STORM TIDE HAZARD STUDY
MORETON BAY REGIONAL COUNCIL
(INCORPORATING CABOOLTURE, PINE RIVERS & REDCLIFFE COUNCILS)

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1. INTRODUCTION

Caboolture Shire Council, acting on behalf of Caboolture Shire Council, Redcliffe City Council and Pine Rivers Shire Council, together with Redland Shire Council (on behalf of Redland Shire Council and Logan City Council), invited tenders from suitable parties to provide consultancy services for a Storm Tide Hazard Study within the south-east Queensland region. The purpose of this study was to enable a standardised best practice, regional approach to be established with regard to storm tide modelling, mapping, risk assessments and mitigation strategies. Cardno Lawson Treloar have been commissioned to undertake that work. Figure 1.1 shows the study area and delineates each Council shoreline region.

Caboolture Shire, Redcliffe City and Pine Rivers Shire Councils amalgamated in March 2008 to form the Moreton Bay Region Council. This report presents study results for all three of the original Council areas.

A parallel report (LJ8824/R2504/02) provides similar information for Redland Shire and Logan City Councils.

The intention of the State Coastal Plan policy 2.2.4 is that coastal areas vulnerable to inundation by storm tide should be identified through a comprehensive and detailed natural hazard assessment study. The purpose of this study is to identify the ‘natural hazard management areas (storm tide)’ in the specified council areas so that a consistent unified approach is developed. The recommended approach for determination of the storm tide is set down in Appendix 2 of Environmental Protection Agency (EPA) document 061218.

The ‘natural hazard management area (storm tide)’ is the area of the coast inundated by the Defined Storm Tide Event and the purpose of this study is to provide this information to the participating Councils.

The EPA Guideline is not specific about the level of risk that should be associated with the management area - it is appropriate to adopt different levels of risk for different activities within an overall management area. Hence each Council is somewhat free to make these policy decisions. However, commonly, they may be:-

- 100-years average recurrence interval (ARI) storm tide for general residential areas
- 1,000-years ARI for evacuation routes and hospitals and similar high level public infra-structure

For the purposes of planning, storm tide in Queensland is defined to be the instantaneous sum of astronomical tide plus storm surge and wave set-up determined assuming a natural beach shoreline. However, there are occasions when it is useful to have data about astronomical tide plus storm surge, together with appropriate wave parameters, so that wave set-up or wave run-up can be calculated for different shoreline types. This is needed because wave set-up and run-up depend upon back-beach form. Both sets of results are presented.

Normal conventions are used in this report, namely:-

- waves and winds – coming from
- currents – flowing towards.

Unless specified otherwise, all levels in this report are to Australian Height Datum (AHD).

The progress of the study has been managed and monitored by the Study Advisory Group (SAG) comprising the Environmental Protection Agency, Bureau of Meteorology and the respective Councils under Project No. Q/GMO/02.

This report describes the data and data sources, study approach, model systems applied and outcomes of this investigation.

2. SCOPE OF WORK

2.1 General

Full details of the work to be undertaken for this study were set out in Part 2 of the Study Brief. The studies are required for Moreton Regional Council (Caboolture Shire, Redcliffe City and Pine Rivers Shire), and also by Redland Shire and Logan City Councils; the last two being reported separately.

The purpose of conducting the storm tide hazard studies was to identify, understand and quantify the risks associated with the possibility of extreme storm tides occurring in the respective Local Government Areas (LGA) for use in long-term town-planning and for emergency response needs. A risk assessment (e.g. DES 2005) of the potential impacts of such events that considers environmental, economic and social perspectives has been undertaken and reported separately. That investigation considered emergency response issues and made recommendations for optimizing the effectiveness of warnings. Recommendations were provided also for a Defined Storm Tide Event (DSTE, as per EPA 2006) applicable to each LGA that participated in this project consistent with the determined level of impact. In fact the functional DSTE has been based on the 100-years and the 1,000-years ARI so that appropriate risk levels can be adopted for a range of development types.

Due to the proximity of each of the LGA's and their common exposure to Moreton Bay and associated islands, a combined investigation was adopted in order to maximize the technical benefits to Councils.

"Storm tide" for this study is defined as the combined effects of astronomical tide, meteorological tide (storm surge) together with and without localized wave-induced effects (breaking wave set-up) on the total still-water ocean level at the shoreline. As part of the hazard study, associated near shore wave parameters were also provided and wave run-up heights determined in specifically nominated areas for selected shoreline edge types. Coastal morphological modifications, rainfall, surface runoff, up-river propagation and river flooding effects were not included in the scope of work. Appendix A provides a glossary of terms.

For quantitative predictions of storm tide levels within the South-East Queensland region, the analysis process was based on recommendations from SEQDMAG (2007); generally:-

- Establishment of the representative storm climatology for the region south of northern Fraser Island;
- Development of numerical models (wind and pressure, hydrodynamic and wave) capable of representing the physical impacts of the storms on coastal water levels;
- Calibration and/or verification of the numerical models, drawing on reliable time series of data relevant to the study, including long term wind, wave, cyclone track and tidal records or Council records;
- Modelling of the storm climatology and its associated storm tide impacts to provide a statistical database of sufficient resolution and range for reliable estimation of low probability events;
- Sensitivity testing of the model assumptions across the range of uncertainty, including the effects of potential enhanced-Greenhouse climate change;
- Comprehensive reporting, supply of electronic mapping datasets – see Cardno Lawson Treloar (2008);
- Reporting detail sufficient to enable a third party technical review.

2.2 Outline Study Approach

2.2.1 Regional Storm Climatology

The region is known to be affected by a wide range of large scale storm systems. Principal amongst these in terms of potential storm tide impact are tropical cyclones. In addition, a number of sub-tropical, extra-tropical and non-cyclonic storm systems can have more frequent, although typically lower impacts, on coastal water levels. Larger scale and remote synoptic systems may also generate persistent, but low amplitude long wave effects (for example, coastally trapped shelf waves). Appendix B provides a detailed description of the SE Queensland storm climatology prepared by SEA (2007). For this study, all non-cyclonic events have been generally classified as east coast low (ECL) events.

Discussions were held with the Bureau of Meteorology (BoM) during the study and they assisted by providing advice on wind field characteristics of historical events such as cyclone Dinah, which is known to have caused local flooding at Sandgate, (which is not within the study area), for example. Improved wind fields for cyclones Dinah and Pam were provided for the study by BoM – based on meteorological observations rather than the Holland (1980) wind field model used generally within this study.

The study has addressed the potential effects of enhanced Greenhouse climate change on mean sea level (MSL) and various storm types – essentially of cyclones and ECLs.

Generally, the numerical results were based on tropical cyclone and ECL storms considered as two separate meteorological populations.

2.2.2 Establishment of Numerical Models

Cardno Lawson Treloar established the numerical storm tide and wave models necessary to enable adequate representation of the various storm influences on the ocean water levels in the region. Tropical cyclone events were explicitly modelled by application of an atmospheric forcing model to an ocean model – Holland wind field model developed for tropical Australia by the Bureau of Meteorology and the Delft3D hydrodynamic and SWAN (wave) models. Following model calibration, sets of basic storm surge plus astronomical tide and wave simulations were undertaken to provide basic data for a Monte Carlo analysis.

Non-cyclonic events were investigated using suitable long term predicted tides and tidal residual data for the area – Brisbane Bar. That data was used to infer and extrapolate the statistical storm surge response of such systems using a range of wind simulations (different speeds and directions) to describe the spatial variability of ECL impacts (surge and waves) relative to Brisbane Bar. An auto-covariance approach (Pugh and Vassie, 1980) was used to develop combined tide and surge water levels up to 10,000-years ARI at the nominated study locations. Wave parameters and wave set-up/run-up were investigated using a set of historical east coast lows and recorded wave data.

(a) Atmospheric Forcing

The minimum requirement for modelling of atmospheric forcing of large scale severe tropical storm (cyclone) systems was to be:-

- A prescribed wind and pressure field at gradient height characterized by a pressure deficit relative to the environment, a scale radius and a forward motion vector;
- A boundary layer gradient wind speed reduction to +10 m;
- Radially variable frictional inflow at the surface;

- A first-order forward speed wind field asymmetry;
- Calibration and verification of the atmospheric model against a minimum of three near-coastal official Bureau of Meteorology weather recording stations (e.g. Brisbane Airport, Cape Moreton, Coolangatta Airport, Maroochydore (Sunshine Coast) Airport or Sandy Cape) for significant historical storm systems (to be agreed with the SAG) before commencement.

The Holland wind model applied to this investigation fulfilled these requirements and was calibrated using data available from those sites. Note that wind data was not available from all sites for each calibration event and that data from every site was not of equal quality for model calibration. Wind data was available also for some events from navigation beacons within Moreton Bay.

(b) Hydrodynamic Modelling of Storm Surge and Astronomical Tide

The hydrodynamic modelling of the ocean response to storm systems undertaken by Cardno Lawson Treloar included:-

- A generalized long-wave model (that is, ignoring vertical accelerations);
- Two dimensional depth-integrated formulation;
- Coriolis acceleration and advection of momentum formulations;
- Non-linear bed friction and surface stress formulations;
- Domains encompassing the expected scale of significant atmospheric forcing - confirmed by model calibration;
- Domains that resolved coastal features of significance to storm tide propagation – typical nearshore grid sizes of 50m:
- Along-shore resolution was no greater than 560m (0.3' arc) - generally much smaller, about 100m, near the shorelines;
- Over-land resolution for tidally-coupled modelling was no greater than 56m (0.03' arc);
- A variable grid-size curvilinear model domain was developed;
- Wetting and drying capability;
- Calibration and verification of a typical spring-neap cycle against the astronomical tide at the Brisbane Bar tide gauge and comparison at other available gauging stations near the LGA shorelines;
- Calibration and/or verification against significant historical cyclones (Dinah and Pam) at Brisbane Bar. Hence both tidal and storm tide calibrations were undertaken.

The adopted model system (Delft3D) plus the linked SWAN wave modeling system more than fulfilled these requirements, see Section 3. It is based on a continually variable spatial domain (curvilinear grid system).

In addition, Cardno Lawson Treloar undertook testing and analysis of combined tide and meteorological effects to determine a suitable relationship, assumption or justification in regard to such interactions. The purpose of this task was to investigate the non-linear relationship between wind set-up and water depth. Regional (non-shoreline) wave set-up was found to be important as well and to be dependent on water level and flood-ebb tidal stage.

All Tasman Sea to Moreton Bay entrances were included in the model set-up - Gold Coast Seaway, Jumpinpin and the channel between Moreton and North Stradbroke Islands.

(c) Hydrodynamic Modelling of Sea Surface Wave Effects

The minimum requirements for modelling the surface (short) wave response of the sea to storm systems were:-

- A shallow water 2nd generation spectral model for open sea conditions and a 3rd generation spectral wave model within Moreton Bay;
- Domains encompassed the expected scale of significant atmospheric input - generally the same extent as the Delft3D storm tide model;
- The model grid layout resolved coastal features of significance to storm tide related wave effects - based on available bathymetric charts;
- Spatial resolution was the same as the hydrodynamic model resolution, generally, but note that both sea and swell modelling were undertaken;
- A curvilinear grid system was adopted;
- Calibration and/or verification against a significant historical storm system (cyclone) at one of the EPA wave recording stations offshore South East Queensland (Brisbane, Mooloolaba or Tweed River) and also at the Moreton Bay site was undertaken.
- Analytical breaking wave set-up calculations at all shoreline locations and analytical run-up calculations at selected nominated locations – based on 2D wave and storm tide modelling was undertaken to ensure 2D wave set-up was described, rather than the more common 1D approach. Moreover, wave run-up depends on edge treatment and a range of run-up calculations were undertaken, based, for example, on a natural beach and a rock revetment.

In addition, waves which propagate into Moreton Bay break on the sandy shoals at its northern end. This wave breaking causes a wave set-up that may raise the level of Moreton Bay - a regional wave set-up. This process is similar to the wave set-up that occurs as a result of nearshore wave breaking. The flood and ebb tide currents and water levels affect this wave breaking and consequent wave set-up and a model based investigation was required to describe these variations.

Although this phenomenon had been estimated empirically as part of storm tide estimation for Brisbane Airport expansion, Blain, Bremner and Williams (1979), it has not been included in previous numerical storm tide studies - its importance is location specific.

The wave model applied to this study was SWAN and it is described in Section 3.

2.2.3 Establishment of Statistical Models

Cardno Lawson Treloar developed statistical models enabling probabilistic quantification of the storm tide hazard, expressed in terms of the Average Recurrence Interval (ARI), and based on the maximum likelihood method of fitting to a range of extremal distributions. The minimum requirement was to define storm tide impacts for the:-

- 50, 100, 200, 500, 1000 and 10,000-years ARI

The 10,000-years ARI was taken to be the *theoretical maximum storm tide level* as per NSTMM (2002).

(a) Statistical Modelling of the Storm Climatology

An outline of the statistical modelling adopted to describe the cyclone climatology follows:-

- A statistical model of the occurrence of the parameters of the identified cyclone climatology consistent with the numerical modelling capability, that is, the cyclone track parameters (track, forward speed, central pressure), was adopted - non-cyclonic storms were treated separately;
- A common radius to maximum winds of 40km was adopted. This leads to slightly conservative storm tide levels;

- Monte-Carlo based sampling of the range of identified storm parameters was adopted;
- Consideration of attenuation of tropical cyclones at landfall, that is, reduction of off-land wind speed and central pressure was included;
- Consideration of the Maximum Potential Intensity of storms - depends on latitude and sea surface temperature – discussed with Bureau of Meteorology and agreed to be 930hPa because cyclones originating from more northerly and warmer sea areas may maintain their higher central pressure as they propagate southward (pers. comm. Callaghan - Treloar/Taylor) was adopted
- Consideration of enhanced-Greenhouse climate change – MSL rise and increased cyclogenesis was included;
- Verification of the statistical model performance in terms of regional wind speeds was undertaken;
- A sensitivity study of the principal parameters and assumptions was included.

(b) Statistical Modelling of the Storm Tide Hazard

An outline description of the statistical modelling of the storm tide hazard follows:-

- Interpolation of results from systematic storm tide modelling (tide, surge, wave parameters) of a set of discrete storm systems that cover the expected range of parameters, for example, central pressure, was undertaken;
- Linear combination of tide, storm surge elevation and shoreline wave set-up elevation time series, together with a more steady state regional wave set-up was undertaken;
- Consideration of non-linear storm tide modifications, including surge-tide interactions and depth-sensitive wave and surge effects was included;
- Determination of the frequency of exceedance of selected ARI water levels (tide + surge + regional wave set-up and associated nearshore wave parameters, and tide + surge + regional and shoreline wave set-up) was included;
- Determination of duration of exceedance (persistence) statistics - duration of water level and potential inundation was investigated – see Cardno Lawson Treloar (2008);
- Verification of the statistical model performance in terms of any available long term water levels – considering cyclonic and non-cyclonic conditions was included;
- Joint probability assessment of tide + storm surge water levels and incident wave heights and periods is included in the outcomes;
- A sensitivity study of the principal parameters and assumptions leading to recommendations for freeboard allowances for planning purposes – depending upon the extent of wave run-up effect. This entailed assessing wave run-up at selected output locations for a natural sand beach and a 1V:2H rock revetment

2.2.4 Risk Assessment

Cardno Lawson Treloar (2008b) have also undertaken a risk assessment (e.g. DES 2005) of the storm tide hazard for each of the LGA areas with respect to the identified ARI storm tide levels to identify, analyze and evaluate the storm tide risk and examine treatment options. These analyses included:-

- Encroachment;
- Depth of inundation and depth × velocity – equates to hazard level;
- Duration of inundation;
- Wave penetration in nominated high resolution areas;
- Population at Risk (PAR) analysis based on LGA-supplied data;
- Assessment of infrastructure impacts;
- [Optional] Estimated economic damage, including Annual Average Damage.

The risk assessment is reported separately in Cardno Lawson Treloar (2008b).

3. MODEL SYSTEMS

3.1 General

Tide and storm surge investigations undertaken throughout the study area required application of high level model systems capable of simulating a range of processes – wind and pressure fields, tidal forcing, hydrodynamic and wave processes.

3.1.1 Hydrodynamic Numerical Scheme

Delft3D is comprised of several modules that provide the facility to undertake a range of hydrodynamic process studies. All studies generally begin with the Delft3D-FLOW module. From Delft3D-FLOW, details such as velocities and water levels can be provided as inputs to the other modules. The wave module works interactively with the FLOW module through a common communications file. In the case of wave modelling this ensures physically realistic wave set-up in a 2D plan layout. This is especially important in complex waterways where the shoreline is not 'straight' and also where regional wave set-up, for example, from Spitfire Banks into Moreton Bay, occurs.

The Delft3D FLOW module is based on the robust numerical finite-difference scheme developed by G. S. Stelling of the Delft Technical University in The Netherlands. Since its inception, the Stelling Scheme has undergone considerable development and review by Stelling and others.

The Delft3D Stelling Scheme arranges modelled variables on a horizontal staggered Arakawa C-grid. The water level points (pressure points) are designated in the centre of a continuity cell and the velocity components are perpendicular to the grid cell faces. Finite difference staggered grids have several advantages including: -

- Boundary conditions can be implemented in the scheme in a rather simple way
- It is possible to use a smaller number of discrete state variables in comparison with discretisations on non-staggered grids to obtain the same accuracy
- Staggered grids minimise spatial oscillations in the water levels.

Delft3D can be operated in 2D (vertically averaged) or 3D mode. In 3D mode, the model uses the σ-coordinate system first introduced by N Phillips in 1957 for atmospheric models. The σ-coordinate system is a variable layer-thickness modelling system, meaning that over the entire computational area, irrespective of the local water depth, the number of layers is constant. As a result, a smooth representation of the bathymetry is obtained. Also, as opposed to fixed vertical grid size 3D models, the full definition of the 3D layering system is maintained into the shallow waters and until the computational point is dried. 2D modelling was adopted for this investigation because it has been found in previous storm tide investigations that there is no significant difference in water levels computed by 2D and 3D models.

Horizontal solution is undertaken using the Alternating Direction Implicit (ADI) method of Leendertse for shallow water equations. In the vertical direction (in 3D mode) a fully implicit time integration method is also applied.

3.1.2 Wetting and Drying of Intertidal Flats

Many nearshore areas include shallow intertidal areas; consequently Delft3D includes a robust and efficient wetting and drying algorithm for handling this phenomenon.

3.1.3 Conservation of Mass

Problems with conservation of mass, such as a 'leaking mesh', do not occur within the Delft3D system.

However, whilst the Delft3D scheme is unconditionally stable, inexperienced use of Delft3D, as with most modelling packages, can result in potential mass imbalances.

Potential causes of mass imbalance and other inaccuracies include: -

- Inappropriately large setting of the wet/dry algorithm and unrefined inter-tidal grid definition
- Inappropriate bathymetric and boundary definition causing steep gradients
- Inappropriate time-step selection (that is, lack of observation of the scheme's allowable Courant Number condition) for simulation

4. DATA

A range of data items were required to set up the numerical storm tide and wave models and then calibrate/verify them, followed by a series of hindcast simulations of historical cyclones.

4.1 Bathymetry

A range of bathymetric and survey data was utilised in this project, including:-

- Land and water survey provided by the Councils,
- Maritime Safety Queensland (MSQ) charts
  - MB1 (Moreton Bay),
  - MB8 (Redland Bay to Cabbage Tree Creek)
  - MB7 (Couran to Redland Bay) and
  - MB6 (Nerang River to Couran),
- Australian Hydrographic Charts
  - AUS 365,
  - AUS 814, and
- Geoscience Australia Australian bathymetric and topographic grid (Petkovic and Buchanan, 2002) - beyond 3,000m depth.

A detailed Digital Terrain Model (DTM) of the model region was developed as indicated in Figure 1.1. The DTM incorporates all of the datasets listed above. The following precedence (highest precedence first) was adopted when developing the DTM:-

1. Data supplied by Councils
2. MSQ charts
3. AUS charts
4. Geoscience Australia data.

The datum of the DTM is Australian Height Datum (AHD). At Brisbane Bar, Australian Height Datum is 1.243m above chart datum.

4.2 Water Level

Tidal data has been obtained from three sources. Tidal constants have been obtained from Australian National Tide Tables – 2007 (Australian Hydrographic Service, 2006). Tidal predictions were undertaken using the so-called Canadian tidal prediction package (Foreman, 1977) and also internally within the Delft3D model system.

Long-term water level (predicted tide and recorded water levels) data obtained from MSQ for Brisbane Bar, Mooloolaba and Gold Coast have also been utilised. The data set at Brisbane Bar covers the period from 1967 to 2008. For selected events, water level data from a variety of gauges around Moreton Bay were also obtained from MSQ.

Offshore tidal data in the form of harmonic constants were required to prepare time series of tidal water levels along the open boundaries of the storm tide model. Tidal constant data for offshore sites has been obtained from the Danish National Space Centre which has a 0.5 degree resolution global tidal model based on Le Provost (1998) for five tidal constants – M_2, S_2, K_1, O_1 and N_2. These are the principal tidal components and generally provide predicted tidal levels in close agreement with water levels predicted at Brisbane Bar, for example, using the 15 constants presented in Australian National Tide Tables (2007), but with high water levels being about 0.1m lower. Note, in the design water level calculations the full range of constants for Brisbane Bar have been used to calculate the predicted tide.

4.3 Cyclone and Wind Data

Cyclone data was obtained from the Bureau of Meteorology cyclone track database (BoM, 2003). Cyclone tracks which passed through the region 151^{o}E to 160^{o}E and 25.5^{o}S to 28.5^{o}S since 1959 were identified. Although track data is available for cyclones occurring before 1959, that data is less reliable. The advent of satellite imagery and over-the-horizon radar has improved cyclone identification and significantly improved the quality of the track data recorded since then. A total of 29 events have been identified in the analysis region. Of these, 23 have been specified as coast-parallel events and 6 as coast-crossing (direction of motion east to west). The general properties of each cyclone event, for example, central pressure, forward velocity and distance from the coast, have been identified. Due to the small cyclone dataset, the analysis window has not been refined into small sections.

The probability distributions obtained from frequency analyses of these data were used in the Monte Carlo modelling phase, applying them in the form of a histogram rather than fitted curves. Neither the coast-parallel nor the coast-crossing populations is defined particularly well because of their small populations.

Offshore tracking cyclones (land to sea) have been omitted from the cyclone statistics due to the extremely small sample size.

Historical synoptic charts have been obtained from the Bureau of Meteorology for the following large-scale cyclones or tropical low pressure storms:-

- Tropical Cyclone Pam,
- Tropical Cyclone David,
- Tropical Cyclone Roger, and
- March 2004 tropical low.

These charts have been used to reconstruct wind fields for at least two of these events. The purpose here was to investigate the storm surge and wave effects of these events, which fall outside of the normal parametric characterisation range of tropical cyclones and the basic simulations adopted for Monte Carlo simulations. That is, in the case of cyclone David, its physical extent within the Coral Sea was very large and uncommon and not described by the Holland wind field model parameters adopted to prepare the basic simulation input for the Monte Carlo process. Windfield analyses have involved digitising the isobars and calculating the geostrophic and 10m above MSL wind speeds and directions using an algorithm provided in the MIKE-21 modelling system (Danish Hydraulics). The purpose was to determine the spatial variation of the outcomes of these events and to confirm that those results did not exceed those determined via the more general Monte Carlo approach – see Section 9.1.

Wind data records have been obtained from the following four BoM sites that are on or close to the coast. Brisbane Airport and Cape Moreton are within the study area. Sunshine Coast Airport (Maroochydore) is the closest long-term wind data site to the north and Coolangatta Airport is the closest long-term site immediately south of the study area. The data record periods at each site are presented below:-

- Brisbane Airport – 1950 to 2007
- Cape Moreton – 1957 to 2007
- Maroochydore Airport – 1994 to 2007
- Coolangatta Airport – 1987 to 2007

Wind data was also obtained from the BoM for three 'over-water' sites within Moreton Bay. The data record periods at each site are presented below:-

- Spitfire Channel Beacon – 2002 to 2008
- Inner Reciprocal Marker – 2002 to 2008
- Banana Bank Beacon – 2002 to 2008

Since the mid-1990's, high resolution satellite derived wind data is available for offshore Queensland. For this study, over-water wind data has been obtained from NOAA. The blended wind dataset is available of a 25km grid, at intervals of six hours. A full description of the dataset is presented in Zhang *et al* (2006). The data is available online at http://www.ncdc.noaa.gov/oa/rsad/seawinds.html.

4.4 Wave Data

Historical wave data was provided by Queensland EPA for the following sites:-

- Brisbane Offshore WRB - 1976 to 2008,
- Gold Coast Offshore WRB - 1987 to 2008, and
- Moreton Bay WRB - 2000 to 2008.

This data was used to calibrate the SWAN wave model. WRB indicates a Waverider buoy wave recording instrument. Analyses of that data by EPA provided wave height and period parameters, commonly H_s and T_z.

5. MODEL SET UP

5.1 Delft3D Storm Tide Model Set Up

Amongst its characteristics, the Delft3D model includes spatially variable bed friction. Bed roughness was set to be a constant Chezy 60m$^{1/2}$/s on the general seabed during the tidal calibration phase. At the Gold Coast Seaway and Jumpinpin Bar Entrances to the Broadwater, a roughness coefficient of 30m$^{1/2}$/s was adopted.

The key model parameters were:-

- Time step – 0.5min,
- Minimum dx, dy – 50m,
- Maximum dx, dy – 2000m, and
- Wind drag coefficients:
  - 0.00100 @ 5m/s
  - 0.00354 @ 15m/s
  - 0.00354 @ 30m/s

The wind drag coefficients were selected during the storm tide calibration process – see Section 5.4.2.

Wind set-up develops across the nearshore area as the result of interfacial shear between the wind and sea surface and the consequent onshore currents. The Coriolis acceleration acting on northward flowing coastal currents may also cause a storm surge component. Set-up is inversely proportional to water depth, directly proportional to fetch and proportional to the square of wind speed - in a steady state system. There is also the inverse barometer component which generally can cause 1cm of sea level rise for each hPa drop in atmospheric pressure below normal for the season. This water level rise may not be achieved in fast moving cyclones, or may be exceeded if resonance occurs between cyclone forward speed and wave celerity. More details are described in Appendix C.

A large area model was established to ensure that physically realistic development of the cyclone-caused currents and set-up occurred over the whole study area. Furthermore, detailed nearshore model output was required at many locations over an extensive length of shoreline. Fine grid models are required in the nearshore areas to properly describe the wave and wind set-up gradients. A series of nested models was developed to overcome these conflicting requirements of large model extent and nearshore resolution, without compromising accuracy whilst still maintaining practical computational times. Using the Delft3D nested grid approach, a total of four separate, interlinked, grids were developed. The domains covered:-

1. Overall model area extending 120km offshore to depths beyond 3,000m
2. Moreton Bay north including the northern entrance and south channel entrances to Moreton Bay. Grid resolution was a minimum of 200m x 200m.
3. Moreton Bay south including the entrance between North and South Stradbroke Islands
4. Pumicestone Passage, which provided a detailed description of the Pumicestone Passage itself from Caloundra to northern Moreton Bay.

Figure 5.1 presents a plan view of the extent of the model grids.

5.2 Wind Model System – Holland Cyclone Model

For calibration, wind fields were computed from the available historical cyclone track data. This includes position, time and central pressure. The wind and pressure fields were prepared using the Holland wind model developed for the Bureau of Meteorology. The model includes first-order asymmetry based on the forward speed of the cyclone. This model is considered to provide the most realistic description of cyclonic wind fields for the Australian region. The empirical formula proposed in Holland (1980) has been used to determine the 'B' parameter value. Neutral pressure has been taken to be 1010hPa. The Holland model was also used for the idealized basic cyclone simulations undertaken for Monte Carlo system input.

5.3 Wave Model System

The first step in this investigation was to set up a large area offshore wind/wave model based on the third generation wind/wave modelling system, SWAN, developed by the Delft Technical University.

The SWAN model is incorporated as part of the Delft3D system. It includes natural bathymetry, offshore wave input (parametric or spectral), wind input, refraction, shoaling, bed friction, full frequency-direction wave propagation, white-capping, wave/current interaction and solutions to third order. Fine grids can be nested within coarser outer grids. The model system is considered to be one of the most reliable available. For this study it was operated outside of the Delft3D system to allow for time varying wind conditions.

The wind/wave model was established on a 5km computational grid with an origin at 35^{o}S; 150^{o}E. The model grid extended northward and eastward over 2,000km from the origin. The large model extent was required to enable realistic simulation of waves generated from gradient winds across the Tasman Sea, as well as describing the rotating wind fields of cyclones.

A time-step of 60 minutes was adopted to ensure physically realistic wave propagation and growth. The frequencies selected for spectral description ranged from 0.05Hz to 1.0Hz - a total of twenty-four frequencies being used. Directional resolution was based on thirty-six divisions of the compass. The Holland wind model, developed by the Australian Bureau of Meteorology for tropical regions of Australia, was used to calculate cyclone wind fields from the cyclone track parameters. The model extent and spatial resolution are considered more than adequate for the description of peak storm wave conditions arising from tropical cyclones and east coast lows with large gradient wind forcing.

In addition to this regional model, a finer grid (500m) SWAN wave model was established for the region between the Gold Coast and Mooloolaba. This grid included Moreton Bay and the Broadwater. Hindcast simulations were undertaken for selected events and the SWAN model was operated in non-stationary mode.

The SWAN model was also operated interactively with the storm tide model so that the spatial and temporal variation in water levels and current speeds due to wave forcing (radiation stresses) could be investigated. A time-series of wave conditions was specified along the Moreton Bay and Broadwater boundaries of the Delft3D-FLOW model for the cyclone hindcast simulations using the regional SWAN model described above.

5.4 Model Calibration

Model calibration was undertaken in stages, the first being tide only in order to separately address bed friction and schematisation, and subsequently to address wind friction in cyclone simulations. In a separate exercise, the Holland wind model was used to generate numerical wind fields for comparison with recorded wind data, mainly at Brisbane Airport and Cape Moreton, though the latter site is high above sea level and possibly affected by topographic features.

5.4.1 Tide Calibration

The Delft3D model has been calibrated using predicted tides to ensure that the model geometry and bed friction provide a suitable hydrodynamic representation of the study area. Deepwater tidal constants from a global tide model have been specified at selected locations along the offshore model boundary. Tide conditions along the northern and southern inshore boundaries were developed from tidal constants from Waddy Point and Point Danger - Australian Hydrographical Service, 2007. Along all boundaries the five principal tidal constants – M_2, S_2, K_1, O_1 and N_2 have been specified. The lack of reliable offshore constants beyond these five is the principal reason for specifying only five constants. In the determination of design water levels within the study area, up to 15 tidal constants were utilised to generate the predicted tide at specified sites within the study area. The tidal calibration simulation covered a 28-days period plus a 3-days warm-up period. The simulation period was selected to be from 1 to 31 January 2007. Figure 5.2 presents a plan view showing the tide calibration sites.

Figures 5.3 to 5.5 present time-series water level plots at the calibration locations over a 14-days spring-neap tidal period extracted from the simulation. In all plots, the Delft3D result is shown by solid black lines and the predicted tide (five constants) is presented as a dashed red line.

Figure 5.3 presents water level time series at Mooloolaba and Point Danger, open coast sites to the north and south of the study area, respectively. The model calibration is generally good, with modelled water levels within 0.1m of predicted water levels.

Figure 5.4 presents water level time-series at a point near the northern entrance to Moreton Bay (BnM2), near the entrance to Pumicestone Passage (Bribie Island) and at Brisbane Bar. The model calibration is generally good with modelled water levels generally within 0.1m of predicted water levels.

Figure 5.5 presents water level time-series at a point near the entrance to the Gold Coast Seaway and a point inside the Broadwater at Runaway Bay. The model calibration at the Gold Coast Seaway is generally good with modelled water levels generally within 0.1m of predicted water levels. At Runaway Bay, the Delft3D model slightly overestimates the predicted tide near high water.

Table 5.1 quantifies the tidal calibration in terms of the mean difference between the predicted and modelled tides at all sites. The maximum and minimum residual for each site is also presented in Table 5.1.

Table 5.1: Water Level Standard Deviations and Residuals – Delft3D Model (Five-Components Predicted Tide)

		Residual (m)	
Site	σ (m)	Min	Max
Mooloolaba	0.01	-0.07	0.06
Point Danger	0.01	-0.03	0.02
BnM2	0.02	-0.07	0.07
Bribie Island (Bongaree)	0.04	-0.15	0.10
Brisbane Bar	0.04	-0.15	0.10
Gold Coast Seaway	0.01	-0.06	0.03
Runaway Bay	0.03	-0.12	0.1

5.4.1.1 Pumicestone Passage

In order to accurately describe storm tide within Pumicestone Passage, it is important to accurately simulate the hydraulics of the system in the Delft3D model. In the model developed for this study, Pumicestone Passage has a dedicated curvilinear grid which provides high resolution through the sinuous channel.

No digital current data was available for this study, however, a report from the EPA which included spring tide currents sampled at two sites in southern Pumicestone Passage was available. During that study, the EPA deployed S4 current instruments for two days off Bellara (Site 1) and Banksia Beach (Site 2). Appendix D presents the reported currents from the EPA study. Figure 5.6 presents time series of spring currents (January 2007) from the Delft3D model at the two locations. The general character of the modelled currents agrees well with the measured currents, with Site 1 experiencing stronger currents during the flood tide, and Site 2 experiencing stronger currents during the ebb tide. This outcome provides confidence that the Delft3D model will accurately describe the propagation of storm tide through Pumicestone Passage.

5.4.2 Cyclone Events

The Delft3D model has been calibrated for modelled storm surge for two severe tropical cyclones that have affected the study area. Tropical Cyclone Daisy (February 1972) and Tropical Cyclone Dinah (January 1967) are two severe ‘close tracking’ cyclones that have affected Moreton Bay.

5.4.2.1 Tropical Cyclone Daisy

Tropical Cyclone Daisy passed close to the northern entrance to Moreton Bay in February 1972. A maximum total storm surge of 0.7m was recorded at Brisbane Bar. Because of the close proximity of the cyclone eye to the Bay, the observed residual water level at Brisbane Bar displays a pronounced peak water-level when the cyclone eye is to the north of Moreton Bay, followed by a negative surge when the cyclone eye passes to the east of Moreton and Stradbroke Islands.

Figure 5.7 presents the predicted, observed and measured water levels at Brisbane Bar for Cyclone Daisy. The modelling does not consider any gradient wind forcing or residual tide due to oceanic processes prior to the cyclone. A background residual water level of 0.15m was specified in the modelling, based on the observed residual tide prior to Cyclone Daisy passing near Moreton Bay. A radius to maximum winds of 50km was specified based on available satellite images and calibration of the recorded winds at Brisbane Airport.

Figure 5.8 presents time series of measured and modelled wind parameters (speed and direction) at Brisbane Airport and Cape Moreton. The modelled wind direction at both sites is good and the modelled wind speed at Brisbane Airport is also generally good. The model does not reproduce the lull in wind speed as the cyclone eye passes north-east of Brisbane Airport; however, the general modelled time series is good surrounding the peak wind conditions. It is difficult to calibrate winds at Cape Moreton because of the location of the anemometer on top of a cliff, 100m above the sea-level.

The focus of the calibration has been to describe the wind speeds at Brisbane Airport where the quality of the data and temporal resolution is better. The measured wind speeds provided by the Bureau of Meteorology are specified at 10m above ground elevation. The Cape Moreton anemometer is on top of a cliff 100m above sea-level. This site is known to over-estimate the 10m elevation wind speed, particularly for wind directions between north-east and south-east.

A range of wind friction parameters were investigated before the selection of the calibration values. Figure 5.9 presents a time series of modelled and measured storm surge at Brisbane Bar and Mooloolaba with only wind and predicted tidal forcing applied to the model. The peak modelled storm surge is reasonable at both sites. The time series at Mooloolaba indicates the modelled storm surge is approximately 3 to 4 hours earlier than the measured peak. It should be noted that the cyclone track adopted in this study is the specified track in the BoM database. Generally the accuracy of the cyclone eye data is at best +/- 10 to 20 km. Passing close to Moreton Bay means that track and windfield shape detail are particularly important to the modelled outcome.

The influence of regional wave set-up (as distinct from nearshore wave set-up) has long been recognised as an important component in the observed storm surge inside Moreton Bay. The momentum flux change caused by wave breaking along the whole northern entrance shoal has the potential to elevate water level inside Moreton Bay by a few decimetres when severe wave conditions persist for a sufficient length of time. The large-scale SWAN wave model has been used to estimate the time-series of wave heights near the northern entrance of Moreton Bay at a depth of 60mAHD. Figure 5.10 presents a time series of modelled wave conditions for Cyclone Daisy. These wave conditions were specified along the northern boundary of the Moreton Bay sub-model to investigate potential wave set-up.

Figure 5.11 presents time series of observed and modelled storm surge, the latter with and without wave set-up included, for Brisbane Bar. The inclusion of wave set-up improves the time series calibration of the model, although the modelled storm surge still has a drop near the peak. The good agreement between the measured and modelled storm surge leading up to the peak and the periodicity of the wave set-up component inside Moreton Bay indicates that the tide phase is important in determining the magnitude of wave set-up – albeit wave conditions varied over the same period. During the ebb tide, the height of wave set-up induced storm surge is highest as the wave momentum flux acts against the tidal forcing (ebb tide) to ‘hold’ water within Moreton Bay.

A correlation analysis has been undertaken for the Cyclone Daisy storm surge results. The correlation coefficient for the modelled and measured surge at Brisbane Bar is 0.87, which indicates very good agreement in the time series trends between the modelled and measured storm surge. The correlation coefficient between the predicted tide and wind set-up component is 0.11, which indicates there is a no identifiable relationship between wind set-up and tide.

The correlation coefficient between the predicted tide and the wave set-up component is -0.47, which indicates that there is a moderate inverse relationship between the two. That is, wave set-up will tend to increase on the ebb tide. The period of the wave set-up component is 12.5 to 13-hours, which is consistent with the semi-diurnal tide period, again indicating the relationship between wind and regional wave set-up and the astronomical tide. The net storm surge, that is, the combined pressure, wind set-up and wave set-up time series, has a harmonic character with a 12 to 13-hours period that is generally in phase with the measured storm surge time-series (R^2=0.87).

Overall the model system developed in this study has been able to simulate storm surge during Cyclone Daisy well. Importantly, the modelling approach is able to separate the wind (plus inverse barometer), and wave set-up components and to demonstrate the importance of regional wave set-up (developed on the shallow sand banks in northern Moreton Bay – Spitfire area) on observed storm tide within Moreton Bay. The model used in the design simulations (see Sections 7 and 8) also includes nearshore wave set-up computation, but that set-up does not occur at the Brisbane Bar tide gauge site.

5.4.2.2 Tropical Cyclone Dinah

Tropical Cyclone Dinah was an intense tropical cyclone which tracked off the South-East Queensland coast in January 1967. It caused extensive damage between Hervey Bay and the Gold Coast through a combination of high waves and storm tide. At Brisbane Bar, the maximum peak surge recorded was approximately 0.4m above the predicted tide. At Mooloolaba, the peak surge was approximately 0.8m above the predicted tide. Figure 5.12 presents a time-series of predicted and measured water level at Brisbane Bar. Although, when compared with Cyclone Daisy, the recorded surge at Brisbane is not high, the peak surge occurred near high water and due to the direction of the wind forcing inside Moreton Bay the observed storm tide at some shoreline sites was considerably higher than recorded at Brisbane Bar. For example, considerable flooding was observed near Sandgate, approximately 9km north-west of the Brisbane Bar tide gauge.

Analysis of synoptic charts for Cyclone Dinah indicated that near the study area the cyclone eye diameter was approximately 80km (Harper *et al*, 2000). It is likely that the radius to maximum winds was approximately 40km. For the calibrated wind field case, a radius to maximum winds of 42km was adopted.

Figure 5.13 presents time series of measured and modelled wind conditions (speed and direction) at Brisbane Airport and Cape Moreton. At Brisbane Airport, the modelled wind speed provides a good description of the measured wind speed near the event peak. Prior to the event peak, it appears that strong gradient winds, which are not described in the Holland model, were significant - pers. comm. Callaghan (BoM) – Taylor/Treloar. Additional information for Cyclone Dinah was provided by the BoM and is presented as Appendix E.

Following the initial simulations of Cyclone Dinah with the Delft3D storm surge model using the Holland wind model, it became evident that the wind forcing from the Holland model did not provide a realistic description of the storm tide observed at Brisbane Bar. A simulation was undertaken applying a wind field based on the measured winds observed at Brisbane Airport (see Figure 5.13). The winds from Brisbane Airport were adjusted upward by 3m/s on 29 January 1967 to reflect the observed over-water wind speed of 12.5m/s – see Appendix E. Figure 5.14 presents a comparison between observed and modelled storm surge and total water level at Brisbane Bar. Measured values are presented in the solid black lines, and the Delft3D model results are presented in the dashed red line. Note, the Delft3D result includes the effect of regional wave set-up, although this is a minor contribution to the peak surge value. This outcome identifies the limitations of the Holland model when strong gradient winds persist prior to the cyclone eye passing close to the study area. The outcome also provides confidence that, provided appropriate wind conditions are applied to the Delft3D model, it is able to accurately simulate the observed storm tide at Brisbane Bar.

Figure 5.15 presents a time series of modelled wave conditions during Cyclone Dinah at a depth of 60m near the northern entrance to Moreton Bay. The wind field applied to the wave model was taken from the Holland model. The winds from the Holland model are likely to underestimate the wave conditions prior to the eye passing close to Moreton Bay, but should provide a reasonable forcing for the peak storm wave heights. The peak wave conditions are easterly, compared with the north-easterly waves developed for Cyclone Daisy. These Cyclone Dinah wave conditions were specified along the northern boundary of the Moreton Bay hydrodynamic model to investigate potential regional wave set-up.

The variation in storm tide between Brisbane Bar and the shoreline areas near Sandgate, where significant inundation during Cyclone Dinah was observed, is presented in Figure 5.16. The peak storm surge at Sandgate was 0.60m compared to 0.47m at Brisbane Bar. The peak modelled storm tide, excluding local shoreline wave set-up, was 1.76m AHD at Sandgate compared to 1.66m AHD at Brisbane Bar. Figure 5.17 presents a plan view of the modelled total water level (excluding local set-up) in northern Moreton Bay at 12:00pm (midday) on 29 January 1967.

Shoreline wave set-up at the time of peak storm tide at Sandgate would likely have added between 0.1 and 0.15m to the water level. This height of local wave set-up would produce a modelled total water level of approximately 1.9m AHD near the shoreline at Sandgate. Cyclone Dinah generated significant rainfall in the Brisbane region. At Brisbane Airport, a total of 360mm of rainfall was observed. Sandgate is a flood prone area during events of rainfall intensity such as that observed during Cyclone Dinah. The ground level of road and houses immediately west of the shoreline is lower than the shoreline crest. It is likely that the storm tide from Cyclone Dinah would have backed-up the stormwater drainage system around Sandgate and increased the flooding of low-lying areas from rainfall.

Overall the model system developed in this study was able to simulate storm surge during Cyclone Dinah to a reasonable level. For Cyclone Dinah, the cyclone track data has lower temporal resolution compared to Cyclone Daisy and the gradient wind forcing prior to the event is significant.

5.5 Large Eye Cyclones and Tropical Low Modelling

Large eye tropical cyclones, tropical lows and East Coast Low systems have the potential to generate strong persistent winds and large offshore waves in the Moreton Bay region. Generally the centres of these low pressure weather systems are located offshore several hundred kilometres from Moreton Bay. Strong isobaric gradients generated from the interaction of the low pressure and a nearby high pressure system causes strong winds across the study area. Synoptic charts for selected large scale cyclones and low pressure storm systems provided by the BoM have been used to hindcast wind conditions in the study area. The third storm surge event used for model calibration in this study is the intense storm which tracked near Moreton Bay in March 2004. This event has been described as a ‘Hybrid’ storm which was observed to have properties of both tropical cyclones and ECL events. This event generated large offshore waves from the east-north-east to east sector and the highest recorded storm surge at the Brisbane Bar site. Although Brisbane Bar is not within the study area, it does provide reliable long term water level data for regional model calibration; noting that the highest storm tides will not normally be recorded there. Appendix F presents a summary of the event prepared by the EPA.

March 2004 Tropical Low Event

In March 2004 a tropical low system developed off the central Queensland coast. Since this event is more recent than others considered for model calibration, there were more wind data locations available for calibration. In addition to Cape Moreton and Brisbane

Airport, calibration of the wind conditions has also been undertaken using data from Coolangatta and Maroochydore Airports.

Initially a wind field generating routine from the MIKE-21 (DHI) model system was used to prepare the wind fields for the regional SWAN wave model grid and the Delft3D hydrodynamic model from the synoptic charts. Figure 5.18 presents time series plots of modelled and measured wind parameters at Brisbane Airport and Cape Moreton. Figure 5.19 presents time series plots of modelled and measured wind conditions at Coolangatta and Maroochydore Airports.

The modelled wind conditions at Brisbane, Coolangatta and Maroochydore Airports are a good representation of the measured 3-hourly wind conditions. At Cape Moreton, as with the hindcast of previous historical events, the modelled wind speeds are lower than the measured values when the wind direction is from the south-east. As the wind tends towards the north the modelled wind speed becomes closer to the measured values.

At all sites the modelled wind direction is generally a good match to the measured wind directions, which gives confidence that the general wind structure during this event is well described in the Moreton Bay region. Although there is some disagreement between the model and measured phases for the storm tide, the peak magnitudes and general character are in good agreement, which provides confidence that the Monte Carlo simulation will be reliable.

During the early stages of the calibration process for the March 2004 event, it became evident that the hindcast winds based on the synoptic charts did not generate the observed offshore wave conditions at the offshore Brisbane WRB. An alternative windfield was obtained from the blended satellite wind dataset provided by NOAA. This data includes high-resolution QuikSCAT satellite data. The data is provided on a 0.25 degree resolution grid (approximately 25km) every six hours. The satellite wind data has been verified using measured winds from the Spitfire Banks AWS in Moreton Bay. Figure 5.20 presents a comparison between measured (blue solid line), satellite (red dashed line), and modelled synoptic chart winds (green dashed line) near Spitfire Banks. The NOAA satellite wind data generally describes the observed over-water winds better. As a result, the NOAA satellite wind data has been adopted as the forcing winds for this event. Atmospheric pressure over the Delft3D model is based on the synoptic charts provided by the Bureau of Meteorology.

Figure 5.21 presents a comparison of the modelled and measured wave conditions at the Brisbane WRB. The modelled wave height and period generally agree well with the observed conditions. Typically the modelled wave direction is more easterly when compared with the observed wave directions. This outcome provides confidence that the SWAN model can reliably simulate the peak offshore storm wave conditions.

Figure 5.22 presents a comparison between the modelled and measured wave conditions at the Moreton Bay WRB. For this simulation, the measured winds at Spitfire Bank beacon were applied to the SWAN model. The modelled wave height and period agree very well with the observed wave conditions. This outcome provides confidence that the SWAN model can reliably simulate the local sea wave conditions within Moreton Bay.

Figure 5.23 presents a comparison of modelled and measured storm surge and storm tide at Brisbane Bar during the March 2004 event. Generally the modelled surge agrees well with the observed surge. During the simulation, the offshore wave conditions have been based on the observed wave conditions at the Brisbane WRB. For the March 2004 event, regional wave set-up is a significant contributor to the total storm surge.

Figure 5.24 presents modelled and measured storm surge (and tide) at Mooloolaba and the North-West 12 Beacon gauge sites. The modelled storm surge agrees well with the observed conditions at both sites. Note that the modelled surge at the North-West 12 Beacon includes wind, pressure and regional wave set-up forcing. This outcome provides confidence that the Delft3D model is able to reliably simulate storm tide over the whole of South-East Queensland and importantly account for local processes, for example regional wave set-up over Moreton Bay.

6. REGIONAL WAVE SET-UP INVESTIGATIONS

6.1 General Process – Wave Set-up inside a Coastal Embayment

Wave set-up is a process commonly observed at open beaches where the mean water level increases between the zone of wave breaking and the shoreline. It is caused by the conservation of momentum flux during wave breaking. In simple terms, wave set-up can be viewed as the conversion of some of the kinetic energy released during wave breaking into potential energy in the form of a rise in the mean water level surface.

Whilst wave set-up is usually associated with open beaches, studies have also shown that wave set-up can also influence water level within estuarine entrance and coastal embayment systems. Wave breaking at the entrance to a coastal embayment can cause a rise in the mean water level, the rise depending upon embayment size and depth, other entrances and storm parameters. This process has been documented in numerous studies that have applied data analysis and numerical modelling techniques. Nguyen *et al* (2007) investigated the impact of wave set-up on measured water levels inside river and inlet entrances on the coast of Japan. These investigations indicated that wave set-up, or wave momentum flux processes in breaking wave conditions, could increase water levels inside entrances by 10% to 15% of the offshore wave height for shallow and narrow entrances, and 0.2% to 4% of the offshore wave height for deep and wide entrances. Tanaka and Debasish (1993) also investigated wave set-up inside a river mouth and compared measured set-up with Goda's irregular wave breaking model. There studies indicated that coupling Goda's model with the effects of currents provided a reasonable model of wave set-up inside the entrance at the study site.

Irish *et al* (2004) adopted an approach similar to that adopted in this study to investigate storm water levels inside coastal embayments along Long Island, USA. That paper is included as Appendix G. In that study the Delft3D FLOW model was coupled with a wave model (HISWA – predecessor to the SWAN model). The modelled water level was compared to measurements at seven sites inside the coastal embayment. A model simulation that was forced using tide, local wind and local wave conditions provided the best agreement with the measured water levels. Based on the calibrated Deflt3D model, wave set-up during the study event contributed 15% of the measured storm tide inside the coastal inlets during the event.

This process has been recognised in a previous storm tide study undertaken by Blain, Bremner and Williams (1979a) for the 'New Brisbane Airport'. Storm tide outcomes from that study were based on tide and surge simulations. Regional wave set-up (termed effective set-up), was included in an empirical manner. Evidence cited by Blain, Bremner and Williams for this phenomenon is the tidal anomalies observed during cyclones David and Pam for which storm surge modelling showed no tidal anomaly, yet differences above the predicted tides were in the order of 0.3m – those cyclones generally tracked no closer than 500km from Brisbane, yet caused very high waves near the Moreton Bay entrance shoals.

The calibration process has shown that during particular storm events, there is a residual water level inside Moreton Bay that cannot be attributed to either inverse barometer or conventional wind set-up processes – as identified by Blain, Bremner and Williams. The magnitude of this residual water level was largest during the Cyclone Daisy and March 2004 calibration events, which generated large offshore waves from the north-east to east sector. Spitfire Banks is a coastal bar system which extends some 30km across the northern entrance to Moreton Bay. The depths along the high points of Spitfire Banks are typically 5m to datum AHD. Offshore of Spitfire Banks the seabed is very steep and due to its orientation, offshore waves originating from the north-east to east sector propagate to Spitfire Banks without significant energy loss due to refraction or bed friction. During large wave events, it is common to observe wave breaking along the entire extent of Spitfire Banks.

The calibration events addressed in Section 5 include significant wind and pressure forcing together with wave forcing. All three processes influence the residual water level. A fourth calibration event from July 2001 has been selected in which the degree of local wind and pressure forcing was relatively small whilst moderate long-period waves were observed offshore which generated significant wave breaking along Spitfire Banks. The calibration of the Delft3D model for this event is discussed in Section 6.2.

6.2 July 2001 Event

A moderate wave event was observed on the 6th and 7th July, 2001. The waves were generated by an intense low in the Tasman Sea, some 1,500km to 2,000km east of Brisbane. Offshore wave heights reached 4m (H_s) at the Brisbane Waverider buoy with peak periods (T_p) of up to 12 seconds. The offshore wave direction was generally east during the peak of the event. Figure 6.1 presents measured wave height, period and direction during the July 2001 event.

During the period of moderate offshore waves, the measured winds inside Moreton Bay were generally calm and the atmospheric pressure stable. Figure 6.2 presents time-series of measured wind speed, direction and mean sea-level air pressure during the wave event.

Observed water levels at Mooloolaba, Brisbane Bar and Southport (Gold Coast) have been analysed during this period. Figure 6.3 presents time-series of the predicted and measured tide at Brisbane Bar, together with the measured residual tide at Mooloolaba, Brisbane Bar and the Gold Coast. Generally the residual tide is small at Mooloolaba; less than 0.05m. At Brisbane Bar, the residual tide shows a clear oscillatory character with a period of oscillation of about 12 hours. The magnitude of the residual tide is up to 0.19m coinciding with the peak offshore wave heights. Southport also shows some residual tide with a similar character to Brisbane Bar near the peak of the event.

The Delft3D model described in Section 5 has been applied to hindcast the residual tide during this event. Satellite ‘over-water’ wind data from NOAA has been applied together with measured air pressure at Brisbane Airport. For the wave simulations, measured offshore wave conditions from the Brisbane Waverider buoy have been specified as the boundary conditions.

Figure 6.4 presents modelled and measured residual tide at Mooloolaba, Brisbane Bar and the Gold Coast for the July 2001 event with tide, wind and pressure forcing only. Generally the model agrees well with the observed residual tide at Mooloolaba, however, the modelled water level at Brisbane Bar is not in good agreement with the measured residual tide. The model also under-estimates the residual water level at Southport. Figure 6.5 presents the modelled residual tide with wave forcing together with the measured residual tide at Brisbane Bar and Southport. Compared to Figure 6.4, the modelled residual tide is in much better agreement with the measured residual at both sites. It should be noted that although the current Delft3D model includes the Broadwater, it does not have the resolution nor data in this area to cover the whole storage of this system; therefore it can be expected that the modelled result at Southport it not as realistic as it is at Brisbane Bar, which is located in the centre of the study area. The inclusion of wave processes significantly improves the temporal agreement of the modelled residual tide compared to the measured residual tide. The modelled peak residual tide is in good agreement with the measured peak residual tide.

The measured residual tide at Brisbane Bar during the July 2001 event and the storm events described in Section 5 show a strong correlation with the tide and offshore wave conditions. The hindcast simulation of the July 2001 event, together with the storm events described in Section 5, demonstrate that the Delft3D model system is capable of simulating this wave induced variation in observed water level.

6.3 Regional Wave Set-up Investigations

The calibration process has demonstrated that the Delft3D model can simulate a wave induced water level variation within Moreton Bay. A series of parametric simulations have been undertaken with the Delft3D model to investigate the relationship between regional wave set-up inside Moreton Bay and offshore wave height, period and direction. A series of 27 simulations were undertaken with the following combinations of wave height, period and direction:-

- Wave Height (H_s) – 5m, 7m, and 9m
- Wave Period (T_z) – 6s, 8s, and 10s
- Wave Direction (deg. TN) – 45, 90 and 135

Each simulation was run for a period of three days. During the first day, the wave height increased from 2m up to the simulation value. During the second day, the wave height remained constant at the specified value and on the third day the wave height again decreased to 2m (H_s). Wave period and direction remained constant at the selected values during the whole simulation. Tide forcing was included in all simulations.

Figure 6.6 presents a time series of predicted tide (modelled), modelled water level with wave forcing and modelled residual tide at Brisbane Bar for the three specified wave directions. The offshore wave height is 7m (H_s) and wave period 8s (T_z). The results indicate that the magnitude of regional wave set-up is strongly influenced by wave direction. The magnitude of wave set-up for north-east and easterly waves is significantly higher than for similar south-easterly waves. South-easterly waves lose significant wave energy due to refraction before reaching Spitfire Banks. Tidal flows also have a significant impact on the magnitude of the modelled regional wave set-up. Regional wave set-up increases on the ebb tide and peaks near low water. Near high-water, the magnitude of the regional wave set-up is significantly reduced. This outcome is, at first, counter-intuitive.

Within Moreton Bay, the magnitude of regional wave set-up is relatively uniform on a magnitude basis although there is some temporal variation. Figures 6.7 to 6.13 present plan views of regional wave setup over a 12-hour period within Moreton Bay. The tide condition at Brisbane Bar is indicated in the bottom panel of each plot. Note that regional wave set-up may not occur at every Queensland coastal site.

6.3.1 Regional Wave Set-up Models – Moreton Bay

The Delft3D model has been demonstrated to simulate regional wave set-up within Moreton Bay that is consistent with observed water level data. However, the influence of wave direction and tide on magnitude of the regional wave set-up limits the ability to directly include it in the design cyclone simulations used to determine the planning levels within the study area. In the design cyclone simulations, astronomical tide is addressed independently in the Monte Carlo simulation – see Section 8. As a result, a series of regression models have been developed based on the simulations described in Section 6.3. These models can be easily implemented within the Monte Carlo procedure whereby, for a modelled offshore wave height, period and direction during a cyclone event, the magnitude of regional wave set-up can be determined realistically.

The regional wave set-up (η) relationship for Moreton Bay has been developed into a simple linear regional model of the form presented in Equation 6.1 where the coefficients β_0 and β_1 are calculated by regression analysis of the simulations described in Section 6.3.

$$\eta = \beta_0 + \beta_1 \left(H_s^{\ 2} \times T_z^{\ 2} \right) \qquad (6.1)$$

Figure 6.14 presents the linear regression model presented in Equation 6.1 for north-east, east and south-east wave directions respectively. For all wave directions, the models show a strong linear trend and the correlation coefficient is greater than 0.96 for all wave directions. Table 6.1 presents the regression coefficients for the regional wave set-up models.

Table 6.1 Regression Parameters for Directional Regional Wave Set-up Models

Offshore Wave Direction	β_0	β_1
North-East	0.1856	3.568×10^{-05}
East	0.1343	2.892×10^{-05}
South-East	0.03963	1.028×10^{-05}

Equation 6.1 has been developed for the peak wave set-up occurring during the tide cycle. Near high water, which is typically where peak storm tide occurs, the magnitude of the regional wave set-up is generally 25% to 35% of the peak wave set-up which occurs near low water. This tidal phase reduction was included in the Monte Carlo analyses.

7. DESIGN WATER LEVEL INVESTIGATIONS – NON-CYCLONIC

Design water levels arising from non-cyclonic events have been determined using a combined numerical modelling and data analysis procedure. The long-term water level record from Brisbane Bar has been used to determine the probability distribution of the residual tide at that site. The Delft3D model described in Section 5 has then been used to determine the relationship between the residual tide at Brisbane Bar and locations within the study area during strong wind conditions that typically prevail during non-cyclonic events, of which East Coast Lows are a significant meteorological case.

7.1 Data Analysis

A common method of extremal analysis of recorded water level data is to adopt the Extreme Value Type 1 distribution and to fit independent event peak water-levels to this distribution. An alternative method, which was adopted for this study, is the joint probability approach described by Pugh and Vassie (1980). That approach separates the astronomical tide (a deterministic phenomenon) and storm surge (a stochastic phenomenon) components because they come from different populations. The probability density function for both populations is formed first, and then a joint probability matrix developed.

Time-series of measured water levels and predicted tides at 1 hour intervals were obtained from Maritime Safety, Queensland, for the Brisbane Bar tide gauge. The data covered the period from 1966 to 2008; however, there were some periods where no measured data was available. The data included periods when cyclones were in the vicinity of Moreton Bay. Therefore those periods were removed from the predicted and measured water level data so that the analysis could be undertaken on times of non-cyclonic storm surge and no surge only. Table 7.1 presents the probability of occurrence of the predicted tide, and Table 7.2 presents the probability of occurrence of the residual water level excluding cyclone events at the Brisbane Bar tide gauge.

The joint probability of the residual tide and predicted tide were considered in the determination of water levels at the tide gauge and then for selected nearshore locations for specified ARI periods. This method is based on research by Pugh and Vassie (1980). A Type 1 Extreme Value distribution is then used to determine the water level at selected ARI intervals. This is the approach that was adopted in the Pine Rivers Storm Surge Study (Lawson and Treloar, 2004).

Table 7.1 Brisbane Bar Predicted Tide - Probability of Occurrence

Water Level Bin (mAHD)	Occurrences	Percentage Occurrence
1.5 - 1.4	91	0.02%
1.4 - 1.3	827	0.22%
1.3 - 1.2	1922	0.52%
1.2 - 1.1	3750	1.02%
1.1 - 1.0	6539	1.77%
1.0 - 0.9	9019	2.44%
0.9 - 0.8	11748	3.18%
0.8 - 0.7	14411	3.90%
0.7 - 0.6	16683	4.52%
0.6 - 0.5	18637	5.04%
0.5 - 0.4	20010	5.42%
0.4 - 0.3	20301	5.49%
0.3 - 0.2	20063	5.43%
0.2 - 0.1	19456	5.27%
0.1 - 0.0	18692	5.06%
0.0 - -0.1	18379	4.97%
-0.1 - -0.2	18781	5.08%
-0.2 - -0.3	20204	5.47%
-0.3 - -0.4	21988	5.95%
-0.4 - -0.5	23235	6.29%
-0.5 - -0.6	23582	6.38%
-0.6 - -0.7	22111	5.98%
-0.7 - -0.8	17782	4.81%
-0.8 - -0.9	12315	3.33%
-0.9 - -1.0	6301	1.71%
-1.0 - -1.1	2282	0.62%
-1.1 - -1.2	347	0.09%
-1.2 - -1.3	0	0.00%

Table 7.2 Brisbane Bar Residual Tide - Probability of Occurrence

Water Level Bin (m)	Occurrences	Percentage Occurrence
0.8 - 0.7	1	0.00%
0.7 - 0.6	2	0.00%
0.6 - 0.5	30	0.01%
0.5 - 0.4	106	0.03%
0.4 - 0.3	842	0.27%
0.3 - 0.2	7378	2.39%
0.2 - 0.1	45342	14.71%
0.1 - 0.0	123995	40.23%
0.0 - -0.1	95203	30.89%
-0.1 - -0.2	30220	9.81%
-0.2 - -0.3	4541	1.47%
-0.3 - -0.4	498	0.16%
-0.4 - -0.5	32	0.01%
-0.5 - -0.6	0	0.00%
-0.6 - -0.7	0	0.00%
-0.7 - -0.8	0	0.00%

7.2 Model Simulations

The Delft3D model presented in Section 5 has been used to determine the relationship between the wind-induced surge at Brisbane Bar and shoreline sites within the study area. Correlation analysis between non-cyclonic storm surge recorded at Brisbane Bar and wind conditions indicated that there is a moderate relationship between wind speed (measured at Brisbane Airport) and the magnitude of the storm surge. The correlation coefficient was 0.525. There was little to no relationship between storm surge and the wind direction, and also between wind direction and wind speed. A series of simulations have been undertaken with the Delft3D model to determine the wind surge ratios between Brisbane Bar and the selected locations within the study area. Simulations were undertaken for all wind directions at 45 degree intervals with a wind speed of 18m/s. This wind speed corresponds to a 20-years ARI 3-hourly average 'over-water' wind speed. For each output location, the maximum wind set-up ratio (output location to Brisbane Bar), was selected from all wind direction results to be applied in the joint probability calculation – see Section 7.3.

Within Moreton Bay, the total non-cyclonic storm surge for an event is formed from the following components:-

1. Oceanographic processes (including coastal trapped waves),
2. Regional wave set-up generated by wave breaking along Spitfire Banks,
3. Inverse barometer (atmospheric pressure),
4. Local wind set-up within Moreton Bay, and
5. Local wave set-up generated near the shoreline.

Components 1 to 4 are all present in the historical record of residual tide at Brisbane Bar. For each event, the contribution of each component will vary. A particular event may be dominated by local wind set-up, whilst another event may be dominated by oceanographic processes and regional wave set-up. For this study, the wind set-up ratios developed from the Delft3D simulations (see above) have been applied to the total residual tide record from Brisbane Bar to estimate the total residual tide at each model output point. This approach is somewhat conservative because Components 1 to 3, which are likely to be relatively uniform across Moreton Bay for any given event, have also been scaled by the wind set-up ratio for each output location. Since there is no reliable method to separate the storm surge components for the whole Brisbane Bar tide record (1966 to 2008), and given that cyclonic storm surge (see Section 8) generally governs the 100-years ARI storm tide level within the study area, the approach adopted to determine the non-cyclonic storm tide levels within the study area, whilst conservative, does not result in unreasonable planning levels.

In the Moreton Bay Regional Council Area, the maximum storm surge was generated in east to south-east wind directions. For Pumicestone Passage, southerly wind generated the largest surge. At all output locations, the wind surges are higher than at Brisbane Bar. Within the study area, the smallest shoreline wind set-up is observed around the Redcliffe peninsula. The largest surges occur within Pumicestone Passage.

7.3 Joint Probability Calculations

Design water levels at selected ARI's have been determined at the output locations by factoring the residual tide histogram at Brisbane Bar, see Table 7.2 by the site specific adjustment factors calculated from the Delft3D investigations. Design levels have been calculated for 20, 50, 100, 200, 500, 1,000 and 10,000-years ARI conditions.

7.4 Wave Parameters

Wave parameters have been calculated at all output locations for sea and swell conditions. With the exception of eastern and southern Bribie Island, all output locations are generally governed by local sea conditions.

7.4.1 Local Sea

The SWAN model presented in Section 5 has been used to hindcast local sea wave conditions between 2001 and 2008. Wind data from the Inner Marker station have been applied as the input wind parameter. Figure 7.1 present a comparison between the wave height probability of exceedance from the measured Moreton Bay Waverider buoy data and the SWAN model. The SWAN model agrees well with the measured data. A Type 1 Extreme Value distribution has been used to determine local sea wave heights for 20, 50, 100, 200, 500, 1,000 and 10,000-years ARI conditions.

7.4.2 Swell Waves

The SWAN model described in Section 5 has been used to hindcast swell waves for the top 500 wave conditions based on the offshore Brisbane Waverider buoy. The measured water level at Brisbane Bar was included in the hindcast to describe the influence of water level on the amount of swell penetration into Moreton Bay. The wave data covered the period from 1996 to 2008, which is the record period of the Brisbane directional Waverider buoy. A Type 1 Extreme Value distribution analysis was applied to the top 30 independent wave heights at each location to determine swell wave heights for 20, 50, 100, 200, 500, 1,000 and 10,000-years ARI conditions.

7.4.3 Wave Set-up

Wave parameters were selected and wave set-up was calculated by adopting the wave conditions most likely to occur jointly with each ARI water level (astronomical tide plus surge) at each site. The Goda formulation for irregular wave set-up was adopted (Goda, 2000). An extrapolation procedure was applied to estimate set-up beyond zero initial depth. Wave set-up has been calculated for a 1V:15H beach slope for the following range of wave heights and periods:-

- Wave Heights (H_s) – 0.5m, 1.0m 1.5m, 2.0m and 2.5m
- Wave Periods (T_z) – 2s, 4s, 6s, 8s, 10s and 12s

7.5 Design Water Levels

Appendix H presents non-cyclonic design water levels for ARI's between 20 and 10,000-years and for all output locations in the study area. Output locations are presented in plan view in Figure 7.2. Figure 7.3 presents a plan view of the 100-years ARI non-cyclonic water levels around the study area – astronomical tide + storm surge + wave set-up, and excluding any climate change aspects. Note, Appendix H also does not include any sea-level rise or freeboard allowance, which should be considered by Council when determining planning levels.

Appendix H includes wave run-up levels for two different edge treatments:-

1. Sandy Beach – 1V:15H average slope
2. Rock Revetment - 1V:2H average slope

Wave run-up levels for the sandy beach have been calculated using the Holman formula (Holman, 1986). Wave run-up levels for the revetment have been calculated using formula for wave run-up on permeable, rough surfaces presented in the USACE (2002) which is based on research published in Delft Hydraulics (1989). Run-up levels are presented for 50%, 2% and 1% exceedence levels. It is common to adopt the 2% run-up exceedence level in design levels. The 2% exceedence level refers to the elevation that is exceeded by wave run-up by only 2% of all waves during the design event.

Table 7.3 presents non-cyclonic storm tide (tide + surge + regional wave set-up) levels for Brisbane Bar, excluding any local wave set-up.

Table 7.3 Brisbane Bar Non-Cyclonic Water Levels at Selected ARI's – No Potential Climate Change Aspects Included – No Shoreline Wave Set-up

ARI (years)	Water Level (mAHD)
20	1.69
50	1.74
100	1.78
200	1.82
500	1.88
1,000	1.92
10,000	2.05

Note that these water levels have been prepared as part of the non-cyclonic storms investigation process and are not suitable for design purposes.

8. DESIGN WATER LEVEL INVESTIGATIONS – TROPICAL CYCLONES

8.1 Cyclone Population Statistics

A total of 29 cyclones which have occurred since 1959 have been identified as having potential significant effects on the study area – see Section 4.3. These events have been analysed to identify values for the following parameters:-

- Track Direction
- Month of Origin
- Landfall Location or Minimum Distance from the Coast
- Minimum Central Pressure
- Average Forward Speed

Cyclones were classified as either 'Coast-Parallel' or 'Coast-Crossing' based on the direction of motion and visual inspection of the recorded tracks. Each track direction was treated as a separate population in the Monte Carlo analysis and as a result the statistics for the other variables have been assembled from only cyclone events with the same track direction. Minimum central pressure was the minimum pressure observed whilst the cyclones were within the designated 'cyclone study area'.

Figure 8.1 presents the cyclone statistics for 'Coast-Crossing' events and Figure 8.2 presents the cyclone statistics for 'Coast-Parallel' events. Appendix I presents track plots for all adopted cyclone events. Note that cyclones which have tracked from west to east, for example Cyclone Althea, have been omitted from the analysis because there were only two such events in the 49 years of record, which is too small a sample from which to generate reliable statistics.

Following discussions with the BoM (pers. com. Taylor/Treloar – Callaghan), the potential for coast-parallel events which track 'in-land' has been included in the cyclone probability functions of the Monte Carlo model. Cyclones with this track have not been observed since 1959, however, they have been observed in earlier historical cases and caused widespread damage in the Moreton Bay region. Since no reliable statistics for the occurrence of these events can be obtained from the post-1959 database, the Monte Carlo model has specified that 2% of coast-parallel cyclones may track 'in-land' through the study area. Since coast-parallel cyclones occur for 79% of all events, the total frequency of occurrence for these events is 1.5 events per 100-years, generally consistent with the long term data.

8.2 Base Simulations

The calibrated Delft3D and SWAN models described in Section 5 have been applied to simulate a series of base cases that provided the interpolation matrix for the Monte Carlo simulation. Based on the analysis of observed cyclone events since 1959, a series of design cyclone tracks were developed for the base simulations. 'Coast-parallel' tracks have been designed to follow the general alignment of the coastline in south-east Queensland. 'Coast-crossing' cyclones track in a south-westerly direction at regular intervals along the coastline. Figure 8.3 presents the 'coast-crossing' and 'coast-parallel' cyclone tracks which have been adopted. There are a total of 9 'coast-parallel' tracks and 7 'coast-crossing' tracks. For both cases, the distance between adjacent tracks is 40km, which corresponds to the radius of maximum winds adopted for these simulations. Based on the historical data, it is difficult to reliably estimate the radius to maximum winds for all the cyclones dating back to 1959. Therefore, a uniform value of 40km has been adopted for this study. The selection of a 40km track grid for the base simulations is designed to minimise interpolation errors in the Monte Carlo procedure.

For each cyclone track specified in Figure 8.3, the following central pressure and forward speed ranges were simulated:-

- Central Pressure: 925hPa, 950hPa, 975hPa and 1000hPa
- Forward Speed: 3m/s and 7m/s

A total of 128 base cases were simulated. Additional simulations were undertaken at high and low water for a ‘coast-crossing’ and ‘coast-parallel’ cyclone case. These simulations were used to develop correction factors for wind set-up based on the tide level. In general, wind set-up is usually higher at low water compared to high water.

8.3 Monte Carlo Modelling

8.3.1 Program Structure

A FORTRAN based Monte Carlo storm tide model has been developed for this study. The program is based on the Monte Carlo models developed by Cardno Lawson Treloar for other studies along the Queensland Coast. The key features and general algorithms of the program are described in the following sections.

8.3.1.1 Astronomical Tide

Astronomical tide is included in the model through an input file of 19-years of 30-minute predicted tide levels for Brisbane Bar to datum AHD. This time period covers the whole astronomical tide cycle of nodal recession along the plane of the ecliptic. For each simulated event, a period of predicted tide is extracted randomly from the pre-calculated input file. The month of origin is included in the random number function which permits predicted tide records to only be extracted from months when cyclones are likely to be observed within the study area. Tidal predictions were based on the so-called Canadian method using 22 tidal constants.

8.3.1.2 Cyclone Parameters

Cyclone parameters, described in Section 8.1 and Appendix K, were selected through random number functions. Once parameters were selected, appropriate base simulations (Section 8.2) were identified for the interpolation procedure. The storm surge time-series and peak wave parameters for the event were then determined through a series of interpolation routines. Interpolation procedures for cyclone track location and central pressure apply a conventional linear interpolation routine.

Forward speeds that were less than 3m/s adopted the 3m/s base simulation case. Forward speed events greater than 7m/s adopted the 7m/s base simulation results. For events between 3m/s and 7m/s, the storm surge time-series is determined for forward speeds of 3m/s and 7m/s, and then a scaling function interpolation routine is applied to calculate the actual event storm surge time series. The scaling interpolation routine calculates the ratio between the peak storm surges for the two base forward speed conditions, and then applies this ratio to the storm surge time series of the base forward speed case which is closer to the event forward speed.

A similar scaling function interpolation routine is applied to the extrapolation routine used to determine the storm tide for events that have tracks outside the region covered by the base simulations.

Based on discussions with the Bureau of Meteorology (Section 4.3), a minimum potential central pressure within the study area of 930hPa has been adopted to present-day climate simulations.

8.3.1.3 Tide Correction

The influence of tide level on the magnitude of storm surge is accounted for through a tide correction module. In this module, the interpolated storm surge for the event is adjusted at each time point based on the predicted tide at the time. Linear interpolation is applied to determine the tide correction factor for each time in the record based on the ratios obtained from the base tide simulations – see Section 8.2.

8.3.1.4 Regional Wave Set-up

Regional wave set-up is determined for each event based on the peak offshore wave conditions determined within the Monte Carlo simulation for that event. Based on these wave conditions, which were obtained from interpolation of the base cyclone wave simulations, the maximum regional wave set-up level for the event was determined through the application of the linear regression models presented in Section 6.3.1. Linear interpolation is applied for wave directions between the specified directions adopted for the wave set-up models – see Section 6.3.1.

The influence of the predicted tide on the magnitude of regional wave set-up is accounted for through a simple tide correction factor. When the predicted tide is above 0.5m AHD, the magnitude of the peak regional wave set-up within Moreton Bay is reduced to one-third of the maximum value based on the results from the investigations reported in Section 6.3; noting that this regional wave set-up component is not the major water level component. For predicted water levels less than -0.5m AHD at Brisbane Bar, the full magnitude of the regional wave set-up is adopted for a particular point in time. Between +0.5m AHD and -0.5m AHD, linear interpolation is applied to simulate the regional wave set-up for the given predicted tide.

8.3.1.5 Greenhouse Related Climate Change

Based on discussions between Moreton Bay Regional Council and the Bureau of Meteorology (pers. com. Davidson – Gunn), this study has adopted a change in maximum wind speed condition for potential Greenhouse related climate change on tropical cyclones within the study area. Changes to other cyclone parameters such as frequencies and southern extents are more un-certain because of the large natural variations in these parameters due to processes such as ENSO and the Inter-decadal Pacific Oscillation. For the potential Greenhouse related change to wind speed in the planning period between 2050 and 2100, the maximum wind speed for each simulation event has been increased by 10%. This may be compared with CSIRO (2001) which provides an estimated average and standard deviation reductions in central pressure of 4.2 and 2hPa, respectively, summing to a mean reduction of 6.2hPa. This may be compared with the present climate mean intensity of 986hPa for the Brisbane region. Cyclonic winds are related to pressure difference between the cyclone and the peripheral pressure, taken to be 1,010hPa. Hence for the present climate condition, the mean cyclone pressure difference is 24hPa. For the maximum climate change, pressure difference may be about 26% larger (central pressure = 980hPa) and for the average climate change pressure difference being 17.5% larger (central pressure = 982hPa). On this basis the adopted procedure provides a reasonable basis for describing potential climate change effects on storm tide.

The Greenhouse module within the Monte Carlo program calculates a new central pressure for each event based on a 10% increase in the wind speed at the radius to maximum winds. Hence, for less severe events, a smaller reduction in central pressure is required to achieve a 10% increase in maximum wind speed. For the Greenhouse simulation cases, the minimum central pressure within the study area has been reduced to 925hPa.

8.3.1.6 Comparison with Measured Cyclone Wind Speeds – Brisbane Airport

The probability distribution of the cyclonic wind speeds at Brisbane Airport developed from the Monte Carlo simulation has been compared to the distribution developed from the measured cyclonic wind speeds at Brisbane Airport from the 29 cyclones included in the population statistics (see Section 8.1).

The peak measured 3-hourly speeds for the selected cyclone events in Section 8.1 have been extracted from the long-term record at Brisbane Airport. The measured wind speeds have been corrected for elevation and 'overland/overwater' effects. The 3-hourly wind speeds have also been converted into 1-hour equivalent winds speeds. Based on the methodology in USACE (2002), the total correction factor applied to the measured wind speeds was 1.50. Type-I extremal analyses have been undertaken on the adjusted, measured winds and the whole Monte Carlo record. Table 8.1 presents a comparison between the measured and Monte Carlo modelled peak cyclone winds at Brisbane Airport up to 100-years ARI. Due the limited record of the measured data, the extremal analysis is only reliable up to 2 to 3 times the length of the record.

Table 8.1 Peak Cyclonic Wind Speeds (m/s) - Brisbane Airport (3-hour, 10-minute Average, 10m Elevation, 'Over-water')

ARI (years)	Measured Cyclone Winds (1959-2008)	Monte Carlo Modelled Wind (Holland Cyclone Wind)
20	18.9	17.1
50	21.0	21.6
100	22.5	25.0

8.4 Design Water Levels – Existing Climate Conditions

Appendix J presents cyclonic design water levels for ARI's between 20 and 10,000 years for all output locations within the study area. Output locations are presented in plan view in Figure 7.2. Figure 8.4 presents a plan view of the 100-years ARI cyclonic water levels around the study area. Appendix J includes wave run-up levels for sandy beach and rock revetment edge treatments (see Section 7.3 for calculation methodology).

Table 8.2 presents cyclonic storm tide (tide + surge + regional wave set-up) levels for Brisbane Bar for the current climate condition.

Table 8.2 Brisbane Bar Cyclonic Storm Tide Levels – No Greenhouse Related Climate Change – No Shoreline Wave Set-up

ARI (years)	Water Level (m AHD)
20	1.62
50	1.70
100	1.76
200	1.82
500	1.90
1,000	1.96
10,000	2.15

Note that, up to the 100-years ARI case, the non-cyclonic storm tide levels of Table 7.2 are marginally higher then the cyclonic storm tide levels – both excluding shoreline wave set-up. It is not possible to be specific about what causes this outcome because all of the computations are inter-linked, but it is most likely caused by the more frequent high wave conditions caused by ECL and higher regional wave set-up, which is included in both results.

8.5 Design Water Levels – Greenhouse Related Climate Change Conditions

Appendix K presents design water levels (tide + storm tide + regional wave set-up and with and without shoreline wave set-up) for all ARI's between 20 and 10,000 years for all output locations in the study area for the case when the adopted Greenhouse climate change in cyclogenesis is included, but excluding sea level rise (SLR). Output locations are presented in plan view in Figure 7.2. Figure 8.5 presents a plan view of the 100-years ARI cyclonic water levels (tide + storm tide + regional wave set-up + local wave set-up) under enhanced 'Greenhouse' climatic conditions around the study area. No sea-level rise is included in Figure 8.5. Appendix K includes wave run-up levels for sandy beach and rock revetment edge treatments (see Section 7.3 for calculation methodology).

Table 8.3 presents the cyclonic water levels (tide + storm tide + regional wave set-up) for Brisbane Bar for potential 'Greenhouse' climate change conditions, but excluding any mean sea-level rise (see Section 9.3). The results in Table 8.3 are not provided for design use.

Table 8.3 Brisbane Bar Cyclonic Water Levels (Tide + Storm Tide + Regional Wave Set-up)– Including Greenhouse Related Cyclogenesis Change but Excluding Sea-Level Rise

ARI (years)	Water Level (mAHD)
20	1.70
50	1.81
100	1.89
200	1.96
500	2.07
1000	2.14
10000	2.40

9. DISCUSSION

9.1 Comparison between Design Levels and Historical 'Large-Eye' Cyclones

Historically it has been observed that very high waves and high storm surges have been observed when large-eye intense cyclone systems move through the Coral Sea. These systems can be several 100km away at their closest point, yet are able to generate strong winds over a wide area. The Holland wind model is not able to accurately simulate the windfield for these events hundreds of kilometres from the study area. Three notable 'large-eye' events which have affected Moreton Bay are:-

- Cyclone Pam – February 1974
- Cyclone David – January 1976
- Cyclone Roger – March 1993

Water level data was recorded at Brisbane Bar during cyclones Pam and Roger; the instrument was not operating during cyclone David. Table 9.1 presents the peak total water levels (m AHD) at the site and the maximum residual values.

Table 9.1 Observed Brisbane Bar Water Levels – Historical Large-Eye Cyclone Events

Event	Peak Predicted Tide (m AHD)	Peak Measured Water Level (m AHD)	Peak Residual (m)
Pam	1.1	1.46	0.53
Roger	1.06	1.03	0.34

A comparison between the observed data in Table 9.1 and the Monte Carlo results for Brisbane Bar has been undertaken. Table 9.2 presents the cyclonic total water levels (astronomical tide + storm surge + regional wave set-up) and surges at Brisbane Bar – excluding potential enhanced Greenhouse changes. It can be seen that, although the water levels recorded during cyclones Pam and Roger were elevated compared to the predicted values, from a design perspective, those cyclones are of much less importance than the cyclone climate adopted for this study. This comparison supports the view that cyclonic storm tide levels, noting that water depths are too deep at Brisbane Bar for there to be shoreline wave set-up, will be determined by storms which track close to the study area where the Holland model provides a reasonable description of the windfield within 100km of the cyclone eye.

Table 9.2 Brisbane Bar Cyclonic Storm Tide Levels and Storm Surge – Cyclone Events (Current Climate Conditions) – No Shoreline Wave Set-up – Includes Regional Wave Set-up

ARI (years)	Storm Tide (m AHD)	Storm Surge (m)
20	1.62	0.81
50	1.70	1.02
100	1.76	1.18
200	1.82	1.33
500	1.90	1.54
1000	1.96	1.70
10000	2.15	2.22

9.2 Design Conditions under Climate Change Scenarios

The climate change cyclogenesis scenario investigated in this study generally increases design water levels by between 0.1m and 0.3m for the 100-years ARI condition; as a result of different effects (wind set-up, regional wave set-up and local wave set-up) throughout Moreton Bay. On the other hand any rise in MSL would affect all sites similarly. Exposed locations, for example, eastern Bribie Island and the eastern shoreline at Redcliffe, have smaller cyclogenesis caused increases in design water levels than Pumicestone Passage, Deception Bay and Pine Rivers/Hays Inlet. Wave set-up does not vary significantly between existing and enhanced 'Greenhouse' climate conditions because wave conditions within the study area are generally fetch and/or depth limited.

No changed wind conditions have been investigated for non-cyclonic conditions because there is presently no clear direction for those storms. Moreover, at 100-years ARI, cyclonic and non-cyclonic water levels are very similar. For less frequent cases (ARI > 100-years), the cyclonic results are higher.

9.3 Sea-Level Rise

Historically, storm tide studies have adopted a sea-level rise allowance of 0.2m for a 50-years planning period, increasing more recently to 0.3m. It is understood that the Queensland EPA is currently revising the sea-level rise estimates for Queensland based on the latest IPCC recommendations as part of the State Coastal Management Plan. Discussions with the EPA (pers. com. Prenzler - Sultmann) indicate that for the 100-years planning period the EPA may recommend 0.8m sea-level rise allowance. The 0.3m (that is, 2058) for the 50-years planning period is likely to remain.

For the 50-years planning period, it is recommended that 0.3m sea-level rise allowance be included. For the 100-years planning period, it is recommended that Council undertake further consultation with the EPA to ensure that any level adopted is consistent with future storm tide studies within the state.

These sea level rises are equally applicable to the non-cyclonic design water levels described in Section 7.

9.4 Inundation Mapping

It is recommended that any inundation mapping undertaken as part of this study adopt an envelope methodology for the selected ARI conditions. That is, both cyclonic and non-cyclonic design levels should be mapped and the larger condition at any location be adopted when determining planning levels. For the 100-years ARI condition, cyclone conditions are generally the higher, with the exception of western Bribie Island where non-cyclonic conditions are higher.

10. CONCLUSIONS

10.1 General Comments

This study was undertaken for the Moreton Bay Regional Council area as part of a larger study which included the Redland Shire and Logan City Council areas.

Detailed wind, storm tide and wave models have been developed for the study area which extended between Byron Bay in the south, Fraser Island in the north and up to 150km offshore. A regional wave (SWAN) model has also been developed which covers the Coral and Tasman Seas up to 1500km offshore of the study area. The model systems have been calibrated for a total of four events (two cyclones, two East Coast Lows) and the models generally are in good agreement with measured storm tide levels at Brisbane Bar, Gold Coast and Mooloolaba.

As part of the calibration process a detailed model investigation has been undertaken of the influence of wave breaking at Spitfire Banks on water levels inside Moreton Bay. Those investigations indicated that, for particular storm events, wave breaking near the entrance to Moreton Bay can contribute a significant amount of the total surge observed within Moreton Bay. This 'Regional Wave Set-up' process is most significant when waves originate from the north-east to east sector offshore, and when the astronomical tide is near low water on the ebb tide. Near high-water for the predicted tide, the influence of this regional wave set-up near high water falling is generally only 25% to 35% of the magnitude near low water for constant offshore wave conditions.

Storm tide levels and associated wave conditions have been specified for non-cyclonic and cyclonic storm events. The non-cyclonic design levels have been determined through combined model simulations and joint-probability analysis of long-term water level record from the Brisbane Bar tide gauge. The results are presented in Section 7.1. At most shoreline locations, particularly within embayed areas and along Pumicestone Passage the non-cyclonic water levels are slightly lower than cyclonic results up 100-years ARI. At the 100-years ARI condition, with the exception of eastern Bribie Island, design water levels are higher for cyclonic conditions. Since cyclonic events generate higher water levels for specific design events, potential climate change impacts on design water levels (excluding sea-level rise) have been investigated for cyclonic events only – see below.

Cyclonic design levels have been calculated using a Monte Carlo model that was based on a large number of simulations. The cyclone parameter distributions for the Monte Carlo model have been developed from analysis of cyclone events that passed within 500km of the study area. Cyclone events were separated into 'Coast-Crossing' and 'Coast-Parallel' populations based on cyclone track directions. Cyclone events that featured a large-eye and/or strong coincident gradient wind have been considered separately. The design cyclonic storm surge and total storm tide levels developed from the Monte Carlo model have been compared with two 'large-eye' cyclone events for which measured water level data from the Brisbane Bar tide gauge were available. These two events, cyclones Pam and Roger, caused storm tides below the 20-years ARI results developed from the Monte Carlo model. Hence this outcome indicates that, although these large-eye events generate reasonably large storm surges and offshore waves, over the long-term, those storm surge levels are significantly lower than those caused by more common smaller cyclones which track close to the study area. Hence the results of the analyses have not been compromised by their exclusion from the main study.

For cyclonic and non-cyclonic design levels, shoreline wave set-up and wave run-up levels have been specified at all output locations. Wave run-up levels have been calculated for sandy beach and rock revetment shoreline edge treatments for 50%, 2% and 1% exceedence levels.

Within the overall study area, at the 100-years ARI design level, cyclonic storm tides are slightly higher than the equivalent non-cyclonic results with the exception of eastern Bribie Island where non-cyclonic conditions are higher.

Within the study area, embayed locations, for example, the Pine River/Hays Inlet and Deception Bay area, have higher storm tide levels (cyclonic and non-cyclonic) compared to other sites. Pumicestone Passage also has higher storm tide levels.

Cyclonic design levels have also been calculated for enhanced 'Greenhouse' climate change conditions. The Greenhouse scenario specified a 10% increase in the maximum cyclone wind speeds and this condition was implemented in the Monte Carlo model. Under enhanced Greenhouse cyclogenesis conditions, design water levels are generally increased by 0.1m to 0.3m depending on the shoreline location. This increase in water level under enhanced 'Greenhouse' conditions does not include any allowance for sea-level rise. For a 50-years planning period, it is recommended that a 0.3m sea-level rise allowance be included. For a 100-years planning period, it is recommended that Council undertake further consultation with the EPA to ensure that any rise adopted is consistent with future guidelines and storm tide studies within the state.

10.2 Planning Recommendations

The following recommendations are made for application of the outcomes of this investigation. Appendix L presents recommended storm tide planning levels for Moreton Bay Regional Council LGA. The planning levels are based on the 100-years ARI storm tide level. Figure 10.1 presents a plan view of the recommended planning levels.

A planning period of 100 years is commonly adopted in Australia for new general infrastructure and housing. Redevelopment or extensions of existing infrastructure will often adopt shorter planning periods, for example 50-years. Critical infrastructure such as hospitals, police stations and evacuation routes may be required to be designed to withstand 500-years ARI design conditions.

As 100-years is the nominal planning period, the recommended storm tide planning levels have been based on the cyclonic storm tide with future enhanced Greenhouse cyclogenesis estimates included. Note, at all locations within the study area future Greenhouse enhanced cyclonic storm tide levels are greater than the non-cyclonic storm tide levels at the specified 100-years ARI.

Sea-level rise estimates for 50-years (2059) and 100-years (2109) planning periods are specified in Appendix L. A SLR allowance of 0.3m has been adopted for the 2059 planning period, and a SLR allowance of 0.8 has been adopted for the 2109 planning period. The 100-years SLR allowance is believed to be consistent with proposed EPA guidelines. As mentioned previously, 50-years planning periods are generally adopted for works associated with existing infrastructure, while 100-years planning periods are adopted for new (general) infrastructure.

A freeboard allowance of 0.3m has been included in the recommended planning levels. When considering freeboard allowances, a number of factors need to be considered including:-

1. Quality and quantity of historical data used in the calculation of storm tide levels.
2. Confidence associated with investigations techniques.

3. Precautionary allowances already adopted within the investigation techniques, for example, including Greenhouse related climate change impacts separately within the study as has been done in this investigation.
4. Whether SLR allowances are included separately in the planning level calculations, as has been done in this study.

Regarding Point 1, the quality of the input data in this study is generally high as there are over 40-years of reliable water level measurements and nearly 50-years of reliable cyclone track data. A key limitation in the input data is caused by the highly variable cyclone climatology of south-east Queensland. Over the last 20 to 30-years, no major cyclone has tracked close to the Moreton Bay Regional Council LGA. Through discussions with the Bureau of Meteorology, this study has attempted to generate a reliable long-term cyclone climatology which is consistent with the present climate condition.

In relation to Point 2, this study has adopted well validated techniques to investigate cyclonic and non-cyclonic storm tide. The study methodology is consistent with guidelines presented by the Queensland EPA (2002). The study has also included more recent storm tide investigation techniques, most notably in the area of variation in storm tide generated by wave processes.

In relation to Point 3, the recommended planning levels are based on storm tide investigations which included an estimate of potential changes to the regional cyclone climatology due to Greenhouse related climate change.

In relation to Point 4, the study has separately addressed the issue of SLR in the recommended planning levels.

Based on the discussion above, adopting a 0.3m freeboard is an appropriate precaution because it is not uncommon for other studies which have adopted higher freeboard allowances to have done so to address uncertainty associated with processes which, unlike this study, have not been included in the planning level investigations.

It is important to understand that design water levels have been presented in two ways. They are:-

- The sum of astronomical tide, storm surge, regional wave set-up and nearshore wave set-up – the common basis in Queensland
- The sum of astronomical tide, storm surge and regional wave set-up in combination with nearshore wave parameters – H_s and T_z in a 2m water depth

The first of these design criteria is suited to sites where wave run-up is not an issue. The second set is more widely useful because wave run-up will be an issue at coastal sites. Note that the underlying nearshore wave set-up is implicitly included in wave run-up calculations. It is common to base wave run-up height on the R_2 parameter. Example run-up levels for rock revetment and sandy shoreline edge treatments are included in the result tables presented in Appendices H, J and K. However, it is recommended that each individual development be considered, by the property owner and his consultant, on the basis of site specific parameters – this basis is being adopted elsewhere, for example, Pittwater and Gosford City Council's in NSW. This approach is recommended because edge treatments may vary from block to block. Where properties are constructed on a natural dune, then the water level and wave run-up parameters presented in Appendices H, J and K may be used as the design basis – then adding freeboard and any adopted allowance for SLR.

11. REFERENCES

Blain, Bremner and Williams Pty Ltd (1979a February): New Brisbane Airport. Storm Surge + Tide Simulations. Report Prepared for the Department of Housing and Construction.

Blain, Bremner and Williams Pty Ltd (1979b April): New Brisbane Airport. Historical Study of Storm Tides in Moreton Bay. Report Prepared for the Department of Housing and Construction.

Cardno Lawson Treloar (2009a): Storm Tide Hazard Study, Redland Shire and Logan City Councils. Report LJ8824/R2504v2.

Cardno Lawson Treloar (2008b). “Storm Tide Hazard Study Summary Report – Moreton Bay Regional Council”. Prepared for Moreton Bay Regional Council. Cardno Lawson Treloar Brisbane. Ref: LJ8824-R1.

CSIRO (2001): Climate Change in Queensland under Enhanced Greenhouse Conditions. Third Annual Report 1999-2000. ISBN 0 643 06643 8.

Delft Hydraulics. (1989). “Slopes of Loose Materials: Wave Run-Up on Statistically Stable Rock Slopes Under Wave Attack,” Report M 1983 (in Dutch), Delft Hydraulics Laboratory, The Netherlands.

Environmental Protection Agency – Document 061218. Mitigating the Adverse Impacts of Storm Tide Inundation. Queensland Government, State Coastal Management Plan.

Foreman, M G G. (1977): Manual for Tidal Heights Analysis and Prediction. Pacific Marine Science Report 77-10, Institute of Ocean Sciences, Patricia bay, B C, Canada.

Harper B., Granger K., Jones T., Stehle J and Lacey R. (2000) “Tropical Cyclone Risks”. Chapter 4 – Natural hazards and the risks they pose to South-East Queensland. Australia Geological Survey Organisation. Commonwealth of Australia 2000.

Hitoshi T. and Debasish P. (1993). “Wave Setup Measured in a River Mouth”. *Proceedings of the 11th Australasian Conference on Coastal and Ocean Engineering.* pp695-700 Engineers Australia, 1993.

Holland, G J (1980): An Analytical Model of the Wind and Pressure Profiles in Hurricanes. Monthly Weather Review, 108, pp 1212-1218.

Holland, G J (1997): The Maximum Potential Intensity of Tropical Cyclones. Journal of Atmospheric Science, Vol. 54, November, pp2519-2541.

Holman, R. A. (1986). “Extreme Value Statistics for Wave Run-up on a Natural Beach,” *Coastal Engineering*, Vol 9, No. 6, pp 527-544.

IPCC (2007): Summary for Policymakers. In; Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the intergovernmental Panel on Climate Change.

Irish J.L., Canizares R., Grosskopf W.G. and Williams B.P. (2004) “The Effect of Hindcasted Waves on Coastal Storm Water Levels During the Blizzard of 2003”. *Proceedings of the 8th International Workshop on Wave Hindcasting and Forecasting*. Hawaii 14-19 November 2004.

Nguyen X. T., Tanaka H. and Nagabayashi H. (2007). "Wave Setup at River and Inlet Entrances Due to an Extreme Event". *Proceedings of International Conference on Violent Flows.* Kyushu University, Fukuoka, Japan 2007.

Pugh, D T and Vassie, J M (1980): Applications of the Joint probability Method for Extreme Sea Level Computations. Proceedings of the Institution of Engineers, Part 2, Vol. 69.

SEA, Bureau of Meteorology and James Cook University (2001): Queensland Climate Change and Community Vulnerability to Tropical Cyclones. Ocean Hazards Assessment – Stage 1. Report Prepared for Queensland Government Departments.

SEA (2007): DRAFT SEQ Storm Tide Study Review.

USACE (2002). "Coastal Engineering Manual" United States Army Corps Engineers. EM 1110-2-1100.

Zhang, H.M., R.W. Reynolds, and J.J. Bates, 2006: "Blended and Gridded High Resolution Global Sea Surface Wind Speed and Climatology from Multiple Satellites: 1987 - Present". American Meteorological Society 2006 Annual Meeting, Paper #P2.23, Atlanta, GA, January 29 - February 2, 2006.

FIGURES

Figure 6.1 Measured Offshore Wave Conditions - Brisbane WRB

Figure 6.2 Measured Wind and Atmospheric Pressure - Brisbane Airport, July 2001

Figure 6.3 Residual Tides - Brisbane Bar, Mooloolaba and Southport, July 2001 Event

Figure 6.4 Delft3D Modelled Residual Tide – Wind and Pressure Forcing Only, July 2001

Figure 6.5 Delft3D Modelled Residual Tide – Wind, Pressure and Wave Forcing, July 2001

Figure 6.6 Delft3D Modelled Regional Wave Setup

Figure 6.7 Delft3D Modelled Regional Wave Setup – Northern Moreton Bay, 06:00

Figure 6.8 Delft3D Modelled Regional Wave Setup – Northern Moreton Bay, 08:00

Figure 6.9 Delft3D Modelled Regional Wave Setup – Northern Moreton Bay, 10:00

Figure 6.10 Delft3D Modelled Regional Wave Setup – Northern Moreton Bay, 12:00

Figure 6.11 Delft3D Modelled Regional Wave Setup – Northern Moreton Bay, 14:00

Figure 6.12 Delft3D Modelled Regional Wave Setup – Northern Moreton Bay, 16:00

Figure 6.13 Delft3D Modelled Regional Wave Setup – Northern Moreton Bay, 18:00

Figure 6.14 Regional Wave Setup Regression Models

Figure 7.1 SWAN Model Calibration - Moreton Bay WRB

Figure 7.2 Reported Output Locations

Figure 7.3 100-Year ARI Non-Cyclonic Design Water Levels (mAHD)

Figure 8.1 Coast-Crossing Cyclone Statistics

Figure 8.2 Coast-Parallel Cyclone Statistics

Figure 8.3 Delft3D Model Design Cyclone Tracks

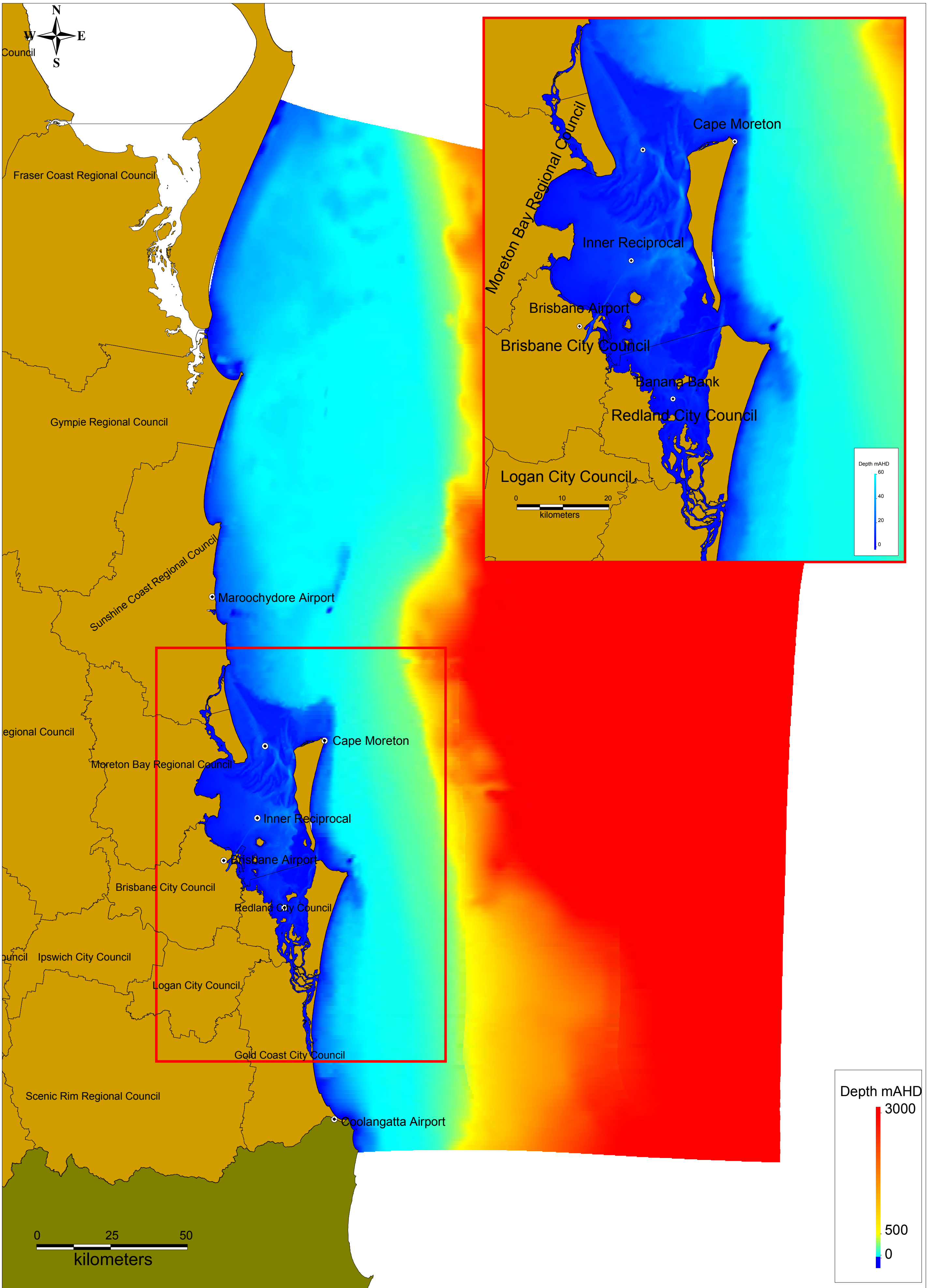
Figure 8.4 100-Year ARI Cyclonic Design Water Levels (mAHD) – Present Climate Condition

Figure 8.5 100-Year ARI Cyclonic Design Water Levels (mAHD) – Greenhouse Related Climate Change Conditions

Figure 9.1 100-Year ARI Cyclonic Design Water Levels (mAHD) – Non-Cyclonic and Cyclonic Comparison

Figure 10.1 100-Year ARI, 100-Year (2109) Planning Levels (mAHD) Greenhouse Related Climate Change Conditions, Includes Freeboard and SLR

FIGURES



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LOCALITY PLAN AND DTM

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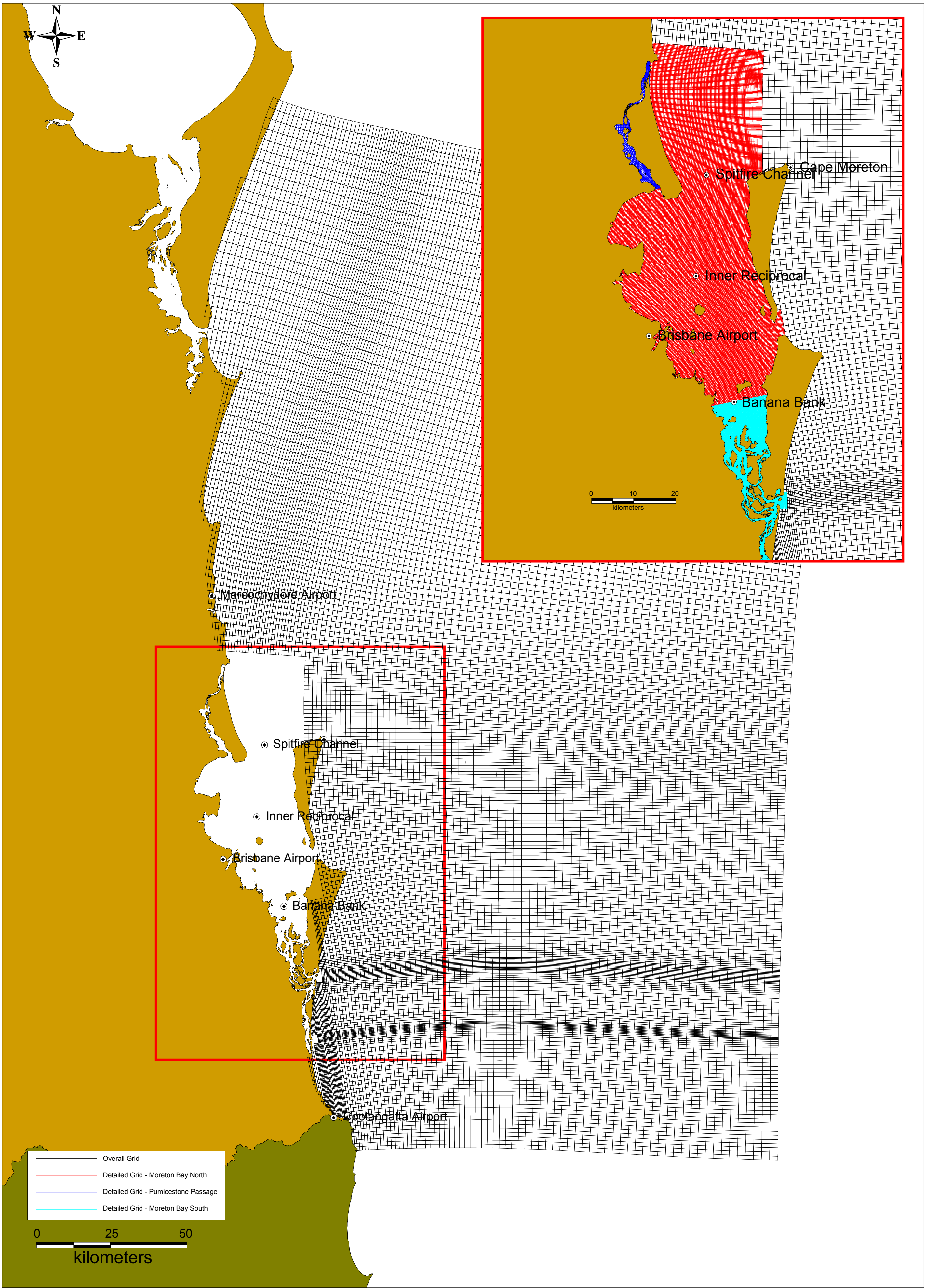

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DELFT3D DOMAIN DECOMPOSITION GRIDS

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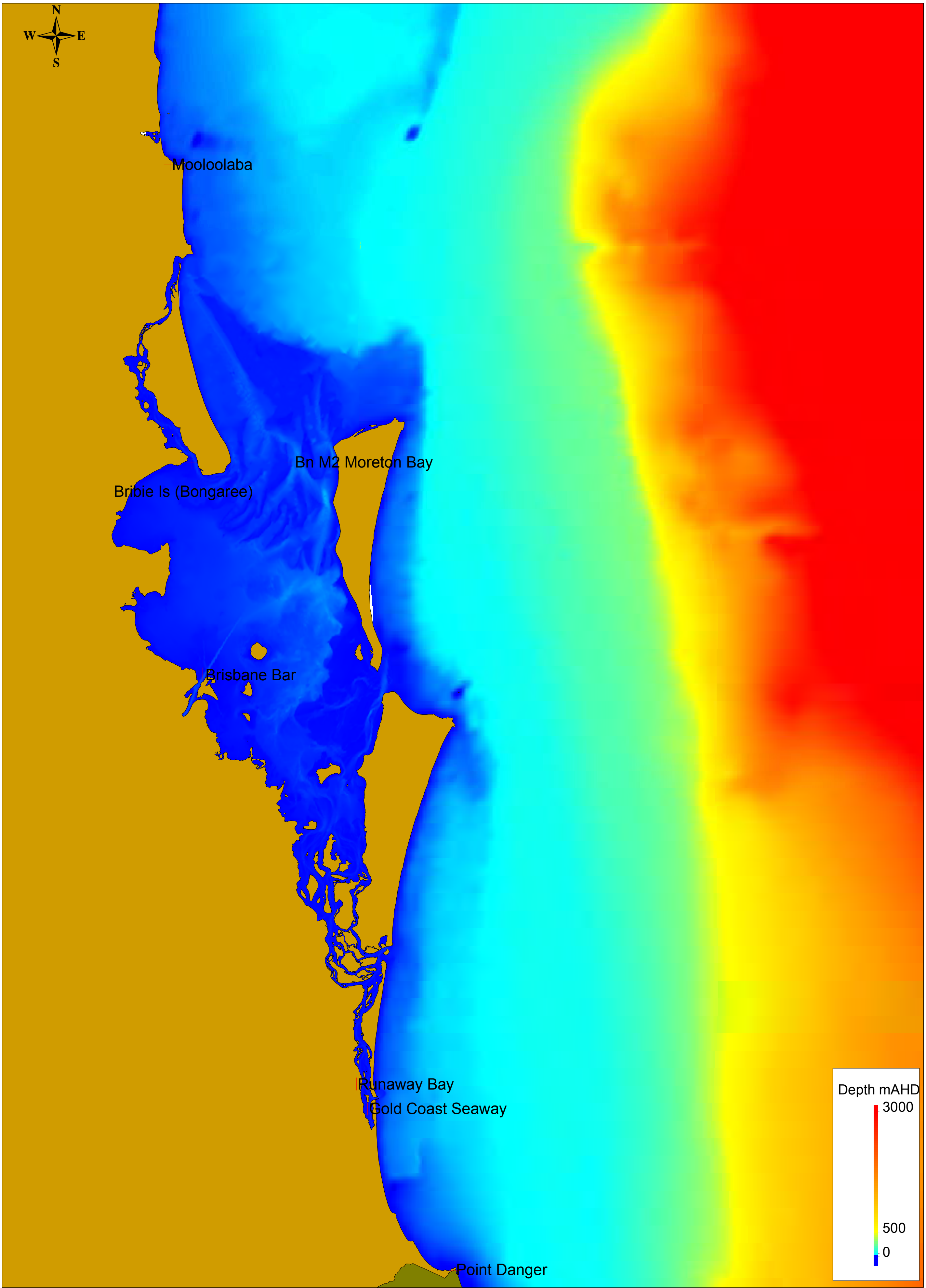
Figure 5.1



Storm Tide Hazard Study - Moreton Bay Regional Council

TIDAL CALIBRATION LOCATIONS

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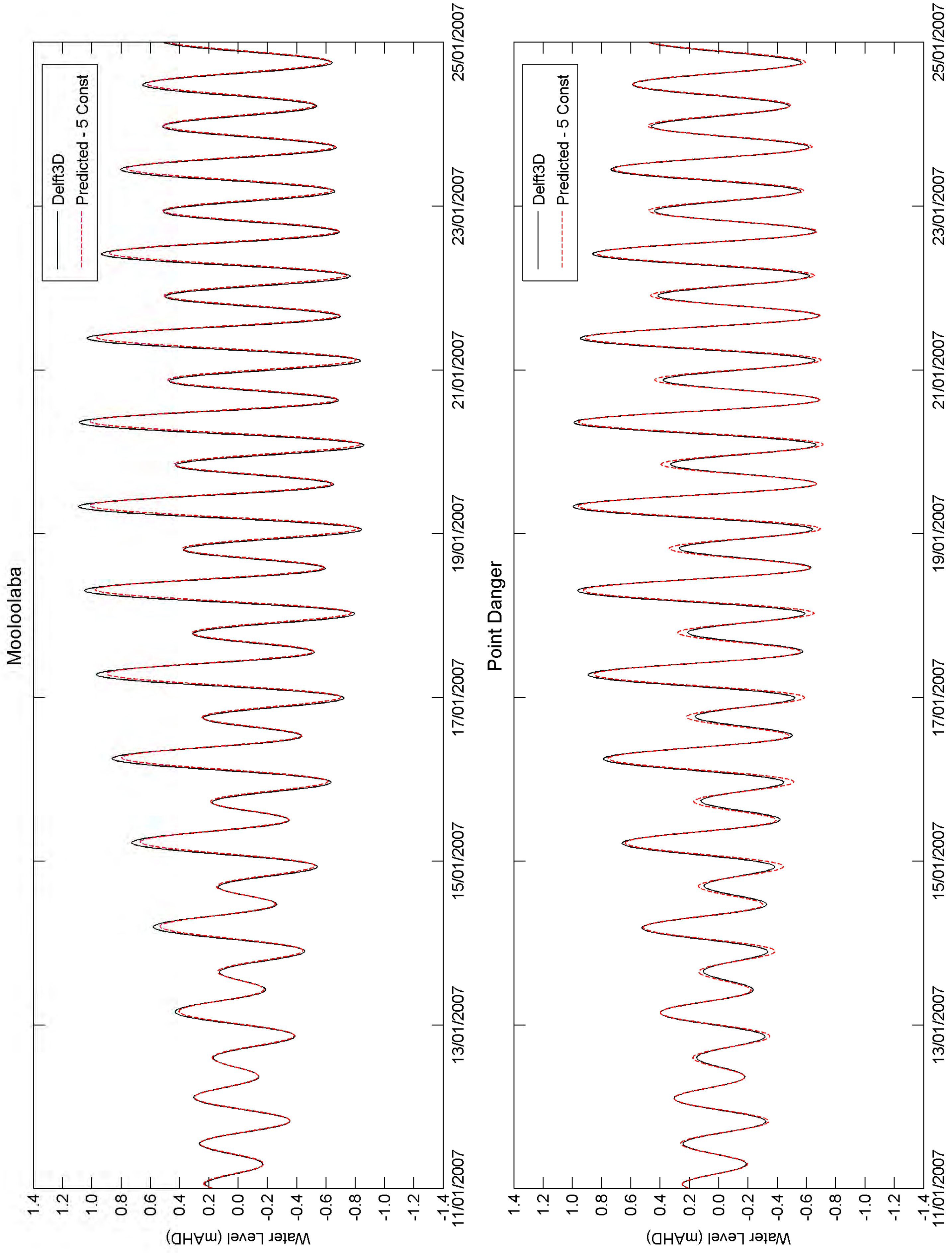
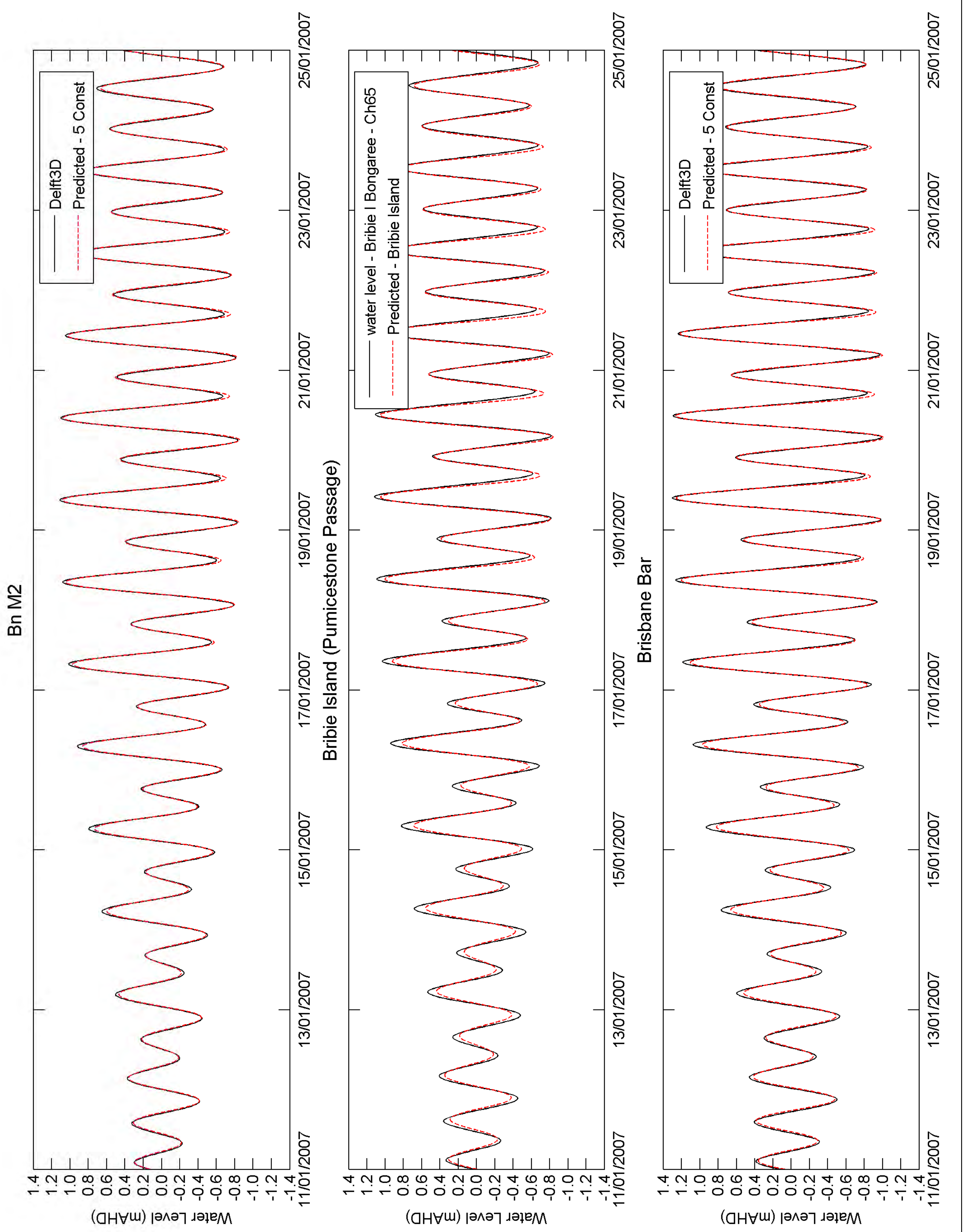
Figure 5.2



Mooloolaba
Point Danger
Delft3D
Predicted - 5 Const
Water Level (mAHD)
11/01/2007
13/01/2007
15/01/2007
17/01/2007
19/01/2007
21/01/2007
23/01/2007
25/01/2007



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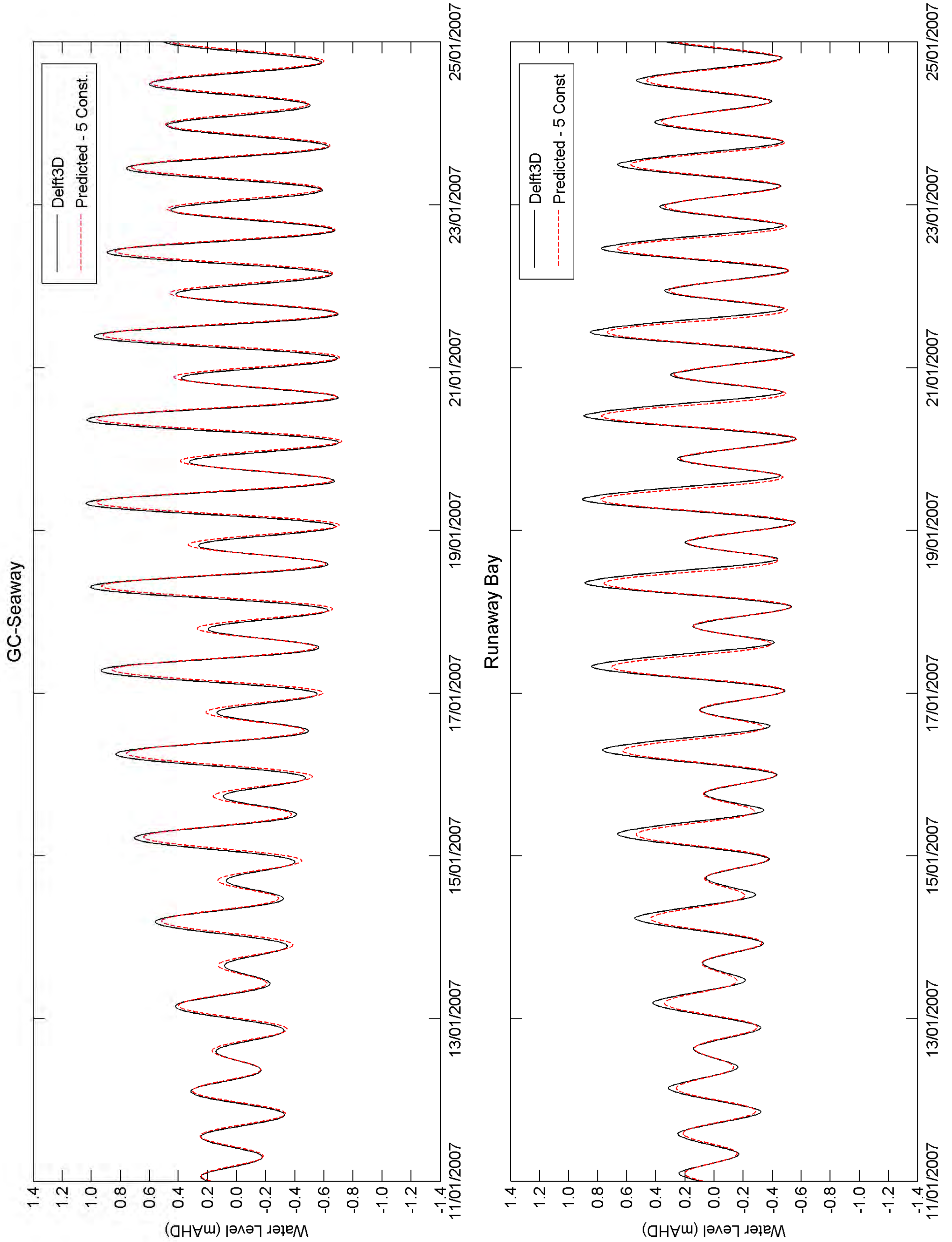
Storm Tide Hazard Study - Moreton Bay Regional Council

TIDE CALIBRATION

Moreton Bay Sites

Figure 5.4

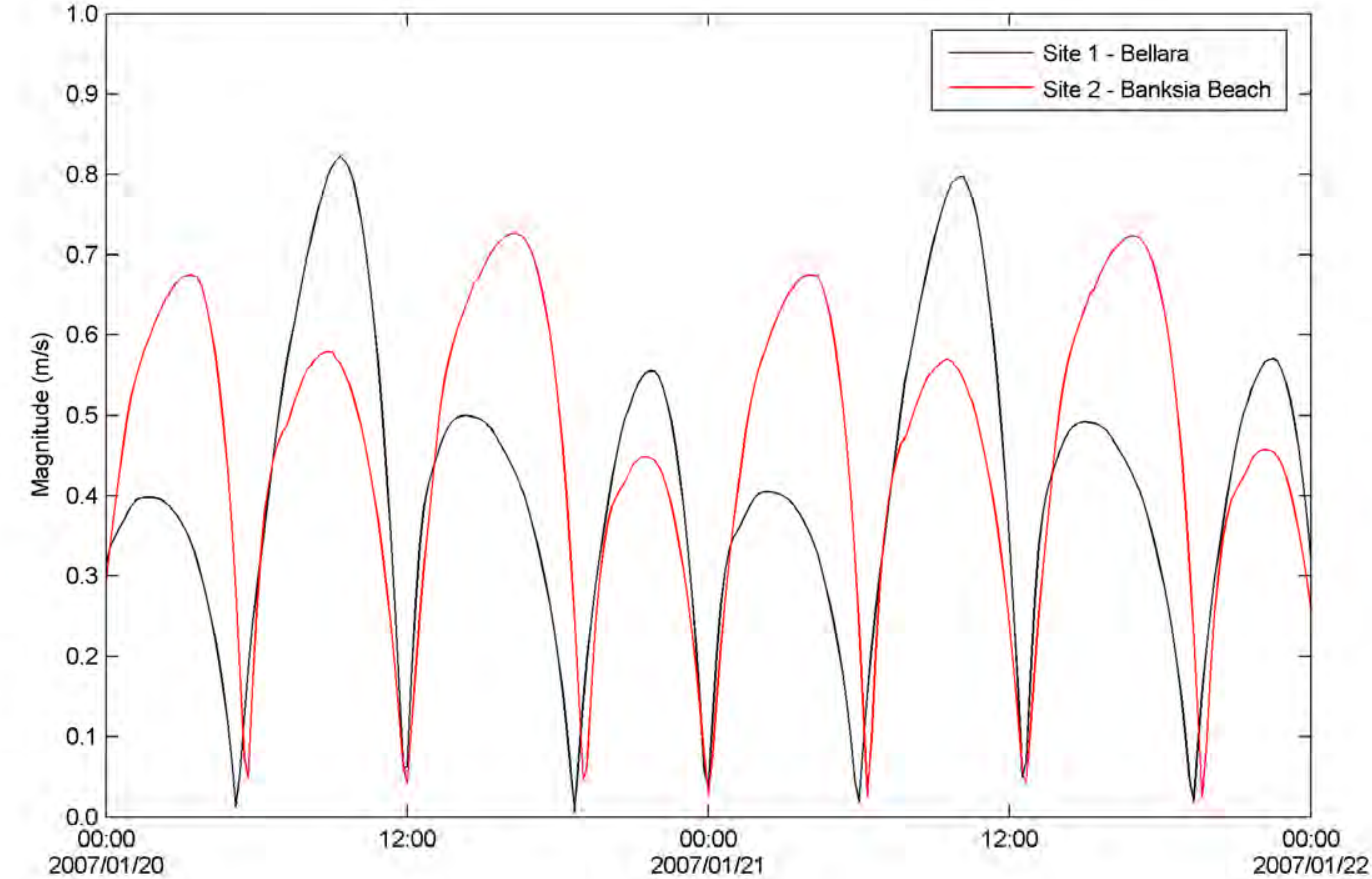


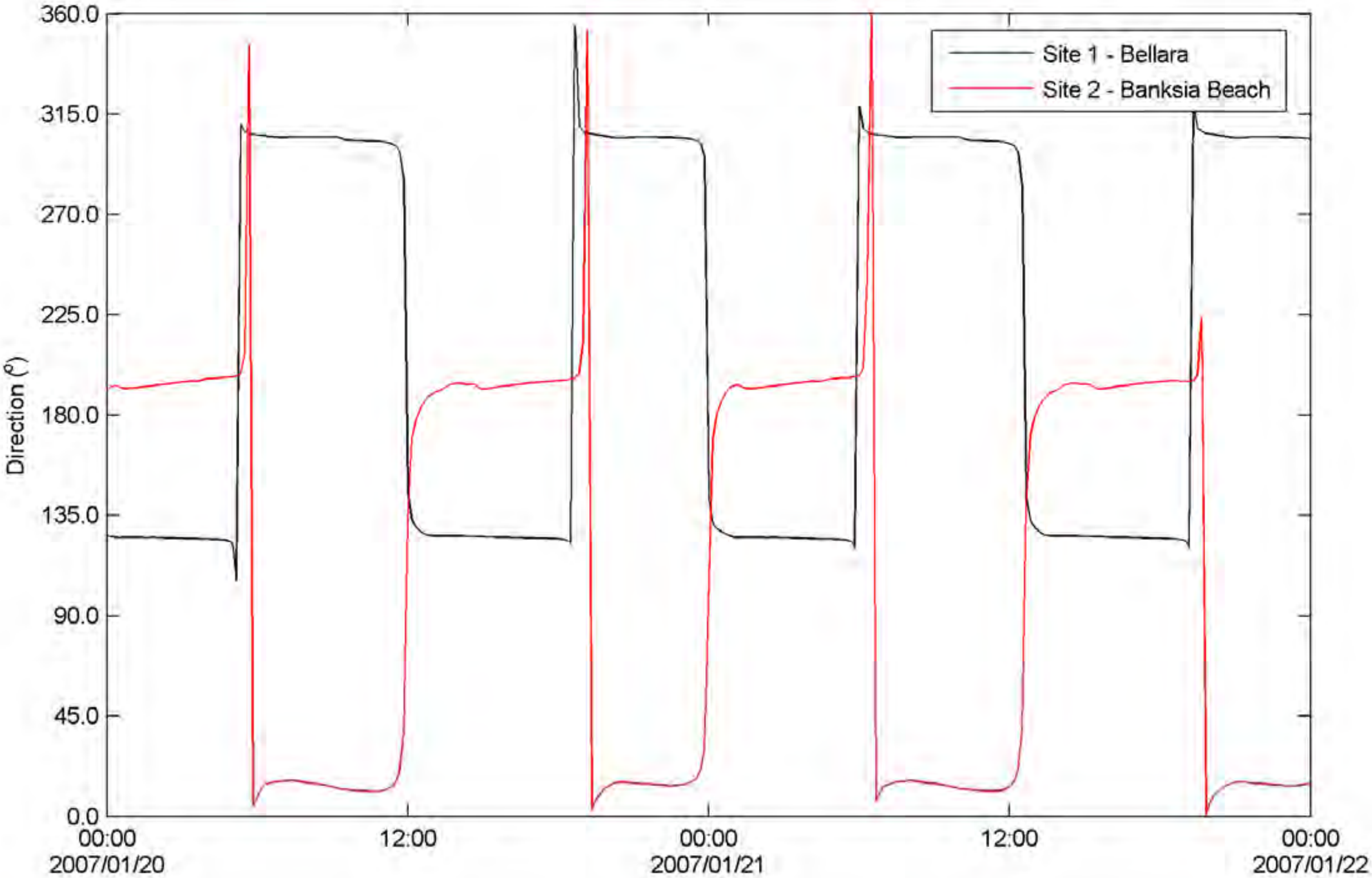
Storm Tide Hazard Study - Moreton Bay Regional Council

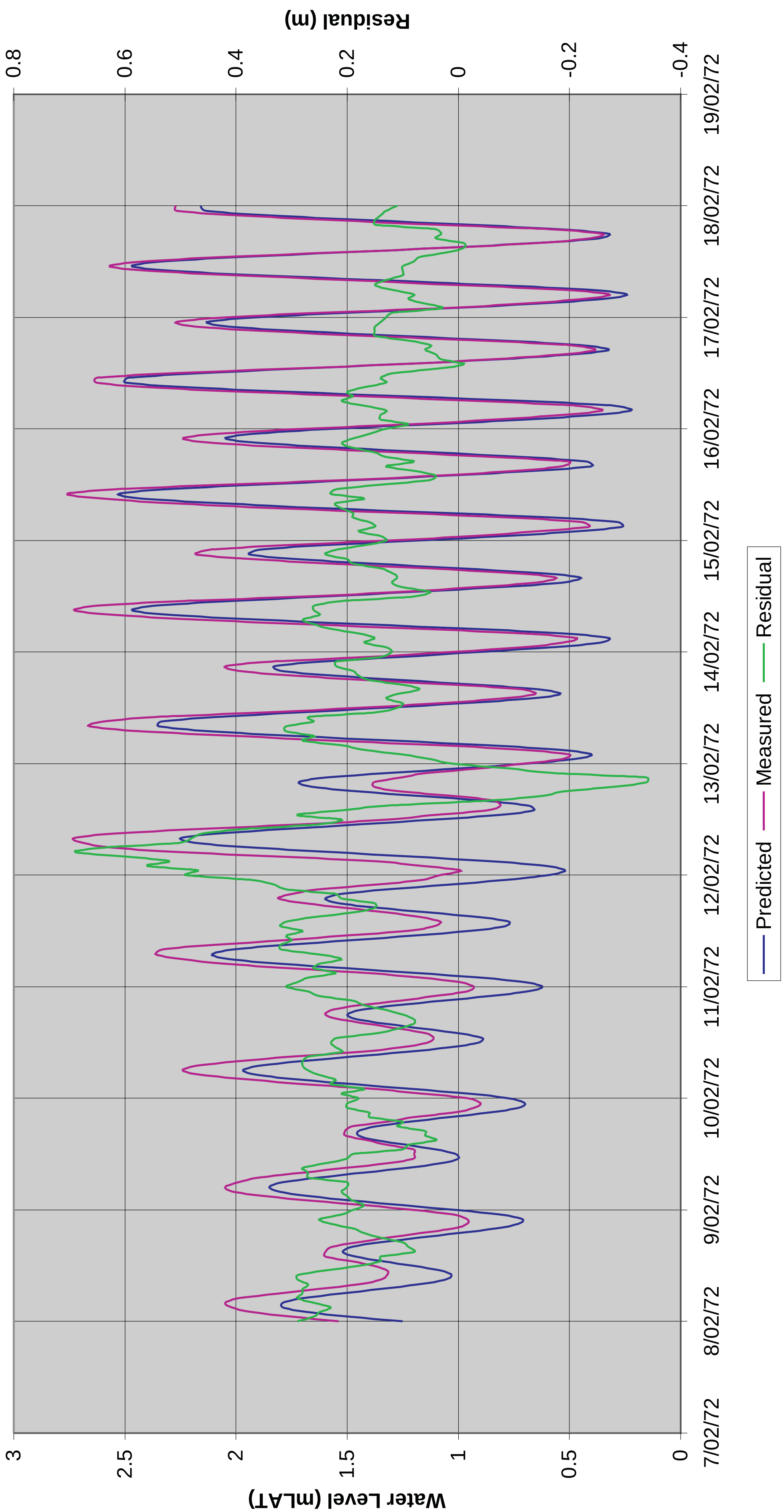
TIDE CALIBRATION

Broadwater Sites

Figure 5.5

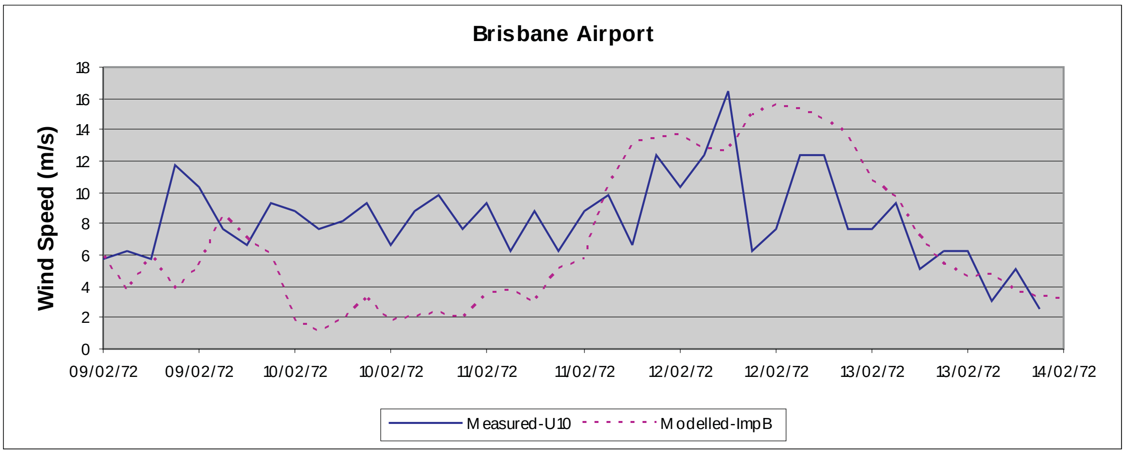

Site 1 - Bellara
Site 2 - Banksia Beach
Magnitude (m/s)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
00:00
2007/01/20
12:00
00:00
2007/01/21
12:00
00:00
2007/01/22

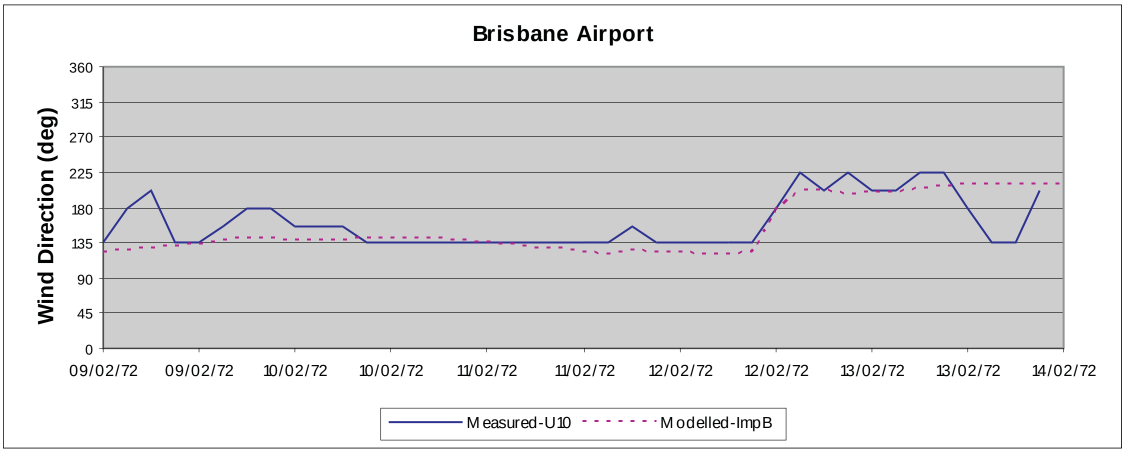

Site 1 - Bellara
Site 2 - Banksia Beach
Direction (°)
360.0
315.0
270.0
225.0
180.0
135.0
90.0
45.0
0.0
00:00
2007/01/20
12:00
00:00
2007/01/21
12:00
00:00
2007/01/22

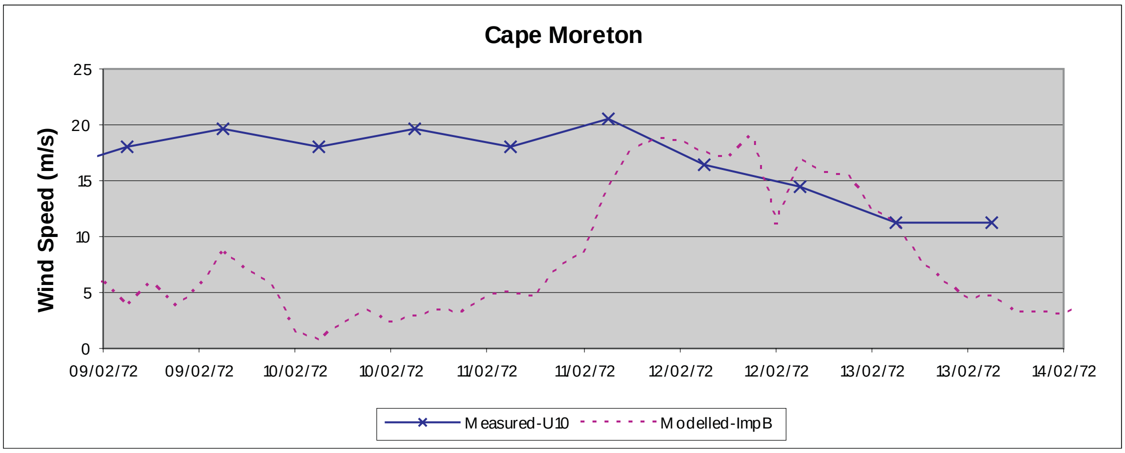


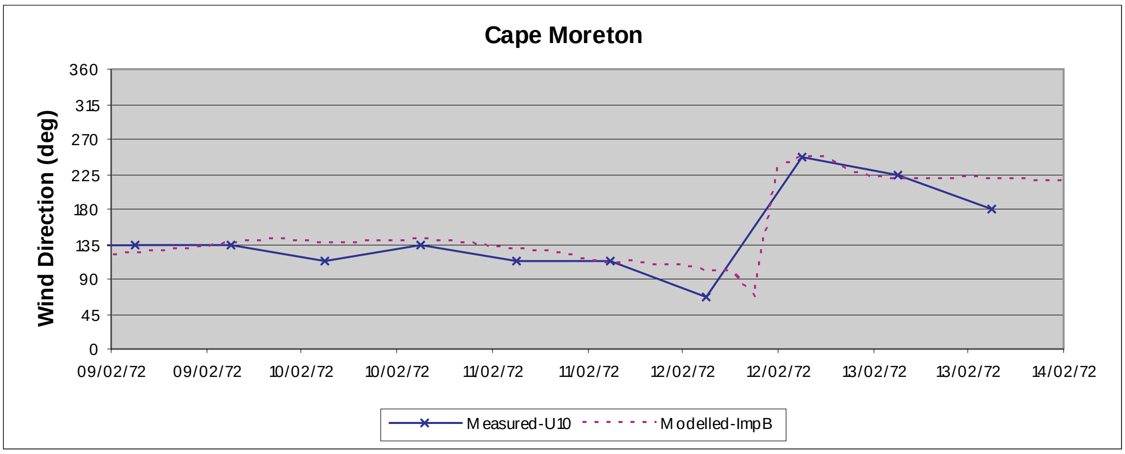
Storm Tide Hazard Study - Moreton Bay Regional Council
CYCLONE DAISY WATER LEVEL - BRISBANE BAR

Figure 5.7

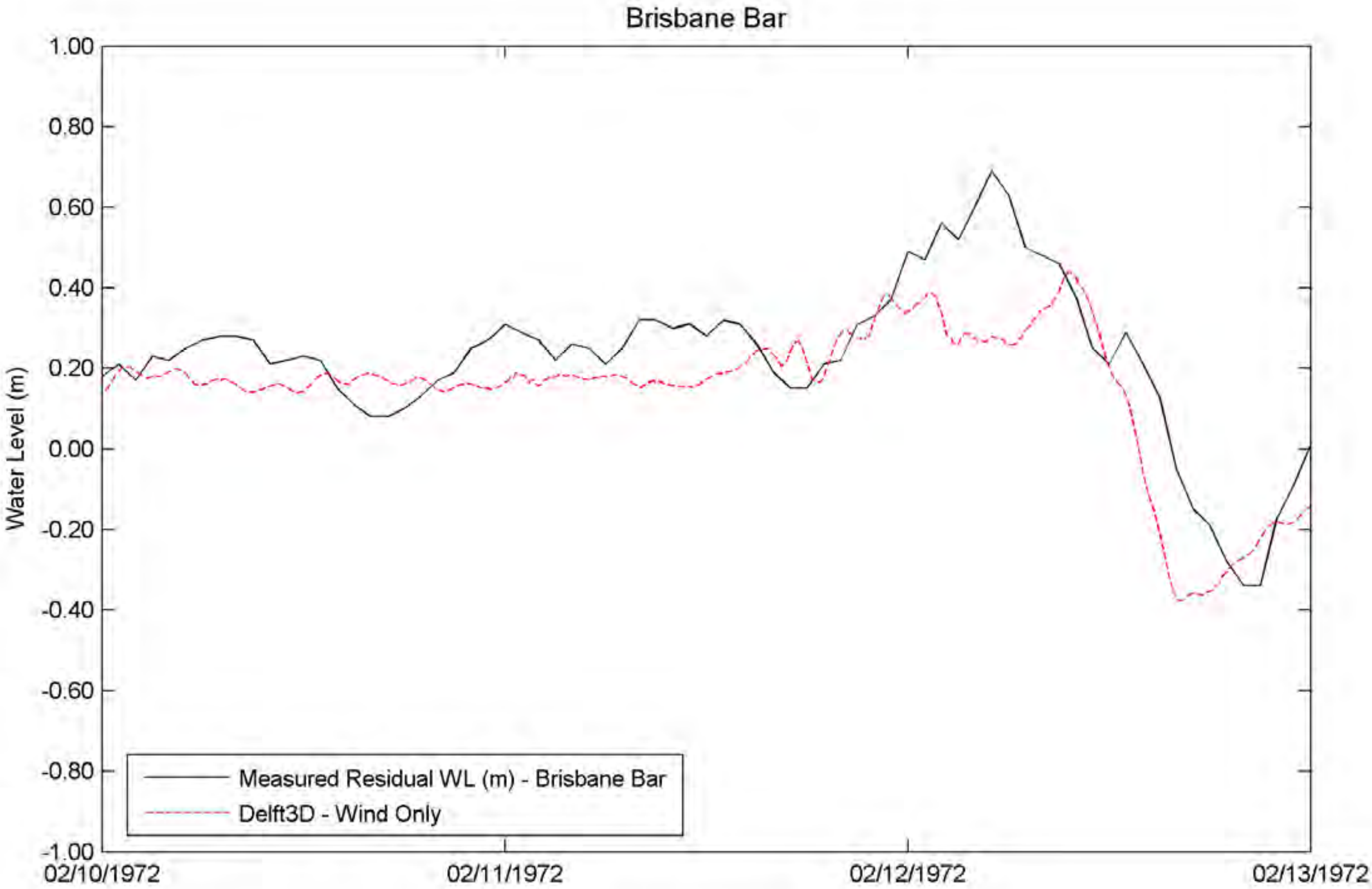


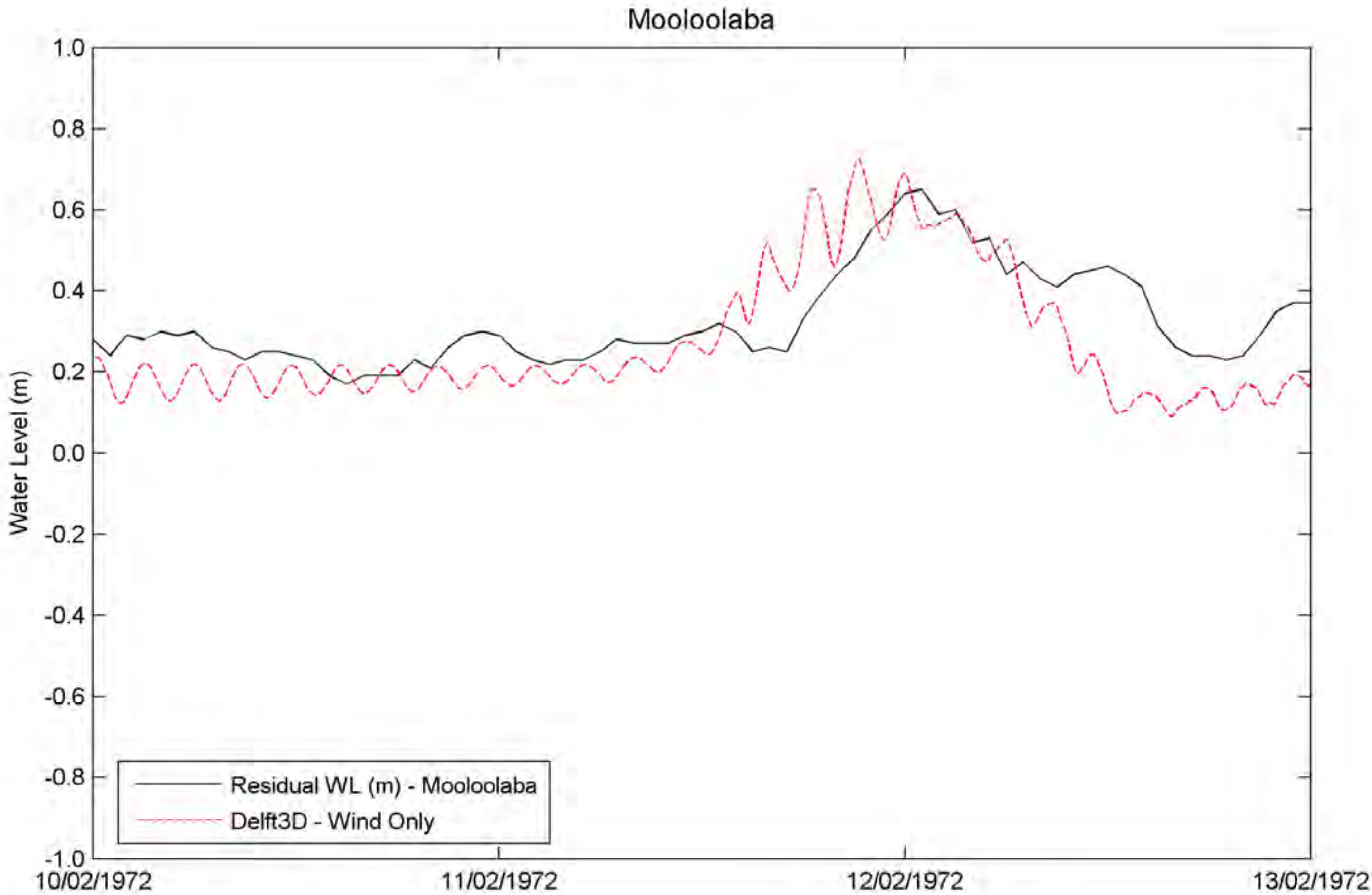




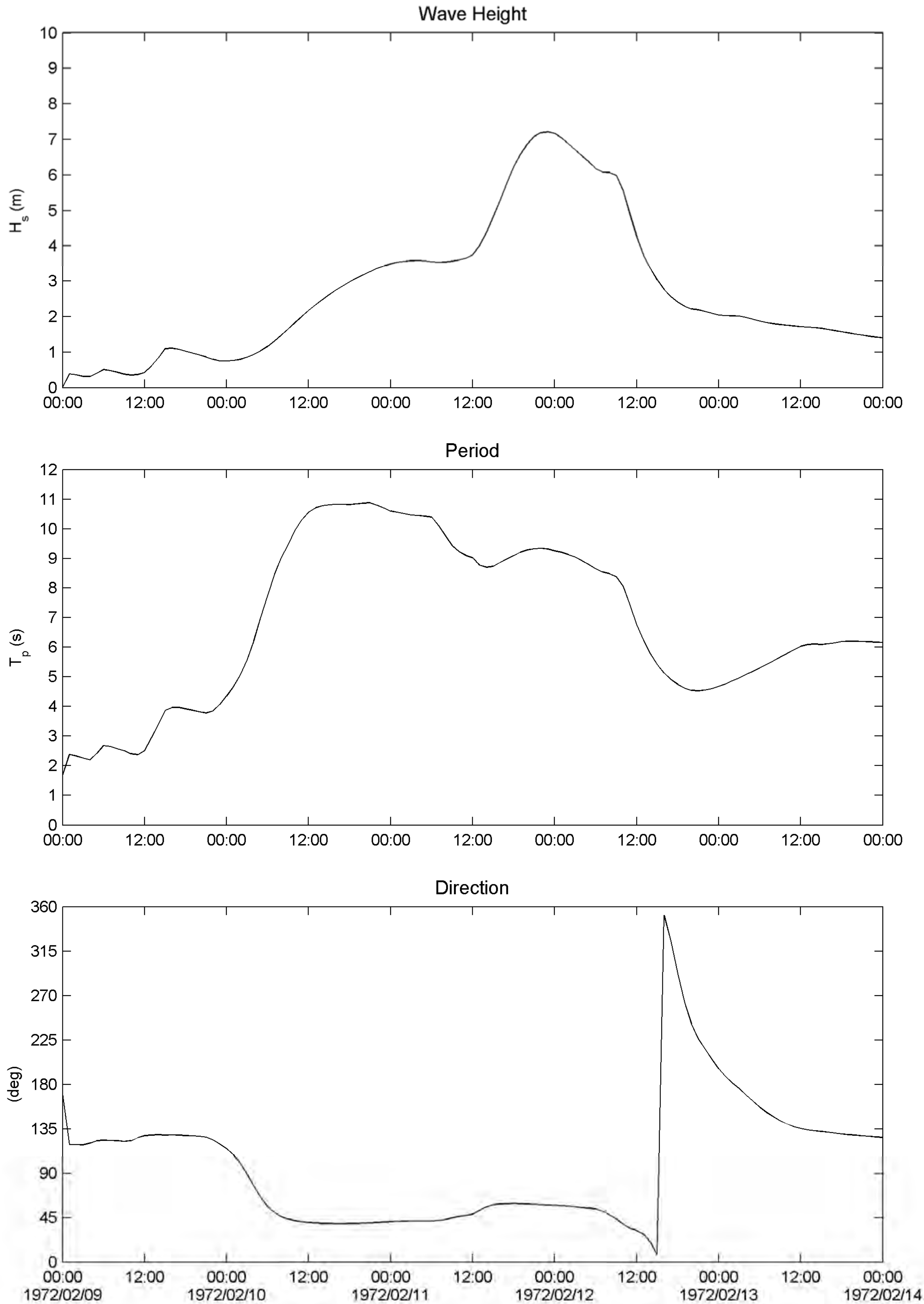


Storm Tide Hazard Study - Moreton Bay Regional Council
MEASURED AND MODELLED WIND CONDITIONS
CYCLONE DAISY
Figure 5.8

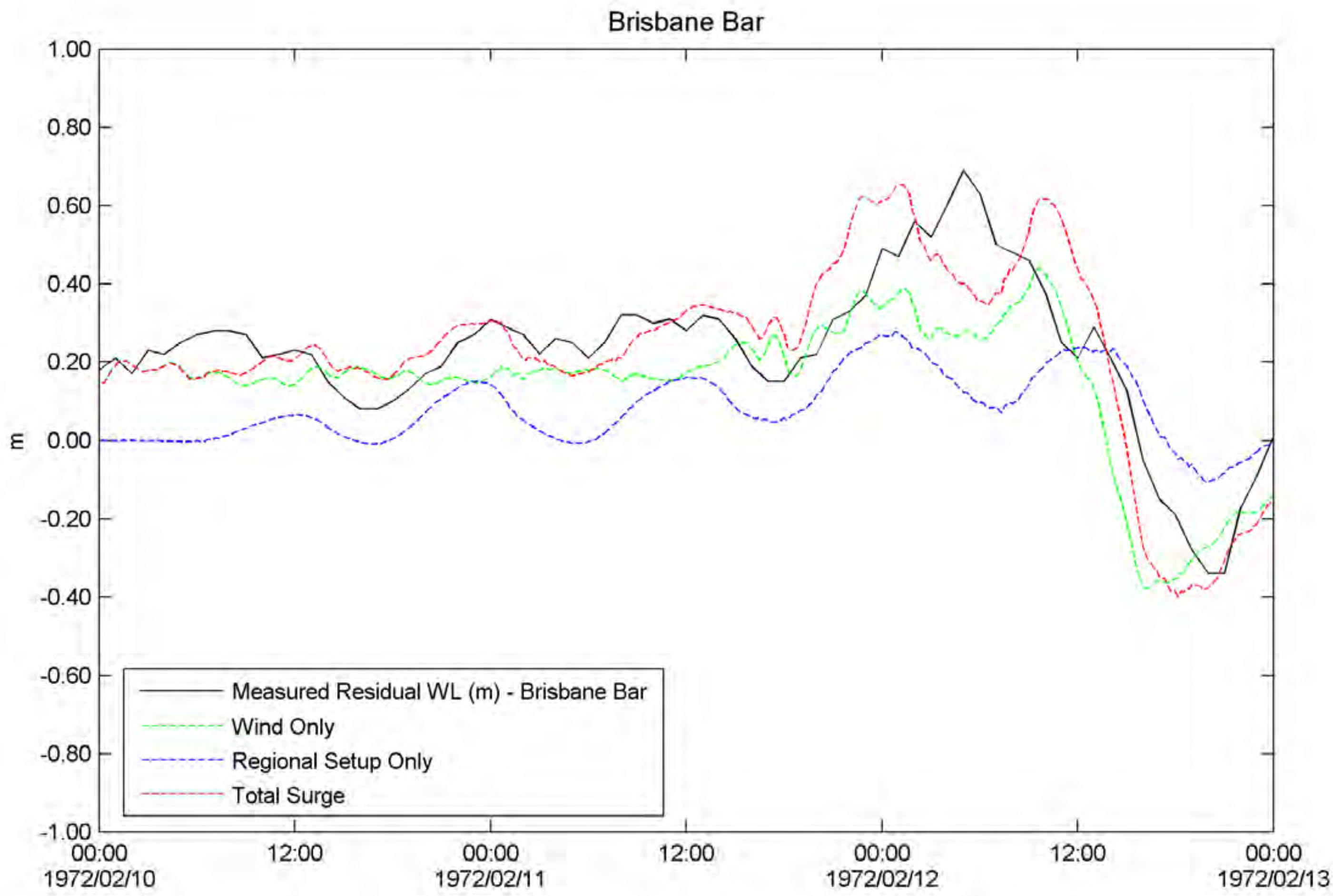




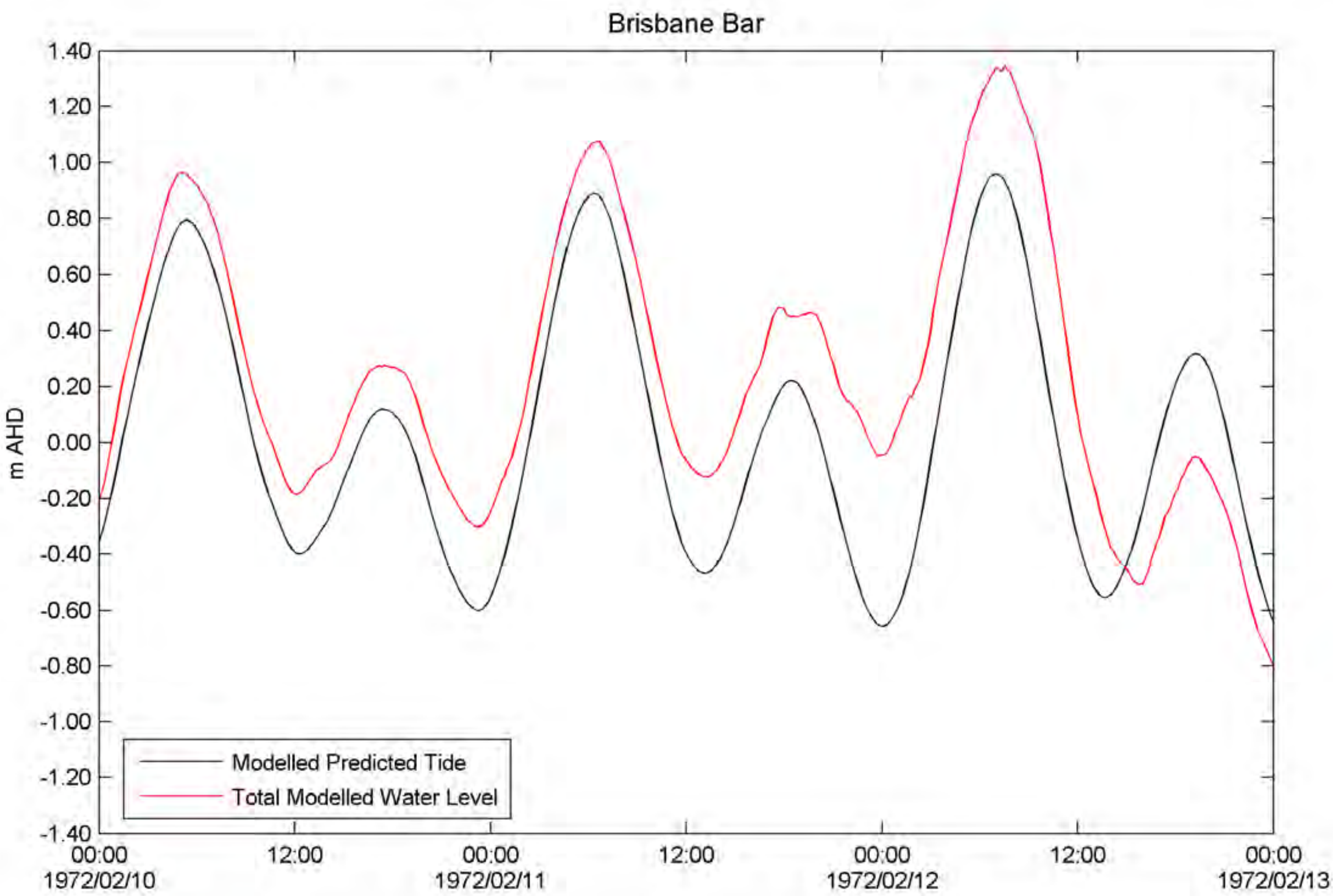
Storm Tide Hazard Study - Moreton Bay Regional Council
TC DAISY
Residual Tide - No Regional Wave Setup
Figure 5.9



Storm Tide Hazard Study - Moreton Bay Regional Council
TC DAISY MODELLED WAVE CONDITIONS
Northern Entrance to Morton Bay (Depth 60m AHD)
Figure 5.10



Brisbane Bar
m
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
Measured Residual WL (m) - Brisbane Bar
Wind Only
Regional Setup Only
Total Surge
00:00
1972/02/10
12:00
00:00
1972/02/11
12:00
00:00
1972/02/12
12:00
00:00
1972/02/13



Brisbane Bar
m AHD
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
Modelled Predicted Tide
Total Modelled Water Level
00:00
1972/02/10
12:00
00:00
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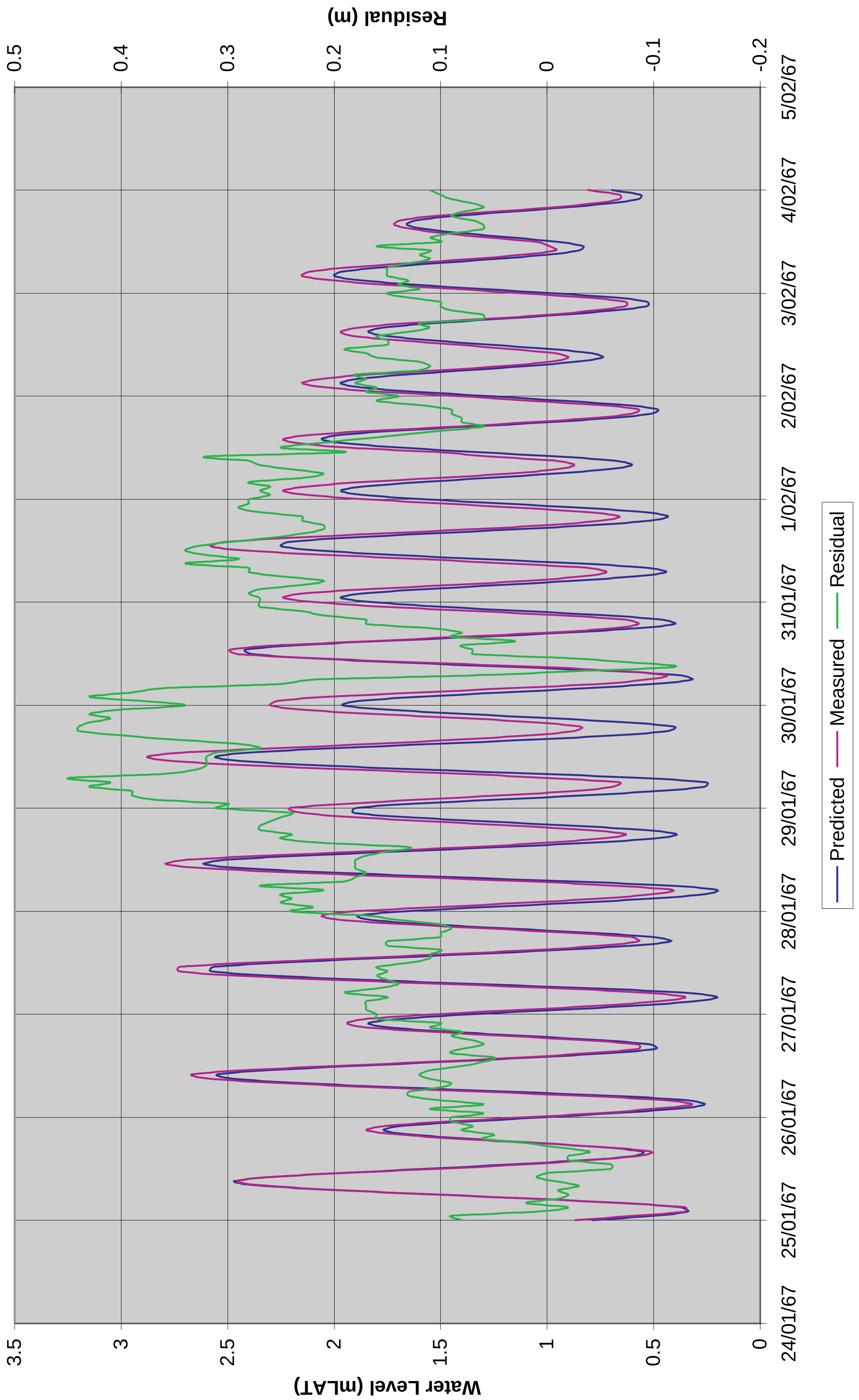
12:00
00:00
1972/02/13



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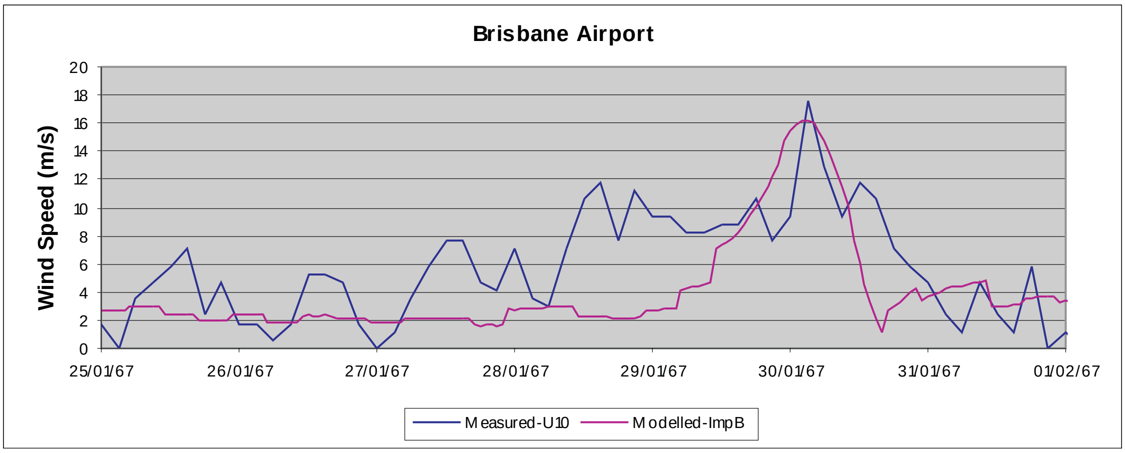
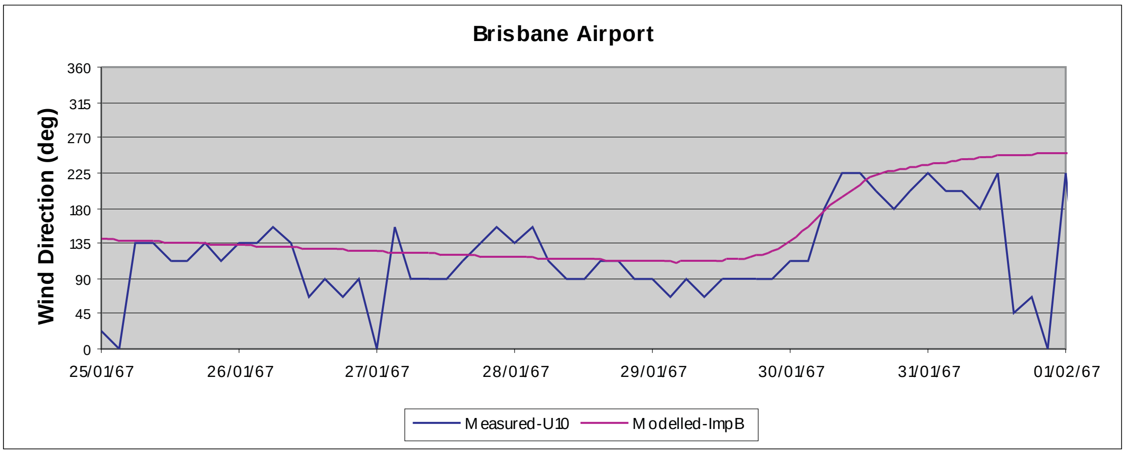
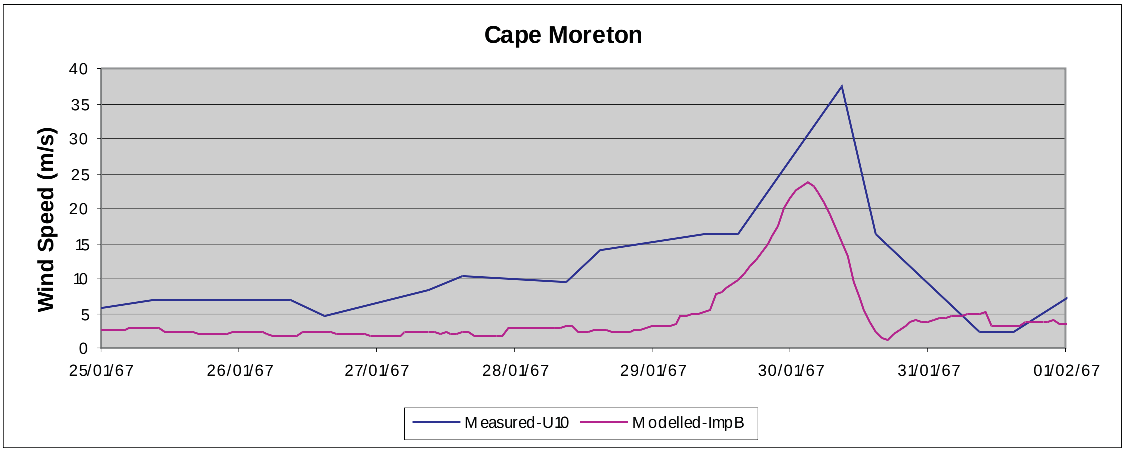
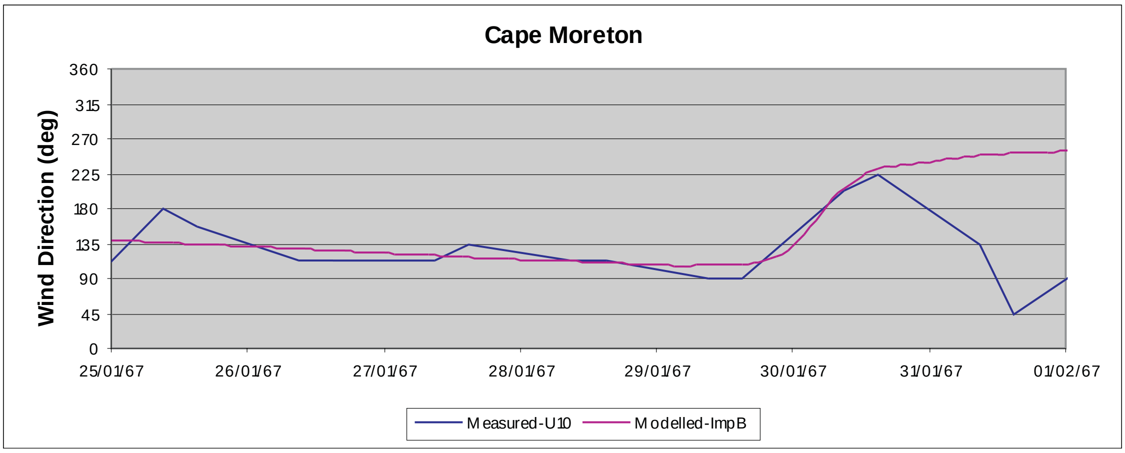
Storm Tide Hazard Study - Moreton Bay Regional Council
CYCLONE DINAH WATER LEVEL - BRISBANE BAR

Figure 5.12

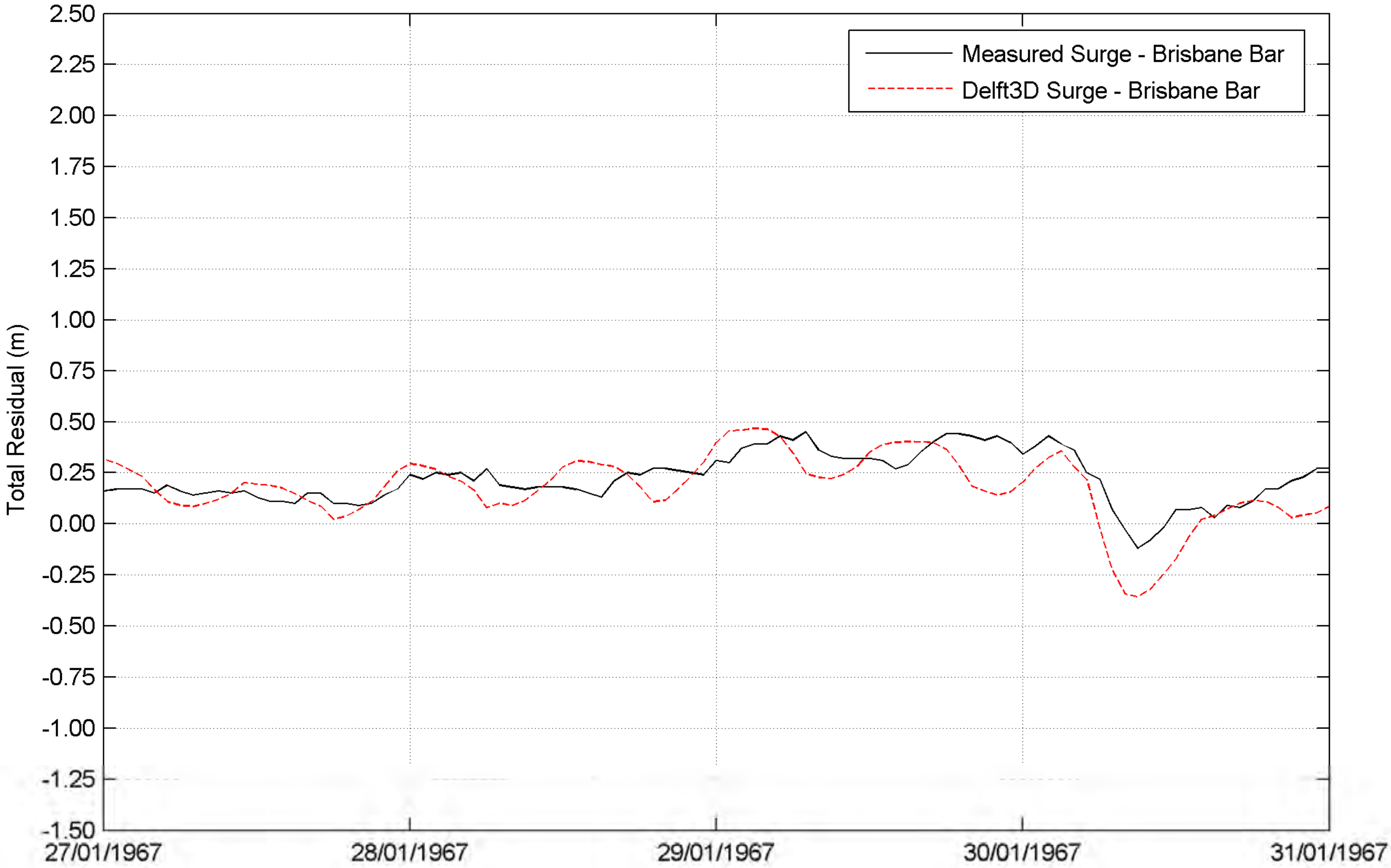


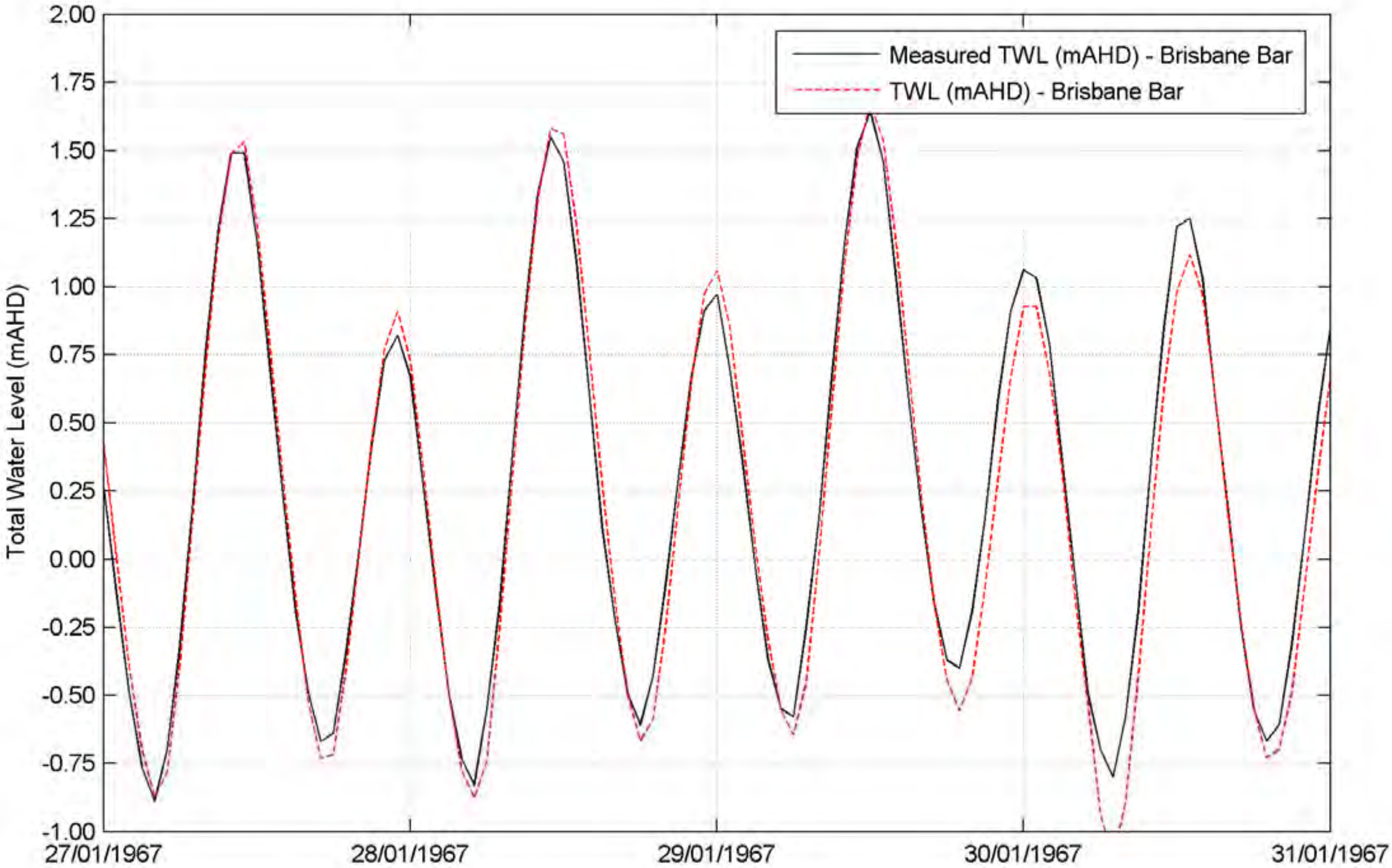




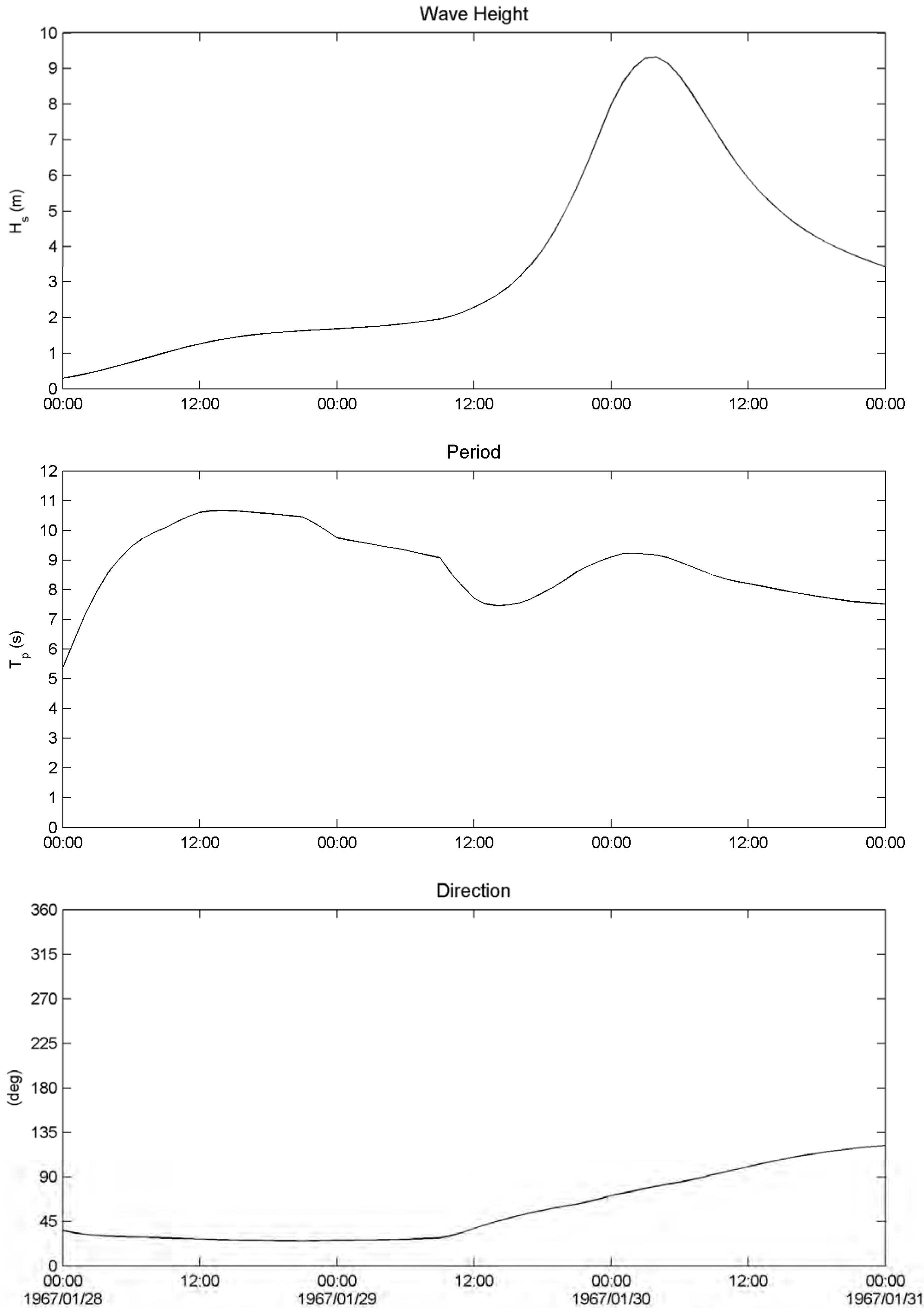


Storm Tide Hazard Study - Moreton Bay Regional Council
MEASURED AND MODELLED WIND CONDITIONS
CYCLONE DINAH
Figure 5.13





Storm Tide Hazard Study - Moreton Bay Regional Council
TROPICAL CYCLONE DINAH
Modelled and Measured Storm Tide - Brisbane Bar
Figure 5.14



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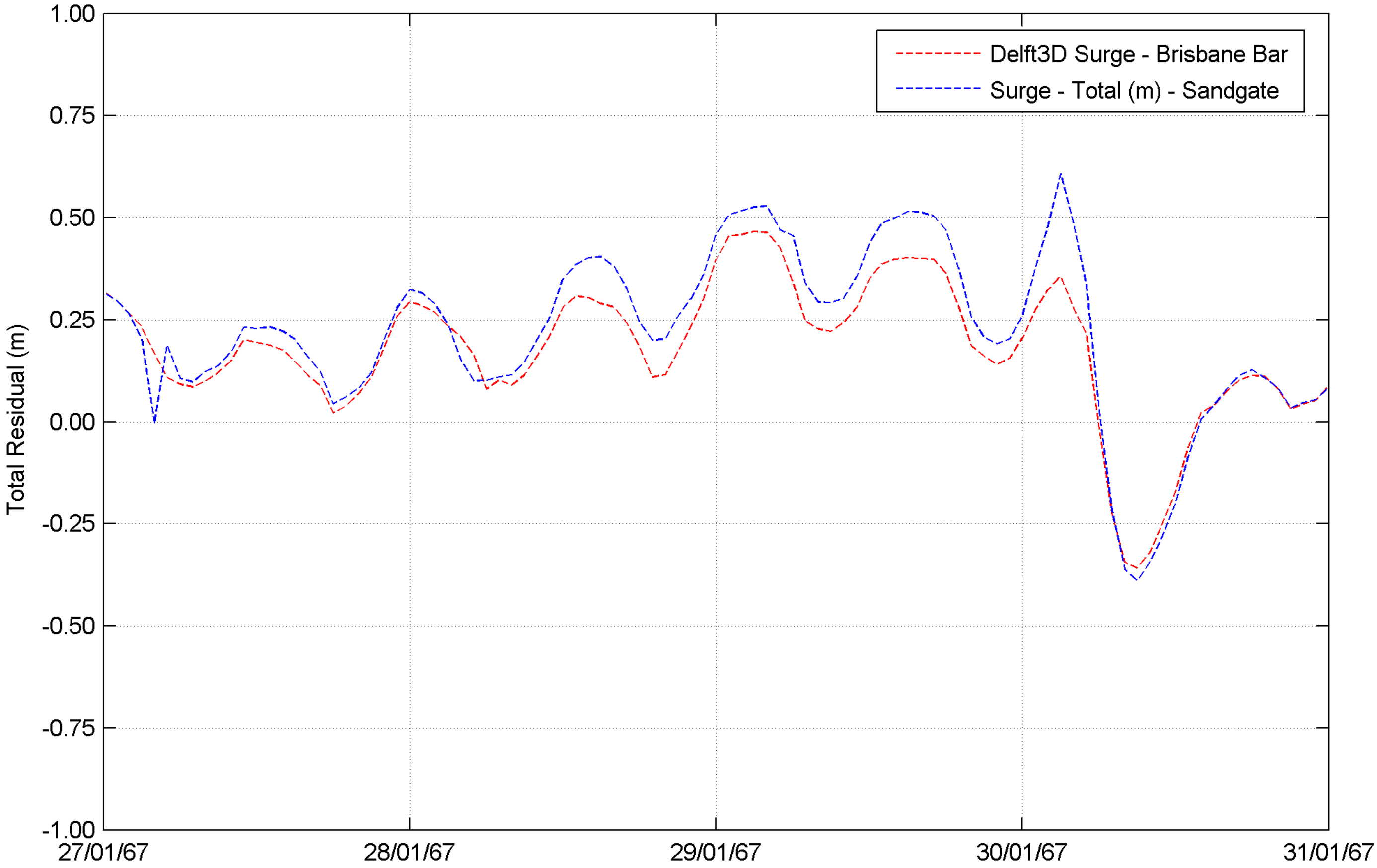
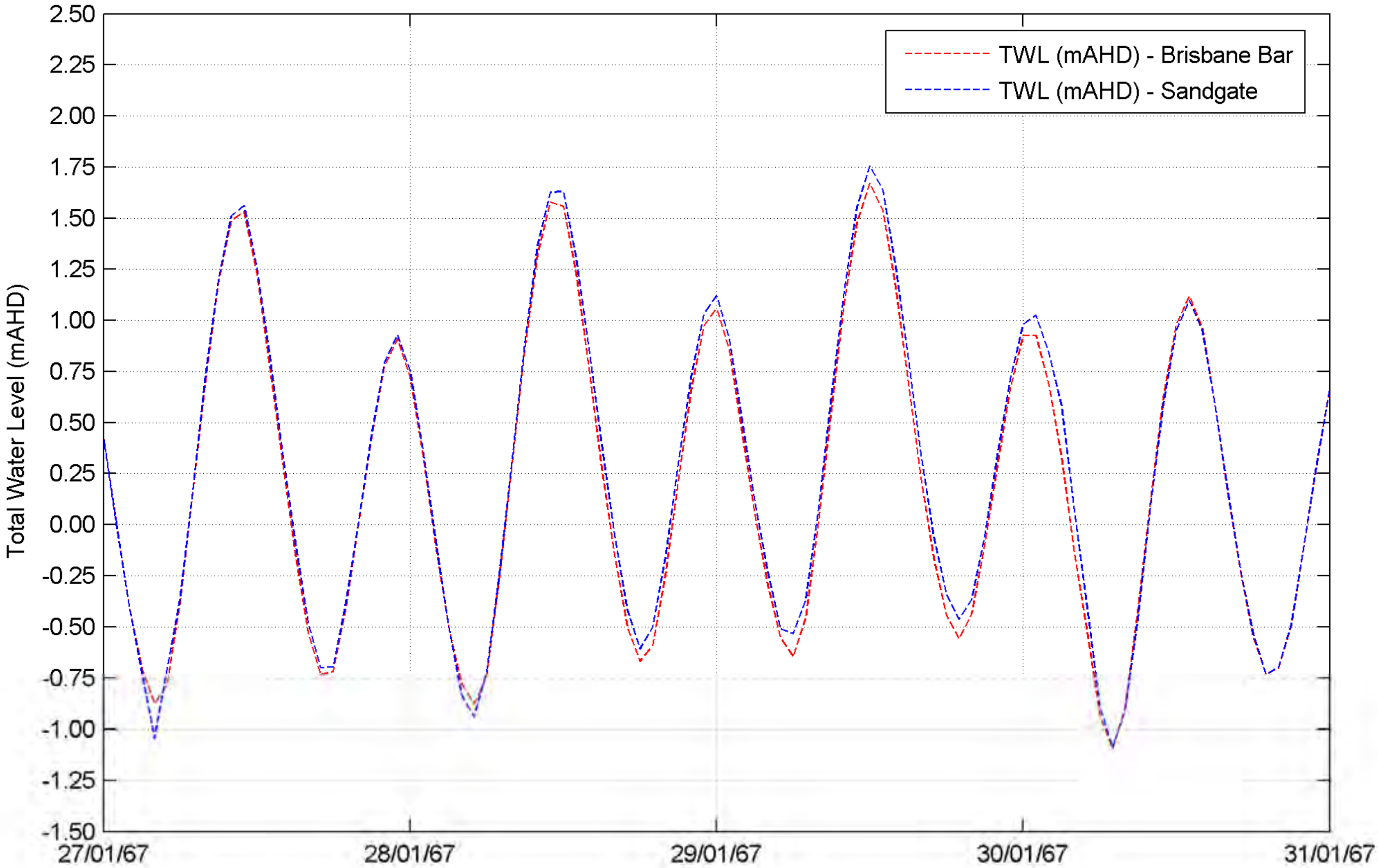
Storm Tide Hazard Study - Moreton Bay Regional Council

TC DINAH MODELLED WAVE CONDITIONS

Northern Entrance to Morton Bay (Depth 60m AHD)

Figure 5.15

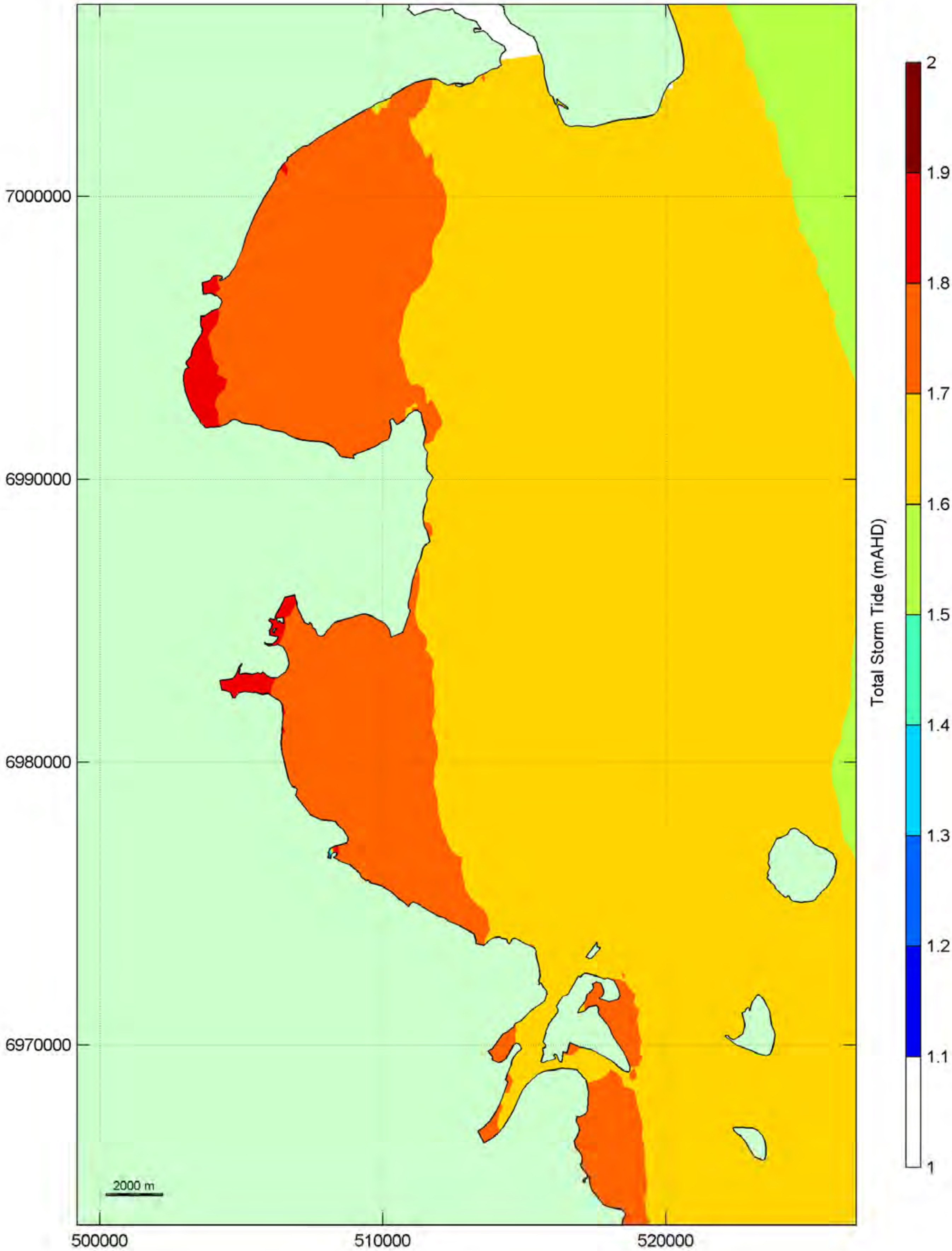




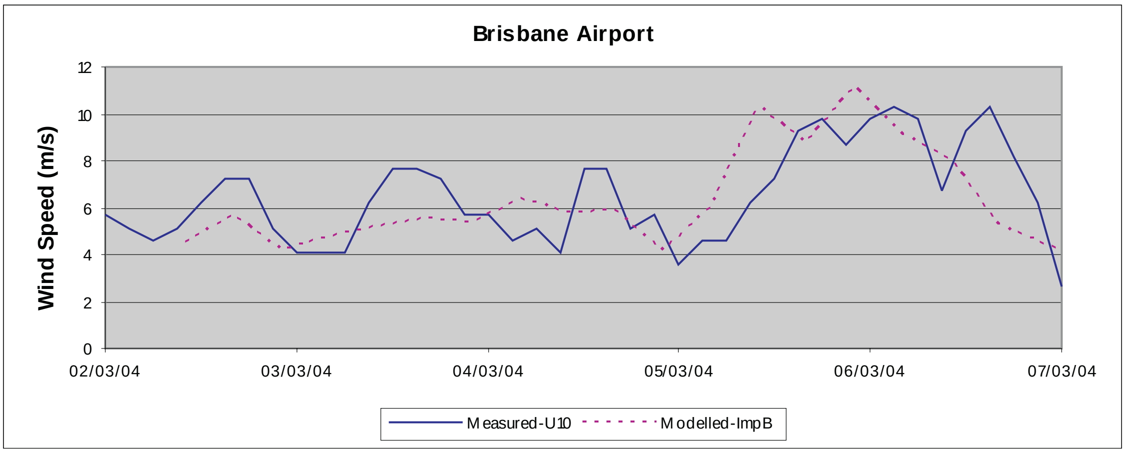
TROPICAL CYCLONE DINAH

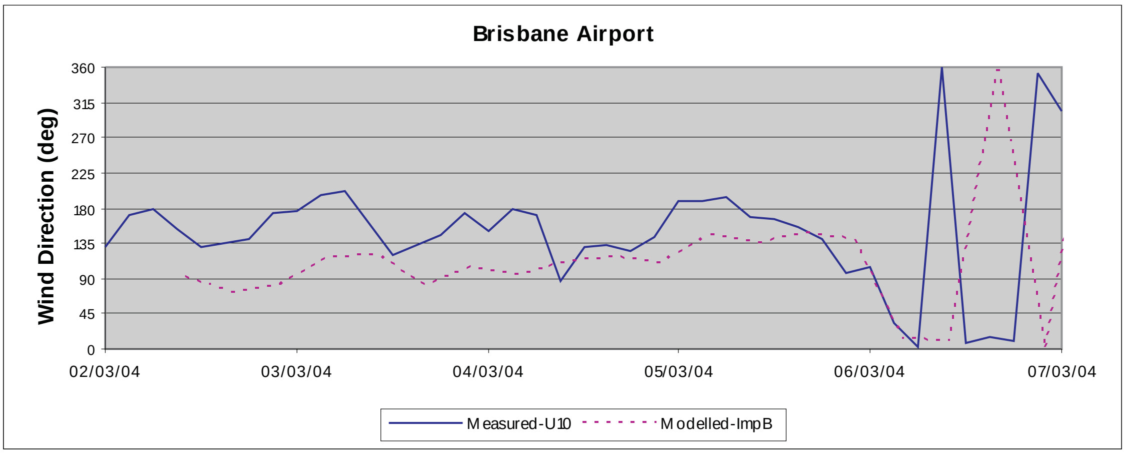
Comparision Between Storm Tide at Brisbane Bar and Sandgate

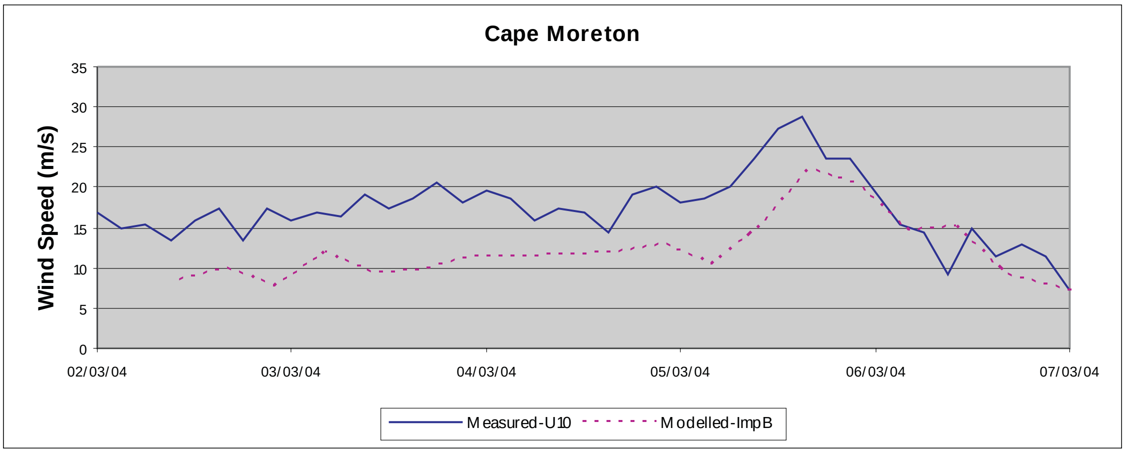
Figure 5.16

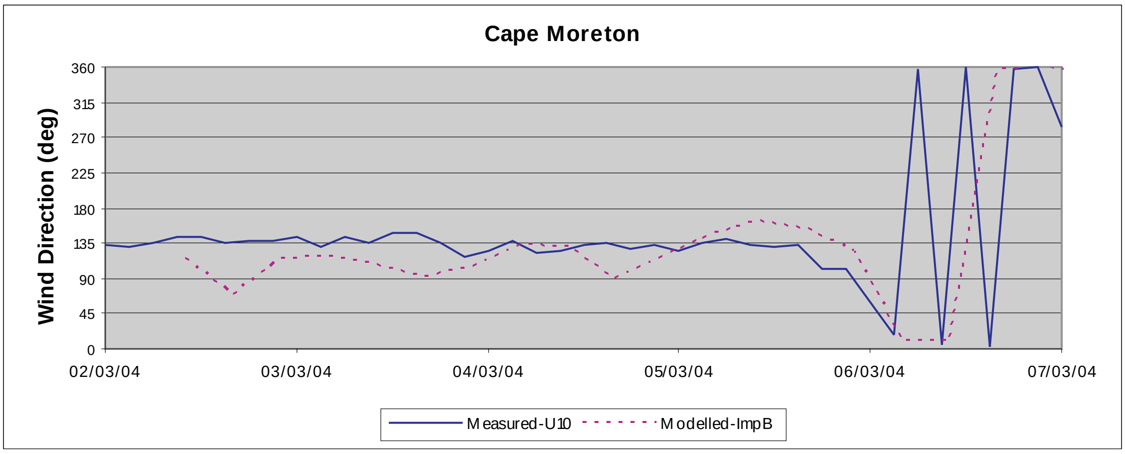


Storm Tide Hazard Study - Moreton Bay Regional Council
TROPICAL CYCLONE DINAH
Total Peak Water Level: 12:00 29/01/1967 (Excluding Local Wave Setup)
Figure 5.17

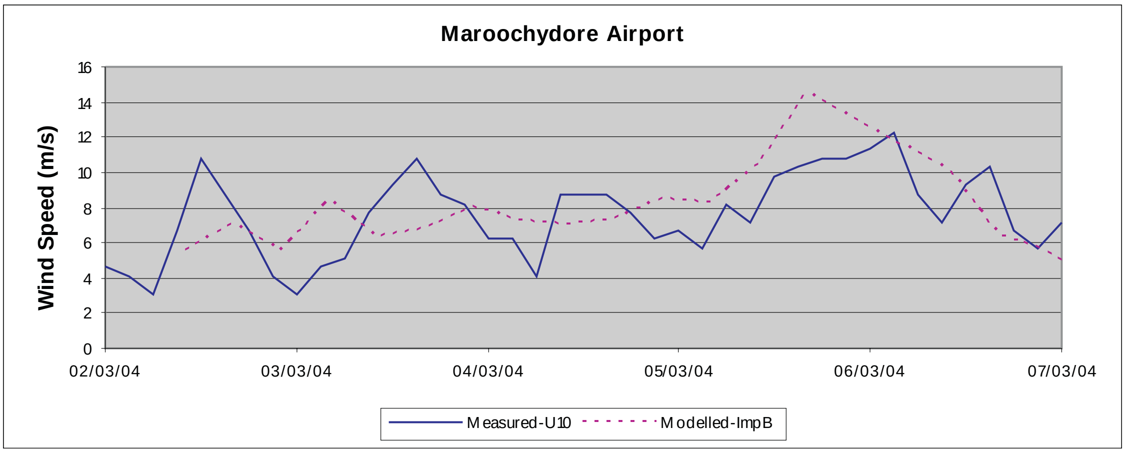


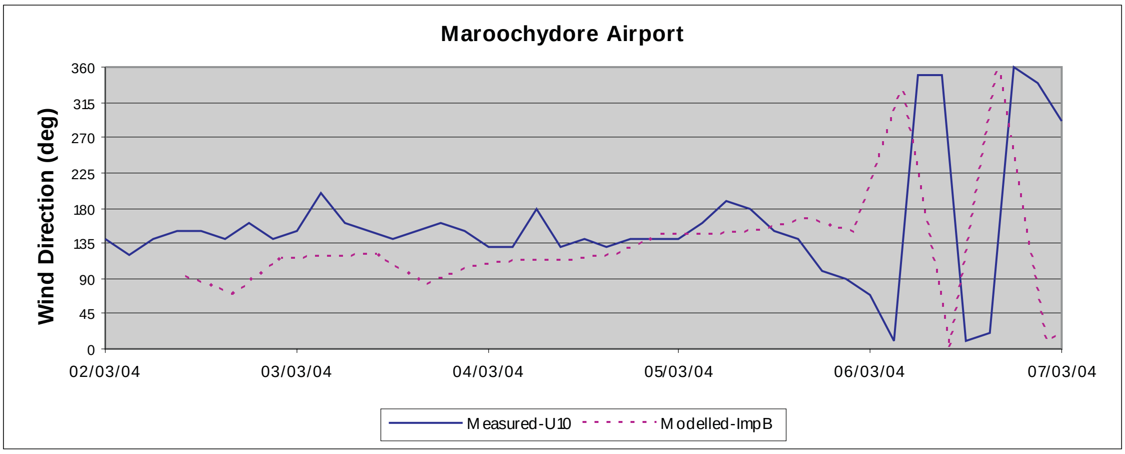


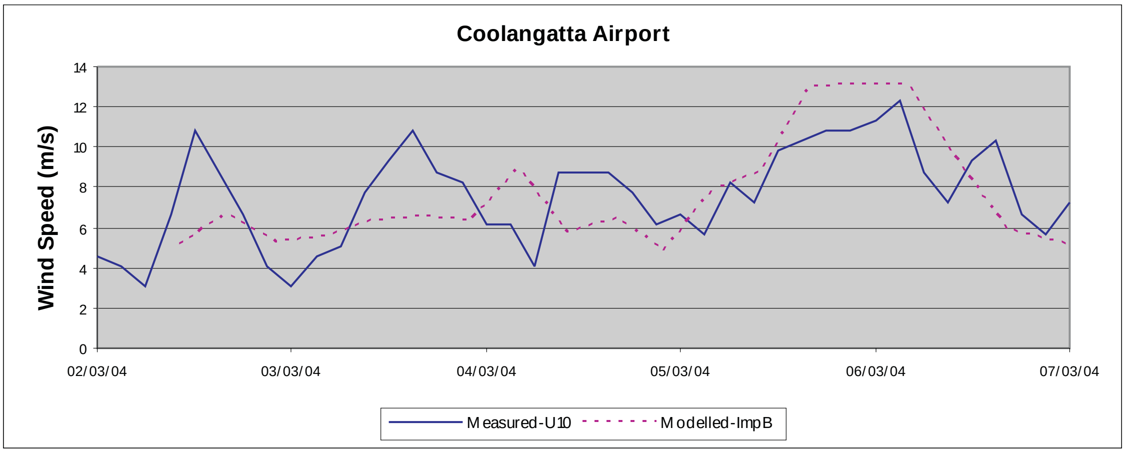


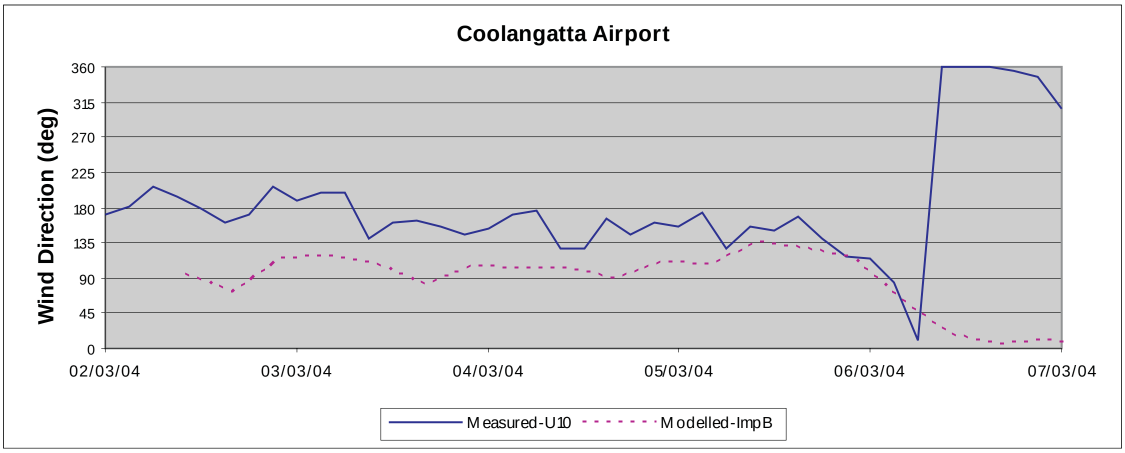


MEASURED AND MODELLED WIND CONDITIONS
MARCH 2004 EVENT
Figure 5.18

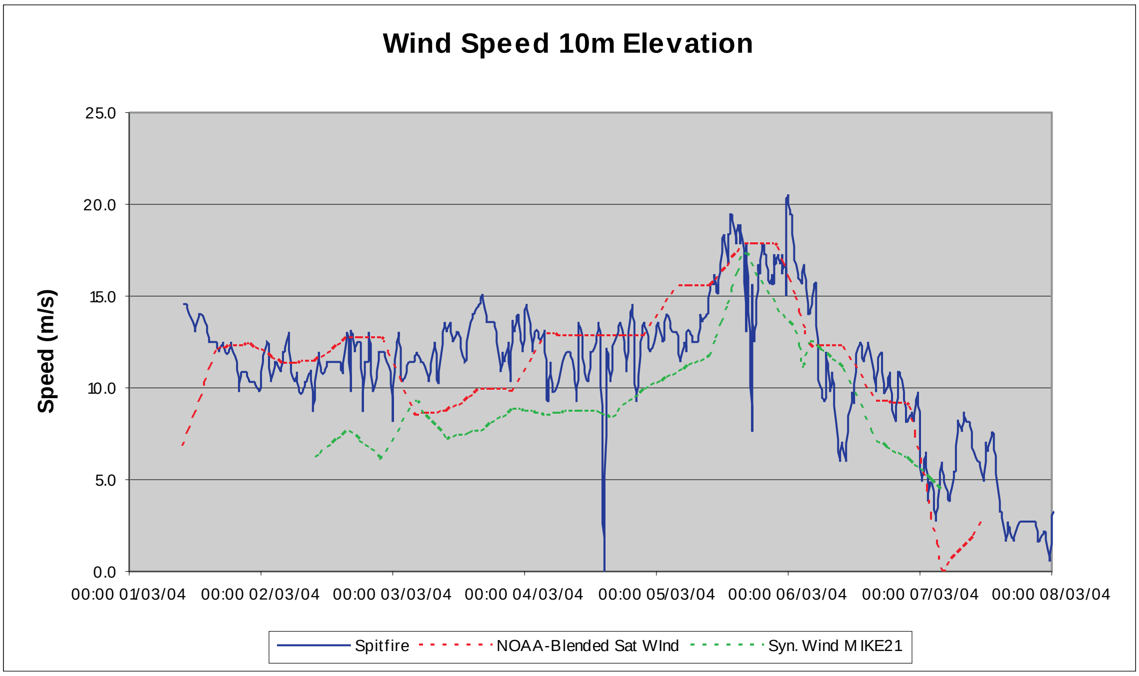


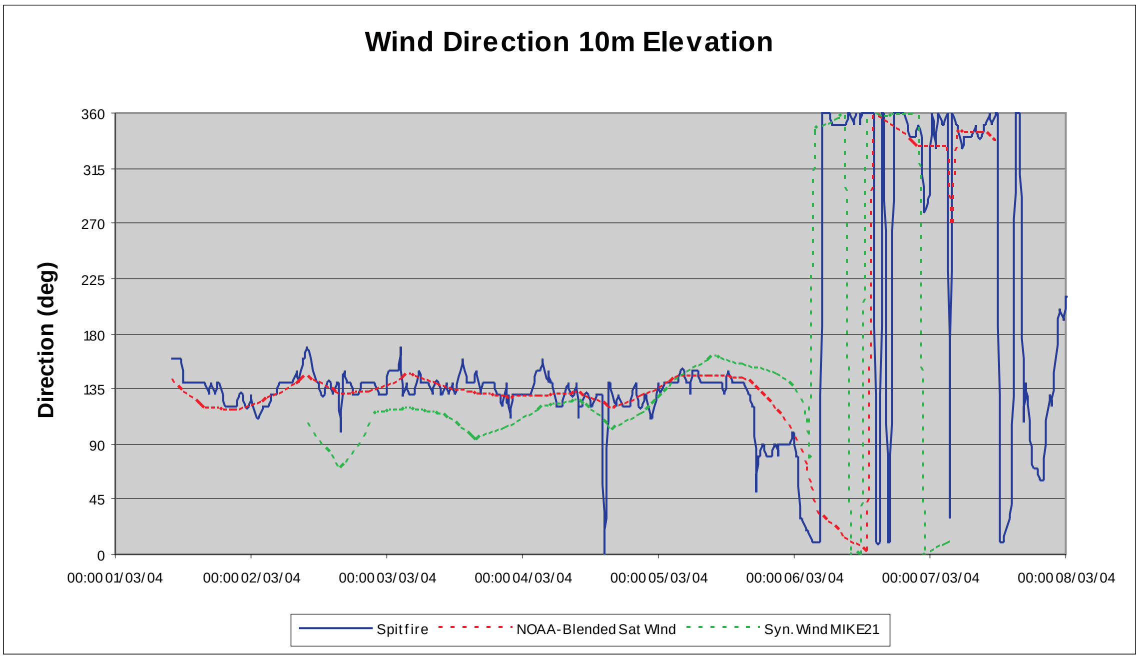




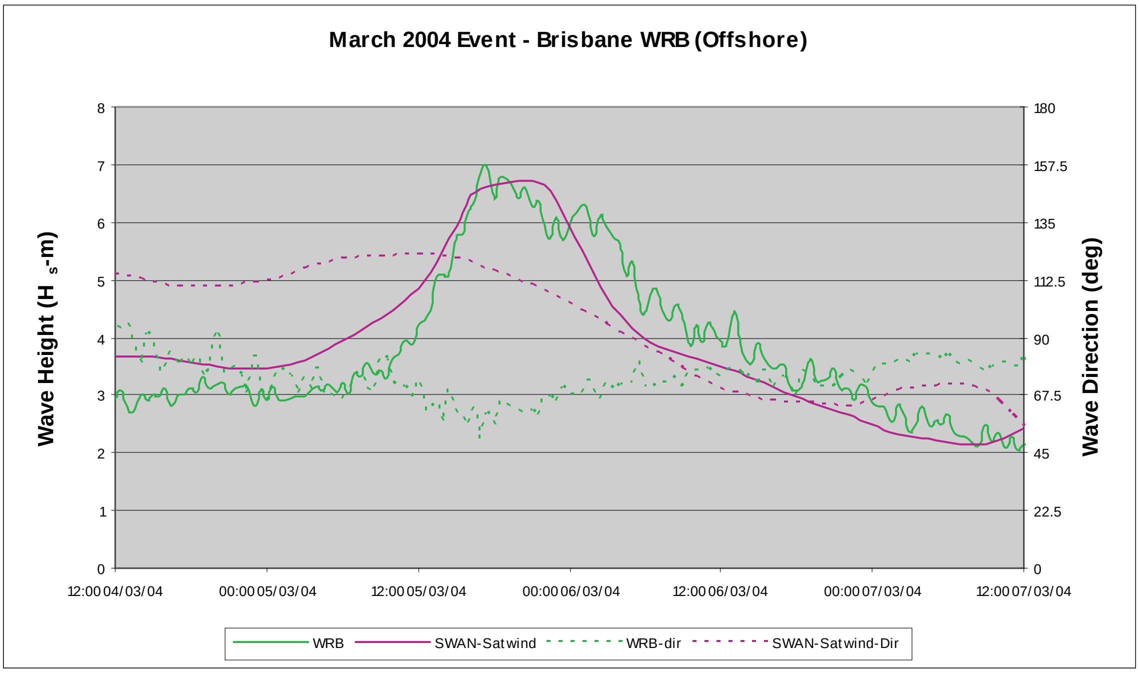


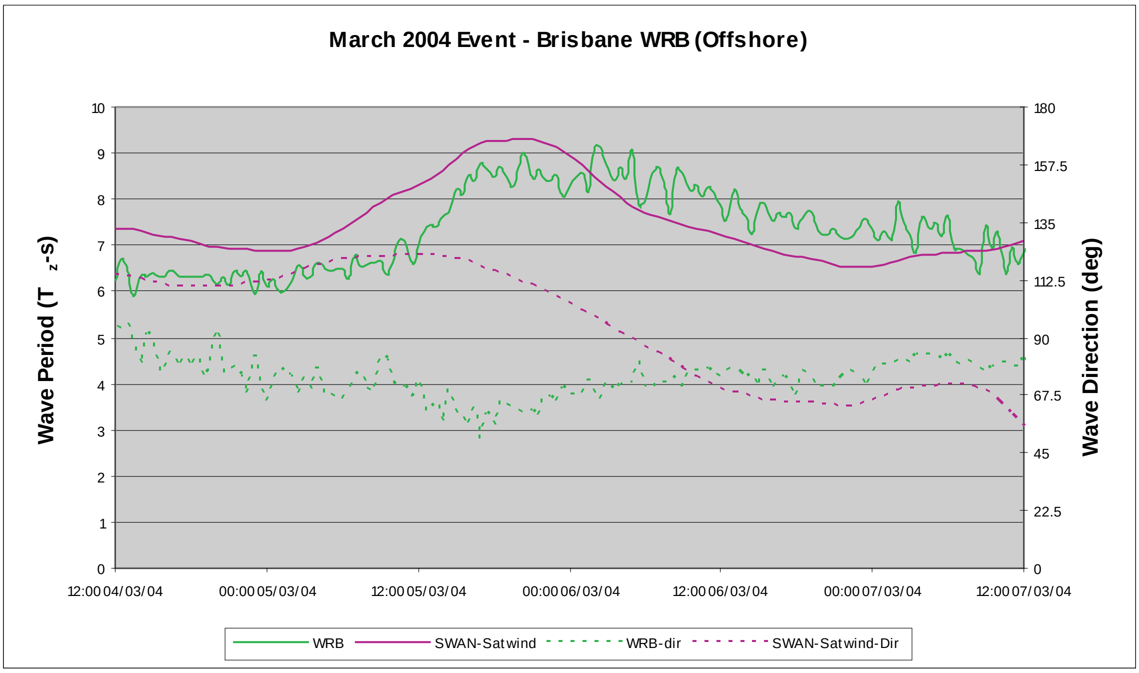
MEASURED AND MODELLED WIND CONDITIONS
MARCH 2004 EVENT
Figure 5.19



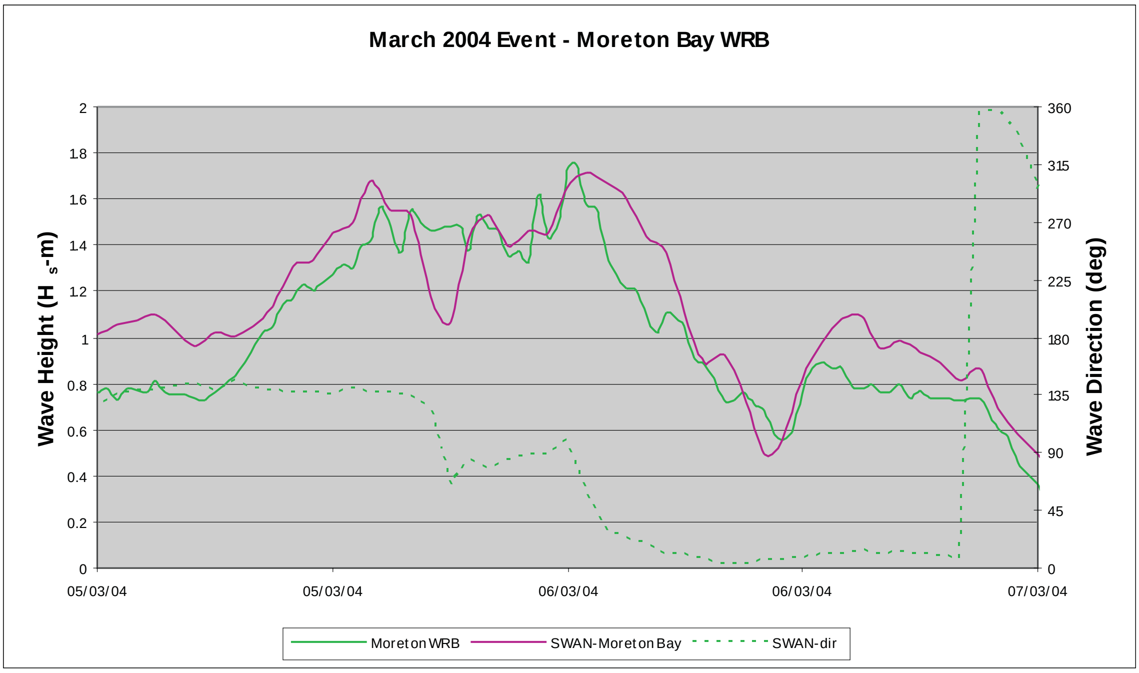


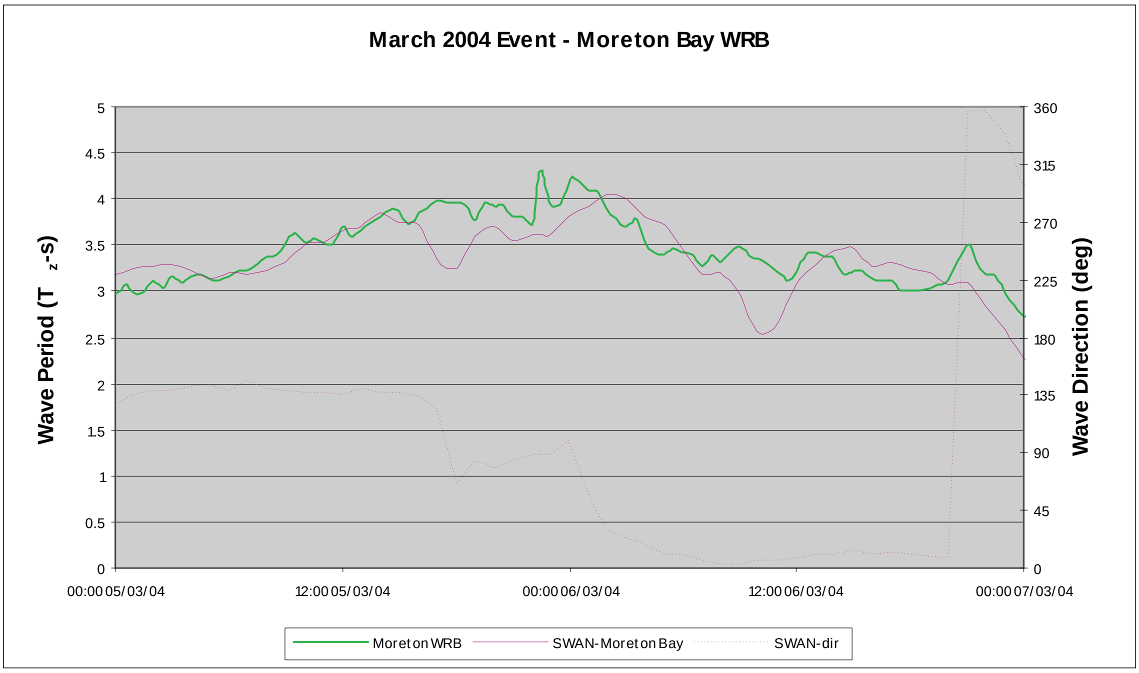
MEASURED AND MODELLED WIND CONDITIONS - MORETON BAY
MARCH 2004 EVENT
Figure 5.20





MEASURED AND MODELLED WAVE CONDITIONS - OFFSHORE BRISBANE
MARCH 2004 EVENT
Figure 5.21





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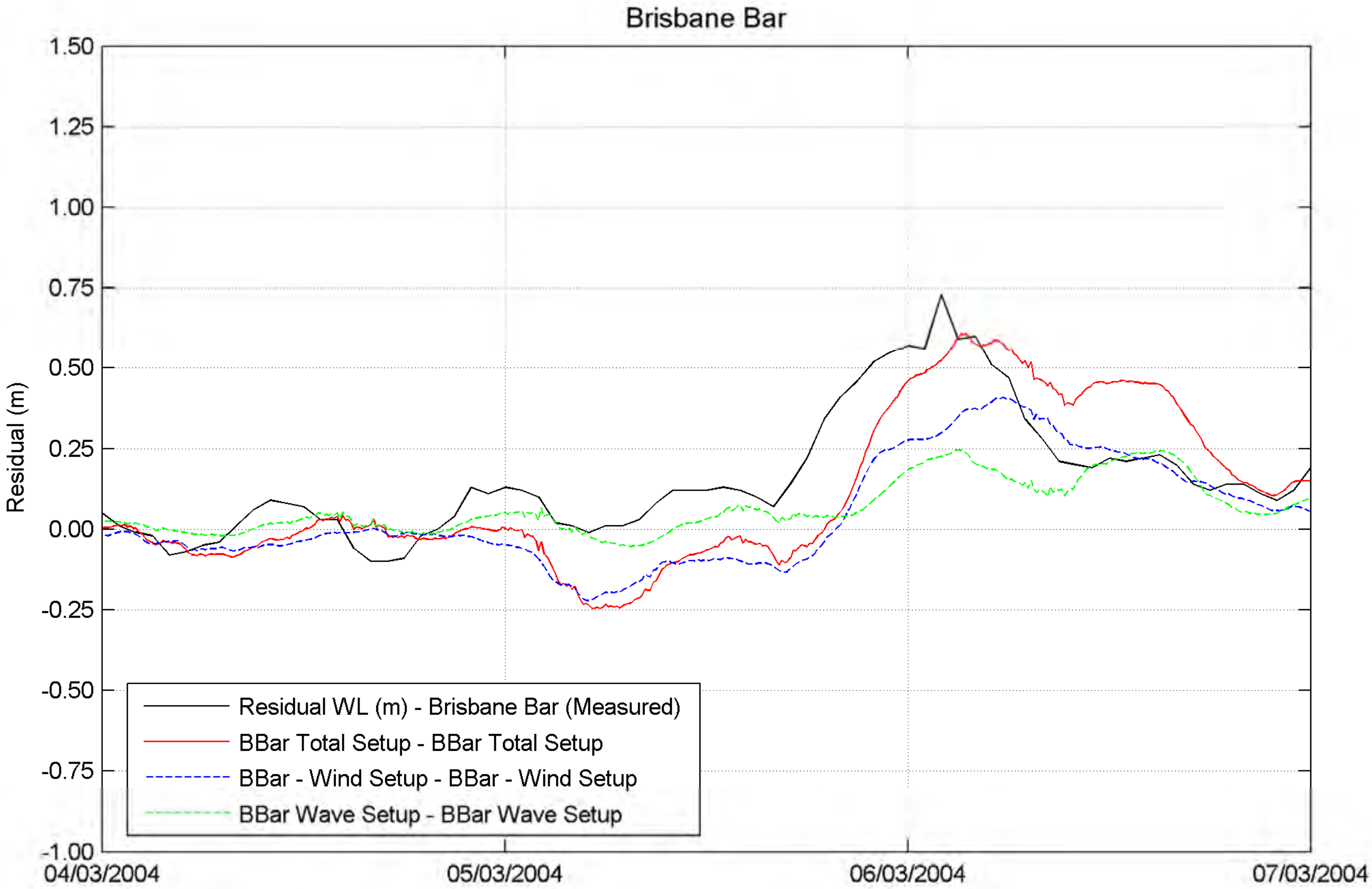
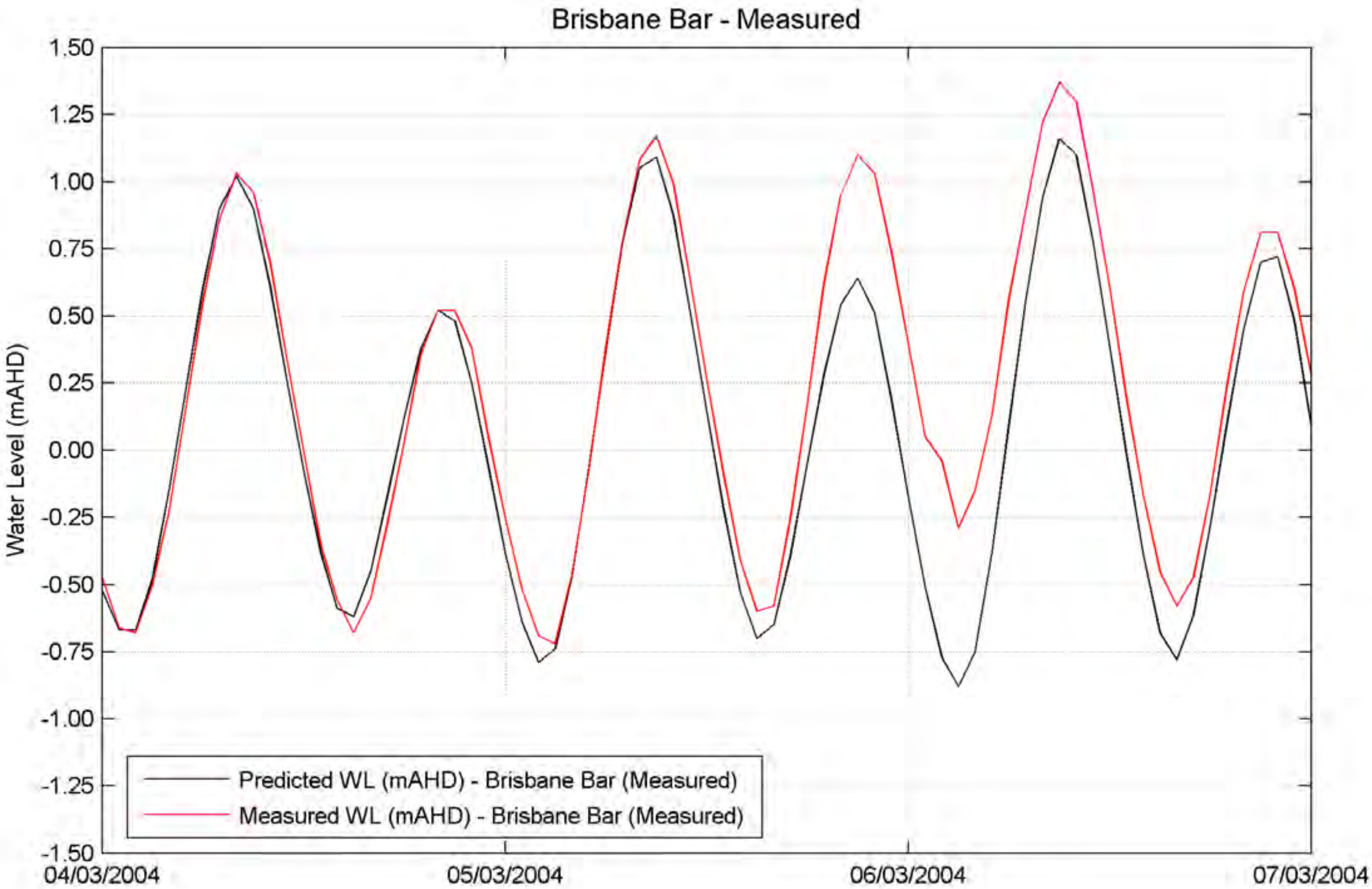
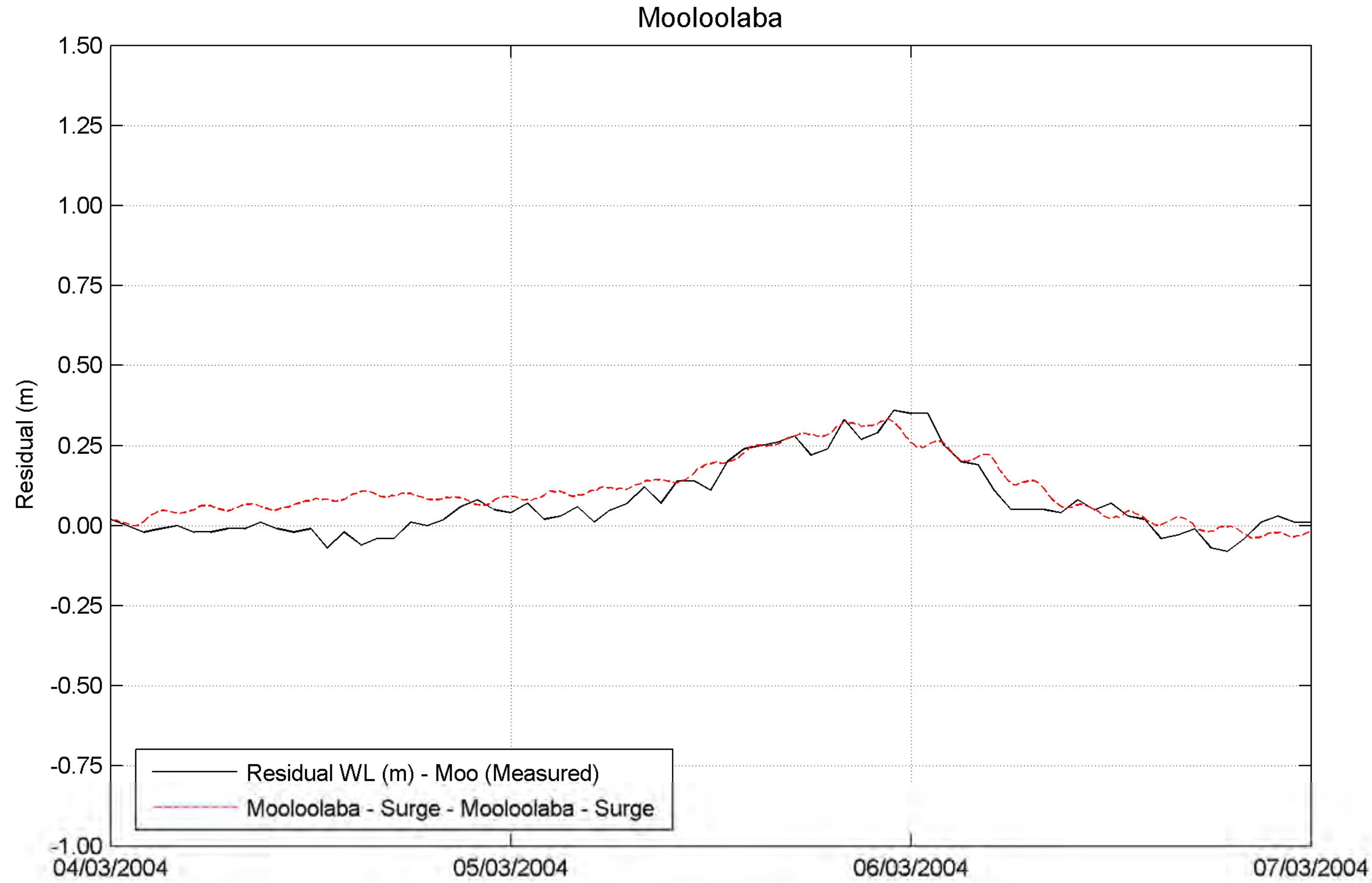
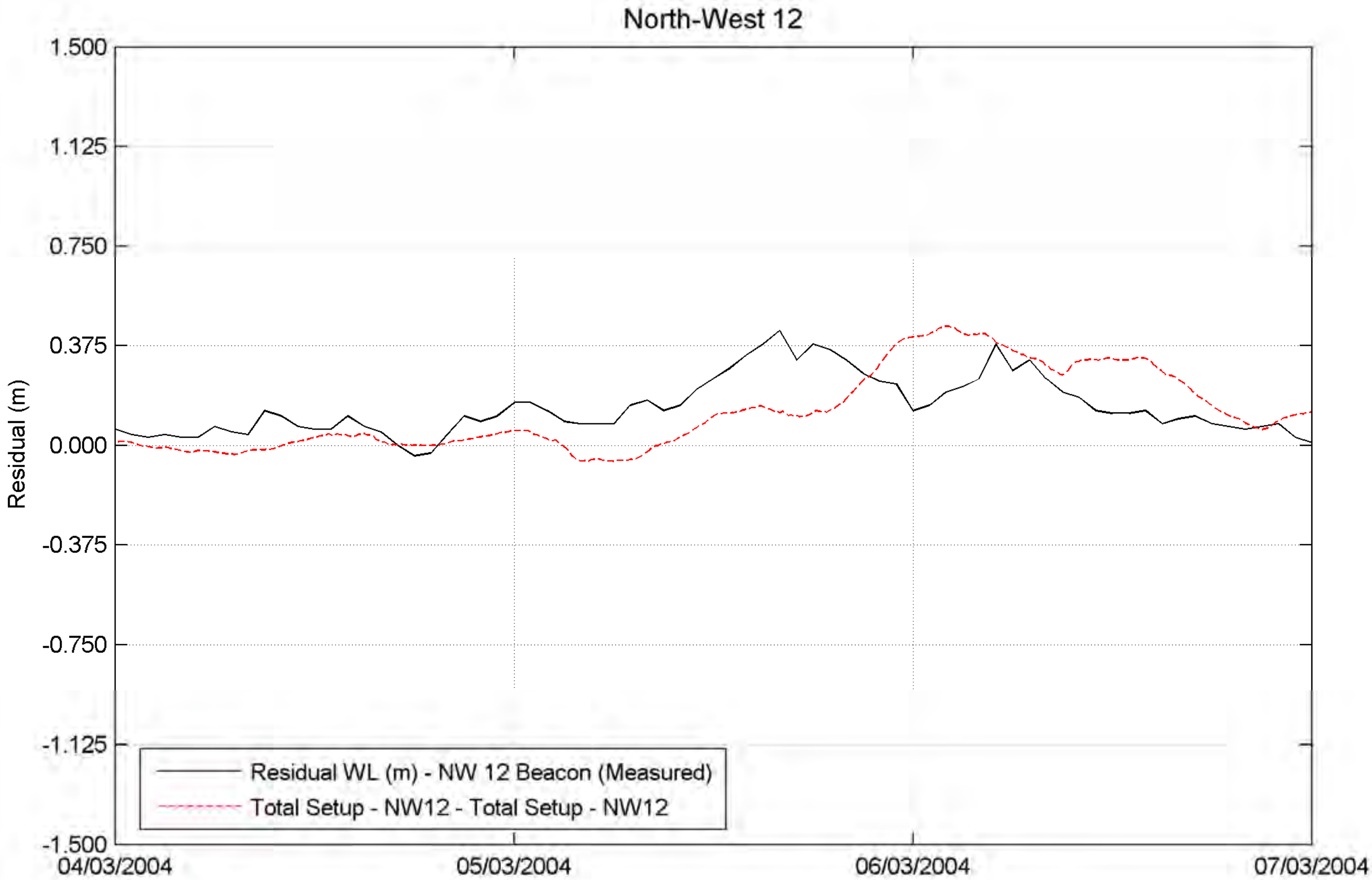
Storm Tide Hazard Study - Moreton Bay Regional Council
MEASURED AND MODELLED WAVE CONDITIONS - MORETON BAY
MARCH 2004 EVENT
Figure 5.22


Brisbane Bar
Residual (m)
1.50
1.25
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
Residual WL (m) - Brisbane Bar (Measured)
BBar Total Setup - BBar Total Setup
BBar - Wind Setup - BBar - Wind Setup
BBar Wave Setup - BBar Wave Setup
04/03/2004
05/03/2004
06/03/2004
07/03/2004


Brisbane Bar - Measured
Water Level (mAHD)
1.50
1.25
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
-1.25
-1.50
Predicted WL (mAHD) - Brisbane Bar (Measured)
Measured WL (mAHD) - Brisbane Bar (Measured)
04/03/2004
05/03/2004
06/03/2004
07/03/2004

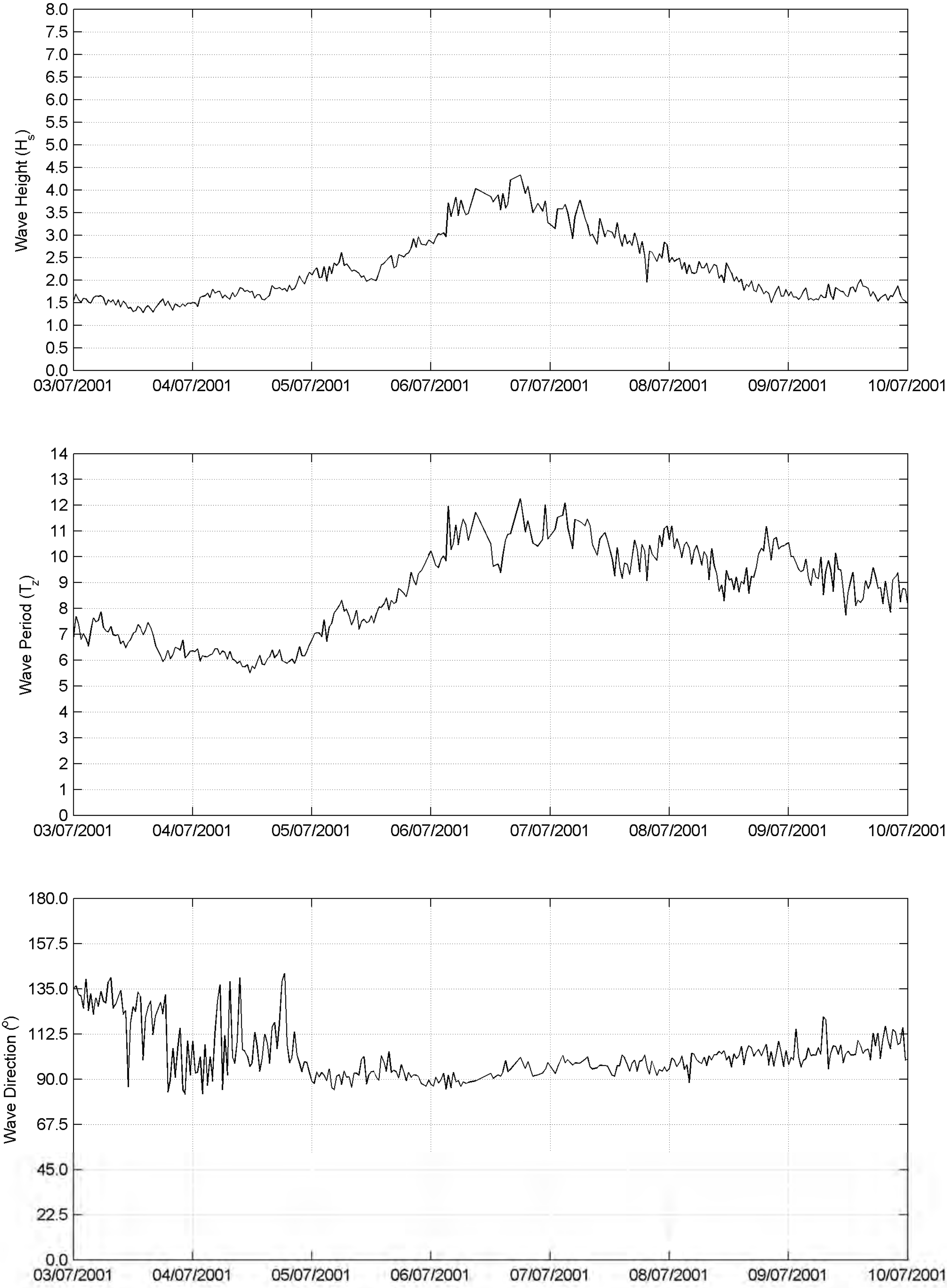




MARCH 2004 Event

Modelled and Measured Storm Surge - Mooloolaba and NW12 Beacon

Figure 5.24



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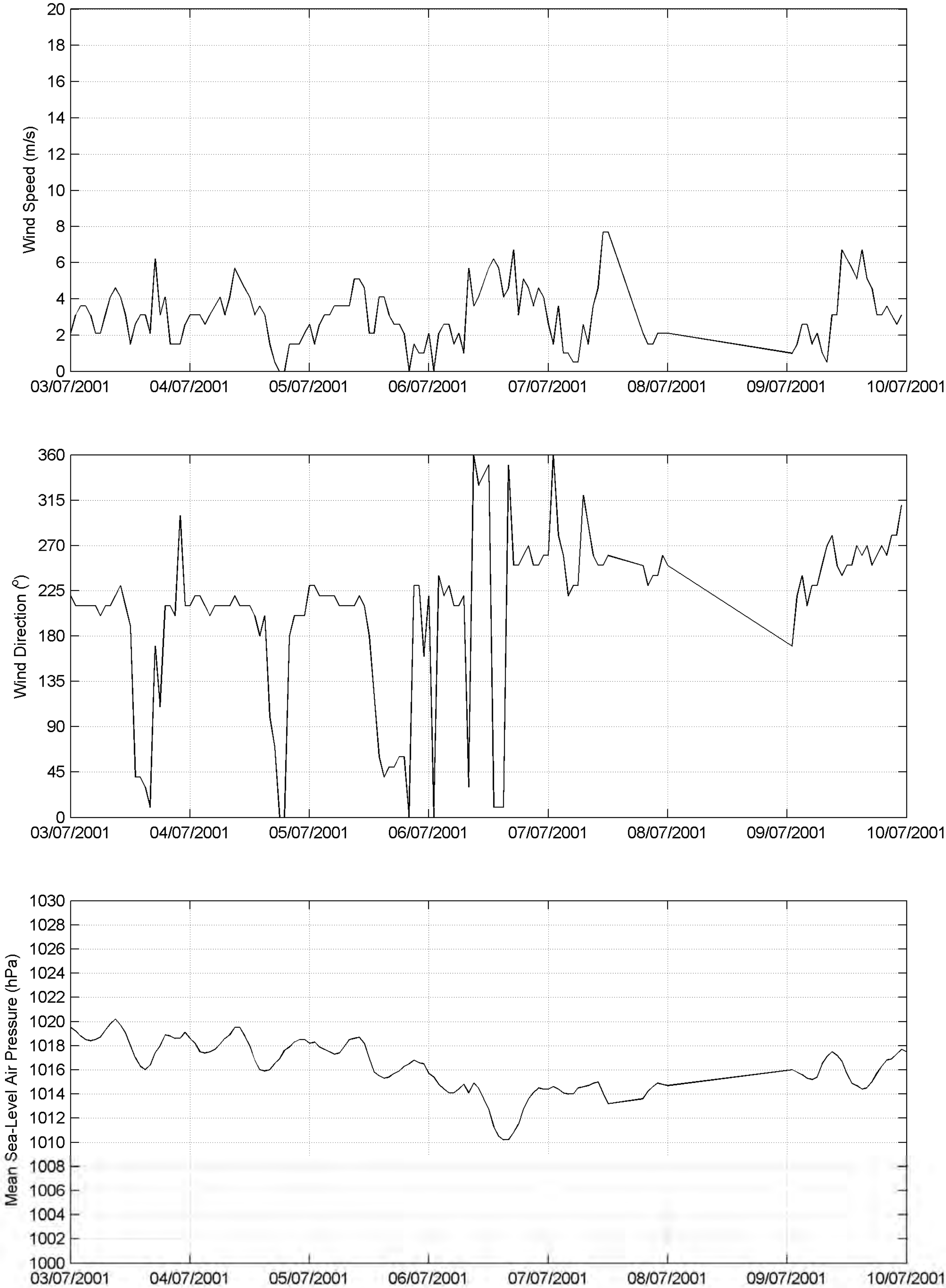
File: J:\CM\LJ8824\Figures\R2461\Figure6.1.png

Storm Tide Hazard Study - Moreton Bay Regional Council

MEASURED OFFSHORE WAVE CONDITIONS

Brisbane WRB

Figure 6.1



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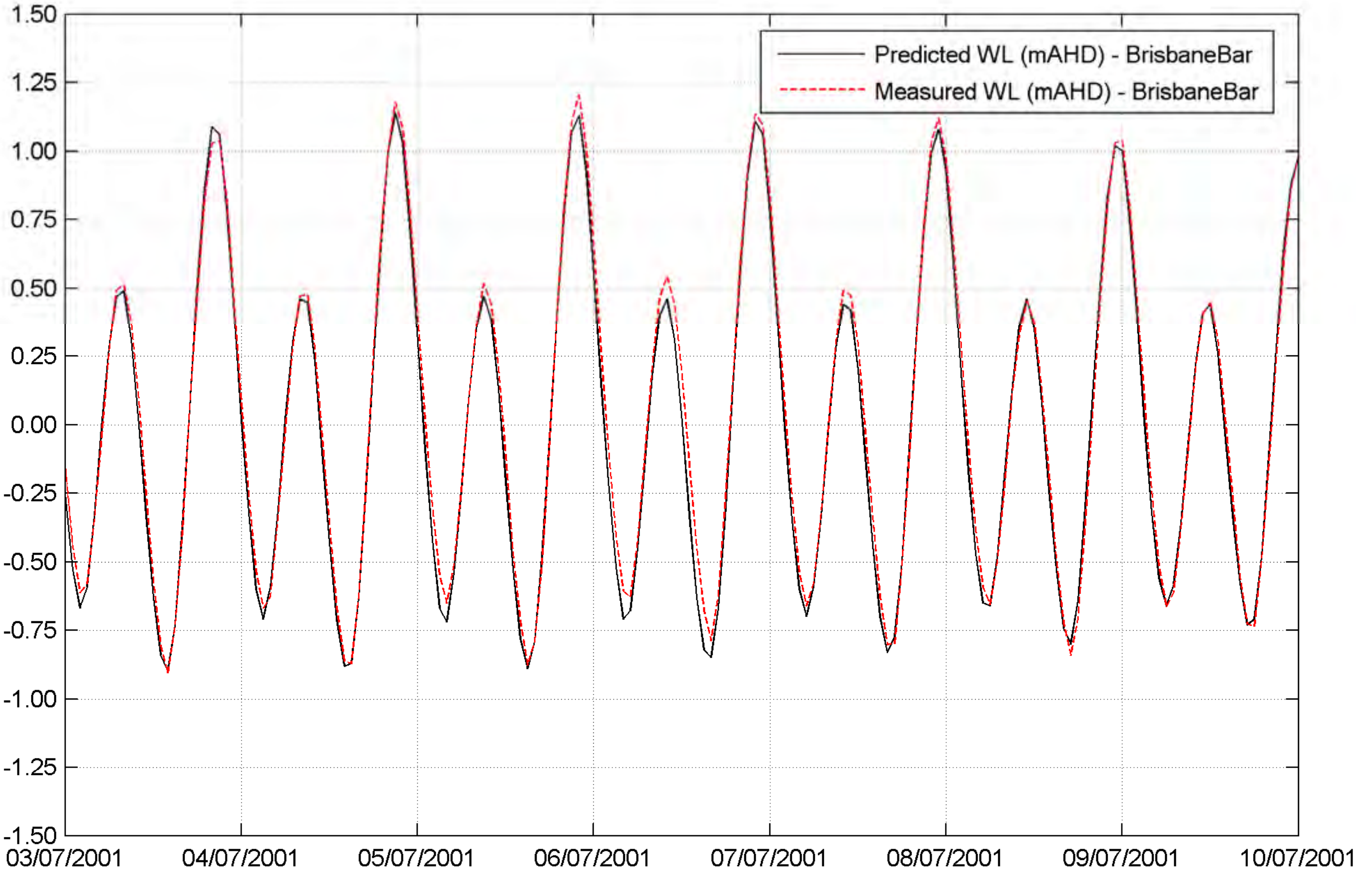
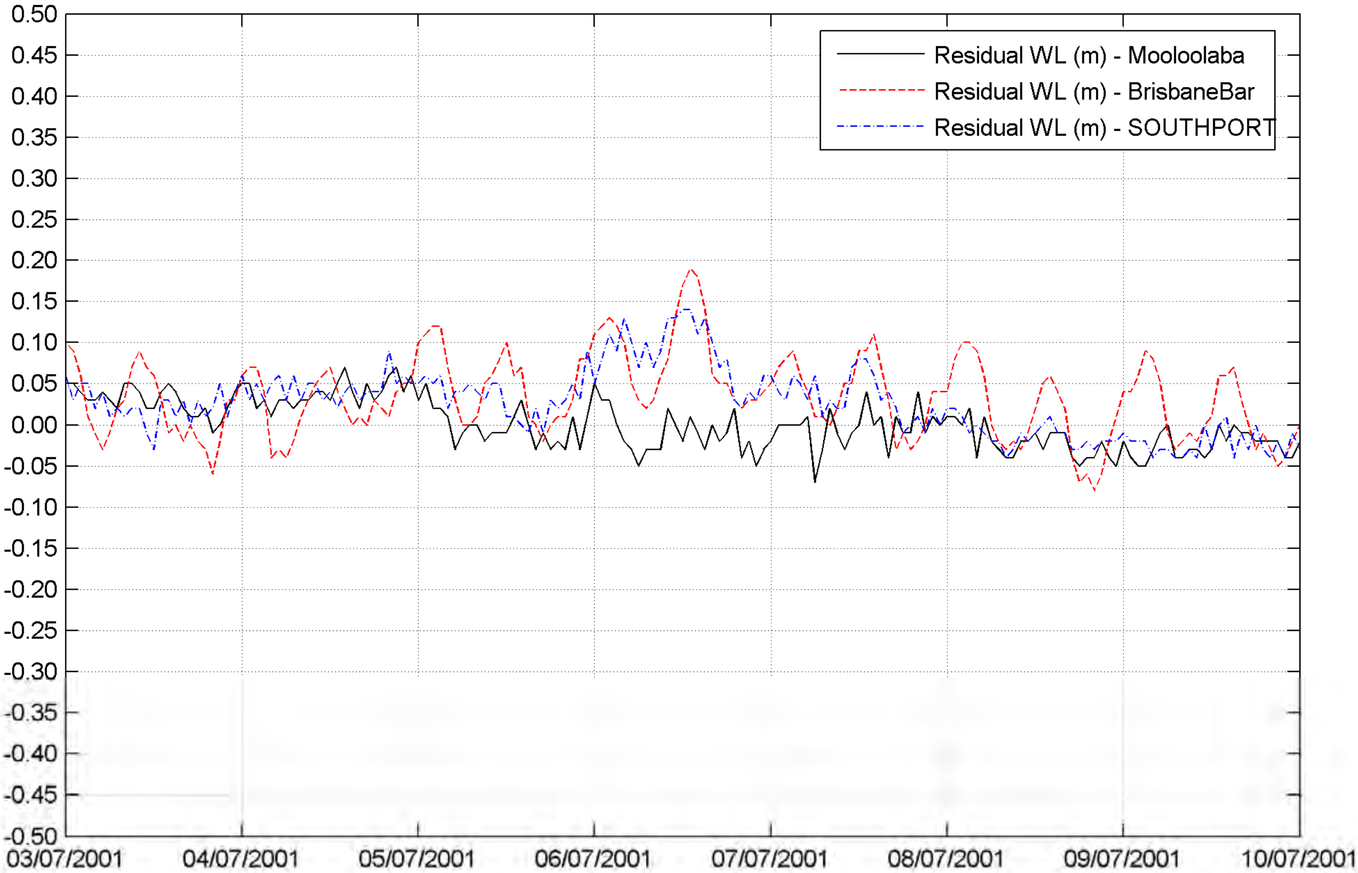
Storm Tide Hazard Study - Moreton Bay Regional Council

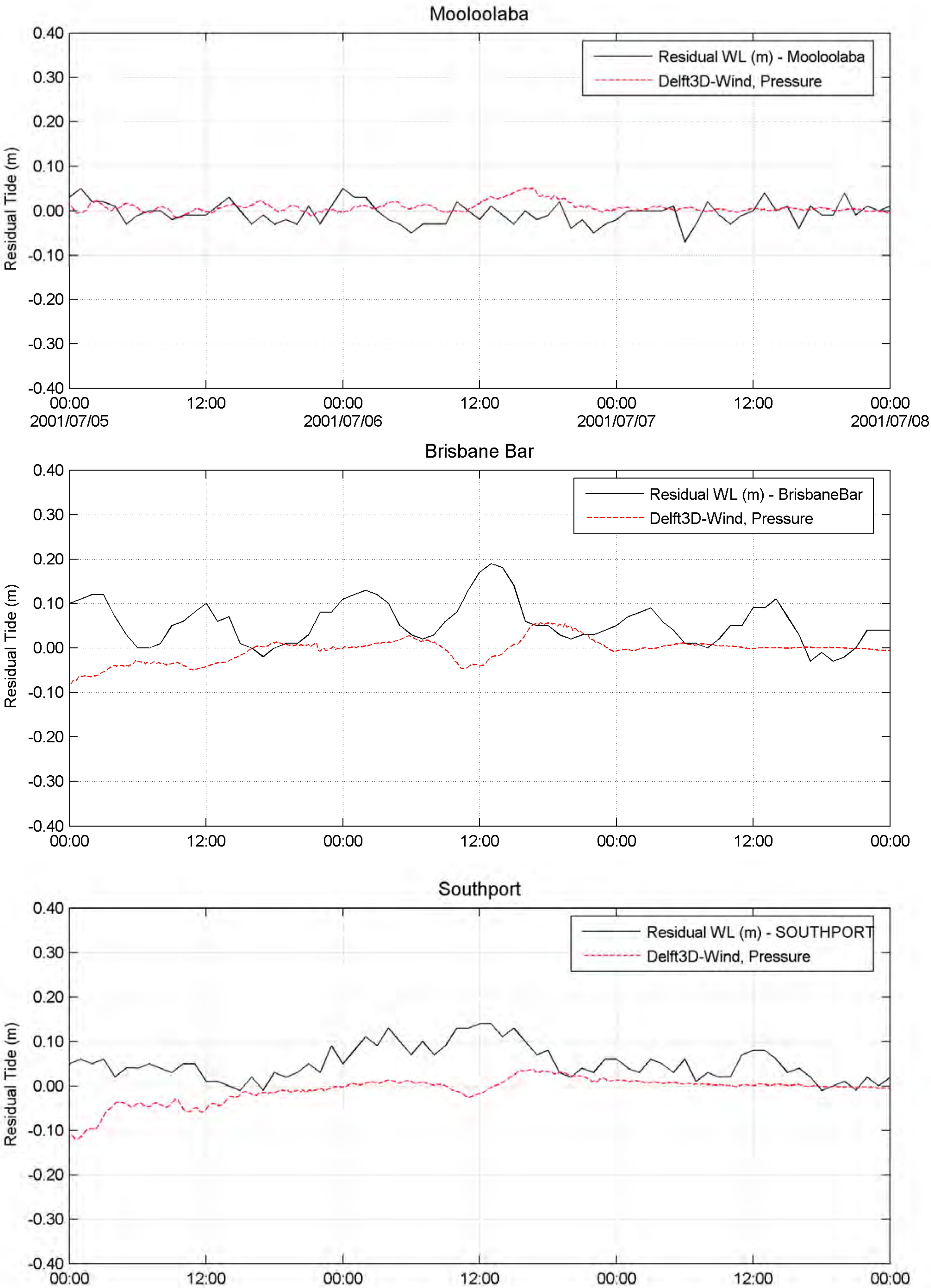
MEASURED WIND AND ATMOSPHERIC PRESSURE

Brisbane Airport - July 2001

Figure 6.2


Predicted WL (mAHD) - BrisbaneBar
Measured WL (mAHD) - BrisbaneBar
1.50
1.25
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
-1.25
-1.50
03/07/2001
04/07/2001
05/07/2001
06/07/2001
07/07/2001
08/07/2001
09/07/2001
10/07/2001


Residual WL (m) - Mooloolaba
Residual WL (m) - BrisbaneBar
Residual WL (m) - SOUTHPORT
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
-0.35
-0.40
-0.45
-0.50
03/07/2001
04/07/2001
05/07/2001
06/07/2001
07/07/2001
08/07/2001
09/07/2001
10/07/2001



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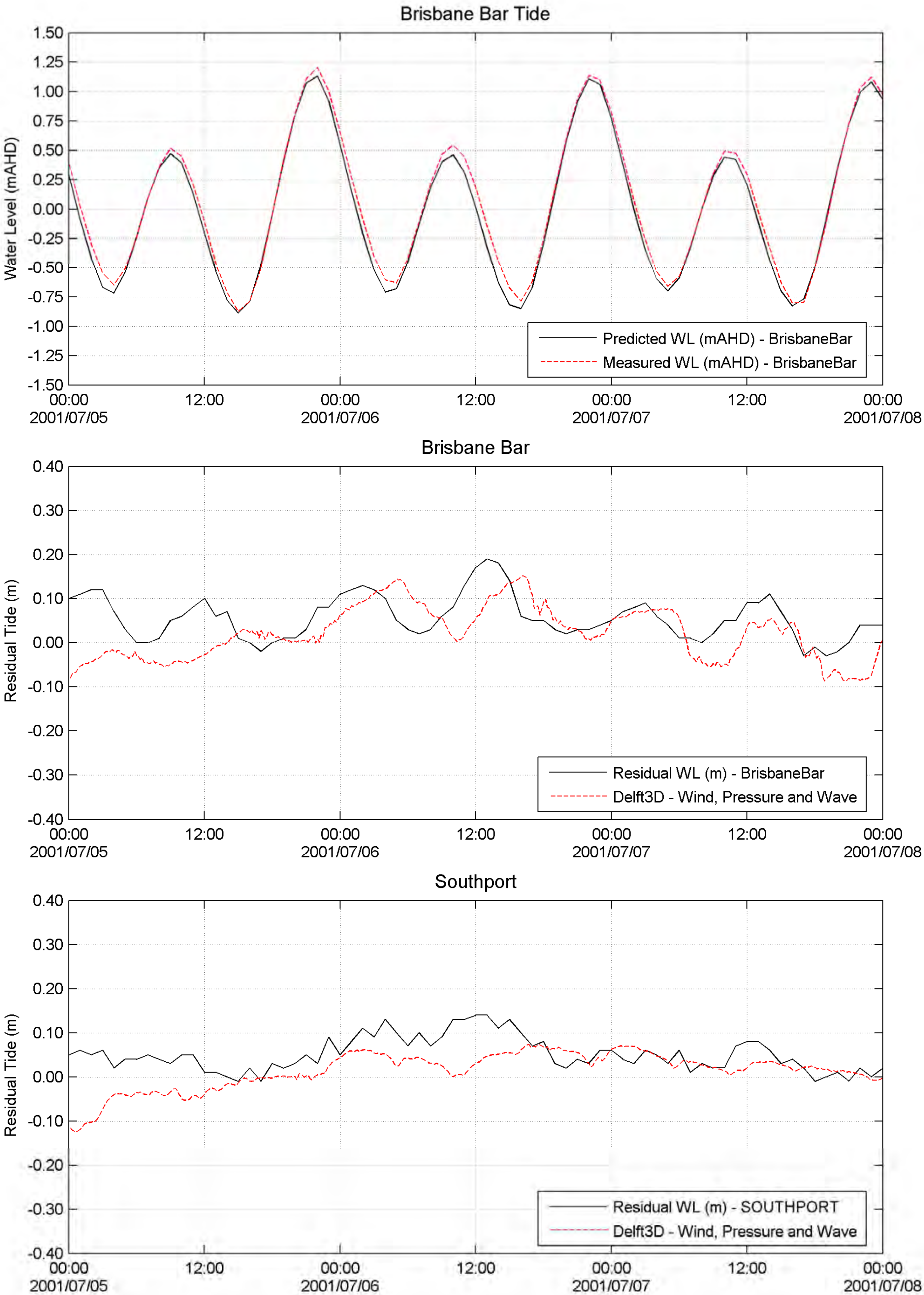
File: J:\CM\LJ8824\Figures\R2461\Figure6.4.png

Storm Tide Hazard Study - Moreton Bay Regional Council

DELFT3D MODELLED RESIDUAL TIDE - JULY 2001

Wind and Pressure Forcing Only

Figure 6.4



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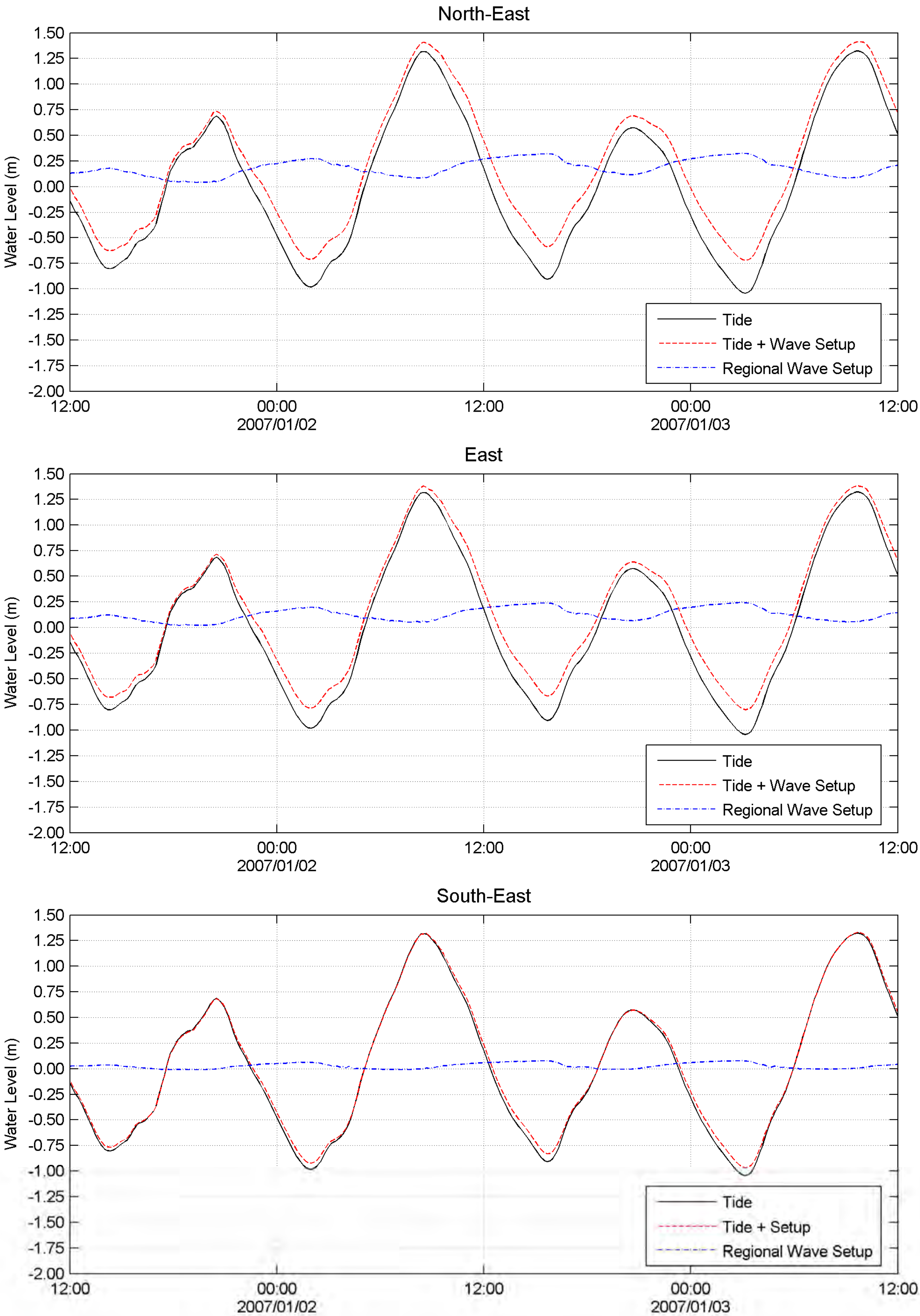
File: J:\CM\LJ8824\Figures\R2461\Figure6.5.png

Storm Tide Hazard Study - Moreton Bay Regional Council

DELFT3D MODELLED RESIDUAL TIDE - JULY 2001

Wind, Pressure and Wave Forcing

Figure 6.5



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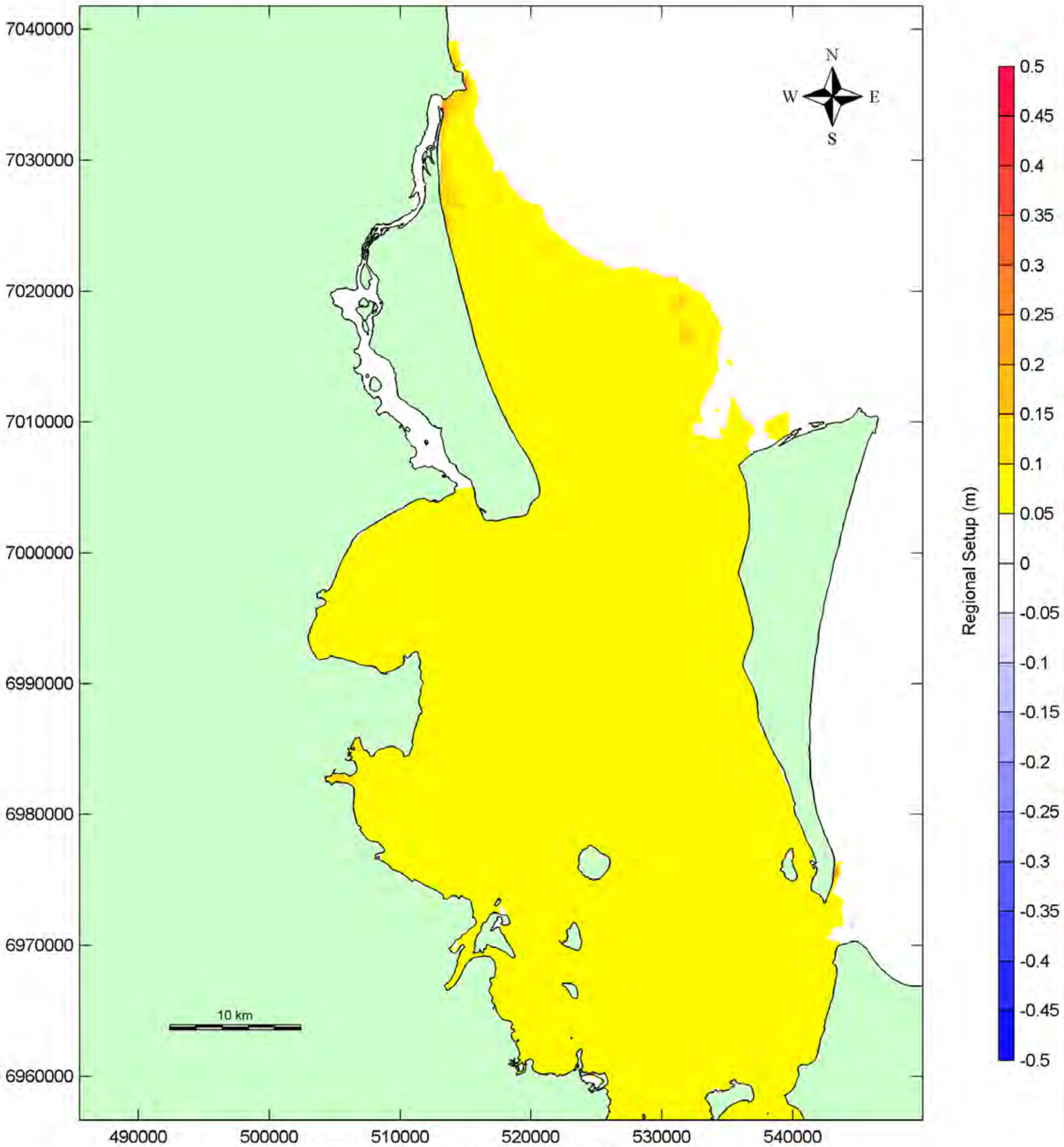
Storm Tide Hazard Study - Moreton Bay Regional Council

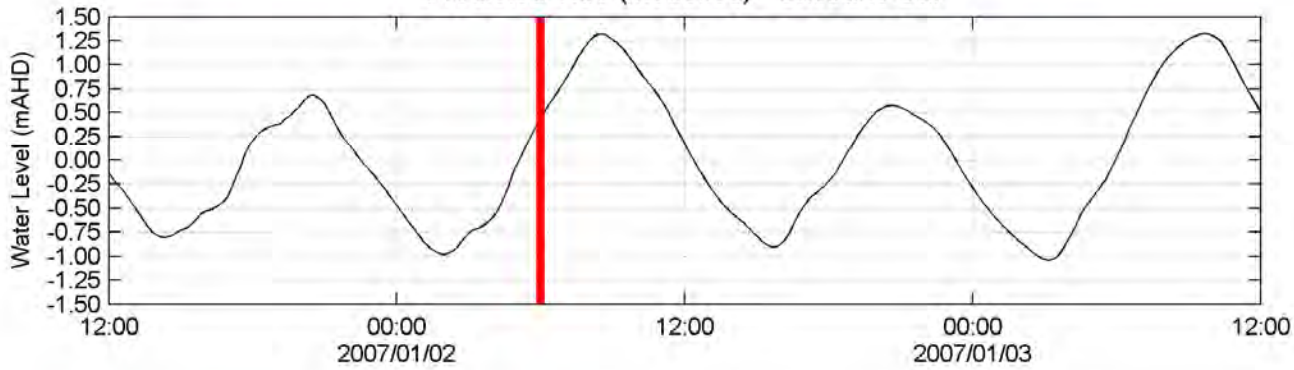
DELFT3D MODELLED REGIONAL WAVE SETUP

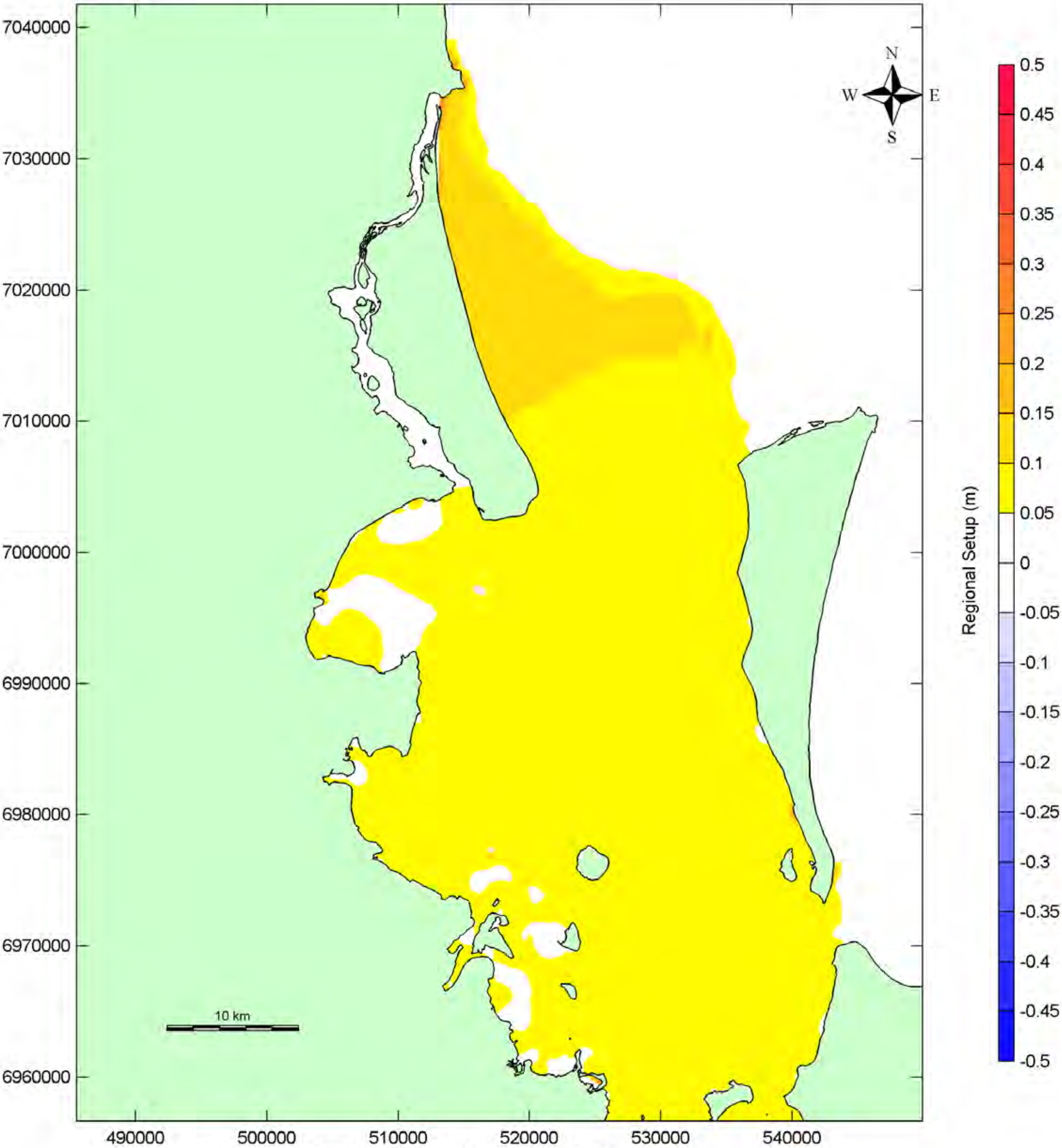
H_s=7m, T_z=8s, Dir=45°, 90°, 135°

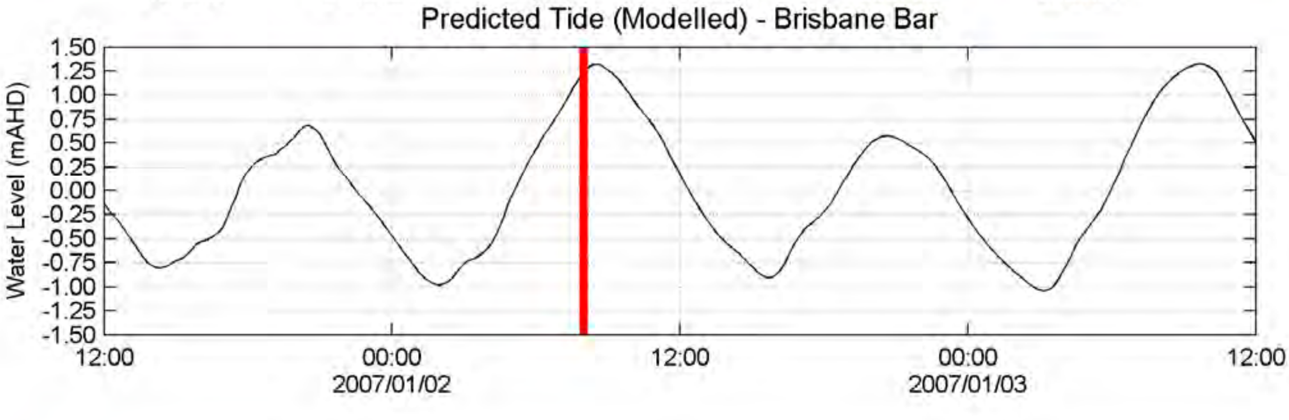
Figure 6.6



Predicted Tide (Modelled) - Brisbane Bar







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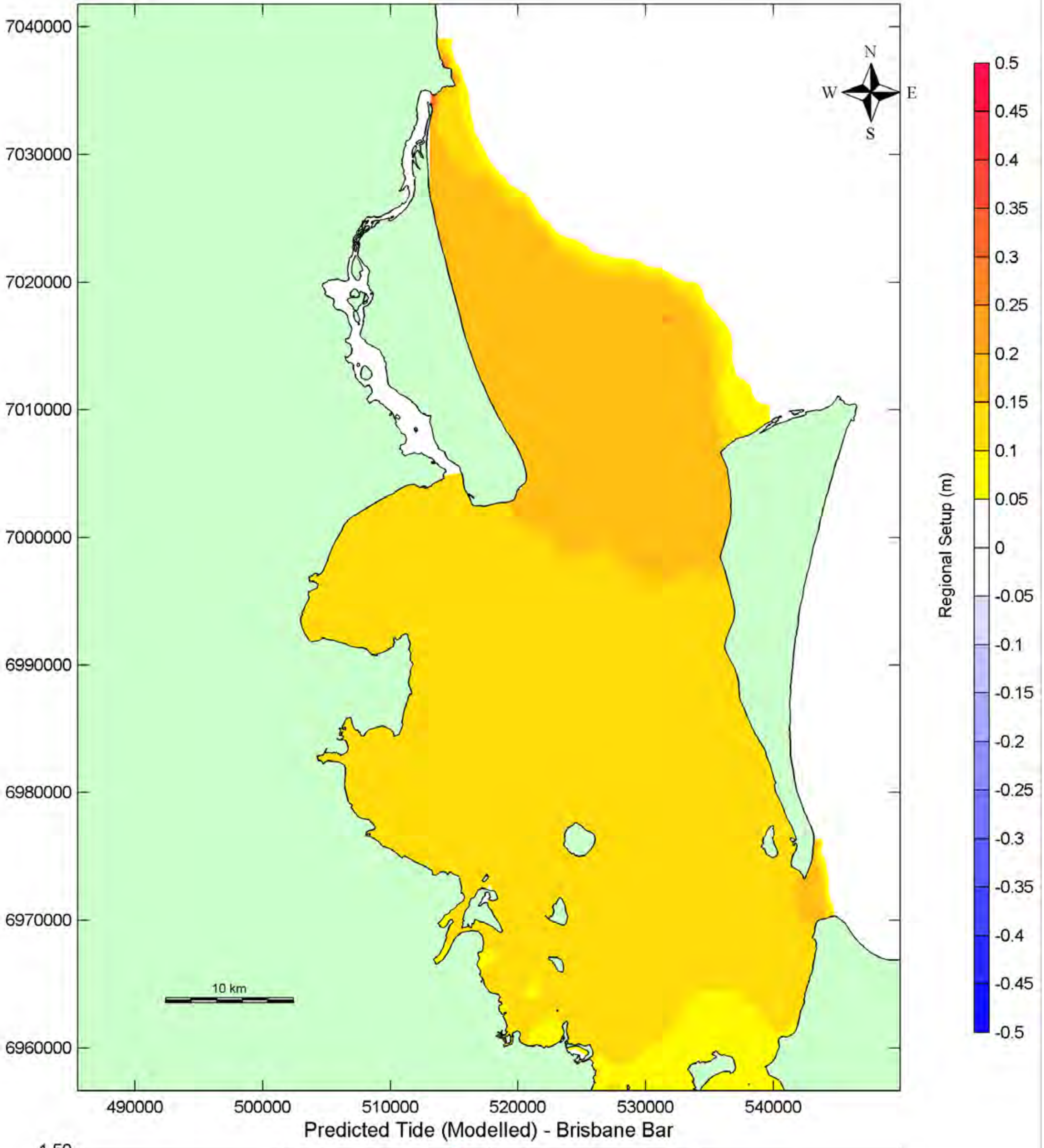
File: J:\CM\LJ8824\Figures\R2461\Figure6.8.png

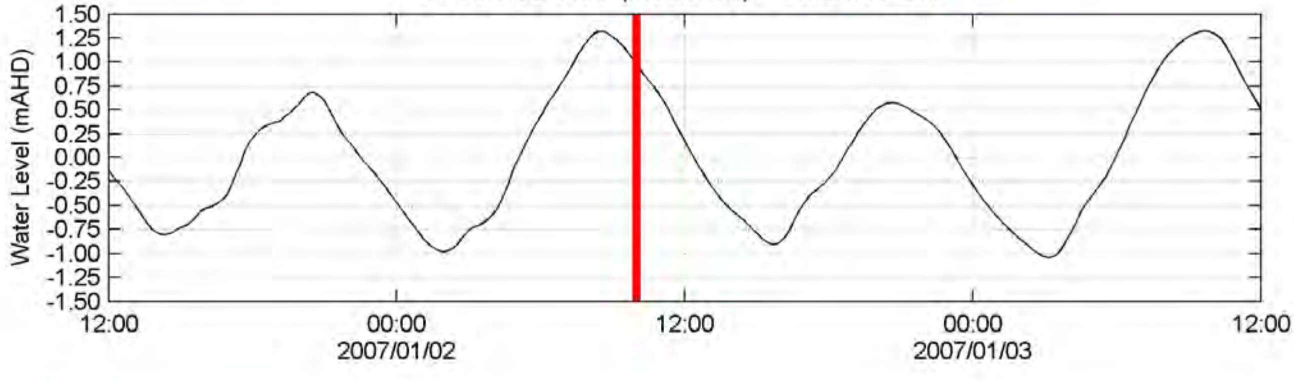
Storm Tide Hazard Study - Moreton Bay Regional Council

DELFT3D MODELLED REGIONAL WAVE SETUP

Northern Moreton Bay - 08:00

Figure 6.8





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LJ8824/R2461 February 2009

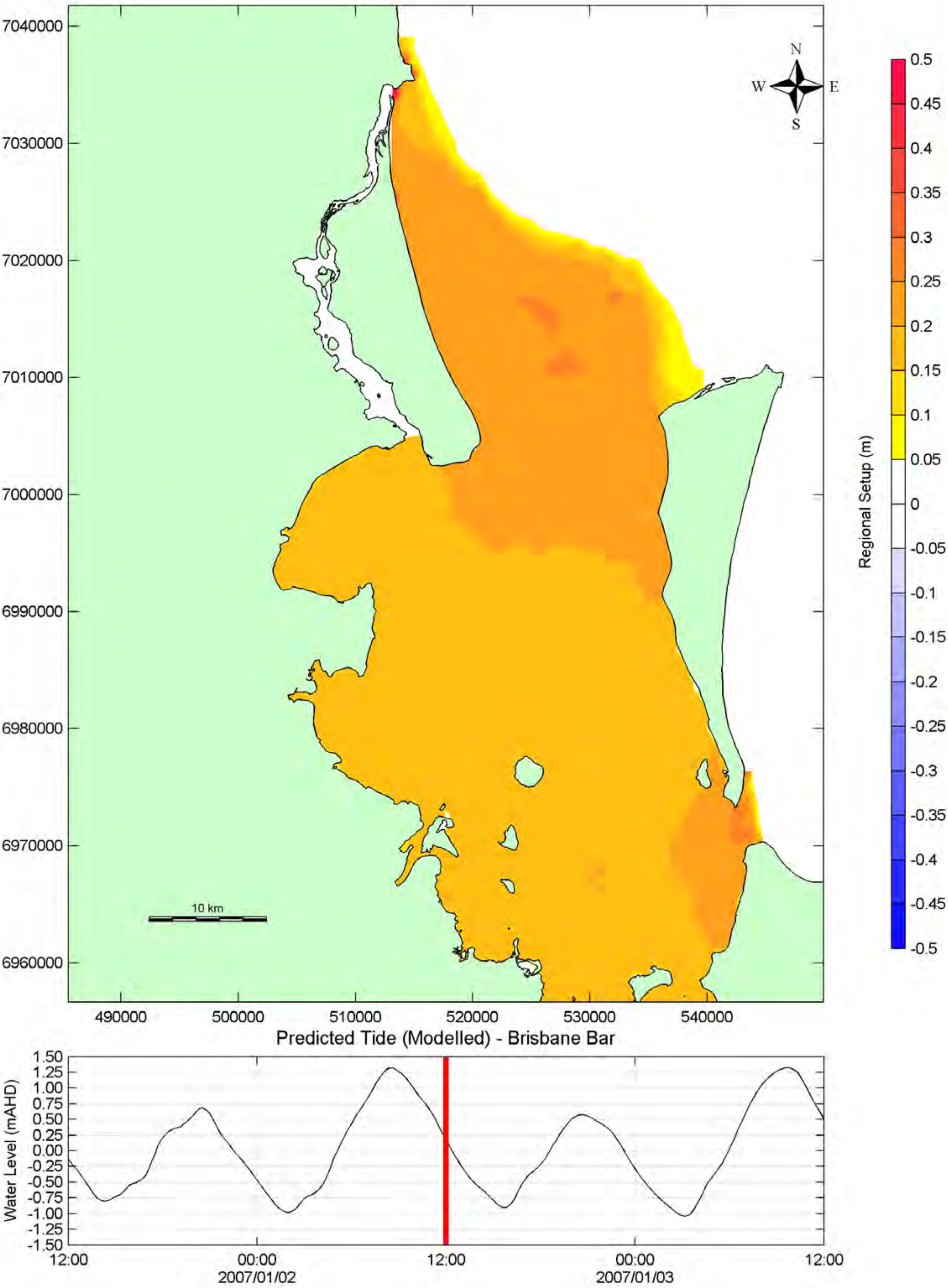
File: J:\CM\LJ8824\Figures\R2461\Figure6.9.png

Storm Tide Hazard Study - Moreton Bay Regional Council

DELFT3D MODELLED REGIONAL WAVE SETUP

Northern Moreton Bay - 10:00

Figure 6.9



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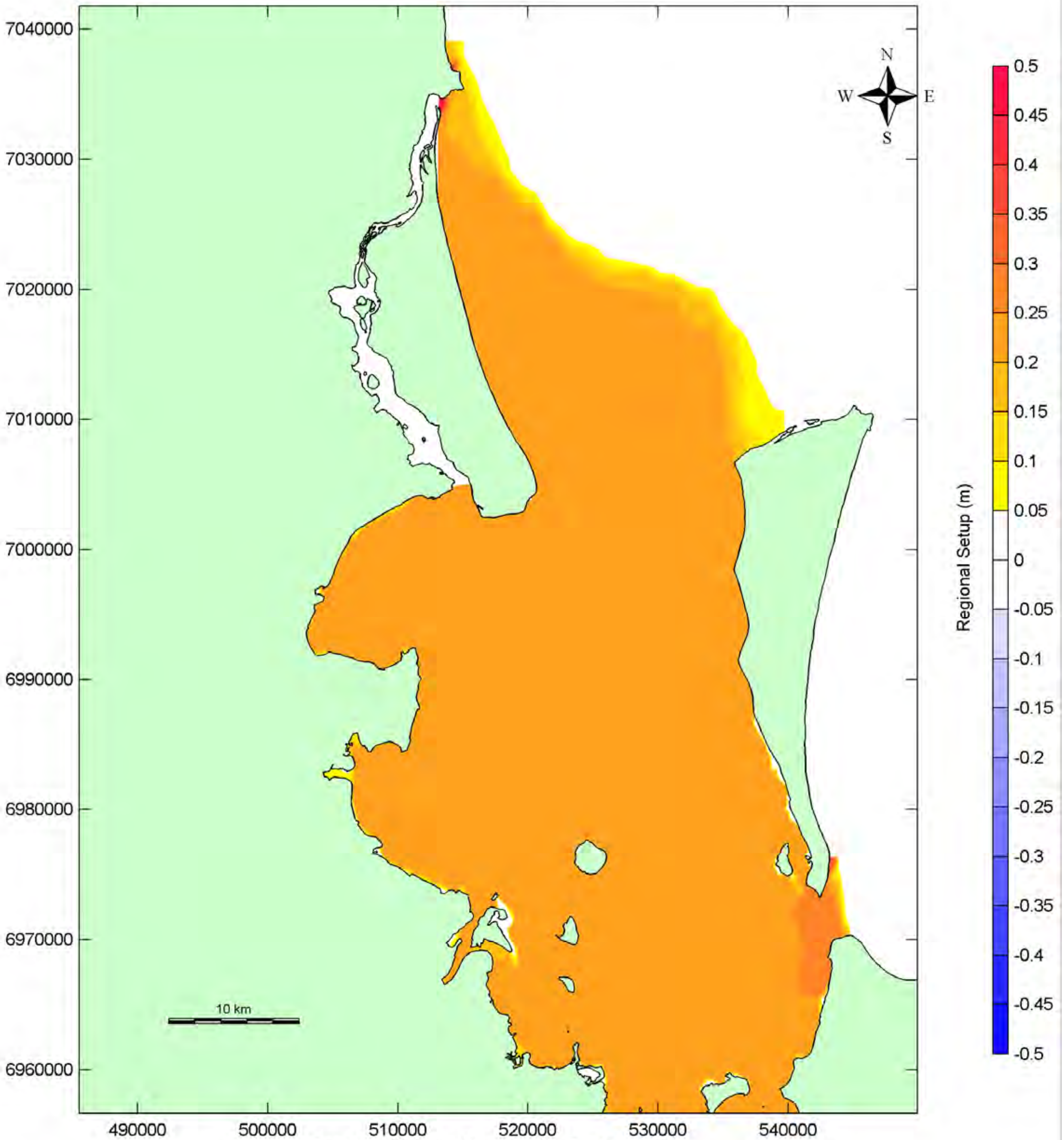
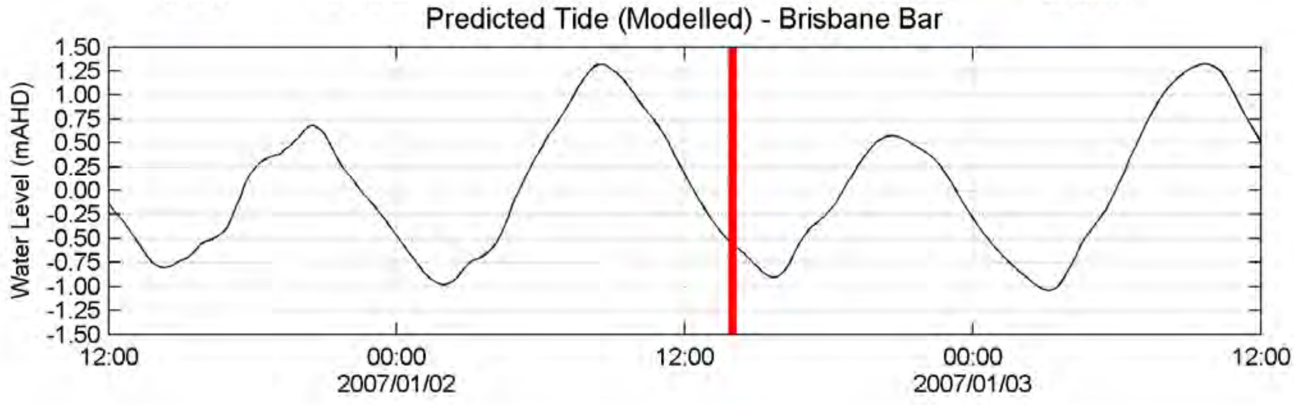
Storm Tide Hazard Study - Moreton Bay Regional Council

DELFT3D MODELLED REGIONAL WAVE SETUP

Northern Moreton Bay - 12:00

Figure 6.10





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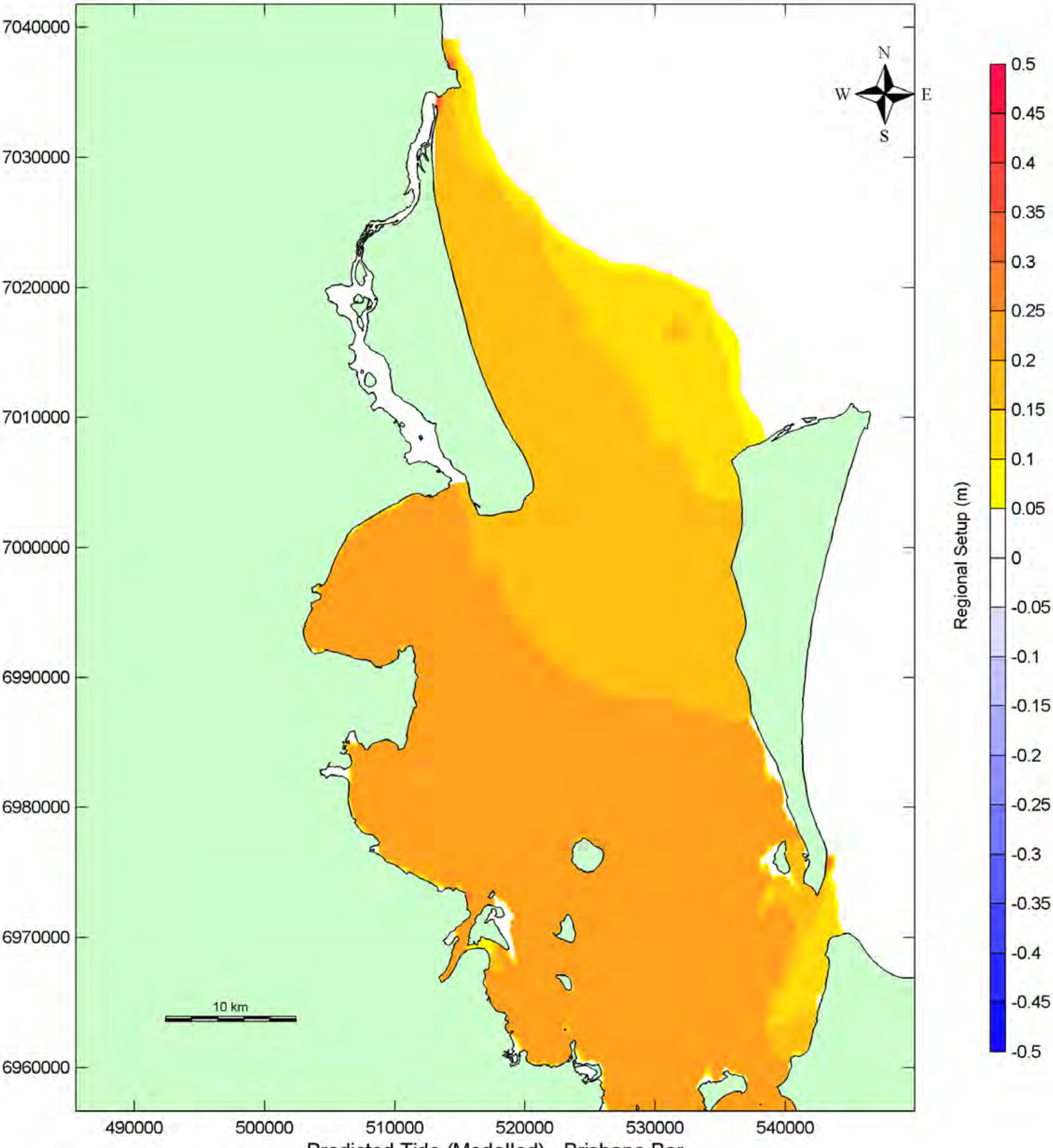
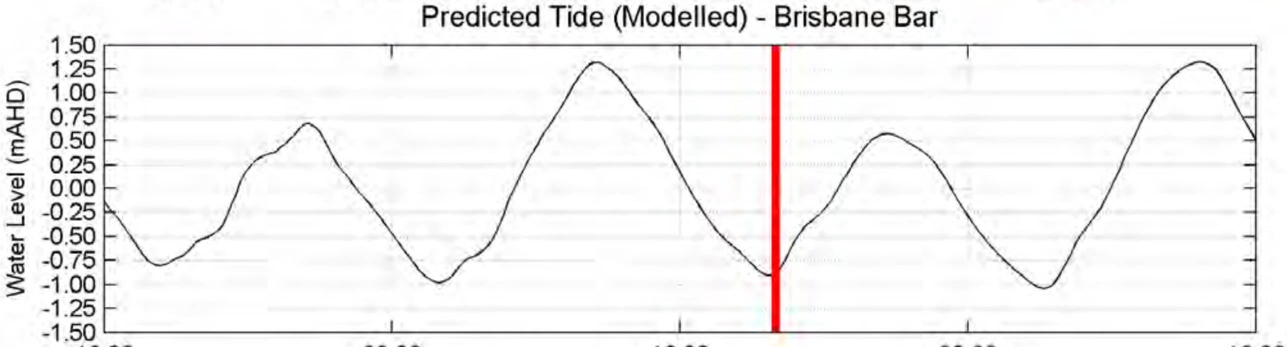
Storm Tide Hazard Study - Moreton Bay Regional Council

DELFT3D MODELLED REGIONAL WAVE SETUP

Northern Moreton Bay - 14:00

Figure 6.11

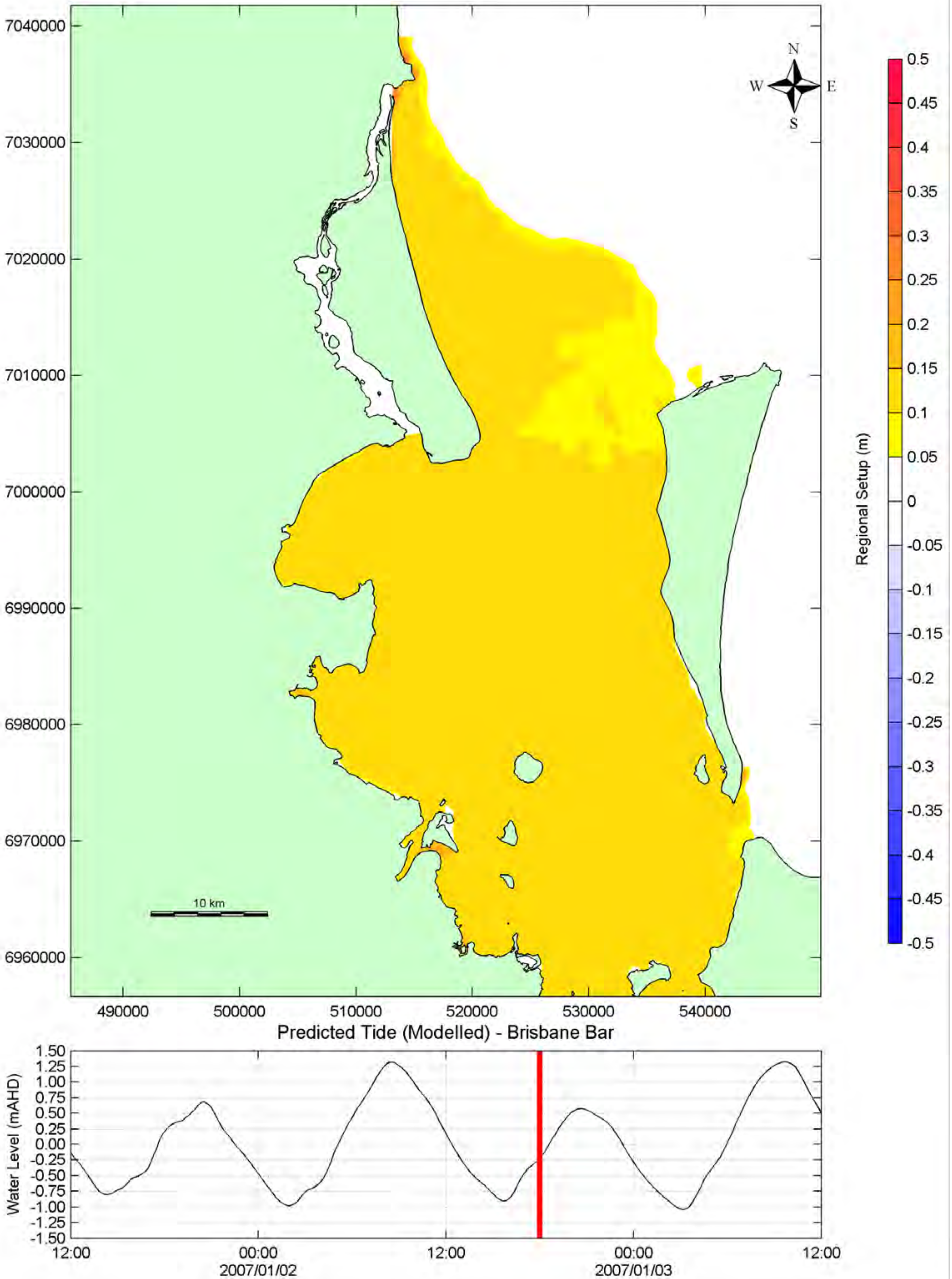




DELFT3D MODELLED REGIONAL WAVE SETUP

Northern Moreton Bay - 16:00

Figure 6.12



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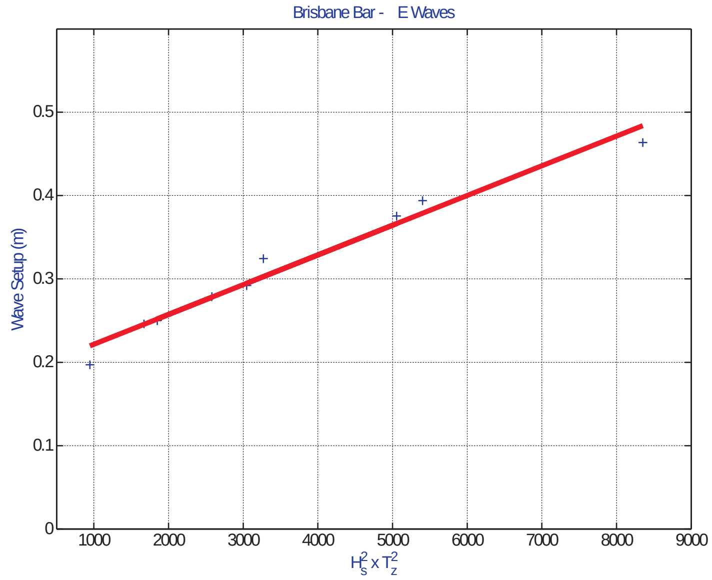
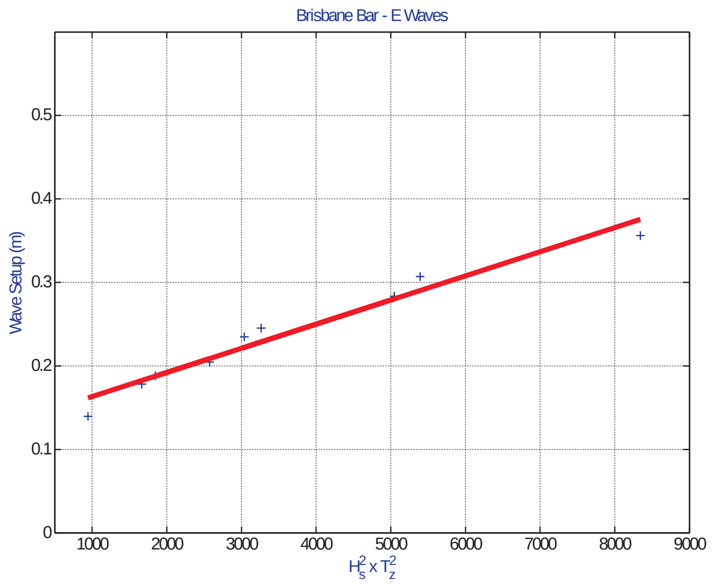
Storm Tide Hazard Study - Moreton Bay Regional Council

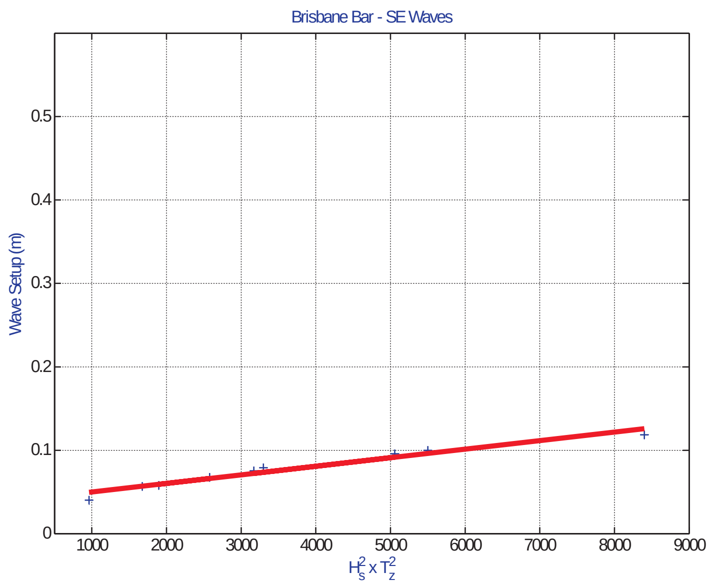
DELFT3D MODELLED REGIONAL WAVE SETUP

Northern Moreton Bay - 18:00

Figure 6.13







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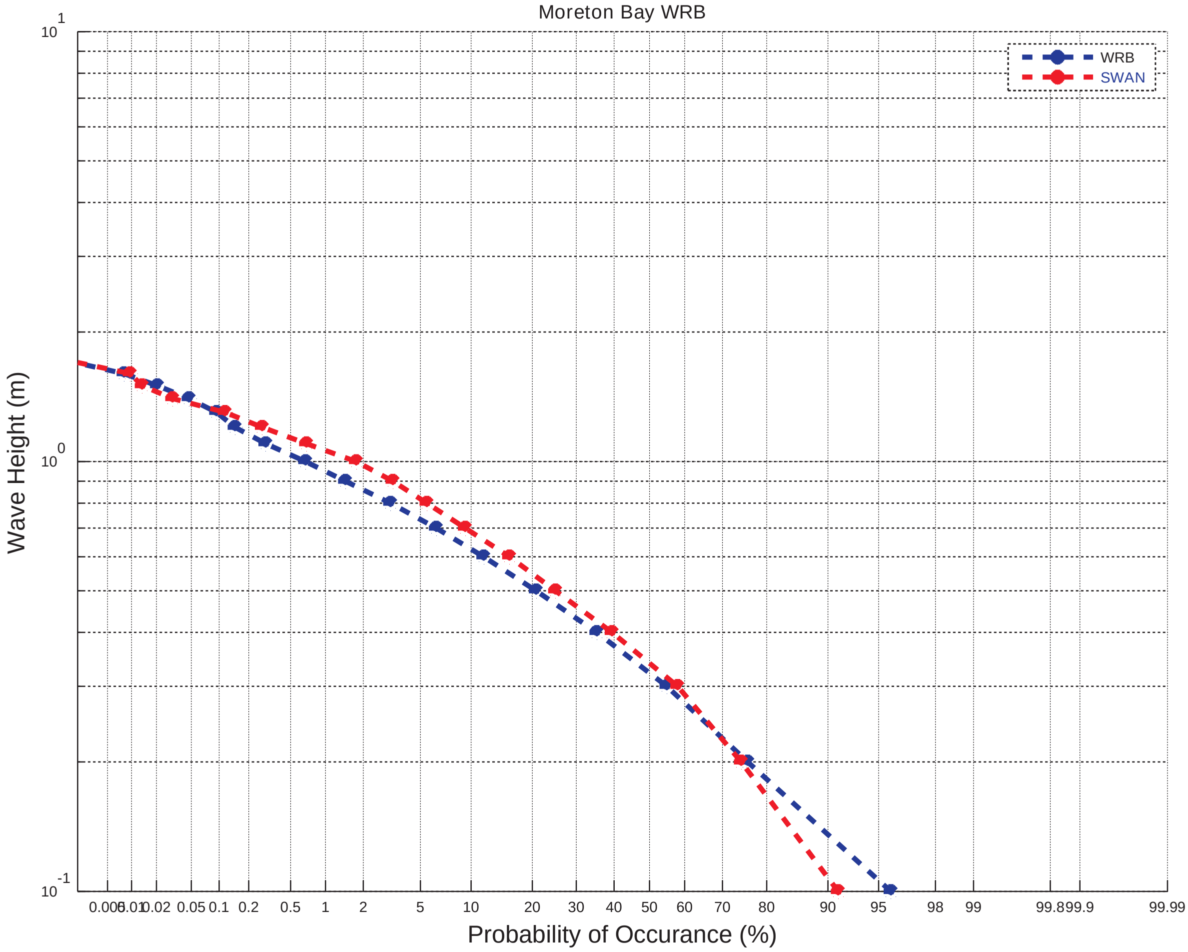
Storm Tide Hazard Study - Moreton Bay Regional Council
REGIONAL WAVE SETUP REGRESSION MODELS

Figure 6.14



Storm Tide Hazard Study - Moreton Bay Regional Council
SWAN MODEL CALIBRATION
MORETON BAY WRB
Figure 7.1

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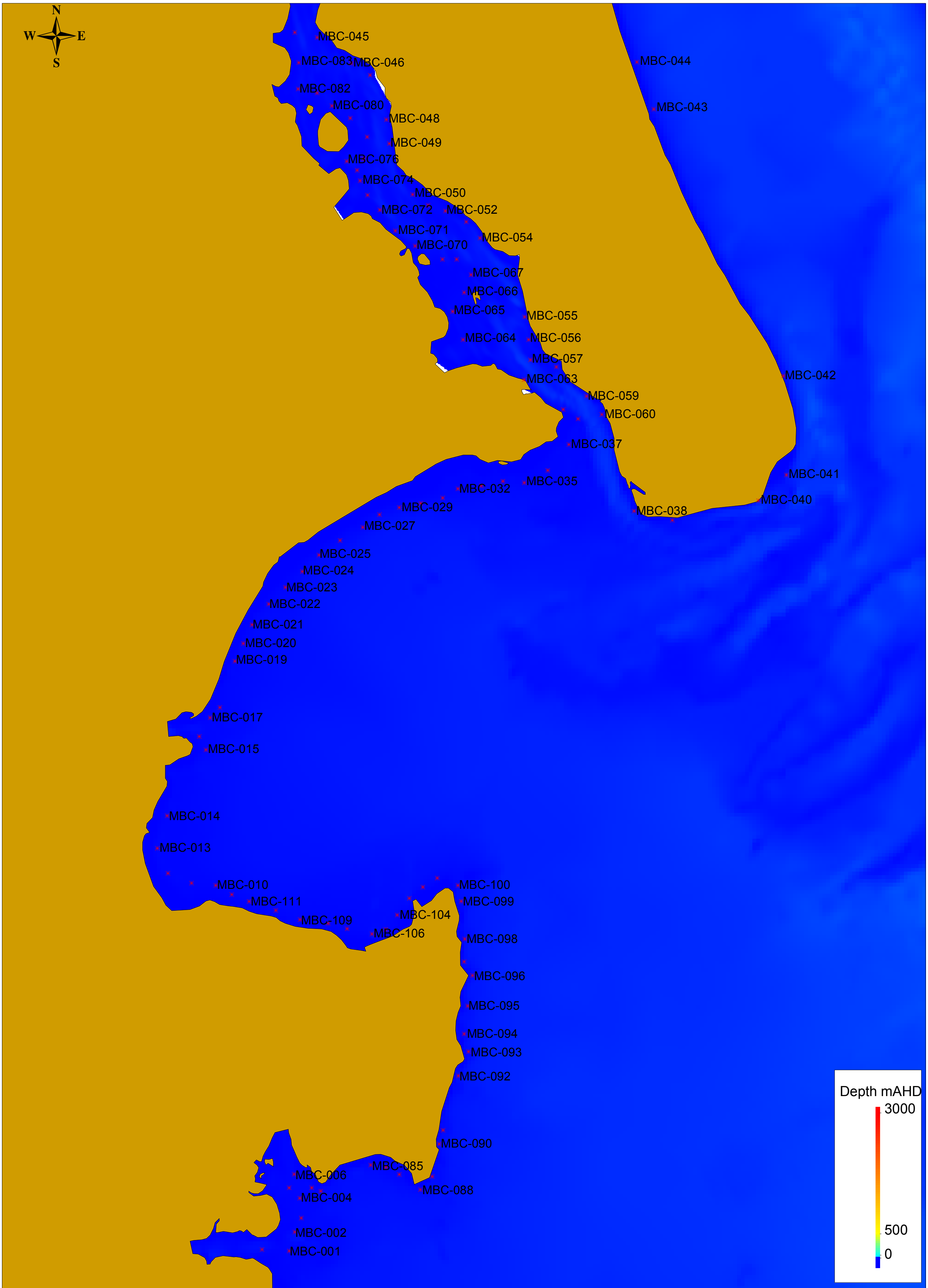

Storm Tide Hazard Study - Moreton Bay Regional Council

REPORTED OUTPUT LOCATIONS

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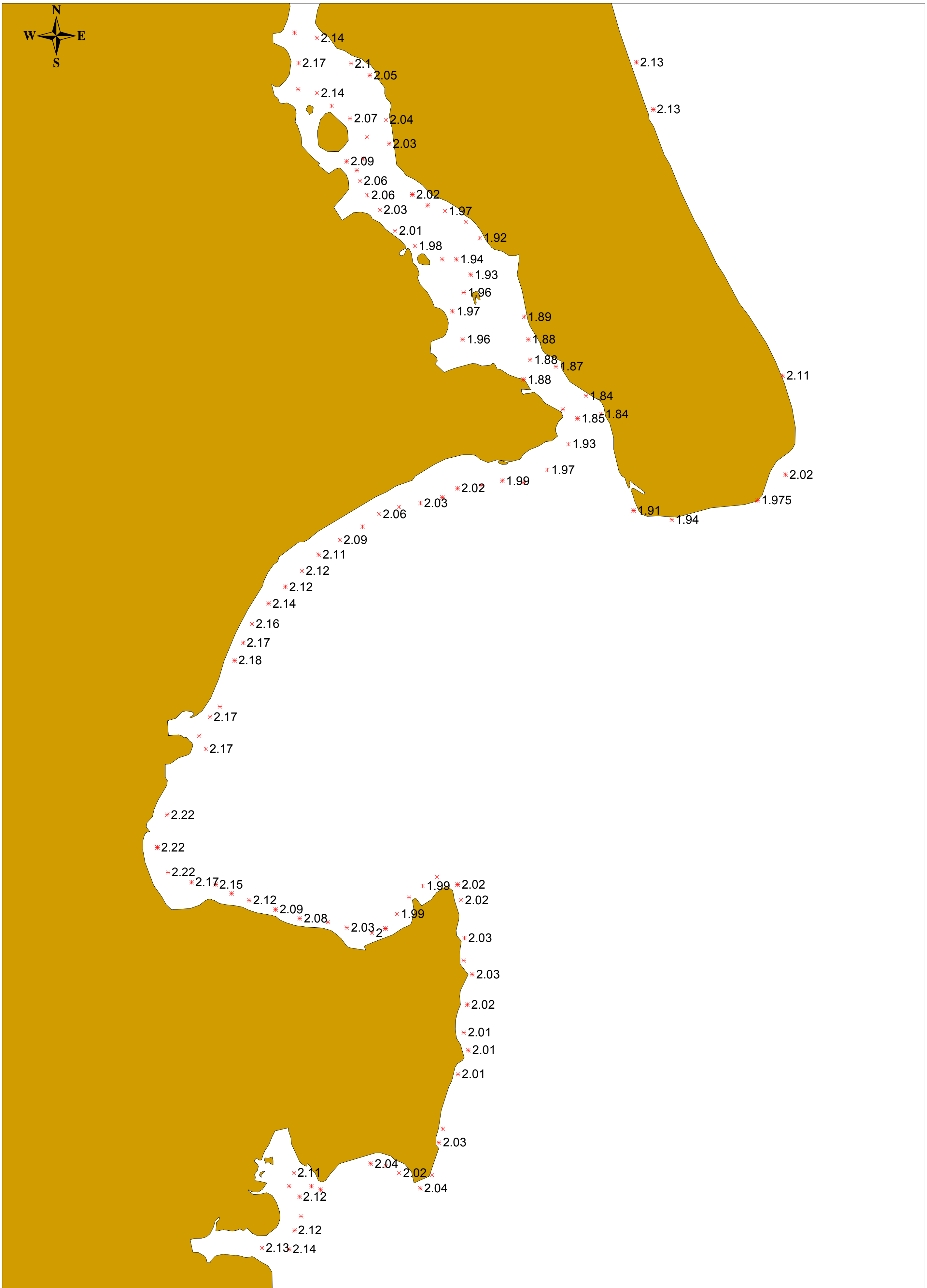
Figure 7.2



Storm Tide Hazard Study - Moreton Bay Regional Council

100-YEAR ARI NON-CYCLONIC DESIGN WATER LEVELS (mAHD)

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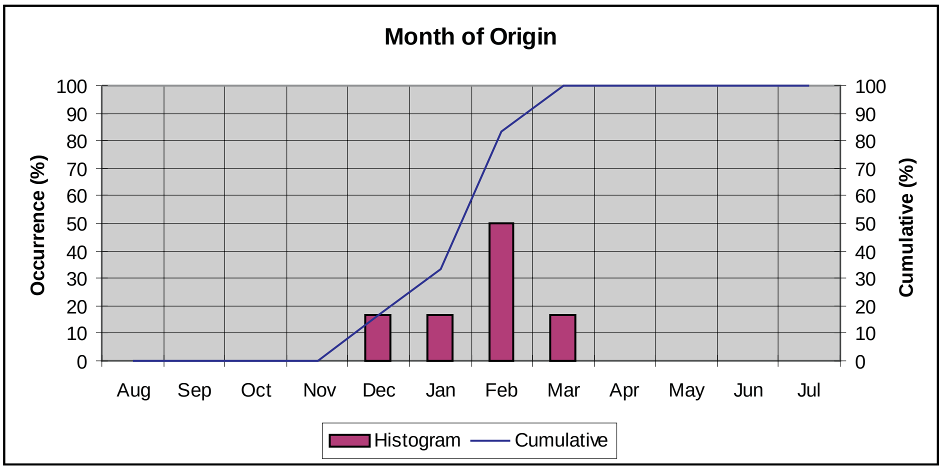
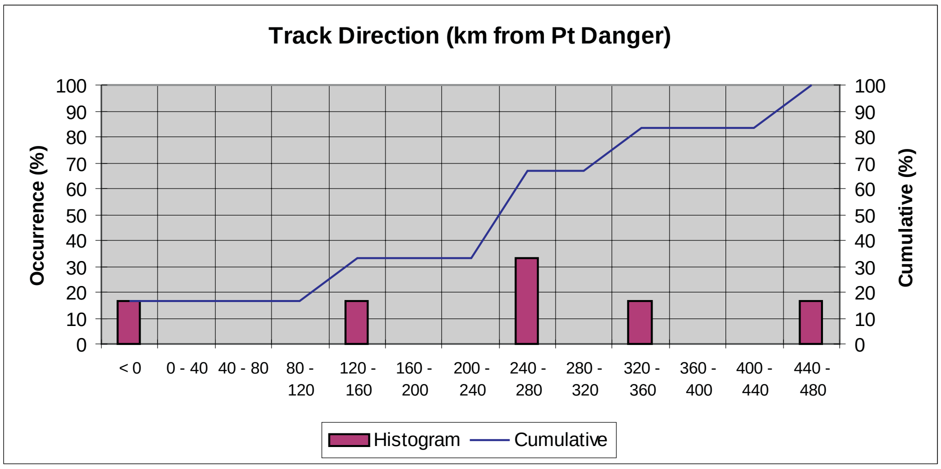
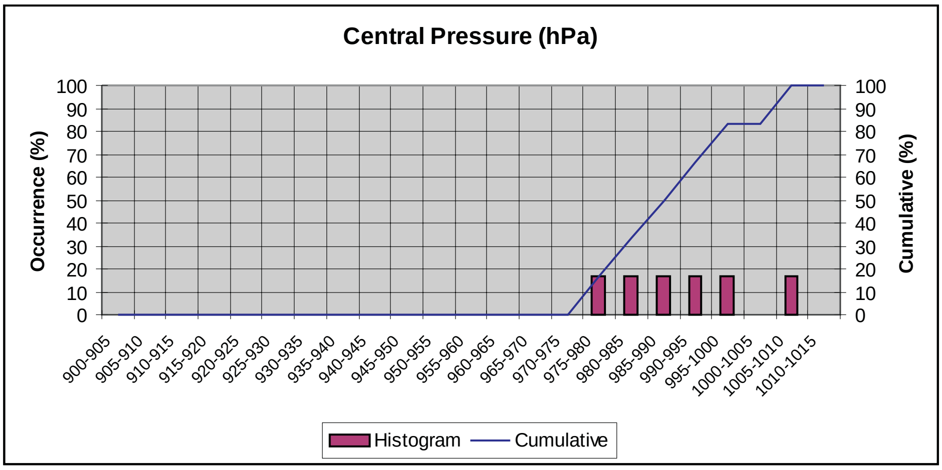
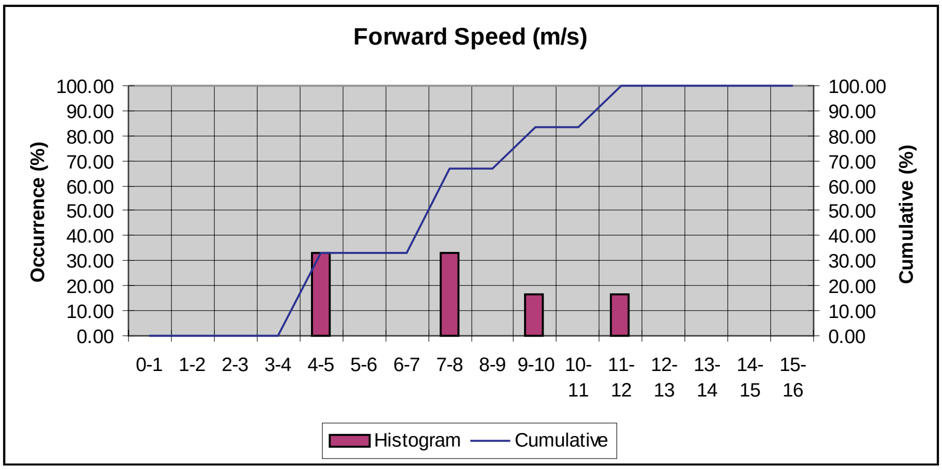
Figure 7.3



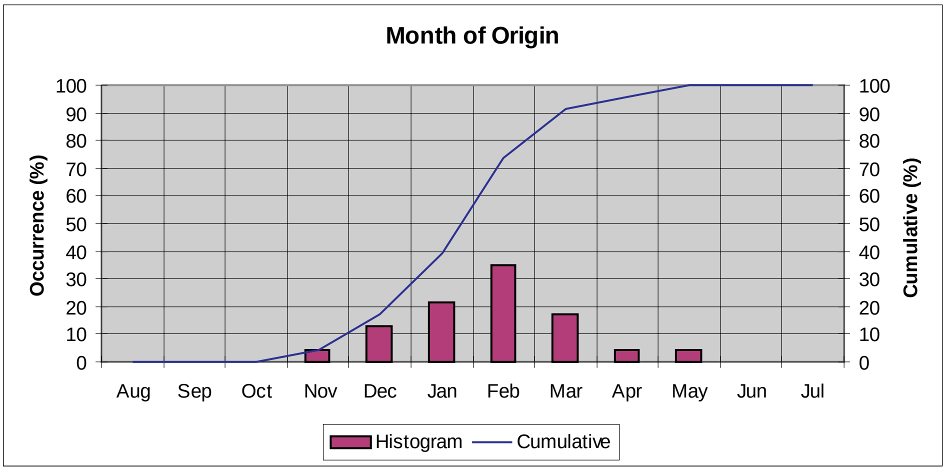


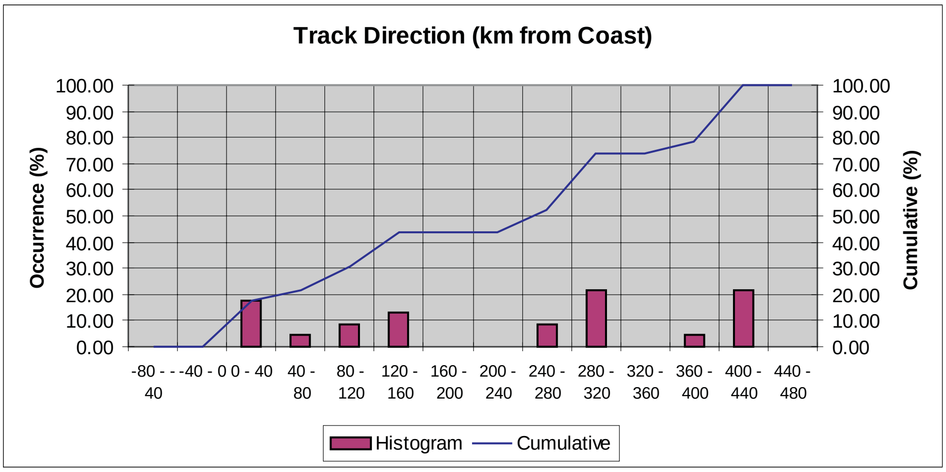


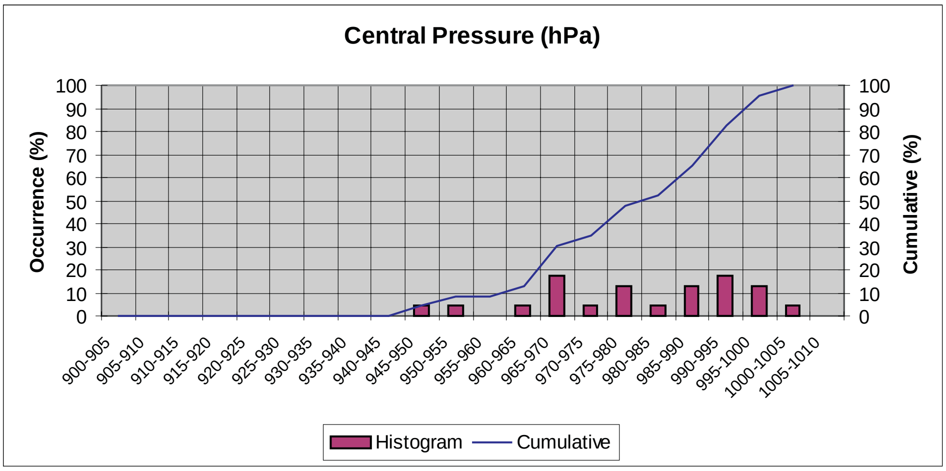


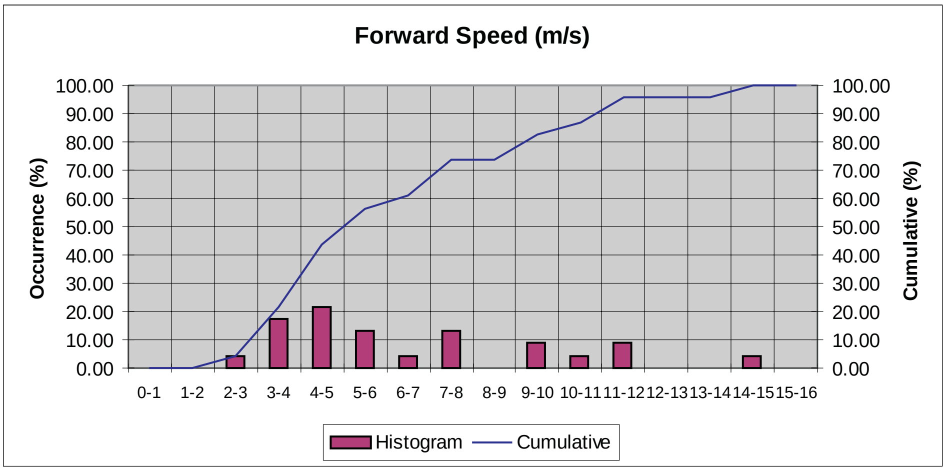
COAST-CROSSING CYCLONE STATISTICS

Figure 8.1









Storm Tide Hazard Study - Moreton Bay Regional Council
COASTCROSSING CYCLONE STATISTICS

Cardno Lawson Treloar

LJ8824/R2461 February 2009
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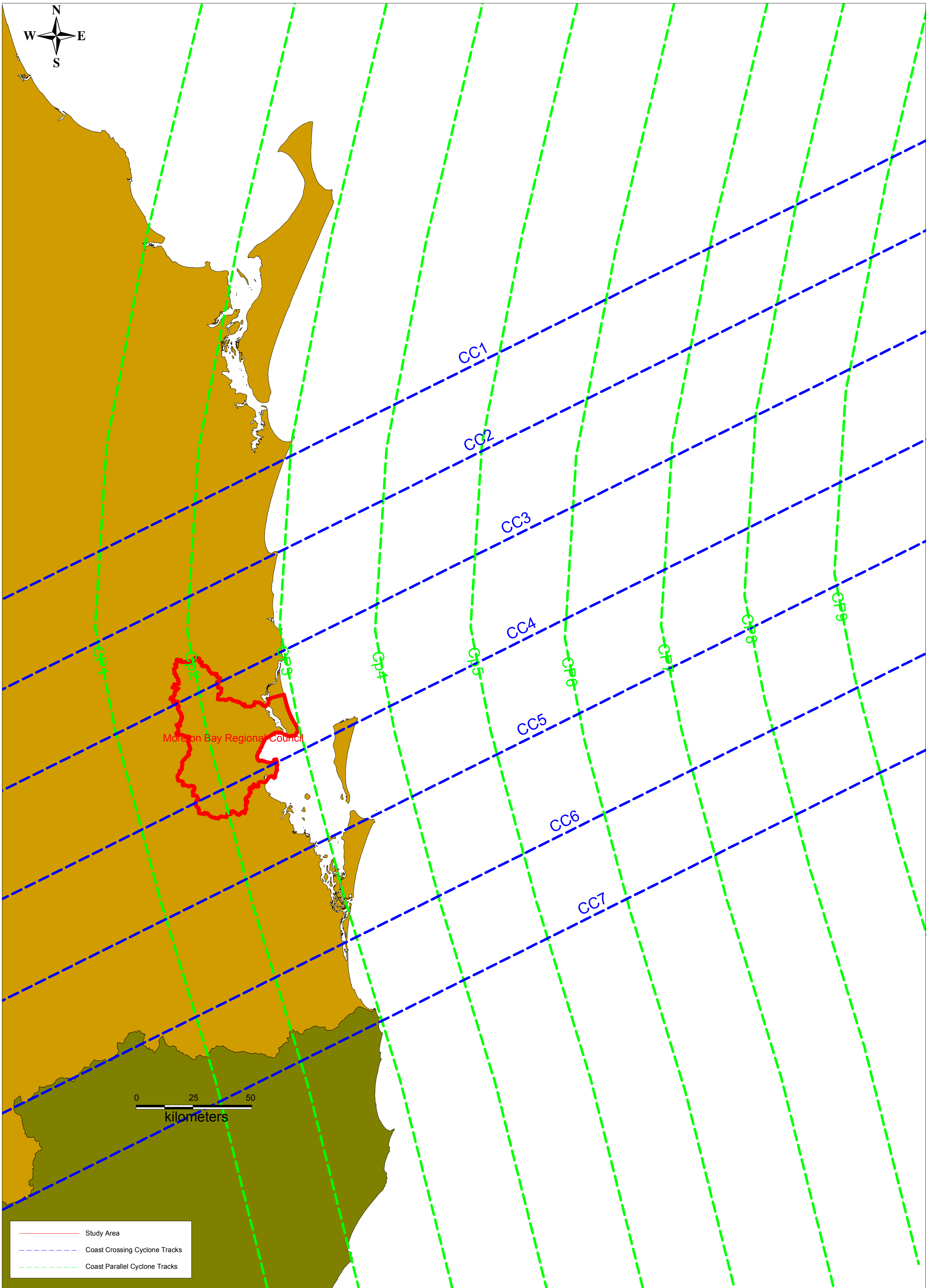
Figure 8.2



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Storm Tide Hazard Study - Moreton Bay Regional Council

DELFT3D MODEL DESIGN CYCLONE TRACKS

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Figure 8.3

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LJ8824/R2461 February 2009
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Storm Tide Hazard Study - Moreton Bay Regional Council

100-YEAR ARI CYCLONIC DESIGN WATER LEVELS (mAHD)
PRESENT CLIMATE CONDITION
Figure 8.4

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Storm Tide Hazard Study - Moreton Bay Regional Council

100-YEAR ARI CYCLONIC DESIGN WATER LEVELS (mAHD)
GREENHOUSE RELATED CLIMATE CHANGE CONDITIONS

Figure 8.5

LJ8824/R2461 February 2009
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LJ8824/R2461 February 2009
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Storm Tide Hazard Study - Moreton Bay Regional Council

100-YEAR ARI DESIGN WATER LEVELS (mAHD)
NON-CYCLONIC AND CYCLONIC COMPARISION
Figure 9.1

Storm Tide Hazard Study - Moreton Bay Regional Council

100-YEAR ARI, 100-YEAR (2109) PLANNING LEVELS (mAHD) GREENHOUSE RELATED CLIMATE CHANGE CONDITIONS, INCLUDES FREEBOARD AND SLR

Figure 10.1

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APPENDIX A

Glossary of Terms

GLOSSARY*

Australian Height Datum (AHD)	A common national plane of level corresponding approximately to mean sea level.
ARI	Average Recurrence Interval
Barometric Set-up	A rise in sea level caused by the low central pressure of a cyclone drawing in water to balance total water level and atmospheric pressure
CD	Chart Datum, common datum for navigation charts - 1.243m below AHD at Brisbane Bar. Equal to Lowest Astronomical Tide (LAT).
Coriolis Force	The force on a moving body caused by changing distance from the polar axis of the Earth.
Diurnal	A daily variation, as in day and night.
Ebb Tide	The outgoing tidal movement of water within an estuary.
Estuary	An enclosed or semi-enclosed body of water having an open or intermittently open connection to coastal waters and in which water levels vary in a periodic fashion in response to ocean tides.
Flood Tide	The incoming tidal movement of water within an estuary.
Foreshore	The area of shore between low and high tide marks and land adjacent thereto.
Fortnightly Tides	The variation in tide levels caused by the monthly variation of Spring and Neap Tides.
H_s (Significant Wave Height)	H_s may be defined as the average of the highest 1/3 of wave heights in a wave record ($H_{1/3}$), or from the zeroth spectral moment (H_{mo}), though there is a difference of about 5 to 8%. The Hmo parameter is used in wave modelling; hence in this study. This is a slightly conservative position.
Intertidal	Pertaining to those areas of land covered by water at high tide, but exposed at low tide, eg. intertidal habitat.
Mathematical/ Computer Models	The mathematical representation of the physical processes involved in runoff, stream flow and estuarine/sea flows. These models are often run on computers due to the complexity of the mathematical relationships. In this report, the models referred to are mainly involved with wave and current processes.
MSL	Mean Sea Level
Neap Tides	Tides with the smallest range in a monthly cycle. Neap tides occur when the sun and moon lie at right angles relative to the earth (the gravitational effects of the moon and sun act in opposition on the ocean).

Numerical Model	A mathematical representation of a physical, chemical or biological process of interest. Computers are often required to solve the underlying equations.
Phase Lag	Difference in time of the occurrence between high (or low water) and maximum flood (or ebb) velocity at some point in an estuary or sea area.
Semi-diurnal	A twice-daily variation, e.g. two high waters per day.
Shoals	Shallow areas in an estuary created by the deposition and build-up of sediments.
Slack Water	The period of still water before the flood tide begins to ebb (high water slack) or the ebb tide begins to flood (low water slack).
Spring Tides	Tides with the greatest range in a monthly cycle, which occur when the sun, moon and earth are in alignment (the gravitational effects of the moon and sun act in concert on the ocean)
Storm Surge	The increase in coastal water levels caused by the barometric and wind set-up effects of storms. Barometric set-up refers to the increase in coastal water levels associated with the lower atmospheric pressures characteristic of storms. Wind set-up refers to the increase in coastal water levels caused by an onshore wind driving water shorewards and piling it up against the coast.
Tidal Exchange	The proportion of the tidal prism that is flushed away and replaced with 'fresh' coastal water each tide cycle.
Tidal Excursion	The distance travelled by a water particle from low water slack to high water slack and vice versa.
Tidal Lag	The delay between the state of the tide at the estuary mouth (eg. high water slack) and the same state of tide at an upstream location.
Tidal Limit	The most upstream location where a tidal rise and fall of water levels is discernible. The location of the tidal limit changes with freshwater inflows and tidal range.
Tidal Planes	A series of water levels that define standard tides, eg. 'Mean High Water Spring' (MHWS) refers to the average high water level of Spring Tides.
Tidal Prism	The total volume of water moving past a fixed point in an estuary during each flood tide or ebb tide.

Tidal Propagation	The movement of the astronomical tide into and out of an estuary.
Tidal Range	The difference between successive high water and low water levels. Tidal range is maximum during Spring Tides and minimum during Neap Tides.
Tidally Varying Models	Numerical models that predict estuarine behaviour within a tidal cycle, i.e., the temporal resolution is of the order of minutes or hours.
Tides	The regular rise and fall in sea level in response to the gravitational attraction of the Sun, Moon and Earth.
T_z (Zero Crossing Period)	The average period of a set of waves. Common wave period parameter used for wave run-up calculation.
Wind Set-up	Onshore winds push water against the coastline causing it to 'pile-up'. Additional wind set-up is caused by northward flowing wind caused coast parallel currents through the Coriolis force and refraction on the continental shelf.

* A number of definitions have been derived from the NSW Estuary Management Manual (1992).