Storm Tide Modelling of The Whitsunday Coast and Resort Islands

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Abstract: A comprehensive assessment has been made of the storm tide risk in the Whitsunday Shire region due to the possible effects of tropical cyclones. The assessment was aimed at the delivery of a fundamental risk management tool with respect to the development of a sound vulnerability-reduction (risk allocation) strategy for the shire and was based on return periods. These provide a conceptual basis for quantifying the uncertainties associated with wind, wave, and storm tide due to tropical cyclones. In total, 236 possible cyclones have been modelled in detail laying the ground for statistical estimates of storm tide levels based on an artificially generated time series of 91,304 cyclones over a 50,000-year period.

The study provided guidance to Shire authorities on the interpretation of storm tide return periods and how such information might be used for decision-making in urban and emergency response planning.

Keywords: Storm tide, storm surge, tropical cyclones, return period, Monte-Carlo statistical model, numerical modelling, hazard mapping, urban and emergency response planning.

1 INTRODUCTION

Tropical cyclones generating storm tides and flooding in Australia rank on top of the list of extreme events (geohazards) according to the most recent natural risk assessment completed by the Natural Hazards Research Centre (NHQ 2000). Yet, the theory and application of storm tide predictions is generally poorly understood by those most likely to have a need to apply the results. The need for studies to be undertaken with this fact in mind, is therefore of paramount importance.

Presented are (1) a comprehensive assessment of the storm tide risk in the Whitsunday Shire region (Figure 1) due to the possible effects of tropical cyclones and (2) the adopted methodology. The assessment was aimed at the delivery of a fundamental risk management tool with respect to the development of a sound vulnerability-reduction (risk allocation) strategy for the shire, which should always be based on statistical return periods. These provide a conceptual basis for quantifying the uncertainties associated with wind, wave, and storm tide due to tropical cyclones.

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.

In total, 236 possible cyclones have been modelled in detail laying the ground for statistical estimates of storm tide levels based on an artificially generated time series of 91,304 cyclones over a 50,000-year period.

State-of-the-art wind, spectral wave (ADFA1) and storm surge (Delft3D) models have been applied with the complex results from the latter two summarized into a parametric model before being rendered for inundation mapping purposes by a discrete Monte-Carlo statistical model (SATSIM).

The adopted methodology for the project was based on the “Queensland Climate Change and Community Vulnerability to Tropical Cyclones: Ocean Hazards Assessment” - the “de facto” best practice guidelines approved by Bureau of Meteorology (BOM) for storm tide studies in Queensland. The principal author (and editor) for these guidelines is also one of the authors of this paper. The outcomes from the project were reviewed by a five-member Advisory Committee including the Environment Protection Agency (EPA) and the Department of Emergency Services.

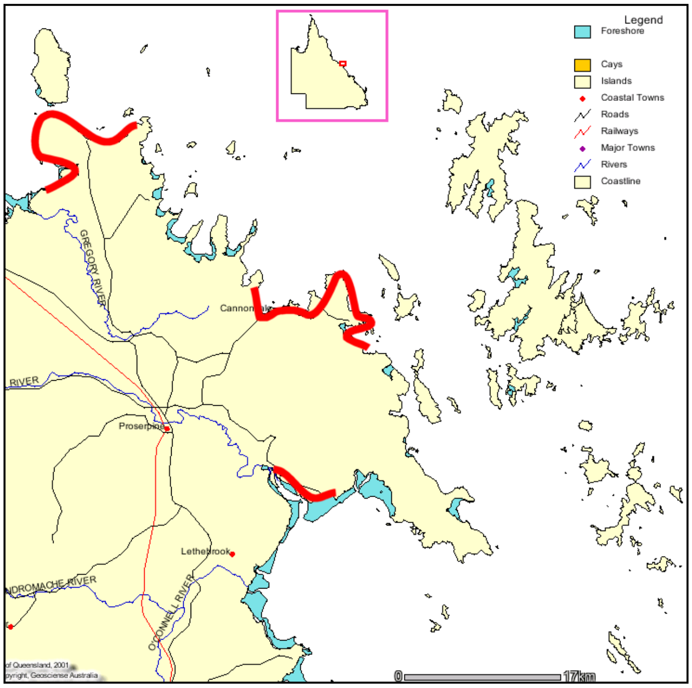

Figure 1 - Study Area With Regions Requiring Hazard Mapping Marked in Red.

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. 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.

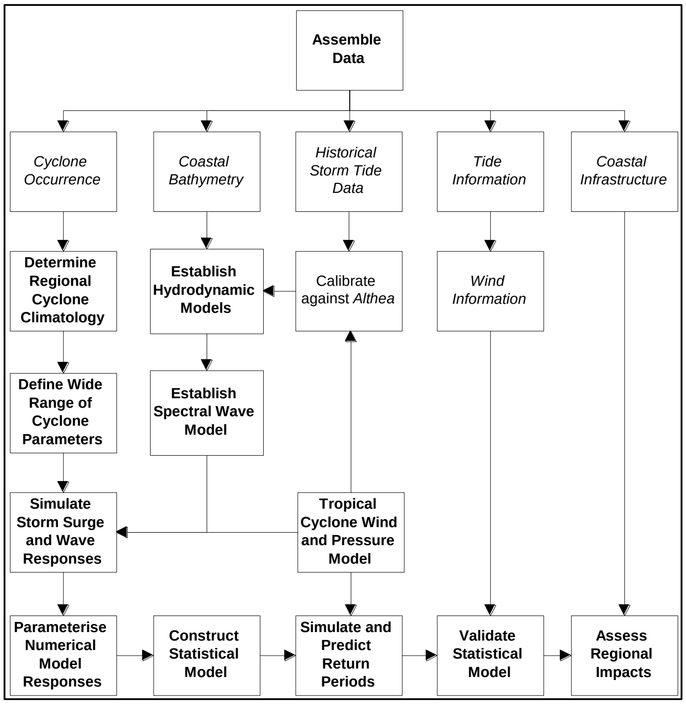

Figure 2 – Overview Of Study Methodology

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 set-up 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.

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 in the region, which are less subject to localised effects.

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 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.

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 Whitsunday region.

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 set-up water level component. The models are constructed based on regional bathymetry data, comprising several nested numerical grids to resolve the numerous near-shore islands and narrow inlets and passages.

The numerical storm surge and wave models are driven by a tropical cyclone wind and pressure field model 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. A much wider set of parameters was then used to simulate the effects of many hundreds of possible cyclones in the Whitsunday region. These parameters were chosen based on the identified range of values from the long-term climatology of the region.

When the results of simulating the wide range of possible cyclones is known, 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 wave setup so that the overall height of the combined storm tide (surge + setup + tide) can be determined at any 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 surge, the tide and the wave setup at each coastal location. In this context, the model is not used to predict the future, but rather to suggest 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.

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.

Finally, 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 then mapped to define the 50, 100 and 1,000 year storm tide elevations. Additionally, the Probable Maximum Flood or PMF 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 greenhouse-induced climate change are considered in a subsequent step, whereby a possible future climate scenario is simulated and those results compared with the estimates for "present climate".

5 DEVELOPMENT AND TESTING OF THE MODELLING SYSTEM

The first module of the system – the tropical cyclone wind and pressure 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: (1) the central Mean Sea Level (MSL) pressure p_0; (2) the surrounding, or ambient, pressure p_n; (3) the radius to maximum winds R; (4) the windfield peakedness factor B; (5) the storm track (speed V_{fm} and direction θ_{fm}). The method used in this study (as developed by SEA) 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 10m above the ocean surface for supply to the hydrodynamic models for storm surge and waves. It also estimates the 3-second wind gust for comparison with long-term wind records at Mackay. The MSL pressure is also supplied to the hydrodynamic model as it has an influence on the generation of the storm surge.

The 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. A single, three-dimensional application of the hydrodynamic model was used to conduct sensitivity tests involving tropical cyclone Althea. Two levels of nesting (using BOM-approved class A, B and C grids, kindly provided by the James Cook University Marine Modelling Unit) were used achieving a maximum coverage of some 0.9×10^{-6} square kilometres along the coast of Queensland.

As the Delft3D model had not previously been coupled with the Harper and Holland (1999) tropical cyclone wind and pressure model, it was deemed necessary to ensure that the combined model, with the above assumptions, would operate reliably in estimating storm surge levels for this study. Ideally, the model would be tested against an historically measured event in the Whitsunday Region but since no suitable data is available, the nearby well-documented 1971 event of Althea at Townsville has been used. Results of the calibration check showed a very favourable comparison 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) were 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).

Estimates of the breaking wave setup component of the total storm tide (3rd row in Figure 2) were provided by a numerical spectral wave model of the Whitsunday Region established using the ADFA1 model – a 2nd-generation spectral wave model which 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).

There is no site-specific wave data for the region that would be suitable for verifying the operation of the wave model. Reliance was therefore made on the well-established performance of this model in many similar studies. However, a number of sensitivity tests were done to determine the effect of different model computational timesteps. Due to the complex island features and the presence of extensive shoals and banks to the south of the study area (Figure 1), a 600 s time step was retained to maintain highest accuracy.

Parametric models (bottom row in Figure 2) were developed to summarise the complex results from the full-scale hydrodynamic and spectral wave models and to express their output in a form that can be readily assimilated by the statistical model. These resulted in 3 sets of tracks, chosen to represent the best coverage of the likely storm surge response: 140° - parallel to the coast; 180° - oblique crossing; 230° - perpendicular crossing.

The tracks were combined with intensity, speed, size and location and were simulated by the hydrodynamic model and the spectral wave model. This required a total of 2 x 2 x 3 x 2 x 9 = 216 simulations, each of which 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 storms, "landfall" is the time of closest approach to Airlie Beach. 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 18 special tests 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.

Finally, since all the preceding simulations were conducted at Mean Sea Level (MSL), a special set of sensitivity tests was undertaken at +1.5m and -1.5m, representative of approximately the Mean High Water Springs and Mean Low Water Springs tidal condition in the region (point of reference Shute Harbour).

Therefore, a total of 236 detailed numerical hydrodynamic and spectral wave model runs have been 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 336 coastal locations in the region.

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 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.

The statistical module of the system – SATSIM, generates an artificial history of tropical cyclones based on the climatology. The model calculates the occurrence of cyclonic events 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. 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. There is no absolute way that the statistical model can be verified, other than ensuring that the various component parts of the model are performing correctly. Performed checks relate to the model’s re-creation of the astronomical tide statistics and a comparison its wind speed predictions with long term regional values.

5 RESULTS

Key results of the study were presented in the form of hazard maps for planning and emergency services related applications with the maps indicating zones of potential inundation as a function of return periods for the coastal areas at risk. The locations most exposed to storm tide in the shire were identified and categorized relative to the risk incurred in strict compliance with the Australian regulatory practices. The estimated return periods (50-year, 100-year, 1000-year and 10000-year) of total storm tide levels for key locations allowed for a detailed assessment of impacts of storm tide on critical infrastructure in inundated areas and a consequent review of Council’s evacuation plans. In addition to the principal predictions of extreme storm tide levels undertaken within the concept of “present” climate, the possible influence of “enhanced greenhouse” climate by the year 2100 has been also estimated.

The study gave guidance to Shire authorities on the interpretation of storm tide return periods and how such information might be used for decision-making in urban and emergency response planning. A computerized database of predicted inundation levels with possibility of extracting data for any point of the affected areas was delivered using high-resolution hazard mapping at 1 m contour intervals for the most populated areas. The ability to query the outcomes of the parametric model for future planning and emergency services applications without re-running the expensive and time consuming full scale hydrodynamic model is of great benefit to the local authorities.

The study results are derived from the statistical 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.

Results from the hydrodynamic (surge-only) modelling of all 236 cyclones are transferred to the parametric model in the form of time series of storm surge elevation at 10-minute intervals and at 336 coastal locations in the region. In addition, for each cyclone, a series of maps illustrating the current fields (in response to the cyclone) in the nearshore zone overlain on water elevation are generated at 15-minute intervals and stored for presentation purposes.

Results from the statistical model are presented in two different formats: (1) Absolute levels relative to Australian Height Datum (AHD); (2) Inundation depths relative to the local Highest Astronomical Tide (HAT).

Each of these is then provided as: (1) Tabulated values for the identified townships and resorts; (2) Regionally ranked summary graphs; (3) Selected site-specific return period graphs; (4) Selected detailed regional mapping.

It should be noted that the actual depth of inundation will vary as the difference between local ground level and storm tide level, both referenced to AHD. 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.

5.1 Storm Tide Levels

Figure 3 summarizes the estimated total storm tide levels for selected sites, grouped by geographic proximity. As a general rule, the further offshore an island site, the lower the expected storm tide, assuming it is also sheltered from extreme waves. Likewise, coastal sites that are located in large shallow bays are likely to experience increased storm tide levels but open coast sites may also be exposed to high breaking wave setup levels.

Figure 4 shows the relative storm tide rankings. The highest indicated storm tide levels of the selected townships and resorts are at Wilson/Conway, near the mouth of the Proserpine River in Repulse Bay, followed by Dingo Beach, south of Cape Gloucester and then Airlie Beach. The lowest indicated levels are at Hook Island Observatory and Hayman Island. The majority of locations have an estimated 10000-year level between 4.0 and 5.0 m AHD.

Figure 5 provides a sample of a series of colour-shaded inundation maps (relative to AHD) designed to enhance the presentation of storm tide data and to facilitate its use by Council's planning department and engineering units. All maps are delivered in digital format and are accessible on ESRI's Arcview Version 8.x and MapInfo Professional Version 6.0 (and later) GIS platforms.

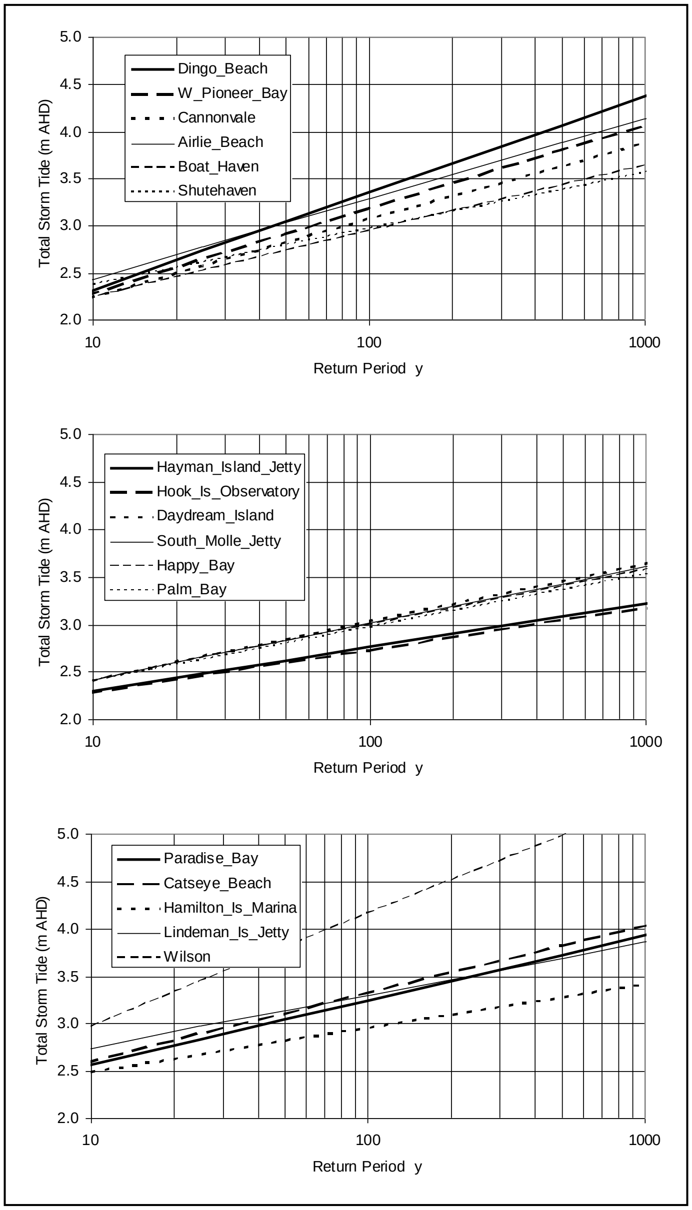

Figure 3 - Estimated Total Storm Tide Levels For Selected Sites

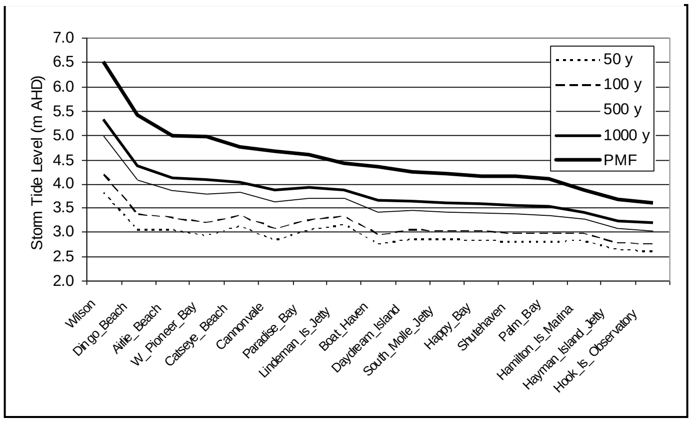

Figure 4 - Relative Ranking Of Estimated Storm Tide Levels

Shown on the map is the impact of storm tide on the coastal zone corresponding to Boathaven Bay.

The red line depicts the extent of the 10,000-year storm tide event. Dashed lines indicate the extent of inundation for the 1 in 50 year, 1 in 100 year and 1 in 1000 year storm tides.

The levels indicated on the map are labelled using two digits after the decimal point to enhance the perception of the storm tide levels spatial variability along the inundated coast and it should not be construed that the accuracy of the prediction is to that precision.

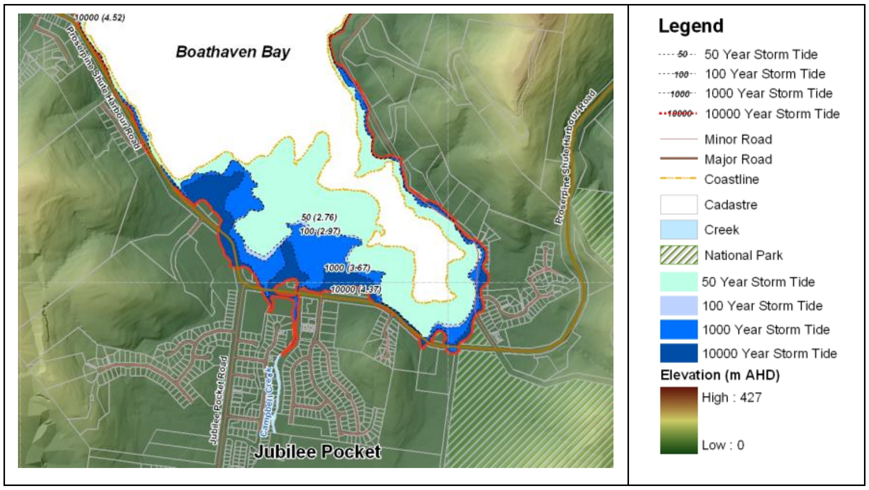

Figure 5 - Example Of Impact Map For Town Planning Applications

The effective resolution for the maps is 1 m contour intervals for Airlie Beach and Shute Harbour areas, 5 m contour intervals for the western part of Cape Gloucester and 10 m contour intervals for Conway and Wilson Beaches. The underlying (topographic) calculations to determine the inundation areas have been carried out at 100 m grid resolution.

All calculations have been carried out on the best available (current) topography (i.e., 1 m contour intervals for Boathaven Bay).

This series of maps is designed for town planning purposes and contains Council's cadastral plan, major roads and localities overlaid on the topography of the area. Storm tide impacts on land use can be assessed by overlaying Council's Planning Scheme on the map and by conducting spatial analysis. Spatial analysis relies on the categories included in the Whitsunday Shire Council Planning Scheme to produce a detailed statement of consequential loss per land category. Table 1 sets out the land area of Airlie Beach occupied by each zone and the area that will be inundated by the 50-year, 100-year, 1000-year and the 10000-year return period storm tide.

Table 1 - Land Use Areas Affected by the 1 in 50-y, 1 in 100-y, 1 in 1000-y and 1 in 10000-y return period storm tide

	Areas in hectares				
Land Use (Code)	**50-y**	**100-y**	**1000-y**	**10000-y**	**Land Use Zones**
Rural (R)	0.48	0.48	0.48	0.48	0.65
Rural Protection (RP)	18.58	23.76	40.70	51.25	939.90
Low Density Residential (LDR)	2.06	3.03	8.23	11.85	427.82
Urban Residential (UR)	0.00	2.27	6.26	10.15	455.00
Industry (I)	0.82	1.25	4.85	10.08	24,35
Commercial (C)	0.84	0.97	1.36	2.02	16.53
Particular Development (PD)	7.73	8.14	9.66	11.88	102.00
Open Space (OS)	12.81	15.82	22.97	28.74	86.04
Public Purpose (SR)	10.97	11.57	12.48	13.10	2739.20
Totals:	**54.30**	**67.32**	**107.00**	**139.55**	**4791.51**

5.1 Inundation Depths

A summary of inundation depths is shown in Figure 6. Inundation depths are expressed relative to the highest astronomical tide (HAT) and therefore represent the additional depth of sea water over and above that associated with HAT.

The relative ranking of storm tide inundation depths for the selection of townships is similar to that for the absolute elevations. Dingo Beach is the highest, followed by Wilson/Conway Beaches and then Airlie Beach. The lowest indicated levels are again at Hook Island Observatory and Hayman Island. The majority of locations have an estimated 10000-year return period storm tide inundation depth between 1.5 and 2.0 m above HAT.

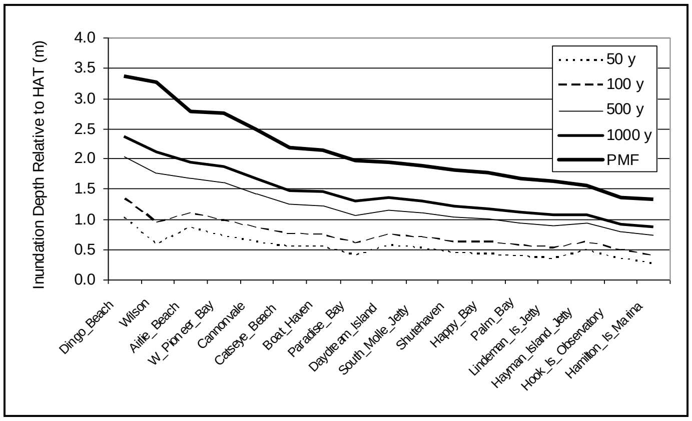

Figure 6 - Relative Ranking Of Estimated Storm Tide Inundation Depths

As discussed in earlier sections, the increasing tidal range from north to south acts to raise the HAT tidal plane. This is combined with the regional sensitivity to storm surge, whereby for example, Wilson is located in a region where the storm surge will always be amplified due to the shallow waters, but is somewhat protected against extreme waves and setup. Dingo Beach however, is a more open coast site with modest exposure to storm surge and a high exposure to extreme waves and setup. The intervening sites, by comparison, are somewhat protected by the complex island geography.

5.1 Interpretation Of The Results

Figure 7 presents the variation in probability of at least one event occurring (the encounter probability) versus the period of time considered (the design life). The intersection of any of these chosen variables leads to a particular return period and a selection of common return periods is indicated. For example, this shows that the 200-year return period has a 40% chance of being equalled or exceeded in any 100-year period.

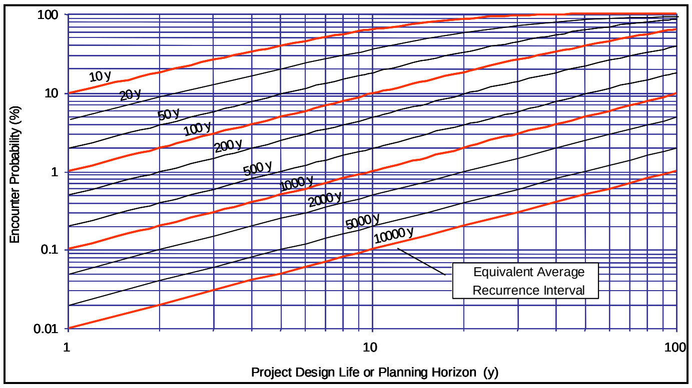

Figure 7 – Relationship Between Return Period and Encounter Probability

The level of risk acceptable in any situation is necessarily a corporate or business decision. Table 2, based on Figure 7, is provided to assist in this decision making process by showing a selection of risk options. Using Table 2, combinations of design life and a comfortable risk of occurrence over that design life can be used to yield the appropriate return period to consider. For example, accepting a 5% chance of occurrence in a design life of 50 years means that the 1000-year return period event should be considered. A similar level of risk is represented by a 1% chance in 10 years. By comparison, the 100-year return period is equivalent to about a 10% chance in 10 years. AS1170.2 (Standards Australia 1989), for example, dictates a 5% chance in 1000-year criteria or the 1000-year return period as the minimum risk level for wind speed loadings on engineered structures.

Considered Design Life or Planning Horizon	**Chosen Level of Risk of at Least One Event Occurring**						Equivalent Return Period
	% Chance						
Years	**1**	**2**	**5**	**10**	**20**	**30**	
10	995	495	195	95	45	29	y
20	1990	990	390	190	90	57	y
30	2985	1485	585	285	135	85	y
40	3980	1980	780	380	180	113	y
50	4975	2475	975	475	225	141	y

9 CONCLUSIONS

A comprehensive assessment has been made of the storm tide risk in the Whitsunday Shire region due to the possible effects of tropical cyclones. The analyses have used a combination of historical data analysis, detailed numerical hydrodynamic modelling and state-of-the-art statistical modelling. The regional impacts have been assessed based on Council-supplied infrastructure information.

The study has considered: (1) the long-term historical record of cyclones in the region, including preferred tracks, speeds, directions and intensities; (2) the spatial and temporal characteristics of storm surges generated by cyclones interacting with the complex coastal features; (3) associated extreme waves and breaking wave setup levels at the coastline; (4) the astronomical tide, which varies significantly across the region.

The accuracy of the various models has been confirmed by comparison with available historical wind and storm surge data and also the published tide tables.

While the principal predictions of extreme storm tide levels has been undertaken within the concept of “present” climate, additional guidance on the possible influence of an “enhanced greenhouse” climate by the year 2100 has also been included.

Guidance has also been provided on the interpretation of storm tide return periods and how such information might be used for decision making.

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