Tropical Cyclone Storm Surge Risk for the Greater Darwin Region
Volume 1 - Executive Summary

Final Report

Report No. 24113-1

Prepared by

VIPAC Engineers & Scientists Ltd, Sydney
SPECIAL SERVICES UNIT - Bureau of Meteorology, Melbourne
GLOBAL ENVIRONMENTAL MODELLING SERVICES Pty Ltd, Melbourne
ACER VAUGHAN Pty Ltd, Darwin

August 1994
FOREWORD & ACKNOWLEDGEMENTS

This Report summarises the results of an evaluation of the tropical cyclone storm surge risk for the Greater Darwin Region.

The analysis of cyclone storm surge risk includes the effects of wave set-up and astronomical tide and covers Darwin Harbour and the nearby coastline stretching between Point Blaze to the southwest and Point Stephens to the northeast.

The study was commissioned and funded by the Northern Territory's Department of Lands, Housing and Local Government, and supervised by the Northern Territory's Department of Transport and Works. Much valuable information relating to previous studies of Darwin area cyclones and their effects was provided by both Departments. The assistance, guidance and enthusiasm of Mr Hermann Mouthaan (Lands, Housing & Local Government) and Mr Phill Piper (Transport & Works) are gratefully acknowledged.

The study was carried out by Vipac Engineers & Scientists Ltd (Sydney), the Special Services Unit (SSU) of the Bureau of Meteorology (Melbourne) and Global Environmental Modelling Services Pty Ltd (Melbourne). The study was coordinated by Acer Vaughan Pty Ltd (Darwin), who were responsible for gathering and documenting information and providing local support for the study team. The guidance and patience of Acer's Mr Paul Grigg and the efforts of Mr Stephen Pendle have been an outstanding feature of the team's effort in this study.

Others who provided valuable reference material and input to the study include Mr Jim Arthur, Regional Director, Bureau of Meteorology, Darwin Office; Mr Frank Woodcock of the Bureau's Severe Weather Warning Program, Melbourne Office; and Mssrs. Steve Oliver and Stuart Smith of the Bureau's Special Services Unit, Melbourne.

- The estimation of cyclone storm surge, that is, the sea level change brought about by surface wind stress and surface pressure, is made using a deterministic regional ocean model, using nested fine grid zones within the overall large scale grid covering the area.

- The estimation of cyclone wave set-up, the secondary effect of water being piled up on the shore as a result of wave action, is made by running a third generation wave model in open waters combined with analytical-empirical techniques in shallow water areas.

- The effect of tidal variation is determined by running a tidal model over the full tidal cycle to establish the probability distribution of tidal height versus return period.

- Finally, the cyclone surge plus cyclone wave set-up plus tidal probability distributions are combined (statistically) to create a total still water elevation probability distribution, termed the cyclone storm tide.
The results obtained in the present study are summarised below. Differences between the present results and those of previous investigations are briefly discussed later in this Executive Summary and, in greater detail, in Volume 2 (Main Report) of this study. The study locations points are shown in Figure I (p.9).

<table>
<thead>
<tr>
<th>Location</th>
<th>Return Period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>1. Point Blaze</td>
<td>3.9</td>
</tr>
<tr>
<td>2. Fog Bay</td>
<td>3.9</td>
</tr>
<tr>
<td>3. Native Point</td>
<td>4.0</td>
</tr>
<tr>
<td>4. Bynoe Harbour</td>
<td>4.0</td>
</tr>
<tr>
<td>5. Masson Point</td>
<td>4.2</td>
</tr>
<tr>
<td>6. Charles Point</td>
<td>3.7</td>
</tr>
<tr>
<td>7. West Point</td>
<td>4.0</td>
</tr>
<tr>
<td>8. West Arm</td>
<td>3.9</td>
</tr>
<tr>
<td>9. Channel Island</td>
<td>3.8</td>
</tr>
<tr>
<td>10. Wickham Point</td>
<td>3.8</td>
</tr>
<tr>
<td>11. East Arm PORT</td>
<td>3.7</td>
</tr>
<tr>
<td>12. Darwin South SEAWALL</td>
<td>3.8</td>
</tr>
<tr>
<td>13. Fannie Bay</td>
<td>4.0</td>
</tr>
<tr>
<td>14. Casuarina Beach</td>
<td>4.0</td>
</tr>
<tr>
<td>15. Lee Point</td>
<td>3.6</td>
</tr>
<tr>
<td>16. Shoal Bay</td>
<td>3.9</td>
</tr>
<tr>
<td>17. Gunn Point</td>
<td>3.7</td>
</tr>
<tr>
<td>18. Point Stephens</td>
<td>3.6</td>
</tr>
</tbody>
</table>

---

Dr. Peter N. Georgiou  
VIPAC

Dr. Graeme D. Hubbert  
GEMS (formerly SSU)

N.T. Dept. of Lands, Housing & Local Government
CONTENTS

Foreword & Acknowledgements

Contents

Glossary of Terms and Symbols

1 Introduction

2 Methodology

3 Model Descriptions

4 Model Verification

5 Cyclone Climatology

6 Storm Surge Modelling

7 Darwin Area Tides

8 Darwin Storm Tide Estimates

9 Comparison with Previous Studies
**GLOSSARY OF TERMS AND SYMBOLS**

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astronomical Tide, $T$</td>
<td>the variation in sea level arising from the combined gravitational effect of the moon and sun. The Full Tidal Cycle is any period during which the full range of tidal elevations is experienced.</td>
</tr>
<tr>
<td>Australian Height Datum (A.H.D.)</td>
<td>0.0 m A.H.D. is equivalent to 0.14 m Mean Sea Level</td>
</tr>
<tr>
<td>Tropical Cyclone</td>
<td>a rotating tropical low pressure system with maximum winds greater than gale force strength</td>
</tr>
<tr>
<td>Central Pressure, $P_c$</td>
<td>minimum pressure value at the centre of a cyclone</td>
</tr>
<tr>
<td>Central Pressure Difference, $\Delta p$</td>
<td>difference between the central pressure in a cyclone and the peripheral value (nominally taken as 1010 hPa)</td>
</tr>
<tr>
<td>Radius of Maximum Winds, $R_{\text{MAX}}$</td>
<td>distance from the cyclone centre to the area of maximum winds, lying just outside the cyclone eyewall</td>
</tr>
<tr>
<td>Translation Velocity, $V_T$</td>
<td>forward speed of a cyclone over the earth's surface</td>
</tr>
<tr>
<td>Minimum Approach Distance, $D_{\text{MIN}}$</td>
<td>minimum perpendicular distance from a site of interest to the cyclone track</td>
</tr>
<tr>
<td>Approach Angle, $\theta$</td>
<td>direction from which a cyclone is travelling, i.e. a north approach angle cyclone moves towards the south</td>
</tr>
<tr>
<td>Surge, $S$</td>
<td>elevation of sea caused by the effects of surface wind stress and surface pressure</td>
</tr>
<tr>
<td>$H_s$</td>
<td>significant wave height, offshore</td>
</tr>
<tr>
<td>$\zeta_{\text{MAX}}$</td>
<td>wave set-up height along the coastline, related to the significant wave height</td>
</tr>
<tr>
<td>Combined Storm Tide Level, $H_c$</td>
<td>elevation of sea (A.H.D.) caused by the combined effect of the cyclone surge plus cyclone wave set-up plus tidal contribution</td>
</tr>
<tr>
<td>Probability Density</td>
<td>probability of occurrence of a particular event</td>
</tr>
<tr>
<td>Return Period</td>
<td>length of time during which an event might be expected to occur on average once every period</td>
</tr>
</tbody>
</table>
INTRODUCTION

In the southern hemisphere, tropical cyclones are clockwise rotating low pressure systems which originate in the tropics and in which the 10-minute mean or average winds exceed 63 km/hr or 34 knots (17 m/sec). The tropical cyclone season in Australia occurs typically from November to April.

- Storm surge is the elevation in sea level which accompanies the movement of a cyclone particularly near, or over, a coastline, attributed to a cyclone's intensity and wind stress build-up. The height of the storm surge is dependent upon, amongst other factors, the local bathymetry, the intensity of the cyclone and its speed and direction of movement.

The intensity of a cyclone is primarily a function of the lowest barometric pressure in the centre of the storm, or central pressure, \( P_C \). Lower pressures will result in stronger winds. Units of \( P_C \) are either hPa (hectoPascals) or mbar (millibars).

- A further contribution to the resulting elevation of the sea at the coast is the effect of wave action. In particular, breaking waves cause an elevation of the sea level through a process known as wave set-up, \( \zeta_{\text{MAX}} \).

- The level of the sea during the passage of a tropical cyclone also depends on the tidal cycle. Hence, the peak sea surface elevation associated with a particular cyclone will depend, not only on its intensity, location etc., but also on the tide at the time it passes.

The combined effect of cyclone surge plus cyclone wave set-up plus tide represents the so-called combined storm tide elevation, \( H_C \).

It is this peak combined water level, and its components, which have been evaluated in this investigation. Throughout this Report, both the cyclone surge, cyclone wave set-up and tide levels are reported with respect to the Australian Height Datum (A.H.D.).
2 METHODOLOGY

Overview

The present study was broken up into the following phases:

• Phase 1  ➤ Set up the five bathymetric grids spanning the study area to run the numerical simulation model generating cyclone surge plus cyclone wave set-up estimates.

➤ Verify the simulation model against historical observations recorded during major Australian tropical cyclone events, in particular Cyclone Tracy (December, 1974).

➤ Analyse Darwin area historical cyclone data records to obtain a statistical representation of the storm parameters of interest.

• Phase 2  ➤ Define a set of 300 "model" cyclones from the range of meteorological parameters (central pressure, translation speed, direction of motion etc.) representative of the historical cyclones which have affected the Darwin area.

➤ Run the cyclone surge and wave simulation models for the 300 representative "model" cyclones on each of the five study grids (a total of 1500 separate cyclone simulation runs).

➤ Generate empirical relationships defining surge and wave set-up heights, at localities of interest around the Darwin area, as functions of any particular combination of cyclone storm climatological parameters.

• Phase 3  ➤ Determine the probability distribution of cyclone storm surge plus cyclone wave set-up from the results of the numerical simulation runs.

➤ Determine the probability distribution governing astronomical tide fluctuations in the Darwin area.

➤ Use the joint probability method to integrate the total probability of peak sea level elevation combining effect of cyclone surge plus cyclone wave set-up plus tidal contribution, i.e. the so-called "storm tide" risk.
Study Area

Storm tide estimates for the range of tropical cyclones affecting the Greater Darwin region have been determined for the locations shown in Figure I. The study area stretches between Point Blaze to the southwest and Point Stephens to the northeast.

The extent of the study area required five separate grid model domains to be established covering the coastline and Darwin Harbour.

Four "coarse grids" (CG1-CG4) with a resolution of 3 km were set up along the coast to establish the cyclone surge plus wave set-up at the specified locations on the open coastline from Point Blaze to Point Stephens. A fifth "fine grid" (FG) was set up with a resolution of about 300 m in Darwin Harbour and was nested inside CG3. Figures showing the bathymetry of these grids can be found in the Main Report.

- CG1 was used to evaluate Point Blaze, Fog Bay and Native Point.
- CG2 was used to evaluate Bynoe Harbour, Masson Point and Charles Point.
- CG3 covered an area of approximately 200 km of coastline with Darwin in the centre and extending to the north past Bathurst and Melville Islands. Nested within this grid was FG which covered the Harbour and the nearby open ocean outside the Harbour entrance. This nesting was carried out in order to provide an open ocean surge on the coarse grid which could then propagate up the Harbour on the fine grid.
- CG3 plus FG were used to evaluate West Point, West Arm, Channel Island, Wickham Point, East Arm Port, Darwin South Seawall and Fannie Bay.
- CG4 was used to evaluate Casuarina Beach, Lee Point, Shoal Bay, Gunn Point and Point Stephens.

Bathymetry for the open ocean grids was obtained from Admiralty Charts. Bathymetry for the fine resolution Darwin Harbour grid was initially obtained from Patterson Britton & Partners, who were at the time carrying out a detailed modelling study of the circulation in Darwin Harbour. At a later stage in the present study, these data were supplemented with an improved data set generated from the relevant Admiralty Chart and local sounding data provided by the Department of Transport and Works and Acer Vaughan.
STUDY LOCATIONS

1 Point Blazé
2 Fog Bay
3 Native Point
4 Bynoe Harbour
5 Masson Point
6 Charles Point
7 West Point
8 West Arm
9 Channel Island
10 Wickham Point
11 East Arm
12 Seawall
13 Fannie Bay
14 Casuarina Beach
15 Lee Point
16 Shoal Bay
17 Gunn Point
18 Point Stephens

Figure 1 Location Map Showing the Sites Where Peak Tropical Cyclone Storm Tides Have Been Evaluated
3 MODEL DESCRIPTIONS

Cyclone Storm Surge Component

The storm surge model used in this study is an updated version of the Hubbert et al. [1990,1991] storm surge hydrodynamic model. This model is used operationally on the Bureau of Meteorology's tropical cyclone workstations. The model is a depth-integrated ocean-current model developed specifically to simulate currents and sea surface elevations on the Australian continental shelf.

Surface wind speeds and pressures which provide the driving mechanism for generating sea surface elevation changes are derived by means of an analytical-empirical tropical cyclone model based on Holland's [1980] cyclone windfield model.

The major features of the simulation model are:

- the shallow water equations are solved on an Arakawa C-grid
- non-linear advection terms are included
- an efficient time-splitting finite difference scheme is used, which yields accurate and stable results and a faster solution than standard explicit techniques (three different time steps are used to solve the gravity wave, advective and the physics components of the equations)
- the model is driven by wind stresses, atmospheric pressure gradients, tides and quadratic bottom friction
- the resolution and the map projection are variable
- a radiation condition which solves for the group velocity is used to compute open boundary values
- a high resolution global bathymetry file is used
- the model can incorporate local very high resolution bathymetric data if available
- the model can be nested inside itself
- output consists of sea surface elevations, depth-integrated ocean currents and individual station time series at any number of locations

The storm surge model, together with the embedded cyclone windfield model, currently form the basis of the Bureau of Meteorology's operational cyclone storm surge forecasting system.

The models are described in detail in the Main Report and in the technical papers which have been included as Appendices to the Main Report.
Cyclone Wave Set-up Modelling

Theoretical studies and field measurements indicate that the maximum wave set-up, designated $\zeta_{\text{MAX}}$, during a cyclone passage occurs at the shoreline. Furthermore, numerous field studies, discussed in the Main Report, indicate that cyclone wave set-up at the coast is related to the so-called "significant wave height" generated in a tropical cyclone.

There is thus a close relationship between $\zeta_{\text{MAX}}$ and $H_{\text{S,w}}$, the significant wave height in deep water (open ocean). Field studies have yielded data which fit the relationship:

$$0.14 < \frac{\zeta_{\text{MAX}}}{H_{\text{S,w}}} < 0.17$$

and for the present study, $\zeta_{\text{MAX}}/H_{\text{S,w}} = 0.15$ was chosen as being a representative value.

Thus, the prediction of wave set-up accompanying a tropical cyclone requires the prediction of the wave field generated by a moving cyclone system and in particular the significant wave height near coastal locations of interest.

In the present study, the significant wave height is estimated using the so-called "WAM" model, a third generation ocean wave prediction model [Hasselmann et al., 1988]. This model is run on the coarse ocean grid to determine offshore significant wave heights for individual cyclone events. The wave model has been adapted to the PC environment where it is driven by the Holland analytical tropical cyclone windfield model.

The WAM model has been verified for water depths greater than about 20 metres and is now providing operational forecasts on a one degree grid for the Australian region driven by winds from the Bureau's operational numerical weather prediction model. For shallow depth areas, and specifically for the Darwin Harbour study locations, empirical relationships were used to convert significant wave height predictions at the Harbour entrance to wave set-up estimates at inner Harbour points, taking into wind stresses and the rate of change of wind approach angle for particular storm paths.

The WAM Model requires much larger computer running time than the storm surge predictions model and, in the present study, this precluded making as many simulation model runs to predict waves as for the surge component of the study. Therefore, separate model simulation runs were made with varying cyclone intensities, directions and tracks to define the range of resultant significant wave heights and resulting cyclone wave set-up in the coastal areas of interest.
4 MODEL VERIFICATION

Published Studies

Verification of model hindcasts of sea-surface elevations generated by several recent tropical cyclone are reproduced in Table II shown below.

<table>
<thead>
<tr>
<th>Cyclone</th>
<th>Location</th>
<th>Observed</th>
<th>Predicted</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winifred</td>
<td>Clump Point</td>
<td>1.6</td>
<td>1.5</td>
<td>-0.1</td>
</tr>
<tr>
<td>Aivu</td>
<td>Upstart Bay</td>
<td>2.8&quot;</td>
<td>2.6</td>
<td>-0.2</td>
</tr>
<tr>
<td>Jason</td>
<td>Karumba</td>
<td>2.0</td>
<td>2.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Burketown</td>
<td>3.5&quot;</td>
<td>3.3</td>
<td>-0.2</td>
</tr>
<tr>
<td>Hazel</td>
<td>Carnarvon</td>
<td>1.3</td>
<td>1.3</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Geraldton</td>
<td>0.7</td>
<td>0.6</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

* - estimated observations from beach surveys

Cyclone Orson

Results of the model simulation of Cyclone Orson (23.4.1989) have been published by Hubbert (1991) (see Main Report, App.F). As Cyclone Orson passed Woodside's North Rankin gas platform, the central pressure was measured as 905 hPa (the lowest ever recorded in the Australian region).

- The model surge reached a maximum of 3.0 metres at the nearest grid point to King Bay; the measured peak surge was 3.1 metres above astronomical tide.

- The peak significant wave height produced by the simulation model at North Rankin was 10.2 metres; the measured peak height was approximately 10 metres.
Cyclone Tracy

Cyclone Tracy is one of the best remembered tropical cyclones in Australia due to the devastating results of its passage over Darwin on Christmas Day, 1974. Tracy was an extremely small cyclone with a radius of maximum winds near landfall of only 6 km, whilst its minimum central pressure was recorded as 955 hPa. The tide gauge at Stokes Hill Wharf in Darwin Harbour recorded a peak storm surge of 1.6 metres whilst a visual appraisal of debris suggested that the storm surge along Casuarina Beach was in the range 3 to 4 metres.

The ability to accurately simulate the Darwin Harbour response to Cyclone Tracy was critical from the point of view of verifying both:

- the reliability of the cyclone windfield and storm surge plus wave set-up models in the general domain area, and
- the accuracy of the nested grid storm surge modelling system set up for grids CG3 and FG.

The tropical cyclone model was run using values of central pressure, translation speed, \( R_{\text{MAX}} \), approach direction etc. documented in the Bureau of Meteorology's Report on Cyclone Tracy [A.G.P.S., 1977]. Using this windfield as the initial input, the storm surge model was run firstly on the Darwin coarse grid, CG3, to generate surges along the open coastline, and then secondly, on the nested fine grid of Darwin Harbour, FG, to propagate the open ocean surge into, and model the response of, the Harbour itself.

Achieving a successful simulation of the ocean response to Cyclone Tracy proved to be a major challenge. Initially, the coarse grid results agreed with the observation of a possible 3 metre surge along Casuarina Beach. However, the model was initially unable to generate a sufficiently large surge in Darwin Harbour itself.

Two contributing factors were identified:

- One major cause was the original Darwin Harbour bathymetric file which had been provided from concurrent work being undertaken to model the circulation in Darwin Harbour. When it was scrutinised in detail, many significant discrepancies from the Admiralty Chart and the available sounding data were identified.

The Darwin Harbour bathymetric file was corrected on the basis of the available Chart data and soundings provided by Acer Vaughan taken specifically for the project in a number of key locations, e.g. East Arm and the proposed Seawall.
A second contributing factor was the small radius of the Cyclone Tracy wind field vortex, which resulted in large wind gradients across the overlapping nesting region of the coarse and fine grids.

Some minor modifications were then made to the nesting transition from coarse to fine grid. This included extending the original fine grid, FG, for the Harbour further out to sea within its parent coarse grid, CG3.

The results improved significantly. The Tracy model run generated a peak storm surge level of 1.56 m (taking into account the small contribution from wave set-up at the tide gauge site).

Figure II indicates the time profile of residual sea level registered during the Cyclone Tracy model run at Stokes Hill Wharf as well as the actual recorded gauge data. The tidal components have been excluded in these data.

![Graph](image-url)

**Figure II** Comparison of Model (Solid Line) versus Actual (Dashed Line) Surface Heights at Stokes Hill Wharf During the Passage of Cyclone Tracy (Tidal Component Removed)
5 CYCLONE CLIMATOLOGY

The climatological analysis of tropical cyclones affecting the Darwin region, used to develop appropriate probability distributions and joint probabilities describing the cyclone meteorological parameters of interest, is based partly on a previous analysis of Darwin region tropical cyclones documented in Vipac Report No. 36499 (1992). An amended excerpt from this Report is included as Appendix A of the Main Report.

The previous study identified 44 tropical cyclones which passed within 300 km of Darwin during the period of cyclone seasons 1957/1958 to 1989/1990. Cyclone occurrences prior to the 1957/58 season were not considered because of deficiencies in the data gathering processes (e.g. no radar, satellite data etc.) used to compile the existing historical record.

In the present study, several storms were eliminated from the data base because of their distance from, or orientation with respect to, Darwin. The remaining storm data base, comprising 33 tropical cyclones, coincidentally gives an occurrence rate of one per year.

The 33 cyclones comprising the basic storm data set for the present study have been listed in the Main Report in Table 2. The track paths of the original 44 storm data set through the region are included in the Main Report in Appendix A (Figures A.2(a)-(e)).

Tropical cyclones affecting the Darwin area conveniently sub-divide into five basic directional groups:

- **east/northeast** storms (i.e. approaching from the east/northeast)
- **east/northeast** storms, but forming to the west of Darwin
- **northerly** storms, initially northeast but gently recurving towards the south
- **westerly** storms
- **northwest** storms, e.g. Tracy (1974) and/or **recurving** storms, e.g. Selma (1974)

The **majority** of these cyclones are from the **northeast quadrants**. However, the storms which have inflicted the **greatest historical damage** on Darwin are the **recurving storms** such as Tracy (1974), which typically had an initial southwesterly direction of motion and then recurved towards the southeast as they approached the Darwin area.

The following tables indicate the probability break-ups that were chosen for the various cyclone groups covering approach angle, translation speed and central pressure.
**Greater Darwin Cyclone Storm Surge Risk**

**Vipac Report 24113-1**

**Executive Summary**

August 1994

---

**Darwin Cyclone Approach Angles**

The cyclones affecting the greater Darwin area were initially sub-divided into five sub-groups, by approach angle, with the following probability ratios:

<table>
<thead>
<tr>
<th>Group</th>
<th>Approach Angle</th>
<th>Occurrence Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theta - 1</td>
<td>280°</td>
<td>10%</td>
</tr>
<tr>
<td>Theta - 2</td>
<td>320°</td>
<td>12%</td>
</tr>
<tr>
<td>Theta - 3</td>
<td>0°</td>
<td>8%</td>
</tr>
<tr>
<td>Theta - 4</td>
<td>40°</td>
<td>35%</td>
</tr>
<tr>
<td>Theta - 5</td>
<td>80°</td>
<td>35%</td>
</tr>
</tbody>
</table>

**Darwin Cyclone Translation Speeds**

From the analysis of the historical data base of cyclone translation speeds, three categories and corresponding probability densities were adopted to cover the range of representative forward speeds for all Darwin area cyclones (i.e. regardless of approach direction):

<table>
<thead>
<tr>
<th>Group</th>
<th>Translation Speed</th>
<th>Occurrence Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>VT - 1</td>
<td>2 m/sec</td>
<td>35%</td>
</tr>
<tr>
<td>VT - 2</td>
<td>5 m/sec</td>
<td>50%</td>
</tr>
<tr>
<td>VT - 3</td>
<td>8 m/sec</td>
<td>15%</td>
</tr>
</tbody>
</table>
Darwin Cyclone Central Pressures

Initially, the central pressures of the 33 cyclones comprising the Darwin region data base were converted to central pressure differences, \( \Delta p \), assuming a representative periphery pressure of 1010 hPa.

It was found that a Weibull type Extreme-Value Distribution fitted the data well in the range up to a \( \Delta p \) value of about 60 hPa (the Cyclone Tracy value). An extreme value asymptote, of the truncated Weibull type, was then developed to fit \( \Delta p \) values greater than 60 hPa. This was done to provide a realistic limit to the values of \( \Delta p \) attainable at very high return periods.

Appendix A of the Main Report discusses how the probability associated with a particular cyclone is related to the annual probability of its occurrence via the distribution of the number of cyclones per year (or per season).

The overall analysis of the complete data set (all 33 cyclones) yielded a central pressure value, \( P_c \), of approximately 917 hPa for the 1000 year return period. A central pressure value of 950 hPa (e.g. Cyclone Tracy) would have a return period of just less than 50 years, which agrees reasonably well with the occurrence rate of severe storms affecting Darwin in the last two hundred years.

However, it was observed from the available historical records dating back to the 1800's, that tropical cyclones ...

- approaching Darwin from the northeast are generally mild, while
- virtually all of the historically severe storms which have impacted upon Darwin have approached from north and northwest quadrants.

This is probably due to the fact that tropical cyclones derive their energy from warm ocean waters and, for the Darwin area, cyclones from the northwest will have a greater part of their circulation, especially in the important front-left quadrant, over water.

Thus it was decided to use two slightly different conditional distributions in the model simulation runs to characterise the variation in \( \Delta p \) value – a stronger distribution, "A", (i.e. stronger relative to the above fitted curve) for northwest quadrant storms and a weaker distribution, "B", for the milder northeast storms:

- \( \Delta p \) Conditional Distribution "A" covers angles ... 280°, 320° and 0°
- \( \Delta p \) Conditional Distribution "B" covers angles ... 40° and 80°
Representative Return Period versus Central Pressure values for the two chosen conditional distributions and the resulting combined distribution for the general Darwin area are listed below in Table V.

<table>
<thead>
<tr>
<th>Minimum Central Pressure</th>
<th>Distribution &quot;A&quot; Return Period (280°, 320°, 0°)</th>
<th>Distribution &quot;B&quot; Return Period (40° and 80°)</th>
<th>Combined Darwin Return Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>980 hPa</td>
<td>3 years</td>
<td>7 years</td>
<td>5 years</td>
</tr>
<tr>
<td>950 hPa</td>
<td>25 yrs</td>
<td>90 yrs</td>
<td>50 yrs</td>
</tr>
<tr>
<td>920 hPa</td>
<td>230 yrs</td>
<td>3870 yrs</td>
<td>665 yrs</td>
</tr>
</tbody>
</table>

Correlations Between Parameters

The Northern Territory's Bureau of Meteorology has conducted a number of recent studies into the correlation between various cyclone parameters of interest. This follows on from similar research conducted on North Atlantic and Northwest Pacific tropical cyclones.

In the present study, some of these correlations have been taken into account. Others have been overlooked on the basis of too little information upon which to make a reasonable decision (see the Main Report for a detailed discussion).

- Only one value of Radius of Maximum Winds, $R_{\text{max}}$, was used for all the model simulation storms, viz. $R_{\text{max}} = 15$ km.

  This appears to be a conservative value for the more severe storms which have affected Darwin, e.g. Cyclone Tracy's $R_{\text{max}}$ value was less than half this value.

- The choice of two distributions, "A" and "B", was used to differentiate the central pressure difference values of Darwin storms approaching from the northwest (more intense storms) versus the northeast quadrants (generally mild storms).

- It was decided that too little data exists within the Darwin area cyclone set to further sub-divide the groupings into generally faster and slower storms depending upon storm intensity.
6 STORM SURGE MODELLING

Model Input Parameters

Examination of the historical cyclone records dictated the break-up of climatological parameters of interest used to characterise cyclone behaviour (surge and wave set-up) for the region. On the basis of the groupings discussed in the previous section, sets of 300 "primary" model runs were run on each of the five model grids using the following variables:

- Storm Approach Angle ...
  \[280°, 320°, 0°, 40°, 80°\]

Five directional paths were chosen to sub-divide all cyclones affecting the area:

- Storm Point of Closest Approach ...
  
  \[-15 \text{ km}, 0 \text{ km}, 15 \text{ km}, 30 \text{ km}, 75 \text{ km} \quad \text{for the } 280°, 320°, 0° \text{ storms}\]
  
  \[-30 \text{ km}, 0 \text{ km}, 15 \text{ km}, 30 \text{ km}, 75 \text{ km} \quad \text{for the } 40° \text{ storms}\]
  
  \[-45 \text{ km}, -15 \text{ km}, 0 \text{ km}, 15 \text{ km}, 60 \text{ km} \quad \text{for the } 80° \text{ storms}\]

For each approach direction, five (5) parallel storm tracks were chosen which passed by the simulation grid central point at varying ratios of the \(R_{\text{MAX}}\) value of the storm. Positive values imply that the simulation centre point was to the LEFT of the storm centre at its point of closest approach. Since for all model storms, the \(R_{\text{MAX}}\) value was taken to be 15 km, the resulting distance of minimum approach, \(D_{\text{MIN}}\), values were:

- Storm Translation Speed ...
  \[2.0, 5.0, 8.0 \text{ m/s}\]

Three representative values were chosen for the primary runs.

- Storm intensities ...
  \[980, 950, 920, 890 \text{ hPa}\]

Storm surge, and to a lesser extent wave set-up, are roughly proportional to the value of central pressure difference, \(\Delta p\). Given the likely maximum possible cyclone intensities able to occur within the Darwin area, the above four values of \(\Delta p\) were chosen to make up the 300 primary simulation runs.

The above combinations resulted in a total of 300 primary model runs for each one of the model grid groupings, made up of:

\[5 \text{ Approach Angles} \times 5 \text{ Minimum Approach Distances} \times 3 \text{ Translation Speeds} \times 4 \text{ Central Pressure Differences}\]
Simulation Model Results

The results for each of the individual 1500 model runs for the 18 study location points have been included in the Main Report (Appendix B).

Some sample results are shown below for the resultant surge at various sites of interest for purposes of general illustration. These all involve 5 m/sec forward speed cyclones.

Figure III(a): The largest surge occurs at a minimum track distance of +15 km, i.e. the cyclone passes to the south of Darwin from the northwest, and the Radius of Maximum Winds passes directly over the Seawall. It can be seen that there is a roughly linear increase in surge with decreasing central pressure. The surge is maintained for storms passing well to the south of Darwin, but quickly becomes negligible as the storms pass to the north.

Figure III(b): As in the previous case, the largest storm surge occurs when the radius of maximum winds is able to pass directly over the site, although it can be seen that there is still substantial surge at the Seawall over a wide range of minimum track distance. The values however are approximately half those for the 320° storms.
Figure III(b) Storm Surge at Darwin South SEAWALL - 40° cyclones

Figure III(c): The storm surge behaviour at the East Arm Port location exhibits "classic" surge profiles with a peak at the positive radius of maximum winds value, quickly tapering off for negative values (i.e. storms passing to the west of Darwin) but tapering much slower to the east.

Figure III(c) Storm Surge at East Arm PORT - 0° cyclones
7 DARWIN AREA TIDES

The present tidal probability distribution has been determined by running a tidal height prediction model (Foreman, 1980) for the study region over the full astronomical cycle (18.6 years).

To estimate the peak sea levels included in the present Report, existing tidal gauge data obtained from Stokes Hill Wharf were used initially estimate tidal heights over the full astronomical cycle.

As part of the coordinating efforts involved with this study, tidal data recorded over a three month period at Mandorah Jetty have been recently obtained for analysis. This data was used to derive an updated tidal height probability distribution. The probability of occurrence for each 0.1 metre increment above or below mean sea level is shown in Figure IV.

![Figure IV: Darwin Harbour Tidal Probabilities](image-url)
8 DARWIN STORM TIDE ESTIMATES

Joint Probability Methodology

The total number of event types involving any particular combination of storm intensity, forward speed, approach direction etc. will be infinite. However, the problem is considerably simplified if discrete, representative intervals are assigned across the range of possibilities for each variable. Such discrete intervals were defined in the previous sections spanning the likely variation over all possible values in cyclone approach direction (5 angles), translation speed (3 speeds) and minimum approach distance (5 values).

The probability of occurrence for each combination of these discrete events is given by:

\[ \text{Prob} \{ \theta, V_T, D_{\text{MIN}} \} = \text{the probability of occurrence associated with cyclones with approach direction, } \theta, \text{ moving with translation speed, } V_T, \text{ and passing by the model centre point at a minimum approach distance of } D_{\text{MIN}}. \]

It is assumed that each one of the individual probabilities concerned is independent of the other. Thus ...

\[ \text{Prob} \{ \theta, V_T, D_{\text{MIN}} \} = \text{Prob} \{ \theta \} \times \text{Prob} \{ V_T \} \times \text{Prob} \{ D_{\text{MIN}} \}. \]

Storm Intensity vs Joint Parameters ...

For each one of the 75 combinations of the "joint parameters", \( \theta-V_T-D_{\text{MIN}} \), it will be recalled that four storm pressure changes were utilised in the 300 "primary" model runs. This enables a continuous relationship to be established between resulting surge and wave set-up versus storm intensity for each discrete combination of \( \theta-V_T-D_{\text{MIN}} \).

For convenience sake, the resultant surge plus wave set-up heights were broken up into discrete intervals of 0.1 metres. For each surge plus wave set-up 0.1 metre interval, \( \Delta S+WS_{x,y} \), there is a corresponding interval of central pressure difference, \( \Delta p_y \), with an associated probability of occurrence, \( \text{Prob} \{ \Delta p_y \} \).

Total Surge Plus Wave Set-Up Probability ...

The total probability of surge plus wave set-up height can then be determined by summing over all "events", i.e. the 75 model "primary" runs, which result in a surge height in that interval, that is:

\[ \text{Prob}\{ S+WS_{x,y} \} = \sum \text{Prob} \{ \Delta p_y : \text{given } \theta, V_T, d_{\text{MIN}} \} \times \text{Prob} \{ \theta, V_T, d_{\text{MIN}} \}. \]
Tidal Probability ...

A similar procedure is adopted to include variation of tidal probability in the analysis. The tidal range is also broken up into 0.1 metre increments and the probability associated with each increment, Prob \{ T_i \}, determined from the tidal model (see Fig.10).

Total Storm Tide Probability ...

The probability of occurrence for some total storm tide level, \( H_c \), representing the sum of the cyclone surge and wave set-up plus tidal contribution is then simply the sum over all possible combinations of the individual components which result in that total level.

\[
\text{Prob}\{H = H_c\} = \sum_{i,j} \text{Prob}\{S + WS = S_i\} \cdot \text{Prob}\{T = H_c - S_j\}
\]

where the sum is over the number of discrete combinations, \( N \), which can combine to produce a particular height, \( H_c \).

Note: This computation is identical to the problem of determining the probability of throwing a total number, "9" say, with two die. The answer is formed by summing over all possible combination of the dice which will add up to a "9", e.g. a "6" plus a "3", a "5" plus a "4", a "4" plus a "5" etc.

Non-Cyclone Event Probabilities ...

These "combined storm tide" estimates, which take into account the tidal variation during the event, only give the predicted probability level of the sea surface elevation, given a cyclone occurrence.

They do not compute the contribution to the sea surface elevation of the tide alone when there is no cyclone event.

Therefore, the probability table of predicted cyclone surge height must take into account the hours during the year when a cyclone is not occurring, but when clearly the tide is occurring.

Thus the final probability estimates of sea level elevations are computed from:

\[
\{\text{Prob. of Tide Only Occurring}\} \times \{\text{Prob. Distrn. of Tidal Heights}\} + \{\text{Prob. of Cyclone Occurring}\} \times \{\text{Prob. Distrn. of Surge + Wave Set-up + Tide}\}
\]

At low return periods (several years), the predicted combined sea surface elevation is dominated by the tidal only contribution. From higher return periods, the extremes are dominated by the effect of the cyclone surge + wave set-up + tide.
Return Period Estimates

The individual extreme value distributions for the 18 study sites have been included in the Main Report in Appendix C. Discrete values of interest for all sites are shown below in Table VI. There is significant variation between the different sites.

<table>
<thead>
<tr>
<th>Location</th>
<th>Return Period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>1. Point Blaze</td>
<td>3.9</td>
</tr>
<tr>
<td>2. Fog Bay</td>
<td>3.9</td>
</tr>
<tr>
<td>3. Native Point</td>
<td>4.0</td>
</tr>
<tr>
<td>4. Bynoe Harbour</td>
<td>4.0</td>
</tr>
<tr>
<td>5. Masson Point</td>
<td>4.2</td>
</tr>
<tr>
<td>6. Charles Point</td>
<td>3.7</td>
</tr>
<tr>
<td>7. West Point</td>
<td>4.0</td>
</tr>
<tr>
<td>8. West Arm</td>
<td>3.9</td>
</tr>
<tr>
<td>9. Channel Island</td>
<td>3.8</td>
</tr>
<tr>
<td>10. Wickham Point</td>
<td>3.8</td>
</tr>
<tr>
<td>11. East Arm PORT</td>
<td>3.7</td>
</tr>
<tr>
<td>12. Darwin South SEAWALL</td>
<td>3.8</td>
</tr>
<tr>
<td>13. Fannie Bay</td>
<td>4.0</td>
</tr>
<tr>
<td>14. Casuarina Beach</td>
<td>4.0</td>
</tr>
<tr>
<td>15. Lee Point</td>
<td>3.6</td>
</tr>
<tr>
<td>16. Shoal Bay</td>
<td>3.9</td>
</tr>
<tr>
<td>17. Gunn Point</td>
<td>3.7</td>
</tr>
<tr>
<td>18. Point Stephens</td>
<td>3.6</td>
</tr>
</tbody>
</table>
Greater Darwin Cyclone Storm Surge Risk

Executive Summary

August 1994

There are significant variations between the different sites:

- **100-year return period estimates (A.H.D.)** vary from 4.2 metres at Point Stephens to 5.5 metres at Masson Point. The 100-year estimates within Darwin Harbour are around 5.0 metres.

Similarly, 1000 year return period values inside Darwin Harbour range between 6.0 metres and 6.4 metres. The comparable estimates for Fannie Bay and Casuarina Beach are 6.4 and 6.6 metres respectively.

In general, it was found that sites located right on coastal promontories exhibited significantly lower values than nearby adjacent coastal locations, e.g. compare Lee Point to Casuarina Beach.

Closer examination of surge predictions with additional model runs showed that this "point" characteristic only occurred very close to the actual promontory at the coastline. It was surmised that the reason for the lower surge levels predicted at such exposed coastal locations was because of the ability of water to "escape" either to the east or southwest along the coast as the surge was building up, as opposed to locations in bay or harbour areas, where the water tended to "pile up".

In order to avoid the misconception that the coastal "point" estimates are representative of extended segments of nearby coastline, we re-computed the surge predictions at locations slightly away (at least one grid point) from exposed coastal points, with the exception of Lee Point, Point Blaze and Point Stephens. The amended "point" values documented in Table VI have retained the promontory names as the locality indicator. However, the reader can now interpolate prudently (i.e. conservatively) between locations given in Table VI.

Locations within Darwin Harbour itself experience complex storm surge and wave set-up effects compared to open coastal locations as a result of the rapid turning of winds accompanying a cyclone passage and the confined fetch of water at interior locations for different cyclone approach directions. For example, a storm moving directly towards Darwin from the west producing local north-northwest winds would be driving water up against Casuarina Beach. At the same time, the winds might be off-land at the proposed site of the Darwin South Seawall even though water was being generally driven into the Harbour area.

It may be noted that the 100-year cyclone return elevations at the Seawall represent conditions which would be produced by a tropical cyclone of central pressure 920 hPa approaching from the northwest with a forward speed of 5 m/sec and passing by with its radius of maximum winds directly over Darwin Harbour (with no tidal contribution taken into account).
9 COMPARISON WITH PREVIOUS STUDIES

The present study predictions vary somewhat from previous estimates made in the GDSSS (1983) as shown in Table VII below.

<table>
<thead>
<tr>
<th>Location</th>
<th>Return Period (years)</th>
<th>100 Vipac (1994)</th>
<th>100 GDSSS (1983)</th>
<th>1,000 Vipac (1994)</th>
<th>1,000 GDSSS (1983)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bynoe Harbour</td>
<td></td>
<td>5.3</td>
<td>4.9</td>
<td>6.6</td>
<td>6.2</td>
</tr>
<tr>
<td>Masson Point</td>
<td></td>
<td>5.5</td>
<td>5.2</td>
<td>6.7</td>
<td>6.5</td>
</tr>
<tr>
<td>Charles Point</td>
<td></td>
<td>4.6</td>
<td>5.1</td>
<td>5.6</td>
<td>6.2</td>
</tr>
<tr>
<td>West Point</td>
<td></td>
<td>5.1</td>
<td>5.3</td>
<td>6.4</td>
<td>6.6</td>
</tr>
<tr>
<td>West Arm</td>
<td></td>
<td>5.1</td>
<td>5.3</td>
<td>6.4</td>
<td>6.8</td>
</tr>
<tr>
<td>Channel Island</td>
<td></td>
<td>5.1</td>
<td>5.0</td>
<td>6.4</td>
<td>6.3</td>
</tr>
<tr>
<td>East Arm PORT</td>
<td></td>
<td>4.9</td>
<td>4.9</td>
<td>6.0</td>
<td>6.2</td>
</tr>
<tr>
<td>Darwin South SEAWALL</td>
<td></td>
<td>5.0</td>
<td>5.1</td>
<td>6.2</td>
<td>6.5</td>
</tr>
<tr>
<td>Fannie Bay</td>
<td></td>
<td>5.2</td>
<td>5.4</td>
<td>6.4</td>
<td>6.6</td>
</tr>
<tr>
<td>Casuarina Beach</td>
<td></td>
<td>5.3</td>
<td>5.2</td>
<td>6.6</td>
<td>6.4</td>
</tr>
<tr>
<td>Shoal Bay</td>
<td></td>
<td>5.1</td>
<td>5.1</td>
<td>6.3</td>
<td>6.5</td>
</tr>
<tr>
<td>Gunn Point</td>
<td></td>
<td>4.5</td>
<td>4.6</td>
<td>5.3</td>
<td>5.8</td>
</tr>
<tr>
<td>Point Stephens</td>
<td></td>
<td>4.2</td>
<td>4.3</td>
<td>4.8</td>
<td>5.3</td>
</tr>
</tbody>
</table>

The reasons for the variations (both up and down) between the present estimates with respect to the previous GDSSS (1983) values lie in the following two areas:

- the current deterministic storm surge model are significantly different (lower) than the GDSSS (1983) model equivalent.
- the climatological input statistical parameters (occurrence rates, cyclone intensity, forward speed etc.) vary widely in the present study.
Comparison of Storm Surge Alone Estimates

From the GDSSS (1983) study, storm surge estimates were obtained for a 920 hPa storm, approaching Darwin from the northwest and with a translation (forward) speed of 5 m/sec. These are compared, in Table VIII below, at Darwin Harbour, Fannie Bay and Charles Point, with the values derived in the present study (storm surge alone, no wave set-up).

<table>
<thead>
<tr>
<th>D_MIN</th>
<th>Darwin Harbour</th>
<th>Fannie Bay</th>
<th>Charles Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>− Rmax</td>
<td>0.3</td>
<td>2.2</td>
<td>0.9</td>
</tr>
<tr>
<td>0</td>
<td>3.3</td>
<td>3.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Rmax</td>
<td>5.9</td>
<td>5.5</td>
<td>5.1</td>
</tr>
<tr>
<td>2 Rmax</td>
<td>4.4</td>
<td>4.9</td>
<td>5.8</td>
</tr>
<tr>
<td>5 Rmax</td>
<td>1.7</td>
<td>3.3</td>
<td>3.0</td>
</tr>
</tbody>
</table>

It can be seen that the current surge estimates are close to the GDSSS (1983) estimates at the peak values, but that they taper off much more quickly at distances greater than one Radius of Maximum Winds value away from the site.

For the northeast approaching storms, the differences in the predictions were found to be substantially different, with even the peak values less than 80% of the comparable GDSSS (1983) estimates, and the values greater R_max values less than 50%.

Thus, it would appear that if both simulations has used the same meteorology (i.e. same climatological probabilities), the present extreme estimates would have been significantly lower.
Climatological Comparison of Current and GDSSS (1983) Study

There are significant differences in the probabilistic representation of cyclones affecting Darwin between the GDSSS (1983) study and the present study.

Occurrence Rate ...

The break-up of cyclones affecting the Darwin areas used in the long-term extreme surge estimates in the GDSSS (1983) study are compared below to the current estimates in Table IX. Included as well are data received from the Darwin Bureau of Meteorology (personal communication, Nov. 1993) for all tropical cyclone occurrences north of 13°S latitude and between 70°E and 160°E longitude.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>West</td>
<td>13 %</td>
<td>10 %</td>
<td>12 %</td>
</tr>
<tr>
<td>Northwest</td>
<td>15 %</td>
<td>12 %</td>
<td>10 %</td>
</tr>
<tr>
<td>North</td>
<td>27 %</td>
<td>8 %</td>
<td>9 %</td>
</tr>
<tr>
<td>Northeast</td>
<td>45 %</td>
<td>35 %</td>
<td>29 %</td>
</tr>
<tr>
<td>East</td>
<td></td>
<td>35 %</td>
<td>40 %</td>
</tr>
</tbody>
</table>

The above percentages indicate a break-up for West–Northwest–North cyclones and all other cyclones of 55% and 45% respectively in the GDSSS (1983) study. This compares with a comparable break-up in the current study of 30% and 70% respectively.

Storms from the northeast quadrants generally produce greater storm surges in the Darwin area than storms from the northeast quadrants. Hence, the above break-up suggests that the original GDSSS (1983) simulation family of cyclones would have been weighted by more storms from the directions which produce greater storm surges.
Central Pressure ...

For return periods up to around 5,000 years, the current study distribution predicts more intense storms for a given return period, compared to the GDSSS (1983) distribution. Some sample return period comparisons are made below in Table X.

<table>
<thead>
<tr>
<th>Minimum Central Pressure</th>
<th>GDSSS (1983) Return Period</th>
<th>Current Study Return Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>980 hPa</td>
<td>9 yrs</td>
<td>5 yrs</td>
</tr>
<tr>
<td>950 hPa</td>
<td>112 yrs</td>
<td>50 yrs</td>
</tr>
<tr>
<td>920 hPa</td>
<td>1508 yrs</td>
<td>665 yrs</td>
</tr>
</tbody>
</table>

These values suggest that in the extreme simulation computations, the current study would be generating given intensity storms more often than in the GDSSS (1983) simulation runs.

Cyclone Translation Speed ...

The GDSSS (1983) study assumed that there is a moderate, linear, increasing variation in peak storm surge with storm forward speed. In the present study, the variation of storm surge (and wave set-up) with storm forward speed has been found to be quite complex, and highly dependent on location and storm approach direction.

As an example, Figure V shows the variation in peak storm surge level at Fannie Bay as a function of oncoming storm direction and for the three model storm forward speeds of 2, 5 and 8 m/sec. From this and all of the 1500 model cyclone runs, it was found that:

- storms approaching Darwin from northwest quadrants generally produce increasing storm surge with increasing forward speed, especially for open coast locations. This can be attributed mainly to the extra component of the cyclone windfield in the area of maximum winds produced by the storm's own forward speed.
storms approaching Darwin from northeast quadrants generally produce their peak storm surge for a forward speed at close to 5 m/sec and then the peak surge decreases, even for 320° and 0° storms. This is especially apparent at internal Harbour locations, e.g. the Seawall.

In the latter situation, although the general cyclone windfield exhibits increased peak winds because of the added forward speed component, there is not enough time for the surge to develop with the limited fetch conditions in internal harbour areas.

It should be repeated, that in the present study, the variation of storm surge with forward speed has not been inferred, but computed directly by utilising the three different model storm speeds in the actual 1500 model cyclone runs.

Figure V Variation of Peak Storm Surge with Cyclone Forward Speed
For the Current Study
Summary ...

The differences between the current estimates and the GDSSS (1983) estimates appear to arise from a number of sources.

Factors leading to higher peak storm surge estimates in the GDSSS (1983) study:

- The GDSSS (1983) cyclone windfield model generated overall higher surge estimates compared to the present study model, especially for storms moving past a site at distances further away than the Radius of Maximum Winds, and at all distances for northeast quadrant storms.

- The occurrence probabilities used in the GDSSS (1983) simulation were biased towards cyclones from northwest quadrants, which produce generally higher storm surges. The GDSSS (1983) probabilities do not agree with observed storm occurrences in the Darwin area.

- The GDSSS (1983) surge model assumed that, regardless of location and approach direction, peak storm surge is linearly related to storm forward speed. This has been found in the present study not to be the case, through the 1500 model cyclone surge runs which have directly determined the influence of storm forward speed on resulting surge. In some cases, especially within Darwin Harbour, the surge actually decreases for the very high forward speed cyclones, as there is insufficient time to generate the water build-up in the Harbour during the cyclone passage.

Factors leading to lower peak storm surge estimates in the GDSSS (1983) study:

- The GDSSS (1983) central pressure distribution yields lower central pressure cyclones for the same return period as the current study. The current study central pressure estimates however agree qualitatively with the occurrence rate of major cyclones affecting Darwin over the last two hundred years.

The above have resulted in variations which produced both increases and decreases in the final extreme estimates. It is believed that the present results, through the simulation of so many more model storms represents a more accurate picture of the storm tide risk in the area.
This Report has been Prepared

for the

NORTHERN TERRITORY
DEPARTMENT OF LANDS, HOUSING & LOCAL GOVERNMENT

by

VIPAC ENGINEERS & SCIENTISTS Ltd
SPECIAL SERVICES UNIT – Bureau of Meteorology
GLOBAL ENVIRONMENTAL MODELLING SERVICES Pty Ltd
ACER VAUGHAN Pty Ltd

Peter N. Georgiou, Ph.D.
Manager
Vipac – N.S.W.
TROPICAL CYCLONE STORM SURGE RISK FOR THE GREATER DARWIN REGION
VOLUME 1 - EXECUTIVE SUMMARY

PREPARED FOR:

DEPARTMENT of LANDS, HOUSING and LOCAL GOVERNMENT
c/o DEPARTMENT of TRANSPORT & WORKS
N.T. Construction Agency
P.O. Box 61
Palmerston, N.T. 0831

Contact(s): Mr. Phil Piper

PREPARED BY:

Vipac Engineers & Scientists Ltd
Unit E1-B, Centrecourt
25 Paul Street North
North Ryde, N.S.W. 2113

Tel. (02) 805 6000
FAX. (02) 878 1112

REVISION HISTORY:

<table>
<thead>
<tr>
<th>Rev. No.</th>
<th>Date Issued</th>
<th>Reason/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30.8.1993</td>
<td>Final Report</td>
</tr>
</tbody>
</table>

DISTRIBUTION:

<table>
<thead>
<tr>
<th>Copy No.</th>
<th>Rev No.</th>
<th>Destination:</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>Project File – Vipac Sydney</td>
</tr>
<tr>
<td>1–10</td>
<td>1</td>
<td>N.T. Transport &amp; Works</td>
</tr>
<tr>
<td>11–12</td>
<td>1</td>
<td>Acer Vaughan Darwin</td>
</tr>
<tr>
<td>13–14</td>
<td>1</td>
<td>S.S.U. – Bureau of Meteorology</td>
</tr>
<tr>
<td>14–15</td>
<td>1</td>
<td>G.E.M.S. – Melbourne</td>
</tr>
</tbody>
</table>

KEY WORDS: Tropical Cyclone Storm Tide Risk, Greater Darwin Region, Volume 1