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Townsville and Thuringowa City Councils

Townsville-Thuringowa Storm Tide Study

Final Report

Part C – Appendices

April 2007

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

Appendix A

Tropical Cyclone Aivu – 1989

The deterministic accuracy of the numerical wind, wave and storm tide models has been further demonstrated here by a hindcast of the effects of tropical cyclone *Aivu* during its landfall in Upstart Bay in 1989.

Background

Severe tropical cyclone *Aivu* developed from a low pressure region off the south-east tip of Papua New Guinea on 31st March 1989 (BoM 1990) and was named by the Port Moresby Tropical Cyclone Warning Centre on 1st April. It continued on a south to south-west path for the next three days before making landfall at the mouth of the Burdekin River immediately east of the town of Home Hill at 10:30 AM EST (04/04 00:30 UTC[6]). Figure A1 shows the path of the storm throughout its life and indicates the location of the important AWS (Automatic Weather Stations) of Willis Island, Holmes Reef and Flinders Reef near its path.

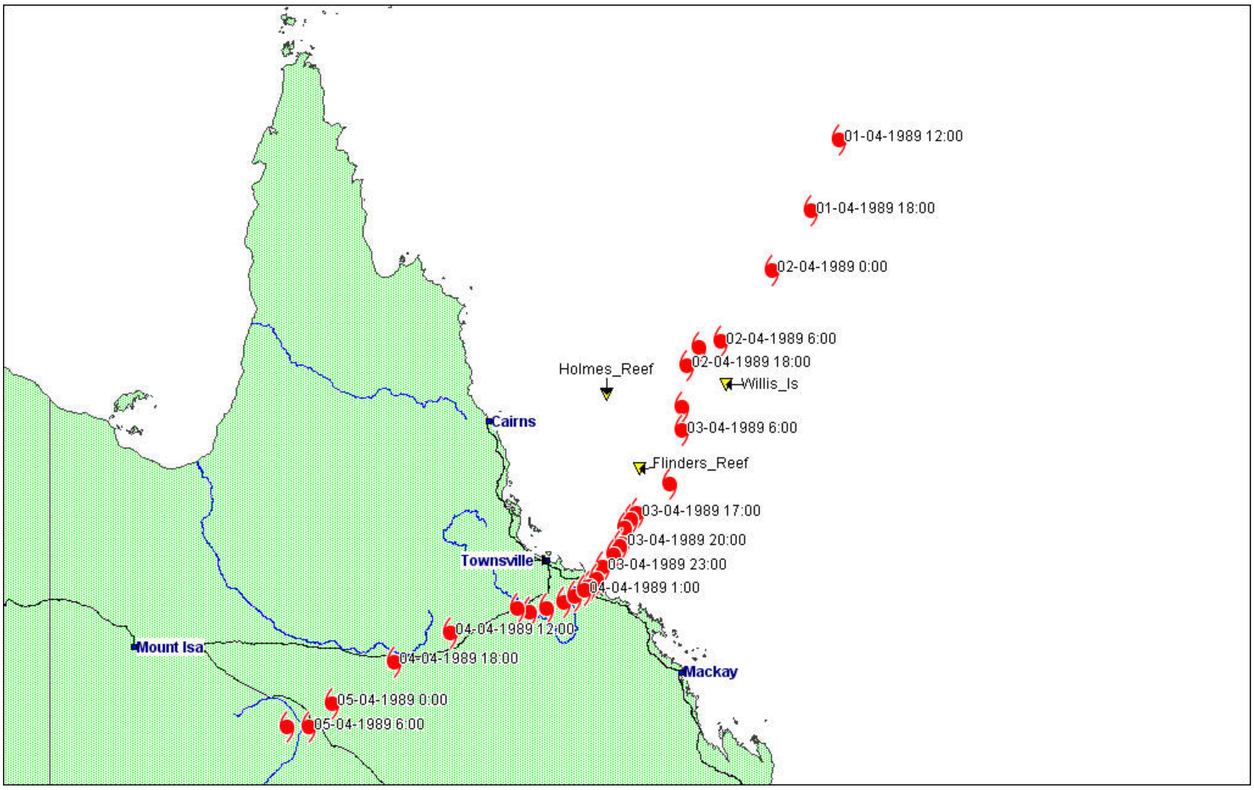


Figure A1 Lifetime track of severe tropical cyclone *Aivu* (times in UTC)

The intensity of *Aivu* was estimated by the Bureau of Meteorology based on the Dvorak (1984) method, which utilises Enhanced Infrared Imagery (EIR) satellite images to infer the maximum surface wind speed and associated central pressure. Official estimates placed *Aivu* at its most intense on 03/04 00:00

[6] UTC refers to the universal time convention, identical to GMT – Greenwich Mean Time, for practical purpose.

UTC when it was between Willis Island and Holmes Reef, with a central pressure (p_0) of 935 hPa. The storm was observed to weaken somewhat rapidly during the latter half of the 3rd and by the time it crossed the coast early on the 4th, an eye passage reading of 959 hPa was registered at Fredericksville, about 1 h after landfall. No wind speed measurements were available from the region of maximum winds during landfall but barographs were recorded to the north (Ayr Post Master) and to the south (Gumlu) of the track. Figure A2 provides a detailed map of the landfall location.

The impacts of *Aivu* included minor to moderate wind damage to buildings in the Ayr – Home Hill region but the most significant effect was from the storm tide that inundated the low lying coastline within Upstart Bay. Fisherman's huts located on the beach at Wunjunga immediately south of the Burdekin River delta were destroyed during the storm, probably due to a combination of wind, wave and storm surge effects. Personal accounts of the passage of the storm tide were available from many coastal residents south to Molongle Creek. One elderly man drowned during the event.

Figure A2 Track of *Aivu* at landfall and affected localities

Track Reconstruction

The published BoM official track was used as the basis of the reconstruction. However, following advice from the Queensland Regional Office Severe Weather Section (J. Callaghan), the intensity of *Aivu* was increased beyond the official estimate during the period of assessed maximum intensity. An unofficial reanalysis of *Aivu's* intensity by Jeff Callaghan reveals that it may well have been the most intense tropical cyclone yet seen in the Australian region. Using updated interpretation, the maximum intensity of the storm during the period 03/04 00:00 to 06:00 may have been as much as 880 hPa, close to the estimated regional Maximum Potential Intensity (MPI) by Holland (1997). Figure A3 presents the satellite imagery at this time. The track parameters were therefore adjusted to accommodate a diversion to the revised maximum intensity over a 24 h period, returning to the official estimates largely after 03/04 18:00 UTC. A nominal landfall intensity of 950 hPa was also applied as it was noted that the storm was weakening and filling near that time. The significant intensity adjustments made offshore are not expected to greatly influence the coastal storm surge impacts.

The official track provided no specific guidance on radius to maximum winds although BoM (1990) postulated a value near 22 km based on radar and other data. Values for *R*, together with an estimate of the Holland peakedness parameter *B* were then obtained by calibration against the wind and pressure records available from the collection of offshore and onshore stations.

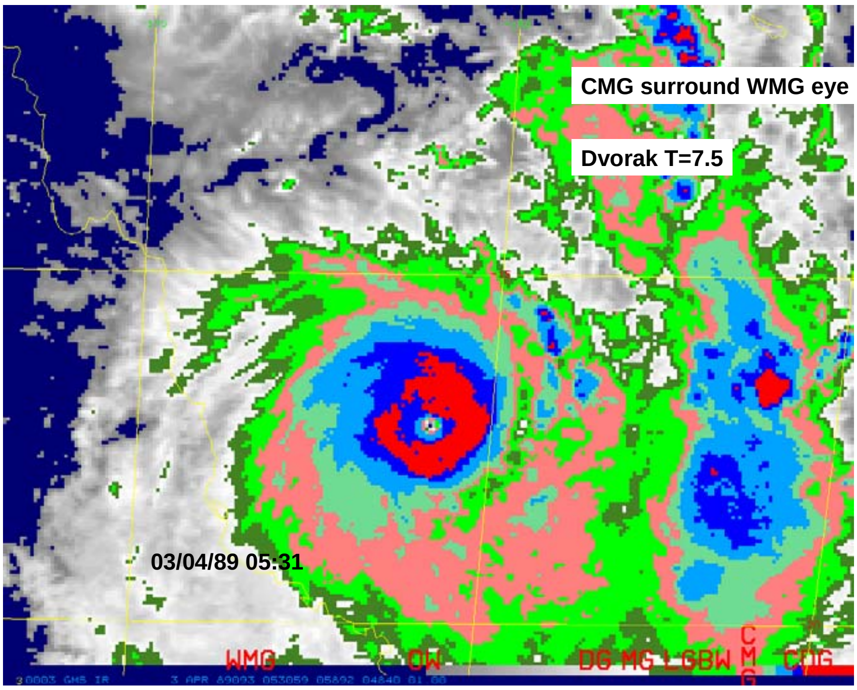


Figure A3 Enhanced infrared satellite imagery at maximum intensity

Wind and Pressure Calibration

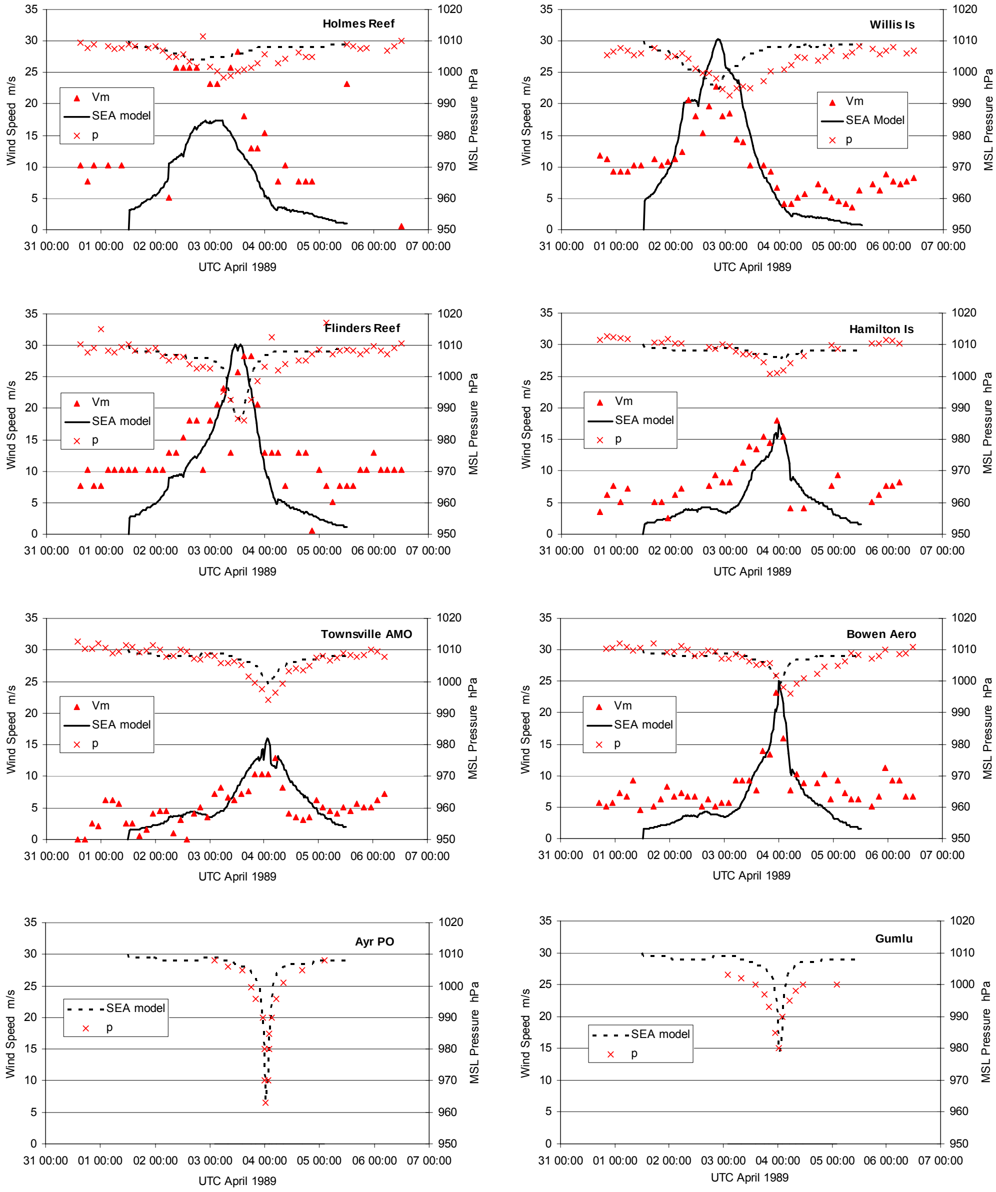
The wind model calibration process attempted to find an optimal set of *R* and B_o that would minimise the error between modelled and measured wind and pressure across all the available sites. This proved difficult in the particular case of Holmes Reef, where the peak winds were recorded some 132 km west of the centre, and to some extent at Willis Island, which was only 72 km east of the centre but experienced unexpectedly lower winds. The storm was at its maximum intensity during this period. In the case of Holmes Reef it is speculated that its higher winds were due to its location relative to the apparent asymmetry seen in Figure 3 to the north-west of the centre. This asymmetry is attributed to an enhancement of the convective processes around the storm (J. Callaghan, personal communication). Such asymmetry of the radial wind profile cannot be accommodated in a single vortex model and so winds in this region remain underestimated in the present reconstruction. However, winds at Willis Island, which appear anonymously low, are slightly overestimated.

The key calibration point for the present interest in coastal storm surge is at the closer Flinders Reef AWS, where both the wind and pressure has been reasonably well matched. Analyses showed that an *R* value of around 25 km and a B_o value of 7.3 were capable of reproducing measured wind speeds well over a wide range and provided a close match to the shape of the landfall pressure profiles available both north and south of the track. Pressure values remote from the storm centre generally remain under predicted (too high) but this would likely be alleviated by the use of a secondary vortex with a 10hPa deficit. Figure A4 summarises the accuracy obtained in fitting the numerical wind (Vm) and pressure (p) model to the available data. All symbols represent measured data and all lines represent modelled results. Furthermore, the solid line relates to wind speed whilst the dashed line represents pressure.

Wave Model Validation

The ADFA1 spectral wave model was established using the same A and B grids used for the Townsville-Thuringowa region, as provided by JCU/MMU. These were then matched with a further JCU/MMU C grid extending from Cape Bowling Green south to Cape Gloucester. Figure A5 shows an expanded regional view of the storm track together with the various measurement stations for wind, waves and tide.

Measured wave data from the Beach Protection Authority waverider buoys located at Townsville (near Cape Cleveland) and at Abbot Point (BPA 1989) were kindly made available to the study. Woodside Energy Limited has also allowed use of directional (WAVEC) and non-directional waverider data from Leopard Reef that was fortuitously collected during an HF radar experiment undertaken by JCU/Physics, using an antenna system based at Cape Ferguson. JCU/MMU also kindly provided waverider data from John Brewer Reef, 70 km NNE of Townsville on the inner side of the main barrier.



Vm	velocity
P	pressure
UTC	Universal Time

Figure A4 SEA wind and pressure model calibration results

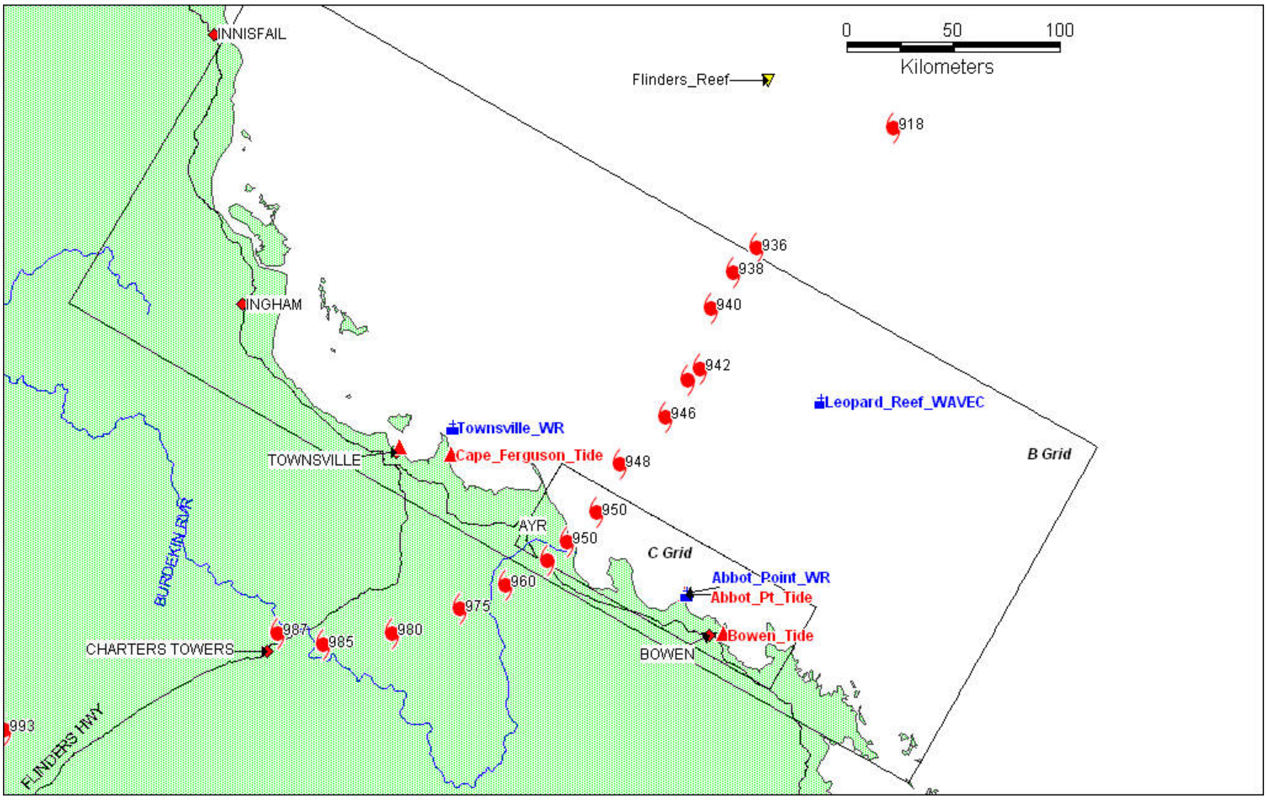


Figure A5 Numerical model limits and wave and tide stations

The results of the wave model validation experiment are given in Figure A6, where it can be seen that the ADFA1 model matched the magnitude and timing of peak significant wave height (H_s) extremely well at all three waverider sites situated in open waters. The peak spectral wave period (T_p) although a sometimes erratic parameter, was also well modelled at the time of the peak H_s. The mean zero crossing period (T_z) was also well matched at that time. All symbols in Figure A6 represent measured data and all lines represent modelled results. The solid line denotes H_s, the large dashed line T_2, and small dashed line T_p.

Some deviations from the measured parameters are evident prior to the arrival of the peak conditions, especially at Leopard Reef located on the outer barrier, and these are probably due to the inaccuracy of representing the full windfield and the pre-existing sea state. The John Brewer location was under-modelled because of a lack of detailed representation of the inner reef and is not shown. However, these results validate the accuracy of the adopted spectral wave modelling approach for estimating nearshore wave conditions.

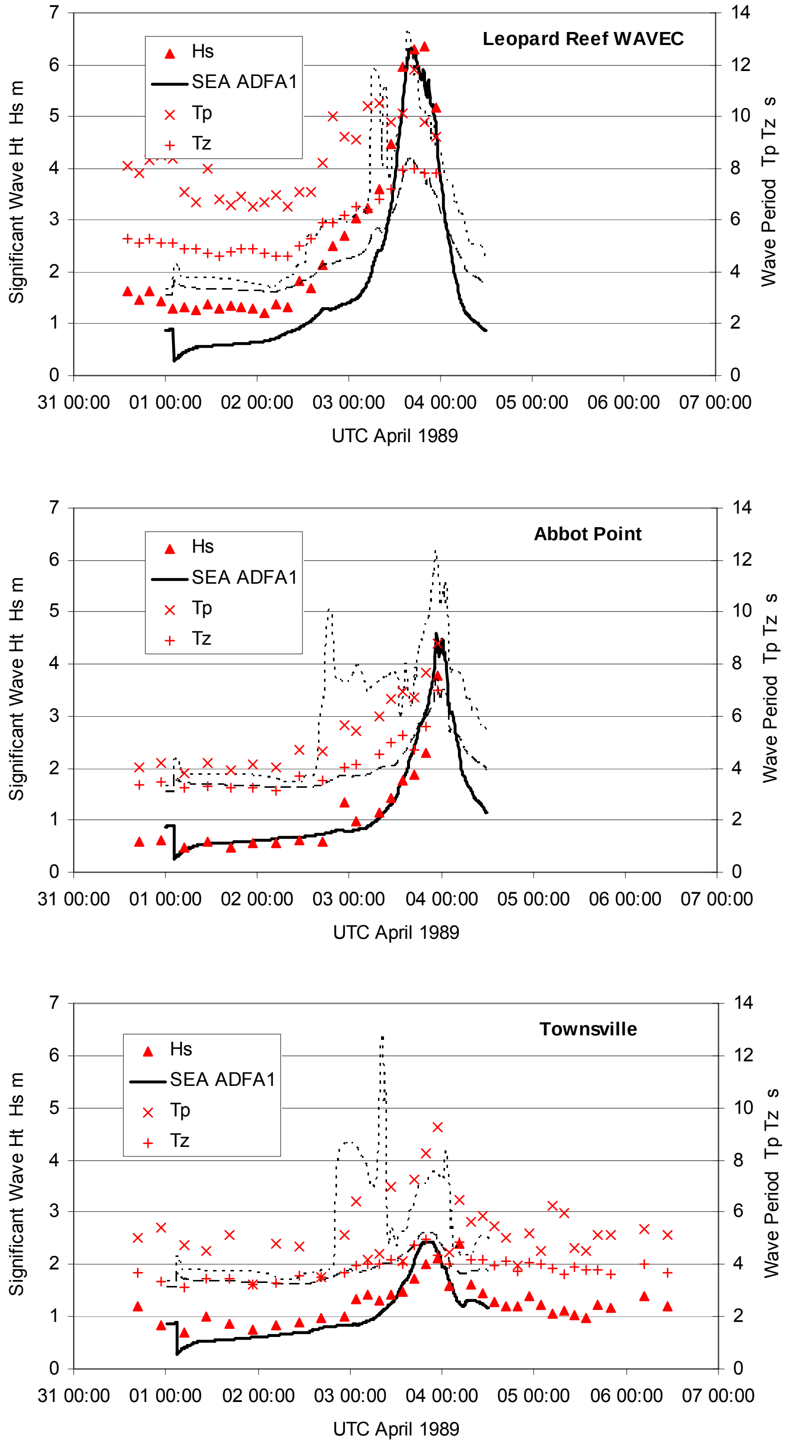


Figure A6 Validation of the ADFA1 spectral wave model.

Cape Ferguson and Townsville tide gauges, which are located similar respective distances to the north, registered only small peaks of the order of 0.5 m. All tide data were kindly supplied by Maritime Safety Queensland.

The peak storm surge at landfall occurred on a falling tide in the Upstart Bay area between Wunjunga and Molongle Creek. Based on anecdotal evidence and a post-storm survey by Bowen Shire Council, the water level was estimated to be about 2.5 to 3 m above the expected 0.5 m AHD tide at the time, reaching levels of approximately 3 to 3.5 m AHD (BoM 1989, Harper 1999). A video taken during the post-storm survey was also provided by the EPA (David Robinson), where eyewitness accounts are given, especially the rapidity of the rise and fall of the water level at Molongle Creek, which was stated to have “come up and down within the hour”. While wave action at the beachfront clearly caused erosion and resulted in the destruction of improvised breakwaters and some fishing huts, eyewitnesses further inland experienced little wave action.

The Delft3d model was applied to the same nested grid arrangement as shown in Figure A5 and a hindcast of the storm undertaken with initial water level at MSL, without the astronomical tide. This was necessary as the scope did not include development of a calibrated tidal model for this region. Based on experience in the Townsville region, the absence of the tidal stream can be expected to affect the peak storm surge only slightly, probably within 5%.

The results of the modelling showed excellent agreement with the Abbot Point tide gauge, matching the tide residual up until the point of failure at 0.95 m and suggesting a peak of 1.1 m occurred at this location. At Bowen, the model slightly under predicted the recorded 1.14 m peak surge by 0.2 m. At Cape Ferguson and Townsville, however, the model overpredicted the recorded 0.5 m surges quite significantly and this suggests that the reconstructed wind field must have been too intense earlier in the track.

Figure A7 shows the model comparison with the Abbot Point tide gauge, which provides a high level of confidence in the predictions at the nearby affected coastal locations of Wunjunga and Molongle Creek. In each case, the predicted tide for Abbot Point has been added to the modelled storm surge response based on MSL, to provide an estimate of the total surge plus tide level to AHD. The modelling suggests that water levels at Wunjunga exceeded local HAT (assumed 1.974 m AHD) for about 4 h, reaching 3.1 m AHD with a 2.4 m surge component. Note that these results do not include the possibility of localised breaking wave setup, which is discussed in the next section. The modelled peak surge arrives at Molongle Creek approximately 30 min later than Wunjunga and is just slightly higher, with a 2.7 m surge component. Because of this slight time lag on the falling tide, plus the fact that the surge response is more peaked, the period of time when water exceeded HAT at Molongle Creek is much less than Wunjunga. The shape of the peak exactly agrees with the eyewitness accounts that it all occurred within a 1 h period.

Wave Setup Estimates

There are no quantitative estimates of nearshore wave height or wave setup that can be used to verify the modelling here, but Figure A8 presents the modelled time histories of waves at Wunjunga and Molongle Creek, from which some insight is possible. Firstly, the peak waves are seen to coincide almost exactly with the peak surge, reaching a peak Hs of 3.8 m at Wunjunga and 3.5 m offshore of Molongle Creek. The ADFA1 modelling assumes both locations have a nominal water depth of 3 m. While the peak wave condition is higher at Wunjunga, it drops away more rapidly as the eye passes overhead than at Molongle Creek.

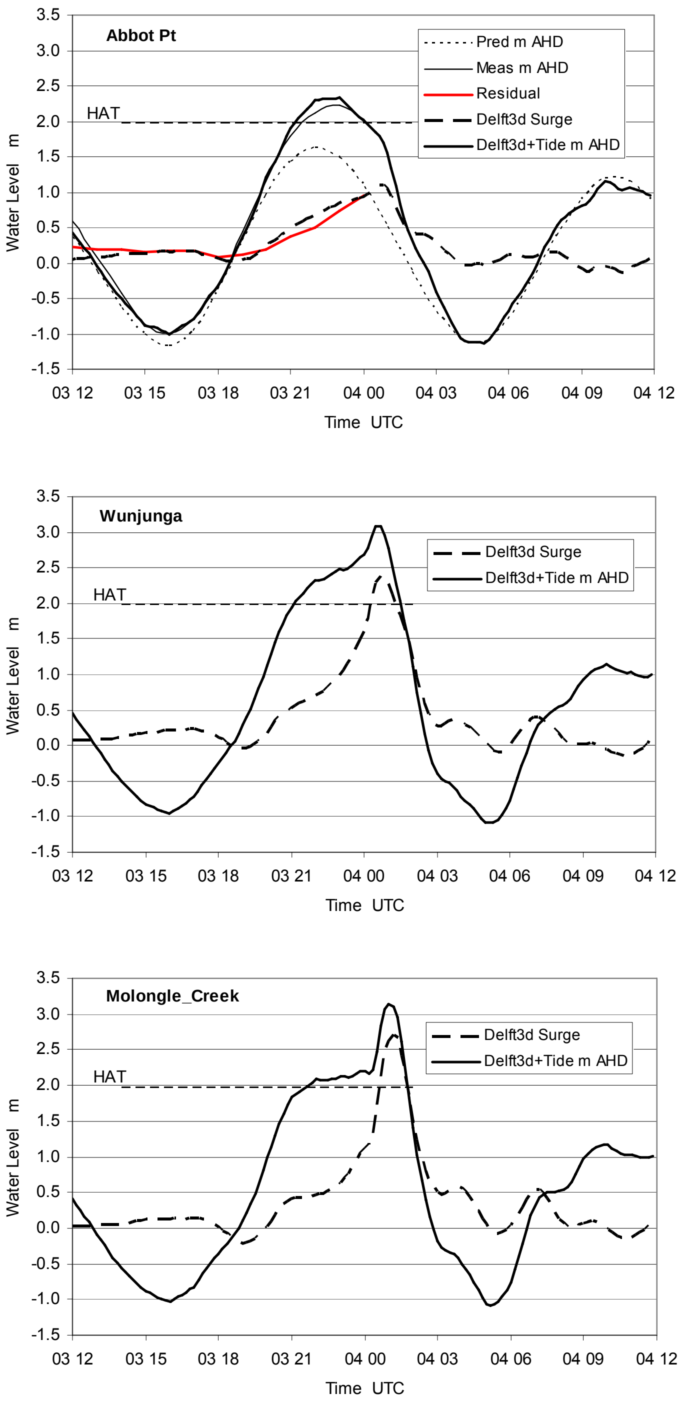
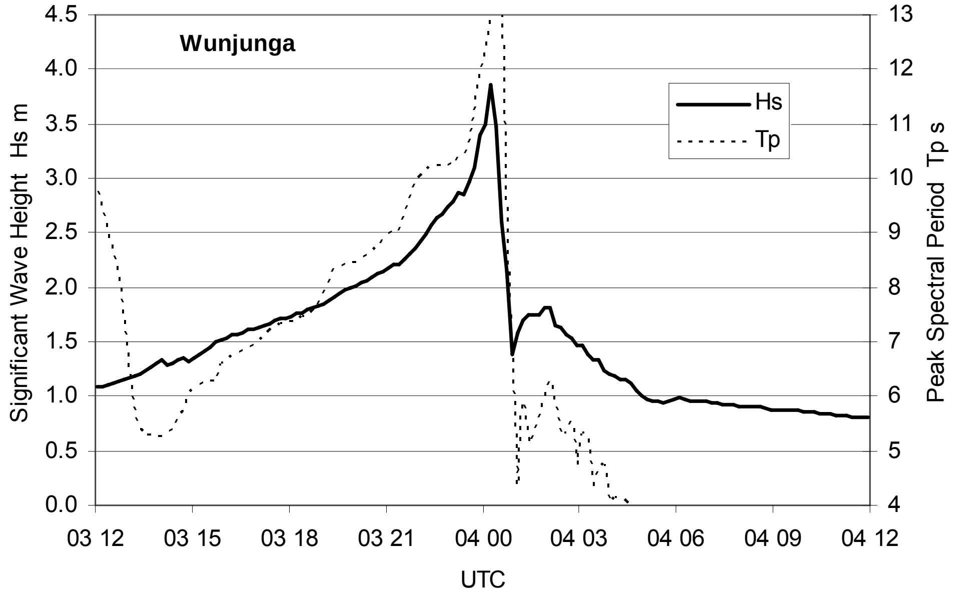


Figure A7 Measured and modelled coastal water levels during *Aivu*.



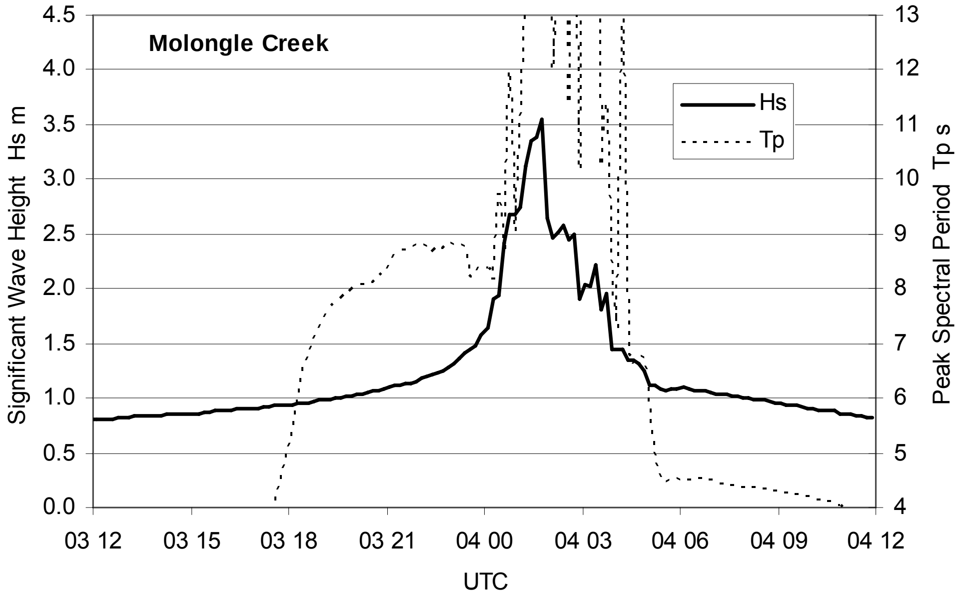


Figure A8 Modelled nearshore wave conditions in Upstart Bay during *Aivu*

The actual degree of breaking wave setup that may have occurred is dependent on the local beach and dune configurations that might have supported the breaking wave condition before inundation and erosion occurred. Without accurate land elevations it is not possible to estimate this effect in detail. However, given the reasonably high wave heights and the long spectral period predicted by the model, breaking wave setup could have contributed between 0.5 m and 1.0 m to the total water level at the exposed frontal areas of Wunjunga. Wave runup would have been additional, where there was a sloped shorefront.

Storm Surge Model Validation

A number of official tide and storm surge gauges recorded aspects of the storm surge generated by *Aivu*. The closest tide gauge to the landfall location was Abbot Pt, approximately 60 km south of the track, which recorded a rapidly rising surge of 0.95 m before the gauge failed, no doubt due to the combination of total surge, tide and wave effects. Bowen, which is 85 km south of landfall, recorded a peak of 1.14 m.

Conclusions

This hindcast of tropical cyclone Aivu has demonstrated the ability of the combined deterministic modelling components applied to this study to quite accurately reproduce the quantitative and qualitative impacts of this real storm event. The winds and pressure near landfall have been very well represented and the local storm surge at the nearest tide gauge has been well matched. It can therefore be expected that the peak surge in Upstart Bay has been reasonably well approximated. The modelled peak surge in the Wunjunga to Molongle Creek area is between 3.0 and 3.4 m AHD, representing a peak surge component between 2.4 and 2.8 m, with the possibility of breaking wave setup adding around 0.5 or more at the earlier stages of inundation at exposed shoreline locations. These values compare very favourably with the post-storm inspections.

References

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Appendix B

Tropical Cyclone Wind & Pressure Field Model

Appendix B – Tropical Cyclone Wind and Pressure Model

The following provides an overview of the parametric tropical cyclone wind and pressure model adopted for this study, which is similar to Harper and Holland (1999). Further elaboration is provided here of specific formulations which have been developed over a number of years as a result of extensive wind, wave and current hindcasting, e.g. Harper *et al.* (1989, 1993) and Harper (1999).

B.1 Definitions and Background

A tropical cyclone (hurricane or typhoon) is defined as a non-frontal cyclonically rotating (clockwise in the Southern Hemisphere) low pressure system (below 1000 hPa) of tropical origin, in which 10 minute mean wind speeds at +10 m MSL (V_m) exceed gale force (63 km/h, 34 kn, or 17.5 m/s). In view of the complex nature of tropical cyclones and their interaction with surrounding synoptic scale mechanisms, most empirical wind and pressure models (Lovell 1990) represent the surface wind field by considering the storm as a steady axisymmetric vortex, which is stationary in a fluid at rest.

The vortex solution is based on the Eulerian equations of motion in a rotating frame of reference (Smith 1968). The analysis begins with a consideration of force balance at the geostrophic, or gradient, wind level above the influence of the planetary boundary layer. The gradient wind speed can be expressed as a function of storm pressure, size, air density and latitude. The gradient wind speed is then reduced to the surface reference level of +10 m MSL (mean sea level) by consideration of gross boundary layer effects, wind inflow (also due to frictional effects) and asymmetric effects due to storm forward motion or surrounding synoptic pressure gradients.

B.2 Radial Pressure Field

A primary assumption of almost all empirical tropical cyclone models is that the radial pressure field at gradient wind speed level can be expressed as:

$$p(r) = p_0 + (p_n - p_0) \exp(-R/r) \qquad \text{(B.1)}$$

where

r	=	radial distance from storm centre
$p(r)$	=	pressure at r
p_0	=	pressure at the storm centre (central pressure)
p_n	=	ambient surrounding pressure field, and
R	=	radius to maximum winds

This exponential pressure profile was first proposed by Schloemer (1954). Holland (1980) noted deficiencies in the ability of Eqn B.1 to represent many observed pressure profiles and that the Schloemer base-profiles resembled a family of rectangular hyperbolae, viz:

$$r^B \ln[p/(p_n - p_0)] = A \qquad \text{(B.2)}$$

where A and B are storm-dependent scaling parameters.

This modification leads to the following radial pressure field, which forms the basis of the 'Holland' model:

$$p(r) = p_0 + (p_n - p_0) \exp(-A/r^B) \qquad \text{(B.3)}$$

B.3 Gradient Wind Speed

The gradient level winds are derived by considering the balance between centrifugal and Coriolis forces acting outwards and the presence gradient force acting inwards, leading to the so-called gradient wind equation:

$V_g^2(r)/r \;+\; f\,V_g = 1/\rho_a \;\; dp(r)/dr$ (B.4)

where $V_g\,(r)$ = gradient level wind at distance r from the centre

ρ_a = air density

f = Coriolis parameter

= $2\omega \sin \phi$

and ω = radial rotational speed of the earth

ϕ = latitude

The pressure gradient term for the Holland model is:

$dp(r)/dr = p\,/\,r\,(AB/r^B)\,\exp\,(-A/r^B)$ (B.5)

and substituting into Eqn B.4 gives

$V_g\,(r) = -r\,f/2 + [(p_n - p_0)/\,\rho_a\,(AB/r^B)\,\exp\,(-A/r^B) + r^2\,f^2/4]^{½}$ (B.6)

The so-called cyclostrophic wind equation, which neglects the Coriolis components, is then

$V_c(r) = [(p_n - p_0)/\,\rho_a\,(AB/r^B)\,\exp\,(-A/r^B)]^{½}$ (B.7)

with $V_c(r)$ attaining its maximum value when $dV_c(r)/dr$ = 0 which, after differentiating, is satisfied when

$-A/r^B + 1 = 0$

and since, by definition, $r = R$ when $V_c(r)$ is a maximum

R = $A^{1/B}$

or A = R^B (B.8)

Back-substituting into the model equations yields:

$p(r)= p_0 + (p_n - p_0)\,\exp\,(-R/r)^B$ (B.9)

$V_g\,(r) = -r\,f/2 + [(\,p_n - p_0)/\rho_a\,B(R/r)^B\,\exp\,(-R/r)^B + r^2\,f^2/4]^{½}$ (B.10)

which, for the particular case of B=1 the basic set of relationships reduces to the Schloemer model.

The influence of B is one of a 'peakedness' parameter, which in the region of R causes an increase in pressure gradient as B increases, and a corresponding increase in peak wind speed of $B^{½}$ near R and with lower wind speeds at increasing r. Holland (1980) uses conservation of angular momentum and a review of pressure gradient and R data to propose restricting the dynamic range of B as 1.0 to 2.5. Furthermore, based on the climatological work of Atkinson and Holliday (1977) and Dvorak (1975), Holland suggested 'standard' B values might be inferred of the form

$B = 2.0 - (p_0 - 900)/160$ (B.11)

making B a direct function of the storm intensity.

However, due to the inherent scatter in the climatological data it is reasonable to allow further variability whilst still maintaining the identified parameter trend, viz:

$B = B_0 - p_0/160$ (B.12)

where B_0 is the so-called intercept value of B.

B.4 Open Ocean Atmospheric Boundary Layer

Following Powell (1980), a gross simplification of the complex atmospheric boundary later is made by transferring gradient level wind speeds (V_g) to the +10 m MSL reference level (V_m) by way of a boundary layer coefficient (K_m) viz:

$V_m = K_m V_g$ (B.13)

Additionally, variation with height above the ground is derived on the basis of a traditional roughness height and logarithmic deficit law approach whereby the near-surface boundary layer profile at any height z is a function of the surface roughness and the reference speed at +10 m MSL, i.e.:

$V_m (z) = V_m (10)\ \ ln(z/z_0)/ln(10/z_0)$ (B.14)

which is terminated at a nominal gradient height z_g such that

$V_m (z_g) = V_g = V_m (10)\ ln(z_g/z_0)/ln(10/z_0)$ (B.15)

hence

$V_m (10)= V_g\ ln(10/z_0)/ln(z_g/10)$ (B.16)

$K_m = ln\ (10/z_0)/ln(z_g/z_0)$ (B.17)

requiring a priori selection of z_0 and z_g which are both known to vary; the former as a function of wave height (wind speed and fetch) and the latter as a function of storm energetics.

North West Cape data sets presented by Wilson (1979) give a lower limit estimate of z_g as 60 m for the open ocean environment, yielding a typical z_0 of 0.3 m for wind speeds of the order of 30 m s^{-1}. Garratt (1977) provides a functional form for z_0 at lower wind speeds (generally agreed to around 20 m s^{-1}) and nominal z_g values form Standards Australia (1989) allow the following representation of the variation of z_0 and z_g:

$\ln(z_0) = 0.367\ V_m - 12$	$0 < V_m < 30$	(B.18)
$\ln(z_0) = -1.204$	$V_m \geq 30$	
$z_g = 228 - 5.6\ V_m$	$0 < V_m < 30$	(B.19)
$z_g = 60$	$V_m \geq 30$	

which, when combined into Eqn B.17 and referenced to the V_g level, yield

$K_m = 0.81$	$0 < V_g < 6$	(B.20)
$K_m = 0.81 - 2.96 \times 10^{-3} (V_g - 6)$	$6 \leq V_g < 19.5$	
$K_m = 0.77 - 4.31 \times 10^{-3} (V_g - 19.5)$	$19.5 \leq V_g < 45$	
$K_m = 0.66$	$V_g \geq 45$	

The above speed-dependent formulation for K_m was devised in an attempt to try to improve wind speed calibrations from a number of tropical cyclones in the North West Shelf region of Australia where measured wind, wave and current data was available. It embodies the observation that winds from more remote storms and/or winds on the "weak" side of storms was generally underpredicted using a constant K_m. This can also be interpreted as an attempt to devise a spatially varying K_m formulation, which has some similarity with, for example, the findings of Kepert and Wang (2000). For practical purposes in strong winds, this Eqn B.20 yields a K_m of about 0.7, which is in the range observed by Powell (1980) and subsequently, for a number of US hurricanes. In Australia, McConochie *et al.* (1999) report favourable results using the above formulation on the east coast of Queensland.

B.5 Inflow Angle and Windfield Asymmetry

In addition to direct boundary layer attenuation, frictional effects cause the inflow of winds across the line of the isobars, towards the centre of the storm. This inflow (β) is typically of the order of 25° but decreases towards the storm centre, viz:

$$\beta = \begin{cases} 10\,(r/R) & 0 \le r < R \\ 10 + 75\,(r/R - 1) & R \le r < 1.2\,R \\ 25 & r \ge 1.2\,R \end{cases} \qquad \text{(B.21)}$$

following Sobey *et al.* (1977).

The observed gross features of moving storms is accounted for by including an asymmetry effect which, on one side of the storm adds the forward speed of the storm centre (V_{fm}) and subtracts it from the other side, relative to an assumed line of maximum wind θ_{max}, i.e.

$$V_m\,(r,\theta) = K_m\,V_g\,(r) + V_{fm} \cos\,(\theta_{max} - \theta) \qquad \text{(B.22)}$$

Where θ_{max} is commonly taken to be in the range of either 65° to 70° (left forward quadrant for Southern Hemisphere) or as 115° (left rear quadrant for Southern Hemisphere) measured upwind from the line of V_{fm} to which θ is referenced.

Figure B.1 presents the geometry of the wind field model in detail, including consideration of north point references for θ_{fm} and V_b (the bearing of V_m).

B.6 Wind Gust Formulae

The wind speed gust factor, G, is defined as the largest value of the average peak gust speed, of a given duration, to the mean wind speed averaged over a specified period. It is related to the longitudinal turbulence intensity Iu as follows:

$$G = 1 + g\,I_u \qquad \text{(B.23)}$$

where g is a 'peak' factor normally determined from the power spectral density of the wind speed record. However, in the absence of measured data the following empirical formula after Ishizaki (1983) are used:

$$G = 1 + 0.5\,I_u \ln\,(T_m/T_g) \qquad \text{(B.24)}$$

where T_m = mean speed reference time

T_g = gust speed reference time

such that

$V(T_g) = G\ V(T_m)$ (B.25)

and

$I_u = I_u\ '/\ln(V_m)$ (B.26)

where I_u ' = 0.6 for "peak gusts" and 0.4 for "mean gusts" based on the assessment of over-water wind gusts on the North West Shelf.

B.7 Radius to Maximum Wind Estimates

Estimates of R are rarely available for storms which are remote from measurement sites and outside radar range but this parameter can have an important influence on, for example, the fetch available for wind-wave generation. As an aid in determining suitable *R* values in the absence of any direct information, an empirical relationship has been developed based on available data from Australian and US sources.

The *R* hypothesis is based on the proposition (Myers 1954) that the storm spatial scale and the central pressure differential are related throughout the life of a given storm. The evidence for this appears reasonably substantial but the physical basis is by no means established. Myers presented an argument based on conservation of kinetic energy within a nominal radius of the storm centre which showed a hyperbolic relationship linking radius to maximum winds and the central pressure deficit viz:

$R = \mathbf{F}\ [p_n\text{-}p_0]$ (B.27)

An analysis of over 20 separate tropical cyclones in the north-west Australian sector was undertaken using the time history of *R* values throughout each storm for both the intensifying and decaying legs and a series of best fit relationships were developed of the form:

$R(t)= R_c\,/\,(p_n\text{-}p_0)(t)$ (B.28)

where R_c represents a scaling parameter with units of hPa.km and *t* is time.

Based on the Australian experience R_c values for the intensifying leg are likely to be in the range of 650 to 3000, with a mean value around 1850 hPa.km. Using US Gulf Coast data from NOAA (1979) a range of 900 to 4300 is indicated with a mean of 2100 hPa.km. Other regions may exhibit slightly different characteristics.

It should be noted that no relationship between R_c and $(p_n\text{-}p_0)$ is itself proposed but rather that for any given storm intensity it is reasonable to ascribe a particular trend in spatial variation over time. On this basis storms of vastly different intensities might still share a common R_c value. In the model the R_c value is applied only to the intensifying leg and is made monatonically decreasing in *R* towards minimum p_0 such that any minor fluctuations in pressure are ignored. Also, based on Holland (1990), *R* is held constant in the decaying leg and is always limited to a practical maximum value in the range of 80 to 100 km.

Where radar eye data is available, the radar radius to the eyewall echo is taken and a constant 5 km added to estimate the position of the radius to maximum winds. This is based on experience and is consistent with available data from historical storms, e.g. Hurricane *Andrew* in 1992.

B.10 References

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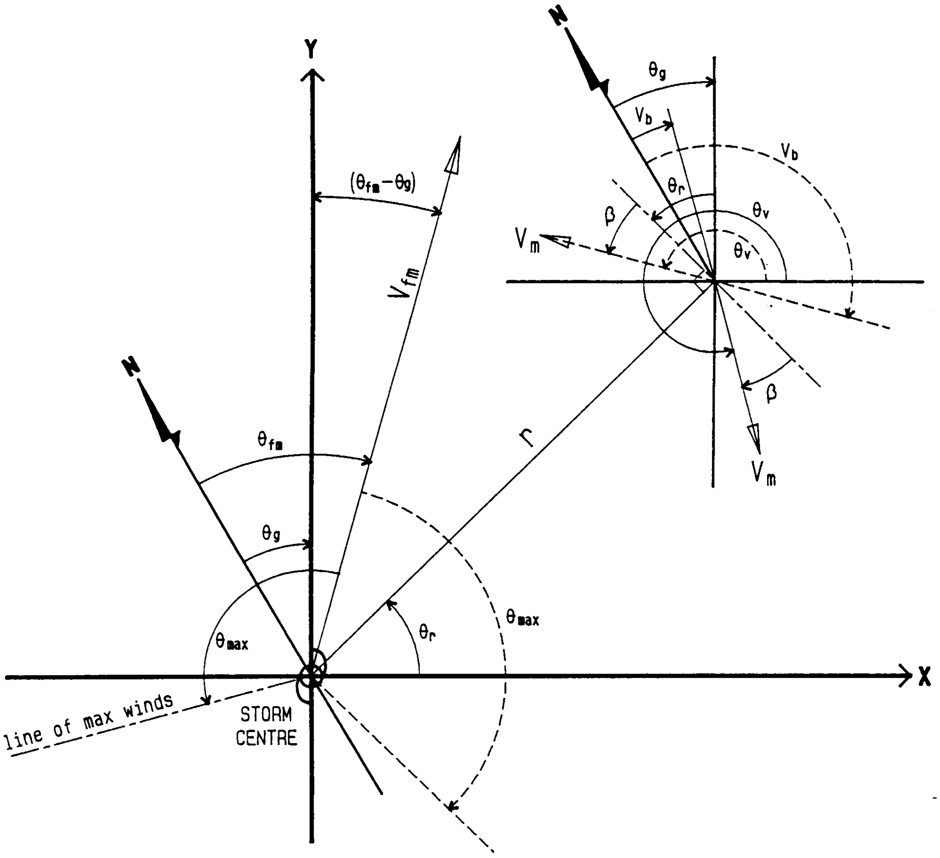

	SOUTHERN HEMISPHERE	NORTHERN HEMISPHERE
θ_{max}	+ 115	− 115
θ_v	$270 + \theta_r - \beta$	$90 + \theta_r + \beta$
V_b	$- \theta_r + \beta + \theta_g$	$180 - \theta_r - \beta + \theta_g$

TROPICAL CYCLONE MODEL
WIND FIELD GEOMETRY

Figure B.1

Appendix C

Numerical Hydrodynamic Model

Appendix C – Numerical Hydrodynamic Model

Delft3D-FLOW – the hydrodynamic module of Delft3D developed by Delft Hydraulics in the Netherlands, is a multi-dimensional hydrodynamic simulation program that calculates non-steady flows and transport phenomena resulting from tidal and meteorological forcing in **two** (depth-averaged) **or three dimensions** on a curvilinear, orthogonal boundary fitted grid or in spherical coordinates. In three-dimensions, the flow module applies the sigma coordinate transformation in the vertical, which results in a smooth representation of the bottom topography.

Delft3D-FLOW solves the Navier Stokes equations for incompressible fluid, under the shallow water and the Boussinesq assumption. In the vertical momentum equation the vertical accelerations are neglected, which leads to the hydrostatic pressure equation. In three-dimensional models the vertical velocities are computed from the continuity equation. The set of partial differential equations in combination with an appropriate set of initial and boundary conditions is solved on a finite difference grid resulting in a highly accurate, unconditionally stable solution procedure.

The flow is forced by tide at the open boundaries, wind stress at the free surface, pressure gradients due to free surface gradients (barotropic) or density gradients (baroclinic). Source and sink terms are included in the equations to model the discharge and withdrawal of water.

If the fluid is vertically homogeneous, a depth-averaged approach is appropriate. In such cases, the hydrodynamic module is able to run in **two-dimensional mode** using only one computational layer – the equivalent of solving the depth averaged shallow water equations. Examples in which the two-dimensional, depth averaged flow equations can be applied are tidal waves, storm surges, tsunamis, harbour oscillations (seiches) and transport of pollutants in vertically well-mixed flow regimes.

Three-dimensional hydrodynamic modelling is of particular interest in transport problems where the horizontal flow field shows significant variations in the vertical direction. This variation may be generated by wind forcing, bed stress, Coriolis force, bed topography or density differences. Examples are dispersion of waste or cooling water in lakes and coastal areas, upwelling and downwelling of nutrients, salt intrusion in estuaries, fresh water river discharges in bays and thermal stratification in lakes and seas.

C.1 Physical Processes

The Delft3D-FLOW model includes mathematical formulations that take into account the following physical phenomena:

- Free surface gradients (barotropic effects)
- The effect of Earth's rotation (Coriolis force)
- Water with variable density (equation of state)
- Horizontal density gradients in the pressure (baroclinic effects)
- Turbulence induced mass and momentum fluxes (turbulence closure models)
- Transport of salt, heat and other conservative constituents
- Tidal forcing at the open boundaries
- Space and time varying wind shear stress at the water surface
- Space varying shear stress at the bottom

- Space and time varying atmospheric pressure on the water surface
- Time varying sources and sinks (e.g. river discharges)
- Drying and flooding of tidal flats
- Heat exchange through the free surface
- Evaporation and precipitation
- Effect of secondary flow on depth averaged momentum equations
- Lateral shear-stress at lateral walls
- Vertical exchange of momentum due to internal waves
- Influence of waves on the bed-shear stress (2D and 3D)
- Wave induced stresses (radiation stress) and mass fluxes
- Flow through hydraulic structures

C.2 Assumptions

Delft3D-FLOW solves the 2D (depth-averaged) or 3D non-linear shallow water equations derived from the three-dimensional Navier-Stokes equations for incompressible free-surface flow. The following assumptions and approximations are applied:

- The depth is assumed to be much smaller than the horizontal length scale. For such small aspect ratios, the shallow water assumption is valid, which means that the vertical momentum equation is reduced to the hydrostatic pressure relation. The vertical accelerations are assumed to be small compared to the gravitational acceleration and are therefore not taken into account.
- The effect of variable density is only taken into account in the pressure term (Boussinesq approximation).
- The immediate effect of buoyancy on the vertical flow in not considered. Vertical density differences are taken into account in the horizontal pressure gradients and in the vertical turbulent exchange coefficients. Applications of Delft3D FLOW are restricted to mid-field and far-field dispersion simulations of discharged water.
- A dynamic online coupling between morphological changes and flow is possible.
- In a Cartesian frame of reference the effect of the Earth's curvature is not taken into account.
- In a Cartesian frame of reference the Coriolis parameter is assumed to be uniform. Optionally, a space varying Coriolis force can be specified. In spherical coordinates, the inertial frequency depends on the latitude.
- A slip boundary condition is assumed at the bottom and a quadratic bottom stress formulation is applied.
- The formulation for the enhanced bed shear stress due to the combination of waves and currents is based on a 2D flow field, generated from the velocity field near the bed using a logarithmic approximation.
- The equations of Delft3D-FLOW are capable of resolving the turbulent scales (large eddy simulation), but usually the hydrodynamic grids are too coarse to resolve the fluctuations. Therefore, the basic

equations are Reynolds-averaged introducing the so-called Reynolds stresses. These stresses are related to the Reynolds-averaged flow quantities by a turbulence closure model.

- The 3D turbulent eddies are bound by the water depth. Their contribution to the vertical exchange of horizontal momentum and mass is modelled through a vertical eddy viscosity and eddy diffusivity coefficient (eddy viscosity concept). The coefficients are assumed proportional to a velocity scale and a length scale. The coefficients may be specified (constant) or computed by means of an algebraic, k-L or k-ε turbulence model, where K is the turbulent energy, L is the mixing length and ε is the dissipation rate of turbulent kinetic energy.
- In agreement with the aspect ratio of shallow water flow, the production of turbulence is based on the vertical gradients of the horizontal flow. In case of small scale flow (partial slip along closed boundaries) the horizontal gradients are included in the production term.
- The boundary conditions for the turbulent kinetic energy and energy dissipation at the free surface and bottom assume a logarithmic law of the wall.
- The eddy viscosity is an-isotropic. The horizontal eddy viscosity and diffusivity coefficients should combine both the effect of 3D turbulent eddies and the horizontal motions that cannot be resolved by the horizontal grid. The horizontal eddy viscosity is generally much larger the vertical eddy viscosity.
- For large-scale flow simulations the tangential shearstress at lateral closed boundaries can be neglected (free slip). In case of small-scale flow partial slip is applied along closed boundaries.
- For large-scale flow simulations the horizontal viscosity terms are reduced to a bi-harmonic operator along coordinate lines. In case of small-scale flow the complete Reynold's stress tensor is computed. The shearstress at the sidewalls is calculated using a logarithmic law of the wall.
- Delft3D-FLOW solves the long wave equation. The pressure is hydrostatic and the model is not capable of resolving the scales of short waves. Therefore, the basic equations are averaged in analogy with turbulence introducing the so-called radiation stresses. These stresses are related to the wave quantities of Delf3D-WAVE by a closure model.
- It is assumed that a velocity point is set dry when the actual water depth is below half of a user-specified threshold. If the point is set dry, then the velocity at that point is set to zero. The velocity point is set wet again when the local water depth is above the threshold. The hysteresis (time lag) between drying and flooding is introduced to prevent drying and flooding in two consecutive time steps. The drying and flooding procedure leads to a discontinuous movement of the closed boundaries at tidal flats.
- A continuity cell is set dry when the four surrounding velocity points at the sides of the cell are dry or when the actual water depth at the cell centre is zero.
- The flux of matter through a closed wall and through the bed is zero.
- Without specification of a temperature model, the heat exchange through the free surface is zero. The heat loss through the bottom is always zero.
- If the total heat flux through the water surface is computed using a temperature excess model, the exchange coefficient is a function of temperature and wind speed. The natural background temperature is assumed to be constant in space and may vary in time. In the other heat flux formulations the fluxes due to solar radiation, atmospheric and back radiation, convection and heat loss due to evaporation are modelled separately.

- The effect of precipitation on the water temperature is accounted for

C.3 Governing Equations

In the vertical direction a σ coordinate system is used, which is defines as:

$$\sigma = \frac{z-\zeta}{d+\zeta} = \frac{z-\zeta}{H}, \qquad \text{(C.1)}$$

where

z	the vertical coordinate in physical space
ζ	the free surface elevation above the reference plane (at $z = 0$)
d	the water depth below the reference plane
H	the total water depth, given by $H = d + \zeta$

At the bottom $\sigma = -1$ and at the free surface $\sigma = 0$. The σ coordinate is boundary fitted both to the bottom and to the moving free surface. The partial derivatives in the original Cartesian coordinate system are expressed in σ coordinates by the chain rule introducing additional terms.

The flow domain of a 3D shallow water model is limited in the horizontal plane by sea and land boundaries and consists in the vertical direction of a number of layers. The number of layers is the same at every location in the horizontal plane, i.e., the layer interfaces are chosen following planes of constant σ. For each layer a set of coupled conservation equations is solved.

The equations are formulated in orthogonal curvilinear coordinates. the velocity scale is in physical space, but the components are perpendicular to the cell faces of the curvilinear grid. The grid transformation introduces curvature terms in the equations of motion.

The depth-averaged continuity equation is given by:

$$\frac{\partial \zeta}{\partial t} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)U\sqrt{G_{\eta\eta}}\right]}{\partial \xi} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)V\sqrt{G_{\xi\xi}}\right]}{\partial \eta} = Q \qquad \text{(C.2)}$$

with Q representing the contributions per unit area due to the discharge or withdrawal of the water precipitation and evaporation.

The momentum equations in ξ and η direction are given by:

$$\begin{aligned}&\frac{\partial u}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial u}{\partial \xi} + \frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial u}{\partial \eta} + \frac{\omega}{d+\zeta}\frac{\partial u}{\partial \sigma} + \frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} + \\ &-\frac{v^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial \sqrt{G_{\eta\eta}}}{\partial \xi} - fv = -\frac{1}{\rho_0\sqrt{G_{\xi\xi}}}P_\xi + F_\xi + \frac{1}{(d+\zeta)^2}\frac{\partial}{\partial \sigma}\left(\nu_V \frac{\partial u}{\partial \sigma}\right) + M_\xi\end{aligned} \qquad \text{(C.3)}$$

and

$$
\frac{\partial v}{\partial t}+\frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial v}{\partial \xi}+\frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial v}{\partial \eta}+\frac{\omega}{d+\zeta}\frac{\partial v}{\partial \sigma}+\frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial \xi}+
$$

$$
-\frac{u^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial \eta}-fu=-\frac{1}{\rho_0\sqrt{G_{\eta\eta}}}P_\eta+F_\eta+\frac{1}{(d+\zeta)^2}\frac{\partial}{\partial\sigma}\left(\nu_V\frac{\partial v}{\partial\sigma}\right)+M_\eta \qquad \text{(C.4)}
$$

Density variations are neglected, except in the pressure terms. P_ξ and P_η represent the pressure gradients. The forces F_ξ and F_η in the momentum equations represent the unbalance of horizontal Reynold's stresses. M_ξ and M_η represent the contributions due to external sources or sinks of momentum by hydraulic structures, discharge or withdrawal of water, wave stresses etc.

The vertical velocity ω in the adapting σ coordinate system is computed from the continuity equation:

$$
\frac{\partial\zeta}{\partial t}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)u\sqrt{G_{\eta\eta}}\right]}{\partial\xi}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)v\sqrt{G_{\xi\xi}}\right]}{\partial\eta}+\frac{\partial\omega}{\partial\sigma}=H\left(q_{in}-q_{out}\right) \qquad \text{(C.5)}
$$

At the surface the effect of precipitation and evaporation is taken into account. The vertical velocity ω is defined at the iso σ-surfaces, with ω being the vertical velocity relative to the moving σ-plane. It may be interpreted as the velocity associated with up- and down-welling motions. The physical vertical velocities w in the Cartesian coordinate system are not involved in the model equations. Computations of the physical vertical velocities is only required for post processing purposes and can be expressed in terms of the horizontal velocities, water depths and vertical ω velocity according to:

$$
w=\omega+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\left[u\sqrt{G_{\eta\eta}}\left(\sigma\frac{\partial H}{\partial\xi}+\frac{\partial\zeta}{\partial\xi}\right)+v\sqrt{G_{\xi\xi}}\left(\sigma\frac{\partial H}{\partial\eta}+\frac{\partial\zeta}{\partial\eta}\right)\right]+\left(\sigma\frac{\partial H}{\partial t}+\frac{\partial\zeta}{\partial t}\right) \qquad \text{(C.6)}
$$

Appendix D

ADFA1 Spectral Wave Model

Appendix D – ADFA1 Spectral Wave Model

D.1 Overview of the Model

A comprehensive description of the numerical spectral wave model ADFA1 can be found in Young (1987a, 1987b). ADFA1 is a further development by the original author of the 2nd generation model SPECT (Sobey and Young 1986), originally from James Cook University, having enhanced shallow water and non-linear source terms.

The complex sea state is described by the model in terms of the directional wave energy spectrum $E(f,\theta,x,y,t)$. At each position x,y and time t, E represents the superposition of free linear wave components of all frequencies f and all directions θ. The evolution of the energy spectrum is then described by the *Radiative Transfer Equation*:

$$\frac{\partial}{\partial t}(C\,C_g\,E) + C_g \cos\theta \frac{\partial}{\partial x}(C\,C_g\,E) + C_g \sin\theta \frac{\partial}{\partial y}(C\,C_g\,E)$$

$$+ \frac{C_g}{C}\left[\sin\theta \frac{\partial C}{\partial x} - \cos\theta \frac{\partial C}{\partial y}\right] \frac{\partial}{\partial \theta}(C\,C_g\,E) = C\,C_g\,S \qquad \text{(D.1)}$$

where

$C\,(x,y,f)$ = the individual wave phase speed

$C_g\,(x,y,f,\theta)$ = the wave group speed

$S\,(f,\theta,x,y,t)$ = a source term representing the net transfer of energy to, from or within the spectrum

The kinematics of wave propagation are described in the model by ray theory, neglecting the effects of currents. This allows wave propagation to be represented by characteristic equations.

The net source term S is represented as the summation of a number of separate influences:

- atmospheric input
- non-linear wave-wave interactions
- white cap energy dissipation
- bottom friction
- shallow water wave breaking

Atmospheric forcing is provided by specification of the 10 minute average wind speed and direction at the standard reference height of +10 m SWL (V_m). In the present investigation, this is provided by the Holland (1980) tropical cyclone wind field model. This was incorporated into ADFA1 and updates wind speed and direction at each x, y location and at each time step t based on the position of the storm centre, and the various storm parameters, central pressure, radius to maximum winds and ambient pressure.

Equation D.1 is solved numerically using a fractional step method consisting of separation of propagation and forcing mechanisms. This method avoids the penalty of numerical dispersion in the solution. The propagation solution (which includes refraction and shoaling) is obtained from the method of characteristics, assuming only the influence of bathymetry. A separate wave characteristic is constructed for each frequency and direction component of the discrete representation of the spectrum and at each model point within the computational grid. The set of characteristic paths need be only determined once for each particular computational grid, provided changes in water depth will not be significant throughout a storm simulation.

Boundary conditions are either of the radiation type where there are no significant generation areas beyond the computational limits, or a system of sub-grids may be used to provide greater geographical detail where necessary. Boundary data for the finer sub-grid are provided post-hoc from the coarser parent grid.

Model output can be either the time history of the relevant spectral parameters ($H_s, T_p, T_z, T_m, \theta_m$) at particular computational grid locations, contours of H_s and vector fields of T_p and θ_m over the entire region, one-dimensional spectral energy plots at particular locations and times or full directional energy density contours throughout the simulation.

D.2 References

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Appendix E

Statistical Simulation Model SATSIM

Appendix E – Statistical Simulation Model SATSIM

E.1 Background

SATSIM (Surge And Tide SIMulation) is a discrete Monte-Carlo statistical model employing tide generation and a parametric tropical cyclone storm surge model, which can be applied to arbitrary coastal or open ocean areas. The early model was based on techniques first described by Stark (1976, 1979) and Harper and Stark (1977) and is similar to Russell (1971) as applied in the Gulf of Mexico. SATSIM was formalised by Harper and McMonagle (1983) and used to establish design water levels along the Queensland coast (Harper 1983, 1985), the Northern Territory (Harper and McMonagle 1983) and parts of Western Australia (Stark and McMonagle 1982). The model was further extensively developed in the late 1980s to include parametric tropical cyclone wave, wind and 3-D current models (Harper et al. 1989). More recently, the same basic technique has been further extended to include wind estimation and building damage in an even more complex model (MIRAM) which includes severe thunderstorms as well as tropical cyclone wind and storm surge (Harper 1996ab, 1997, 1999). The latest variant of SATSIM includes breaking wave setup over coral reefs and shallow water bathystrophic storm tide effects (SEA 2001).

E.2 Definitions

The total water level experienced at a coastal, ocean or estuarine site during the passage of a severe meteorological event such as a tropical cyclone, is made up of contributions from some or all of the following components. The combined water level is termed the **storm tide**, refer Figure E.1.

(a) The Astronomical Tide

This is the regular periodic variation in water levels due to the gravitational effects of the Moon and Sun. With a suitably long period of tide measurements at a specific location, combined with harmonic analysis, the tide can be predicted with very high accuracy at any point in time (past and present). The highest expected tide level is termed Highest Astronomical Tide (HAT) and occurs once each 18.6-year period, although at some sites tide levels similar to HAT may occur several times per year.

(b) Storm Surge

This is the combined result of the severe atmospheric pressure gradients and wind shear stresses of a significant meteorological event such as a tropical cyclone acting on the underlying water body. 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 which is severely affected by a tropical cyclone storm surge is of order 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 create abnormally high sea conditions and extreme waves may propagate large distances from the centre of the storm 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. Just prior to breaking, a phenomenon known as wave setdown occurs where the average stillwater level is slightly lower than the same level further offshore. After breaking, a portion of the wave energy is converted into forward momentum which, through the continuous action of many waves, is capable of sustaining shoreward water levels which are above the stillwater level further offshore. This quasi-steady increase in stillwater level after breaking is known as breaking wave setup and applies to most natural beaches and reefs.

There remain other related phenomena which can also affect the local water level. These may include long period shelf waves, unsteady surf beat, wave runup, stormwater and/or river runoff etc. Any phenomenon which can be deterministically described in space and time with respect to the incident storm parameters can be incorporated into the SATSIM methodology.

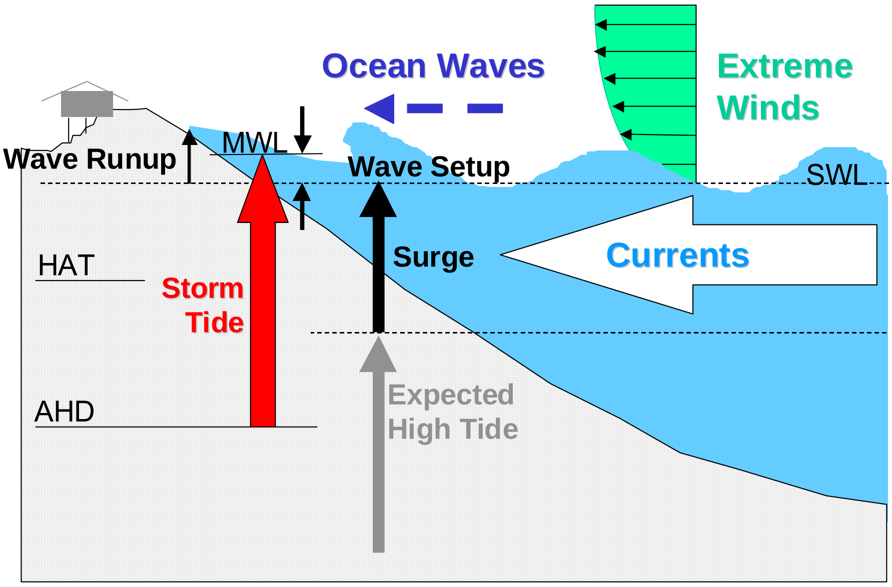

Figure E.1 Components of total water level.

E.2 Basic Methodology

(a) Deterministic Phase

SATSIM consists of a series of water level forcing modules which can provide an estimate of the time history of each of the water level components of interest. In the case of the astronomical tide, the time history of water levels is provided directly from a set of harmonic constituents for the site under consideration and tidal planes (e.g. AHD) provide a base water level datum. The storm surge and breaking wave setup time histories are provided by a series of parametric models which describe the likely behaviour of the respective component as a function of the incident storm parameters (e.g. distance of approach, intensity, track, size etc). These parametric models are derived from a combination of complex numerical hydrodynamic models (e.g. SURGE, ADFA1) as well as analytical approximations such as those for breaking wave setup (e.g. Nielsen and Hanslow 1991; Gourlay 1997).

The model typically considers a 36 h "window" for each storm tide event and generates simultaneous and independent estimates of each of the water level components at a time interval of 30 mins. These are then linearly combined using superposition to provide the estimated total storm tide level over that time as shown schematically in Figure E.2, which closely approximates the Cyclone Althea storm tide at Townsville in 1971 (Stark 1972).

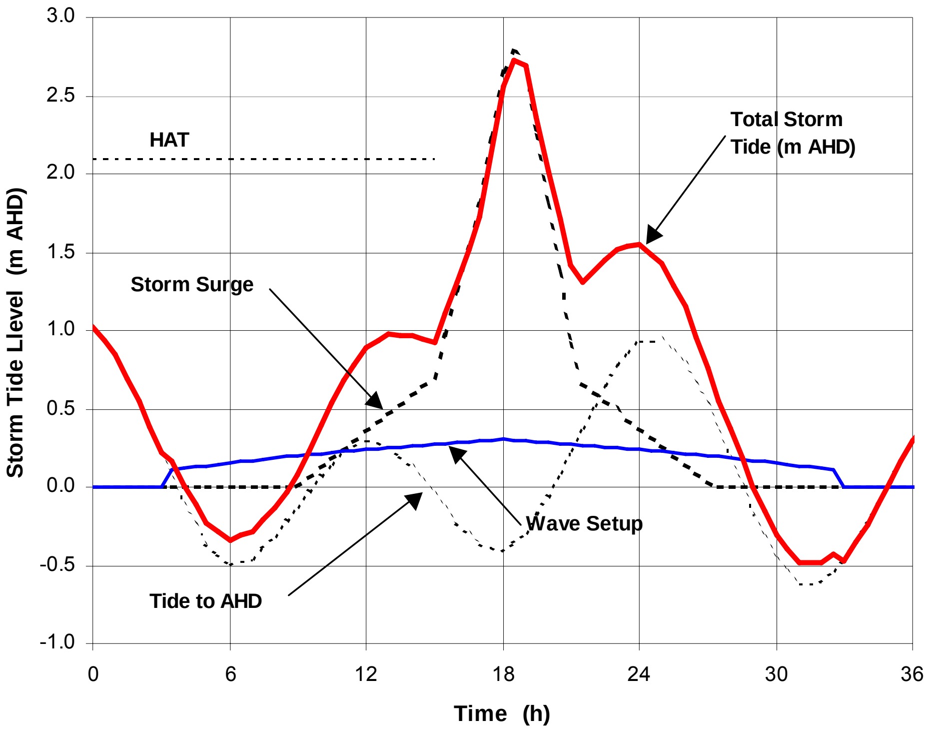

Figure E.2 Example of the superposition process.

(b) Probabilistic Phase

A number of different probabilistic variants of the model have been developed. All approaches are based on the concept of defining a statistical control volume around the site of interest. This may be in any geometric form such as a square or rectangular domain or a radius from the site, termed the target site (refer Figure E.3). The climatology of the meteorological forcing within that control volume is then determined based on either the analysis and interpretation of historical data or, where no data exists, hypothetical statistical distributions of the parameters of interest.

In Australia, tropical cyclone tracks and estimates of central pressure have been variously recorded and archived by the Bureau of Meteorology since the early 1900s. The quality of the data is quite variable in space and time (e.g. Holland 1981) and as a general rule is only suitable for statistical analysis from around 1959/60 onwards. This marks the commencement of routine satellite imagery and the adoption of objective intensity estimation methods. Individual storms which passed close to recording sites prior to this time are still suitable for inclusion but care must be taken not to bias the overall statistical descriptions.

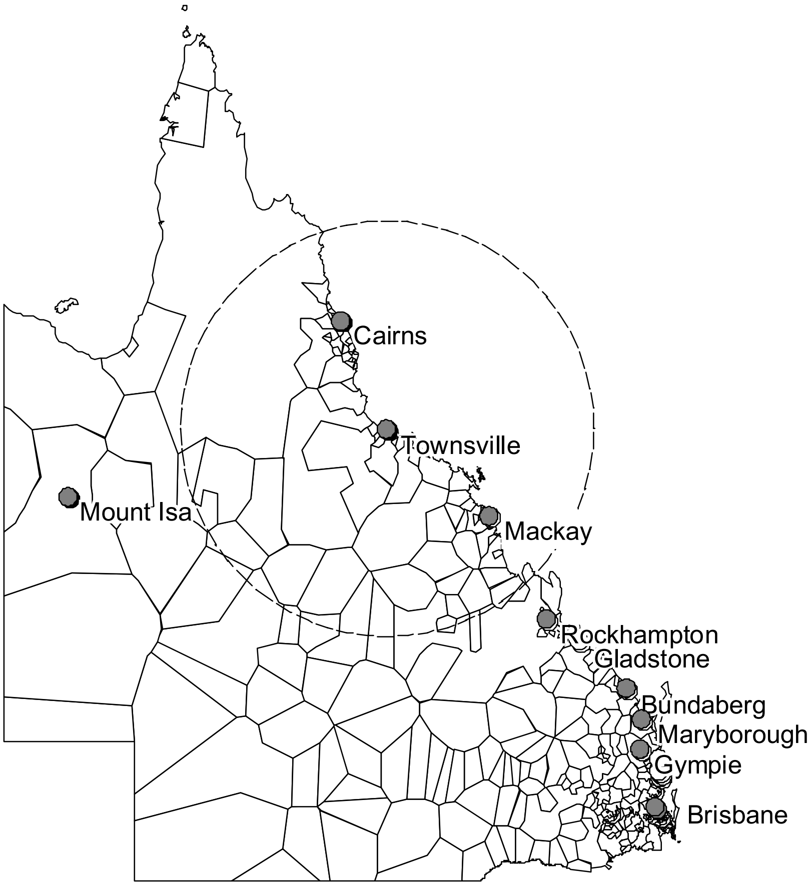

Figure E.3 Example of a 500 km radius statistical control volume with Townsville as the target site.

The climatology of storms within the control volume then is normally expressed in terms of the following major components:

Population class

At any single location it is common for the incidence of tropical cyclones to be due to two or more separate storm populations. These can normally be clearly identified by origin and track but other more complex discriminators may be required.

Frequency of occurrence

The relative frequency of occurrence between populations is often a further discriminator.

Intensity

Different populations often exhibit varying intensity behaviour which is typically related to the origin and track of the storms relative to the prevailing atmospheric patterns and landmass effects.

Scale

This typically relates to the radius of maximum winds or the radius to gales and influence the extent of storm surge or wave generation fetch etc.

Forward speed and track

The speed of approach to the coast and the angle of crossing, for example, influence the generation of storm surge.

Distance of closest approach

This is one of the principal determinants of impact at any site, the tropical cyclone structure is spatially variable and the region of maximum effect is typically within 2 to 3 radius to maximum winds of the centre.

E.3 Statistical Model

The model utilises a discrete Monte Carlo approach, whereby a random number generator is used to provide a source of unbiased probability, and a series of individual storm events are created based on the climatological description. The deterministic output from each hypothetical storm event is then created, based on the relationships determined between the storm parameters and the impacts of interest (surge, waves, wave setup etc). A 36 h window is typically allowed for each event and simultaneous time histories of each impact at a resolution of 0.5 h are assembled and combined as required to yield the output of interest (e.g. storm tide level). The statistics of each event are then recorded in terms of the frequency of exceedance of a range of given magnitude levels. After many thousands of samples from the control volume, the statistical exceedance function becomes smoothed and simulation ends when the function has converged sufficiently at the desired probability level. For example, to estimate the 100-year return period (or 1% annual exceedance), at least 1000 years of simulation is recommended so that there will be at least 10 estimates of the 100-year magnitude. Figure E.4 illustrates the basic model structure in flowchart format.

The forms of the statistical representations used are typically:

Frequency of Occurrence	Poisson
Storm Intensity	Gumbel (EV Type I)
Forward Speed	Smoothed Data CDF
Track	Smoothed Data CDF
Closest Approach	Smoothed Data CDF
Radius to Maximum Winds	Normal CDF
Windfield Peakedness	Normal CDF

Any of the input statistical distributions may then be altered to test the sensitivity of the model results to the input assumptions.

E.4 Model Variants

SATSIM has been variously developed over a number of years according to the needs of the particular analysis. The following provides an introduction to some of the specific versions which were used in major or landmark studies. Individual study reports should be consulted for further details.

V3 through V4

These versions were used for the series of studies conducted during the early 1980s (e.g. Harper 1983; Harper and McMonagle 1983, 1985). It considers a rectangular control volume of nominally 5º of latitude alongshore (556 km) and 2.5º of longitude offshore (278 km). Tidal constituent data for the target site was provided and extended to up to 10 secondary sites by the use of published range ratios. The coastal storm surge response was parameterised according to intensity, track, closest approach and forward speed based on the results of a series of numerical hydrodynamic model tests (e.g Harper 1977 for each of 10 locations along the Queensland coast). Some versions incorporated breaking wave setup and also coastal wave height, these being derived from a series of model tests using the SPECT model (Sobey and Young 1986).

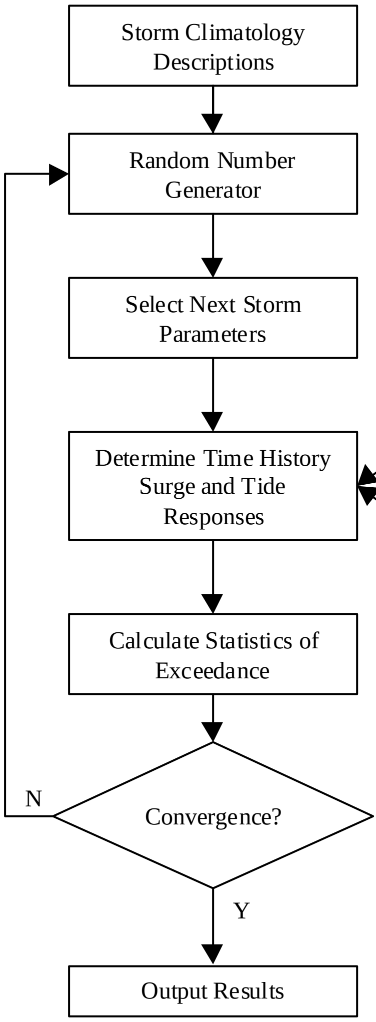

Figure E.4 Flowchart of the model simulation process.

V5 through V8

These versions were developed under licence by Woodside Offshore Petroleum Pty Ltd in the late 1980s to provide design criteria for the Goodwyn 'A' offshore production platform on the North West Shelf of Western Australia (Harper et al. 1989, 1990). A radius of influence of 1000 km was taken to represent the statistical control volume around a single site. These versions provided full (contemporaneous) statistical descriptions of environmental loadings on an offshore platform allowing phase separation at very long return periods (10,000yr). Hurricane wind fields could be specified as NHRP circa 1970 or according to a modified and extended Holland (1980). Each site impact of interest was separately modelled, e.g.

V5 deepwater storm surge (inverted barometer effect) driven directly from the parametric wind and pressure field model dependent upon the relative position of the site and the storm centre.

V6 wind speed and direction (mean and gust) driven directly from the parametric wind and pressure field model, as above.

V7 wave height (Hs, Hmax), period (Tz, Tm, Tp), direction (θm) parameterised based on over 200 separate spectral wave model tests using the ADFA1 model (Young 1987) - an updated version of the SPECT model. A two-stage nested-model domain system was used with resolutions of 54 km and 10.8 km. Results were summarised in terms of a series of complex tabular functions describing the wave conditions of straightline tracks as a function of various storm parameters and position relative to the target site. Long-term directional wave counts were also estimated for structural fatigue considerations. Maximum wave heights and associated periods were determined by numerical integration of the time history of significant wave heights and periods (e.g. Sobey et al. 1990).

V8 3D currents (barotropic, baroclinic, pulsed) were similarly parameterised on the basis of a series of sensitivity tests using a hydrodynamic model after Fandry (CSIRO Division of Marine Research.

The Woodside developments included significant calibration and verification testing of the various parametric model components against extensive measured wind, wave and current datasets.

V9a

This version was developed to represent storm tide impacts at the Cocos (Keeling) Islands in the Southern Indian Ocean on behalf of GHD Pty Ltd, acting for the Commonwealth Department of Transport and Regional Services (SEA 2001). The selected radius of influence was 500 km. The model combines a number of aspects of previous models, namely:

- Astronomical tide
- Deepwater inverted barometer effect
- Mean and gust wind speed
- Parametric open ocean tropical cyclone waves

As well as some additional capabilities:

- Ability to represent up to 20 sites around the island by a directionally sensitive wave sub-model, further modifying the V7 open ocean model
- Breaking wave setup over the fringing reefs based on Gourlay (1997)
- Bathystrophic storm tide effects within the island lagoon

This version of the model simultaneously generates estimates of all impacts for all sites.

V9b

This version was developed to represent storm tide impacts within the Whitsunday region of the Queensland coast on behalf of GHD Pty Ltd, acting for Whitsunday Shire Council (GHD 2003). The model retains a number of aspects of previous versions, namely:

- Astronomical tide based on a regional reference with site specific range ratios
- Mean and gust wind speed at the regional reference site
- Parametric open coast storm surge model based on SEA (2002)
- Parametric open ocean tropical cyclone wave model based on SEA (2002)
- Breaking wave setup for plane beaches based on Nielsen and Hanslow (1991)

This version of the model simultaneously generates estimates for up to 350 sites.

E.5 Algorithms

E.5.1 Astronomical Tide

The astronomical tide is specified only for the target site and secondary sites may have an associated range ratio to allow variation from the target site. No phase differences are incorporated, with phase being regarded as a random variable in this context. The target site tide is specified by up to 36 harmonic constituents (amplitudes , phases) together with the relevant datum planes for z0, MSL and HAT.

E.5.2 Tropical Cyclone Winds and Pressures

The Holland (1980) model formulation is used, as modified and extended by Harper and Holland (1999).

E.5.3 Inverted Barometer Effect (IBE)

This is represented by

$$\Delta B = \frac{(p_n - p_s)}{\rho_w \, g}$$

where p_s is the local MSL atmospheric pressure; p_n is the ambient or surrounding MSL atmospheric pressure; ρ_w is seawater density; g is gravity. The magnitude of ΔB is then typically 10 mm for each 1 hPa pressure difference.

E.5.4 Bathystrophic Storm Tide (BST)

This is the first-order 1D momentum balance for a steady-state wind stress scenario which, considering the x direction is given by:

$$0 = -g\,(h+\eta)\frac{\partial \eta}{\partial x} - \frac{(h+\eta)}{\rho_w}\frac{\partial p_s}{\partial x} + \frac{1}{\rho_w}(\tau_{sx} - \tau_{bx})$$

where the *x-y* datum plane is located at the mean water level with the *z* axis directed vertically upwards; the water surface elevation w.r.t. datum is η *(x,y,t),* the seabed is *h (x,y)* below datum. The forcing influence of the tropical cyclone is represented through the surface wind shear stress vector component τ_{sx} and the *x* gradient of the MSL atmospheric surface pressure p_s(*x,y,t*). The effect of bottom stress is represented by the bottom shear stress vector component τ_{bx}.

Following the SURGE model (Sobey *et al.* 1977), the surface stress and bottom stress components are represented parametrically. For example, the surface wind stress forcing is parameterised w.r.t. the 10-minute mean wind speed component W_{x10} at the standard reference height of +10 m MSL by

$$\tau_{sx} = C_{10}\ \rho_a\ W_{x10}{}^2$$

where ρ_a is the air density and C_{10} is an empirical coefficient whereby (Wu 1982)

$$\tau_{bx} = \frac{\lambda}{8}\ \rho_w\ \frac{U^2}{(h+\eta)^2}$$

The effect of bottom stress is parameterised by a Darcy-Weisbach equation with *U* the *x* component of flow and λ the Darcy-Weisbach friction factor, e.g.

$$\frac{1}{\lambda} = -2\log_{10}\left[\frac{k_b}{14.8\,(h+\eta)}\right]$$

where k_b is typically set at 0.025 m for coastal areas.

However, *U* remains an unknown in this context and is therefore further parameterised by the surface wind speed

$$U = k_u\ W_{x10}$$

assuming k_u is a fixed nominal value of 0.03 (e.g. Bishop 1979).

The surface elevation η is then calculated based on a given fetch and depth profile using a Runge-Kutta integration technique.

E.5.5 Coastal Storm Surge

Versions prior to V9b follow the method outlined in Harper and McMonagle (1985). Version 9b is based on the method outlined in SEA (2002).

E.5.6 Tropical Cyclone Waves and Currents

V9b:

Follows the method outlined in SEA (2002).

V7, V8, V9a:

These follow the tabular look-up methodology described in Harper et al. (1989), which is based on a schematised storm reference system as shown in Figure E.5. Straightline tracks of constant speed are assumed but with a symmetric variation in central pressure based on a Gaussian function. Radius to maximum winds varies as a function of pressure differential for a given Rc constant.

The model incorporates a bias adjustment for Hs determined from detailed calibration studies with 23 tropical cyclones which identified an apparent cross-track bias in the ADFA1 spectral wave model, thought to be due to non-linear wave-wave interactions in the rotating wind field (Young pers. comm.). The adjustment is implemented here as a linear function according to the relative x position within a nominal y domain, as follows:

$$U = k_u W_{x10}$$

where

$$E_r = 0.00196\,x + 0.92089 \qquad -100 < x < 100$$

with x in km and a clipped linear return to unity at -200 and +200 . The applicable y domain is defined by

y0 < -100 and y2 > 0

E.5.7 Breaking Wave Setup

The method of Nielsen and Hanslow (1991) is applied for plane beaches while that of Gourlay (1997) is applied for reefs.

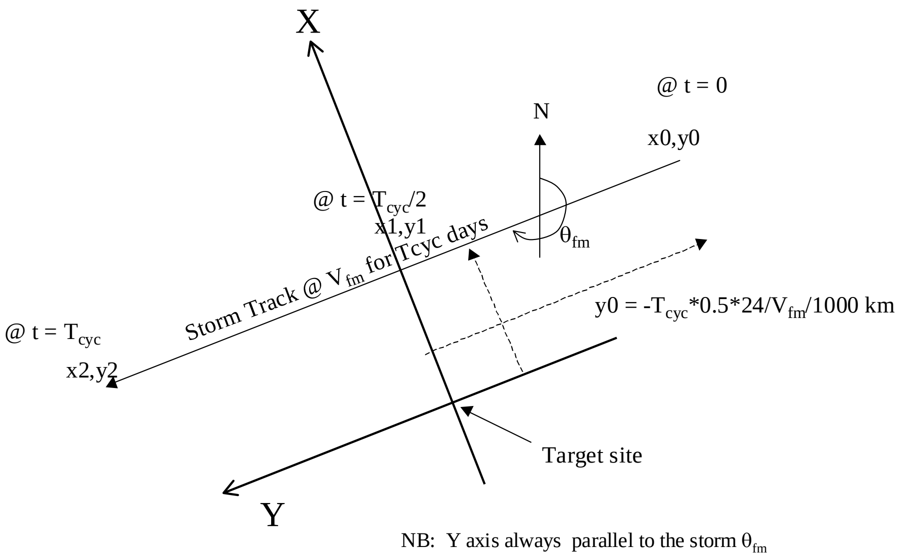

Figure E.5 Model reference system for schematised tropical cyclones.

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Appendix F

Technical Note on the Interpretation of Statistical Return Periods

Appendix F – A Note on the Interpretation of Statistical Return Periods

This study has presented its analyses of risk in terms of the so-called *Return Period* (or average recurrence interval *ARI*). The return period is the “average” number of years between successive events of the same or greater magnitude. For example, if the 100-year return period storm tide level is 3.0 m AHD then on average, a 3.0 m AHD level storm tide *or greater* will occur due to a single event once every 100 years, but sometimes it may occur more or less frequently than 100 years. It is important to note that in any “N”-year period, the “N”-year return period event has a 64% chance of being equalled or exceeded. This means that the 3.0 m storm tide has a better-than-even chance of being exceeded by the end of any 100-year period. If the 100-year event were to occur, then there is still a finite possibility that it could occur again soon, even in the same year, or that the 1000 year event could occur, for example, next year. Clearly if such multiple events continue unchecked then the basis for the estimate of the 100 year event might then need to be questioned, but statistically this type of behaviour can be expected.

A more consistent way of considering the above (NCCOE 2003) is to include the concepts of “design life” and “encounter probability” which, when linked with the return period, provide better insight into the problem and can better assist management risk decision making. These various elements are linked by the following formula (Borgman 1963):

$$Tr = - L / \ln [1 - p]$$

where	p	=	encounter probability	$0 \leq 1$
	L	=	the design life	(years)
	Tr	=	the return period	(years)

This equation describes the complete continuum of risk when considering the prospect of at least one event of interest occurring. More complex equations describe other possibilities such as the risk of only two events in a given period or only one event occurring.

Figure F1 illustrates the above equation graphically. It 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.

The level of risk acceptable in any situation is necessarily a corporate or business decision. Table F1, based on Figure F1, is provided to assist in this decision making process by showing a selection of risk options. Using Table F1, 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.

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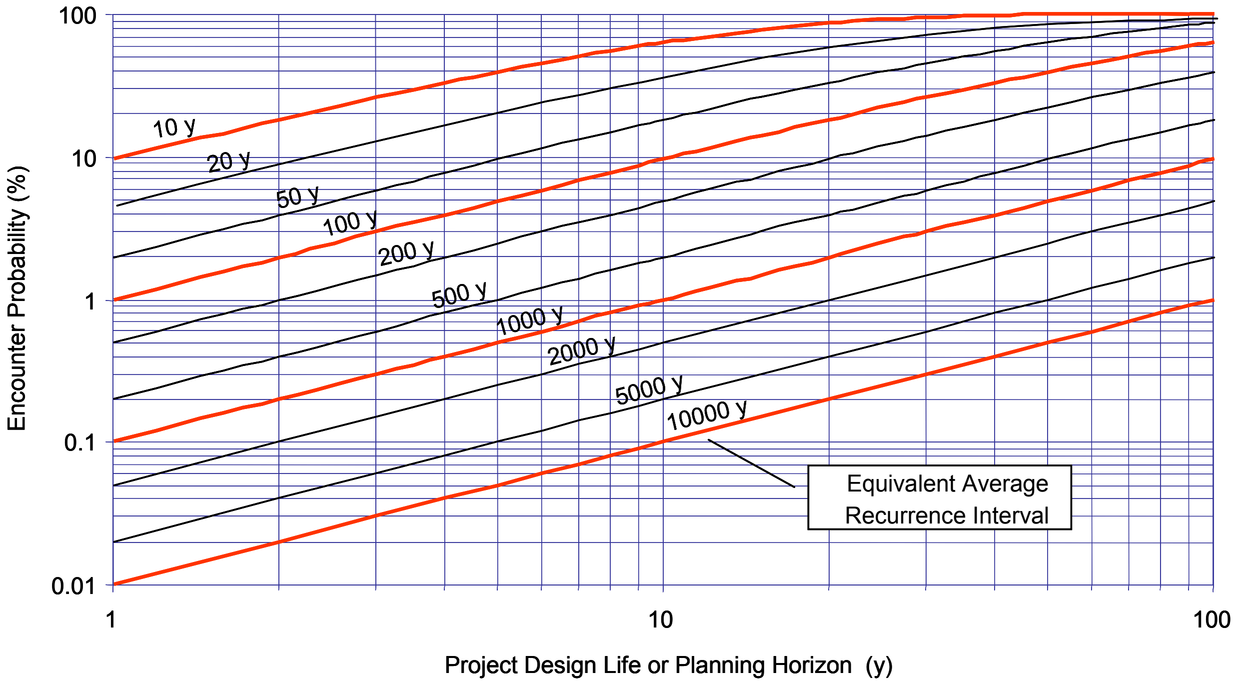


Figure F1: Relationship between Return Period and Encounter probability

Table F1: Risk selection based on encounter probability concepts.

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

Appendix G

Bathymetry

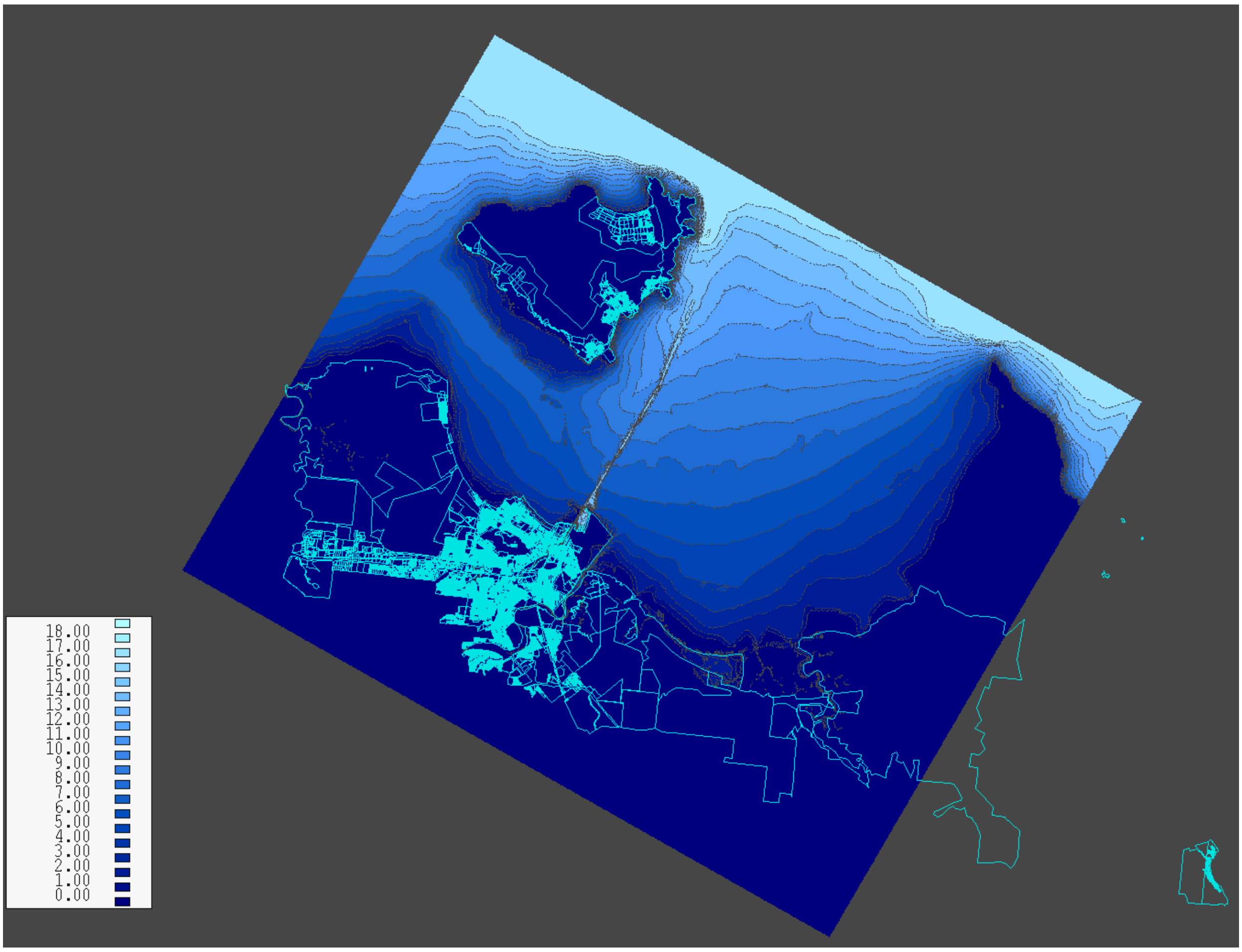


Figure G-1 Regional bathymetry reconstructed on the D52 grid featuring 620x520 grid cells at 55 m resolution.

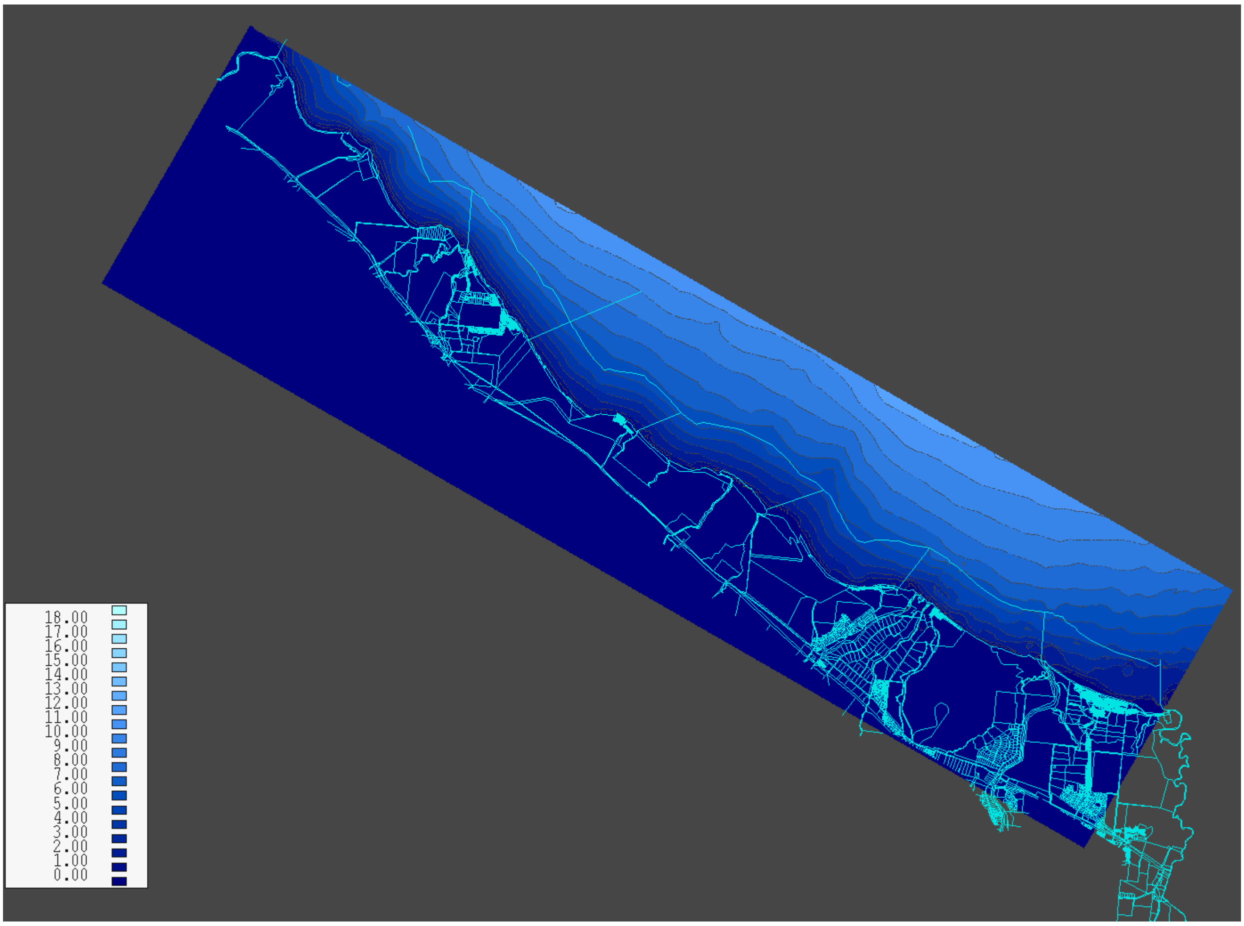


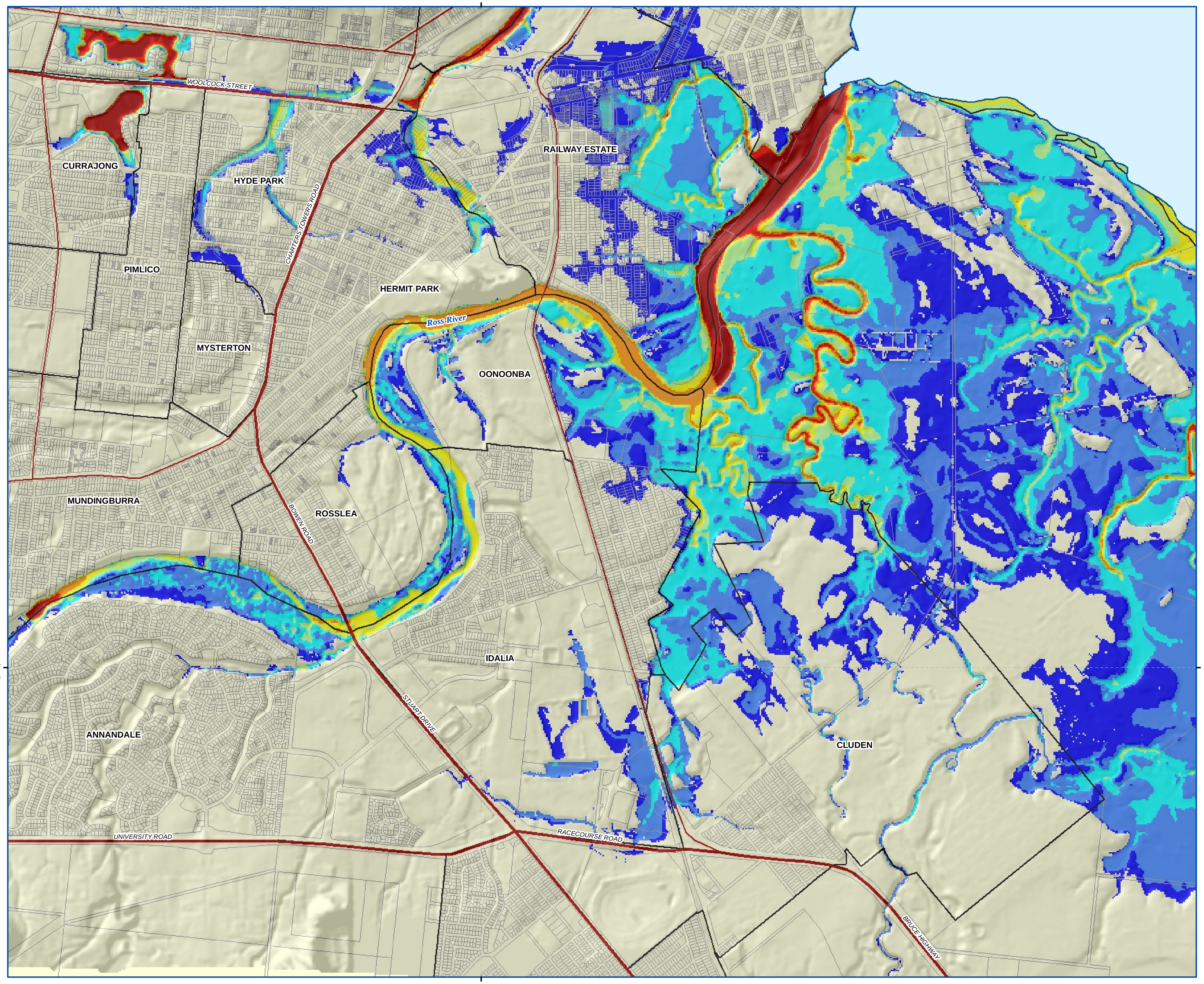
Figure G-2 Regional bathymetry reconstructed on the D51 grid featuring 920x242 grid cells at 55 m resolution.

Appendix H

Example Inundation Maps

Townsville

Toolakea and Saunders Beach



Townsville - Thuringowa Storm Tide Study 2005

100 Year Event Inundation Depth

Map 5 of 8

TCC Plan No: 14
TCC Plan Index No: 66521

Legend

Inundation Depth (m)

- 0.00 - 0.5
- 0.51 - 1.0
- 1.01 - 1.5
- 1.51 - 2.0
- 2.01 - 2.5
- 2.51 - 3.0
- 3.01 - 3.5
- Greater than 3.5 metres
- Digital Cadastre Database
- Suburbs
- Highways
- Major Roads

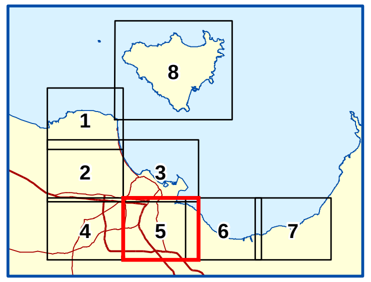
N
W E
S

0 500 1,000
Metres

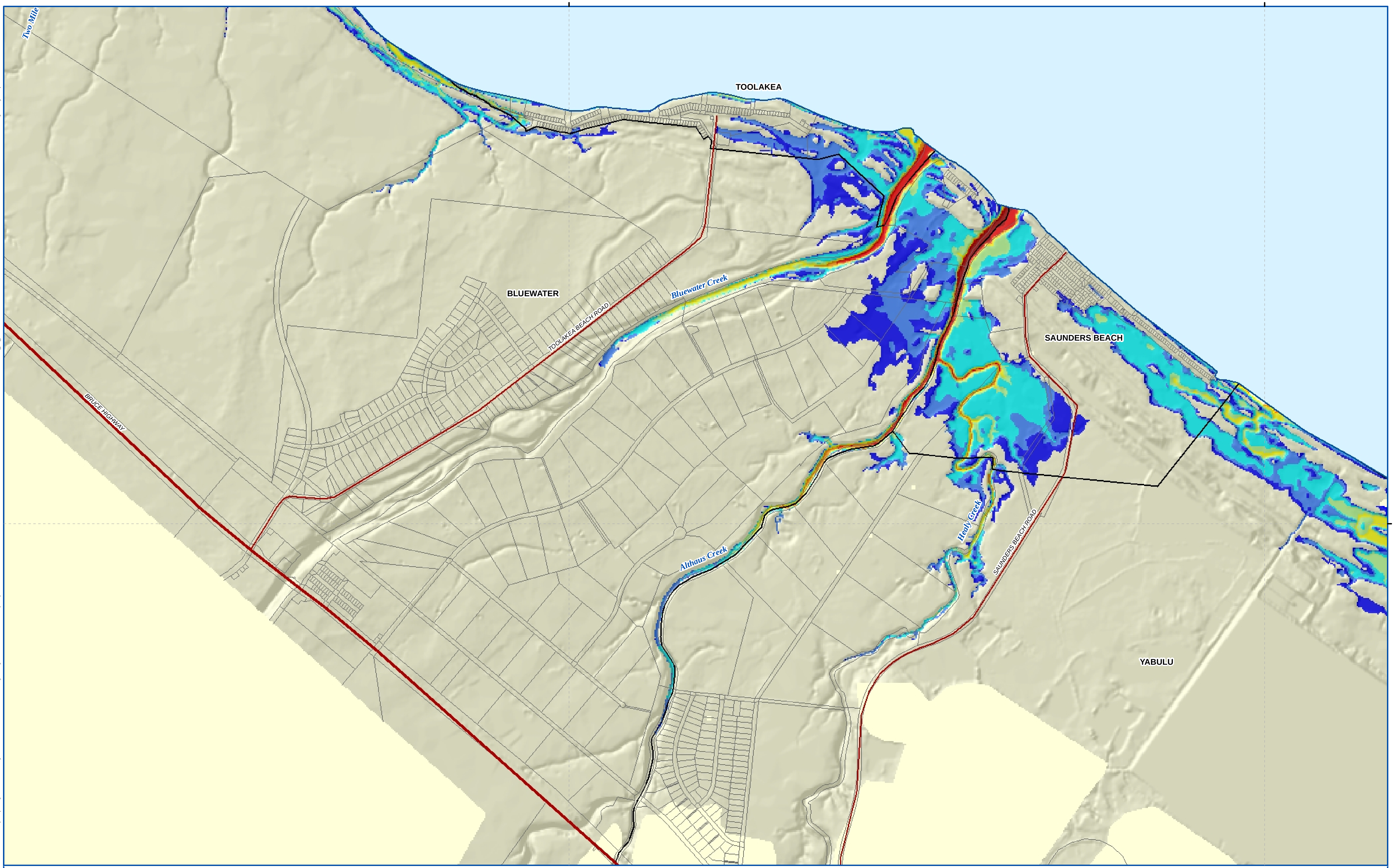
1:25,000

The Digital Elevation Model (DEM) and Digital Cadastral DataBase (DCDB) information used in this Storm Tide Study is valid as of September 1999 except for parts of Annandale and Idalia which were updated in July 2003.

Data supplied by the City of Townsville and City of Thuringowa.
Projection: Australian Map Grid (AGD84) Zone 55
Date Printed: 3/1/07
Reference: 41.13819
Original Size: A3



City of Townsville
THE CITY of THURINGOWA
SEA
GHD



Legend

Inundation Depth (m)

- 0.00 - 0.5
- 0.51 - 1.0
- 1.01 - 1.5
- 1.51 - 2.0
- 2.01 - 2.5
- 2.51 - 3.0
- 3.01 - 3.5
- Greater than 3.5 metres

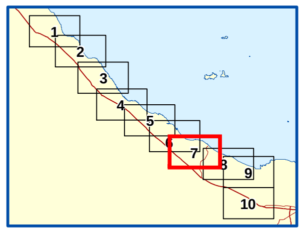
- Digital Cadastre Database
- Suburbs
- Highways
- Major Roads

N W E S

0 500 1,000

Metres

1:25,000



Data supplied by the City of Townsville and City of Thuringowa.
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Townsville - Thuringowa Storm Tide Study 2005

100 Year Event Inundation Depth

Map 7 of 10

(COT Dwg 17597A)

Appendix I

National Storm Tidal Mapping Model

Appendix I – National Storm Tidal Mapping Model

The National Storm Tide Mapping Model for Emergency Response is an Emergency Management Australia Projects Program initiative managed by Department of Emergency Services or DES. The project aim is to deliver a draft National Storm Tide Mapping Model for Emergency Response endorsed by the Queensland, Western Australian and Northern Territory Government agencies responsible for emergency management and mapping.

The purpose of the mapping model is to facilitate the production of a common series of maps to be used to identify storm tide hazard areas for emergency response purposes and, with suitable modification, to provide information to the public.

The Department of Emergency Services stipulates that the maps should indicate up to seven emergency management zones measured from Highest Astronomical Tide (HAT) and referenced from Australian Height Datum (AHD). These zones should correspond to areas of inundation caused by extreme coastal water level scenarios. In Queensland it is intended that maps will be based on 0.5 metre intervals, however it is recognised that this will be a gradual process with some maps based on 1 metre intervals until more accurate data is obtained from a formal storm surge study of the area. Other States may elect to map at 1 metre intervals, dependant upon their local circumstances. It is strongly recommended that adjacent local governments use a consistent approach to mapping to assist cross-jurisdictional emergency response.

The sea level should be marked as white with black stipple up to HAT

The first zone or Zone 1 should extend from HAT up to the next even 0.5 metre (or 1 metre) level so that subsequent zones commence from either an even 0.5 metre level (or 1 metre). This is illustrated by a location with a HAT of 1.68 metres AHD where the zones would be measured as follows (according to 0.5 metre intervals):

- Zone 1: 1.68m AHD to 2.00m AHD
- Zone 2: 2.00m AHD to 2.50m AHD
- Zone 3: 2.50m AHD to 3.00m AHD
- Zone 4: 3.00m AHD to 3.50m AHD
- Zone 5: 3.50m AHD to 4.00m AHD
- Zone 6: 4.00m AHD to 4.50m AHD
- Zone 7: 4.50m AHD to 5.00m AHD

With respect to the theoretical Maximum Storm Tide Waterlevel for Emergency Response, maps are required to indicate the maximum possible extent of storm tide inundation by a 1.0mm wide red dashed line. This should be determined by considering the worst-case scenario of the maximum potential storm surge for that location coinciding with HAT or similar. Information to assist in the development of this line can be obtained from the Bureau of Meteorology. Additionally, local governments will need to take local circumstances into consideration when mapping this line, e.g., river runoff and velocity of waters. This line is optional on maps provided for public information.

The colours used in the maps are considered to be easily recognised by their name and differentiated both in colour and black and white photocopies. These are follows:

- Sea Level: Black Stipple to HAT (Caution: stipple should be open enough to ensure visual clarity of any underlying text and/or information).
- Zone 1: Green (Pantone 359PC: C=36, M=0, Y=49, K=0)
- Zone 2: Purple (Pantone 681PC: C=21, M=61, Y=0, K=4)
- Zone 3: Grey (Pantone 3PC: C=2, M=0, Y=0, K=17)
- Zone 4: Orange (Pantone 144PC: C=0, M=48, Y=100, K=0)
- Zone 5: Pink (Pantone 1895PC: C=0, M=28, Y=7, K=0)
- Zone 6: Brown (Pantone 4655PC: C=0, M=26, Y=45, K=18)
- Zone 7: White (C=0, M=0, Y=0, K=0)

Theoretical Maximum Storm Tide Waterlevel for Emergency Response: Red dashed line, 1 mm thickness (Pantone 485PC: C=0, M=95, Y=100, K=0)

Appendix J

Tropical Cyclone Dataset Summary

Table J.1 - Lifetime Summary of Tropical Cyclones: 1959/1960 to 2003/2004 within 500km Townsville

	Start			Finish			At Maximum Intensity Within Radius						At Closest Approach					
Name	Date	Lat	Long	Date	Lat	Long	pc	Date	Dist	Bear	Vfm	Theta	pc	Date	Dist	Bear	Vfm	Theta
		deg	deg		deg	deg	hPa		km	deg	m/s	deg	hPa		km	deg	m/s	deg
CY0286_1959	24-Dec-59	-12.5	133.2	31-Dec-59	-17.5	164.0	993	26-Dec-59	485	322	2.7	112	997	28-Dec-59	82	61	5.5	79
CY0649_1960	03-Mar-60	-13.5	154.5	09-Mar-60	-18.7	146.5	1000	06-Mar-60	470	43	3.9	202	1003	09-Mar-60	61	357	3.4	270
CY0293_1961	02-Jan-61	-18.6	146.5	06-Jan-61	-18.2	150.6	996	03-Jan-61	334	88	6.4	130	998	03-Jan-61	54	20	5.3	112
CY0301_1961	02-Mar-61	-11.1	136.8	08-Mar-61	-13.3	159.7	990	03-Mar-61	335	12	7.2	124	990	03-Mar-61	309	35	7.2	124
CY0304_1961	22-Dec-61	-16.7	148.7	25-Dec-61	-25.3	159.7	1000	22-Dec-61	301	43	3.9	141	1000	23-Dec-61	298	52	3.9	141
Cy310_1962	29-Dec-62	-17.7	150.8	31-Dec-62	-26.0	151.7	1000	29-Dec-62	454	67	10.2	120	1000	29-Dec-62	454	67	10.2	120
CY0656_1963	26-Mar-63	-10.7	137.8	30-Mar-63	-22.4	144.9	998	28-Mar-63	439	285	3.2	162	1000	29-Mar-63	363	260	3.7	195
Gertie_1964	14-Mar-64	-16.3	149.7	17-Mar-64	-20.4	155.6	999	15-Mar-64	321	70	3.0	150	999	15-Mar-64	321	70	3.0	150
Flora_1964	30-Nov-64	-10.7	134.5	08-Dec-64	-20.0	152.8	996	05-Dec-64	390	296	4.5	76	996	06-Dec-64	124	24	4.9	115
Judy_1965	25-Jan-65	-11.6	133.0	05-Feb-65	-31.5	164.5	992	30-Jan-65	397	54	8.4	90	996	30-Jan-65	223	354	10.4	84
Elaine_1967	13-Mar-67	-14.7	149.3	19-Mar-67	-32.0	164.0	996	15-Mar-67	378	11	4.5	117	997	14-Mar-67	287	10	3.0	279
Cy562_1967	06-Dec-67	-15.5	151.6	10-Dec-67	-27.7	163.7	1003	07-Dec-67	486	49	2.0	104	1005	06-Dec-67	370	45	5.6	62
Cy568_1968	12-Feb-68	-16.7	138.5	16-Feb-68	-22.2	140.3	996	15-Feb-68	444	273	5.8	165	997	15-Feb-68	421	257	6.1	203
Bridget_1969	23-Jan-69	-13.0	148.0	26-Jan-69	-18.0	147.0	1002	25-Jan-69	378	11	2.1	193	1009	26-Jan-69	140	7	1.6	197
Ada_1970	02-Jan-70	-15.8	165.1	18-Jan-70	-21.1	148.5	962	17-Jan-70	241	115	1.8	212	963	17-Jan-70	240	122	1.8	212
Cy576_1970	01-Mar-70	-13.6	147.0	04-Mar-70	-16.7	153.1	1002	03-Mar-70	451	26	2.5	90	1003	02-Mar-70	424	11	3.0	99
Gertie_1971	10-Feb-71	-16.9	149.5	16-Feb-71	-17.5	144.5	983	14-Feb-71	449	115	5.2	293	988	15-Feb-71	67	36	7.2	305
Fiona_1971	16-Feb-71	-16.0	140.8	28-Feb-71	-20.8	161.8	990	19-Feb-71	405	285	9.3	123	994	20-Feb-71	126	212	9.3	123
Althea_1971	19-Dec-71	-10.9	159.0	29-Dec-71	-34.8	164.7	950	22-Dec-71	457	58	5.9	235	950	23-Dec-71	35	341	11.7	253
Bronwyn_1972	02-Jan-72	-16.2	138.7	11-Jan-72	-25.1	142.6	995	08-Jan-72	482	298	3.1	170	995	09-Jan-72	414	280	2.6	190
Una_1973	14-Dec-73	-13.9	156.8	19-Dec-73	-23.7	148.3	988	18-Dec-73	55	133	6.7	180	988	18-Dec-73	40	84	4.6	180
Vera_1974	17-Jan-74	-20.2	149.4	21-Jan-74	-23.7	164.6	996	18-Jan-74	144	59	3.0	80	998	18-Jan-74	110	68	1.8	32
Wanda_1974	20-Jan-74	-17.7	148.8	25-Jan-74	-27.3	149.9	1002	20-Jan-74	325	68	2.7	112	1004	20-Jan-74	271	50	5.1	120
Yvonne_1974	08-Feb-74	-18.3	152.6	11-Feb-74	-16.6	139.8	995	09-Feb-74	168	333	4.9	275	999	09-Feb-74	113	20	5.8	290
Gloria_1975	15-Jan-75	-16.2	146.5	19-Jan-75	-26.0	165.0	979	16-Jan-75	353	66	10.3	126	988	16-Jan-75	231	32	2.5	90
David_1976	13-Jan-76	-15.4	167.4	21-Jan-76	-27.9	143.2	961	19-Jan-76	481	129	6.8	261	972	19-Jan-76	388	156	10.4	246

Table J.1 - Lifetime Summary of Tropical Cyclones: 1959/1960 to 2003/2004 within 500km Townsville

	Start			Finish			At Maximum Intensity Within Radius						At Closest Approach					
Name	Date	Lat	Long	Date	Lat	Long	pc	Date	Dist	Bear	Vfm	Theta	pc	Date	Dist	Bear	Vfm	Theta
		deg	deg		deg	deg	hPa		km	deg	m/s	deg	hPa		km	deg	m/s	deg
Alan_1976	29-Jan-76	-12.5	162.0	09-Feb-76	-25.9	138.9	994	31-Jan-76	402	18	6.9	270	994	01-Feb-76	382	0	6.9	270
Beth_1976	13-Feb-76	-16.5	149.9	22-Feb-76	-24.9	151.3	1000	14-Feb-76	486	43	1.6	17	1003	13-Feb-76	447	46	3.2	37
Dawn_1976	03-Mar-76	-17.4	145.6	06-Mar-76	-30.4	155.7	995	04-Mar-76	166	309	7.2	125	995	04-Mar-76	12	37	6.7	127
Watorea_1976	25-Apr-76	-9.5	152.6	28-Apr-76	-27.1	158.9	970	27-Apr-76	418	14	3.6	180	978	27-Apr-76	264	56	10.5	146
June_1977	16-Jan-77	-15.4	150.2	19-Jan-77	-17.5	160.5	994	17-Jan-77	497	65	6.6	76	998	17-Jan-77	486	57	3.2	142
Keith_1977	29-Jan-77	-15.2	148.2	31-Jan-77	-19.6	147.4	992	30-Jan-77	350	4	3.0	260	999	31-Jan-77	18	49	4.2	136
Lily_1977	08-Feb-77	-15.8	148.0	11-Feb-77	-15.0	150.2	999	08-Feb-77	402	18	0.0	90	999	08-Feb-77	402	18	0.0	90
Nancy_1977	12-Feb-77	-15.5	147.7	13-Feb-77	-15.7	144.6	998	12-Feb-77	413	11	1.1	242	998	12-Feb-77	382	359	6.4	270
Otto_1977	06-Mar-77	-14.0	140.1	10-Mar-77	-22.6	145.4	987	08-Mar-77	344	341	15.0	138	987	09-Mar-77	92	92	5.0	157
Gwen_1978	25-Feb-78	-11.2	136.4	27-Feb-78	-17.0	144.0	1002	27-Feb-78	389	310	7.2	124	1002	27-Feb-78	389	310	7.2	124
Hal_1978	06-Apr-78	-12.2	138.1	11-Apr-78	-21.0	154.0	994	09-Apr-78	335	54	5.4	90	999	08-Apr-78	258	37	5.4	95
Peter_1978	29-Dec-78	-12.7	137.7	03-Jan-79	-15.3	145.3	992	01-Jan-79	497	334	3.5	98	995	01-Jan-79	442	340	0.7	315
Greta_1979	08-Jan-79	-13.9	137.2	13-Jan-79	-17.8	139.3	994	11-Jan-79	497	334	4.3	248	994	11-Jan-79	497	334	4.3	248
Gordon_1979	08-Jan-79	-19.6	162.6	11-Jan-79	-20.6	148.5	1001	11-Jan-79	463	97	4.4	263	1001	11-Jan-79	230	130	5.2	246
Kerry_1979	12-Feb-79	-8.1	170.1	04-Mar-79	-21.5	150.7	993	03-Mar-79	171	41	4.8	149	999	02-Mar-79	75	68	2.7	339
Paul_1980	02-Jan-80	-15.1	137.1	08-Jan-80	-30.0	159.6	995	05-Jan-80	488	275	3.5	98	995	06-Jan-80	80	208	11.0	111
Ruth_1980	11-Feb-80	-19.7	151.2	19-Feb-80	-21.1	153.4	1003	11-Feb-80	462	96	2.1	43	1003	11-Feb-80	462	96	2.1	43
Freda_1981	24-Feb-81	-14.4	140.6	07-Mar-81	-24.0	165.1	982	27-Feb-81	463	76	7.1	136	989	26-Feb-81	351	30	6.9	121
Dominic_1982	04-Apr-82	-11.4	139.7	14-Apr-82	-15.9	143.9	1000	08-Apr-82	463	353	3.2	71	1005	13-Apr-82	296	34	9.4	303
Des_1983	14-Jan-83	-16.3	146.9	23-Jan-83	-13.5	157.0	999	15-Jan-83	436	60	6.4	113	1002	15-Jan-83	298	9	5.5	79
Elinor_1983	10-Feb-83	-10.6	158.0	03-Mar-83	-21.8	149.9	980	02-Mar-83	473	115	2.6	190	999	03-Mar-83	427	131	3.4	270
Fritz_1983	09-Dec-83	-14.4	147.8	13-Dec-83	-15.7	151.2	1004	09-Dec-83	487	14	2.0	90	1004	09-Dec-83	487	14	2.0	90
Grace_1984	11-Jan-84	-18.5	148.5	20-Jan-84	-23.4	163.0	986	15-Jan-84	485	83	2.9	122	1007	11-Jan-84	196	64	5.2	27
Ingrid_1984	20-Feb-84	-17.4	147.6	25-Feb-84	-23.9	157.6	995	21-Feb-84	463	57	1.6	109	1001	20-Feb-84	221	21	2.0	75
Lance_1984	04-Apr-84	-13.5	153.4	07-Apr-84	-23.7	159.3	995	06-Apr-84	498	68	6.8	167	995	06-Apr-84	490	78	6.8	167
Nigel_1985	14-Jan-85	-16.5	150.3	16-Jan-85	-16.0	159.0	1005	14-Jan-85	479	50	1.5	90	1005	14-Jan-85	479	50	1.5	90
Pierre_1985	18-Feb-85	-11.8	143.3	24-Feb-85	-23.8	160.0	986	21-Feb-85	205	65	9.8	153	986	20-Feb-85	203	58	7.3	147
Rebecca_1985	20-Feb-85	-11.1	135.7	23-Feb-85	-16.7	143.5	1001	23-Feb-85	451	308	5.7	189	1001	23-Feb-85	451	308	5.7	189

Table J.1 - Lifetime Summary of Tropical Cyclones: 1959/1960 to 2003/2004 within 500km Townsville

	Start			Finish			At Maximum Intensity Within Radius						At Closest Approach					
Name	Date	Lat	Long	Date	Lat	Long	pc	Date	Dist	Bear	Vfm	Theta	pc	Date	Dist	Bear	Vfm	Theta
		deg	deg		deg	deg	hPa		km	deg	m/s	deg	hPa		km	deg	m/s	deg
Vernon_1986	21-Jan-86	-16.5	139.5	24-Jan-86	-24.0	160.0	991	23-Jan-86	351	72	10.4	110	995	23-Jan-86	197	20	7.8	109
Winifred_1986	27-Jan-86	-12.9	144.8	05-Feb-86	-20.9	144.2	957	01-Feb-86	188	346	4.5	260	957	01-Feb-86	188	346	4.5	260
Manu_1986	21-Apr-86	-8.0	156.0	27-Apr-86	-16.0	144.6	994	25-Apr-86	482	357	3.4	242	1007	27-Apr-86	430	326	1.8	235
Charlie_1988	21-Feb-88	-12.8	159.1	01-Mar-88	-20.9	147.5	972	29-Feb-88	90	114	1.1	154	982	29-Feb-88	53	107	1.8	125
Delilah_1988	28-Dec-88	-16.7	148.4	01-Jan-89	-18.4	160.0	995	31-Dec-88	470	69	8.2	64	999	30-Dec-88	176	24	3.6	106
Aivu_1989	01-Apr-89	-12.1	152.0	05-Apr-89	-22.0	142.2	880	03-Apr-89	387	40	2.0	180	967	04-Apr-89	76	148	6.6	242
Felicity_1989	13-Dec-89	-11.6	134.0	19-Dec-89	-20.2	160.2	992	17-Dec-89	493	48	3.8	66	999	16-Dec-89	222	355	8.4	86
Ivor_1990	16-Mar-90	-15.8	160.8	26-Mar-90	-21.9	146.8	999	22-Mar-90	475	325	4.7	122	1000	24-Mar-90	42	69	6.0	160
Joy_1990	18-Dec-90	-11.5	158.0	27-Dec-90	-20.0	146.7	940	23-Dec-90	360	358	1.5	180	991	26-Dec-90	0	270	2.5	258
Kelvin_1991	24-Feb-91	-11.7	141.9	05-Mar-91	-14.7	150.0	980	26-Feb-91	497	53	6.7	297	980	26-Feb-91	456	42	3.0	90
Sadie_1994	29-Jan-94	-12.3	137.8	31-Jan-94	-20.1	142.5	1000	31-Jan-94	462	258	8.1	162	1000	31-Jan-94	462	258	8.1	162
Barry_1996	03-Jan-96	-15.0	136.8	09-Jan-96	-23.1	147.5	995	07-Jan-96	388	287	4.3	163	995	08-Jan-96	252	220	7.4	131
Celeste_1996	26-Jan-96	-18.2	146.3	28-Jan-96	-19.2	151.3	960	27-Jan-96	213	103	5.8	90	999	26-Jan-96	75	23	6.2	109
Gillian_1997	09-Feb-97	-12.5	150.5	12-Feb-97	-19.3	146.8	995	11-Feb-97	352	36	3.3	201	1006	12-Feb-97	1	297	1.0	180
Ita_1997	23-Feb-97	-15.1	148.3	24-Feb-97	-20.0	146.6	994	24-Feb-97	51	82	5.3	219	994	24-Feb-97	34	131	5.3	219
Justin_1997	06-Mar-97	-17.0	153.5	23-Mar-97	-19.2	147.3	974	09-Mar-97	492	66	1.5	0	1001	23-Mar-97	14	36	6.6	117
Katrina_1998	02-Jan-98	-15.0	152.0	29-Jan-98	-17.2	149.6	960	16-Jan-98	466	29	1.0	180	1004	28-Jan-98	316	68	2.0	0
Nathan_1998	20-Mar-98	-11.1	143.3	31-Mar-98	-13.8	145.0	1008	30-Mar-98	498	8	6.1	279	1007	30-Mar-98	498	10	5.6	280
Rona_1999	09-Feb-99	-15.1	146.8	12-Feb-99	-15.8	145.0	970	11-Feb-99	362	339	5.0	275	975	11-Feb-99	283	359	6.5	293
Frank_1999	16-Feb-99	-21.5	150.1	18-Feb-99	-20.2	159.8	1004	16-Feb-99	423	125	8.4	75	1004	16-Feb-99	423	125	8.4	75
Steve_2000	25-Feb-00	-17.2	153.0	11-Mar-00	-37.0	127.5	980	27-Feb-00	292	338	7.9	270	980	27-Feb-00	292	338	7.9	270
Vaughan_2000	28-Mar-00	-20.0	168.0	07-Apr-00	-14.6	146.3	975	05-Apr-00	483	21	4.0	262	991	06-Apr-00	447	8	3.5	278
Tessi_2000	31-Mar-00	-14.8	156.2	03-Apr-00	-17.5	143.5	980	02-Apr-00	67	319	0.0	90	987	02-Apr-00	39	357	2.9	270
Abigail_2001	24-Feb-01	-16.6	146.1	26-Feb-01	-16.7	137.8	992	24-Feb-01	303	345	4.4	277	992	24-Feb-01	303	345	4.3	277
Erica_2003	01-Mar-03	-21.0	147.5	12-Mar-03	-16.9	160.0	998	01-Mar-03	266	121	2.2	62	999	01-Mar-03	205	159	7.7	70
Grace_2004	20-Mar-04	-16.6	149.3	23-Mar-04	-22.6	160.0	992	20-Mar-04	394	41	6.1	75	992	20-Mar-04	394	41	6.1	75

Appendix K

Open Coast Storm Tide Estimates Including Breaking Wave Setup

Appendix K - Open Coast SatSim Results (including breaking wave setup)

Site	ID	Latitude (AGD 84)	Longitude (AGD 84)	Total Storm Tide (incl wave setup) 50 yr	100 yr	500 yr	1000 yr	10,000 yr
	67	-18.9196	146.3126	3.14	3.47	4.59	5.01	6.94
	68	-18.9222	146.3172	2.92	3.28	4.03	4.09	6.94
Crystal_Creek	69	-18.9247	146.3218	2.75	3.09	4.02	4.10	7.30
	70	-18.9315	146.3237	2.89	3.28	4.50	4.54	7.00
	71	-18.9341	146.3283	2.76	3.11	3.57	4.07	7.30
	72	-18.9409	146.3302	2.80	3.06	4.00	4.09	7.20
	73	-18.9478	146.3321	2.63	2.96	3.57	4.09	7.40
	74	-18.9547	146.3340	2.67	2.99	4.06	4.76	7.20
	75	-18.9572	146.3386	2.94	3.33	4.46	5.20	8.60
	76	-18.9597	146.3431	3.03	3.43	4.62	5.37	7.06
	77	-18.9579	146.3503	2.74	3.07	4.14	4.80	6.74
	78	-18.9604	146.3549	2.96	3.35	4.59	5.01	6.80
	79	-18.9629	146.3595	2.90	3.27	4.02	4.07	6.64
Ollera_Creek	80	-18.9654	146.3640	2.66	2.97	3.23	3.87	6.74
Mutarnee	81	-18.9723	146.3660	2.52	2.56	3.28	3.92	6.90
	82	-18.9791	146.3679	2.77	3.01	3.30	3.95	6.82
	83	-18.9860	146.3698	2.68	2.97	4.01	4.09	7.10
	84	-18.9885	146.3744	2.69	3.01	4.11	4.52	6.80
	85	-18.9954	146.3763	2.67	2.99	4.06	4.52	6.70
Road_End_(Moongabulla)	86	-18.9979	146.3809	2.65	2.96	4.00	4.68	6.60
	87	-18.9961	146.3881	2.57	2.85	3.80	4.45	6.30
	88	-18.9986	146.3926	2.63	2.92	3.92	4.05	6.40
	89	-19.0011	146.3972	2.67	2.95	3.54	3.75	6.30
	90	-19.0036	146.4018	2.70	3.02	3.55	3.74	6.30
	91	-19.0105	146.4037	2.83	3.17	3.55	3.76	6.32
Balgal	92	-19.0130	146.4083	2.70	3.00	3.99	4.50	6.20
	93	-19.0199	146.4102	2.59	2.85	3.82	4.42	6.24
Rollingstone	94	-19.0224	146.4147	2.57	2.85	3.78	4.38	6.04
	95	-19.0249	146.4193	2.63	2.91	3.90	4.65	6.10
Mystic_Sands	96	-19.0318	146.4212	2.72	3.00	4.00	4.74	6.20
	97	-19.0343	146.4258	2.69	3.00	4.10	4.69	6.12
	98	-19.0412	146.4277	2.90	3.24	4.35	5.00	6.04
	99	-19.0437	146.4323	2.78	3.08	4.13	4.78	6.12
	100	-19.0505	146.4342	2.92	3.26	4.02	4.06	6.00
Surveyors_Creek	101	-19.0530	146.4388	2.68	2.98	3.54	3.77	6.04
	102	-19.0599	146.4407	3.01	3.02	3.23	3.83	6.10
	103	-19.0624	146.4453	2.80	3.01	3.21	3.77	5.94
	104	-19.0649	146.4498	2.51	2.55	3.19	3.75	5.92
	105	-19.0718	146.4518	2.63	2.91	3.21	3.80	5.92
	106	-19.0743	146.4563	2.74	3.03	4.00	4.56	5.80
	107	-19.0725	146.4636	2.81	3.13	4.10	4.75	6.74
	108	-19.0750	146.4681	2.71	3.00	3.93	4.52	6.60
	109	-19.0775	146.4727	2.57	2.82	3.73	4.02	5.62
Toomulla	110	-19.0800	146.4773	2.57	2.82	3.71	4.26	5.64
	111	-19.0826	146.4818	2.58	2.83	3.74	4.32	5.74
	112	-19.0894	146.4838	3.27	3.63	4.59	5.01	5.70
	113	-19.0919	146.4883	2.77	3.04	4.03	4.60	5.74
	114	-19.0944	146.4929	2.68	2.97	3.92	4.04	5.64
	115	-19.0970	146.4975	2.77	3.07	3.54	3.63	5.60
	116	-19.0951	146.5047	2.66	2.91	3.52	3.58	5.40
	117	-19.0976	146.5093	2.62	2.88	3.09	3.52	5.50
	118	-19.1002	146.5138	2.51	2.54	2.98	3.48	5.40
Leichhardt_Creek	119	-19.1027	146.5184	2.24	2.40	3.03	3.55	5.54
	120	-19.1052	146.5230	2.51	2.54	3.01	3.53	5.60
	121	-19.1077	146.5275	2.51	2.54	2.97	3.47	5.50
	122	-19.1102	146.5321	2.24	2.39	3.00	3.51	5.70
Christmas_Creek	123	-19.1127	146.5367	2.51	2.54	2.95	3.47	5.60
	124	-19.1153	146.5413	2.53	2.75	3.07	3.47	5.60
	125	-19.1221	146.5432	2.88	3.01	3.09	3.55	5.90
	126	-19.1246	146.5478	2.51	2.54	2.93	3.43	5.64
	127	-19.1271	146.5523	2.52	2.75	3.09	3.58	5.80
	128	-19.1340	146.5543	2.71	2.97	3.87	4.04	5.84
	129	-19.1365	146.5588	2.64	2.89	3.71	4.02	5.81
	130	-19.1390	146.5634	2.54	2.77	3.08	3.47	5.54
	131	-19.1415	146.5680	2.59	2.82	3.08	3.53	5.60
	132	-19.1441	146.5726	2.68	2.94	3.08	3.46	5.44
	133	-19.1422	146.5798	2.55	2.77	3.52	4.00	5.20
	134	-19.1447	146.5843	2.60	2.80	3.50	3.57	5.50
Toolakea	135	-19.1473	146.5889	2.57	2.79	3.06	3.39	5.30
	136	-19.1454	146.5961	2.50	2.53	2.90	3.36	5.20
Bluewater_Beach	137	-19.1479	146.6007	2.50	2.72	3.06	3.36	5.30
Deep/Healy_Creek	138	-19.1548	146.6026	2.73	2.97	3.07	3.43	5.34
Saunders_Beach	139	-19.1573	146.6072	2.56	2.79	3.54	4.07	5.50
	140	-19.1598	146.6118	2.51	2.74	3.47	4.00	5.40
	141	-19.1623	146.6164	2.50	2.72	3.06	3.37	5.40
	142	-19.1648	146.6209	2.51	2.72	3.06	3.36	5.30

Appendix K - Open Coast SatSim Results (including breaking wave setup)

Site	ID	Latitude (AGD 84)	Longitude (AGD 84)	Total Storm Tide (incl wave setup) 50 yr	100 yr	500 yr	1000 yr	10,000 yr
	143	-19.1674	146.6255	2.53	2.75	3.49	3.56	5.40
	144	-19.1699	146.6301	2.53	2.76	3.07	3.37	5.40
	145	-19.1724	146.6347	2.66	2.91	3.06	3.35	5.40
	146	-19.1749	146.6392	2.52	2.54	2.91	3.34	5.40
	147	-19.1731	146.6465	2.50	2.52	2.85	3.24	5.10
Black_River	148	-19.1756	146.6510	2.51	2.53	2.90	3.34	5.30
	149	-19.1781	146.6556	2.51	2.53	2.86	3.28	5.20
	150	-19.1806	146.6602	2.50	2.53	2.87	3.30	5.20
	151	-19.1831	146.6648	2.51	2.72	3.05	3.30	5.30
	152	-19.1856	146.6693	2.52	2.74	3.48	3.54	5.40
	153	-19.1881	146.6739	2.55	2.78	3.57	3.97	5.30
	154	-19.1906	146.6785	2.57	2.81	3.58	4.03	5.40
Bushland_Beach	155	-19.1931	146.6831	2.63	2.89	3.61	4.03	5.30
	156	-19.1913	146.6903	2.66	2.89	3.51	3.54	5.10
	157	-19.1938	146.6949	2.63	2.85	3.50	3.54	5.10
	158	-19.1963	146.6994	2.51	2.53	2.85	3.26	5.00
Bohle_River	159	-19.1920	146.7021	2.21	2.33	2.80	3.17	4.80
	160	-19.1876	146.7047	2.50	2.52	2.79	3.14	4.74
	161	-19.1833	146.7074	2.48	2.52	2.75	3.11	4.74
	162	-19.1858	146.7119	2.50	2.71	3.03	3.09	4.66
	163	-19.1883	146.7165	2.50	2.71	3.41	3.83	5.04
	164	-19.1865	146.7237	2.57	2.76	3.42	3.81	5.62
	165	-19.1821	146.7264	2.52	2.71	3.33	3.73	4.62
	166	-19.1778	146.7290	2.45	2.63	3.24	3.62	4.52
	167	-19.1803	146.7336	2.50	2.68	3.29	3.64	4.50
	168	-19.1828	146.7382	2.62	2.83	3.54	3.94	5.86
	169	-19.1809	146.7454	2.66	2.87	3.57	3.95	6.00
Shelly_Beach	170	-19.1835	146.7500	2.88	3.14	3.97	4.38	6.50
	171	-19.1816	146.7572	2.50	2.68	3.31	3.67	5.40
	172	-19.1841	146.7618	2.49	2.68	3.34	3.73	5.70
Cape_Pallarenda	173	-19.1866	146.7664	2.48	2.66	3.30	3.73	5.60
	174	-19.1891	146.7709	2.46	2.63	3.26	3.66	5.60
	175	-19.1916	146.7755	2.56	2.76	3.46	3.90	5.94
Pallarenda	176	-19.1985	146.7774	2.63	2.85	3.63	4.09	5.20
	177	-19.2054	146.7794	2.65	2.90	3.71	4.01	5.60
	178	-19.2097	146.7767	2.88	3.15	3.53	3.58	5.80
	179	-19.2166	146.7787	2.84	3.10	4.00	4.03	5.90
	180	-19.2234	146.7806	2.95	3.26	4.28	4.51	5.90
	181	-19.2303	146.7826	3.06	3.39	4.43	4.52	6.00
	182	-19.2328	146.7871	2.71	2.97	3.87	4.50	5.90
Rowes_Bay	183	-19.2397	146.7891	2.74	3.00	3.84	4.37	5.90
	184	-19.2422	146.7937	2.71	2.99	3.87	4.45	5.80
	185	-19.2403	146.8009	2.79	3.08	3.92	4.50	5.50
Kissing_Point	186	-19.2385	146.8081	2.65	2.91	3.76	4.27	5.50
	187	-19.2453	146.8100	2.61	2.85	3.64	4.15	5.50
North_Ward	188	-19.2478	146.8146	2.74	3.00	3.87	4.43	5.40
	189	-19.2504	146.8192	2.75	3.01	3.82	4.40	5.40
Breakwater_Casino	190	-19.2485	146.8264	2.61	2.84	3.57	4.00	5.14
Townsville_Harbour	191	-19.2510	146.8310	2.64	2.89	3.52	3.58	5.40
	192	-19.2535	146.8356	2.65	2.87	3.63	4.01	5.30
	193	-19.2517	146.8428	2.58	2.82	3.57	4.00	5.14
	194	-19.2542	146.8474	2.55	2.77	3.48	3.97	5.14
	195	-19.2611	146.8493	2.56	2.80	3.54	4.00	5.24
South_Townsville	196	-19.2629	146.8421	2.63	2.90	3.73	4.02	5.60
	197	-19.2672	146.8395	2.80	3.07	3.53	3.60	5.60
Ross_River	198	-19.2716	146.8368	2.94	3.01	3.18	3.68	5.70
	199	-19.2741	146.8414	3.25	3.50	3.55	3.63	5.70
	200	-19.2723	146.8486	2.70	2.96	3.09	3.48	5.30
	201	-19.2748	146.8532	2.51	2.55	3.02	3.46	5.40
	202	-19.2816	146.8551	2.29	2.48	3.08	3.60	5.50
	203	-19.2841	146.8597	2.28	2.47	3.06	3.50	5.40
	204	-19.2910	146.8617	2.30	2.49	3.10	3.61	5.50
	205	-19.2935	146.8663	2.52	2.56	3.11	3.60	5.34
	206	-19.2960	146.8708	2.52	2.56	3.12	3.53	5.34
	207	-19.2985	146.8754	2.52	2.56	3.11	3.55	5.25
	208	-19.3010	146.8800	2.51	2.56	3.09	3.51	5.30
	209	-19.3035	146.8846	2.29	2.47	3.08	3.53	5.30
	210	-19.3060	146.8892	2.30	2.47	3.08	3.54	5.40
	211	-19.3042	146.8964	2.28	2.45	3.05	3.46	5.30
	212	-19.3023	146.9036	2.26	2.43	2.99	3.41	5.20
	213	-19.3005	146.9108	2.25	2.41	2.95	3.37	5.10
	214	-19.2986	146.9181	2.25	2.41	2.93	3.35	5.00
	215	-19.3011	146.9226	2.25	2.42	2.95	3.38	5.10
	216	-19.2968	146.9253	2.24	2.40	2.91	3.30	5.00
	217	-19.2993	146.9299	2.25	2.40	2.90	3.30	5.00
	218	-19.2993	146.9299	2.25	2.40	2.90	3.30	5.00

Appendix K - Open Coast SatSim Results (including breaking wave setup)

Site	ID	Latitude (AGD 84)	Longitude (AGD 84)	Total Storm Tide (incl wave setup) 50 yr	100 yr	500 yr	1000 yr	10,000 yr
	219	-19.2974	146.9371	2.24	2.38	2.87	3.26	4.90
	220	-19.2931	146.9397	2.65	2.85	3.05	3.24	4.90
	221	-19.2956	146.9443	2.91	3.15	3.98	4.02	4.90
	222	-19.2981	146.9489	2.84	3.12	3.97	4.59	5.10
	223	-19.2963	146.9561	2.61	2.84	3.56	4.07	5.03
	224	-19.2919	146.9587	2.53	2.74	3.41	3.86	5.03
	225	-19.2876	146.9614	2.52	2.71	3.37	3.82	5.01
	226	-19.2832	146.9640	2.48	2.66	3.31	3.75	5.01
	227	-19.2814	146.9712	2.50	2.69	3.35	3.80	5.01
	228	-19.2770	146.9739	2.48	2.67	3.29	3.72	5.01
	229	-19.2726	146.9765	2.45	2.63	3.26	3.66	5.01
	230	-19.2683	146.9791	2.43	2.59	3.22	3.57	5.00
	231	-19.2639	146.9818	2.43	2.60	3.20	3.60	5.00
	232	-19.2621	146.9890	2.43	2.59	3.17	3.50	4.94
	233	-19.2577	146.9916	2.42	2.57	3.15	3.46	4.90
	234	-19.2534	146.9943	2.41	2.56	3.12	3.43	4.80
Launs_Beach	235	-19.2490	146.9969	2.41	2.56	3.12	3.42	4.80
	236	-19.2447	146.9995	2.38	2.52	3.04	3.35	4.60
	237	-19.2403	147.0022	2.38	2.53	3.04	3.37	4.60
	238	-19.2360	147.0048	2.38	2.53	3.06	3.35	4.70
Whiterock_Bay	239	-19.2316	147.0074	2.35	2.50	3.01	3.31	4.50
	240	-19.2273	147.0101	2.34	2.49	2.97	3.31	4.50
	241	-19.2229	147.0127	2.34	2.46	2.92	3.25	4.40
	242	-19.2186	147.0154	2.33	2.45	2.88	3.19	4.34
Long_Beach	243	-19.2142	147.0180	2.31	2.44	2.86	3.17	4.30
	244	-19.2074	147.0160	2.33	2.46	2.88	3.17	4.20
Red_Rock_Bay	245	-19.2005	147.0141	2.33	2.47	2.88	3.15	4.20
	246	-19.1936	147.0121	2.40	2.52	2.93	3.25	4.14
	247	-19.1868	147.0102	2.33	2.43	2.79	3.04	3.85
Cape_Cleveland	248	-19.1824	147.0128	2.30	2.40	2.74	2.99	3.90
	249	-19.1849	147.0174	2.39	2.52	2.96	3.25	4.34
	250	-19.1874	147.0220	2.40	2.54	3.01	3.28	4.44
	251	-19.1943	147.0239	2.59	2.77	3.27	3.63	4.84
	252	-19.2011	147.0259	2.52	2.73	3.32	3.71	5.00
	253	-19.2037	147.0305	2.39	2.56	3.08	3.39	4.60
	254	-19.2062	147.0351	2.45	2.61	3.09	3.43	4.80
	255	-19.2087	147.0396	2.42	2.57	3.03	3.40	4.62
	256	-19.2155	147.0416	2.30	2.44	2.88	3.21	4.45
	257	-19.2224	147.0435	2.46	2.63	3.12	3.52	4.90
	258	-19.2292	147.0455	2.42	2.60	3.20	3.60	5.00
Paradise_Bay	259	-19.2336	147.0428	2.48	2.70	3.42	3.82	5.40
	260	-19.2404	147.0448	2.74	2.96	3.59	4.00	5.50
	261	-19.2429	147.0494	2.82	3.04	3.75	4.10	5.80
	262	-19.2454	147.0540	2.63	2.87	3.58	4.03	5.44
	263	-19.2523	147.0559	2.66	2.86	3.46	3.90	5.40
	264	-19.2548	147.0605	2.46	2.65	3.34	3.72	5.30
	265	-19.2616	147.0625	2.33	2.53	3.22	3.67	5.00
	266	-19.2660	147.0598	2.41	2.60	3.19	3.63	5.00
Cape_Ferguson	267	-19.2729	147.0618	2.38	2.55	3.13	3.52	5.00
	268	-19.2797	147.0637	2.29	2.48	3.09	3.54	4.34
	269	-19.2816	147.0565	2.30	2.50	3.02	3.08	4.54
	270	-19.2834	147.0493	2.48	2.69	3.04	3.13	4.70
	271	-19.2878	147.0466	2.60	2.83	3.05	3.16	4.80
Chunda_Bay	272	-19.2946	147.0486	2.09	2.24	2.75	3.20	4.82
	273	-19.3015	147.0505	2.09	2.23	2.73	3.20	4.80
	274	-19.3083	147.0525	2.54	2.78	3.05	3.21	4.82
	275	-19.3152	147.0544	2.60	2.83	3.05	3.22	4.90
	276	-19.3220	147.0564	2.58	2.80	3.05	3.24	5.00
	277	-19.3245	147.0610	2.49	2.71	3.04	3.21	4.90
	278	-19.3314	147.0629	2.55	2.79	3.05	3.21	5.00
	279	-19.3339	147.0675	2.42	2.63	3.04	3.20	4.90
	280	-19.3408	147.0695	2.50	2.74	3.05	3.22	5.00
	281	-19.3476	147.0714	2.74	2.99	3.05	3.25	5.00
	282	-19.3501	147.0760	2.57	2.79	3.05	3.21	4.92
	283	-19.3526	147.0806	2.43	2.63	3.04	3.17	4.82
	284	-19.3595	147.0826	2.57	2.80	3.05	3.27	4.80
	285	-19.3620	147.0871	2.54	2.77	3.05	3.22	4.70
	286	-19.3645	147.0917	2.52	2.75	3.05	3.25	4.94
	287	-19.3713	147.0937	2.67	2.90	3.05	3.30	4.90
	288	-19.3738	147.0983	2.53	2.76	3.05	3.27	4.90
	289	-19.3763	147.1029	2.50	2.74	3.04	3.24	4.80
	290	-19.3788	147.1074	2.57	2.81	3.05	3.28	4.90
	291	-19.3813	147.1120	2.64	2.89	3.05	3.24	4.90
	292	-19.3882	147.1140	2.60	2.85	3.51	3.55	5.00
Cungulla	293	-19.3950	147.1159	2.47	2.70	3.49	3.56	4.90
	294	-19.4019	147.1179	2.55	2.80	3.51	3.56	5.20

Appendix K - Open Coast SatSim Results (including breaking wave setup)

Site	ID	Latitude (AGD 84)	Longitude (AGD 84)	Total Storm Tide (incl wave setup) 50 yr	100 yr	500 yr	1000 yr	10,000 yr
	295	-19.4087	147.1198	2.65	2.94	3.08	3.47	5.34
	296	-19.4112	147.1244	2.15	2.34	2.95	3.48	5.35
Haughton_River	297	-19.4181	147.1264	2.17	2.36	2.99	3.56	5.60
	298	-19.4206	147.1310	2.17	2.36	2.99	3.58	5.52
	299	-19.4162	147.1336	2.15	2.33	2.93	3.52	5.35
	300	-19.4119	147.1363	2.14	2.31	2.87	3.42	5.10
	301	-19.4050	147.1343	2.12	2.29	2.84	3.32	5.00
	302	-19.4032	147.1415	2.11	2.27	2.79	3.27	4.80
	303	-19.4057	147.1461	2.11	2.26	2.77	3.24	4.80
	304	-19.4038	147.1533	2.09	2.25	2.77	3.23	4.70
	305	-19.4063	147.1579	2.10	2.26	2.78	3.25	4.80
	306	-19.4045	147.1651	2.09	2.23	2.75	3.22	4.64
	307	-19.4113	147.1671	2.11	2.27	2.81	3.30	4.84
	308	-19.4095	147.1743	2.10	2.24	2.75	3.22	4.80
	309	-19.4076	147.1816	2.08	2.22	2.70	3.18	4.70
	310	-19.4101	147.1861	2.08	2.23	2.70	3.18	4.80
	311	-19.4126	147.1907	2.09	2.23	2.73	3.20	4.80
	312	-19.4151	147.1953	2.10	2.24	2.74	3.21	4.80
	313	-19.4176	147.1999	2.11	2.25	2.78	3.25	4.90
	314	-19.4157	147.2071	2.10	2.23	2.72	3.19	4.80
	315	-19.4182	147.2117	2.10	2.23	2.75	3.23	4.64
	316	-19.4207	147.2163	2.10	2.25	2.78	3.25	4.74
	317	-19.4189	147.2235	2.09	2.22	2.73	3.21	4.55
	318	-19.4170	147.2308	2.08	2.21	2.71	3.18	4.54
Florence_Bay	319	-19.1167	146.8820	2.78	3.04	3.75	4.13	5.54
	320	-19.1210	146.8793	3.16	3.47	4.28	4.64	6.10
	321	-19.1279	146.8813	2.40	2.54	3.00	3.34	4.90
Arthur_Bay	322	-19.1322	146.8786	2.38	2.53	3.03	3.38	5.10
	323	-19.1366	146.8760	2.36	2.52	3.04	3.39	5.10
	324	-19.1409	146.8734	2.39	2.55	3.08	3.41	5.20
	325	-19.1478	146.8753	2.41	2.58	3.17	3.54	5.50
Arcadia_(Alma_Bay)	326	-19.1521	146.8727	2.43	2.59	3.21	3.56	5.00
	327	-19.1565	146.8700	2.44	2.62	3.22	3.57	5.00
	328	-19.1583	146.8628	2.44	2.62	3.22	3.56	5.01
	329	-19.1602	146.8556	2.41	2.59	3.23	3.58	5.01
Nelly_Bay	330	-19.1645	146.8530	2.45	2.65	3.32	3.68	5.02
	331	-19.1689	146.8503	2.52	2.75	3.48	3.87	5.07
	332	-19.1732	146.8477	2.55	2.78	3.60	3.98	6.00
	333	-19.1801	146.8496	2.46	2.68	3.41	3.81	5.94
	334	-19.1844	146.8470	2.46	2.66	3.40	3.79	6.10
Picnic_Bay	335	-19.1819	146.8424	2.50	2.70	3.38	3.75	5.80
	336	-19.1838	146.8352	2.54	2.76	3.49	3.90	5.07
	337	-19.1813	146.8306	2.50	2.72	3.48	3.88	5.07
	338	-19.1788	146.8260	2.45	2.62	3.19	3.61	4.30
	339	-19.1762	146.8215	2.44	2.62	3.21	3.50	4.30
	340	-19.1737	146.8169	2.46	2.64	3.02	3.06	4.30
	341	-19.1712	146.8123	2.45	2.63	3.02	3.06	4.30
	342	-19.1687	146.8077	2.42	2.58	3.01	3.05	4.30
	343	-19.1662	146.8031	2.43	2.51	2.59	2.82	4.30
	344	-19.1594	146.8012	2.08	2.16	2.50	2.74	4.10
	345	-19.1569	146.7966	2.50	2.51	2.57	2.76	4.12
Bolger_Bay	346	-19.1500	146.7947	2.62	2.82	3.01	3.04	3.90
	347	-19.1475	146.7901	2.41	2.50	2.57	2.71	4.00
	348	-19.1450	146.7855	2.38	2.50	2.57	2.72	4.02
	349	-19.1381	146.7836	2.39	2.53	3.00	3.03	3.95
	350	-19.1356	146.7790	2.42	2.56	3.13	3.42	4.05
West_Point	351	-19.1287	146.7771	2.39	2.54	3.10	3.40	4.91
	352	-19.1244	146.7797	2.37	2.52	3.05	3.41	5.00
	353	-19.1226	146.7869	2.65	2.86	3.57	3.95	5.60
	354	-19.1182	146.7896	2.43	2.60	3.17	3.50	5.00
	355	-19.1139	146.7922	2.30	2.43	2.92	3.24	4.80
Huntingfield_Bay	356	-19.1164	146.7968	2.32	2.44	2.95	3.26	4.80
	357	-19.1145	146.8040	2.55	2.70	3.21	3.53	5.00
	358	-19.1170	146.8086	2.57	2.74	3.23	3.60	4.94
Wilson_Bay	359	-19.1152	146.8158	2.37	2.51	3.04	3.32	4.80
	360	-19.1177	146.8204	2.41	2.57	3.14	3.45	4.90
	361	-19.1133	146.8230	2.35	2.51	3.03	3.33	4.70
	362	-19.1090	146.8256	2.33	2.46	2.99	3.27	4.56
	363	-19.1046	146.8283	2.31	2.44	2.96	3.26	4.70
	364	-19.1072	146.8329	2.68	2.87	3.46	3.73	5.20
	365	-19.1097	146.8374	2.76	3.00	3.64	4.00	5.70
	366	-19.1122	146.8420	2.66	2.87	3.45	3.80	5.40
	367	-19.1147	146.8466	2.48	2.62	3.14	3.46	4.90
	368	-19.1172	146.8512	2.38	2.53	3.03	3.33	4.70
Horseshoe_Bay	369	-19.1153	146.8584	2.38	2.52	3.00	3.32	4.70
	370	-19.1110	146.8610	2.35	2.50	2.98	3.29	4.54

Appendix K - Open Coast SatSim Results (including breaking wave setup)

Site	ID	Latitude (AGD 84)	Longitude (AGD 84)	Total Storm Tide (incl wave setup) 50 yr	100 yr	500 yr	1000 yr	10,000 yr
	371	-19.1066	146.8637	2.36	2.50	2.89	3.21	4.34
	372	-19.1023	146.8663	2.32	2.44	2.87	3.14	4.34
	373	-19.1048	146.8709	2.34	2.47	2.89	3.23	4.35
Radical_Bay	374	-19.1117	146.8728	2.49	2.64	3.12	3.43	4.56
	375	-19.1142	146.8774	2.75	2.91	3.39	3.64	4.64
Rattlesnake_Island	376	-19.0384	146.6124	2.47	2.66	3.40	3.83	5.80
Havannah_Island	377	-18.8474	146.5395	2.46	2.63	3.33	3.71	5.50

Appendix L

Open Coast Storm Tide Estimates Without Breaking Wave Setup

Appendix L - Open Coast SatSim Results (without breaking wave setup)

Site	ID	Latitude (AGD 84)	Longitude (AGD 84)	Tide plus surge (excl wave setup) 50 yr	100 yr	500 yr	1000 yr	10,000 yr
	67	-18.9196	146.3126	2.30	2.52	3.38	4.06	6.94
	68	-18.9222	146.3172	2.28	2.51	3.38	4.06	6.94
Crystal_Creek	69	-18.9247	146.3218	2.27	2.50	3.39	4.07	7.30
	70	-18.9315	146.3237	2.28	2.51	3.37	4.03	7.00
	71	-18.9341	146.3283	2.27	2.50	3.37	4.07	7.30
	72	-18.9409	146.3302	2.27	2.49	3.34	4.02	7.20
	73	-18.9478	146.3321	2.30	2.53	3.44	4.09	7.40
	74	-18.9547	146.3340	2.30	2.52	3.39	4.07	7.20
	75	-18.9572	146.3386	2.28	2.50	3.34	4.03	7.00
	76	-18.9597	146.3431	2.28	2.49	3.31	4.00	6.94
	77	-18.9579	146.3503	2.25	2.44	3.24	3.90	6.74
	78	-18.9604	146.3549	2.25	2.44	3.24	3.87	6.80
	79	-18.9629	146.3595	2.24	2.43	3.21	3.83	6.64
Ollera_Creek	80	-18.9654	146.3640	2.24	2.43	3.23	3.87	6.74
Mutarnee	81	-18.9723	146.3660	2.25	2.45	3.28	3.92	6.90
	82	-18.9791	146.3679	2.26	2.46	3.30	3.95	6.82
	83	-18.9860	146.3698	2.28	2.49	3.40	4.04	7.10
	84	-18.9885	146.3744	2.26	2.47	3.32	3.94	6.80
	85	-18.9954	146.3763	2.28	2.48	3.30	3.92	6.70
Road_End_(Moongabulla)	86	-18.9979	146.3809	2.26	2.45	3.27	3.85	6.60
	87	-18.9961	146.3881	2.24	2.42	3.17	3.75	6.30
	88	-18.9986	146.3926	2.23	2.42	3.17	3.75	6.40
	89	-19.0011	146.3972	2.24	2.42	3.18	3.75	6.30
	90	-19.0036	146.4018	2.23	2.41	3.19	3.74	6.30
	91	-19.0105	146.4037	2.24	2.43	3.22	3.76	6.32
Balgal	92	-19.0130	146.4083	2.25	2.43	3.17	3.73	6.20
	93	-19.0199	146.4102	2.27	2.45	3.23	3.77	6.24
Rollingstone	94	-19.0224	146.4147	2.25	2.43	3.17	3.69	6.04
	95	-19.0249	146.4193	2.25	2.42	3.17	3.74	6.10
Mystic_Sands	96	-19.0318	146.4212	2.26	2.44	3.21	3.75	6.20
	97	-19.0343	146.4258	2.26	2.44	3.19	3.75	6.12
	98	-19.0412	146.4277	2.26	2.45	3.18	3.75	6.04
	99	-19.0437	146.4323	2.26	2.45	3.19	3.76	6.12
	100	-19.0505	146.4342	2.27	2.45	3.20	3.78	6.00
Surveyors_Creek	101	-19.0530	146.4388	2.27	2.45	3.20	3.77	6.04
	102	-19.0599	146.4407	2.28	2.47	3.23	3.83	6.10
	103	-19.0624	146.4453	2.27	2.46	3.21	3.77	5.94
	104	-19.0649	146.4498	2.27	2.45	3.19	3.75	5.92
	105	-19.0718	146.4518	2.28	2.46	3.21	3.80	5.92
	106	-19.0743	146.4563	2.26	2.44	3.16	3.73	5.80
	107	-19.0725	146.4636	2.24	2.41	3.08	3.65	5.60
	108	-19.0750	146.4681	2.25	2.42	3.13	3.66	5.70
	109	-19.0775	146.4727	2.24	2.41	3.09	3.63	5.62
Toomulla	110	-19.0800	146.4773	2.25	2.41	3.09	3.63	5.64
	111	-19.0826	146.4818	2.26	2.42	3.12	3.67	5.74
	112	-19.0894	146.4838	2.26	2.44	3.13	3.68	5.70
	113	-19.0919	146.4883	2.26	2.43	3.10	3.65	5.74
	114	-19.0944	146.4929	2.26	2.42	3.07	3.65	5.64
	115	-19.0970	146.4975	2.26	2.42	3.07	3.63	5.60
	116	-19.0951	146.5047	2.23	2.38	2.99	3.47	5.40
	117	-19.0976	146.5093	2.24	2.40	3.03	3.52	5.50
	118	-19.1002	146.5138	2.24	2.39	2.98	3.48	5.40
Leichhardt_Creek	119	-19.1027	146.5184	2.24	2.40	3.03	3.55	5.54
	120	-19.1052	146.5230	2.24	2.40	3.01	3.53	5.60
	121	-19.1077	146.5275	2.24	2.39	2.97	3.47	5.50
	122	-19.1102	146.5321	2.24	2.39	3.00	3.51	5.70
Christmas_Creek	123	-19.1127	146.5367	2.23	2.38	2.95	3.47	5.60
	124	-19.1153	146.5413	2.23	2.38	2.96	3.47	5.60
	125	-19.1221	146.5432	2.25	2.40	3.01	3.55	5.90
	126	-19.1246	146.5478	2.23	2.36	2.93	3.43	5.64
	127	-19.1271	146.5523	2.25	2.41	3.06	3.58	5.80
	128	-19.1340	146.5543	2.27	2.44	3.09	3.64	5.84
	129	-19.1365	146.5588	2.25	2.41	3.05	3.56	5.81
	130	-19.1390	146.5634	2.24	2.39	2.98	3.47	5.54
	131	-19.1415	146.5680	2.24	2.40	3.02	3.53	5.60
	132	-19.1441	146.5726	2.24	2.39	2.98	3.46	5.44
	133	-19.1422	146.5798	2.22	2.36	2.92	3.37	5.20
	134	-19.1447	146.5843	2.23	2.38	2.97	3.44	5.50
Toolakea	135	-19.1473	146.5889	2.23	2.36	2.92	3.39	5.30
	136	-19.1454	146.5961	2.21	2.35	2.90	3.36	5.20
Bluewater_Beach	137	-19.1479	146.6007	2.22	2.35	2.91	3.36	5.30
Deep/Healy_Creek	138	-19.1548	146.6026	2.24	2.39	2.94	3.43	5.34
Saunders_Beach	139	-19.1573	146.6072	2.23	2.39	2.98	3.46	5.50
	140	-19.1598	146.6118	2.23	2.38	2.96	3.42	5.40
	141	-19.1623	146.6164	2.22	2.37	2.93	3.37	5.40
	142	-19.1648	146.6209	2.22	2.36	2.91	3.36	5.30

Appendix L - Open Coast SatSim Results (without breaking wave setup)

Site	ID	Latitude (AGD 84)	Longitude (AGD 84)	Tide plus surge (excl wave setup) 50 yr	100 yr	500 yr	1000 yr	10,000 yr
	143	-19.1674	146.6255	2.23	2.38	2.95	3.37	5.40
	144	-19.1699	146.6301	2.23	2.38	2.95	3.37	5.40
	145	-19.1724	146.6347	2.23	2.37	2.92	3.35	5.40
	146	-19.1749	146.6392	2.22	2.37	2.91	3.34	5.40
	147	-19.1731	146.6465	2.21	2.34	2.85	3.24	5.10
Black_River	148	-19.1756	146.6510	2.22	2.37	2.90	3.34	5.30
	149	-19.1781	146.6556	2.22	2.36	2.86	3.28	5.20
	150	-19.1806	146.6602	2.22	2.37	2.87	3.30	5.20
	151	-19.1831	146.6648	2.23	2.38	2.87	3.30	5.30
	152	-19.1856	146.6693	2.23	2.39	2.90	3.30	5.40
	153	-19.1881	146.6739	2.23	2.39	2.88	3.29	5.30
	154	-19.1906	146.6785	2.23	2.40	2.90	3.33	5.40
Bushland_Beach	155	-19.1931	146.6831	2.24	2.40	2.90	3.32	5.30
	156	-19.1913	146.6903	2.22	2.36	2.85	3.24	5.10
	157	-19.1938	146.6949	2.23	2.36	2.85	3.26	5.10
	158	-19.1963	146.6994	2.22	2.37	2.85	3.26	5.00
Bohle_River	159	-19.1920	146.7021	2.21	2.33	2.80	3.17	4.80
	160	-19.1876	146.7047	2.21	2.33	2.79	3.14	4.74
	161	-19.1833	146.7074	2.20	2.32	2.75	3.11	4.74
	162	-19.1858	146.7119	2.20	2.31	2.73	3.07	4.66
	163	-19.1883	146.7165	2.22	2.36	2.82	3.20	4.94
	164	-19.1865	146.7237	2.20	2.32	2.74	3.08	4.64
	165	-19.1821	146.7264	2.19	2.31	2.72	3.05	4.62
	166	-19.1778	146.7290	2.18	2.29	2.68	3.00	4.52
	167	-19.1803	146.7336	2.18	2.29	2.66	2.99	4.50
	168	-19.1828	146.7382	2.21	2.33	2.78	3.15	4.80
	169	-19.1809	146.7454	2.19	2.30	2.68	3.02	4.50
Shelly_Beach	170	-19.1835	146.7500	2.21	2.33	2.76	3.15	4.80
	171	-19.1816	146.7572	2.18	2.30	2.67	3.01	4.60
	172	-19.1841	146.7618	2.18	2.30	2.73	3.06	4.80
Cape_Pallarenda	173	-19.1866	146.7664	2.18	2.30	2.74	3.05	4.80
	174	-19.1891	146.7709	2.17	2.29	2.74	3.06	4.80
	175	-19.1916	146.7755	2.19	2.31	2.79	3.18	5.00
Pallarenda	176	-19.1985	146.7774	2.22	2.35	2.88	3.27	5.20
	177	-19.2054	146.7794	2.24	2.39	2.98	3.36	5.60
	178	-19.2097	146.7767	2.25	2.41	3.03	3.44	5.80
	179	-19.2166	146.7787	2.26	2.42	3.07	3.49	5.90
	180	-19.2234	146.7806	2.27	2.44	3.11	3.53	5.90
	181	-19.2303	146.7826	2.27	2.45	3.11	3.60	6.00
	182	-19.2328	146.7871	2.27	2.44	3.09	3.58	5.90
Rowes_Bay	183	-19.2397	146.7891	2.28	2.46	3.11	3.60	5.90
	184	-19.2422	146.7937	2.28	2.45	3.09	3.56	5.80
	185	-19.2403	146.8009	2.26	2.42	2.98	3.45	5.50
Kissing_Point	186	-19.2385	146.8081	2.25	2.41	2.98	3.43	5.50
	187	-19.2453	146.8100	2.26	2.42	2.98	3.46	5.50
North_Ward	188	-19.2478	146.8146	2.25	2.41	2.98	3.43	5.40
	189	-19.2504	146.8192	2.26	2.41	2.96	3.43	5.40
Breakwater_Casino	190	-19.2485	146.8264	2.24	2.39	2.90	3.30	5.14
Townsville_Harbour	191	-19.2510	146.8310	2.25	2.41	2.98	3.42	5.40
	192	-19.2535	146.8356	2.23	2.39	2.91	3.36	5.30
	193	-19.2517	146.8428	2.22	2.36	2.86	3.26	5.14
	194	-19.2542	146.8474	2.22	2.37	2.88	3.29	5.14
	195	-19.2611	146.8493	2.24	2.40	2.95	3.37	5.24
South_Townsville	196	-19.2629	146.8421	2.27	2.44	3.04	3.49	5.60
	197	-19.2672	146.8395	2.29	2.48	3.10	3.58	5.60
Ross_River	198	-19.2716	146.8368	2.31	2.51	3.18	3.68	5.70
	199	-19.2741	146.8414	2.31	2.51	3.15	3.63	5.70
	200	-19.2723	146.8486	2.27	2.44	3.01	3.48	5.30
	201	-19.2748	146.8532	2.26	2.44	3.02	3.46	5.40
	202	-19.2816	146.8551	2.29	2.48	3.08	3.60	5.50
	203	-19.2841	146.8597	2.28	2.47	3.06	3.50	5.40
	204	-19.2910	146.8617	2.30	2.49	3.10	3.61	5.50
	205	-19.2935	146.8663	2.29	2.48	3.11	3.60	5.34
	206	-19.2960	146.8708	2.29	2.47	3.12	3.53	5.34
	207	-19.2985	146.8754	2.29	2.47	3.11	3.55	5.25
	208	-19.3010	146.8800	2.29	2.48	3.09	3.51	5.30
	209	-19.3035	146.8846	2.29	2.47	3.08	3.53	5.30
	210	-19.3060	146.8892	2.30	2.47	3.08	3.54	5.40
	211	-19.3042	146.8964	2.28	2.45	3.05	3.46	5.30
	212	-19.3023	146.9036	2.26	2.43	2.99	3.41	5.20
	213	-19.3005	146.9108	2.25	2.41	2.95	3.37	5.10
	214	-19.2986	146.9181	2.25	2.41	2.93	3.35	5.00
	215	-19.3011	146.9226	2.25	2.42	2.95	3.38	5.10
	216	-19.2968	146.9253	2.24	2.40	2.91	3.30	5.00
	217	-19.2993	146.9299	2.25	2.40	2.90	3.30	5.00
	218	-19.2993	146.9299	2.25	2.40	2.90	3.30	5.00

Appendix L - Open Coast SatSim Results (without breaking wave setup)

Site	ID	Latitude (AGD 84)	Longitude (AGD 84)	Tide plus surge (excl wave setup) 50 yr	100 yr	500 yr	1000 yr	10,000 yr
	219	-19.2974	146.9371	2.24	2.38	2.87	3.26	4.90
	220	-19.2931	146.9397	2.23	2.37	2.85	3.24	4.90
	221	-19.2956	146.9443	2.25	2.40	2.89	3.30	4.90
	222	-19.2981	146.9489	2.26	2.42	2.96	3.38	5.10
	223	-19.2963	146.9561	2.25	2.40	2.90	3.34	4.92
	224	-19.2919	146.9587	2.24	2.39	2.88	3.31	4.90
	225	-19.2876	146.9614	2.23	2.36	2.83	3.22	4.80
	226	-19.2832	146.9640	2.22	2.34	2.79	3.17	4.70
	227	-19.2814	146.9712	2.22	2.36	2.81	3.22	4.70
	228	-19.2770	146.9739	2.21	2.33	2.76	3.13	4.60
	229	-19.2726	146.9765	2.18	2.30	2.71	3.02	4.50
	230	-19.2683	146.9791	2.17	2.28	2.70	2.99	4.40
	231	-19.2639	146.9818	2.16	2.27	2.67	2.96	4.30
	232	-19.2621	146.9890	2.16	2.27	2.67	2.96	4.20
	233	-19.2577	146.9916	2.16	2.26	2.64	2.91	4.10
	234	-19.2534	146.9943	2.15	2.25	2.62	2.88	4.00
Launs_Beach	235	-19.2490	146.9969	2.15	2.25	2.61	2.86	4.00
	236	-19.2447	146.9995	2.12	2.22	2.56	2.81	3.86
	237	-19.2403	147.0022	2.12	2.21	2.55	2.80	3.84
	238	-19.2360	147.0048	2.12	2.21	2.53	2.77	3.80
Whiterock_Bay	239	-19.2316	147.0074	2.12	2.20	2.51	2.77	3.75
	240	-19.2273	147.0101	2.11	2.20	2.49	2.75	3.70
	241	-19.2229	147.0127	2.11	2.19	2.48	2.72	3.66
	242	-19.2186	147.0154	2.11	2.18	2.46	2.71	3.66
Long_Beach	243	-19.2142	147.0180	2.10	2.17	2.45	2.70	3.60
	244	-19.2074	147.0160	2.09	2.15	2.40	2.60	3.40
Red_Rock_Bay	245	-19.2005	147.0141	2.09	2.15	2.37	2.56	3.36
	246	-19.1936	147.0121	2.08	2.14	2.36	2.52	3.34
	247	-19.1868	147.0102	2.07	2.13	2.33	2.48	3.23
Cape_Cleveland	248	-19.1824	147.0128	2.04	2.11	2.32	2.47	3.23
	249	-19.1849	147.0174	2.06	2.13	2.36	2.53	3.40
	250	-19.1874	147.0220	2.06	2.14	2.39	2.59	3.60
	251	-19.1943	147.0239	2.08	2.15	2.43	2.64	3.80
	252	-19.2011	147.0259	2.05	2.13	2.40	2.62	3.70
	253	-19.2037	147.0305	2.05	2.13	2.40	2.61	3.70
	254	-19.2062	147.0351	2.05	2.13	2.40	2.62	3.70
	255	-19.2087	147.0396	2.06	2.14	2.43	2.66	3.74
	256	-19.2155	147.0416	2.04	2.12	2.41	2.64	3.73
	257	-19.2224	147.0435	2.05	2.14	2.47	2.77	4.00
	258	-19.2292	147.0455	2.05	2.15	2.48	2.80	4.04
Paradise_Bay	259	-19.2336	147.0428	2.06	2.16	2.52	2.82	4.20
	260	-19.2404	147.0448	2.05	2.15	2.49	2.82	4.04
	261	-19.2429	147.0494	2.04	2.14	2.47	2.79	4.10
	262	-19.2454	147.0540	2.04	2.14	2.47	2.76	4.10
	263	-19.2523	147.0559	2.03	2.12	2.45	2.71	3.90
	264	-19.2548	147.0605	2.03	2.13	2.48	2.82	4.10
	265	-19.2616	147.0625	2.04	2.15	2.55	2.92	4.20
	266	-19.2660	147.0598	2.04	2.15	2.56	2.94	4.20
Cape_Ferguson	267	-19.2729	147.0618	2.03	2.15	2.56	2.95	4.20
	268	-19.2797	147.0637	2.04	2.17	2.61	3.00	4.34
	269	-19.2816	147.0565	2.05	2.20	2.68	3.05	4.54
	270	-19.2834	147.0493	2.06	2.22	2.73	3.13	4.70
	271	-19.2878	147.0466	2.07	2.24	2.75	3.16	4.80
Chunda_Bay	272	-19.2946	147.0486	2.07	2.24	2.75	3.20	4.82
	273	-19.3015	147.0505	2.07	2.23	2.73	3.20	4.80
	274	-19.3083	147.0525	2.07	2.24	2.74	3.21	4.82
	275	-19.3152	147.0544	2.08	2.24	2.77	3.22	4.90
	276	-19.3220	147.0564	2.09	2.25	2.78	3.24	5.00
	277	-19.3245	147.0610	2.08	2.23	2.74	3.21	4.90
	278	-19.3314	147.0629	2.08	2.24	2.76	3.21	5.00
	279	-19.3339	147.0675	2.08	2.24	2.74	3.20	4.90
	280	-19.3408	147.0695	2.08	2.24	2.76	3.22	5.00
	281	-19.3476	147.0714	2.09	2.25	2.78	3.25	5.00
	282	-19.3501	147.0760	2.09	2.25	2.74	3.21	4.92
	283	-19.3526	147.0806	2.08	2.24	2.72	3.17	4.82
	284	-19.3595	147.0826	2.09	2.25	2.75	3.27	4.80
	285	-19.3620	147.0871	2.09	2.24	2.73	3.22	4.70
	286	-19.3645	147.0917	2.10	2.26	2.77	3.25	4.94
	287	-19.3713	147.0937	2.09	2.26	2.78	3.30	4.90
	288	-19.3738	147.0983	2.09	2.25	2.77	3.27	4.90
	289	-19.3763	147.1029	2.09	2.25	2.77	3.24	4.80
	290	-19.3788	147.1074	2.10	2.27	2.77	3.28	4.90
	291	-19.3813	147.1120	2.10	2.25	2.77	3.24	4.90
	292	-19.3882	147.1140	2.11	2.28	2.82	3.32	5.00
Cungulla	293	-19.3950	147.1159	2.13	2.30	2.90	3.36	4.90
	294	-19.4019	147.1179	2.14	2.32	2.93	3.41	5.20

Appendix L - Open Coast SatSim Results (without breaking wave setup)

Site	ID	Latitude (AGD 84)	Longitude (AGD 84)	Tide plus surge (excl wave setup) 50 yr	100 yr	500 yr	1000 yr	10,000 yr
	295	-19.4087	147.1198	2.16	2.34	2.98	3.47	5.34
	296	-19.4112	147.1244	2.15	2.34	2.95	3.48	5.35
Haughton_River	297	-19.4181	147.1264	2.17	2.36	2.99	3.56	5.60
	298	-19.4206	147.1310	2.17	2.36	2.99	3.58	5.52
	299	-19.4162	147.1336	2.15	2.33	2.93	3.52	5.35
	300	-19.4119	147.1363	2.14	2.31	2.87	3.42	5.10
	301	-19.4050	147.1343	2.12	2.29	2.84	3.32	5.00
	302	-19.4032	147.1415	2.11	2.27	2.79	3.27	4.80
	303	-19.4057	147.1461	2.11	2.26	2.77	3.24	4.80
	304	-19.4038	147.1533	2.09	2.25	2.77	3.23	4.70
	305	-19.4063	147.1579	2.10	2.26	2.78	3.25	4.80
	306	-19.4045	147.1651	2.09	2.23	2.75	3.22	4.64
	307	-19.4113	147.1671	2.11	2.27	2.81	3.30	4.84
	308	-19.4095	147.1743	2.10	2.24	2.75	3.22	4.80
	309	-19.4076	147.1816	2.08	2.22	2.70	3.18	4.70
	310	-19.4101	147.1861	2.08	2.23	2.70	3.18	4.80
	311	-19.4126	147.1907	2.09	2.23	2.73	3.20	4.80
	312	-19.4151	147.1953	2.10	2.24	2.74	3.21	4.80
	313	-19.4176	147.1999	2.11	2.25	2.78	3.25	4.90
	314	-19.4157	147.2071	2.10	2.23	2.72	3.19	4.80
	315	-19.4182	147.2117	2.10	2.23	2.75	3.23	4.64
	316	-19.4207	147.2163	2.10	2.25	2.78	3.25	4.74
	317	-19.4189	147.2235	2.09	2.22	2.73	3.21	4.55
	318	-19.4170	147.2308	2.08	2.21	2.71	3.18	4.54
Florence_Bay	319	-19.1167	146.8820	2.07	2.15	2.44	2.71	3.70
	320	-19.1210	146.8793	2.08	2.17	2.48	2.77	3.94
	321	-19.1279	146.8813	2.09	2.17	2.50	2.78	4.00
Arthur_Bay	322	-19.1322	146.8786	2.10	2.19	2.53	2.81	4.20
	323	-19.1366	146.8760	2.10	2.19	2.53	2.82	4.20
	324	-19.1409	146.8734	2.10	2.20	2.55	2.86	4.30
	325	-19.1478	146.8753	2.10	2.20	2.55	2.86	4.30
Arcadia_(Alma_Bay)	326	-19.1521	146.8727	2.10	2.20	2.56	2.86	4.40
	327	-19.1565	146.8700	2.11	2.21	2.59	2.89	4.40
	328	-19.1583	146.8628	2.11	2.22	2.63	2.93	4.60
	329	-19.1602	146.8556	2.12	2.23	2.65	2.97	4.70
Nelly_Bay	330	-19.1645	146.8530	2.12	2.23	2.66	2.99	4.70
	331	-19.1689	146.8503	2.12	2.24	2.67	3.00	4.80
	332	-19.1732	146.8477	2.12	2.24	2.69	3.00	4.80
	333	-19.1801	146.8496	2.13	2.25	2.68	2.99	4.80
	334	-19.1844	146.8470	2.13	2.25	2.70	2.99	4.84
Picnic_Bay	335	-19.1819	146.8424	2.13	2.26	2.72	3.01	4.90
	336	-19.1838	146.8352	2.13	2.26	2.73	3.04	4.94
	337	-19.1813	146.8306	2.13	2.26	2.73	3.04	4.84
	338	-19.1788	146.8260	2.09	2.19	2.55	2.83	4.30
	339	-19.1762	146.8215	2.11	2.21	2.60	2.87	4.30
	340	-19.1737	146.8169	2.10	2.20	2.59	2.86	4.30
	341	-19.1712	146.8123	2.09	2.19	2.58	2.83	4.30
	342	-19.1687	146.8077	2.09	2.18	2.55	2.81	4.30
	343	-19.1662	146.8031	2.09	2.18	2.55	2.82	4.30
	344	-19.1594	146.8012	2.08	2.16	2.50	2.74	4.10
	345	-19.1569	146.7966	2.08	2.16	2.51	2.76	4.12
Bolger_Bay	346	-19.1500	146.7947	2.07	2.15	2.49	2.71	3.90
	347	-19.1475	146.7901	2.08	2.15	2.50	2.71	4.00
	348	-19.1450	146.7855	2.08	2.16	2.50	2.72	4.02
	349	-19.1381	146.7836	2.07	2.15	2.48	2.70	3.95
	350	-19.1356	146.7790	2.07	2.16	2.48	2.71	4.00
West_Point	351	-19.1287	146.7771	2.07	2.15	2.46	2.70	3.95
	352	-19.1244	146.7797	2.08	2.16	2.49	2.75	4.10
	353	-19.1226	146.7869	2.08	2.16	2.48	2.71	4.00
	354	-19.1182	146.7896	2.06	2.14	2.44	2.63	3.80
	355	-19.1139	146.7922	2.07	2.15	2.46	2.70	4.00
Huntingfield_Bay	356	-19.1164	146.7968	2.07	2.15	2.46	2.70	3.95
	357	-19.1145	146.8040	2.08	2.16	2.50	2.73	4.00
	358	-19.1170	146.8086	2.07	2.15	2.48	2.69	3.95
Wilson_Bay	359	-19.1152	146.8158	2.07	2.15	2.46	2.65	3.90
	360	-19.1177	146.8204	2.08	2.16	2.48	2.71	4.00
	361	-19.1133	146.8230	2.07	2.14	2.44	2.63	3.80
	362	-19.1090	146.8256	2.06	2.13	2.42	2.61	3.74
	363	-19.1046	146.8283	2.06	2.13	2.41	2.58	3.70
	364	-19.1072	146.8329	2.06	2.13	2.42	2.62	3.70
	365	-19.1097	146.8374	2.08	2.16	2.46	2.71	3.85
	366	-19.1122	146.8420	2.07	2.15	2.45	2.71	3.84
	367	-19.1147	146.8466	2.07	2.15	2.45	2.67	3.84
	368	-19.1172	146.8512	2.07	2.15	2.45	2.66	3.84
Horseshoe_Bay	369	-19.1153	146.8584	2.06	2.14	2.43	2.62	3.74
	370	-19.1110	146.8610	2.06	2.13	2.39	2.60	3.64

Appendix L - Open Coast SatSim Results (without breaking wave setup)

Site	ID	Latitude (AGD 84)	Longitude (AGD 84)	Tide plus surge (excl wave setup) 50 yr	100 yr	500 yr	1000 yr	10,000 yr
	371	-19.1066	146.8637	2.06	2.13	2.39	2.60	3.60
	372	-19.1023	146.8663	2.06	2.13	2.41	2.61	3.60
	373	-19.1048	146.8709	2.06	2.13	2.38	2.58	3.60
Radical_Bay	374	-19.1117	146.8728	2.06	2.13	2.39	2.59	3.60
	375	-19.1142	146.8774	2.05	2.12	2.36	2.54	3.54
Rattlesnake_Island	376	-19.0384	146.6124	2.11	2.22	2.72	3.02	4.80
Havannah_Island	377	-18.8474	146.5395	2.12	2.22	2.70	3.02	4.60

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