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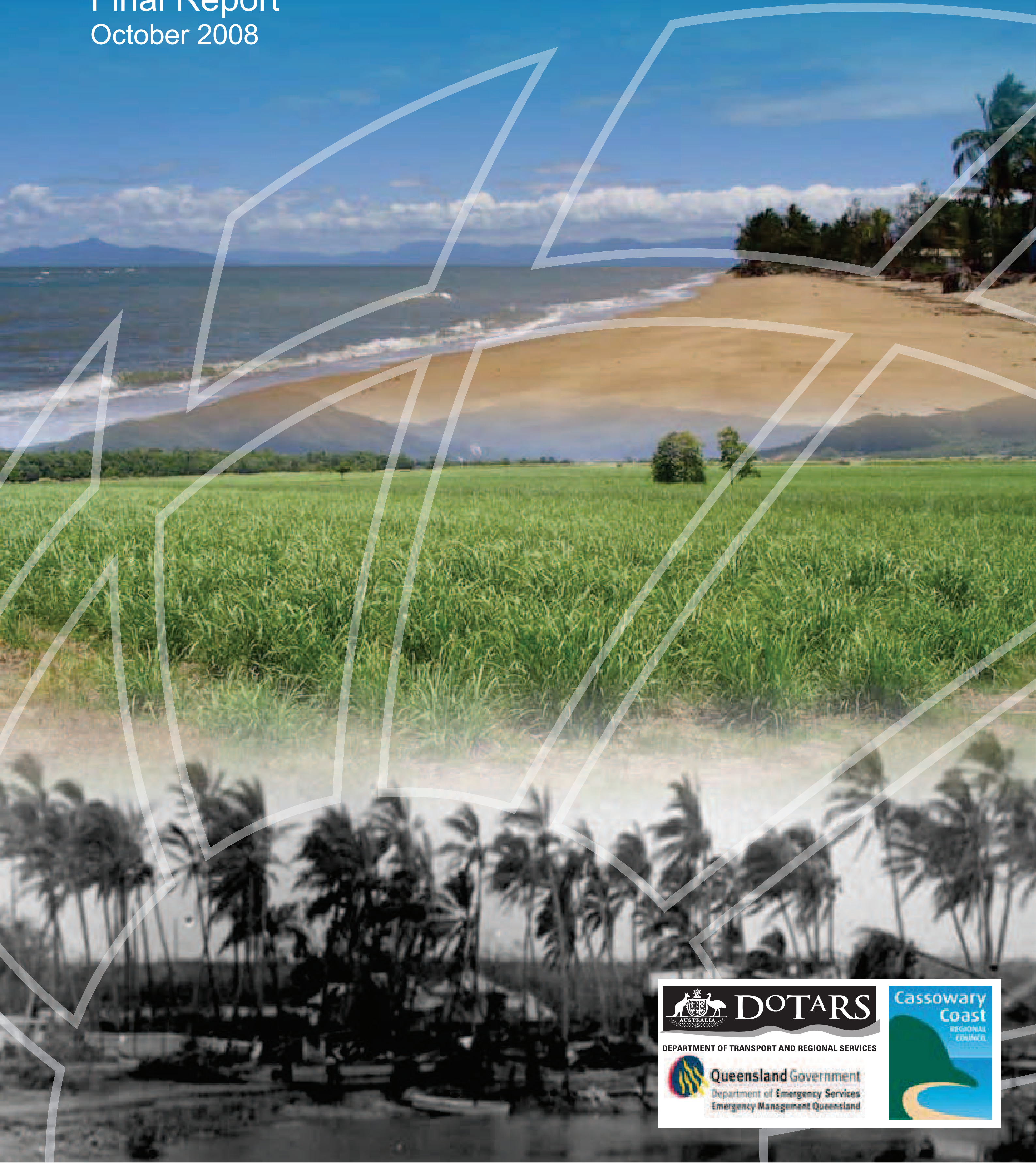
Cardwell Inundation Study

Final Report
October 2008



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Cardwell Inundation Study:

Final Report

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Title :	Cardwell Inundation Study – Final Report
Author :	Greg Rogencamp, Chris Huxley, Ian Teakle
Synopsis :	This report documents the findings of the Cardwell Inundation Study, which is aimed at reducing community vulnerability to the adverse effects of inundation caused by flooding and storm surge.

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FORWARD

The Queensland Department of Emergency Services is administrating the Queensland studies under the Federal Department of Transport and Regional Services “Natural Disaster Risk Management Studies Program.” The aim of the program is to identify, analyse and evaluate the risks from natural disasters and to identify risk management measures to reduce the risk to life and property.

Inundation from flooding and storm surge were identified as major risks for the residents of the southern part of Cassowary Coast Regional Council (i.e. the old Cardwell Shire area) and funding has been obtained through this program to carry out the Cardwell Inundation Study.

The publication “Floodplain Management in Australia – Best Practice Principles and Guidelines” (CSIRO, 2000) provides the framework for the development and implementation of a Floodplain Management Plan. The process outlined in CSIRO (2000) is described below and is applied in this study to both flood inundation and coastal / storm surge inundation.

Floodplain Management Process

Stage	Description
1. Flood Behaviour Definition	The nature and extent of the flood problem are determined.
2. Floodplain Management Measures Investigation	Management measures for the floodplain are investigated in respect of both existing and proposed developments. These options are evaluated based on the impact on flood risk, while considering social, ecological and economic factors.
3. Floodplain Management Plan	Following acceptance of Stage 2 recommendations, the preferred management options are documented in a plan.
4. Implementation of the Plan	Involves formal adoption by Council of the floodplain risk management plan and a process of implementation for the selected flood, response and property modification options.

BMT WBM was commissioned by Cassowary Coast Regional Council to carry out the Cardwell Inundation Study and this report documents the findings of this process. It defines the existing flooding and storm surge risks for the shire and assesses a range of measures and their ability to reduce the impact of this inundation.

EXECUTIVE SUMMARY

INTRODUCTION

Cassowary Coast Regional Council has identified that there is a risk to the community from inundation resulting flooding and storm surge. Council applied for funding under the Natural Disaster Mitigation Programme to carry out a Flood and Storm Surge Inundation Study. Following a tender period in November, 2005 the study was awarded to BMT WBM on 16th February, 2006.

OBJECTIVES & STUDY APPROACH

Cassowary Coast Regional Council commissioned the project with the intent to reduce community vulnerability to the adverse effects of inundation caused by flooding and storm surge. BMT WBM's approach to the study involved a five-stage approach involving development of numerical flood and coastal models to assist in the prediction of inundation behaviour.

STORM SURGE MODEL DEVELOPMENT & CALIBRATION

A number of numerical models were developed to simulate tropical cyclone storm surges and their impact along the southern part of Cassowary Coast Regional Council (i.e. the old Cardwell Shire area) coastline. These models included a model of the entire Coral Sea, a more detailed in-shore model (from the reef to the coast) and other wind models.

These models were then calibrated to two major cyclones, Larry (2006) and Winifred (1986). The calibration focussed on replication of the wind, storm surge and debris measurements at various locations in and adjacent to the study area.

FLOOD MODEL DEVELOPMENT & CALIBRATION

Numerical flood models of the Tully-Murray River system as well as the Meunga Creek system were developed using topographical data of the floodplain and watercourses. These hydraulic models required estimation of time-varying inflows, which were derived from calibrated hydrological models provided by the Bureau of Meteorology.

These models were then calibrated to two flood events in 2006 and 1999. The calibration focussed on replication of the peak flood levels on the floodplain and gauge measurements at two locations along the Bruce Highway.

DESIGN FLOOD ASSESSMENTS

The calibrated flood models (hydrological and 2D/1D hydraulic) were then used to simulate a range of design flood events (i.e. 10%, 2%, 1%, 0.5% and 0.01% AEP flood events as well as the Probable Maximum Flood Event). Flood behaviour was examined and flood maps were produced for each event showing levels, depths, velocities and velocity-depth products.

DESIGN STORM SURGE ASSESSMENTS

The calibrated coastal models (wind, wave and storm surge) were then used to simulate a range of design storm surge events (i.e. 1%, 0.5%, 0.2, 0.1% and 0.01% AEP storm tide events). The procedure involved in making these estimates included the following components:

- Derivation of historical cyclone climatology (statistics);
- Simulation of 112 representative cyclone events;
- Development of storm surge and wave parametric models;
- Simulation of 50,000 years of cyclone activity (Monte Carlo simulation); and
- Statistical interpretation and mapping of results.

These simulations resulted in inundation maps for the coastline for the five events considered with an allowance for sea level rise (due to the predictions for the Enhanced Greenhouse Effect) and wave run-up.

COMMUNITY VULNERABILITY ASSESSMENT

This Community Vulnerability Assessment was based on the results of the flood and storm surge modelling as well as profiles of the various communities (using ABS and other data).

As part of this assessment, a damages assessment was carried out in order to quantify the average annual flood and coastal inundation damages to the study area. This was carried out based on some relatively coarse but necessary assumptions regarding floor levels and expected damages.

The results of this Community Vulnerability Assessment indicated that the areas of Tully Heads and Hull Heads are highly vulnerable communities due partly to the high number of low-income households (45%) and the high number of residents that have recently moved to Far North Queensland (37%). As well, this area is at a relatively high risk of inundation and isolation during a storm surge event, resulting in a conclusion that the area is a High Risk area for inundation.

The township of Cardwell was also identified as a highly vulnerable community due partly to the high number of low-income households (45%), the high proportion of elderly residents (27%) and the high number of residents that have recently moved to Far North Queensland (35%). However, the probability of inundation for the township of Cardwell is not as high as for Tully Heads and Hull Heads and it was classified as a Moderate to High Risk area on that basis.

MANAGEMENT MEASURES

The assessment of management measures aimed to reduce the risk exposure of the community was focussed on non-structural measures (e.g. planning and development control) and flood warning / emergency response measures.

In order to identify the areas potentially requiring special development control, a range of hazard categories for the floodplain were developed. These were then mapped based on the results of the flood modelling for a range of flood events.

The planning and development control measures are focussed on the use of a matrix approach to future developments on the floodplain and coastal areas. The traditional floodplain planning approach has relied almost entirely on the definition of a single flood standard, which has usually been based on the 100 year ARI flood event. Overall, this approach has worked satisfactorily. However, it is now viewed as simplistic and inappropriate in certain situations. In particular, it has failed to comprehensively consider the varying land uses and flood risks on the floodplain.

A number of new planning approaches have emerged in recent years that provide a transitional level of control based on flood hazard and the sensitivity of the possible range of land-uses to the flood risk. Using this approach, a matrix of development controls, based on the flood hazard and proposed land use, was developed.

An estimate was made of the financial benefits that could accrue from improved development control. If development controls as outlined in this report were introduced, the Average Annual Damages would decrease by $ 800,000/a. This annual saving in damages has a Net Present Worth to the community of $ 11 million (approximately 14 times the annual savings).

It is recognised that the estimate of benefits relies upon a number of assumptions and possibly conservative estimates. However, the order of the savings to the community is still expected to be at least $ 3 million. The cost of this study and implementation of the planning controls would be in the order of $ 350,000. Hence, this exercise demonstrates that the study and proposed approach represents a considerable benefit for the community for a relatively small cost.

The flood warning / emergency response measures considered included:

- increased public awareness (possibly through the development of an education DVD)
- an evacuation refuge for Tully Heads / Hull Heads; and
- improved mapping for the operations and planning of the local SES.

RECOMMENDATIONS AND CONCLUSIONS

The following measures are recommended for further consideration.

1 Adoption of a planning matrix and integration of the planning matrix into the Town Plan.

2 The development of public education tools such as regular brochures and a DVD should be considered for further action;

3 Improved maps for use by the local SES; and

4 Coordination of study outcomes with those of the Johnstone Shire Storm Surge Study.

A number of additional studies and tasks are recommended below to add to the value of this study.

a. It is recommended that a local drainage / creek study be carried out for One Mile Creek (Cardwell town) which would focus on local flooding issues including the possibility that inundation from One Mile Creek can jeopardies the access to the main evacuation centre for Cardwell.

b. It has also been identified that the modelling tasks in this study could be improved through the acquisition of more accurate survey over the floodplain and a floor level survey (possibly targeted on those houses expected to be inundated).

The study has concluded the following:

- The coastal areas of Tully Heads and Hull Heads are High Risk areas with regard to storm surge inundation;
- The mapping of storm surge inundation and flood inundation will enable Council to better manage the risks associated with this type of natural hazard;
- If development controls as outlined in this report are introduced, there is the potential for considerable long-term savings to the community through reduced inundation damages.

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GLOSSARY

annual exceedance probability (AEP)	The chance of a flood of a given size (or larger) occurring in any one year, usually expressed as a percentage. For example, if a peak flood discharge of 500 m^3/s has an AEP of 5%, it means that there is a 5% chance (i.e. a 1 in 20 chance) of a peak discharge of 500 m^3/s (or larger) occurring in any one year (see also average recurrence interval).
Australian Height Datum (AHD)	National survey datum corresponding approximately to mean sea level.
average annual damage (AAD)	Depending on its size (or severity), each flood will cause a different amount of flood damage. The annual average damage is the average damage per year that would occur in a designated area from flooding over a very long period of time. In many years there may be no flood damage, in some years there will be minor damage (caused by small, relatively frequent floods) and, in a few years, there will be major flood damage (caused by large, rare flood events). Estimation of the average annual damage provides a basis for comparing the effectiveness of different floodplain management measures (i.e. the reduction in the annual average damage).
average recurrence interval (ARI)	The long-term average number of years between the occurrence of a flood as big as (or larger than) the selected event. For example, floods with a discharge as great as (or greater than) the 20yr ARI design flood will occur on average once every 20 years. ARI is another way of expressing the likelihood of occurrence of a flood event (see also annual exceedance probability).
catchment	The catchment at a particular point is the area of land that drains to that point.
design floor level	The minimum (lowest) floor level specified for a building.
design flood	A hypothetical flood representing a specific likelihood of occurrence (for example the 100 year or 1% probability flood).
development	Existing or proposed works that may or may not impact upon flooding. Typical works are filling of land, and the construction of roads, floodways and buildings.
discharge	The rate of flow of water measured in terms of volume over time (i.e. the amount of water moving past a point). Discharge and flow are interchangeable.
DEM	Digital Elevation Model - a three-dimensional model of the ground surface.
effective warning time	The available time that a community has from receiving a flood warning to when the flood reaches them.
flood	Relatively high river or creek flows, which overtop the natural or artificial banks, and inundate floodplains and/or coastal inundation resulting from super elevated sea levels and/or waves overtopping coastline defences.

flood awareness	An appreciation of the likely threats and consequences of flooding and an understanding of any flood warning and evacuation procedures. Communities with a high degree of flood awareness respond to flood warnings promptly and efficiently, greatly reducing the potential for damage and loss of life and limb. Communities with a low degree of flood awareness may not fully appreciate the importance of flood warnings and flood preparedness and consequently suffer greater personal and economic losses.
flood damage	The tangible and intangible costs of flooding.
flood behaviour	The pattern / characteristics / nature of a flood.
flood frequency analysis	An analysis of historical flood records to determine estimates of design flood flows.
flood fringe	Land that may be affected by flooding but is not designated as floodway or flood storage.
flood hazard	The potential risk to life and limb and potential damage to property resulting from flooding. The degree of flood hazard varies with circumstances across the full range of floods.
flood level	The height or elevation of floodwaters relative to a datum (typically the Australian Height Datum). Also referred to as “stage”.
flood liable land	See flood prone land.
floodplain	Land adjacent to a river or creek that is periodically inundated due to floods. The floodplain includes all land that is susceptible to inundation by the probable maximum flood (PMF) event.
floodplain management	The co-ordinated management of activities that occur on the floodplain.
floodplain management measures	A range of measures that are aimed at reducing the impact of flooding. This can involve reduction of flood damages, disruption and psychological trauma.
floodplain management plan	A document outlining a range of measures aimed at reducing the flood risk. The plan is the principal means of managing the risks associated with the use of the floodplain. The plan usually contains both written and diagrammatic information describing how particular areas of the floodplain are to be used and managed to achieve defined objectives.
floodplain management scheme	A floodplain management scheme comprises a combination of floodplain management measures. In general, one scheme is selected by the floodplain management committee and is incorporated into the plan.
flood planning levels (FPL)	Flood planning levels selected for planning purposes are derived from a combination of flood levels and a freeboard. Selection should be based on an understanding of the full range of flood behaviour and the associated flood risk. It should also take into account the social, economic and ecological consequences associated with floods of different severities. Different FPLs may be appropriate for different categories of landuse and for different flood plans. As FPLs do not necessarily extend to the limits of flood prone land, floodplain risk management plans may apply to flood prone land beyond that defined by the FPLs.

flood prone land	Land susceptible to inundation by the probable maximum flood (PMF) event. The flood prone definition should not be seen as necessarily precluding development. Floodplain Management Plans should encompass all flood prone land (i.e. the entire floodplain).
flood proofing	Measures taken to improve or modify the design, construction and alteration of buildings to minimise or eliminate flood damages and threats to life and limb.
flood source	The source of the floodwaters.
flood storages	Floodplain areas that are important for the temporary storage of floodwaters during a flood.
floodway	A flow path (sometimes artificial) that carries significant volumes of floodwaters during a flood.
freeboard	A factor of safety usually expressed as a height above flood level thus determing a flood planning level. Freeboard tends to compensate for factors such as wind/boart wave action, localised hydraulic effects and uncertainties in the design flood levels.
historical flood	A flood that has actually occurred.
hydraulics	The term given to the study of water flow in rivers, estuaries and coastal systems.
hydrograph	A graph showing how a river or creek's discharge or water level changes with time.
hydrology	The term given to the study of the rainfall-runoff process in catchments.
peak flood level, flow or velocity	The maximum flood level, flow or velocity occurring during a flood event at a particular location.
probable maximum flood (PMF)	An extreme flood deemed to be the maximum flood likely to occur.
probability	A statistical measure of the likely frequency or occurrence of flooding.
runoff	The amount of rainfall from a catchment that actually ends up as flowing water in the river or creek.
stage	See flood level.
stage hydrograph	A graph of water level over time.
TUFLOW	Fully two-dimensional and one dimensional unsteady flow hydraulic modelling software.
URBS	Hydrological computer model software.
velocity	The speed at which the floodwaters are moving. Typically, modelled velocities in a river or creek are quoted as the depth and width averaged velocity, i.e. the average velocity across the whole river or creek section if a one-dimensional solution is used; and depth average if a two-dimensional solution is used.
water level	See flood level.

LIST OF ABBREVIATIONS

1D / 2D/ 3D	One dimensional / Two dimensional / Three dimensional
AEP	Annual Exceedance Probability
AHD	Australian Height Datum
ARI	Average Recurrence Interval
AR&R	Australian Rainfall and Runoff
BoM	Bureau of Meteorology
CCRC	Cassowary Coast Regional Council
CSC	Cardwell Shire Council
CDC	Counter Disaster Committee
cm	centimetre
cumecs	cubic metres per second
DA	Development Application
DCP	Development Control Plan
DEM	Digital Elevation Model
DES	Queensland Department of Emergency Services
DMR	Queensland Department of Main Roads
DoT	Queensland Department of Transport
EIS	Environmental Impact Study
EPA	Queensland Environmental Protection Agency
ERA	Environmentally Relevant Activity
FPL	Flood Planning Level
GIS	Geographic Information System
km	kilometre
m	metre
m^3/s	cubic metres per second (same as cumecs)
m AHD	Elevation in metres relative to the Australian Height Datum
NRW	Queensland Department of Natural Resources & Water & Water
PMF	Probable Maximum Flood
QR	Queensland Rail
SD	State Datum
SES	QLD State Emergency Services

1 INTRODUCTION

1.1 Background

Cassowary Coast Regional Council has identified that there is a risk to the community from inundation resulting flooding and storm surge. Council applied for funding under the Natural Disaster Mitigation Programme to carry out a Flood and Storm Surge Inundation Study.

Following a tender period in November, 2005 the study was awarded to BMT WBM on 16th February, 2006. Coincidentally, one of the most severe cyclones to hit the area (Severe Tropical Cyclone Larry) crossed the coast just north of the shire in March 2006.

1.2 Study Area

The study area (see Figure 1-2) covers an area of almost 700km^2 and is located in north Queensland and is approximately 140km by road south of Cairns.

1.2.1 Flooding Risk

Cassowary Coast Regional Council is located in one of the highest rainfall areas in Australia, with the town of Tully regularly vying for the title of “wettest town in Australia”. Flooding can originate from monsoonal depressions, or from tropical cyclones. The entire population of the shire (some 11,000 people) is directly affected by flooding on an annual basis, particularly with main access routes closed for up to four days at a time. The Tully and Murray River systems flood regularly. Within the last 38 years, the Bruce Highway in this area has been closed no less than 22 times. This causes major disruption to the local community, with major transport routes for bananas and sugar cane blocked.

There are almost 5,000 properties recorded in southern part of Cassowary Coast Regional Council (i.e. the old Cardwell Shire area). Of this number, some 25% are potentially affected by river flooding. The total number of people potentially affected by property flooding is estimated to be of the order of 2,500 in over 1,200 properties. Aged care facilities exist in Tully and Cardwell.

The most significant flooding occurs from the Tully and Murray Rivers, which cross the Bruce Highway within 10km of each other in the vicinity of Tully. Creek flooding can also affect areas further to the south, and in particular to the north and south of Cardwell.

The floodplain of the Tully and Murray Rivers is complicated, being largely flat, and crossed by numerous cane railways, roads and informal levees. Consequently, flows move slowly and minor changes in slope can have a significant impact on the direction of flow.

1.2.2 Storm Surge Risk

The region lies within an active cyclone zone. Since 1969, it is estimated that almost 30 cyclones have passed within 200km of Cardwell. This equates to approximately one cyclone per year. Typically, these occur between the months of December and March. The accompanying storm surges pose significant inundation risks to the study area.

Aged care facilities exist in Tully and Cardwell, with those in Cardwell at the greatest level of risk.

1.2.3 Topography and Natural Features

The southern part of Cassowary Coast Regional Council (i.e. the old Cardwell Shire area) is approximately 2,900 km^2 and is dominated by coastal floodplains with a steep mountain range to the west. There are three major river systems: the Murray River, the Tully River and the Hull River. The systems are short run, due to the surrounding mountain ranges, and flow quickly to the coastal plains, with broad mouths at the coast. Each has an extensive tributary system that quickly funnels rainwater run-off into the main river systems. The Banyan Creek runs through Tully and causes local flooding of the surrounding area.

These river systems flood easily isolating a major portion of the community. Because of the steep nature of the mountains to the west, this has limited the construction of roads in and out of the area. There are only two roads out of the southern part of Cassowary Coast Regional Council (i.e. the old Cardwell Shire area), both of these are on the coastal plain and are subject to flooding. The roads to Mission Beach and Tully/Hull Heads would also be cut, thus isolating these communities from Tully as well.

All major townships are located in or around the river delta system or coastal fringe. It comprises the townships of Cardwell in the south, Tully/Bulgun and Wongaling/South Mission Beaches in the north and Tully/Hull Heads to the east as well the islands of Hinchinbrook, Dunk and Bedarra and other settlements throughout the area.

1.2.4 Population

The population of the southern part of Cassowary Coast Regional Council (i.e. the old Cardwell Shire area) is approximately 11,000. This number increases and decreases during and at the end of the tourist season. Listed hereunder is the population of communities within the area:

- Cardwell 1,700
- Kennedy 200
- Upper Murray 200
- Jumbun Community 100
- Euramo/Riversdale 300
- Lower Tully/Silky Oak 450
- Tully Heads/Hull Heads 500
- Syndicate/Jarra Creek 400
- South Mission Beach 900
- Wongaling Beach 1,200
- Feluga area 300
- Tully/Bulgun 3,700
- Dunk and Bedarra Islands 300
- Hinchinbrook Island 50
- **TOTAL 10,300**

1.2.5 Economic Base

Cassowary Coast Regional Council is experiencing continual economic growth. The mainstay of the economy, agriculture, in its many forms is in a healthy condition, despite the fluctuations in market price for a number of commodities. Principal agricultural pursuits involve sugar cane and fruit growing.

Tourism is increasing in the Shire. There is a range of tourism opportunities, such as environmental, historical, agricultural and traditional touring.

1.3 Objectives and Study Approach

1.3.1 Objectives

Cassowary Coast Regional Council commissioned the project with the intent to reduce community vulnerability to the adverse effects of inundation caused by flooding and storm surge.

1.3.2 Study Approach

The main stages in the study are presented in Figure 1-1. However, it is worth noting that the majority of the time ands effort in the project was spent on Stage 2 (Definition of Existing Inundation Behaviour). This stage required the development of high quality flood models and coastal inundation models. These models were then calibrated to historical events prior to simulation of design events (eg. 1% AEP event).

Figure 1-1 Study Approach

1.4 Study Management

1.4.1 Cardwell Study Advisory Group

Cassowary Coast Regional Council formed a Study Advisory Group (SAG) to oversee the Cardwell Inundation Study and to ensure that issues important to the local community have been addressed. The SAG comprised:

- Local Councillors;
- Council officers;
- State Government representatives from the EPA, NRM and DES.

A series of discussion papers were presented and reviewed during the course of the study. These discussion papers represent the collective ideas of the consultant (BMT WBM), the SAG and the community.

Throughout the study, regular meetings were held in Tully with the SAG at which the findings documented in the papers were discussed and issues were resolved. The discussion papers outlined the interim study findings at five different stages.

1.4.2 Brisbane Technical Reference Group

Early in the study, it was identified that the elements of the study are highly technical in nature and adequate review / input could only be provided by those with expertise in the areas of flood modelling and storm surge modelling. To meet this need, a Brisbane Technical Reference Group was formed with the specific aim of providing technical review of these elements and other aspects of the study as required.

The members of this group are listed in Table 1-2.

Table 1-1 Members of Brisbane Technical Reference Group

Name	Organisation
Graham Buchanan	
Greg Rogencamp	BMT WBM
Jim Davidson	Bureau of Meteorology
Peter Baddiley	Bureau of Meteorology
Paul Boswood	EPA Coastal
Chris Voisey	EPA Planning
Robert Schwartz	EPA
Upali Jayasinghe	NRM
Peter Nardi	NRM
David Robinson	EPA Coastal
Robert Schwartz	EPA Coastal

This group played a critical role in reviewing the study outcomes at various stages. The input from the BTRG members provided invaluable direction and authenticity to the study.

1.5 Community Consultation

1.5.1 Community Reference Group

An important aspect of the Community Consultation in the study was the development of a Community Reference Group. The members of this group are listed in Table 1-2.

It provided another conduit for the community to have input into the study and to suggest specific matters for investigation during the study and to provide input on management measures. It ensured that the community was involved in the study from the outset and developed a sense of ownership of the study.

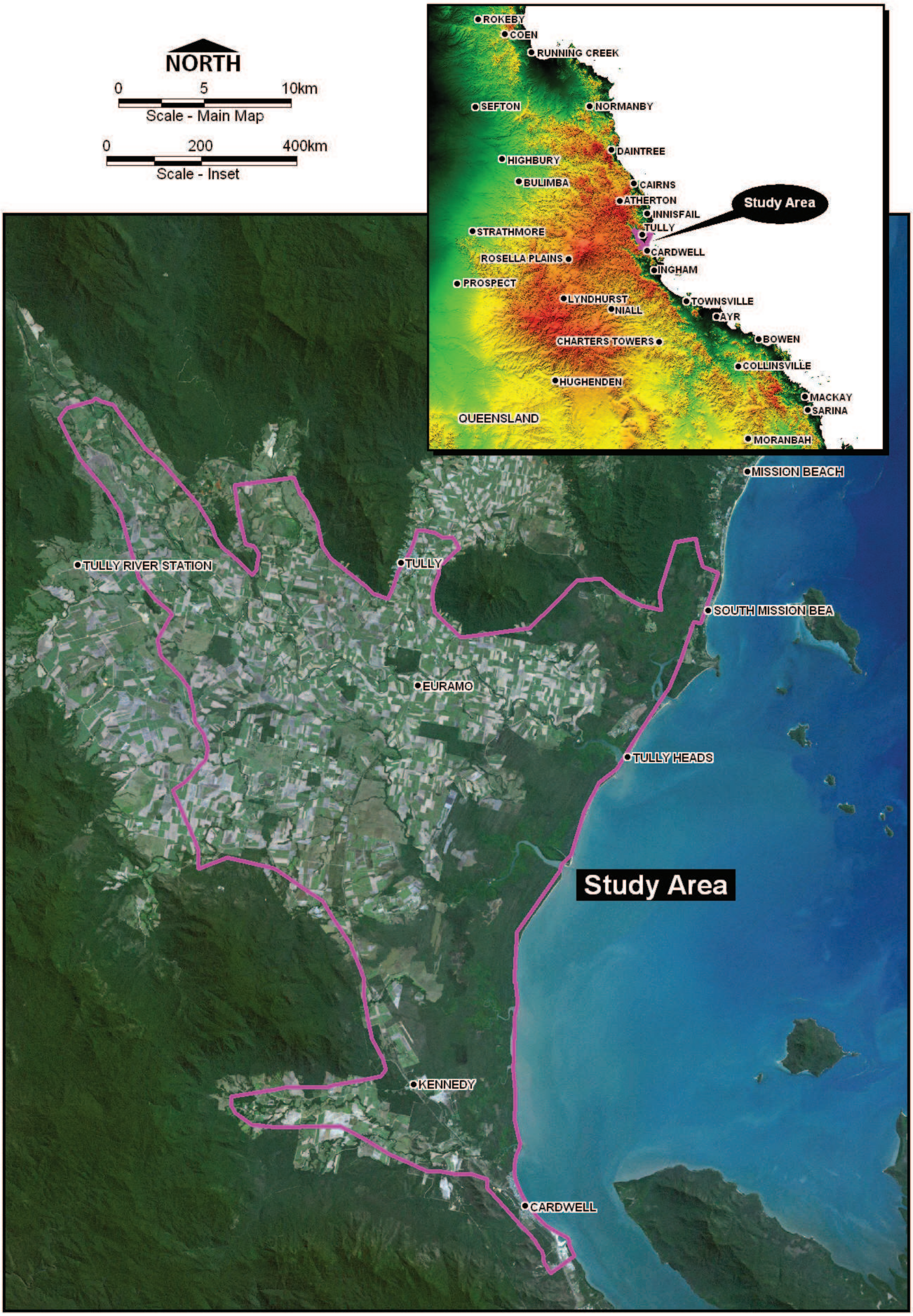
Table 1-2 Members of Community Reference Group

Name	Title	Organisation
Graham Buchanan	Project Facilitator	
Greg Rogencamp	Project Manager	BMT WBM
Cr Joe Galeano	Mayor	Cassowary Coast Regional Council
Cr Rod Bradley	Councilor	Cassowary Coast Regional Council
Cr Carmel Silvestro	Councilor	Cassowary Coast Regional Council
Cr Jim Nicolson	Councilor	Cassowary Coast Regional Council
Alf Raiti	Director of Engineering Services	Cassowary Coast Regional Council
Paul Devine	Technical Supervisor: Parks, Gardens & Revegetation CCRC	Cassowary Coast Regional Council
Dick Camilleri	Board Member	Tully Sugar Limited
Peter Luch	Manager	Tully & District Canegrowers
Sheila Lawler	Tourism & Area Promotions Officer	Cassowary Coast Regional Council
Keith Noble	Division 1	Community Representative
Bill Shannon	Division 2	Community Representative
Angelo Crema	Division 3	Community Representative

1.5.2 Public Advertising of Study

A website (www.cardwellinundationstudy.com) was established to inform the community on the progress of the study throughout its duration.

As well, numerous brochures and media releases were distributed to also provide the community with an update on the interim study findings and direction.



Locality Plan **Figure 1-2**

2 STORM SURGE MODEL DEVELOPMENT AND CALIBRATION

2.1 Introduction

A storm surge model was developed to simulate tropical cyclone storm surges and their impact along the southern part of Cassowary Coast Regional Council (i.e. the old Cardwell Shire area) coastline. The storm surge impact model comprises the following three components:

- Parametric wind field model;
- 2D hydrodynamic model for simulating storm generated long waves; and a
- 2D spectral wave model for simulating storm generated short waves.

Figure 2-1 shows the study area along with the extents of the offshore hydrodynamic and Figure 2-2 the wave model extents.

The Bureau of Meteorology provides “best tracks” of historical tropical cyclones, comprising estimates of position and central pressure. The cyclone track forms the basic input to the parametric wind model, although further parameters describing the cyclone size and windfield ‘peakedness’ must also be estimated and input. This usually necessitates calibrating the wind and pressure field model to measured wind and pressure data.

The 2D hydrodynamic model simulates the surge generated in the water surface by the low-pressure field and wind stresses applied by the tropical cyclone. It requires as input the wind and pressure field estimated using a parametric wind field model as described above. In instances where the tide is being modelled, an offshore tidal water level boundary condition is also required.

The spectral wave model predicts the generation of short waves by a moving tropical cyclone windfield and their subsequent propagation and transformation as they approach the coastline. It requires as input the results from a parametric wind field model as described above.

The 2D hydrodynamic model results can be used to estimate the storm surge and storm tide generated by a tropical cyclone excluding the effects of wave setup and runup. The spectral wave model results can be used to estimate the additional shoreline water surface elevation due to the effects of short wave setup and runup.

This chapter describes the development of the storm surge model and its calibration to two historical tropical cyclone events.

2.2 Data Collection

The development and calibration of the storm surge model required the collection of the following data:

- Bathymetric data;
- Cyclone track data;
- Measured tide data;

- Offshore tidal boundary condition data;
- Measured wind data;
- Measured wave data; and
- Surveyed debris level data

The data collected for this study is discussed below.

2.2.1 Bathymetric Data

Offshore bathymetric data was required for development of the 2D hydrodynamic and spectral wave models. The base bathymetry data used was a 250 m grid Digital Elevation Model (DEM) supplied by Geoscience Australia. More detail within the immediate study area was obtained by digitising Australian Hydrographic Service navigation charts. The floodplain DEM provided additional high-resolution detail of the beach face and dune system. The bathymetric data sources used in the offshore storm surge model development are summarised in Table 2-1.

Table 2-1 Bathymetric Data Sources

Source	Description	Model Application
Geoscience Australia	Australian Bathymetry and Topography 250m Grid	Base bathymetry data for the Coral Sea and Great Barrier Reef (GBR).
Australian Hydrographic Service - AUS 828	Palm Isles to Brook Islands 1:150,000	More detailed data inside GBR.
AUS 829	Brook Islands to Russell Islands 1:150,000	More detailed data inside GBR.
AUS 258	Dunk Island Waters 1:50,000	More detailed inshore data.
AUS 259	Hinchinbrook Channel 1:50,000	More detailed inshore data.
Floodplain DEM	See Section 3.2.5	Beach and dune profile.

The offshore Digital Elevation Model (DEM) is shown Figure 2-1.

2.2.2 Cyclone Track Data

Historical cyclone track data was obtained from the Bureau of Meteorology (BOM) website: ftp://ftp.bom.gov.au/anon2/home/ncc/cyclone/cyclones_newformat.zip. This database contains available information on cyclones within Australian waters between 1907 and April 2005. Data from the 2005/06 cyclone season was not included in this database at the time of this study.

Severe Tropical Cyclone Larry crossed the coast just north of southern part of Cassowary Coast Regional Council (i.e. the old Cardwell Shire area) on the 20/03/2006, creating a significant storm surge along the coastline of the study area. TC Larry was subsequently selected as the primary calibration event for the storm surge model. Initially, an operational track for TC Larry was sourced from the BOM (Jeff Callaghan pers. comm.) and subsequently a "best track" was obtained from the BOM (Peter Otto pers. comm.).

Tropical Cyclone Winifred was selected as the second calibration event. The track data for this cyclone was obtained from the BOM database. Further information in relation to the track was obtained from a study by the Beach Protection Authority (BPA, May 1986), which contained a detailed “best track” prepared by the Bureau of Meteorology.

Severe Tropical Cyclone Winifred was present in the western Coral Sea between 27/01/1986 and 02/02/1986. Prior to landfall the cyclone travelled parallel to the North Queensland coastline with its eye approximately 250 km offshore. TC Winifred crossed the coast just north of southern part of Cassowary Coast Regional Council (i.e. the old Cardwell Shire area) on the 01/02/1986, creating a significant storm surge along the coastline of the study area.

2.2.3 Measured Tide Data

Measured tide data was obtained in order to calibrate the 2D hydrodynamic model. The Coastal Sciences Unit of the Environment Protection Agency (EPA) operates storm tide warning gauges at population centres along the Queensland Coast and this network of gauges provided the data used in this study. The data was provided by Queensland Transport (QT) Maritime Safety on behalf of the EPA. Tide predictions were also obtained for each gauge so that the tidal anomaly (storm surge) could be evaluated. The collected tide data is summarised in Table 2-2.

Table 2-2 Collected Tide Gauge Data

Gauge Name	Gauge Number/s	Collected data period/s
Cairns Storm Tide	056001A; 056012A	21/01/1986-09/02/1986; 01/01/2006-31/03/2006
Mourilyan Storm Tide	063001A; 063012A	21/01/1986-09/02/1986; 01/01/2006-31/03/2006
Clump Point Storm Tide	035003A; 035002B	21/01/1986-09/02/1986; 01/01/2006-31/03/2006
Cardwell Storm Tide	035004A; 035012A	21/01/1986-09/02/1986; 01/01/2006-31/03/2006
Lucinda Storm Tide	062005A; 062006A	21/01/1986-09/02/1986; 01/01/2006-31/03/2006
Townsville Storm Tide	055005A; 055003A	21/01/1986-09/02/1986; 01/01/2006-31/03/2006

The tide gauge locations are shown in Figure 2-3.

The maximum recorded storm tide levels and associated surge (tide anomaly) measured at the EPA storm tide warning gauges during TC Larry is summarised in Table 2-3. The measured water levels, predicted tide and storm surge during TC Larry is shown in Figure 2-5 to Figure 2-8. A peak surge height of 2.39 m was recorded at Clump Point. The TC Larry storm surge occurred towards the top of a neap tide. The Highest Astronomic Tide (HAT) level was exceeded by 0.66 m at Clump Point.

The maximum recorded storm tide levels and associated surge (tide anomaly) measured at the EPA storm tide warning gauges during TC Winifred are summarised in Table 1-3. The measured water levels, predicted tide and storm surge during TC Winifred is shown in Figure 2-10 to Figure 2-13. The peak of the TC Winifred storm surge occurred during an ebbing neap tide, approximately 3 to 4 hours after high water. For this reason the recorded storm tide levels were relatively moderate.

Table 2-3 Maximum Recorded Storm Tide Levels And Surge During TC Larry

Gauge Name	Maximum Recorded Water Level (m AHD)	Time of Maximum Recorded Water Level (AEST)	Maximum Surge (m)	HAT Level (m AHD)
Cairns Storm Tide	0.89	20/03/2006 9:00	0.53	1.78
Mourilyan Storm Tide	1.59	20/03/2006 8:20	1.38	1.65
Clump Point Storm Tide	2.57	20/03/2006 7:00	2.30	1.91
Cardwell Storm Tide	2.17	20/03/2006 8:10	1.77	2.20
Lucinda Storm Tide	1.15	20/03/2006 8:10	0.86	2.05
Townsville Storm Tide	1.13	20/03/2006 10:00	0.71	2.15

Table 2-4 Maximum Recorded Storm Tide Levels And Surge During TC Winifred

Gauge Name	Maximum Recorded Water Level (m AHD)	Time of Maximum Recorded Water Level (AEST)	Maximum Surge (m)	HAT Level (m AHD)
Cairns Storm Tide	0.94	1/02/1986 14:00	0.35	1.78
Mourilyan Storm Tide	1.03	1/02/1986 14:00	0.96	1.65
Clump Point Storm Tide	1.63	1/02/1986 18:15	1.70	1.91
Cardwell Storm Tide	1.37	1/02/1986 14:00	1.29	2.20
Lucinda Storm Tide	1.17	1/02/1986 13:00	0.63	2.05
Townsville Storm Tide	1.17	1/02/1986 14:00	0.42	2.15

2.2.4 Offshore Tidal Boundary Condition Data

The 2D hydrodynamic model has its offshore boundary approximately 900 km offshore of the Queensland Coast as shown in Figure 2-1. Hydrodynamic simulations including the tidal motion require prescribed tidal water levels along this boundary. Harmonic tidal constituents along this boundary were obtained from the National Tide Centre (NTC). The 16 tidal constituents were originally derived from a global ocean model.

2.2.5 Measured Wind Data

Measured wind and atmospheric pressure data during TC Larry was obtained from the gauge locations summarised in Table 1-5. The wind data was used to calibrate a hindcast parametric wind model of the cyclone event.

Table 2-5 Collected Wind Data For TC Larry

Station Name	Station Number	Recording times/interval	Pressure	Wind Speed
Flinders Reef AWS	200783	10 min	Yes	Yes
South Johnstone Exp Stn	32037	Hourly or more often when required.	Yes	Yes
Innisfail	32025	0600, 0900, 1500	No	Yes
Cardwell Marine Pde	32004	0600, 0900, 1500	Yes	Yes
Green Island	31192	Half-hourly or more often when required.	Yes	Yes
Mareeba Airport	31210	Hourly or more often when required.	Yes	Yes

The weather station locations are shown in Figure 2-3.

2.2.6 Measured Wave Data

Measured wave data during TC Larry was obtained from the Coastal Sciences Unit of the EPA, which has waverider buoys installed at Cairns and Townsville. The waverider buoy locations are shown in Figure 2-3.

2.2.7 Surveyed Debris Level Data

Surveyed ocean debris level data from TC Larry was obtained from the Coastal Sciences Unit of the EPA (Robert Schwarz pers. comm.) and are reported in Table 2-6. These results are also shown in Figure 2-9. The surveyed debris levels are typically 1m to 2 m higher than the levels measured at the storm tide warning gauges. The storm tide gauges measure a mean water level (filtered of short wave motion) at an offshore position (usually at the end of a jetty). The debris levels additionally include the contribution from wave setup and runup at the beach face.

Table 2-6 Surveyed Debris Levels From TC Larry

Location	Debris Level (m AHD)	HAT Level (m AHD)
Flying Fish Point	3.5	1.7
Etty Bay	4.5	-
Cowley Beach	3.7	1.6
Kurrimine	3.5	1.9
Bingil Bay	4.7	-
Mission Beach	3.5	1.9
Wongaling Beach	3.4	1.9
South Mission Beach	3.1	-
Tully Heads	3.2	1.8

Surveyed ocean debris level data from TC Winifred was sourced from a Beach Protection Authority report on Cyclone Winifred (May 1986) and is summarised in Table 2-7.

Table 2-7 Surveyed Debris Levels From TC Winifred

Location	Debris Level (m AHD)	HAT Level (m AHD)
Etty Bay	4.1 (m SD)	-
Cowley Beach	3.6 (m SD)	1.6
Kurrimine	2.8	1.9
Mission Beach	2.6	1.9
Hull Heads	2.6	1.8
Cardwell	2.0	2.2

2.3 Cyclone Wind Model

A parametric model of the cyclone wind and pressure fields is required to provide the necessary forcing to the 2D hydrodynamic and spectral wave models. A Holland (1980) model, as recommended by the Ocean Hazards Assessment – Stage 1 (Blue Book), has been used in this study. The Holland model provides an analytical representation of the cyclone wind and pressure field based on the specification of the following time-varying parameters:

- Cyclone position
- Central pressure
- Ambient pressure
- Radius to maximum winds
- Cyclone forward motion vector
- Wind field "peakedness"
- Line of maximum winds

The cyclone position and central pressure of historically occurring cyclones are usually available from the BOM best track database. The radius to maximum wind, wind field peakedness and line of maximum wind parameters must be estimated from available information and usually require calibration of the parametric wind model to available wind and pressure data for the event.

Holland models have been developed to hindcast pressure and wind fields for both TC Larry and TC Winifred. The TC Larry and TC Winifred hindcast have been calibrated against available wind and pressure data, as discussed in Section 2.7 and Section 2.8 respectively.

2.4 Storm Surge Model

The 2D hydrodynamic model TUFLOW has been used to simulate the generation of ocean surges due to cyclone generated low-pressure and wind fields. It is also capable of simulating tidal hydrodynamics within the Great Barrier Reef.

A nested grid approach has been used for this study with a coarse (2500 m) grid covering the Western Coral Sea from approximately 900 km offshore of the Queensland Coast and southern and northern boundaries around Fraser Island and Papua New Guinea, as shown in Figure 2-1. Nested within this coarse grid is a medium scale (500 m) grid of the Great Barrier Reef between Cape Bowling Green and Cape Grafton (also shown in Figure 2-1). The fine scale floodplain models detailed in Chapter 3 are capable of being nested within the 500 m offshore grid.

The most critical exercise in developing and calibrating a hydrodynamic model is the construction of an accurate and sufficiently detailed Digital Elevation Model (DEM) of the study area from the available data (Section 2.2.1), and representing this sufficiently accurately in the model grid. It has been confirmed through the model calibration (Sections 2.6–2.8) that the grids used are of satisfactory resolution for this purpose.

The offshore TUFLOW model has been calibrated to ensure that it can correctly simulate the tidal water level dynamics within the Great Barrier Reef when driven by a tidal water level boundary condition along the Coral Sea boundary. The tidal calibration results are detailed in Section 2.6.

The offshore TUFLOW model has also been calibrated to the TC Larry and TC Winifred storm surge events, involving refinement of model parameters (bed friction, viscosity) such that the model accurately reproduces the prototype water levels.. Measured tide data and surveyed debris levels have been used to calibrate the model. The results of this calibration process are detailed in Sections 2.7 and 2.8

2.5 Wave Model

The spectral wave model SWAN (Delft University of Technology) has been used to simulate the generation of short waves by cyclonic wind fields and their subsequent transformation as they propagate towards the coast. The modelled nearshore wave heights and wave periods are used to calculate the wave setup contribution to the shoreline mean water level using the formula of Hanslow and Nielsen (1993). The statistical distribution of wave runup heights can also be calculated assuming a Rayleigh distribution model (Hanslow and Nielsen, 1993). The wave runup process needs to be considered when comparing storm surge model results with measured debris levels as it can cause peak water levels associated with wave action along the exposed the study area coastline to be a metre or more higher than the storm tide levels measured at the warning gauges. This can be seen in the comparison of storm tide gauge measurements and measured debris levels in Figure 2-9.

The extents of the wave model used for calibration are shown in Figure 2-2. The wave model had a 500 m grid size over most of the area and a 50m grid size in the near-shore area.

In order to simulate a moving cyclone it is necessary to run SWAN in non-stationary mode. The Holland model is used to calculate a spatially and temporally varying wind field, which is then used as the wave model input. The SWAN model has been run using third generation wave energy source and sink terms in order to best represent the complex processes that occur under a transient severe wind field.

The wave model performance has been validated against measured wave data during TC Larry (Sect. 2-10). The nearest wave-rider buoys to the study area are at Cairns and Townsville. The wave model performance has also been indirectly verified through the calculation of wave setup and runup and comparison with surveyed debris levels along the coastline of Cardwell and Johnstone Shires.

2.6 Tidal Calibration

A month of tide corresponding to January 2006 was simulated with the TUFLOW model in order to calibrate/validate its performance. As discussed in Sect. 2.2.4 the offshore boundary condition is a predicted tide based on 8 tidal constituents that have been derived from a global tide model and supplied by the National Tide Centre. As the driving boundary condition in this simulation was a predicted tide, the modelled inshore water levels have been compared with predicted water levels (from Queensland Transport) at the tide gauge locations in Table 2-2.

Time series of modelled water levels compared with predicted water levels are shown in Figure 2-14 to Figure 2-17. The TUFLOW model does a reasonably good job of predicting the tidal water level variation throughout the month. Peak spring tide levels are generally quite well reproduced by the model. There is a slight tendency for the model to systematically predict low tide levels that are lower than the QT predictions. The quality of the TUFLOW model predictions is better during spring tides than during the neap tide periods, which is often the case with coastal tide models due to the complex harmonic interactions occurring at neap tides.

The root mean square (RMS) error of the instantaneous tidal predictions is summarised in Table 2-8. These results suggest that the TUFLOW model can predict the instantaneous tidal water level with an accuracy generally of ± 0.2m, however sometimes up to ± 0.3m during neap tide periods. Some of this error can be possibly be attributed to the boundary conditions, which are derived from a global tide model and include only 8 of the tidal harmonic components. It should be noted that the outcomes of this study do not rely on the TUFLOW model's capability to predict astronomic tide water levels, as it will only be used to predict the storm surge (tide anomaly) generated by tropical cyclones. The coastal inundation risk assessment will use astronomic tide predictions calculated by standard tide prediction techniques using tidal constituents supplied by QT.

Table 2-8 Summary of RMS Error in Tidal Calibration Comparison.

Location	RMS Error in Instantaneous Water Level (m)
Cairns	0.11
Mourilyan	0.10
Clump Point	0.11
Cardwell	0.15
Lucinda	0.15
Townsville	0.17
Cape Ferguson	0.14

2.7 TC Larry Calibration

The offshore TUFLOW model and spectral wave model were primarily calibrated/validated to the TC Larry event on the 20/03/2006.

Firstly a hindcast parametric wind and pressure field model for TC Larry was developed and validated against available data. The estimated "best track" derived by the BOM for TC Larry is shown in

Figure 2-4. The adopted Holland wind field model track parameters are summarised in Table 2-9. A comparison of the adopted Holland model predictions at various weather station locations with measured wind and pressure data is shown in Figure 2-18 to Figure 2-23. The hindcast windfield is in reasonably good agreement with observations at Flinder's Reef where the cyclone traversed approximately 30 km to the south less than 12 hours before making landfall.

The TUFLOW model was run for the TC Larry event using the following combinations of forcing/boundary conditions;

- Hindcast wind and pressure forcing but no tidal forcing.
- Hindcast wind and pressure forcing and tidal forcing.

The run with no tidal forcing will simulate just the storm surge (tidal anomaly) whereas the run with tidal forcing will simulate the actual water level (storm tide level not including wave setup and runup) during the cyclone. It should be kept in mind that the accuracy of storm tide level predictions will be dependent on the accuracy with which astronomic tide predictions can be made with the TUFLOW model (i.e. ± 0.2–0.3m).

The spectral wave model has been run in order to predict short wave conditions during TC Larry. In the absence of closer observations, waverider buoy measurements at Townsville and Cairns have been used for wave model verification. The predicted wave heights and periods have also been used to estimate the wave runup contribution along the study area open coastline. These wave runup estimates have been combined with the modelled storm tide levels to calculate predicted inundation levels along the open coastline and these have been compared with surveyed debris levels.

2.7.1 Storm Surge

The run with no tidal forcing has been compared with measured tidal anomalies at the EPA storm tide warning gauges in Figure 2-24 to Figure 2-27. The peak surges are compared in Table 1-10.

Table 2-9 Holland Wind and Pressure Model Parameters for TC Larry

Date & Time (AEST)	Long. (deg.)	Lat. (deg.)	P_0 (hPa)	P_N (hPa)	R (km)	B (-)	θ_{max} (deg.)	δ_{fm} (-)
17/03/2006 22:00	159.00	-16.10	999	1007	40	1.39	65	1.0
18/03/2006 4:00	158.00	-16.30	995	1007	38	1.41	65	1.0
18/03/2006 10:00	156.60	-17.20	985	1007	35	1.47	65	1.0
18/03/2006 16:00	155.40	-17.10	975	1007	32	1.54	65	1.0
18/03/2006 22:00	154.60	-17.20	970	1007	30	1.57	65	1.0
19/03/2006 4:00	152.80	-17.50	970	1007	28	1.57	65	1.0
19/03/2006 10:00	151.20	-17.70	970	1007	28	1.57	65	1.0
19/03/2006 16:00	149.60	-17.60	955	1007	27	1.66	65	1.0
19/03/2006 19:00	148.90	-17.60	935	1007	25	1.79	65	1.0
19/03/2006 22:00	148.30	-17.50	935	1007	30	1.79	65	1.0
20/03/2006 1:00	147.55	-17.47	940	1007	35	1.76	65	1.0
20/03/2006 2:20	147.27	-17.49	940	1007	35	1.76	65	1.0
20/03/2006 3:00	147.13	-17.52	935	1007	35	1.79	65	1.0
20/03/2006 3:20	147.03	-17.53	935	1007	33	1.79	65	1.0
20/03/2006 4:00	146.87	-17.52	935	1007	28	1.79	65	1.0
20/03/2006 4:20	146.77	-17.54	935	1007	26	1.79	65	1.0
20/03/2006 4:40	146.69	-17.53	935	1007	24	1.79	65	1.0
20/03/2006 5:10	146.59	-17.54	935	1007	22	1.79	65	1.0
20/03/2006 5:20	146.52	-17.55	935	1007	22	1.79	65	1.0
20/03/2006 5:30	146.49	-17.56	935	1007	22	1.79	65	1.0
20/03/2006 5:40	146.46	-17.56	935	1007	22	1.79	65	1.0
20/03/2006 5:50	146.43	-17.57	935	1007	22	1.79	65	1.0
20/03/2006 6:00	146.39	-17.59	935	1007	22	1.79	65	1.0
20/03/2006 6:10	146.31	-17.59	935	1007	22	1.79	65	1.0
20/03/2006 6:20	146.24	-17.60	935	1007	22	1.79	65	1.0
20/03/2006 6:30	146.19	-17.59	935	1007	22	1.79	65	1.0
20/03/2006 6:40	146.15	-17.58	935	1007	22	1.79	65	1.0
20/03/2006 6:50	146.10	-17.58	935	1007	22	1.79	65	1.0
20/03/2006 7:00	146.05	-17.56	940	1007	22	1.76	65	1.0
20/03/2006 7:10	145.99	-17.55	940	1007	22	1.76	65	1.0
20/03/2006 7:20	145.95	-17.52	945	1007	22	1.72	65	1.0
20/03/2006 7:30	145.89	-17.51	945	1007	22	1.72	65	1.0
20/03/2006 7:40	145.84	-17.49	945	1007	22	1.72	65	1.0
20/03/2006 7:50	145.80	-17.47	950	1007	22	1.69	65	1.0
20/03/2006 8:00	145.77	-17.46	950	1007	22	1.69	65	1.0
20/03/2006 8:10	145.74	-17.45	950	1007	22	1.69	65	1.0
20/03/2006 8:30	145.69	-17.45	955	1007	22	1.66	65	1.0
20/03/2006 9:00	145.60	-17.43	959	1007	22	1.64	65	1.0
20/03/2006 10:00	145.30	-17.50	965	1007	26	1.60	65	1.0
20/03/2006 16:00	143.80	-17.80	980	1007	40	1.51	65	1.0
20/03/2006 22:00	142.20	-18.70	990	1007	50	1.44	65	1.0

Table 2-10 Measured vs Modelled Peak Surges: TC Larry

Location	Measured peak surge (m)	Modelled peak surge (m)	Error (m)
Mourilyan storm tide warning gauge	1.38	1.30	-0.08
Clump Point storm tide warning gauge	2.30	2.35	+0.05
Cardwell storm tide warning gauge	1.77	1.73	-0.04
Lucinda offshore storm tide warning gauge	0.86	0.46	-0.40

The model predicts the surge magnitude to within ± 0.1m at Mourilyan, Clump Point and Cardwell. At Lucinda, which is more than 100 km south of where TC Larry made landfall, the surge is under-predicted by 0.40m probably because of the windfield model is not a good representation of actual conditions at such a distance from the cyclone eye. The timing of the modelled surge is slightly early at Mourilyan but is quite accurately reproduced at both Clump Point and Cardwell. The modelled drop in surge at Mourilyan occurs more rapidly than shown by the data and this is likely to be because of the position of the tide gauge within a natural harbour, which is not resolved by the model. The modelled time series at Cardwell exhibits a draw-down prior to the surge event due to the strong South-Easterlies predicted by the hindcast wind field pushing water out of the Hinchinbrook Channel. In reality there would have been significant sheltering of Hinchinbrook Channel from the South-Easterlies by Hinchinbrook Island, however this is not resolved in the current model.

2.7.2 Storm Tide

The run with tidal forcing has been compared with measured water levels at the EPA storm tide warning gauges in Figure 2-28 to Figure 2-31. The peak water levels are compared in Table 2-11.

Table 2-11 Measured vs Modelled Peak Water Levels: TC Larry

Location	Measured Peak Storm Tide (m AHD)	Modelled Peak Storm Tide (m AHD)	Error (m)
Mourilyan storm tide warning gauge	1.59	1.27	-0.32
Clump Point storm tide warning gauge	2.57	2.47	-0.10
Cardwell storm tide warning gauge	2.17	1.81	-0.36
Lucinda offshore storm tide warning gauge	1.15	0.76	-0.39

The model results with tidal forcing somewhat under-predict the peak water levels during TC Larry. This is predominantly due to inaccuracies in the representation of the underlying tide which is predicted to within ± 0.3m by the model. There is a systematic under-prediction of the astronomic tide water level of between 0.2–0.3 m at the time that TC Larry made landfall. This is reflected in the under-prediction of the storm tide levels in Table 2-11 and shown in Figure 2-28 to Figure 2-31.

As discussed in Section 2.6 the offshore TUFLOW model will only be used to simulate storm surge (tidal anomaly only) for the calculation of inundation risk levels along the study area coastline. Therefore the inaccuracies encountered when simulating astronomic tides will not impact upon the study outcomes.

2.7.3 Storm Waves

The results of the wave model are compared with waverider buoy measurements from Townsville and Cairns in Figure 2-32 and Figure 2-33. The measured and modelled peak significant wave heights are compared in Table 2-12.

Table 2-12 Measured vs Modelled Peak Significant Wave Heights: TC Larry

Location	Measured peak Hs (m)	Modelled peak Hs (m)	Error (m)
Townsville waverider buoy	2.91	2.84	-0.07
Cairns waverider buoy	1.37	0.85	-0.52

The model adequately replicates the measured wave heights at the Townsville waverider buoy, though the timing of the peak wave occurrence is a little early. The model predictions at Cairns are not as good. This is probably due in part to the hindcast wind being a relatively poor representation of the actual windfield at such a distance (≈ 100 km) from the cyclone eye. As well, the DEM at Cairns has not been refined to the same extent as the study area and may also be affecting the wave model performance at this location. It is considered that the model adequately reproduces the prototype wave conditions in those critical areas in the region of intense cyclone activity.

2.7.4 Inundation Levels

The predicted nearshore wave results were used to predict the shoreline wave setup and 2% exceedance wave runup heights (i.e. the runup height exceeded by 2% of the randomly distributed incoming waves). The empirical formula of Hanslow and Nielsen (1993) has been used to predict the shoreline wave setup and the empirical relationship of Nielsen and Hanslow (1991) has been used to determine the 2% exceedance wave runup. The latter result was added to the predicted storm tide levels (Section 2.7.2) to predict the peak inundation levels created by TC Larry. These results are compared against the surveyed debris levels in Table 2-13 and Figure 2-34.

In locations where the dune was not overtopped the comparison between surveyed debris levels and predicted inundation levels is generally quite reasonable (e.g. Tully Heads). At Cowley Beach, Kurrimine Beach, Mission Beach and Wongaling Beach the inundation levels are over-predicted (generally by less than 1 m). This is most likely due to the dunes being overtopped at these locations, which is a process not accounted for in the wave runup calculations. At Bingil Bay, where the highest debris levels were recorded, the total inundation level was under-predicted by 0.5m.

The predicted inundation level at Flying Fish Point is within 0.2m of the surveyed debris level, however at nearby Etty Bay a similar inundation level is predicted by the modelling but a debris level of 4.5 m AHD was surveyed. These locations are more than 40 km north of study area and the nearshore bathymetry representation in the models is not as refined as within the study area.

Table 2-13 Comparison of Surveyed Debris Levels With Predicted Inundation Levels

Location	Measured peak storm tide gauge height	Surveyed debris level	Modelled storm tide level (excluding wave effects)	Predicted 2% exceedance inundation level (including wave runup)
Flying Fish Point		3.5	1.48	1.85
Etty Bay		4.5	1.49	1.94
Mourilyan Harbour	1.59		1.27	
Cowley Beach		3.7*	2.69	3.80
Kurrimine Beach		3.5*	3.13	4.10
Bingil Bay		5.2	2.57	4.05
Clump Point	2.57		2.47	3.73
Mission Beach		3.5*	2.28	3.45
Wongaling Beach		3.4*	2.20	3.34
Sth Mission Beach		3.1	2.07	2.65
Tully Heads		3.2	1.86	3.43
Cardwell	2.17		1.81	2.46

Notes: *Dune overtopping occurred limiting the peak debris levels.*
All Levels in mAHD

2.8 TC Winifred Calibration

Subsequent to the calibration to the TC Larry event, the offshore TUFLOW model was calibrated/validated to the TC Winifred event. The TC Winifred event occurred during the period from 21st of January 1986 to 7th of February 1986.

TC Winifred made landfall near Mourilyan between 6 and 7 pm on 1st February, approximately 4 to 5 hours after high water. The peak storm surge along the study area's coastline was experienced between 6 and 7pm. Due to the fact that the storm surge occurred several hours into ebbing, the recorded storm tide levels remained fairly moderate and were well under HAT levels.

For several days prior to TC Winifred crossing the coast, a tidal anomaly of approximately +0.30 m was experienced along the central and northern Queensland coastline (increase in water levels above the astronomic predictions). This increased water level is likely to be caused by strong winds in land inwards direction that were experienced throughout the region in the days prior to TC Winifred crossing the coast At the offshore wind stations Fitzroy and Lucinda a persistent South-easterly wind with speeds up to 60-80 km/h was recorded during the 3 to 4 days prior to TC Winifred crossing the coast (see Figure 2-35).

To investigate the impacts of this relatively strong South-easterly wind on the tidal anomaly, a background wind was applied in the model simulations of the TC Winifred event. The applied background wind had a wind speed of 72 km/h and a direction from SE.

TUFLOW has the capability of combining a prevailing background wind field with the vortex wind field predicted by the Holland wind model. It is noted that the background wind in the offshore TUFLOW model has only an impact on the model results in circumstances where the background wind is dominant over the wind resulting from the Holland wind field model (ie. If the magnitude of the background wind specified is greater than the magnitude predicted by the Holland wind field model). In all other circumstances, the wind resulting from the Holland wind field model is used by the TUFLOW model.

The estimated “best track”, which was adopted for the numerical modelling, was derived from BOM and BPA data and is shown in Figure 2-4. The Holland wind field model track parameters derived from BoM and BPA data are summarised in Table 2-14.

The wind and air pressure predicted by the Holland model was compared with weather measurements. A comparison of the model predictions at various weather stations with measured wind and pressure is shown in Figure 2-36 to Figure 2-37.

From Figure 2-36 to Figure 2-37, it can be seen that for the TC Winifred event the Holland wind model predicts the wind and air pressure while the cyclone is passing the weather station with a reasonable level of accuracy. The timing of the minimum pressure is accurately reproduced. However, Figure 2-36 and Figure 2-37 show that the predicted pressure time-series are considerably more “peaky” than those measured. This results in over-estimation of the pressure during the cyclone approach of around 15 hPa. Unfortunately it was not possible to completely reconcile the simple Holland model with both wind and pressure measurements during TC Winifred. This shortcoming of the wind and pressure model would be expected to impact on the storm surge tide predictions as seen in Section 2.8.1 and 2.8.2.

The TUFLOW model was run for the TC Winifred event using the following combinations of forcing/boundary conditions:

- Hindcast wind and pressure forcing but no tidal forcing.
- Hindcast wind and pressure forcing and tidal forcing.

Table 2-14 Holland Wind and pressure Model Parameters for TC Winifred

Date & Time (AEST)	Long. (deg.)	Lat. (deg.)	P_0 (hPa)	P_N (hPa)	R (km)	B (-)	θ_{max} (deg.)	δ_{fm} (-)
27/01/1986 16:00	144.8	-12.9	1003	1010	27.0	1.36	65	1.0
27/01/1986 22:00	144.8	-12.7	1004	1010	27.0	1.36	65	1.0
28/01/1986 4:00	145.1	-12.7	1003	1010	27.0	1.36	65	1.0
28/01/1986 10:00	145.4	-12.6	1004	1010	27.0	1.36	65	1.0
28/01/1986 16:00	145.7	-12.6	1003	1010	27.0	1.36	65	1.0
28/01/1986 22:00	146.1	-12.6	1003	1010	27.0	1.36	65	1.0
29/01/1986 4:00	146.6	-12.8	1002	1010	27.0	1.37	65	1.0
29/01/1986 10:00	146.7	-13.0	1000	1010	27.0	1.38	65	1.0
29/01/1986 16:00	146.6	-13.4	998	1010	27.0	1.39	65	1.0
29/01/1986 22:00	146.6	-13.8	998	1010	27.0	1.39	65	1.0
30/01/1986 4:00	146.5	-14.1	995	1010	27.0	1.41	65	1.0
30/01/1986 10:00	146.5	-14.4	994	1010	24.8	1.42	65	1.0
30/01/1986 16:00	146.5	-14.7	991	1010	23.8	1.44	65	1.0
30/01/1986 22:00	146.7	-14.9	987	1010	23.8	1.46	65	1.0
31/01/1986 4:00	147.0	-15.1	983	1010	23.8	1.49	65	1.0
31/01/1986 10:00	147.3	-15.3	978	1010	22.7	1.52	65	1.0
31/01/1986 16:00	147.7	-15.7	975	1010	21.6	1.54	65	1.0
31/01/1986 22:00	147.9	-16.1	973	1010	21.6	1.55	65	1.0
1/02/1986 4:00	147.7	-16.4	972	1010	32.4	1.56	65	1.0
1/02/1986 10:00	147.1	-16.9	961	1010	32.4	1.62	65	1.0
1/02/1986 11:15	146.9	-17.0	961	1010	32.4	1.62	65	1.0
1/02/1986 12:00	146.9	-17.1	961	1010	30.0	1.62	65	1.0
1/02/1986 13:00	146.8	-17.2	961	1010	30.0	1.62	65	1.0
1/02/1986 14:00	146.6	-17.3	961	1010	27.0	1.62	65	1.0
1/02/1986 15:00	146.6	-17.4	961	1010	27.0	1.62	65	1.0
1/02/1986 16:00	146.4	-17.5	961	1010	27.0	1.62	65	1.0
1/02/1986 17:00	146.3	-17.6	959	1010	25.2	1.64	65	1.0
1/02/1986 18:00	146.2	-17.6	958	1010	23.4	1.64	65	1.0
1/02/1986 19:00	146.1	-17.6	957	1010	22.5	1.65	65	1.0
1/02/1986 20:00	146.0	-17.7	965	1010	25.2	1.6	65	1.0
1/02/1986 21:00	145.9	-17.7	975	1010	27.0	1.54	65	1.0
1/02/1986 21:30	145.8	-17.7	980	1010	27.0	1.51	65	1.0
1/02/1986 22:00	145.7	-17.8	982	1010	27.0	1.49	65	1.0
2/02/1986 4:00	145.0	-18.5	991	1010	27.0	1.44	65	1.0
2/02/1986 10:00	144.3	-19.3	995	1010	27.0	1.41	65	1.0
2/02/1986 16:00	143.5	-20.2	996	1010	27.0	1.41	65	1.0
2/02/1986 22:00	142.8	-20.5	997	1010	27.0	1.4	65	1.0
3/02/1986 4:00	142.3	-20.6	998	1010	27.0	1.39	65	1.0
3/02/1986 10:00	141.8	-20.6	999	1010	27.0	1.39	65	1.0
3/02/1986 16:00	141.4	-20.8	999	1010	27.0	1.39	65	1.0

2.8.1 Storm Surge

The run with no tidal forcing will simulate just the storm surge (tidal anomaly) whereas the run with tidal forcing will simulate the actual water level experienced during the cyclone. The run with no tidal forcing has been compared with measured tidal anomalies at the EPA storm tide warning gauges in Figure 2-38 to Figure 2-41. The peak surges are compared in Table 2-15.

Table 2-15 Comparison of Measured and Modelled Peak Surges During TC Winifred

Location	Measured peak surge (m)	Modelled peak surge (m)	Error (m)
Mourilyan storm tide warning gauge	0.96	0.66	-0.30
Clump Point storm tide warning gauge	1.70	1.38	-0.32
Cardwell storm tide warning gauge	1.29	1.09	-0.20
Lucinda offshore storm tide warning gauge	0.63	0.48	-0.15

From Table 2-15, it can be seen that the model slightly under-predicts the peak surge magnitude at all the four gauges. The under prediction of the peak surge is the greatest at the two gauges in the vicinity of the cyclone track and is approximately 0.3 m.

Analysing the storm surge profiles in Figure 2-38 to Figure 2-41, it can be concluded that the model replicates the storm surge profile at Clump Point and Cardwell with a reasonable level of accuracy. One can see that the timing of the modelled peak surge is accurately reproduced at the four gauging stations. The greatest discrepancy between modelled and measured storm surge occurs in the build up to the peak surge level and a possible reason for this under prediction is the over prediction of the air pressure by the Holland wind field model as is evident in Figure 2-42 and Figure 2-43.

Further, one can see that the tidal anomaly experienced in the days prior to TC Winifred landfall (caused by the strong SE winds during this time) is predicted by the model with a relatively high level of accuracy at all gauging stations.

Sensitivity analysis TC Winifred

To further optimise the performance of the TUFLOW model for replicating peak surges, model simulations were undertaken with revised central pressures.

Figure 2-42 to Figure 2-47 show the model results of the simulation with a central pressure that was 10 hPa lower than the air pressure from the BoM records. A comparison between the wind and air pressure predicted by the Holland model and the measurements at various weather stations is shown in Figure 2-42 and Figure 2-43. The predicted storm surge at the four EPA storm tide warning gauges is shown in Figure 2-44 to Figure 2-47.

From Figure 2-42 to Figure 2-47, it can be concluded that model with decreased central pressure replicates the recorded storm surge with a higher level of accuracy; the predicted peak surge at

Clump Point and Cardwell matches the measured peak surge with a great level of accurately (deviation between predicted and recorded peak surge is 0.03 m and less than 0.01 m for Clump Point and Cardwell respectively).

However analysing Figure 2-42 and Figure 2-43, it can be seen that the decreased central pressure has a negative impact on the model performance in terms of both air pressure and wind speed. The predicted minimum air pressure at Holmes Reef and Cowley Beach is significantly lower than the measured minimum air pressure. The air pressure is under predicted by approximately 11 and 9 hPa respectively. The peak wind speed at Cowley Beach is approximately 10 % greater than the measured peak wind speed (138 km/h vs. 126 km/h).

2.8.2 Storm Tide

The analysis of the model simulations with tidal forcing was undertaken with the Holland hindcast wind and pressure model settings as shown in Table 2-14. The model results with tidal forcing have been compared with measured water levels at the EPA storm tide warning gauges in Figure 2-48 to Figure 2-51. The peak water levels are compared in Table 2-16.

Table 2-16 Comparison of Measured and Modelled Peak Storm Tide During TC Winifred

Location	Measured Peak Storm Tide (m AHD)	Modelled Peak Storm Tide (m AHD)	Error (m)
Mourilyan storm tide warning gauge	1.03	0.77	-0.26
Clump Point storm tide warning gauge	1.63	1.29	-0.34
Cardwell storm tide warning gauge	1.37	0.97	-0.40
Lucinda offshore storm tide warning gauge	1.17	0.90	-0.27

From Table 2-16, it can be seen that the TUFLOW Storm Surge model somewhat under-predicts the peak water levels during TC Winifred. The peak storm tide levels during TC Winifred did not generally coincide with the peak storm surge but occurred near the preceding high tide (peak surge occurred late in the ebbing stage of the tide). The predominant reason that the model under predicts the peak storm tide levels is considered to be related to inaccuracies in the predicted air pressure around the high tide prior TC Winifred crossing the coast. During this period the model predicts a significantly higher pressure than the measured air pressure. Further inaccuracies are introduced by the representation of the underlying tide, which is generally predicted to within ± 0.2 to 0.3m by the model.

2.8.3 Inundation levels

Calculation of inundation levels combining the effects of atmospheric tide, storm surge, wave setup and runup were undertaken to compare with debris levels observed after TC Winifred at the beaches within study area.

The nearshore wave results derived with the SWAN wave model were used to predict the shoreline wave setup and 2% exceedance wave runup heights (i.e. the runup height exceeded by 2% of the randomly distributed incoming waves). The latter result was added to the predicted storm tide levels (Section 2.8.2) to predict the peak inundation levels created by TC Winifred.

The model results are compared with the surveyed debris levels in Table 2-17 and Figure 2-52.

Table 2-17 Comparison of Surveyed Debris Levels With Predicted Inundation Levels

Location	Measured peak storm tide gauge height	Surveyed debris level	Modelled storm tide level (excluding wave effects)	Predicted peak mean shoreline level (including wave setup)	Predicted 2% exceedance inundation level (including wave runup)
Etty Bay		4.1*	0.75	1.49	2.71
Mourilyan Harbour	1.03		0.72	1.62	3.01
Cowley Beach		3.5*	1.34	2.21	3.49
Kurrimine Beach		2.8	1.70	2.32	3.24
Clump Point	1.63		1.24	2.12	3.43
Mission Beach		2.7	1.31	2.29	3.77
Hull Heads		2.6	1.28	1.96	2.98
Cardwell Beach	1.37	2.2	1.00	1.26	1.65

** Note: Surveyed debris levels at these locations are in State datum and not AHD. All other levels in mAHD*

From Table 2-17 and Figure 2-52, it can be concluded that the calculated inundation levels correspond with a reasonably level of accuracy with the surveyed debris levels. For most beaches the inundation levels are slightly over-predicted by the model (generally by less than 0.5 m). There is a tendency for the runup heights to be over-predicted in cases where the frontal dune is overtopped.

At Cardwell Beach, the predicted inundation level is approximately 0.5 m under the surveyed debris level. The under-prediction at this location is mainly due to the under-predicted storm tide level.

The surveyed debris level at Etty Bay is discarded for the comparison of the inundation levels at beaches as the datum of this debris level is undefined.

2.9 TC Aivu Wave Modelling Calibration

In order to further validate the SWAN wave model, the TC Aivu event was simulated. Model results were then compared with recorded waves at two locations as well as model predictions by Young and Hardy (Young, 1993).

The TC Aivu event occurred during the period from 31 March 1989 to 5 April 1989. The Cyclone originated from the southern tip of Papua New Guinea and throughout 2 and 3 April, it tracked in a general south-westerly direction across the Coral Sea towards the Northeast coast of Australia at speeds averaging 15 to 20 km/h. Early on 4 April TC Aivu began to accelerate towards the coast.

Travelling at 30 km/h, TC Aivu made landfall between Home Hill and Inkerman at 10:30 on 4 April. The lowest estimated central pressure was 935 hPa at 16:00 on 3 April. The estimated "best track" for TC Aivu was derived from the BOM TC database and (Young 1993) and is shown in Figure 2-53.

Wave records from the wave measurement stations at Leopard Reef and John Brewer Reef were used for comparison with the wave modelling results. The wave station at Leopard Reef was located 75 km southeast of the track of TC Aivu and is on the seaward edge of the GBR. The wave station at John Brewer Reef was located 80 km northwest of the track of TC Aivu, and is on the inner edge of the GBR. Both wave stations were deployed in relative deep water (approximately 50 to 55 m). The location of both wave stations is shown in Figure 2-53.

As the wave station at John Brewer Reef was located on the inner edge of the GBR, it is expected to have been significant sheltered by the reefs further seawards. This is in contrast to the wave station at Leopard Reef, which is more exposed.

Significant wave heights (Hs), peak wave period (Tp) and wave direction at Leopard Reef are presented in Figure 2-54 and at John Brewer Reef in Figure 2-55. Measured and modelled maximum significant wave heights are compared in Table 2-18. The maximum significant wave heights as predicted by (Young, 1993) are also shown in Table 2-18.

Table 2-18 Measured vs Modelled Peak Significant Wave Heights: TC Aivu

Location	Measured peak Hs (m)	Modelled peak Hs (m)	Predicted peak Hs by (Young, 1993) (m)
Leopard Reef	7.37	8.26	9.10
John Brewer Reef	2.77	2.90	3.61

The model adequately predicts the measured wave heights at the John Brewer Reef wave station during the peak of the storm. This provides confidence that the wave model is capable of replicating extreme wave conditions inside the GBR during cyclonic conditions.

From Table 2-18, it can be seen that the model over-predicts the wave heights at the Leopard Reef wave station during the peak of the storm. However, it is noted that the over-prediction of the peak significant wave height is significantly smaller than model predictions by Young (Young, 1993). Amongst other things, the over-prediction of the wave heights at Leopard Reef (outside of the GBR) is likely to be related to inaccuracies in the cyclone track as the location where the cyclone passes the GBR differs by approximately 75 km between the track from (Young, 1993) and track information from the BoM's TC database (Refer to Figure 2-53). For the GBR and the landfall location, the track proposed by Young is considered to be a better representation than BoM's of the real track of TC Aivu. For this part of TC Aivu's track, the route proposed by Young has been used for the wave modelling analysis.

2.10 Conclusions on Storm Surge Model Calibration

A storm surge model has been developed for the study area comprising a tropical cyclone wind hindcast model, an offshore hydrodynamic model and a wave model. The tropical cyclone wind hindcast model and the offshore hydrodynamic model were developed using the modelling software TUFLOW. For the wave model the wave modelling software SWAN was utilised.

Calibration of the hydrodynamic model was firstly undertaken by simulating tidal water levels within the Great Barrier Reef. This exercise demonstrated that the model is capable of simulating tidal hydrodynamics with an acceptable level of accuracy. It is noted that the hydrodynamic model will not be used to predict astronomic tide water levels for the design runs as these can be more accurately and efficiently calculated by standard tide prediction procedures.

To analyse the performance of the Storm Surge Model developed, two significant historical Tropical Cyclone events were simulated and the model results were compared with measurements. The two significant historical Tropical Cyclone events were TC Larry (January 2006) and TC Winifred (January/February 1986).

A critical component in the storm surge model calibration was the development of parametric wind– and pressure–field models using data obtained from the Bureau of Meteorology. It is believed that this remains the most uncertain part of the current cyclone storm surge model, and the limitations of the simplified parametric wind models at simulating the complexities of real-life tropical cyclones such as TC Larry and TC Winifred probably accounts for a significant amount of the remaining difference between calibrated model results and measured surge levels. The hindcast model developed for TC Larry is believed to provide a better representation of the actual wind and pressure during this event than was achieved for TC Winifred. Correspondingly the storm surge predictions for TC Larry were more accurate than those for TC Winifred.

From the model calibration of the TUFLOW Cyclone Wind / Hydrodynamic Model developed, the following can be concluded:

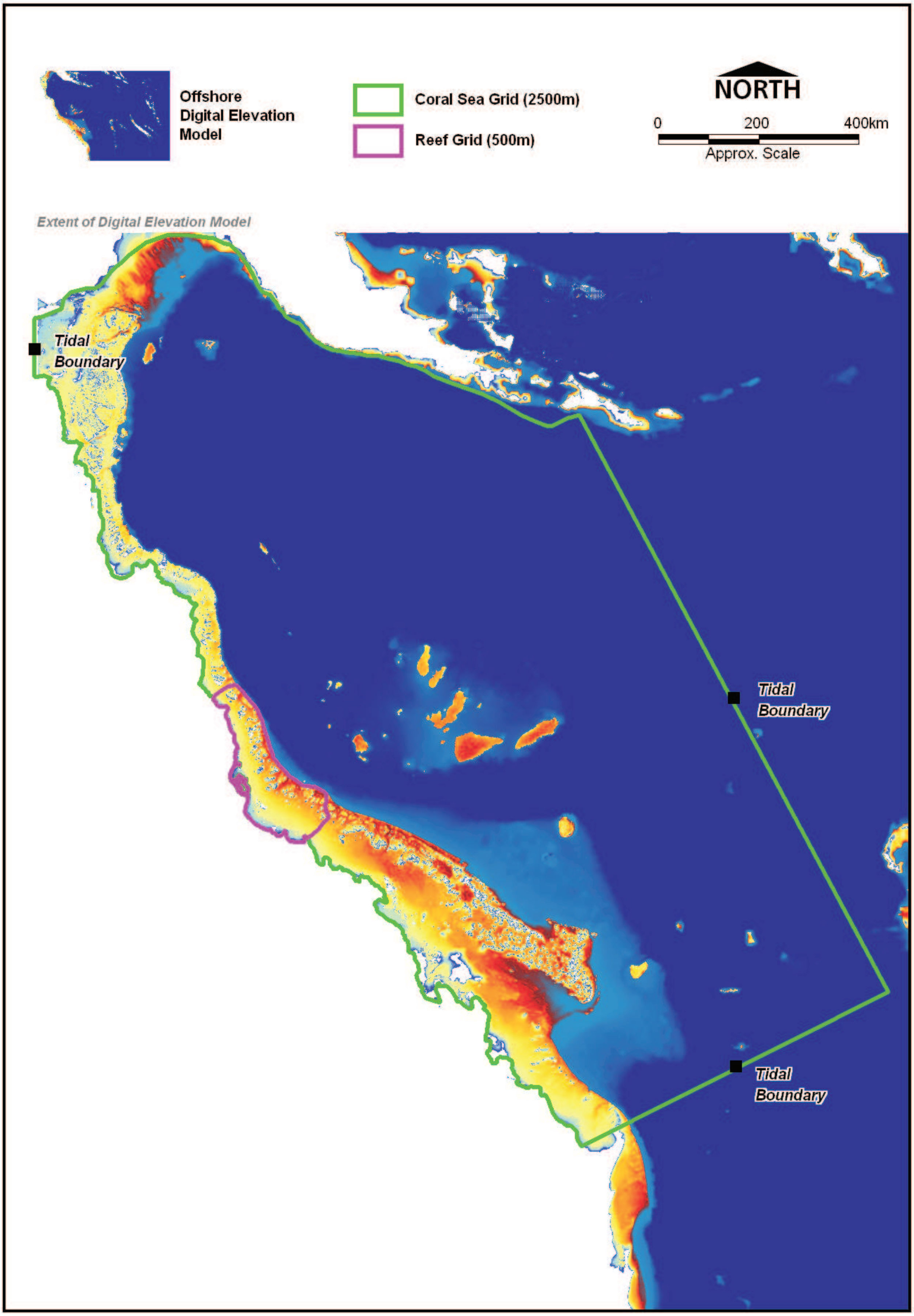
- The TUFLOW model replicates the atmospheric pressure, wind speed and wind direction in the vicinity of the cyclone eye with a suitable level of accuracy
- The TUFLOW model replicates Storm Tides including peak surges as a consequence of a tropical cyclone event with a good level of accuracy.

From the model calibration of the SWAN Wave Model developed, the following can be concluded:

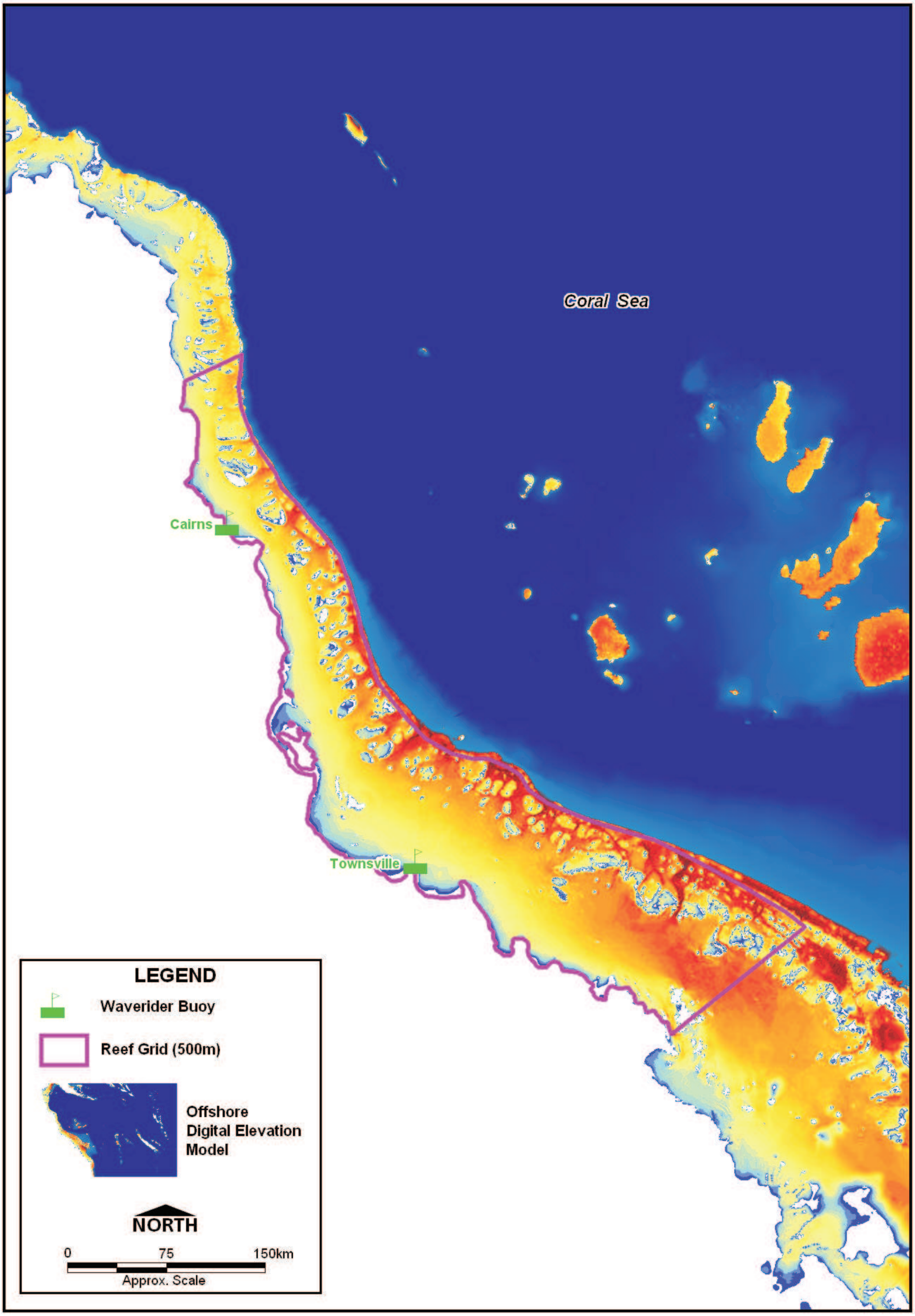
- The SWAN Wave model replicates the offshore wave in terms of wave height and wave period with a suitable accuracy within the region of key interest.

The model results provide confidence that the Storm Surge Model developed is capable of predicting storm tides due to tropical cyclones. The model replicates the measured surge during the two tropical cyclones considered quite accurately within the study area.

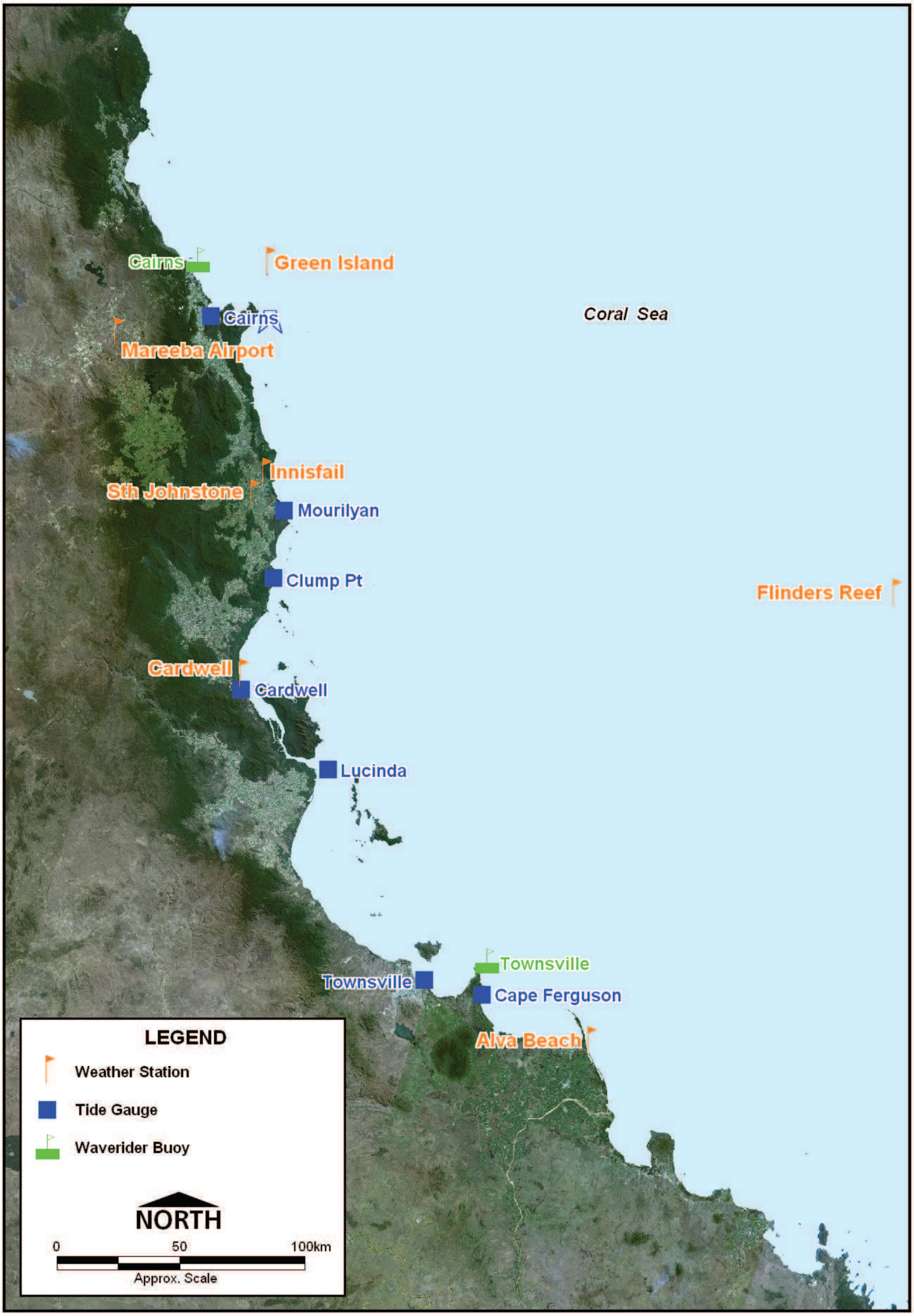
The satisfactory model performance for the two TC events considered suggests that the storm surge model will be suitable for undertaking design simulations in order to quantify the risk of coastal inundation due to storm surge to the study area. It is recommended that the model be adopted for design coastal inundation simulations.



Offshore TUFLOW Model Boundaries **Figure 2-1**

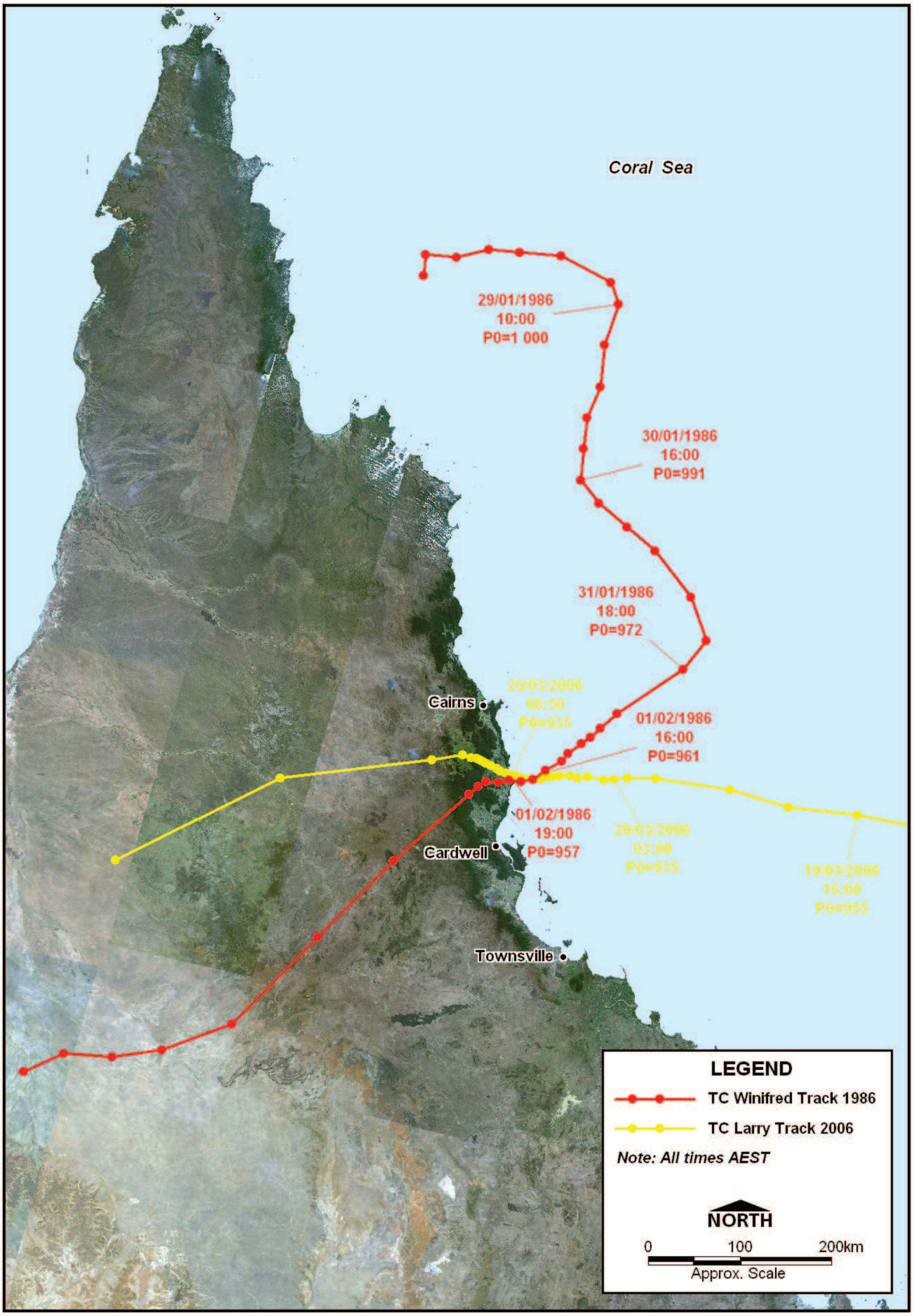


Boundary of Wave Model Used in Calibration **Figure 2-2**



Tide Gauge, Weather Station and Waverider Buoy Locations

Figure 2-3



Tropical Cyclone Tracks used for Model Calibration

Figure 2-4

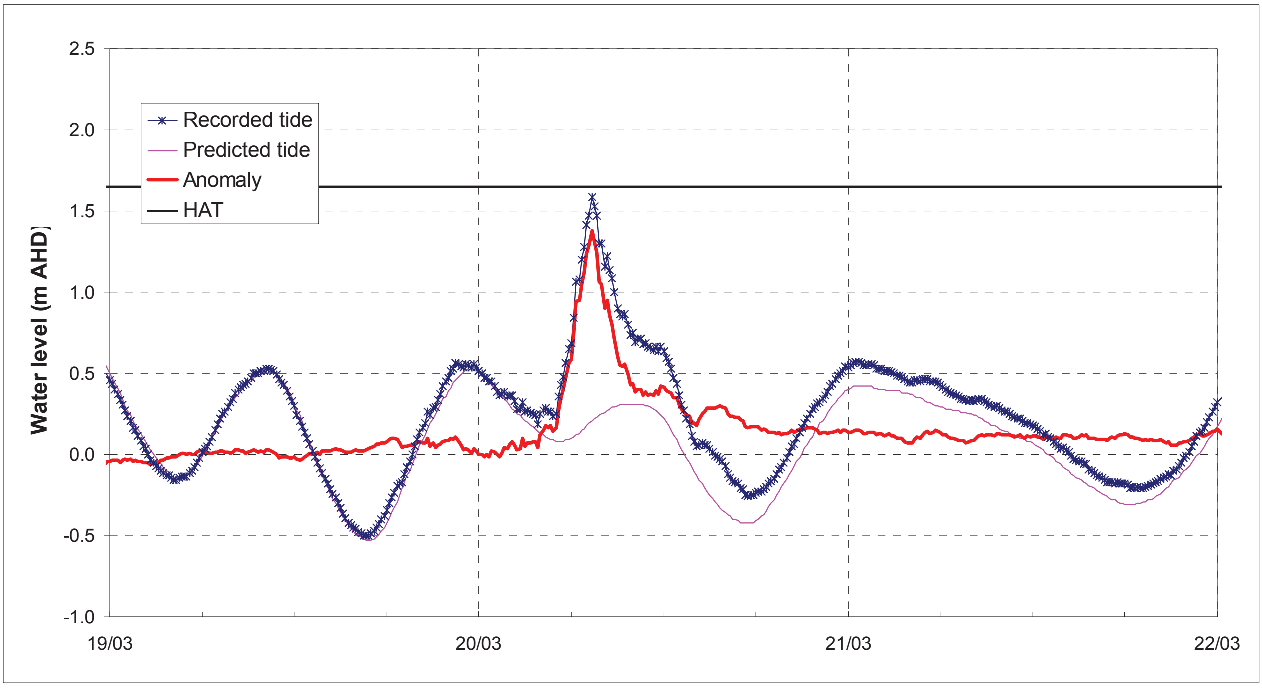


Figure 2-5 Measured Water Level & Storm Surge: TC Larry at Mourilyan

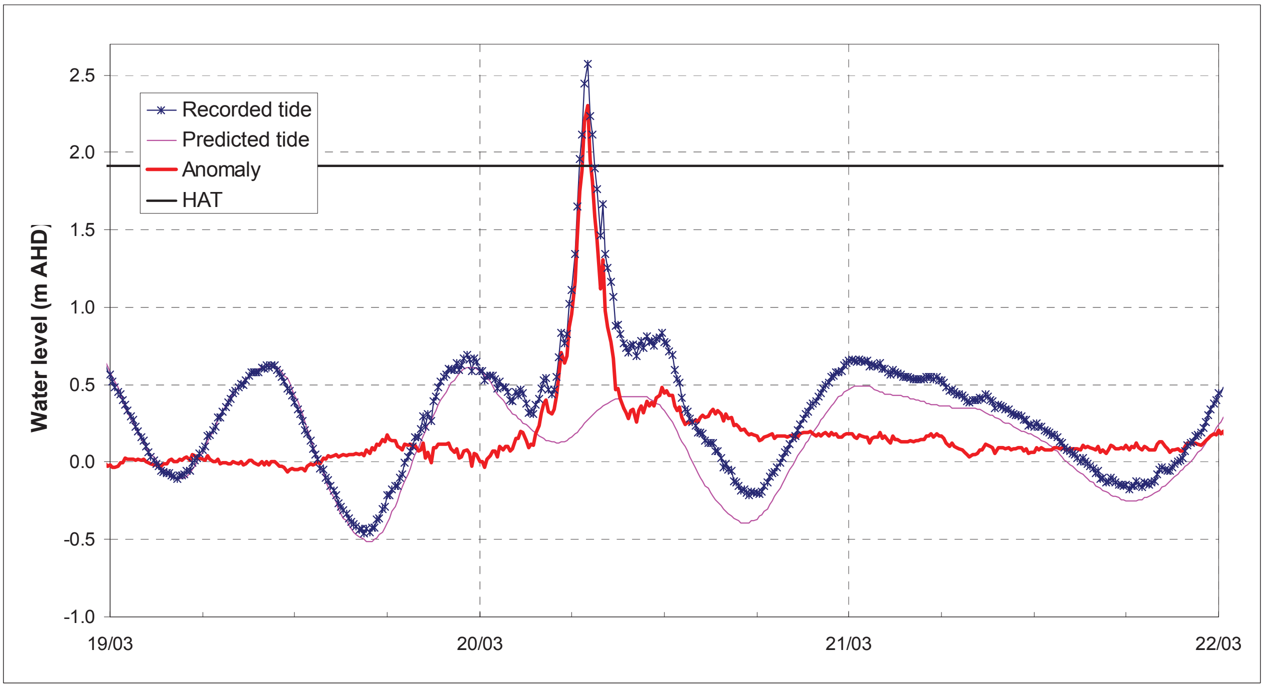


Figure 2-6 Measured Water Level & Storm Surge: TC Larry at Clump Point

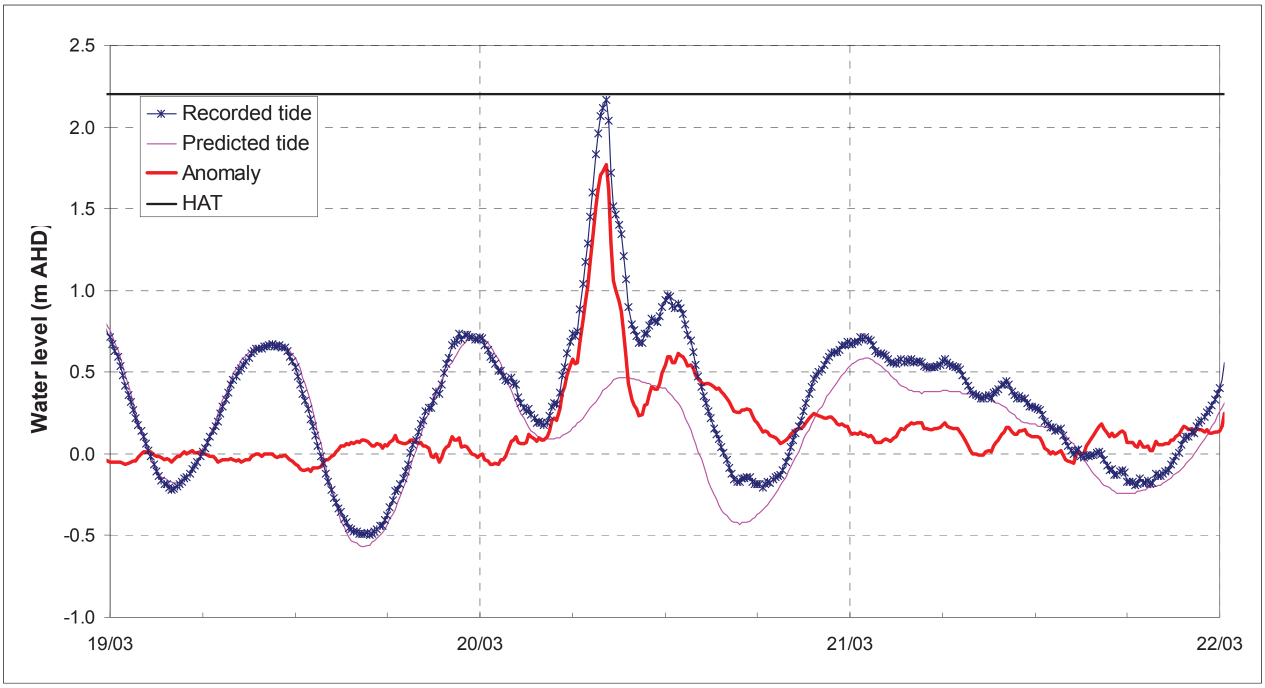


Figure 2-7 Measured Water Level & Storm Surge: TC Larry at Cardwell

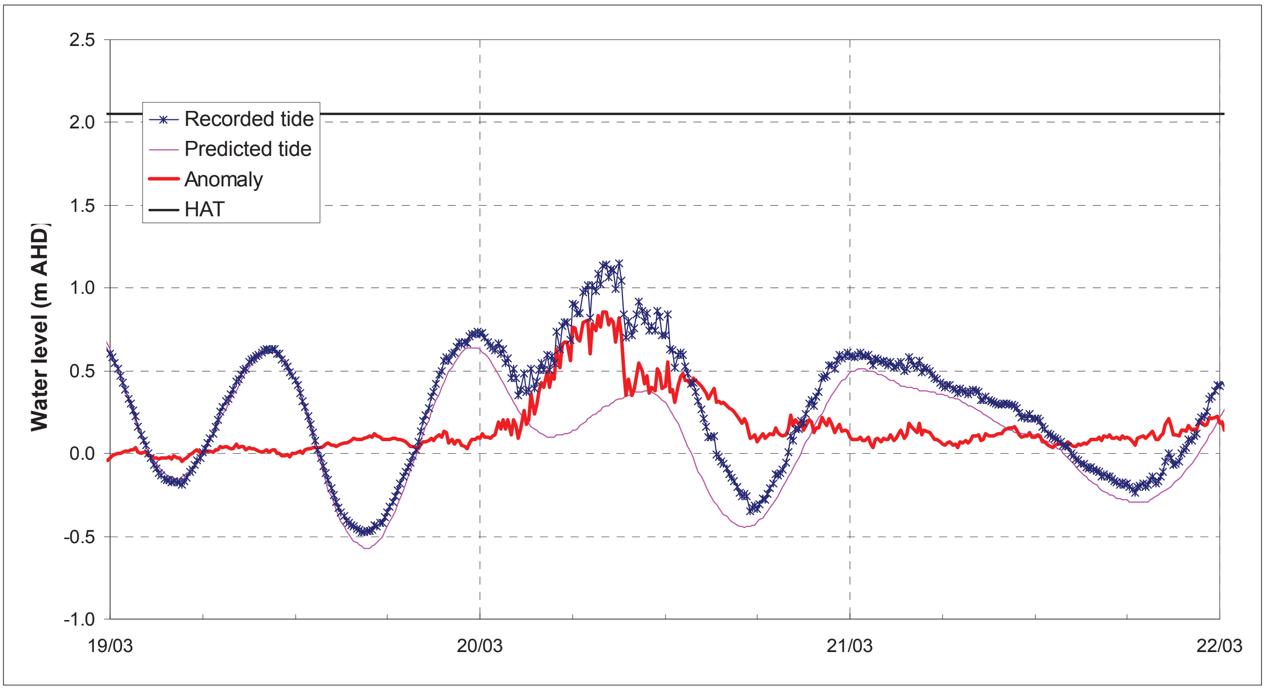


Figure 2-8 Measured Water Level & Storm Surge: TC Larry at Lucinda

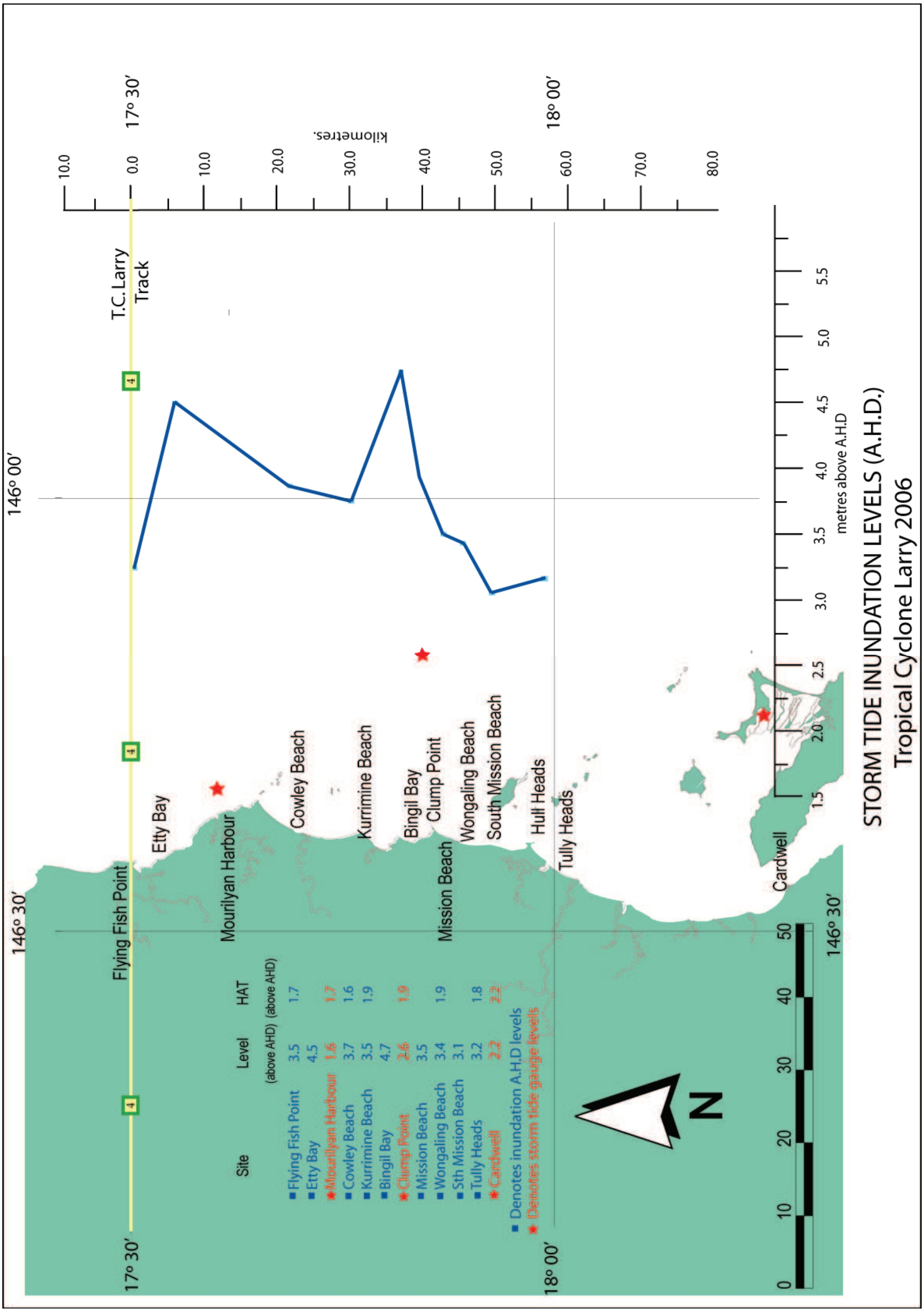


Figure 2-9 Surveyed Storm Tide Debris Levels: TC Larry

(courtesy of EPA, Robert Schwarz pers. comm.)

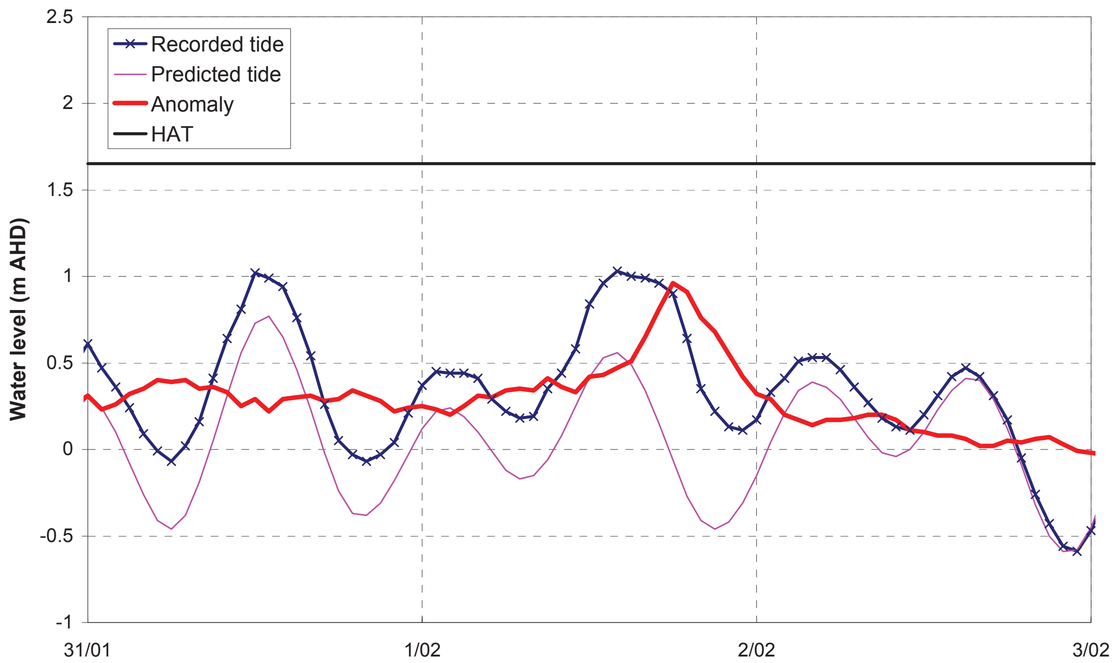


Figure 2-10 Measured Water Level & Storm Surge: TC Winifred at Mourilyan

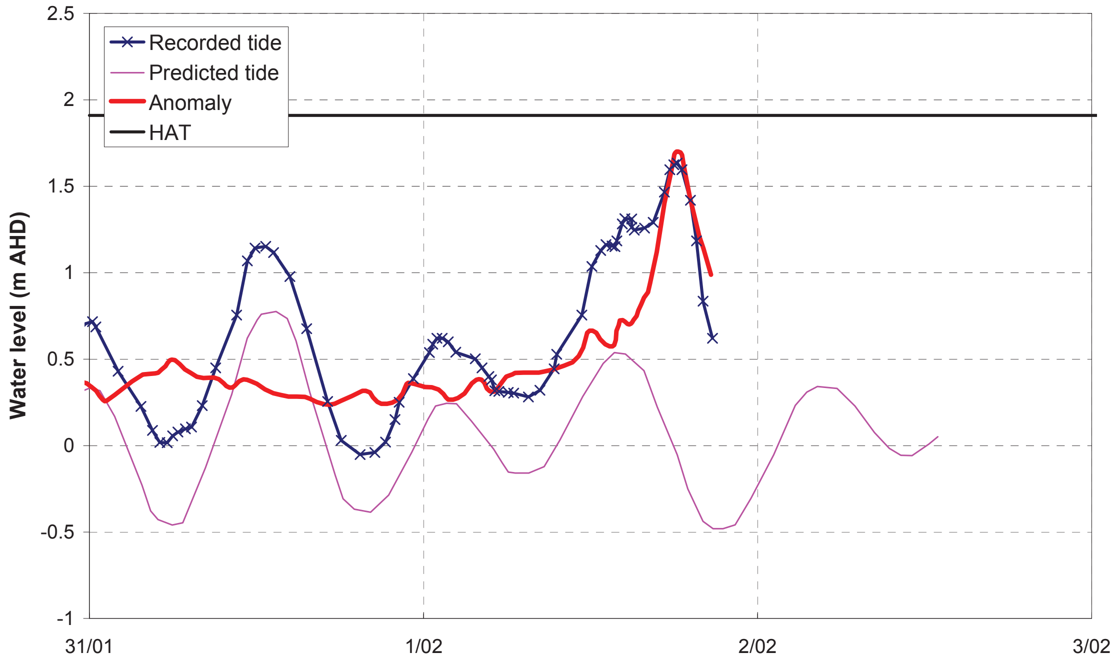


Figure 2-11 Measured Water Level & Storm Surge: TC Winifred at Clump Point

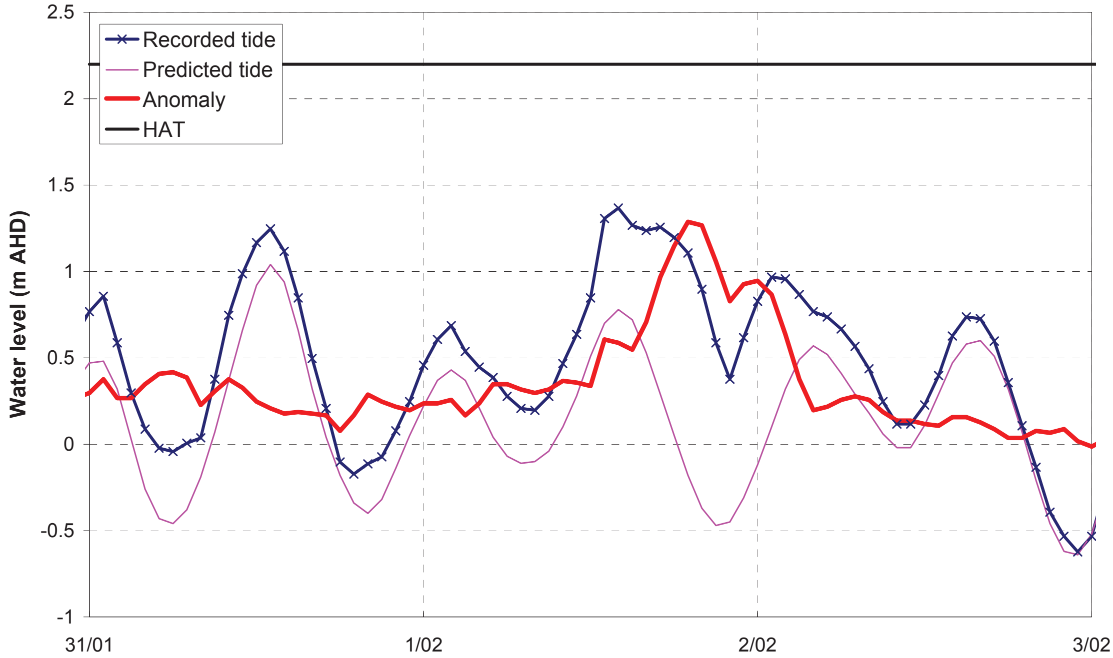


Figure 2-12 Measured Water Level & Storm Surge: TC Winifred at Cardwell

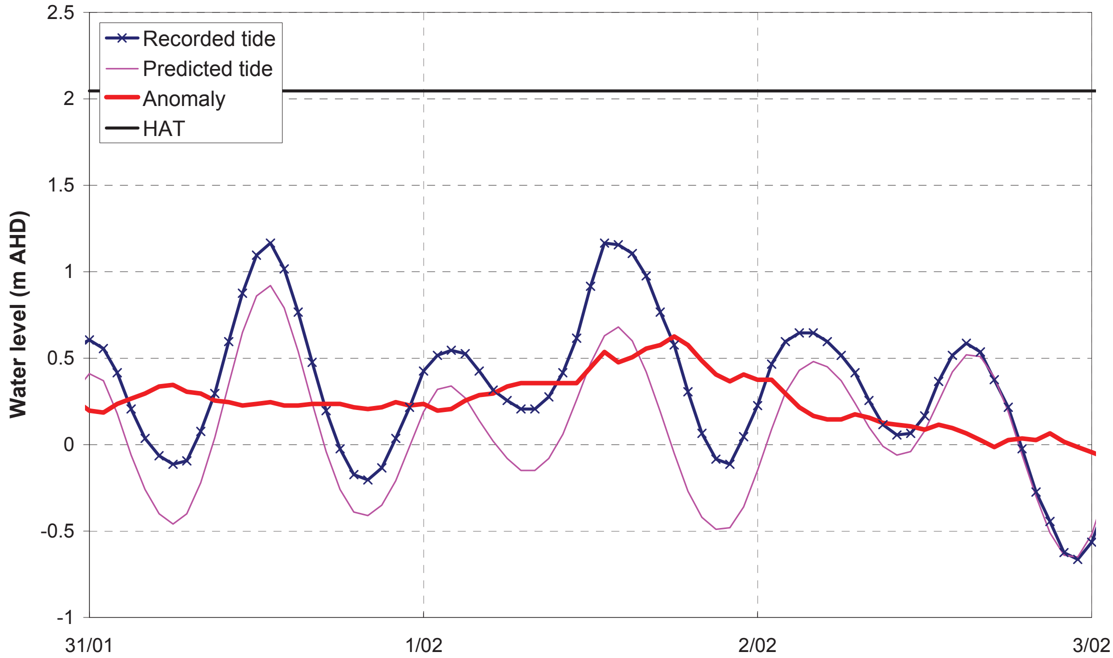


Figure 2-13 Measured Water Level & Storm Surge: TC Winifred at Lucinda

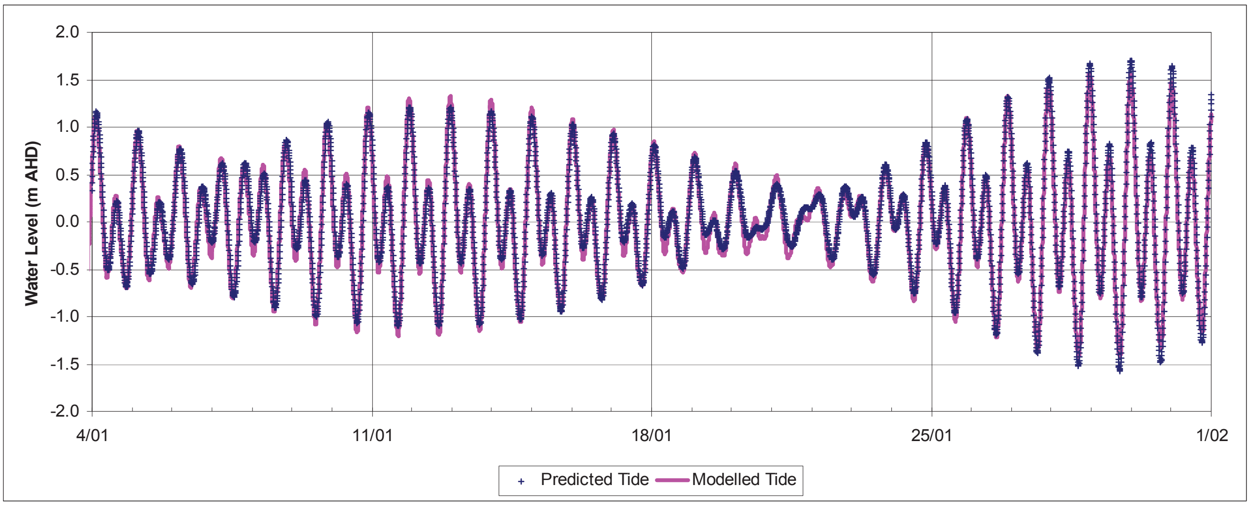


Figure 2-14 Modelled Water Level vs Tidal Predictions: Mourilyan

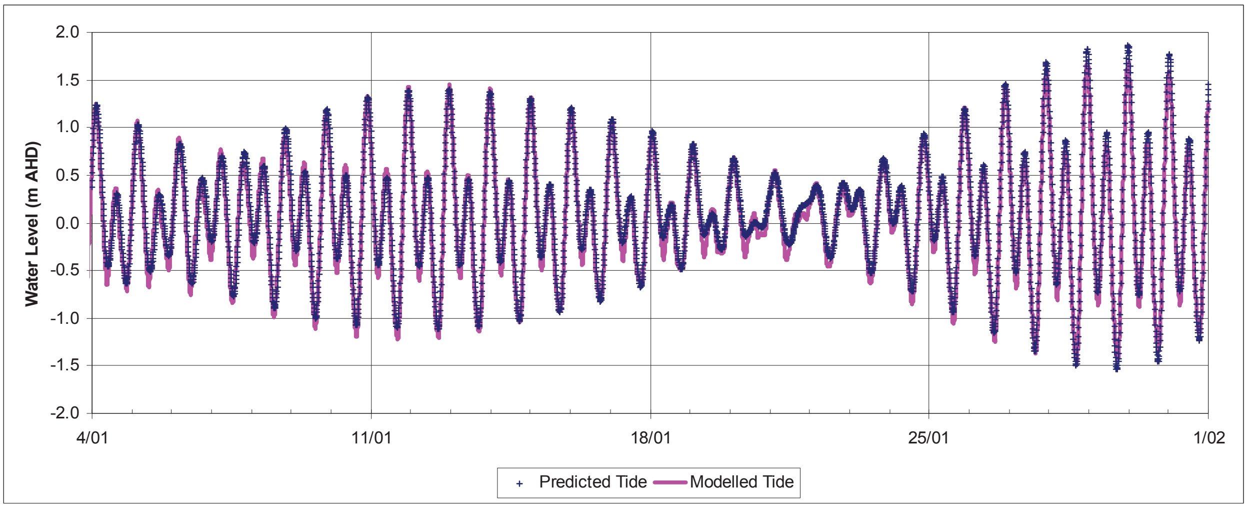


Figure 2-15 Modelled Water Level vs Tidal Predictions: Clump Point

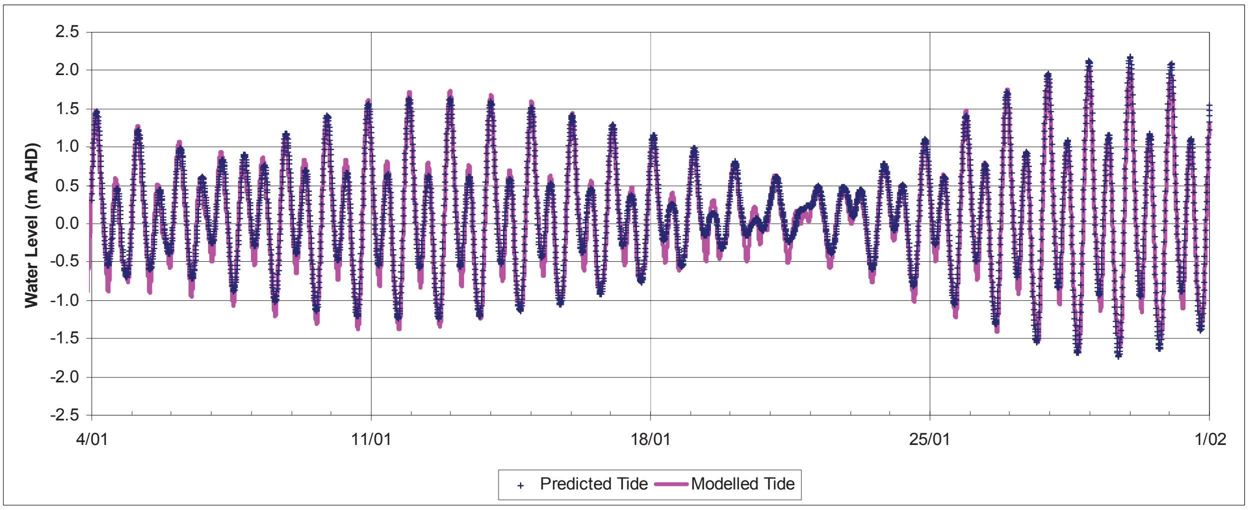


Figure 2-16 Modelled Water Level vs Tidal Predictions: Cardwell

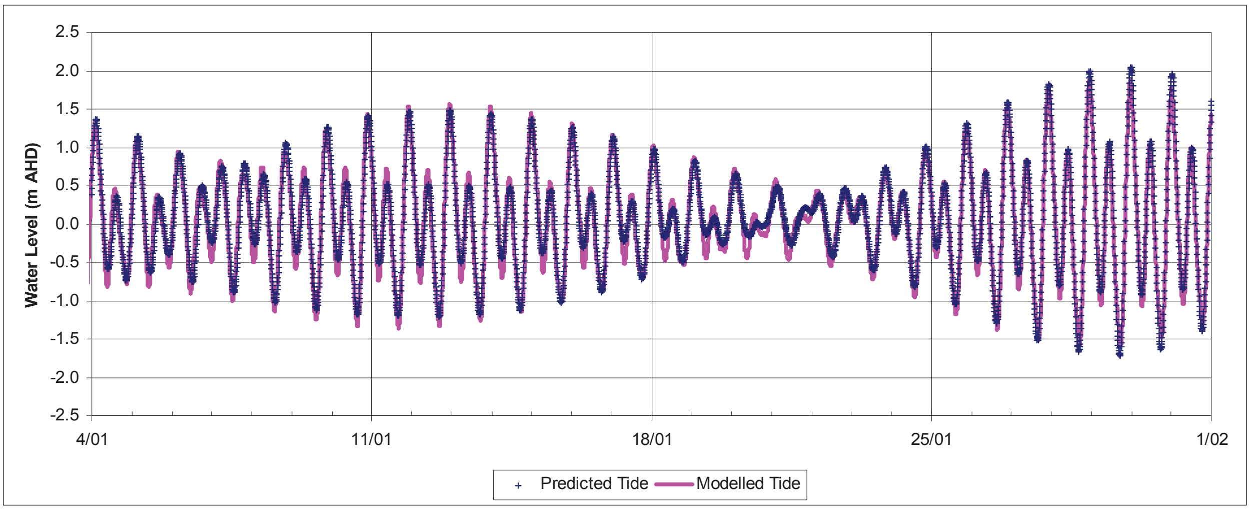


Figure 2-17 Modelled Water Level vs Tidal Predictions: Lucinda

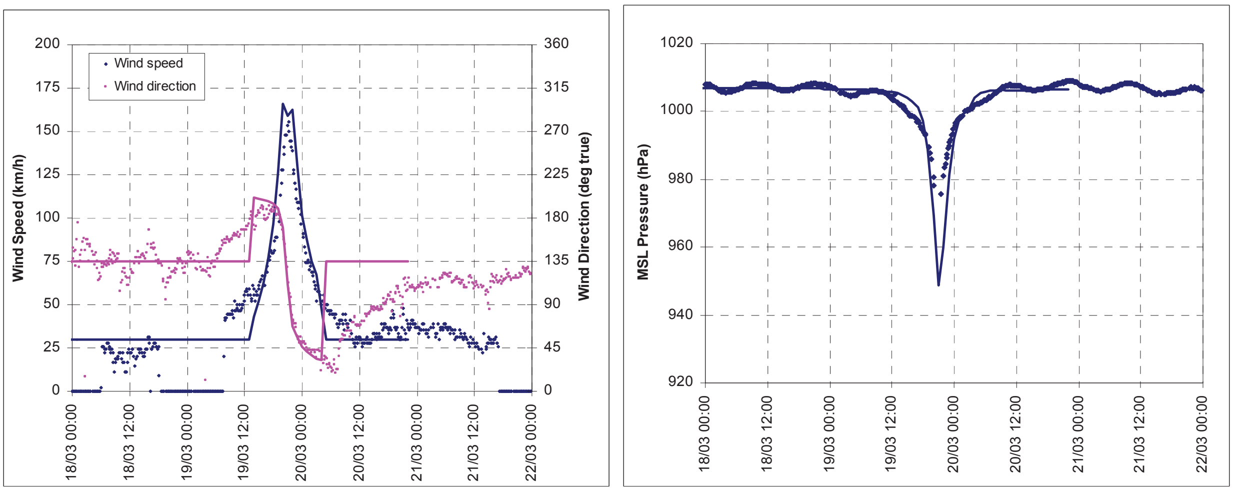


Figure 2-18 Hindcast Wind & Pressure Comparison: TC Larry at Flinders Reef AWS.

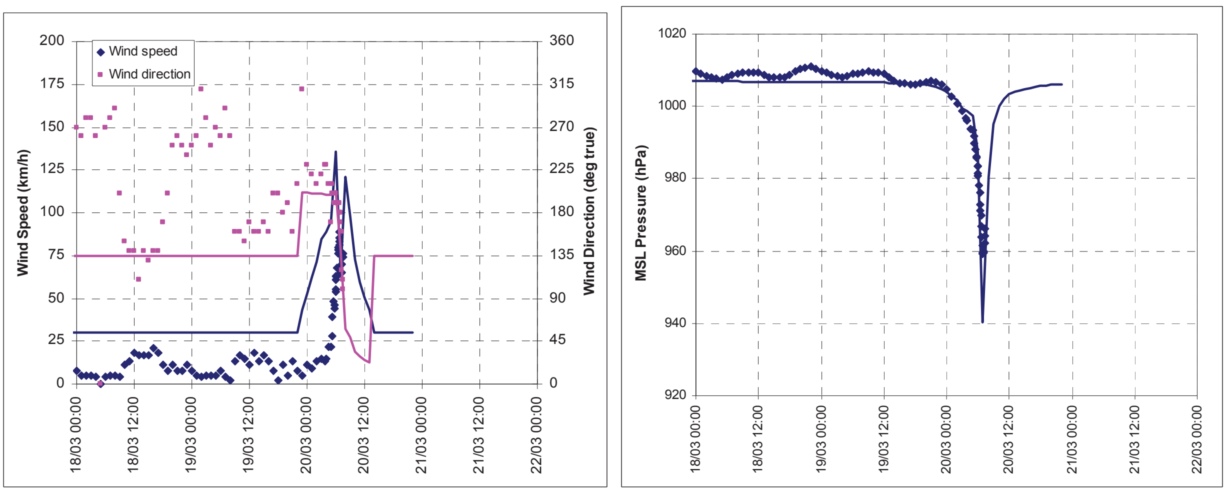


Figure 2-19 Hindcast Wind & Pressure Comparison: TC Larry at South Johnstone AWS.

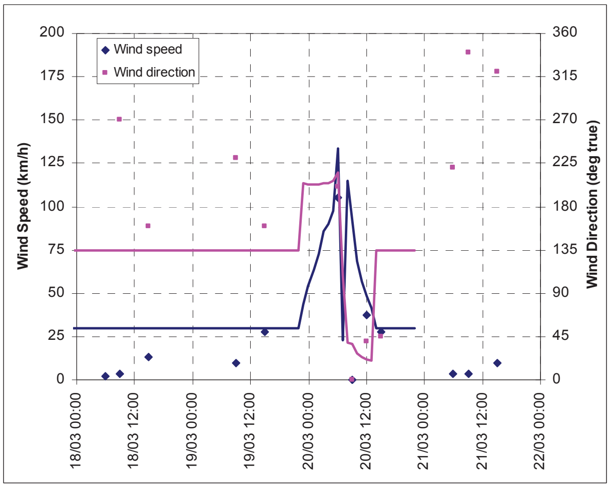


Figure 2-20 Hindcast Wind Comparison: TC Larry at Innisfail.

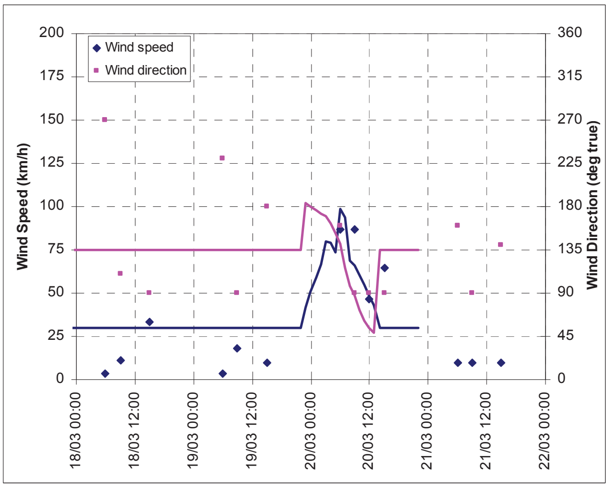
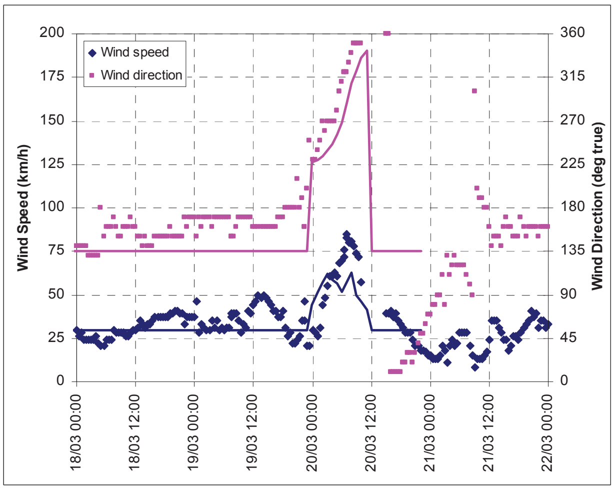


Figure 2-21 Hindcast Wind Comparison: TC Larry at Cardwell.



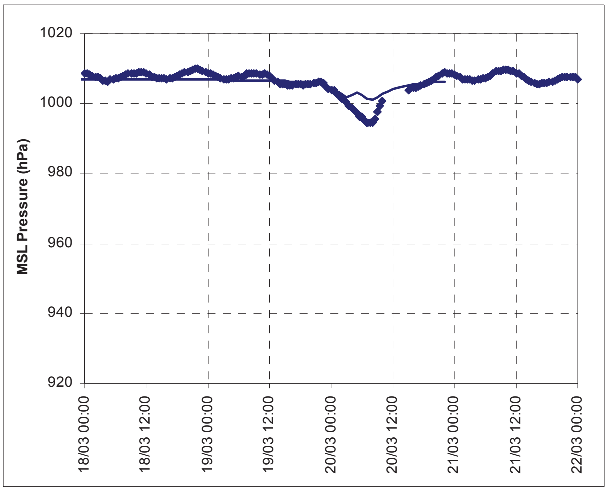


Figure 2-22 Hindcast Wind & Pressure Comparison: TC Larry at Green Island AWS.

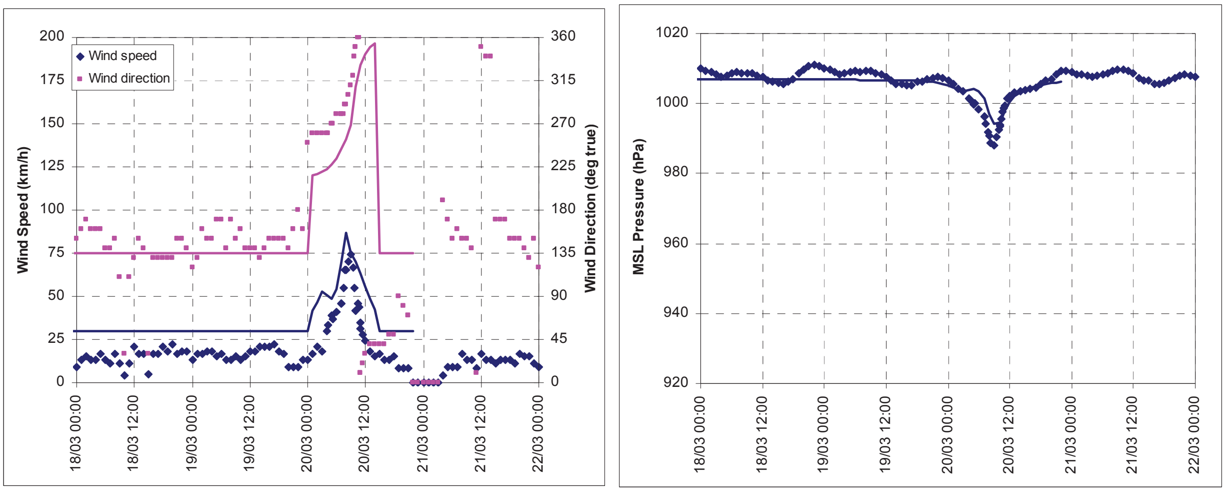


Figure 2-23 Hindcast Wind & Pressure Comparison: TC Larry at Mareeba Airport AWS.

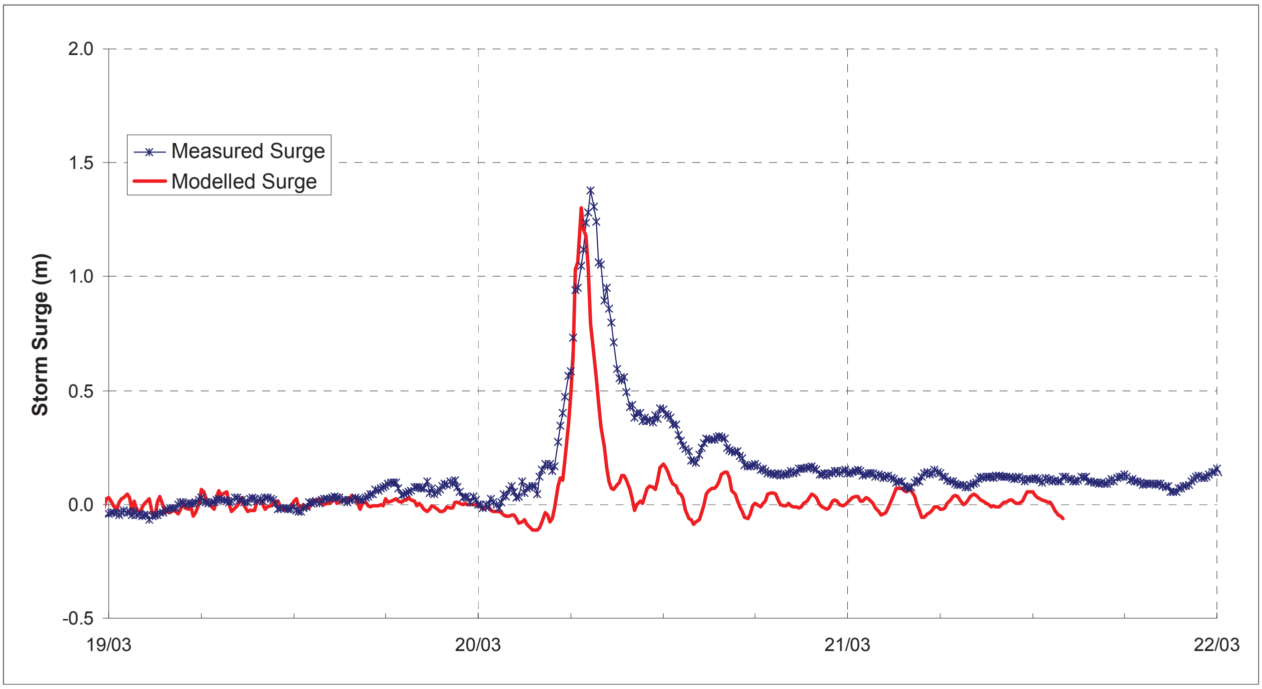


Figure 2-24 Measured vs Modelled Storm Surge: TC Larry at Mourilyan Harbour

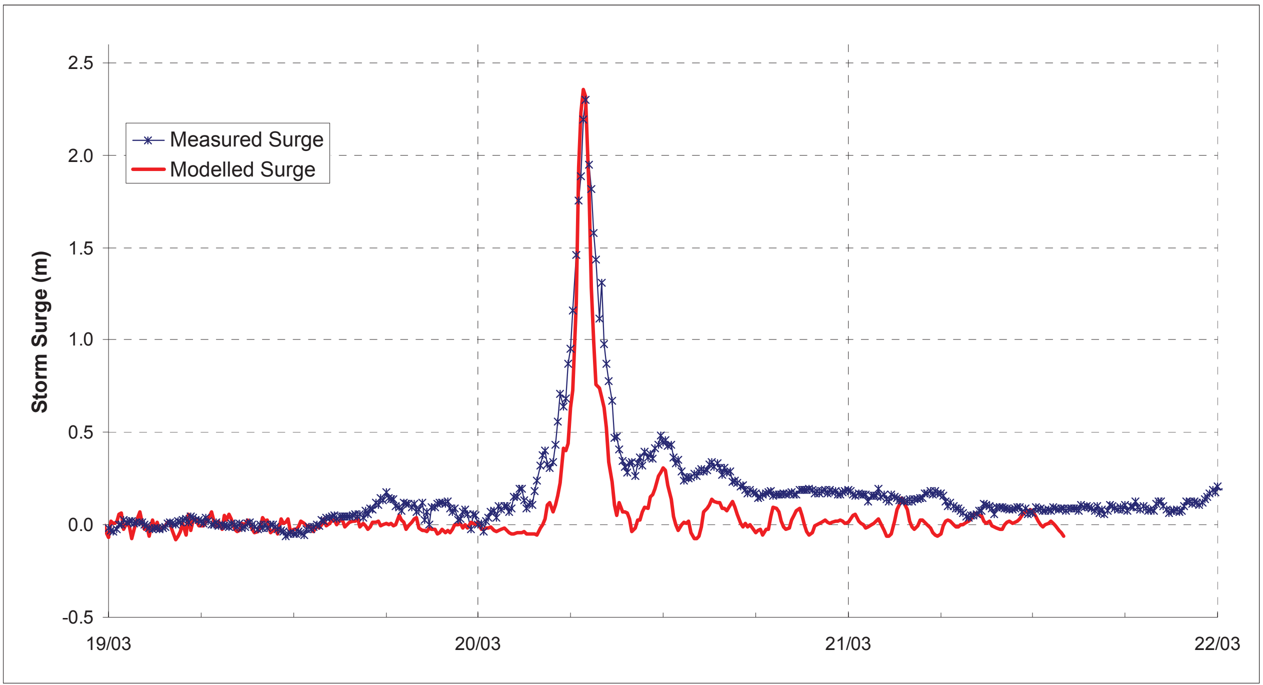


Figure 2-25 Measured vs Modelled Storm Surge: TC Larry at Clump Point

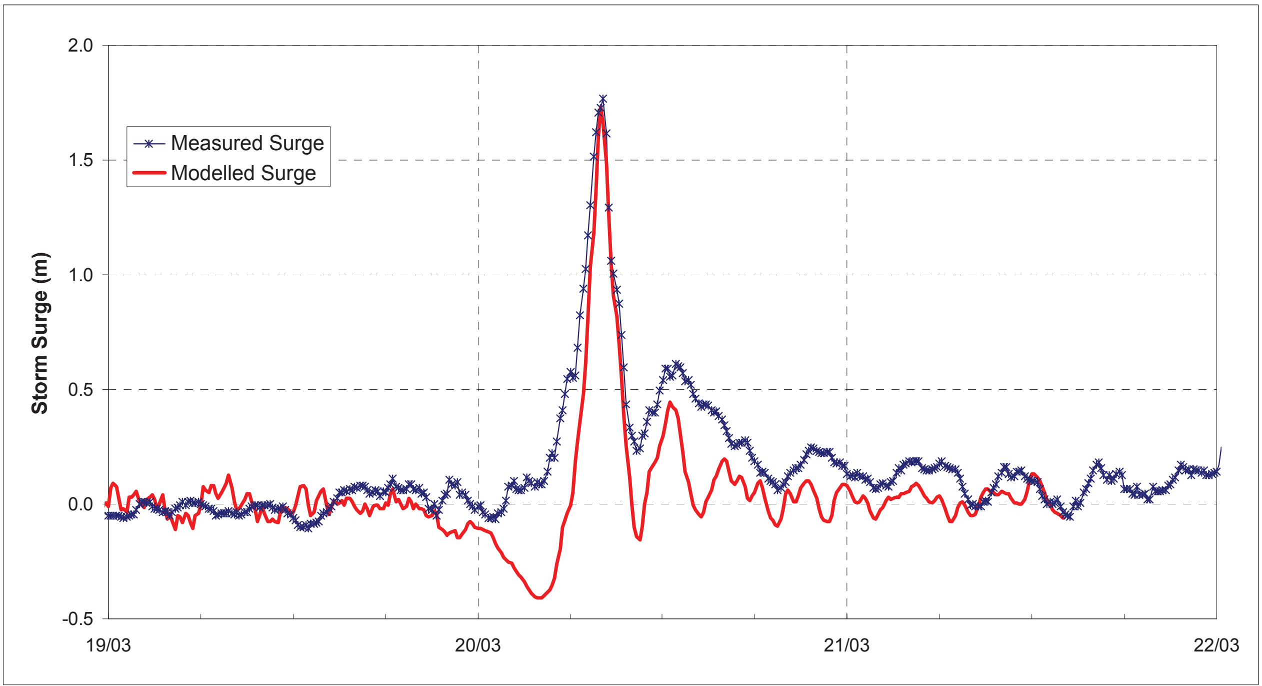


Figure 2-26 Measured vs Modelled Storm Surge: TC Larry at Cardwell

Figure 2-27 Measured vs Modelled Storm Surge: TC Larry at Lucinda

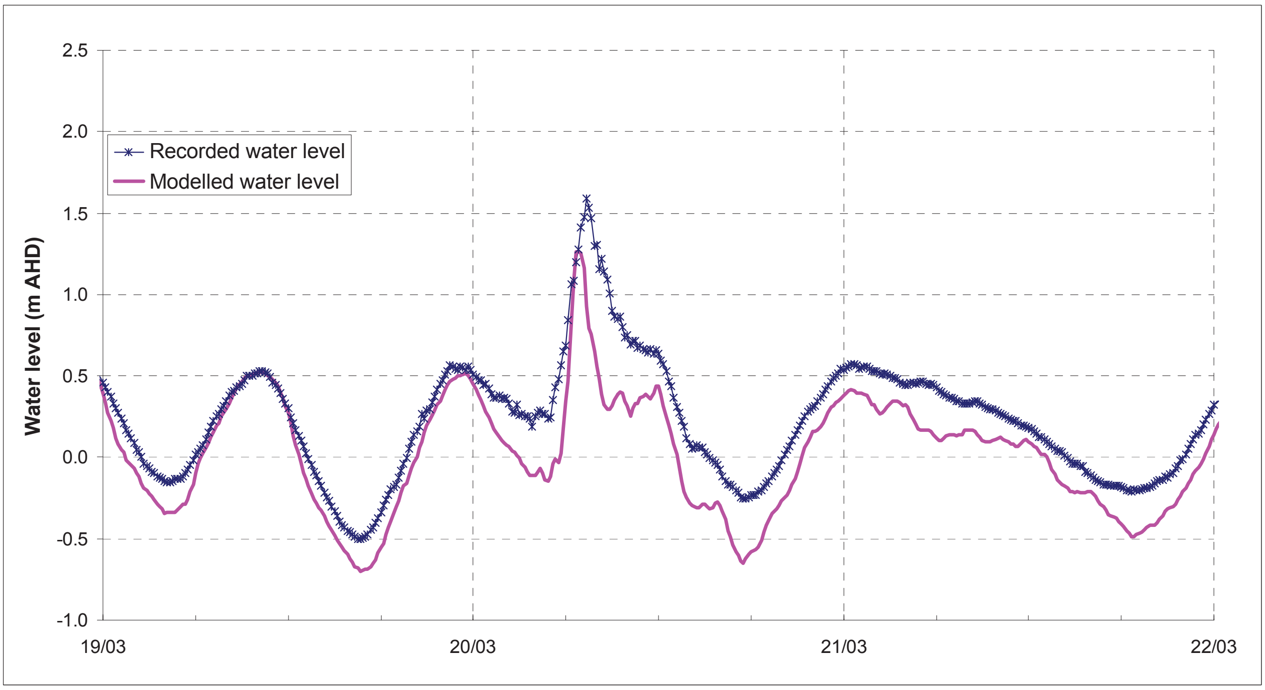


Figure 2-28 Measured vs Modelled Storm Tides: TC Larry at Mourilyan Harbour

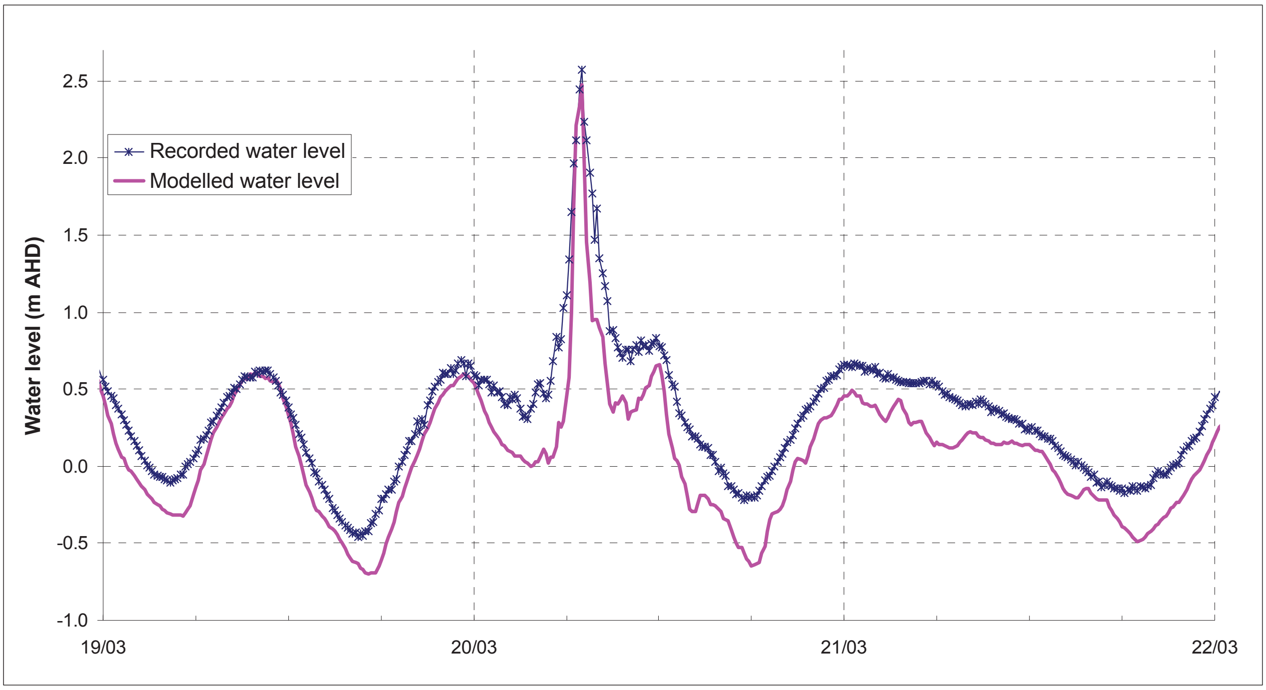


Figure 2-29 Measured vs Modelled Storm Tides: TC Larry at Clump Point

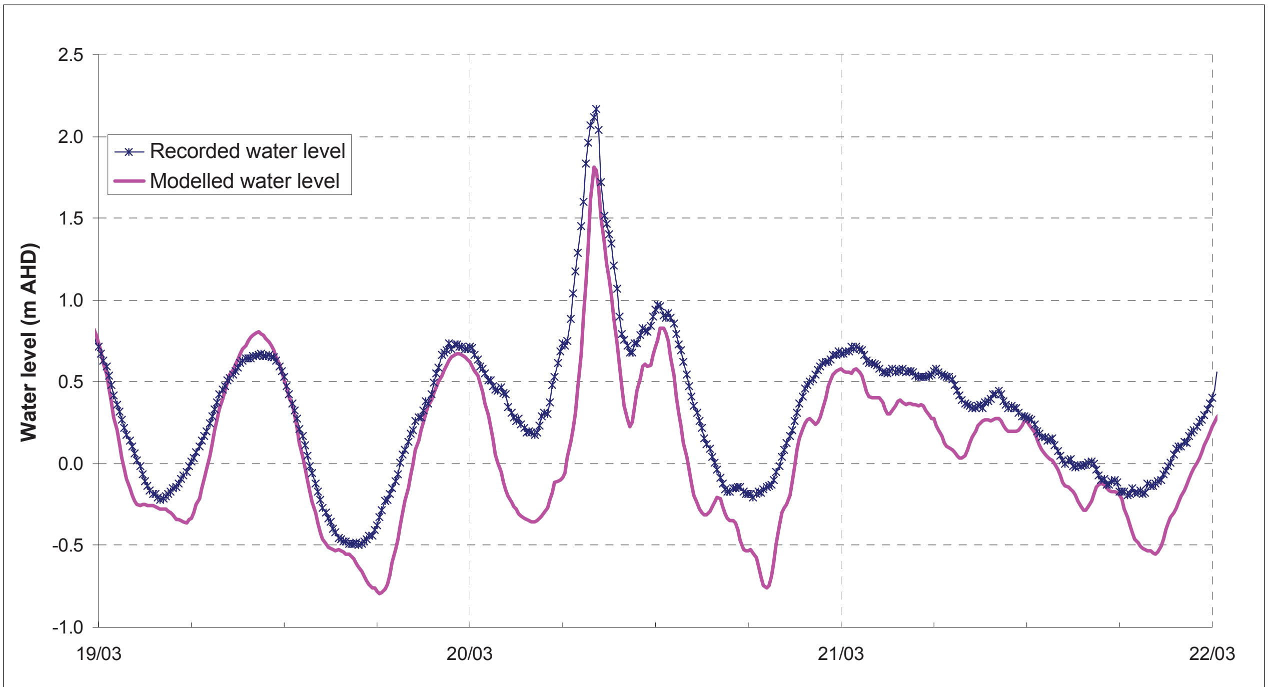


Figure 2-30 Measured vs Modelled Storm Tides: TC Larry at Cardwell

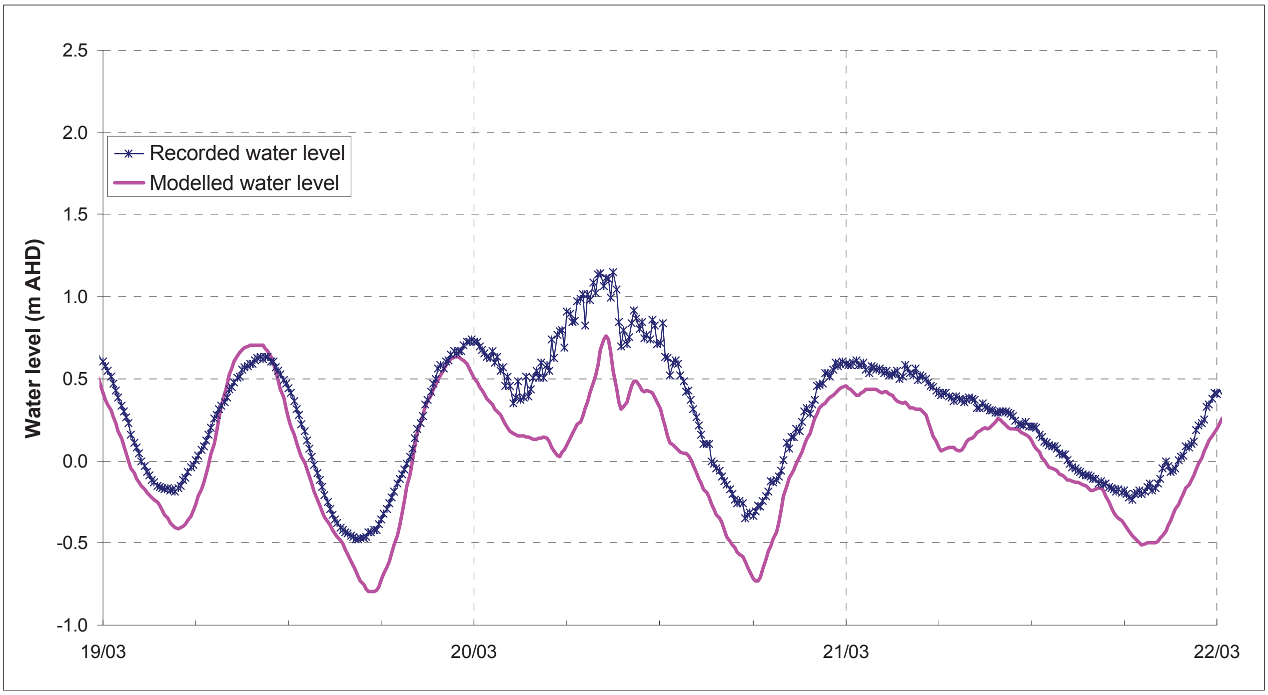


Figure 2-31 Measured vs Modelled Storm Tides: TC Larry at Lucinda

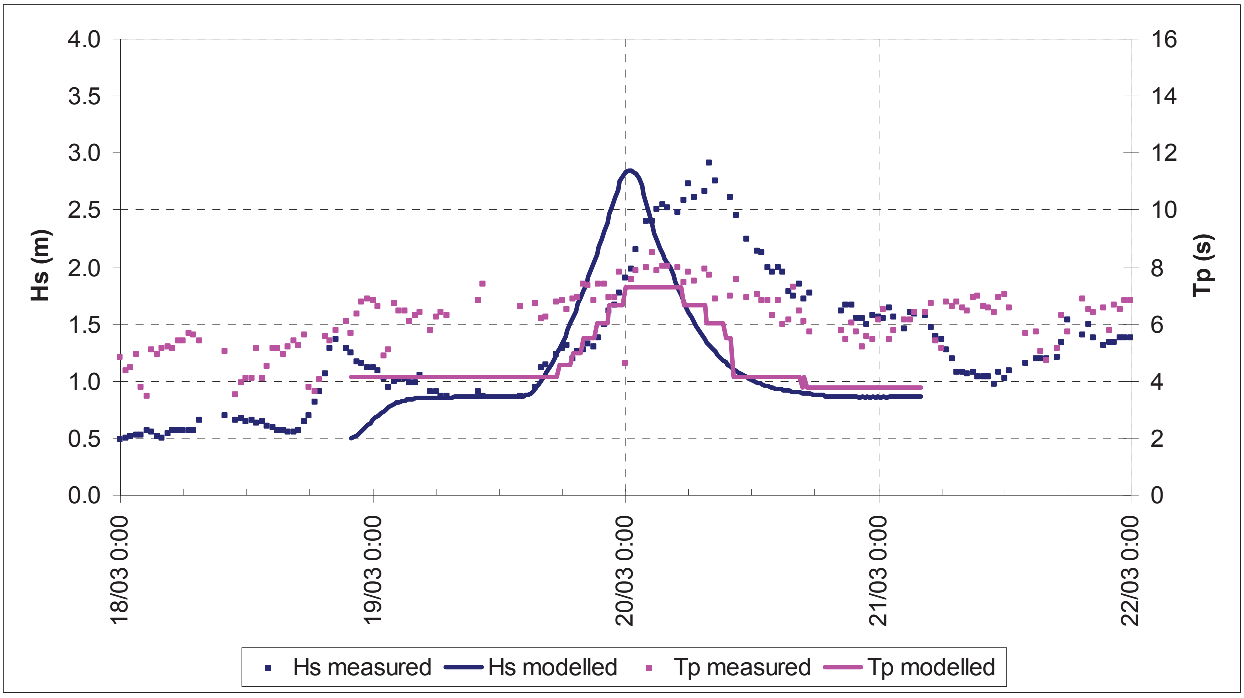


Figure 2-32 Measured vs Modelled Wave Climate at Townsville During TC Larry.

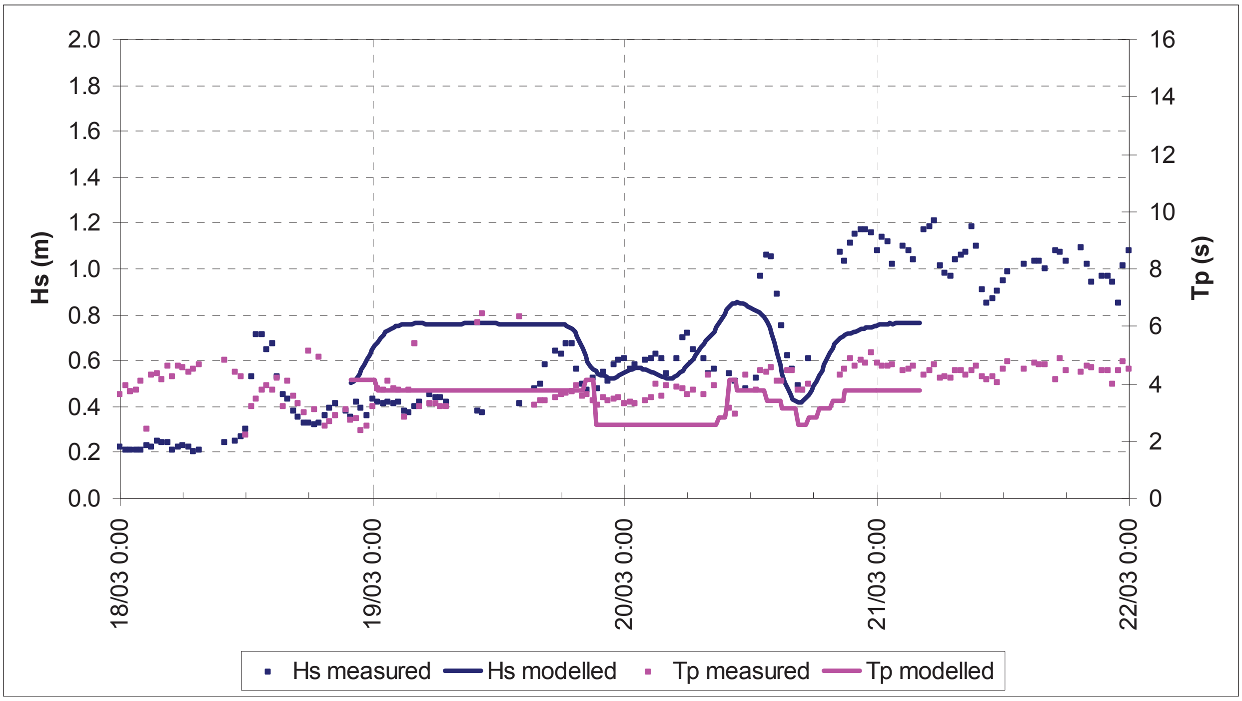


Figure 2-33 Measured vs Modelled Wave Climate at Townsville During TC Larry.

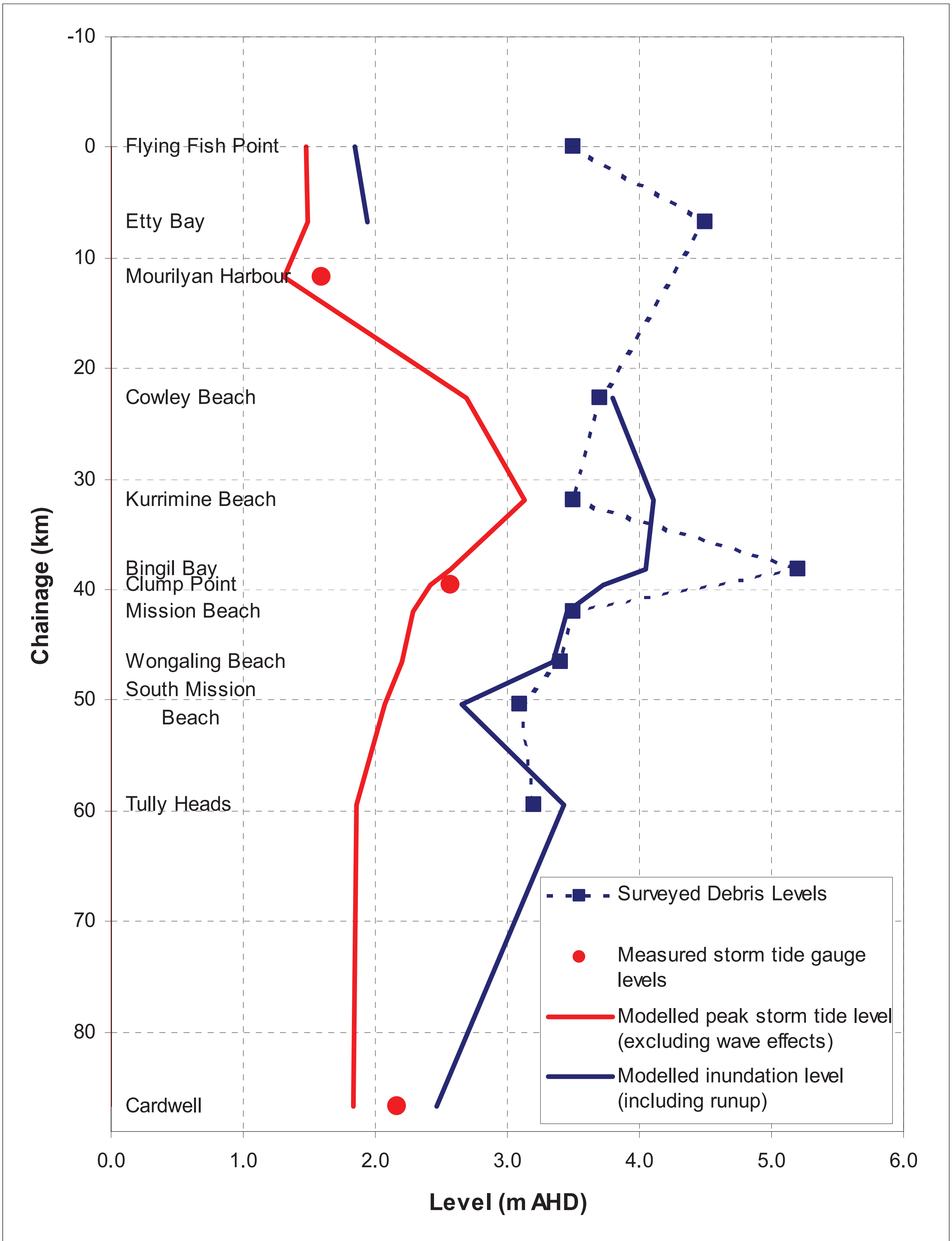


Figure 2-34 Predicted Inundation Level Comparison: TC Larry

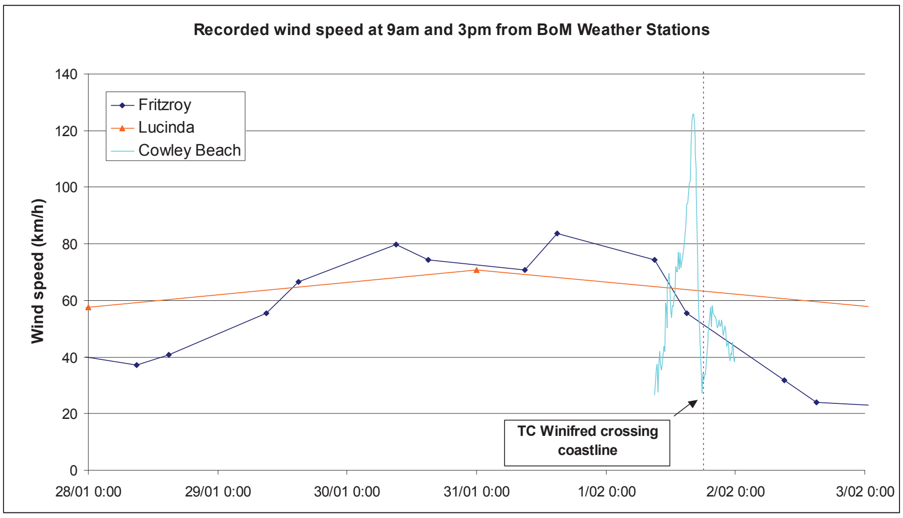


Figure 2-35 Recorded wind speed at offshore weather stations before TC Winifred crossing coastline

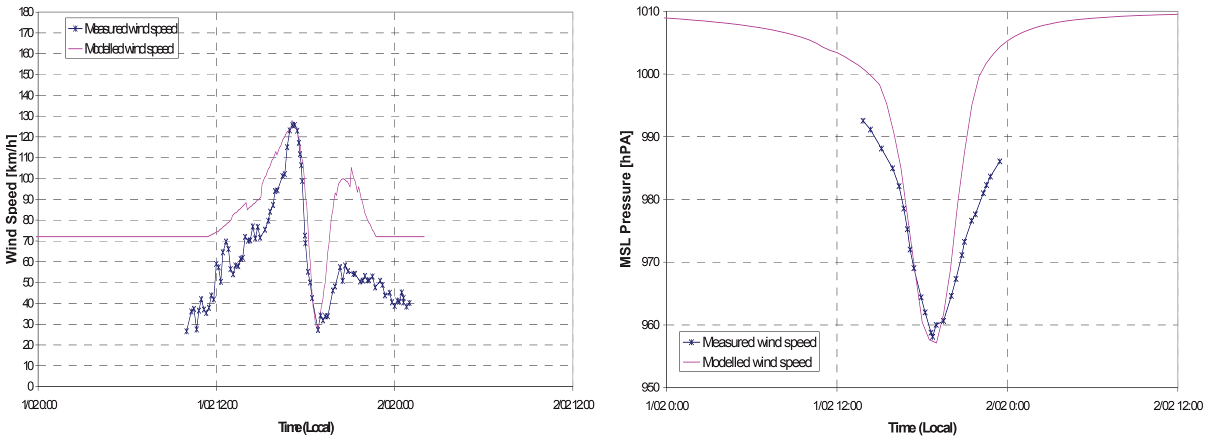


Figure 2-36 Hindcast Wind & Pressure Comparison during TC Winifred: Cowley Beach

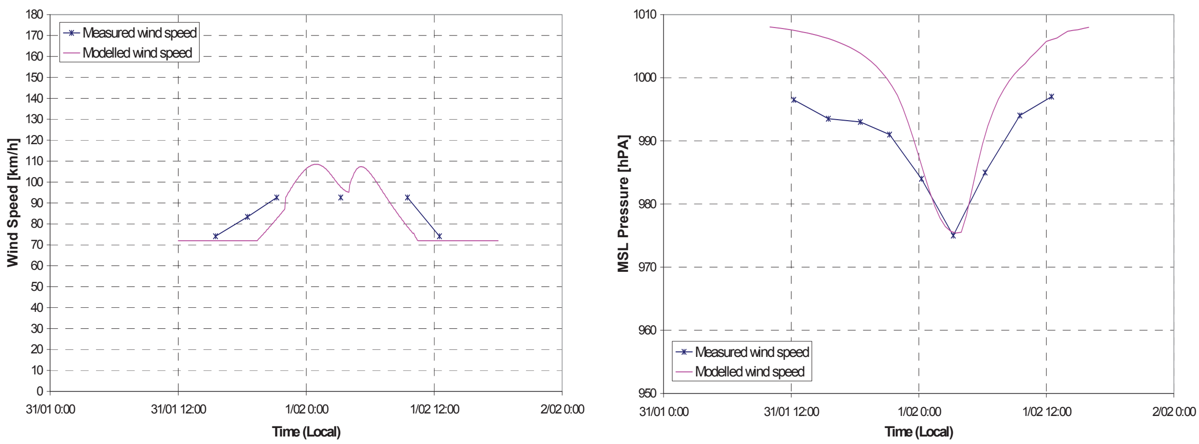


Figure 2-37 Hindcast Wind & Pressure Comparison during TC Winifred: Holmes Reef

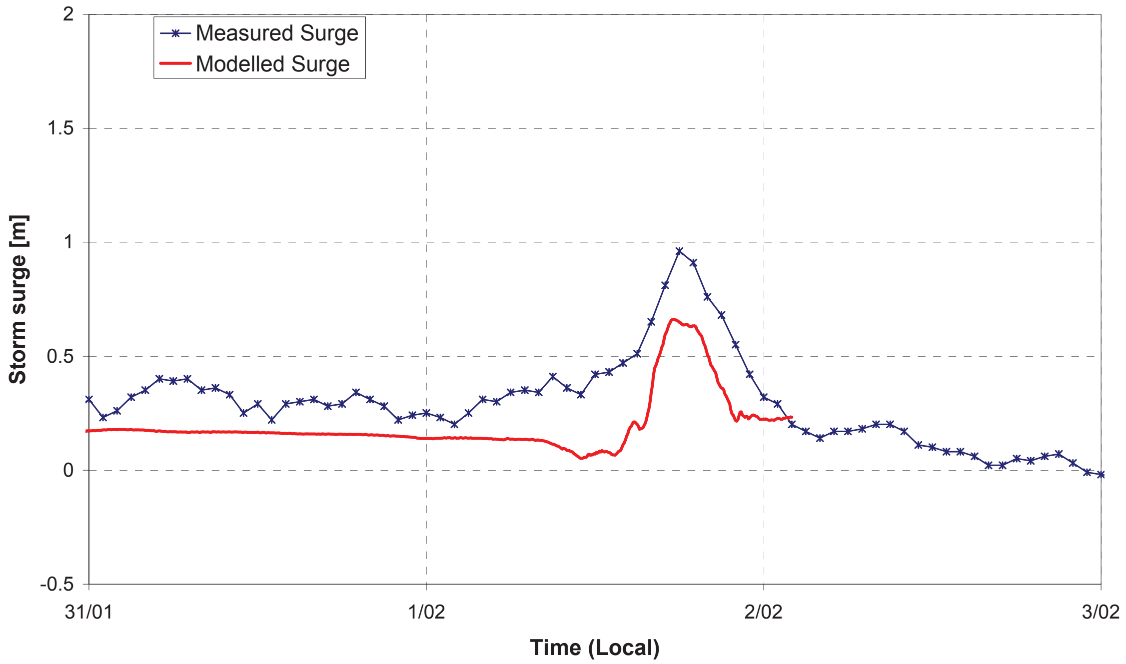


Figure 2-38 Measured vs Modelled Storm Surge: TC Winifred at Mourilyan Harbour

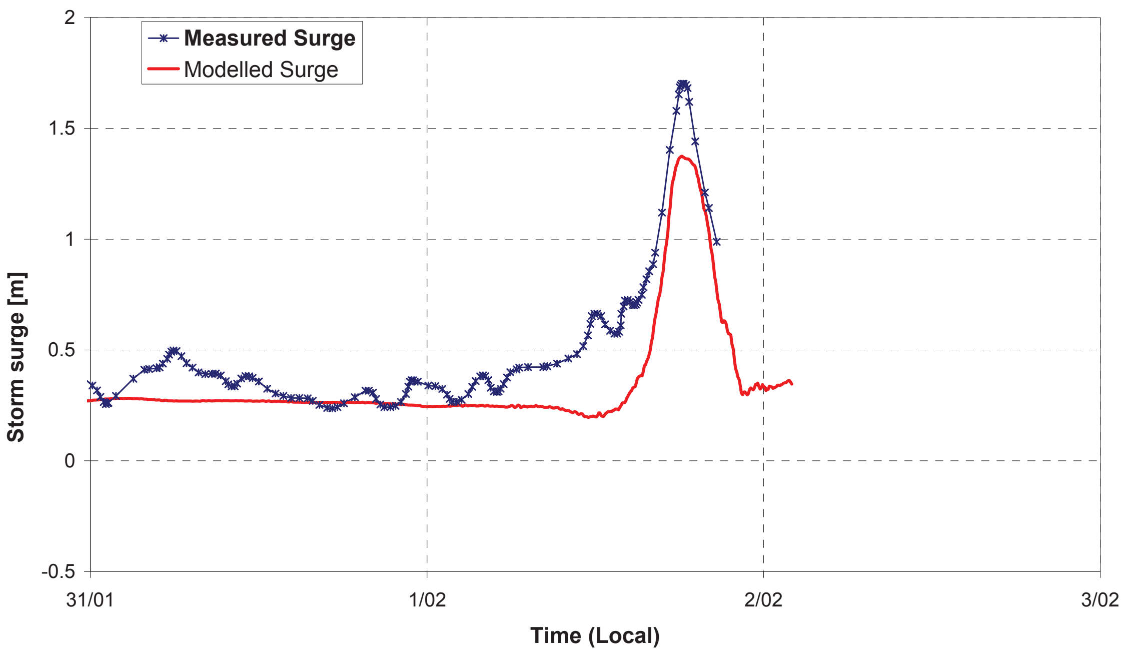


Figure 2-39 Measured vs Modelled Storm Surge: TC Winifred at Clump Point

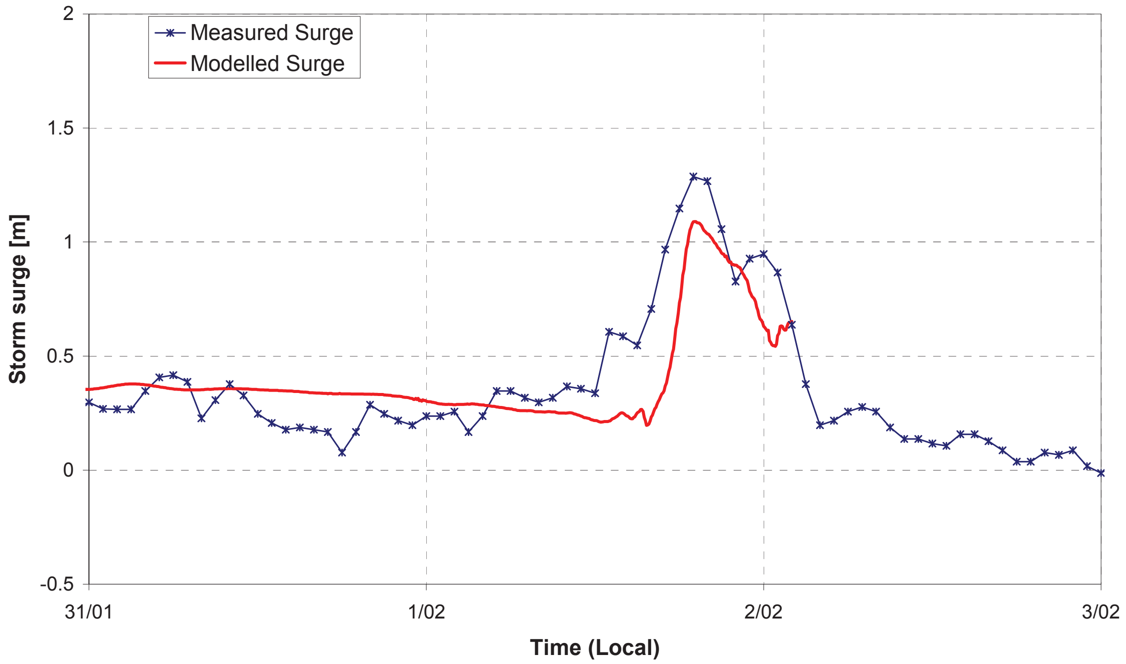


Figure 2-40 Measured vs Modelled Storm Surge: TC Winifred at Cardwell

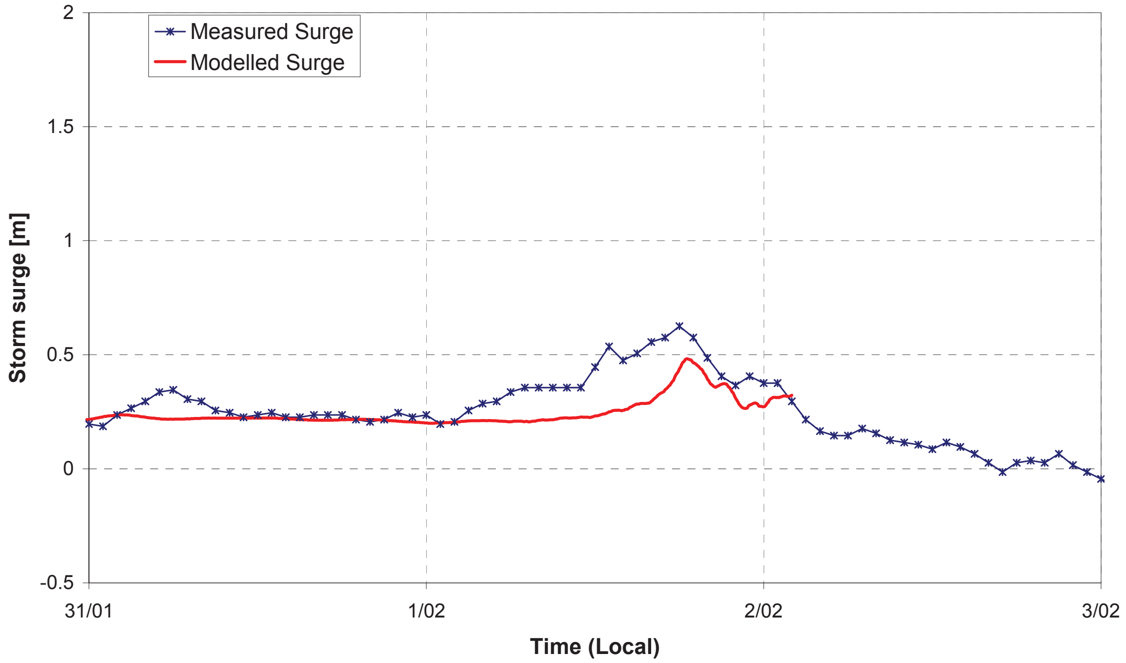


Figure 2-41 Measured vs Modelled Storm Surge: TC Winifred at Lucinda

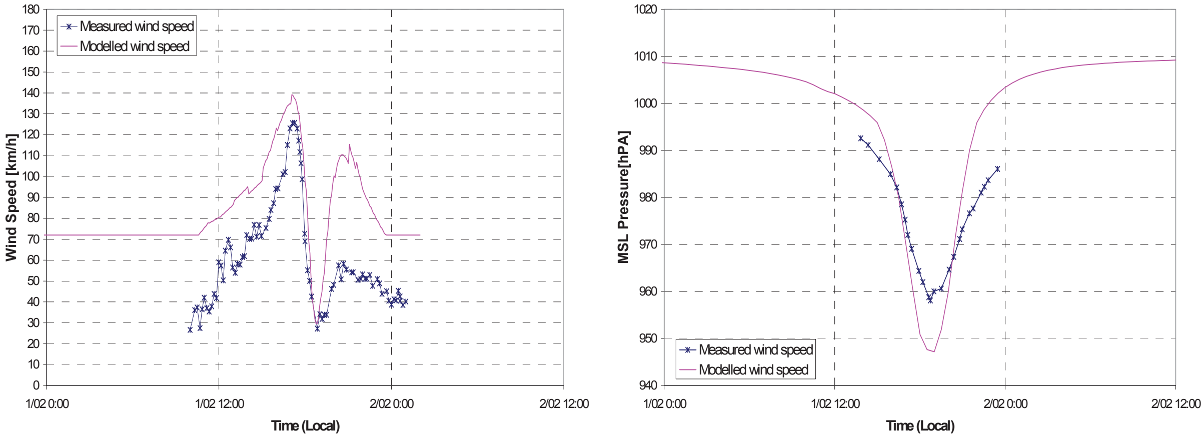


Figure 2-42 Hindcast Wind & Pressure Comparison during TC Winifred: Cowley Beach – Model Simulation with Reduced Central Pressure

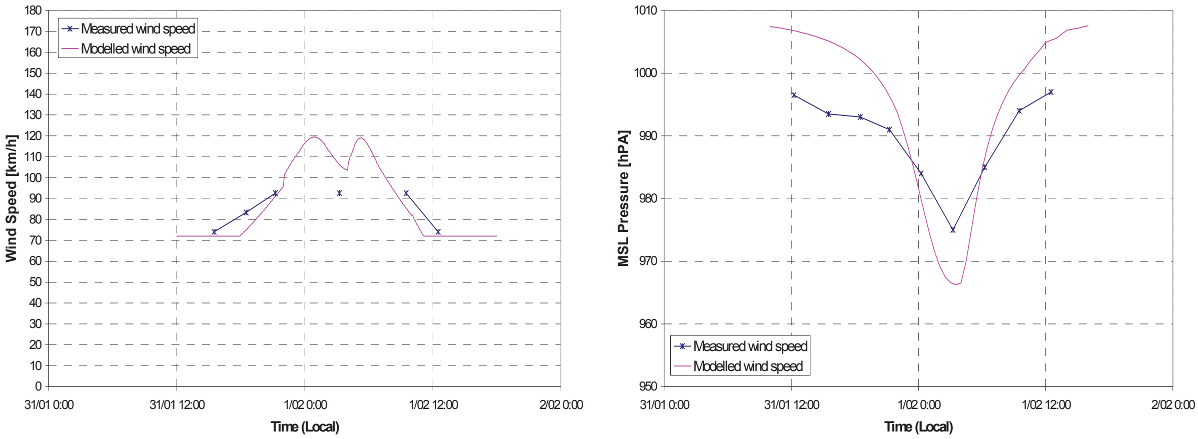


Figure 2-43 Hindcast Wind & Pressure Comparison during TC Winifred: Holmes Reef Beach – Model Simulation with Reduced Central Pressure

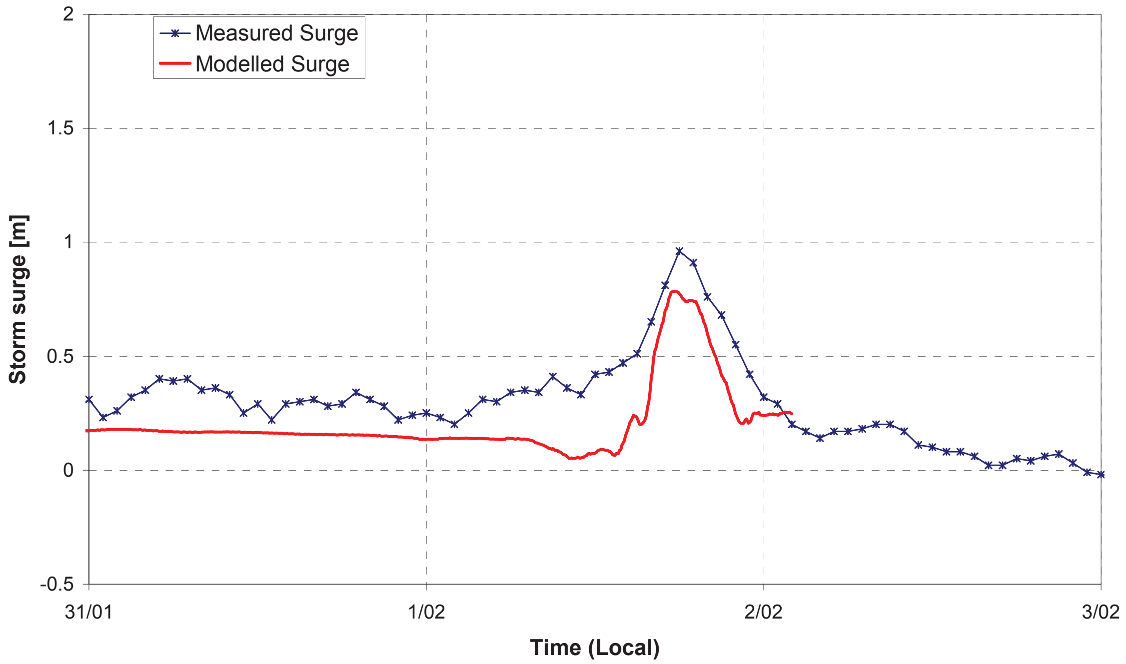


Figure 2-44 Measured vs Modelled Storm Surge: TC Winifred at Mourilyan Harbour Beach – Model Simulation with Reduced Central Pressure

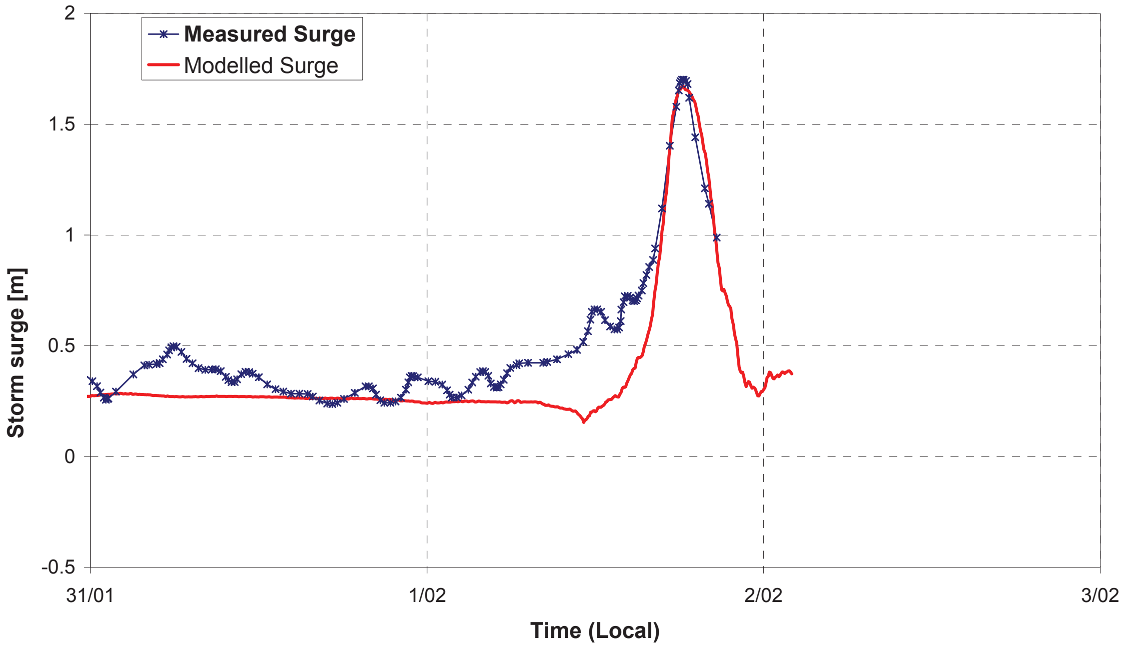


Figure 2-45 Measured vs Modelled Storm Surge: TC Winifred at Clump Point Beach – Model Simulation with Reduced Central Pressure

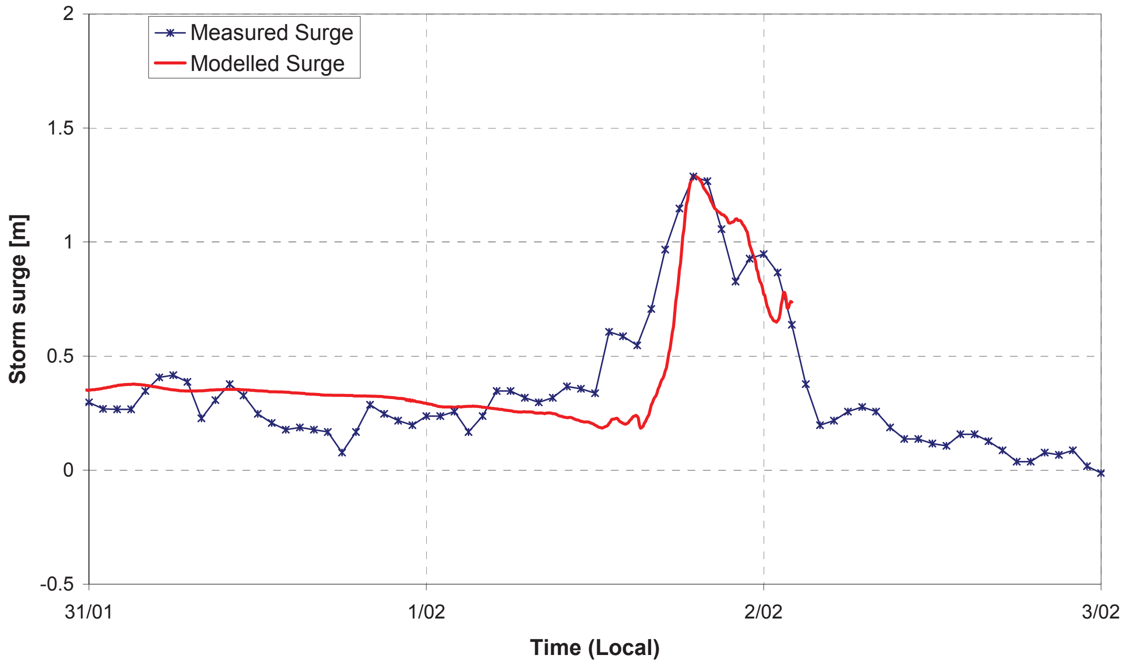


Figure 2-46 Measured vs Modelled Storm Surge: TC Winifred at Cardwell Beach – Model Simulation with Reduced Central Pressure

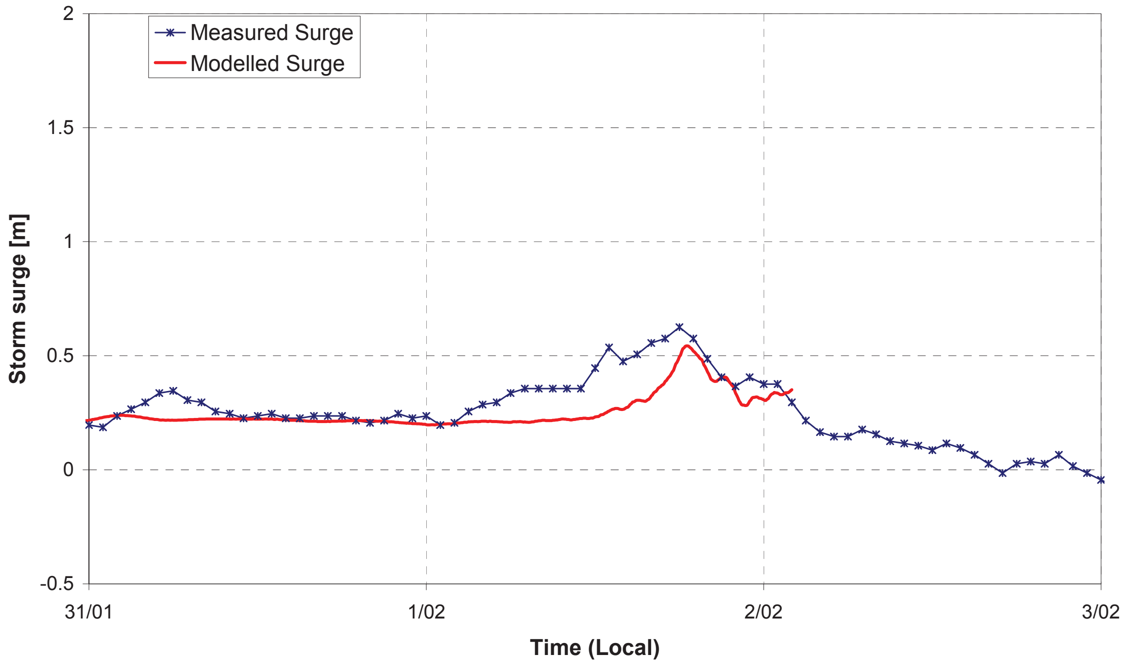


Figure 2-47 Measured vs Modelled Storm Surge: TC Winifred at Lucinda Beach – Model Simulation with Reduced Central Pressure

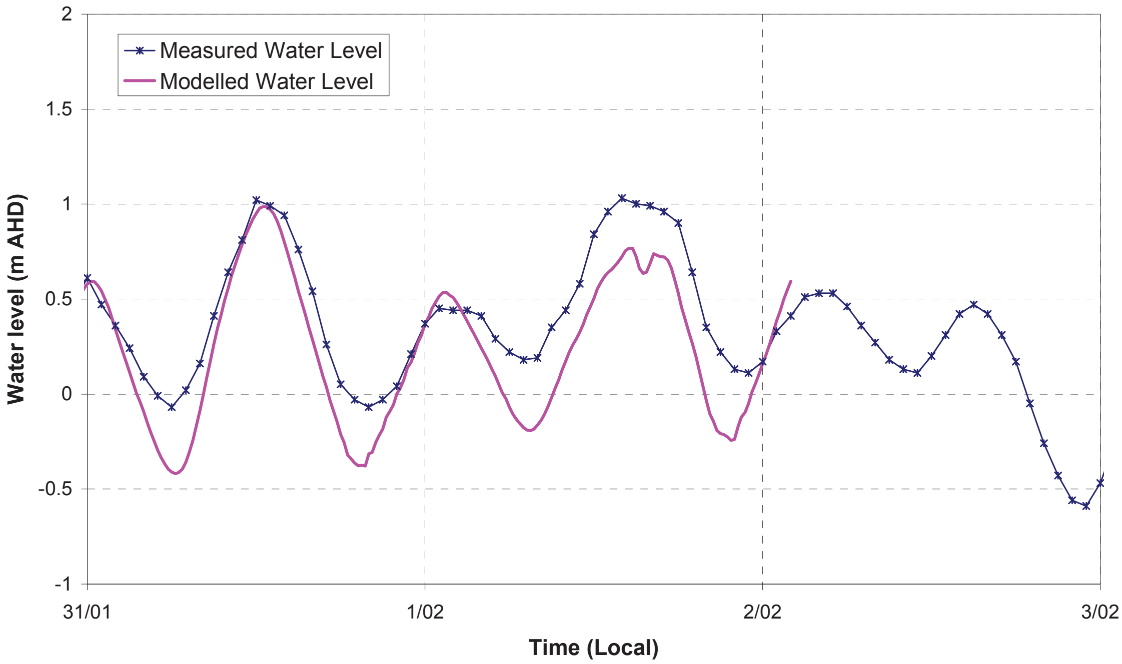


Figure 2-48 Measured vs Modelled Storm Tides: TC Winifred at Mourilyan Harbour

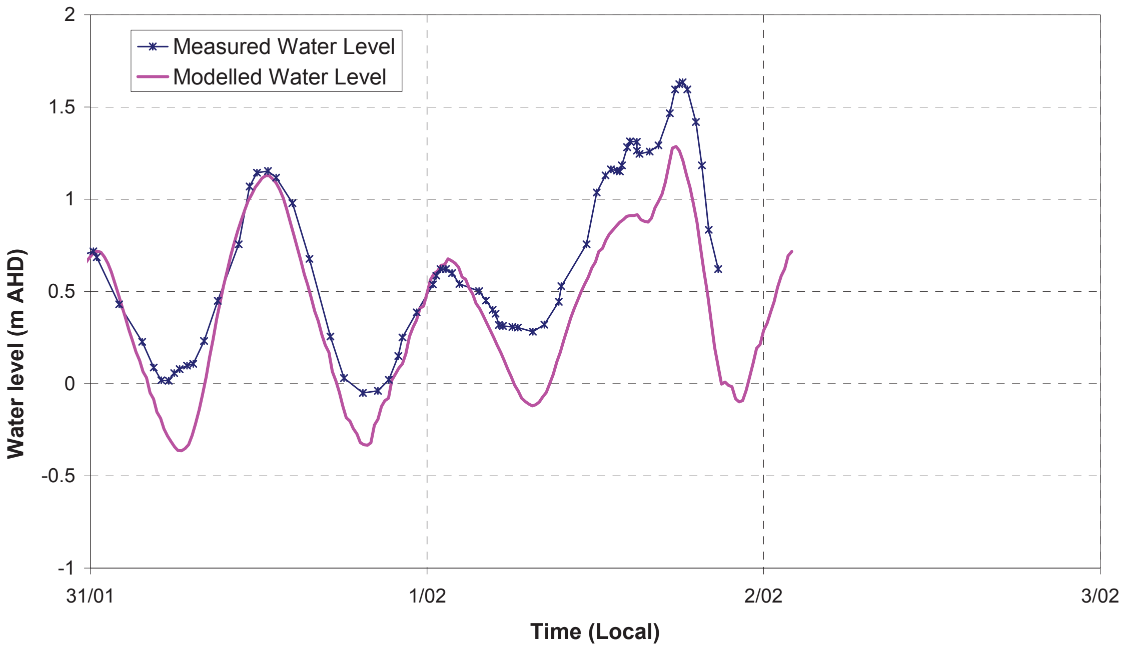


Figure 2-49 Measured vs Modelled Storm Tides: TC Winifred at Clump Point

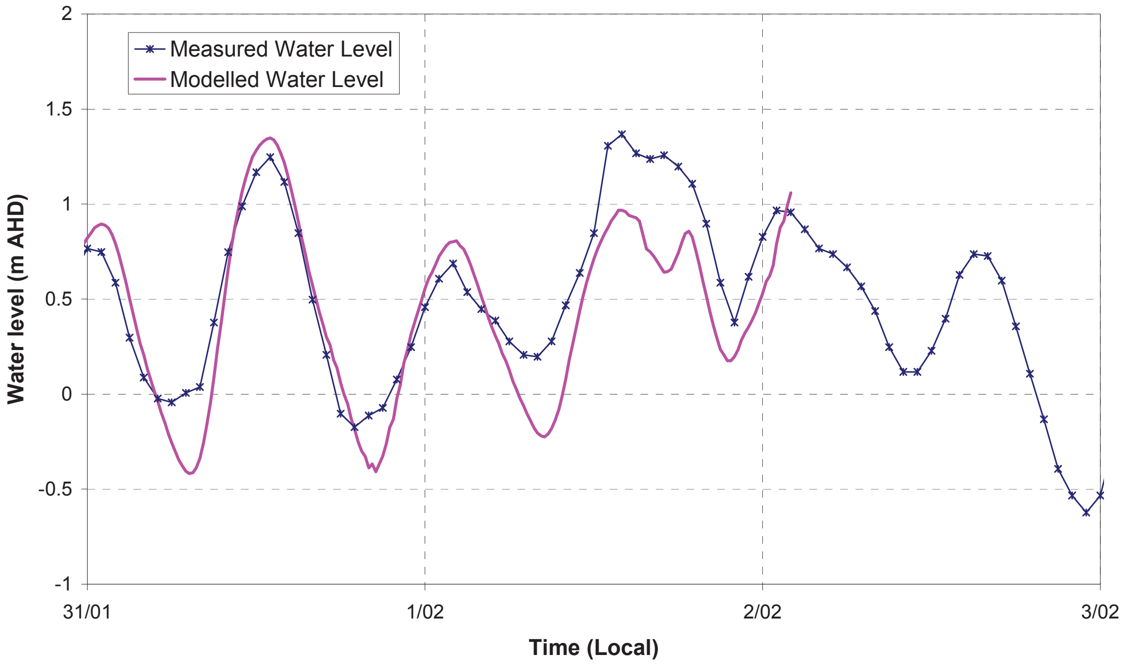


Figure 2-50 Measured vs Modelled Storm Tides: TC Winifred at Cardwell

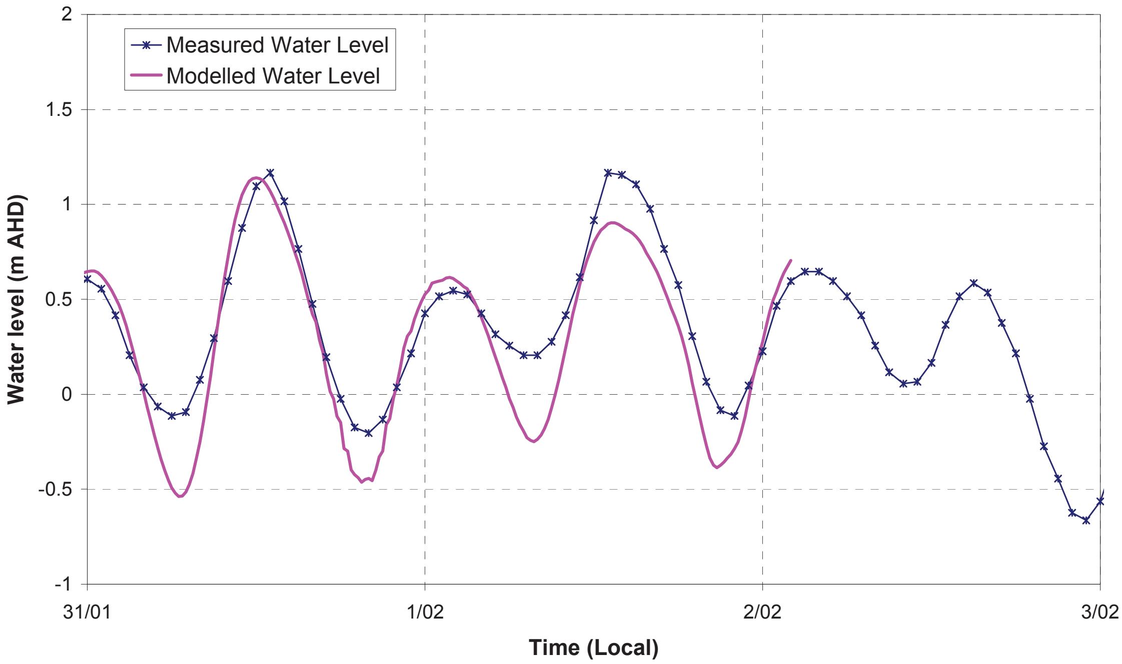


Figure 2-51 Measured vs Modelled Storm Tides: TC Winifred at Lucinda

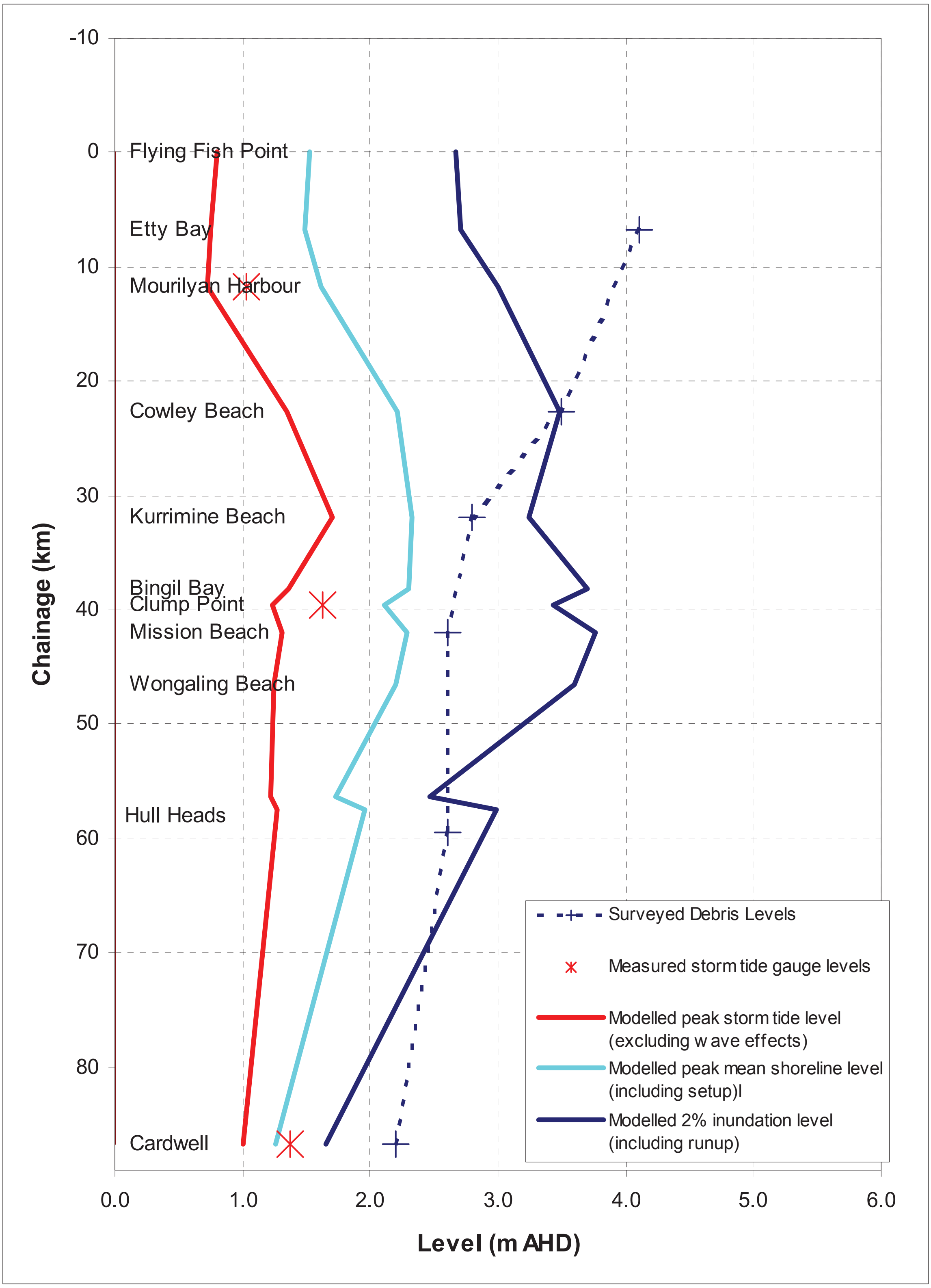
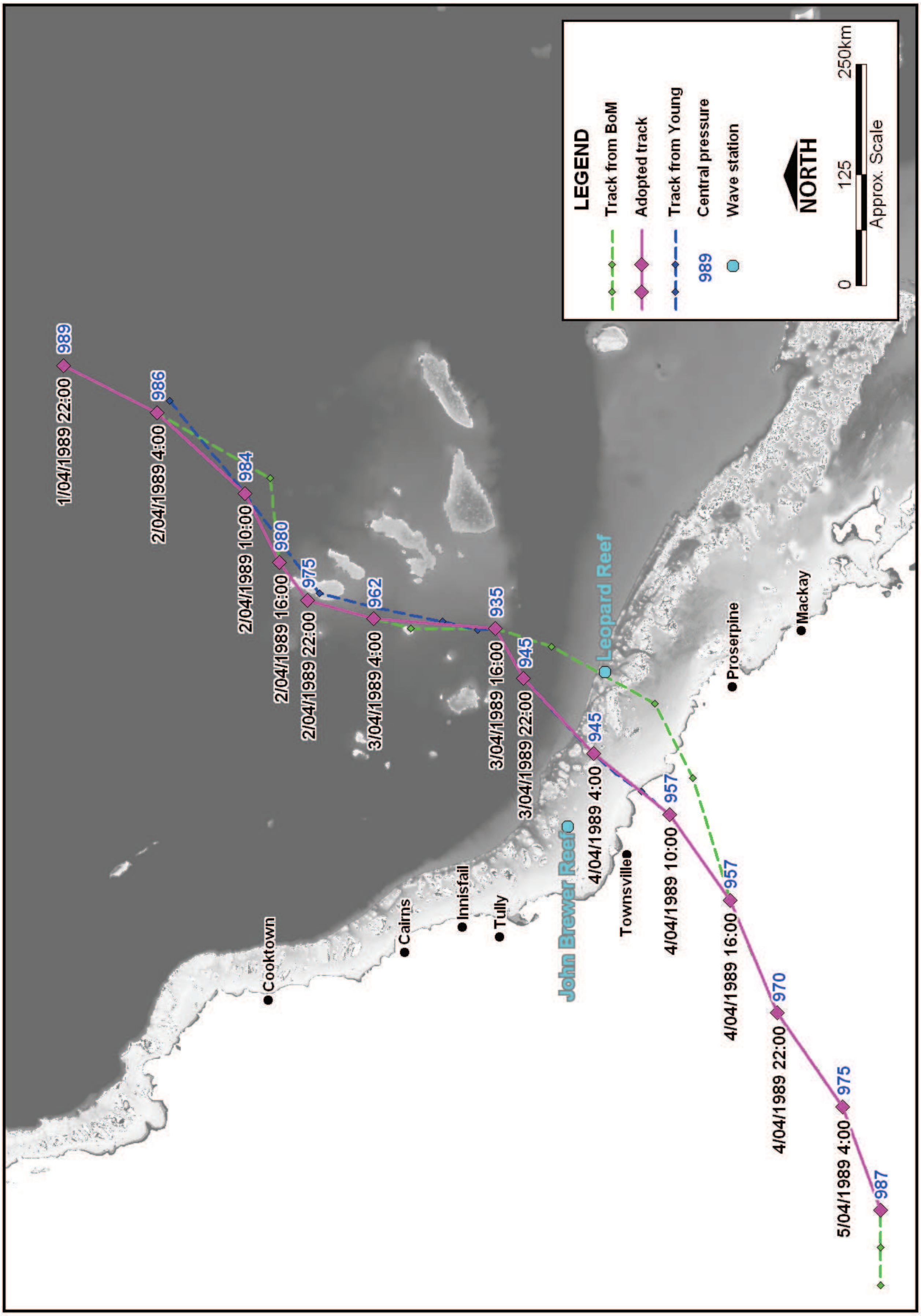


Figure 2-52 Predicted Inundation Level Comparison: TC Winifred



Adopted Track for TC Aivu

Figure 2-53

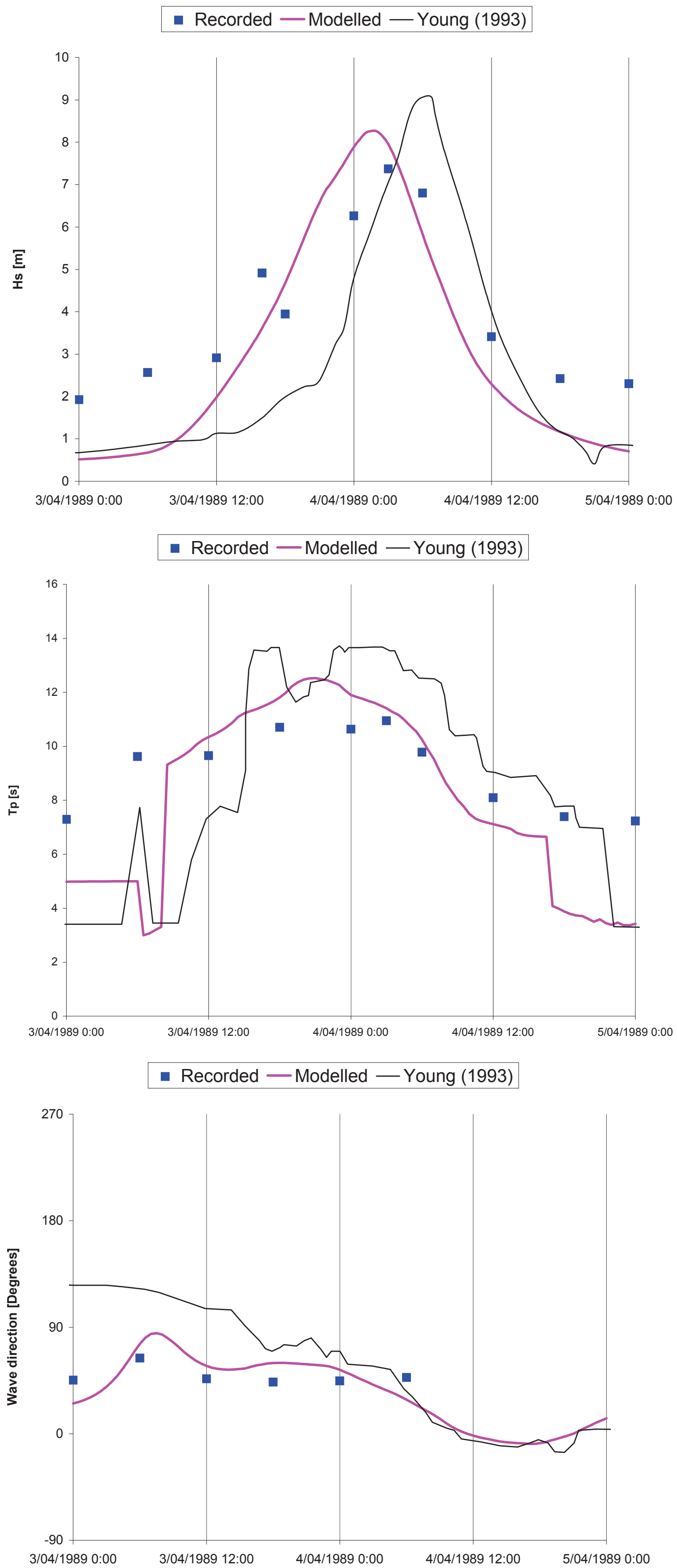


Figure 2-54 Comparison of Wave Conditions at Leopard Reef: TC Aivu

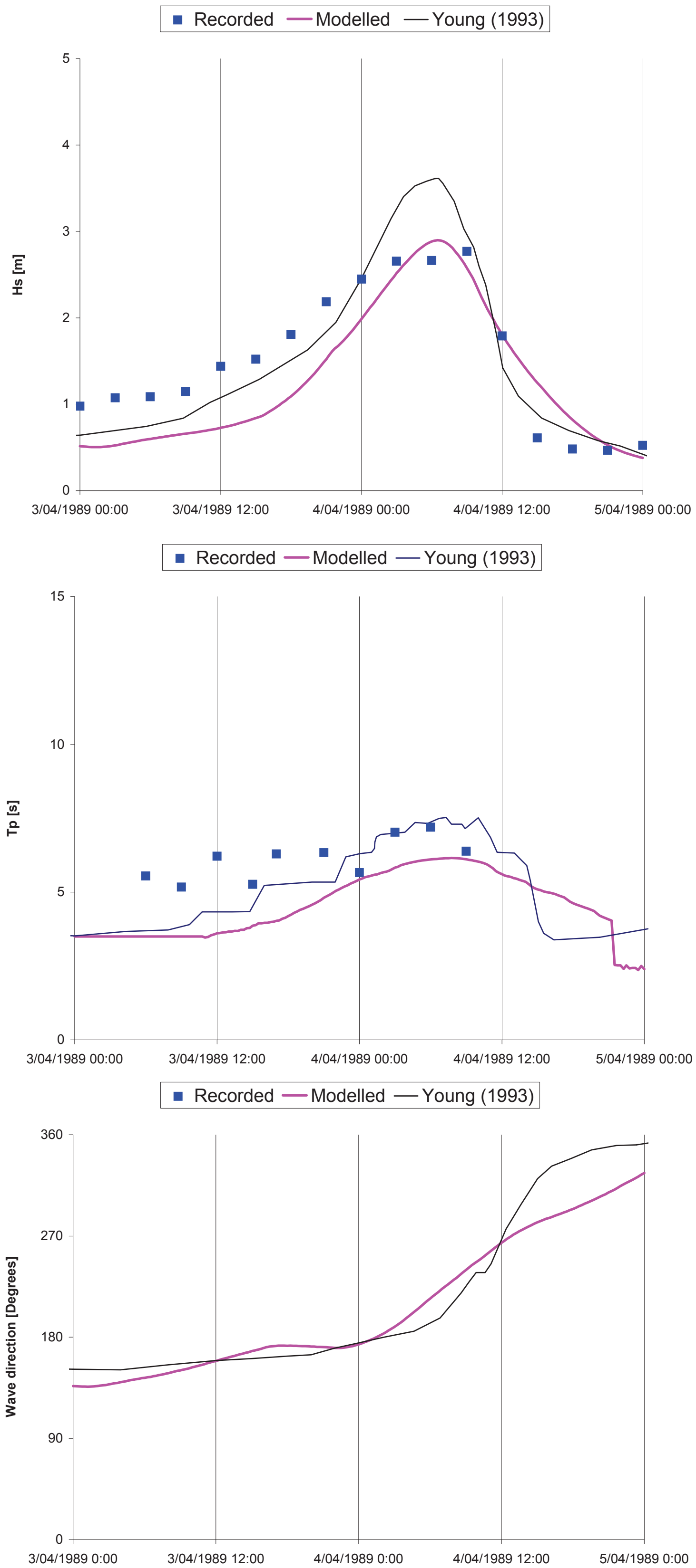


Figure 2-55 Comparison of Wave Conditions at John Brewer Reef: TC Aivu

3 FLOOD MODEL DEVELOPMENT AND CALIBRATION

3.1 Introduction

A flood model of Tully and Murray Rivers and their floodplain was developed for the purposes of defining the flood behaviour and assessing flood hazard and vulnerability of the study area. The flood modelling tasks comprise of a hydrologic model and a hydraulic model.

The hydrologic model determines the runoff resulting from a particular rainfall event. The primary output from the hydrologic model are hydrographs for varying locations along the waterways describing the quantity, rate and timing of stream flow that results from rainfall events. These hydrographs then become a key input into the hydraulic model.

The hydraulic model simulates the movement of floodwaters through waterway reaches, storage elements, and hydraulic structures. The hydraulic model calculates flood levels and flow patterns and also models the complex effects of backwater, overtopping of embankments, waterway confluences, bridge constrictions and other hydraulic structure behaviour.

In conjunction with the Bureau of Meteorology (BoM), a calibrated URBS hydrologic model of the Tully and Murray River catchments was developed. WBM then developed a hydro-dynamically linked one-dimensional/two-dimensional hydraulic model of the study area using the software TUFLOW.

The hydrologic and hydraulic models were calibrated to historical flood events to demonstrate the validity of the models. To calibrate the models, it was first necessary to obtain information such as flood heights, flooding patterns and velocities during historical flood events. The BoM provided river gauge data from the Bolinda and Euramo gauges in the Tully River and gauge data from the Upper Murray and Murray Flats on the Murray River. In addition, the CCRC provided flood level information obtained from various flood boards across the catchment and resident surveys.

This chapter describes the development of the hydrologic and hydraulic models and presents the calibration of the models to two flood events.

3.2 Data Collection

3.2.1 Site Inspection

Over the period 29-30 March 2006, six days after the moderate flood resulting from Cyclone Larry, WBM personnel undertook a site inspection of the study area that included:

- discussion with local residents;
- discussion with personnel from Council;
- independent touring of the catchment.

Information gained during this stage of the study included:

- Several flood marks identified for survey;
- The timing and duration of the 2006 event;

- Identification of flow paths;
- The importance of the interaction between the Murray and the Tully River during major flood events.

3.2.2 RAFTS Hydrological Model

Connell Wagner has previously established and calibrated a RAFTS hydrologic model of the Tully and Murray River catchments for the 1977, 1986, 1994 and 1999 events. These models were developed as part of a flood study used for the design of the Bruce Highway upgrade between Cardwell and Tully.

The RAFTS model represented the Tully River catchment using 85 sub-catchments. The Murray River was represented using 71 sub-catchments. For the 1999 calibration the RAFTS model used two pluviograph stations and eight daily rainfall stations to represent to rainfall distribution across the Tully and Murray River catchments.

3.2.3 URBS Hydrological Model

The BoM has also previously established and calibrated an URBS hydrologic model of the Tully and Murray River catchments for the 1977, 1986, 1994, 1999 and 2006 events. The BoM URBS models represented the Tully River catchment using 33 sub-catchments and the Murray River using 13 sub-catchments. The URBS model used eight pluviograph stations for the 1999 calibration and 12 pluviograph stations for the 2006 calibration.

Since the BoM URBS model was based on a more complete set of pluviograph data to represent to rainfall distribution across the catchment, it was chosen as the model to be used as part of this study. For the purpose of this study it was considered that BoM URBS models sub-catchment representation was too coarse. Furthermore, a model of the Kennedy/Meunga Creek Catchment was required.

It was agreed between WBM and BoM that WBM would upgrade the discretisation of the Tully and Murray River and Kennedy/Meunga Creek catchments in the URBS model and forward the upgraded model to the BoM for their use. In exchange, the BoM was to supply rainfall, stream gauge and gauge rating information to be used to calibrate the upgraded hydrologic model. This information is presented in Figure 3-1 to Figure 3-4 for each of the chosen calibration events (refer Section 3.5.2).

3.2.4 Flood Gauge Recording Stations

The BoM URBS model uses stream ratings at the locations given in Table 3-1. The ratings were either obtained from the Department of Natural Resources & Water and Water (NRW) HYDSYS records or developed by the BoM using flows calculated by URBS and observed flood heights from manual or instrument readings.

Table 3-1 Stream Gauge Information

River	Station Name	Station Number	Date Opened
Tully River	Bolinda	113903	10/9/1994
Tully River	Euramo	113006	1972
Murray River	Upper Murray	114001A	1970
Murray River	Murray Flats	114902	6/8/2001

It is worth noting that, based on historic events the BoM has developed a rating curve for the Euramo gauge on the Tully River. The BoM has also developed a rating curve for the Murray Flats gauge. However, due to the recent installation of the gauge (2001), the limited available dataset of flood information restricts the development of a complete and well calibrated rating curve for the Murray Flats gauge.

No rating adjustment was undertaken for this study. The BoM flood level data was used for calibration.

3.2.5 Topographic Data

Several sources of topographic data were required for hydraulic model development. These sources, along with their use during the hydraulic modelling, are detailed in Table 3-2.

The Digital Elevation Model (DEM), along with the location of ground surveys excluding the flood marks, is shown in Figure 3-5.

Table 3-2 Topographic Information

Source	Description	Model Application
Photogrammetry – Department of Natural Resources & Water (NRW)	Photogrammetry of the study area to an accuracy of +/- 0.7 metres	The NRW photogrammetry was used as the base DEM for the study.
Photogrammetry – Department of Main Roads QLD (DMR)	Photogrammetry of the Bruce Highway corridor between Tully and Kennedy to an accuracy of +/- 0.15 metres	Areas covered by the DMR photogrammetry supersede the NRW and Schlenker photogrammetry.
Photogrammetry – Schlenker Mapping	Photogrammetry of the Tully town area to an accuracy of +/- 0.15 metres	Areas covered by the Schlenker photogrammetry supersede the NRW data.
Photogrammetry – Schlenker Mapping	Photogrammetry of the Cardwell town area to an accuracy of +/- 0.15 metres	Areas covered by the Schlenker photogrammetry supersede the NRW data.
Photogrammetry – Schlenker Mapping	Photogrammetry of the Kennedy/Meunga Creek area to an accuracy of +/- 0.7 metres	Areas covered by the Schlenker photogrammetry supersede the NRW data.
Photogrammetry – Schlenker Mapping	Photogrammetry of the south Mission Beach and Hull Heads areas to an accuracy of +/- 0.15 metres	Areas covered by the Schlenker photogrammetry supersede the NRW data.
River/ Creek Cross-Sections – Cardwell Shire Flood Management Study (Ullman and Nolan Pty Ltd, 1983)	32 cross sections of the Tully River 22 cross-sections of the Murray River	Cross-Sections from the Cardwell Shire Flood Management Study were used to represent to in-bank areas of the model represented in 1D.
River/ Creek Cross-Sections – Brazzier Mottie	4 cross sections of the Tully River 5 cross-sections of the Upper Murray River 8 cross sections of the Lower Murray River 24 cross-sections of Kennedy Creek 24 cross sections of Meunga Creek 13 cross sections of Alma Creek 5 cross sections of Attie Creek	Cross-Sections from the Brazzier Mottie survey were used to represent to in-bank areas of the model represented in 1D. These cross section were taken where gaps in the Cardwell Shire Flood Management Study cross-sections were apparent.
Ground Survey – Brazzier Mottie	11 flood marks from the 2006 Event	Surveyed flood debris marks used for model verification during the calibration of the hydraulic model.
Ground Survey – CCRC	100+ flood marks from the 1999 and 2006 Event	Surveyed peak flood levels used for model verification during the calibration of the hydraulic model.

3.3 Hydrologic Model Development

As discussed in Section 3.2.3, URBS was the hydrologic model chosen to represent catchment rainfall-runoff relationships. It was chosen instead of the RAFTS model for the following reasons;

- The BoM URBS model used a more complete set of pluviograph data to represent the rainfall distribution across the catchment; and
- The further development of this model would aid future flood forecasting for the study area.

URBS is a networked runoff-routing model of sub-catchments based on centroidal inflows. Three routing options are available to describe catchment and channel storage routing behaviour. For this study, the Split Routing Model was used, which separates the channel and catchment storage components of each sub-catchment for routing purposes, each of which is represented using a non-linear reservoir. In keeping with the BoM model, catchment area and stream length were the only variables used to define routing within the model.

A Uniform Continuing Loss Model was used for this study. An initial loss of rainfall occurs before any rainfall becomes effective as runoff. A continuing loss rate (millimetres per hour) was then applied to the rainfall to derive excess rainfall to be converted to runoff.

The BoM URBS model catchment discretisation was refined such that three separate models for the Tully River, Murray River and Kennedy / Meunga Creek were created. In total 47 sub-catchments were used to represent the Tully River catchment, 30 sub-catchments the Murray River catchment and 46 sub-catchments the Kennedy / Meunga Creek catchment. Figure 3-6 shows the sub-catchment delineation for the three separate models.

Updated URBS model files were forwarded to BoM personnel, who then determined the following for each calibration event:

- Which of the recorded temporal patterns should be applied to each sub-catchment. This was based on the proximity of the pluvio-stations to the centroid of sub-catchments;
- The total depth of rainfall to be applied to each sub-catchment for the duration of the event. This is calculated using the "inverse distance squared" method and rainfall totals from nearby pluvio-stations and daily rainfall gauges;
- Available stream gauge data and associated rating curves to convert water levels to stream flows for comparison with flows calculated by the URBS model.

The BoM then returned the model to WBM with rainfall and stream gauge time-series files.

3.4 Hydraulic Model Development

The complicated nature of the floodplain flow patterns and importance of obtaining community confidence in the process required that state-of-the-art modelling techniques be adopted. Hence, TUFLOW, a fully 2D dynamic hydraulic modelling system, was used to model the floodplain within the area of interest.

3.4.1 2D Model Extent

The floodplain area within the study area, north of Cardwell, has been represented using a hydraulic model. The model has been created to represent the Tully and Murray River catchments and the Kennedy/Meunga Creek catchments.

The hydraulic model covers an area of approximately 695 km^2. The model extent covers the floodplain areas from the town of Tully in the north to the Port of Hinchinbrook in the south. The model is based on a 50m x 50m square grid, resulting in approximately 278,000 grid cells.

Each square grid element contains information on ground topography sampled from the DEM at 25 m spacing, surface resistance to flow (Manning's n value) and initial water level. Twelve areas of different land-use type based on aerial photography and site inspections were identified for setting Manning's n values. The extent of the 2D models is shown in Figure 3-7.

3.4.2 1D/2D Model Interaction

While the floodplain is aptly represented using 50m grid cells, the following major waterways have been modelled with the 1D model, ESTRY:

- Tully River;
- Murray River;
- Bulgun Creek;
- Banyan Creek;
- Kennedy Creek; and
- Meunga Creek.

The waterway widths modelled using 1D were removed from the 2D calculations for the length of the creeks to prevent 'doubling up' of creek conveyance. Surveyed cross-sections were used to determine 1D model node and channel characteristics.

The 1D and 2D components of the hydraulic model were dynamically linked, allowing water to flow out of the 1D model into the 2D floodplain once the water level reached bank height, and vice versa.

3.4.3 Inflow Boundaries

The following inflow boundaries were obtained from the URBS hydrological model:

- Tully River approximately 7km downstream of the Bolinda estate and the Bolinda stream gauge station;
- Murray River approximately 4km upstream from the community known as Murray Upper;
- Hull River at the Mission Beach Road crossing
- Bulgun Creek at the railway bridge
- Banyan Creek at Jacobs Knob
- Jarra Creek at the Jarra Creek Road crossing on the confluence with the Marquette Creek

- Flows from peripheral sub-catchments draining into the floodplain;
- Rainfall on the area covered by the TUFLOW model.

The locations of these boundaries are shown in Figure 3-8.

3.4.4 Structures

Within the 2D model area, bridge structures were represented in one of two ways. The first uses width and height restrictions on 2D elements to represent flow constriction caused by the bridges. The specification of additional losses for the bridge piers and vena-contracta losses were included in this method (if appropriate).

The second method is as a dynamically nested 1D bridge channel based on a cross-section through under the bridge deck. Bridge decks were modelled as dynamically nested 1D broad-crested weirs to allow flow over the bridge. Small culverts were modelled as dynamically nested 1D culvert structures and larger culverts were modelled using 2D elements similar to bridges.

Within the 1D model area, bridge structures were modelled using cross-sections to represent the open waterway area underneath the bridge deck and weirs to represent flow over the bridge deck.

3.5 Flood Model Calibration

3.5.1 Calibration Procedure

The general steps of the calibration and verification process were:

- Review available historical data to establish appropriate calibration events;
- Process data for the selected events and set up boundary conditions for the hydrologic model;
- Carry out initial calibration and verification of the URBS model for selected events using parameters set at best estimate based on experience and advise received from Terry Malone of BoM;
- Carry out initial calibration and verification of the TUFLOW model with parameters set at best estimate based on experience;
- Continue calibration and verification of both hydrologic and hydraulic models using an iterative process which seeks to find the optimum combination of hydrologic and hydraulic parameters;
- Present preliminary calibration to study advisory group for review and feedback on flood extent and flooding patterns;
- Finalise calibration based on feedback.

3.5.2 Selection of Calibration/Verification Events

For this project, the hydrologic and hydraulic models were calibrated/verified to two historical flood events. Selection criteria for calibration events are as follows.

5 The amount of good quality historical data (rainfall and flood height records) available.

Data availability for a number of floods that were experienced in study area is shown in Table 3-3.

Table 3-3 Calibration Data Availability

Event	Pluviograph Stations	Stream Gauges (URBS Calib)	Floodplain Gauges (TUFLOW Calib)	Peak Flood Levels - Debris Marks	Peak Flood Levels - Resident Survey	Peak Flood Levels - NRW
1977	2	2	2	40	13	1
1986	2	2	2	21	15	58
1994	4	3	3	5	4	41
1999	8	3	3	94	213	2
2006	12	4	4	10	1	0

It can be seen from Table 3-3 that there is limited rainfall data available for the 1977, 1986 and 1994 floods. The 1999 event has good rainfall, stream gauge and flood height data. Similarly the 2006 event has good rainfall and stream gauge data available.

6 The quality of boundary condition data such as the hydrologic model calibration.

The upstream boundary condition for the hydraulic model is largely dependent on the accuracy of the hydrologic model. Factors that ensure good hydrologic calibration (eg data records) are therefore important for hydraulic model boundary conditions also.

The downstream boundary condition must be an accurate record of flood heights during a possible calibration event. The downstream boundary conditions were obtained from the Coral Sea modelling component of the study.

7 The variability of events.

Preferably the calibration events cover a range of flood conditions to ensure accuracy of the model over a range of flood magnitudes.

8 Changes to the floodplain since a possible calibration event.

Recent floods will typically provide a better calibration because the topographic data used in the model is also recent. Modifications can be made to the model representation of the floodplain for older events, but the reliability of the data, and therefore the model, decreases.

9 Public perception and memory of floods.

Public perception of floods can be an important factor in the selection of an event. For example, residents typically remember the 1999 as being the major flood in the Cardwell both due to its recency and size, demonstrating a significant flood such as this on the model can be important in obtaining public confidence in the model.

Taking these factors into consideration, it was decided that the 2006 and the 1999 events would be used as the calibration events for this study. For both events sufficient topographic, pluviograph and stream gauge information was available for calibration of the hydrologic and hydraulic model.

The 2006 event was a moderate size event. During moderate size events in-bank flows generally accommodate for a significant portion of the flood flows. Calibration of the hydraulic model to a moderate size flood is a good check that the conveyance of the in-bank areas is replication accurately in the model. The recency and the additional stream gauge information for the Murray Flats warranted the use of the 2006 event as a calibration event. The calibration of the 2006 event using the gauge information for from the Euramo and Murray Flats gauge stations concurrently was extremely important to ensure the interaction between the Tully and Murray Rivers upstream of the Bruce Highway was being modelled accurately.

As mentioned previously, the 1999 event was a major event. During major events, in contrast to minor/moderate events, floodplain flows/storage can accommodate for significant portions of the flood flows. Calibration of a large event such as the 1999 event is important to verify that the floodplain areas of the model are accurately represented in the model. The recency, size and the number of peak flood heights associated with it, warranted its inclusion of the 1999 flood event in the model calibration.

3.6 Hydrologic Model Calibration

Hydrologic model calibration focussed primarily on the flow hydrograph at Euramo and, post 2001, the Murray Flats gauge stations.

3.6.1 March 2006 Flood Event

The March 2006 event was a multi-peak event. Good calibration for all peaks is sometimes difficult for multi-peaked events, as is adequate representation of the recession between peaks.

Figure 3-9 and Figure 3-10 show a comparison of the recorded and predicted flow hydrographs at Bolinda and the Upper Murray stream gauges in the upper catchment and the Euramo and the Murray Flats stream gauges in the lower catchment.

Figure 3-9 shows good correlation of timing for the two peaks of the event for the Bolinda stream gauge. The predicted peak flow for the first and highest peak is lower than recorded. The second peak shows a good match between recorded and predicted peak flows. Similarly shown in Figure 3-9 shows good correlation of timing of the event for the Euramo stream gauge. The Euramo Gauge results show the first peak of the event is underestimated. However, the second and more significant peak shows a good match.

Figure 3-10 shows good correlation of timing and magnitude for the second main peak of the event for the Upper Murray stream gauge. The predicted peak flow for the first peak is earlier than record than recorded, though is of comparable magnitude. Similarly shown in Figure 3-10 shows reasonable correlation of timing of the event for the Murray Flats stream gauge. The Murray Flats Gauge results shows an over estimation of the peak flows for the rising and falling limb of the 2006 event. This is accounted to the complex interactions between the Tully and the Murray River not being represented in the hydrologic model. These complex flows will be represented in the hydraulic model.

Based on these results, the models representing the 2006 event have bee found to successfully simulate the major flood peaks, shape, timing and recession between peaks.