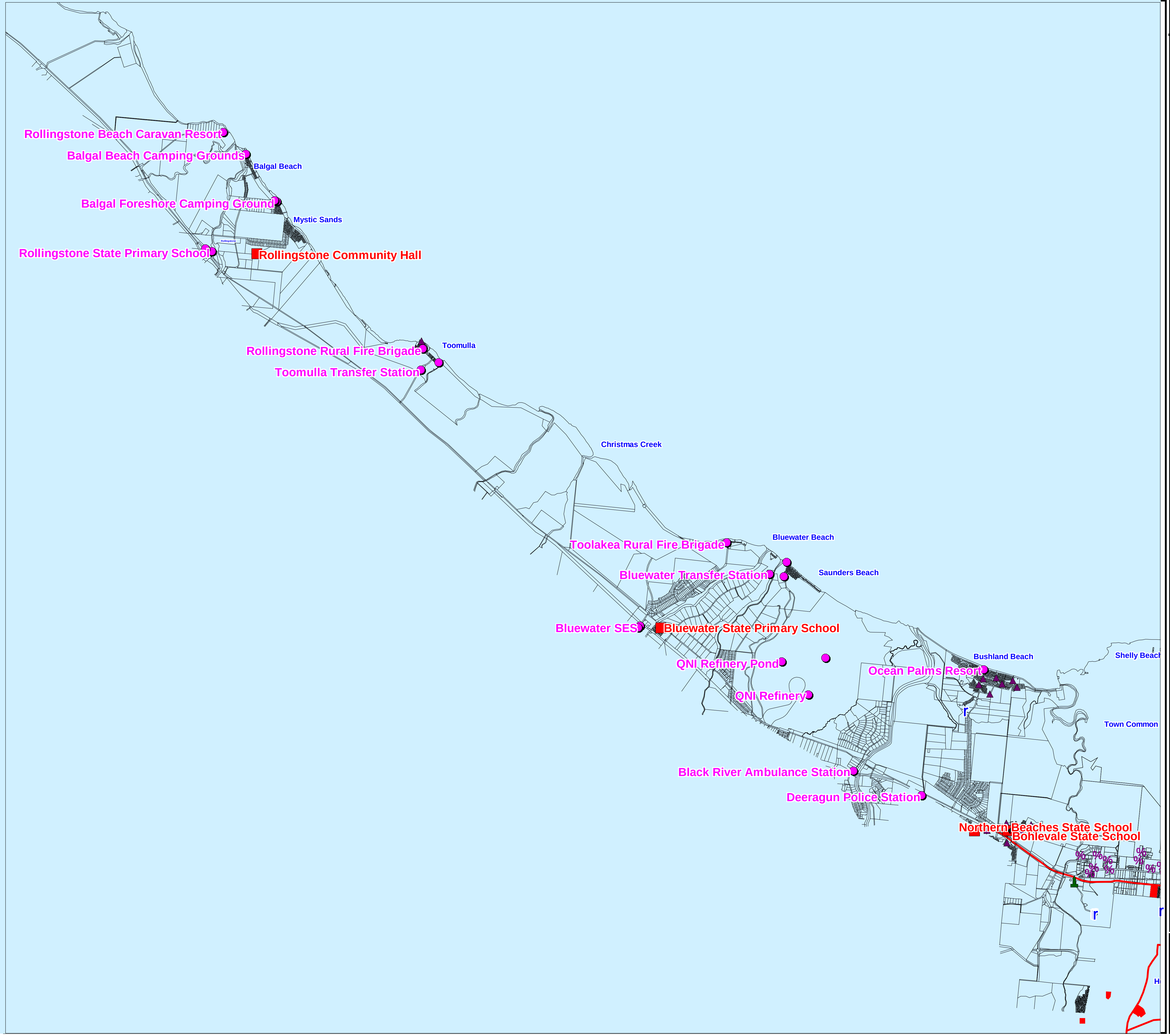
- Review of the Townsville and Thuringowa Counter Disaster Plan; and
- Discussions with key infrastructure stakeholders including Townsville and Thuringowa Councils, Ergon Energy, Telstra, Department of Main Roads, and the Department of Emergency Services.

A Risk Register (Table 8-5) has been prepared that lists the risks elements vulnerable to storm tide inundation within the Townsville-Thuringowa area and the likely consequences should inundation occur. The Risk Register has been compiled as per the "Natural Disaster Risk Management – Guidelines for Reporting" (DES, 2001).

A more detailed assessment of the critical and community infrastructure at risk from the 100 yr ARI storm tide is provided in Table 8-6 to Table 8-13. These tables identify specific critical and community infrastructure within each of the nominated sub areas in Townsville and Thuringowa that have been identified as potentially at risk from the 100yr ARI storm tide. They exclude the vulnerable elements listed in Table 8-5.

TOWNSVILLE & THURINGOWA STORM SURGE STUDY

FIGURE 8.1
Thuringowa Critical Infrastructure



Legend

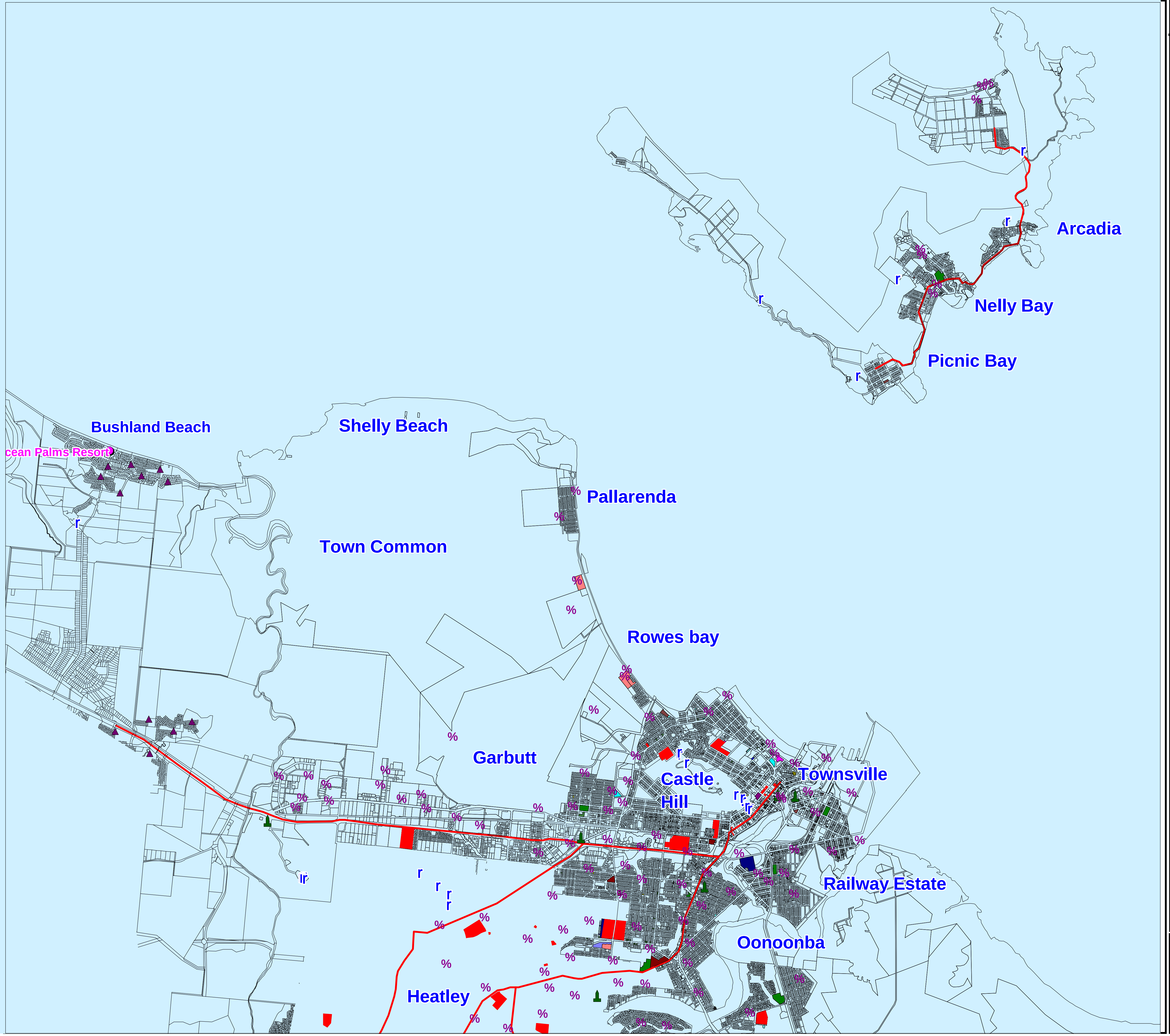
- Thuringowa Community Infrastructure
- r Water Reservoirs
- % Sewage Pump Stations
- Power Sub-stations
- Evacuation Centres
- Evacuation Routes
- Cadastre

North

Source Information: DCDB Supplied by Department of Natural Resources.

GHD MANAGEMENT ENGINEERING ENVIRONMENT

G:\41\G:\41\13819\Mapinfo\Critical_Infrastructure_Thuringowa.WOR



TOWNSVILLE & THURINGOWA STORM SURGE STUDY

FIGURE 8.2

Townsville Critical Infrastructure

Legend

Townville Community Infrastructure

- DWELLING - Hospital Residences
- EDUCATION - Boarding School
- EDUCATION - Comb Non State Primary/Sec School
- EDUCATION - Kindergarten Preschool (State)
- EDUCATION - Non State School Primary
- EDUCATION - State School Primary
- EDUCATION - State School Secondary
- EDUCATION - Technical & Further Education College
- EDUCATION - University
- FLATS - Townsville Hopsital Board
- HOSPITALS - Aged Persons Homes
- HOSPITALS - All State Hospital Property
- HOSPITALS - Church Hospitals
- HOSPITALS - Maternal and Child Welfare
- HOSPITALS - Special Schools
- KINDERGARTEN - PRE-SCHOOL (Private/Church)
- PUBLIC UTILITIES - Ambulance/Fire/Police Stations
- SURGERIES - Doctors/Dentists/Vets

- Thuringowa Community Infrastructure
- r Water Reservoirs
- % Sewage Pump Stations
- Power Sub-stations
- Evacuation Centres
- Evacuation Routes
- Cadastre

North

Source Information: DCDB Supplied by Department of Natural Resources.

GHD MANAGEMENT ENGINEERING ENVIRONMENT

G:\41\13819\Mapinfo\Critical_Infrastructure_Townsville.WOR

Table 8-5 Storm Tide Hazard Identification

Vulnerable Elements	Risks	Consequences
People	Flooding of low-lying areas particularly the Thuringowa coastal communities of Balgal Beach, Mystic Sands, Toomulla, Toolakea, Saunders Beach, & Bushland Beach. **Table 8-1** provides an estimation of the number of people at risk for different ARI Storm Tide events. In Townsville, people at potentially higher risk are those located in the industrial areas of Townsville South and Railway Estate and the low areas in Cungulla, Oonoonba and West End.	At lower levels, primarily industrial areas within Townsville South only are affected. Potential for injury should be low as there is adequate time for evacuation. At higher levels, when more houses are also inundated, flooding could cause injuries and fatalities, but should be minimised through evacuation. Evacuation and emergency accommodation and sustenance may be required, post-traumatic stress, recovery services and financial assistance required: temporary loss of jobs due to displacement, lack of access. Financial hardships may be faced (short and long term) - inability to obtain insurance. Typically pets may not able to be evacuated with their owners. Particularly vulnerable groups are the aged, very young and disabled. Also, occupants of coastal caravan parks.
Buildings	At lower levels primarily industrial areas within Townsville South and Railway Estate. At higher levels, houses also inundated in many Townsville suburbs particularly in Pallarenda, Belgian Gardens, Cungulla, Oonoonba, West End, and Rosslea. Within Thuringowa risk is confined to buildings within the coastal communities of Balgal Beach, Mystic Sands, Toomulla, Toolakea, Saunders Beach, & Bushland Beach.	The level of damage caused to buildings by storm tide will vary depending on a number of factors including house type (shape, cladding, foundations, age and methods of construction); shelter from surrounding structures; and local ground conditions. Houses can be destroyed where wave or current forces are applied to ground floor walls.

Vulnerable Elements	Risks	Consequences
		Damage to caravan parks.
		Increased maintenance requirement.
Environment	Potential for spills of fuel, oil and other hazardous chemicals.	Pollution of waterways, flora and fauna impacts. Potential for damage to fuel storage facilities, which could result in oil/fuel spillage.
Business	Industrial areas within the above zones, particularly within Townsville South and Railway Estate, could be affected. Tourism infrastructure such as holiday flats; unit accommodation and caravan parks within the effected (coastal) areas of Thuringowa could be affected.	Structural damage to seawalls, marinas, foreshore erosion. Potential for significant economic losses. Economic loss of capital and income within tourism industry.
	Impact on wider business community due to disruption, loss of business.	Temporary/permanent job losses depending on scale; loss of income due to direct closure or access closure. Inability to service customers, possible panic buying.
Lifelines	Lifeline damage should be restricted to the inundated area.	Where water supply reticulation is exposed to storm tide, damage may occur. However, water mains are generally protected (buried) from storm tide events. Water mains attached to road bridges, of major creek crossings, may sustain damage in high velocity areas. Where sewerage reticulation is located below inundation levels, some infiltration may occur. While sewer and manhole structures are protected (buried), manhole lids may be damaged by wave action and may allow ingress of seawater into the sewerage system. This has downstream effects of sewage pump station capacity and the hydraulic and biological performance of the sewage

Vulnerable Elements	Risks	Consequences
		treatment system. This could result in poor effluent quality and possible overflows with subsequent risk to human health. Power supply lines to properties may be at risk from storm tide inundation and from the associated strong wind hazard. Telecommunication cabling to properties will be at risk from storm tide. Mobile phone infrastructure is not expected to be at risk from storm tide, however may be affected by other associated hazards such as strong winds.
	Road and rail transport within the inundated area could be disrupted. Will generally not impact on through routes.	Road access may be progressively cut off as inundation level rises; structural damage to roads, rail and bridges; disruption of access to/from inundated areas.

* Source: “Natural Disaster Risk Management – Guidelines for Reporting” (DES, 2001)

8.2.1 Thuringowa Specific Storm Tide Risks

Mount Low

The coastal area of Mount Low directly affected by storm surge is Bushland Beach.

Table 8-6 Mount Low Infrastructure Vulnerability Profile

Infrastructure Type	Item	Comments
Sewerage	Pump Stations	There are no sewage pump stations inundated.
Community Infrastructure	Planned Evacuation Centres	Bohlevale State School is not inundated in any event.
	Planned Evacuation Routes	Mount Low Parkway is inundated in the 10,000 yr ARI event.
	Ocean Palms Resort	Inundated in the 10,000 yr ARI event

Rollingstone

The areas of Rollingstone directly affected by storm tide are the coastal townships of Balgal Beach and Mystic Sands.

Table 8-7 Rollingstone Infrastructure Vulnerability Profile

Infrastructure Type	Item	Comments
Sewerage	Septic Tanks	Some saltwater infiltration of septic tanks is expected but should cause minimal long-term disruption to operation.
	Pump Stations	There are no sewage pump stations in the Balgal beach or Mystic Sands areas.
Community Infrastructure	Planned Evacuation Centres	Rollingstone District & Community Hall, is not inundated in any event.
	Planned Evacuation Routes	The main access roads into Balgal Beach and Mystic Sands are Balgal Beach Rd. and Mystic Sands Ave, respectively. These are potentially inundated in the 10,000 yr ARI event.

Infrastructure Type	Item	Comments
	Balgal Beach Holiday Units	Inundated in the 10,000 yr ARI event

Bluewater and Yabulu

The areas of Bluewater and Yabulu directly affected by storm tide are the coastal townships of Toolakea, Bluewater Beach and Saunders Beach.

Table 8-8 Bluewater & Yabulu Infrastructure Vulnerability Profile

Infrastructure Type	Item	Comments
Sewerage	Septic Tanks	Some saltwater infiltration of septic tanks is expected but should cause minimal disruption to operation. The flora and hydraulic design of septic tanks are robust enough to endure short periods of inundation.
	Pump Stations	There are no sewage pump stations in the Toolakea or Saunders Beach areas.
Industry	Nickel Treatment Plant	The QNI Ltd. Yabulu Refinery will not be inundated in any event. However, the tailing ponds will be inundated in the 10,000 yr event.
Community Infrastructure	Rural Fire Brigade	The Toolakea Rural Fire Brigade will be inundated in the 10,000 yr event.
	Planned Evacuation Centres	The Bluewater State School is not inundated in any event.
	Planned Evacuation Routes	100-200 m of Saunders Beach Road (RL +2.7m AHD) may be inundated (< 250 mm) during a 100 yr ARI storm tide, approx. 1.5 km from the coast. The extent of inundation increases significantly in the 500, & 10,000 yr events.
	Saunders Beach Community Centre	Inundated in the 10,000 yr ARI event

Clement

The main area of Clement directly affected by storm tide is Toomulla.

Table 8-9 Clement Infrastructure Vulnerability Profile

Infrastructure Type	Item	Comments
Sewerage	Pump Stations	There are two sewage pump station located in Toomulla. They are potentially inundated in the 10,000 yr event.
	Toomulla STP	Aerobic basin approx. 3.7m above ground level. Ground level approx. 4 m AHD. Effluent stored in evaporation lagoon approx. RL 3.05 at lowest point. The STP will not be directly affected by the 100 yr ARI storm tide. However, storm tide tide may result in infiltration into sewage reticulation, which may cause the STP capacity to be exceeded with resultant overflow.
Roads	Creek Crossings	The Herald St crossing of Saltwater Creek is inundated by the 500 yr ARI storm tide event.
Community Infrastructure	Planned Evacuation Centres	Evacuation of Toomulla would be to Rollingstone District & Community Hall, which is not inundated in any event.
	Planned Evacuation Routes	The major access route into and out of Toomulla is via Toomulla Beach Road, which is inundated by the 500 yr ARI storm tide event.

Mutarnee

The township of Mutarnee is generally above 7m AHD is not affected by any of the nominated ARI storm tide events. There appears to be no permanent settlement along the coastline in this area.

Access into and out of Mutarnee is via the Bruce Hwy, which is not inundated in any of the analysed storm tide events.

8.2.2 Townsville Specific Storm Tide Risks

Pallarenda

Table 8-10 Pallarenda Infrastructure Vulnerability Profile

Infrastructure Type	Item	Comments
Sewerage	Pump Stations	Four pump stations are located above the 100 yr ARI level in the Pallendra area. However all will be inundated in the 10,000 yr ARI event.
Roads	Creek Crossings	Refer Planned Evacuation Routes
Community Infrastructure	Hospitals	Aged persons home on Cape Pallendra Road is marginally inundated in the 100 & 500 yr ARI events but access does not appear to be affected and inundation is unlikely. It is totally inundated in the 10,000 yr ARI event.
	Planned Evacuation Centres	Belgian Gardens State School is not inundated in any event.
	Planned Evacuation Routes	The planned evacuation route for Pallendra is Cape Pallendra Road, which crosses Three Mile Ck. This road is not inundated in the 100 yr ARI event. Most of its length however will be inundated in the 10,000 yr ARI event up to a depth of approx 2.5 m.

Magnetic Island

Table 8-11 Magnetic Island Infrastructure Vulnerability Profile

Infrastructure Type	Item	Comments
Water Supply	Reservoirs	Water reservoirs on Magnetic Island are not at risk from any storm tide event.
Sewerage	Pump Stations	There are seven pump stations on Magnetic Island, all of which are not at risk from the 100 yr ARI storm tide. Several of these may be inundated in the larger ARI events.
Airports	Helipad	The Helipad at Nelly Bay is not at risk in the 100 yr ARI storm tide. It may be inundated in the 10,000 yr event.
Seaports and Marinas	Magnetic Quay	Magnetic Quay is at risk from storm tide however the breakwater should offer some protection. Detailed survey of the breakwater or GIS database entry of breakwater details (if existing) will be required to determine levels of protection.
Community Infrastructure	Police	The Magnetic Island Police Station is not at risk from the 100 yr ARI storm tide
	Hospitals	The All State Hospital on Sooning St. is not at risk from the 100 yr ARI storm tide. It may be inundated in the 10,000 yr event.
	Ambulance	The ambulance station on Kelly St. is not at risk from any ARI storm tide.
	Planned Evacuation Centres	M.I. Sports & Recreation Club (approx. 20m AHD); Camp Irwin (approx. 5m AHD); Qld Recreation Council Camp (15m AHD) are not at risk from the 100 yr ARI storm tide. Camp Irwin may be inundated in the 10,000 yr ARI storm tide.

Infrastructure Type	Item	Comments
	Planned Evacuation Routes	The planned evacuation route along Nelly Bay Rd. and onto Marine Parade is not inundated in the 100 yr ARI storm tide. It may be inundated in the 10,000 yr ARI storm tide between Nelly Bay and Picnic Bay and between Nelly Bay and Arcadia.

Cleveland Bay – Industrial

Table 8-12 Cleveland Bay - Industrial Infrastructure Vulnerability Profile

Infrastructure Type	Item	Comments
Sewerage	Pump Stations	There is one pump station (approx. 4.2 m AHD), which is not at risk from the 100 yr ARI storm tide. It will be inundated in the 10,000 yr ARI event.
Roads	Major access road	Main roads servicing the Port of Townsville are Dean St. and Benwell Rd.; these are not inundated in the 100 yr ARI storm tide level. Both roads will be inundated in the 500 & 10,000 yr ARI events.
Seaports and Marinas	Roll on Roll off Terminal Bulk Sugar Loading Bulk Sugar Loading Bulk Mineral Terminal/Container Terminal	Sea terminal design generally allows for storm tide hazard, but operations may be affected during a storm tide event.

Townsville City

Table 8-13 Townsville City Infrastructure Vulnerability Profile

Infrastructure Type	Item	Comments
Water Supply	Creek Crossings	In Townsville City there are four crossings of Ross Creek (refer to roads). These bridges, and therefore the services attached to them may be at risk from storm tide.
	Reservoirs	All reservoirs in Townsville City are located on and around Castle Hill and are above the 100 Yr ARI storm tide levels.
Sewerage	Pump Stations	There are two sewage pump stations, which will be inundated in a 100 yr ARI storm tide. (1A WL @ 2.50m AHD); (3C WL @ 2.58m AHD); Although these pumps are buried (protecting the underground structure), surface infrastructure (switchboard, vent) are vulnerable. Additionally, the pump station lid may be dislodged allowing saltwater ingress into the sewage system.
Roads	Creek crossings	The 100 yr ARI storm tide levels for the major bridges in Townsville are: George Roberts Bridge on Dean St (WL 2.50m AHD), Stanley St (WL 2.50m AHD); Boundary St (WL 2.51m AHD); Queens Rd (WL 2.55m AHD); Ross River Bridge on Stuart Drive (WL 2.37m AHD); Rooneys Bridge on Abbott Street (WL 2.61m AHD); Bridge with decks below the corresponding level above will be at risk from storm tide. Council to record deck levels.
	Major Roads Inundated	Approx. 1km of Boundary Rd inundated to a depth of approx.< 0.5 m (WL @ 2.5-2.6m AHD); Approx. 200 m of Abbott Rd inundated to a depth of approx. < 0.5 m (WL @ 2.58 m AHD). The extent of inundation increases in the larger (500 & 10,000 yr) events.

Infrastructure Type	Item	Comments
Airports	The Townsville International and Domestic Airports	The Townsville International Airport is at risk from the 100 Yr ARI storm tide. The runways are not inundated. However, parts of the Airport complex are inundated (< 0.4 m depth) (WL @ <2.44 m AHD). Operations of the airport will be significantly affected during the passage of the tropical cyclone. The airport will be inundated during the 10,000 yr storm tide event.
Seaports and Marinas	Breakwater Marina	The Breakwater Marina Complex is protected from the 100 yr storm tide and is not at risk from inundation. For larger events, the potential for wave setup to cause elevated water levels should be noted.
Power supply	Sub Stations	Townsville has five power substations Neil Smith (RL @ 2.8m AHD); Max Fulton (RL @ 3.6m AHD); Garbutt (RL @ 6.3m AHD); Hermit Park (RL @ 5.0 m AHD); Aitkenvale (RL @ 7.9m AHD). None of which are inundated in the 100 yr ARI storm tide.
Rail	Creek crossings	The 100 yr ARI storm tide levels for the following Townsville Rail Bridges are: Stanley St. (WL @ 4.2m AHD); Adjacent to Bridge St. (WL @ 5.3m AHD); and Reid Park (WL @ 3.9m AHD) Survey of the bridge deck levels will be required to determine the levels of risk from storm tide.
Community Infrastructure	Police	No police station in Townsville City is inundated in a 100 yr storm tide event. The Hermit park police station will be inundated in the 10,000 yr ARI event.
	Fire Station	Townsville South Fire Station on Morey St. Inundated to a depth of approx. 0.1 m (WL @ 2.48m AHD). The extent of inundation increases in the larger (500 & 10,000 yr) events.

Infrastructure Type	Item	Comments
	Hospitals	None of the three major hospitals, The Townsville Hospital; The Mater Private; and The Wesley Park Haven are inundated in a 100 yr storm tide event. The Mater Private and Wesley Park Haven will be inundated in the 10,000 yr ARI event.
	Planned Evacuation Centres	There are no evacuation centres inundated in the 100 yr storm tide event. Any of the nominated evacuation centres in Townsville under approx. 7 m AHD may be at risk from the 10,000 yr ARI storm tide.
	Planned Evacuation Routes	The two major evacuation routes for Townsville, Woolcock St. and Flinders Hwy/Ross River Rd. are not inundated in a 100 yr storm tide event. Generally any parts of the major evacuation routes in Townsville under approx. 7 m AHD may be at risk from the 10,000 yr ARI storm tide.

Cungulla

Specific critical infrastructure was addressed in Table 8-3. However no additional items appear to be at risk during the 100 yr ARI storm tide event.

Townsville Common

The Town Common is a conservation area and has no rural, urban or industrial development. There is no critical infrastructure in the Town Common. Approximately 90% of the Town Common will be inundated in the 100 yr ARI storm tide.

8.3 Review of Local Disaster Management Plan

A review of the Townsville & Thuringowa Local Disaster Management Plan (TTLDMP) Plan (June 2005) was completed during the study. Much of the content of the TTLDMP relates to roles and responsibilities, with a generic overview of the types of risk that may occur. However, several sections of the plan may need to be updated in response to the findings of this study.

In particular, Appendix A (Considerations for Decision to Evacuation) has the most relevance to this study. The review has therefore focused on the implications of a storm tide event on the execution of this sub-plan.

The following queries have been addressed:

- Should there be any changes to roles and responsibilities?
- Does the existence of detailed maps and the storm tide warning system necessitate changes to the TTLDMP plan?
- Are the nominated evacuation centers and evacuation routes adequate for the various storm tide events considered?

Responses to the above items are embedded within the suggestions below:

Main Plan

Section 15 of the Main Plan details roles and responsibilities. In Section 15.02 (ii), cyclones and storm tide are the focus. It is noted that the District Disaster Coordinator (DDC) is nominated as the provider of information pertaining to predicted storm tide. This could be augmented to reflect the legislative role that the Bureau of Meteorology plays.

Considerations for Decision to Evacuation

In Appendix A Considerations for Decision to Evacuation, two options are proposed for consideration:

- Section 7 – The provision of a storm tide warning system may allow a training responsibility to be added to the list of responsibilities.
- Section 9 – There is no mention of the Bureau of Meteorology (BoM) in the sequence of warnings.

Appendices to Considerations for Decision to Evacuation

- Appendix B – The figures provided as Appendix B do not include Thuringowa sites (as noted on the map itself). These sites have been highlighted on Figure 8.1 of this report, and hence could be added to Appendix B, or alternatively, a cross reference to the Storm Tide study report could be made.
- Appendix B. As with the locations of evacuation centres, evacuation routes for Thuringowa's beachside communities are not included. For this study evacuation routes were obtained from Townsville GIS section, and include all access routes from the Bruce Highway to Thuringowa's various beachside communities. It is

noted that whilst the nominated major Townsville City evacuation routes appear acceptable for all events other than the 10,000 year event, and that the Bruce Highway sits above storm tide levels, several access roads to the coast are likely to be affected. Roads that appear to be affected by the 100 yr ARI event include:

  – The road from Moongobulla; and
  – Access road north of Balgal.

- Consider referencing maps in Appendix A "*Considerations for Decision to Evacuation*". Reference could be made to the water surface / depth maps, or to the "emergency services" maps, which comprise plots at half metre intervals, up to the extent of inundation determined through this study.

8.4 Regional Damage Assessment

This section describes the results of a regional damage assessment that has been carried out to provide an estimate of the potential community cost of storm tide events to Townsville/Thuringowa. The assessment is derived from a MIRAM analysis (Monte Carlo Insurance Risk Assessment Model), which is Systems Engineering Australia Pty Ltd's discrete insurance loss simulation model. MIRAM is an extended form of the SATSIM model, whereby in the case of storm tide, the predicted inundation and associated wave action is combined with a description of the regional building vulnerability and insurance damage functions are applied to convert the impacts into estimated insured losses. MIRAM has been utilised by a number of Australian insurers over the past 10 years to estimate their exposure to tropical cyclone winds and storm surge. Aspects of the basic model operation are described in Harper (1996a,b) and (1999b).

The MIRAM storm tide sub-model was originally based on Harper and McMonogle (1985), combined with a Digital Elevation Model (DEM) of the study region to estimate encroachment and local depths of inundation relative to nominal floor levels. The damage functions consider the conventional terrestrial stage-damage of buildings and contents, separating residential and commercial interests. Additionally, a wave-decay sub-model estimates the degree to which incident waves might penetrate the nearshore regions. The relative distribution of insured risks is estimated on the basis of a current representative industry portfolio, allocating nominal $ values to residential buildings and contents and commercial buildings and contents, as well as business interruption. Note that infrastructure losses such as seawalls, wharfs, jetties, roads, or power distribution are not included in this model. The predicted damage for residential and commercial categories is then estimated as both a $ loss and a % of the insured value of property and expressed in a return period context. Although the actual spatial resolution of the model is approximately 50m, the spatial aggregation of sums insured and insured loss is at a postcode level. Accordingly, statistical distributions of building type are also specified and applied as averages across postcodes. Coastal water levels are assumed to extend inland on a horizontal plane.

In the present study context, MIRAM and SATSIM generate the same statistics of exceedance of total water level and associated wave conditions. Also, distributions of building structure types for the potentially surge-affected postcodes have been updated based on the client-supplied building survey data. These have been interpreted into the three categories shown in Table 8-14, the most resistant class being the ">2m high" indicating high-set with clear understorey. The original MIRAM DEM, based on storm tide evacuation maps circa 1993, has been retained as it can not easily be updated without considerable spatial reanalysis, outside of the scope of the present investigation.

Table 8-14 Adopted building vulnerability distributions

Name	Postcode	% Distribution		
		1 storey	2 storey	>2m High
Townsville	4810	40.4	5.9	53.7
James Cook University	4811	46.5	4.6	48.9
Hermit Park	4812	37.2	5.0	57.7
Aitkenvale	4814	41.2	2.0	56.8
Crystal Creek/Bohle River	4818/4816	80.0	15.0	5.0
Magnetic Island	4819	84.3	15.0	5.0

The results of the MIRAM simulation are presented below in Table 8-15, aggregated for the whole Townsville/Thuringowa region. The predicted losses are principally concentrated in the Townsville 4810 postcode, followed by 4812 Hermit Park and are particularly sensitive to assumptions regarding commercial contents exposure.

Table 8-15: Estimated regional loss due to storm tide

Return Period	Estimated Insured Loss	
y	$M	%
50	0	0.0
100	50	0.3
500	1050	5.5
1000	2150	11.2

Figure 8-3 is a graphical summary of Table 8-13, showing an exponentially rising loss on a log return period basis. This represents essentially a linear loss increase with return period from a threshold return period of about 60 years onwards.

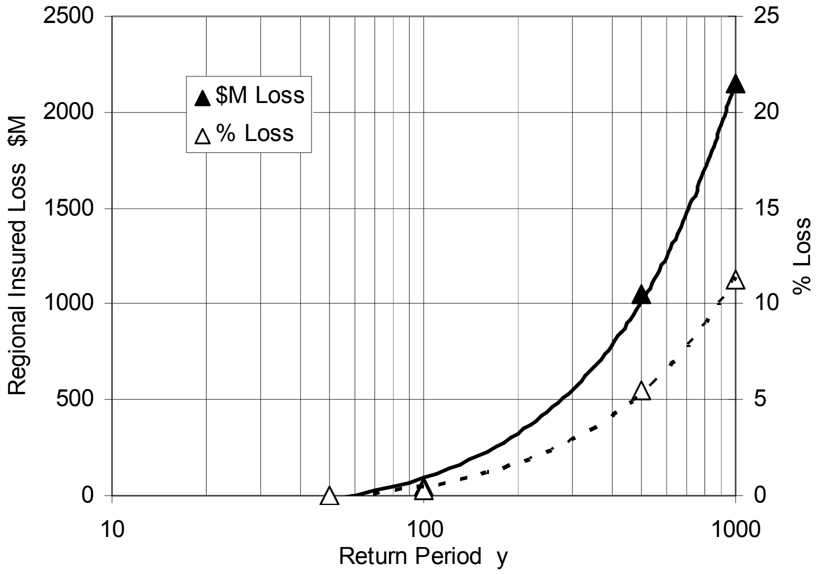


Figure 8-3 Estimated regional insurance losses due to storm tide.

The $ loss estimates here should be regarded as order-of-magnitude only, dependent on the current true regionally aggregated sums insured, which will be gradually changing over time. The % loss calculation here also includes the base contribution of sums insured from other regional postcodes (e.g. 4813, 4815 and 4817). These could be updated based on a survey of valuations and the like and the estimated % loss used to obtain a new total. Also, these losses are only those determined by the model to be due to storm tide effects alone, separate from wind-related damage. Typically, wind damage is more widespread than the narrow region impacted by storm tide. Accordingly, even though the % loss here on a regional aggregate basis appears low, some portions of 4810 for example are estimated to experience near-total destruction at or beyond the 1000 y return period probability level.

Finally, while the prediction here is described as a “loss”, equally it will represent the influx of “investment” to be made available for rebuilding the damaged region.

Although the above damage estimates are derived from an “insurance loss” model, it should be noted that no specific household storm surge insurance cover is known to be presently provided by the general insurance companies.

9. Storm Tide Warning Application

The storm tide warning application is implemented in the *SEAtide* interactive software system (SEA 2005) that operates on personal computers using 32 bit Microsoft Windows™ operating systems (e.g. Windows 2000 and XP). The purpose of *SEAtide* is to provide a rapid prediction and analysis system to enable suitably trained and experienced tropical cyclone forecasters and emergency managers to evaluate the possible impact of storm tide threats to coastal communities.

9.1 Overview

The system uses the same parametric storm tide prediction sub-system that is used in the preparation of the storm tide statistics. An overview of the system operation is shown in Figure 9-1.

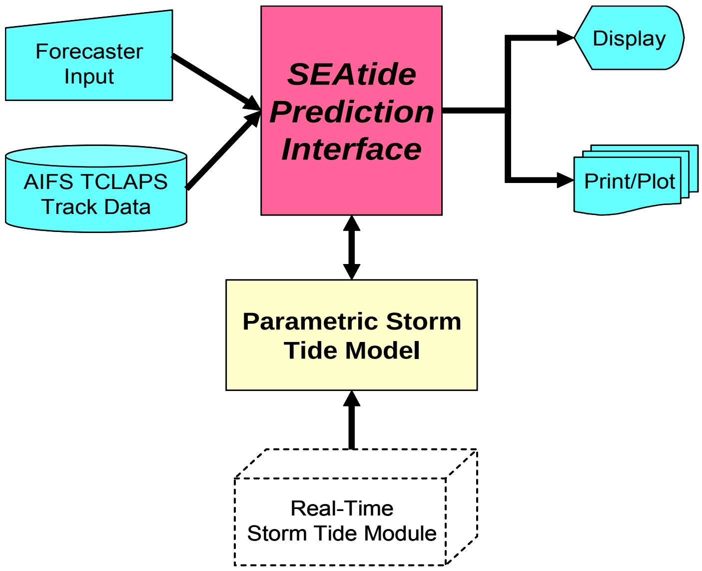


Figure 9-1 Overview of the SEAtide warning application.

SEAtide provides an operating interface that is designed to be intuitive, easy to learn for an experienced professional and economical in its operation. The *SEAtide* concept focuses on the importance of allowing for uncertainty in the forecast tropical cyclone track and intensity parameters and the inter-relationship with the astronomical tide. The predictions from the system are targeted towards providing clear and concise information about location, magnitude and timing of storm tide events as well as the probability associated with a range of possible outcomes. This information can then be assessed to determine what actions might be necessary to advise the community on precautionary or evasive actions, or to initiate evacuation and the like.

Specific features of *SEAtide* include:

- Generalised application to any coastal region;
- Rapid simulation of storm tide scenarios;
- Consideration of storm surge, tide and breaking wave setup;
- Easy entry of tropical cyclone parameters, including import of Bureau of Meteorology TC module track files;
- Deterministic (single storm scenario) or probabilistic (simulation) modes;
- Predictions in UTC or local time zones;
- Hazard-line (MEOW-style) warning maps in standard EMA colouring;
- Concise browsing and sorting of model predictions;
- Time history graphs for all available locations;
- Profiles of predicted storm tide levels or components at specific times;
- Summary probability distributions at a specific site;
- Ability to "step through" a scenario within the hazard map;
- Ability to import externally modelled data for comparison;
- Extensive hardcopy, numeric and graphics export capabilities.

9.2 Example Operation

The following screen views illustrate the operation of the warning system. In Figure 9-2 the hazard map shows the result of simulating *Althea*. The central red arrow is the forecast position of the storm and the coloured hazard line along the coast is reporting the maximum storm tide levels generated by the model. On the left of the image is the map layer control that allows the user to change the displayed predictions. Along the top are various mapping tools that enable zooming and panning to investigate the area of interest. Also shown on the map are the tracks of ten probabilistic storms that have been automatically generated by the model with slightly different sets of parameters. The results of the probabilistic simulations are also available for mapping and reporting. In Figure 9-3 the time history plot of the predicted storm tide at Townsville Harbour is shown, illustrating that the warning system reproduces the recorded water levels during *Althea*.

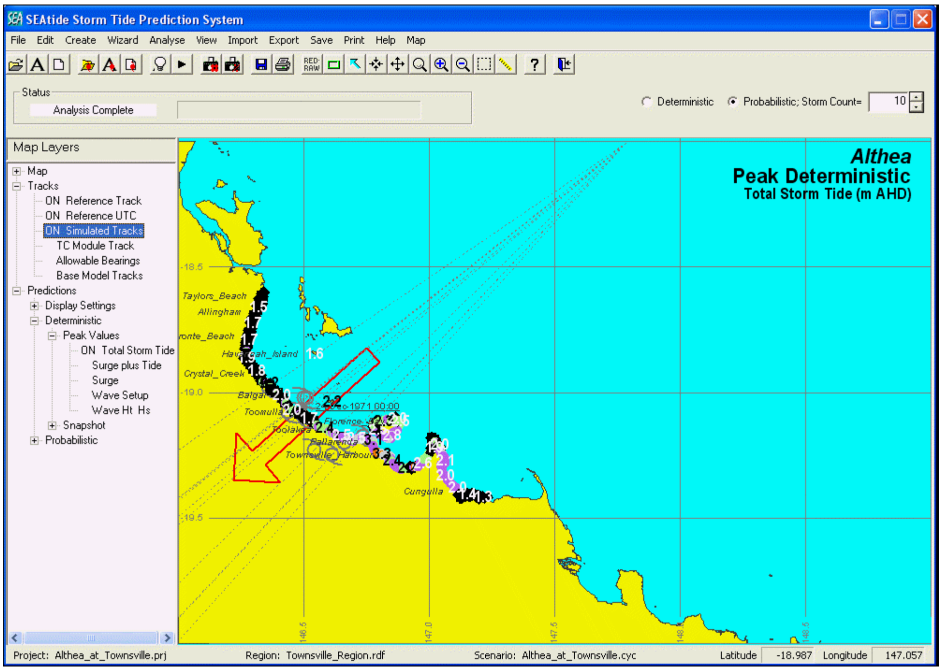


Figure 9-2 SEAtide hazard map view of Althea prediction.

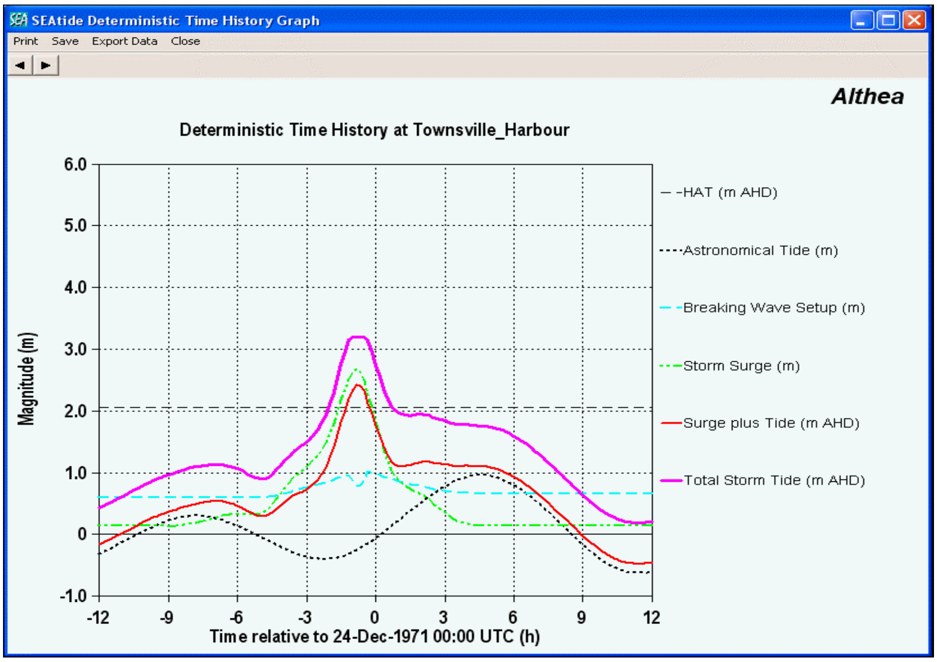


Figure 9-3 SEA*tide* prediction of *Althea* at Townsville Harbour.

10. Conclusions and Recommendations

10.1 Conclusions

The following sections highlight some of the key findings of this study. This is followed by a series of recommendations, with respect to how the study results would be best applied.

10.2 Inundation Maps

This study represents a comprehensive assessment of storm tide risk for the Townsville-Thuringowa region. Using a variety of mathematical modelling tools and data sources, some 90,000 cyclones have been simulated in a statistical framework, thereby allowing the estimation of storm tide levels for four different design events. These consist of the 50yr, 100yr, 500yr, and 10,000 yr average recurrence interval (ARI) events.

Predictions have been generated in two formats:

- Estimates of storm tide level at 500m intervals along the coastline of the study area (with and without wave setup); and
- Estimates of the inland penetration of storm tide, up to the maximum extent of inundation.

It should be noted that both sets of predictions produce water surfaces that vary in space. That is, storm tides are not horizontal, but reflect the influences of the offshore bathymetry, the point of landfall, the topography of the region, and the influence of coastal barriers (e.g. dune systems) and wind stress.

10.3 Storm Tide Warning System

In addition, a storm tide warning system has been prepared. This has been submitted to the Bureau of Meteorology, who agreed to use / test the system over the (2005/2006) cyclone season. Whilst the system cannot be used by either Council to publicly predict storm tide inundation during an event (this remains the legislative responsibility of the Bureau of Meteorology), the tool can readily be used for training and preparation purposes.

10.4 Vulnerability

Review of the Townsville/Thuringowa Counter Disaster Plan (June 2000), and of key infrastructure within both local authority areas, shows that the majority of key infrastructure lies above the 100yr ARI storm tide surface, though population will be at risk. Evacuation routes are generally reasonable, though during the 10,000 year event many of these would be inundated.

It is estimated that for the 100yr event, approximately 33 habitable properties will be subject to some form of inundation within Thuringowa, of which half might be inundated to more than 0.5m depth. The population at risk is approximately 3 times the number of properties, with depths of greater than 0.5m associated with a higher risk of death. For the 10,000 year event, the number of properties affected would be significantly higher (of the order of 1600), with most of these subject to depths of 0.5m or more.

For Townsville, the numbers are somewhat higher. For the 100 yr ARI event, the number of properties affected is estimated at 230 (but only 10 at greater than 0.5m depth). For the 10,000 yr event, this number increases up to 10,196 (9,352). These numbers equate to populations at risk of 644 (29) for the 100 yr event and 28,549 (25,186) at risk for the 10,000 yr event.

10.5 Key Issues and Qualifications

There are several key points that must be understood in interpreting the results of this study:

- The extent of inundation is not directly linked to the category of cyclone. At any given location, a Category 2 cyclone crossing the coast immediately to the north of a point of interest, may produce a higher surge than a larger category cyclone crossing some distance away.
- Storm tide levels are largely influenced by the tide at the time of crossing, and the direction that the cyclone is travelling.
- The key benefit of the maps is for planning purposes. Their purpose is not to facilitate emergency services during an event. Rather, it is the ability to better plan for an event, and to plan where future developments may or may not be appropriate.
- The maps can also be used to assess roads at risk, and where such roads form the only point of access for a community, the maps may then facilitate the prioritisation of upgrade works.
- Results have been presented with and without wave setup. Wave setup only applies at the coastline, and only at points where large waves are breaking against a sloping coastal barrier (e.g. beachface or sand dunes), which act to prevent the inland penetration of the storm tide. All points where inland inundation occurs are based on results exclusive of wave setup.
- The 10,000 year event has been selected to represent the probable maximum event for the region. However, given the rarity of the event, the predicted inundation extents must be treated with caution, and used as a guide only.

10.6 Recommendations and Use of Results

The recommendations of this report relate to use of the products that have been created. These comprise:

- Inundation depth maps;
- Inundation extent maps;
- Predicted water surface maps;

- A GIS database of results; and
- A storm tide warning system.

Depth maps provide a means to assess hazard. During an event, and given the strong winds that occur at the time, any depth greater than half a metre represents a risk to life. These maps can also be used to assess the potential depth of inundation at any given structure, and hence the potential risk of wave attack that may lead to failure of the building. Consideration as to the design of future buildings in inundated areas should be given.

Inundation extent maps provide a means to assess the total extent of area that may be affected during any given event. When consideration is given to the incremental increase in extent associated with each design event, a stronger appreciation of risk can be obtained.

Water surface maps illustrate the significant variation that can occur along the coastline, and inland from the coastline. This has particular implications for long term planning of the region, such that all areas will have development levels with the same design standard.

The **GIS database** will allow results to be accessed at any site within the study area. This allows consideration of inundation on a lot scale, with subsequent benefits associated with the development approval process.

The **storm tide warning system** will greatly facilitate training exercises for emergency services planning. Official use of the system will be undertaken by the Bureau of Meteorology.

11. References

Basher, R. E. and Zheng, X. (1995) Tropical cyclones in the Southwest Pacific: spatial patterns and relationships to southern oscillation and sea surface temperature, *Journal of Climate*, Vol 8, May, 1249-1260.

Benjamin and Cornell (1970) Probability, statistics and decision for civil engineers, *McGraw-Hill*.

Bode, L. and Mason, L. B. (1992) Numerical modelling of tidal currents in the southern Great Barrier Reef. Marine Modelling Unit, Dept of Civil and Systems Engineering, *James Cook University of North Queensland*. (Prepared for the Department of Transport and Communications through the Victorian Institute of Marine Science)

CSIRO (2001) Climate change projections for Australia. Climate Impact Group, *CSIRO Div Atmospheric Research*, Melbourne, 8 pp.
http://www.dar.csiro.au/publications/projections2001.pdf

Emanuel, K. (2005) Increasing destructiveness of tropical cyclones over the past 20 years. *Nature*, 436, 686-688.

Foreman, M.G.G. (1996), Manual for Tidal Heights Analysis and Prediction, Pacific Marine Science Report 77-10, Department of Fisheries and Oceans, Institute of Ocean Sciences, Patricia Bay, Victoria, B.C.

Hardy, T.A., McConochie, J.D. and Mason, L.B. (2001) A wave model for the Great Barrier Reef. *Ocean Engineering*, 28 (1), 45-70.

Hardy T.A., Mason L.B. and Astorquia A. (2004) Queensland climate change and community vulnerability to tropical cyclones – ocean hazards assessment: Stage 3 - the frequency of surge plus tide during tropical cyclones for selected open coast locations along the Queensland East coast, *Queensland Government*, Jul, 61pp.

Harper B.A., Sobey R.J. and Stark K.P. (1977) Numerical simulation of tropical cyclone storm surge along the Queensland coast - Part VI: Townsville, Department of Civil and Systems Engineering, *James Cook University*, Nov, 90pp.

Harper, B. A. and McMonagle, C. J. (1985) Storm tide statistics - methodology, Blain Bremner and Williams Pty Ltd, *Beach Protection Authority of Queensland*, January, 120 pp.

Harper, B. A., Mason, L. B. and Bode, L. (1993)Tropical cyclone *Orson* - a severe test for modelling, Proc 11th Australasian Conference on Coastal and Ocean Engineering, *IEAust*, Townsville, Aug, pp 59-64.

Harper, B. A. (1999a) Storm tide threat in Queensland: history, prediction and relative risks. Conservation Tech Rep No. 10, RE 208, *Dept of Environment and Heritage*, Jan.

Harper, B. A. (1999b) Numerical modelling of extreme tropical cyclone winds, APSWE Special Edition, *Journal of Wind Engineering and Industrial Aerodynamics*, 83, 35 - 47.

Harper B A (ed) (2001) Queensland climate change and community vulnerability to tropical cyclones - ocean hazards assessment - Stage 1, Report prep by Systems Engineering Australia Pty Ltd in association with James Cook University Marine Modelling Unit, *Queensland Government*, March, 375pp.

Harper B.A. (2004) Queensland climate change and community vulnerability to tropical cyclones – ocean hazards assessment: Synthesis Report, *Queensland Government*, Aug, 38pp.

Harper B.A., Hardy T.A., Mason L.B. and McConochie J.D. (2001) Cyclone *Althea* Revisited, Proc 15th Australasian Conference on Coastal and Ocean Engineering, Coasts & Ports 2001, *IEAust*, Gold Coast, Sept.

Harper, B. A. and Holland, G. J. (1999) An updated parametric model of the tropical cyclone. Proc. 23rd Conf. Hurricanes and Tropical Meteorology, *American Meteorological Society*, Dallas, Texas, 10-15 Jan, 1999.

Harper B.A. and McMonogle C.J. (1985) Storm Tide Statistics - Methodology, Report prep by Blain, Bremner and Williams Pty Ltd for the Beach Protection Authority, Queensland Government.

Harper B A, (1996a) Risk Modelling of Cyclone Losses, Proc IEAust Annual Engineering Conf, *Institution of Engineers Australia*, Darwin, April, 53-88.

Harper B A, (1996b) The Application of Numerical Modelling in Natural Disaster Risk Management, Proc Conf on Natural Disaster Reduction NDR'96, *Institution of Engineers Australia*, 107-114

Henderson-Sellers, A., Zhang, H., Bertz, G., Emanuel, K., Gray, W., Landsea, C., Holland, G., Lighthill, J., Shieh, S-L., Webster, P. and McGuffie, K. (1998) Tropical cyclones and global climate change: a post-IPCC assessment. *Bulletin of the American Meteorological Society*, 79, 1, January, 19-38.

Holland G. J. (1980) An analytic model of the wind and pressure profiles in hurricanes, *Monthly Weather Review*, Vol 108, No.8, Aug, pp 1212-1218.

Holland G. J. (1981) On the quality of the Australian tropical cyclone data base, *Aust Met Mag*, Vol.29, No.4, Dec, pp. 169-181.

Holland G. J. (1997a) Personal communication.

Holland G.J. (1997b). The maximum potential intensity of tropical cyclones. *J. Atmos. Sci.*, 54, Nov, 2519-2541.

Holthouse H. (1971). Cyclone. *Rigby*.

IPCC (2001) Climate change 2001 – synthesis report. Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, *Cambridge University Press*, 398pp.

McConochie, J.D., Hardy, T.A. and Mason, L.B. (2004) Modelling tropical cyclone over-water wind and pressure fields. *Ocean Engineering*, 31, 1757-1782.

NCCOE (2004) Guidelines for responding to the effects of climate change in coastal and ocean engineering. National Committee on Coastal and Ocean Engineering, Engineers Australia, *EA Books*, Barton, ACT, 76 pp.

Nicholls N. (1992) Historical El Nino / Southern Oscillation variability in the Australian region. In Diaz, H.F. and Margraf, V. (Eds), El Nino, historical and paleoclimate aspects of the Southern Oscillation. *Cambridge University Press*, Cambridge, UK pp151-174.

Pielke R.A. (Jr) and Landsea C.W. (1999) La Niña, El Niño, and Atlantic hurricane damages in the United States, *Bulletin of the American Meteorological Society*, 80, 2027-2033.

Power, S., Casey, T., Folland, C., Colman, A. and Mehta, V. (1999) Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics*, 15, 319-324.

QDOT (1998) Tide tables for Queensland with notes on boating. *Department of Transport*, Brisbane.

SEA (2002) Parametric tropical cyclone wave model for Hervey Bay and South East Queensland. Queensland Climate Change and Community Vulnerability to Tropical Cyclones: Ocean Hazards Assessment - Stage 2. Prepared by Systems Engineering Australia Pty Ltd for JCU Marine Modelling Unit and the Bureau of Meteorology, March.

SEA (2005) SEAtide V1.1 User Guide. Systems Engineering Australia Pty Ltd.

Sobey R.J., Harper B.A. and Stark K.P. (1977) Numerical simulation of tropical cyclone storm surge along the Queensland coast, Department of Civil and Systems Engineering, Research Bulletin No. CS14, *James Cook University*, May, 300pp.

Standards Australia (2002) Structural Design actions, Part 2: wind actions. AS/NZ 1170.2:2002

Webster, P.J., G.J. Holland, J.A. Curry, and H-R. Chang (2005) Changes in tropical cyclone number, duration and intensity in a warming environment. Science, 309,

1844-1846.

WMO. (2006) Workshop Topic Reports, Sixth WMO International Workshop on Tropical Cyclones. Tropical Meteorology Research Programme Report Series. TMRP No. 72. WMO, Geneva.

GHD Pty Ltd ABN 39 008 488 373

201 Charlotte Street Brisbane Qld 4000
GPO Box 668 Brisbane Qld 4001 Australia
T: (07) 3316 3000   F: (07) 3316 3333   E: bnemail@ghd.com.au

Document Status

Rev No.	Author	Reviewer		Approved for Issue		
		Name	Signature	Name	Signature	Date
A	BAH, IBB, DCT	R Fryar		R Fryar		May 2005
B	BAH, IBB, DCT	R Fryar		R Fryar		Oct 2005
C	BAH, IBB, DCT	R Fryar		R Fryar		22/02/2006
0	BAH, IBB, DCT	R Fryar		R Fryar		01/09/2006
1	BAH, IBB, DCT	R Fryar		R Fryar		05/01/2007
2	BAH, IBB, DCT	R Fryar		R Fryar		03/04/2007