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Bowen Shire Storm Tide Study
Final Report
Bowen Shire Council

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Glossary

AHD – Australian Height Datum
ARI – Average Recurrence Interval
BoM – Bureau of Meteorology
BPA – Beach Protection Authority
CL – Confidence Limits
CP – Central Pressure (hPa)
DCDB – Digital Cadastral Data Base
DES – Department of Emergency Services (Qld)
DoE – Department of Environment (now the Environmental Protection Agency)
EMA – Emergency Management Australia
HAT – Highest Astronomical Tide
Hmax – Maximum wave height observed in a wave record
Hs – Significant Wave Height
PSM – Permanent Survey Mark
RL – Reduced Level
Rm – Radius to maximum cyclone wind speed
R2 – Wave Run-up Height not exceeded by more than 2% of waves
Tp – Peak Spectral Period
Vf – Cyclone Forward Speed

1. Introduction

Bowen Shire Council obtained funding from the Federal and Queensland State Governments to undertake a Storm Surge Study of the Bowen Shire coastline. The funding was made available through the Natural Disaster Risk Management Studies Program, administered in Queensland by the Department of Emergency Services (DES).

Connell Wagner was commissioned by Bowen Shire Council to undertake the Storm Surge Study. Connell Wagner commissioned Lawson and Treloar as specialist sub-consultants to undertake the storm surge and wave numerical modelling, followed by the Monte Carlo analyses.

The specific objectives of the Study were to identify the true risk of storm surge inundation along the coastal region extending from Greta Creek in the south to Wangaratta Creek in the north of the Shire, as shown in Figures 1 and 2. This was undertaken by predicting extreme water levels, and the effects of actual storm surge inundation combined with wave penetration across the specific coastal areas. In addition, flood modelling of the Don River was carried out to allow preliminary examination of combined freshwater and storm tide events to be undertaken.

Although cyclones have caused flooding of low-lying areas in the region, for example, the so-called Bowen cyclone of 1958 and Cyclone Aivu in 1989, much of the historical flooding has been caused by rainfall and associated local runoff, rather than high tides and storm surge. High ocean water levels may also be caused by east-coast lows, but those systems are not being addressed in this study and affect southern Queensland more frequently than this region. Other non-cyclonic events may cause elevated ocean levels. Significant coastal damage with some overtopping of the back-beach area will be caused by the severe waves that occur with many cyclones, especially in the region of Queens Beach where land levels as low as 2.5m AHD occur. Cyclone Aivu, which occurred in April, 1989 caused a storm surge of about 1.2m and peak water level of 2.3m AHD. Wave overtopping of the back-beach area would have occurred at that time.

A specific task within this overall investigation was to undertake an analysis of historical storm surge and cyclone data within the region and then to undertake a series of numerical cyclone simulations. This was to be followed by a Monte Carlo analysis to determine peak cyclone event water level recurrence relationships. Additionally, wave conditions associated with selected cyclones were to be hindcast and those waves propagated to the shoreline to investigate associated wave set-up and wave runup.

Generally, within this report, storm tide is combined astronomical tide and storm surge and peak cyclone water level is peak storm tide level plus wave set-up. At the coastline itself, wave runup can be an additional cause of ocean inundation.

This report describes the data, study methods, model systems and results of the overall investigation.

2. Study Area

The Storm Surge Study includes all coastline areas within Bowen Shire Council as presented in Figures 2 and 3. The Study Area extends from Greta Creek in the south to Wangaratta Creek in the north of the Shire. There are several minor and major watercourses in the study area including:

- Greta Creek;
- Eden Lassie Creek;
- Yeates Creek;
- Don River;
- Euri Creek;
- Branch Creek;
- Splitters Creek;
- Saltwater Creek;
- Elliot River;
- Sandy Creek;
- Cape Creek;
- Armstrong Creek;
- Molongle Creek;
- Rocky Ponds Creek; and
- Wangaratta Creek.

For the purposes of this investigation, the detailed on-shore inundation analysis has focussed upon the Don River. This is due to the fact that this large river can severely impact on Bowen and Queens Beach, which are the two main population centres within the Shire.

The Study Area is predominantly formed of open coast beaches that are provided with some protection by offshore islands and reefs. There is a significant range of shoreline aspect, which affects storm tide and wave activity at individual sites. Beach slopes are typically flat with extensive inter-tidal zones that are exposed at low tide. The back-beach area is generally of medium height and may be protected by a low frontal dune, for example, but in some locations, as is the case at Bowen itself, there is no dune in some areas and some form of coast protection works have been built to prevent shoreline recession and to protect public and private property, refer Figure 4. Where dunes occur, the dune system generally does not extend landward more than the frontal dune itself. Rocky patches occur at Bowen and Heronvale, but generally the shoreline is sandy, refer Figure 5, which presents parts of Heronvale and Queens Beach.

Within Bowen itself, the Don River forms a major coastal feature at the northern end of the Queens Beach area, refer Figure 3. There are two entrance channels and they exhibit some meandering character. Rock stabilisation has been placed in parts of the river channel, refer Figure 6, upper photograph. The Queens Beach area may be inundated by river flooding.

Berth facilities in Molongle Creek near Gumlu provide the only practical access to Cape Upstart – by boat, refer Figure 6, lower photograph.

The Shire has experienced some damage from cyclone surge, apart from wind, wave and rainfall effects, which are more common causes. Notable amongst these is the 1958 cyclone. Most reported damage relates to buildings. Nevertheless, coast protection works at Bowen attest to past coastal damage, which is likely to have been caused by historical cyclone activity.

3. Previous Studies

Several studies have taken place documenting the existence of tropical cyclone storm surge and river flooding along the Bowen area of the Queensland Coast. These include:

- Numerical Simulation of Tropical Cyclone Storm Surge along the Queensland Coast, James Cook University of North Queensland Department of Civil and Systems Engineering, November 1977.
- Report on Don River Flood Plain Management Study, prepared by Ullman and Nolan Pty Ltd. Consulting Engineers – Australia, September 1993 on behalf of The Don River Improvement Trust
- Don River Flood Plain – Bowen, Upgrading Strategies North Coast Railway Line and Bruce Highway, prepared by Ullman and Nolan Pty Ltd. Consulting Engineers – Australia, December 1993 on behalf of Queensland Rail and Queensland Department of Transport.
- Storm Tide Statistics – Bowen Region, prepared by Blain, Bremner and Williams Pty Ltd, 1985 on behalf of Beach Protection Authority, Queensland.

The Numerical Simulation of Tropical Cyclone Storm Surge along the Queensland Coast was prepared for the Beach Protection Authority, Brisbane and describes the results of an extensive analysis of the tropical cyclone storm surge hazard in the Bowen area. It comprised the development of a numerical hydrodynamic model of the area, which accounts for variations in water depth, coastline shape, changes in cyclone path, speed and intensity.

The Don River Flood Plain Management Study describes the potential of the Don River to cause serious damage due to flooding. Past events of 1918, 1946, 1970 and 1980 have demonstrated the propensity for damage. The 1946 flood is generally regarded as the worst flood in recent history. The purpose of the study was to identify the particular problems that exist with respect to the 100 year ARI and management strategies needed to deal with these problems.

Previous cyclone storm tide investigations for the Bowen region are reported in Blain, Bremner & Williams (1985). The study approach adopted at that time was similar to the one followed in this study. However, this study has been able to use much finer grid resolution, a 3D model and a much larger set of basic cyclone simulations to provide input to the Monte Carlo analysis. These changes were possible because of the much increased computing power that is now available. Another issue is that at that time no Greenhouse related climate changes were considered.

4. Available Data

A range of data items were required to undertake the Storm Surge Study including:

- Data to set up and calibrate the numerical storm surge model;
- Data to establish a numerical wave model;
- Data to develop and calibrate the MIKE 21 Don River model; and
- Data to allow the preparation of inundation maps for affected coastal areas.

The following sections detail the data collected and used on this project.

4.1 Bathymetric Data

Bathymetric data is required to describe the topography of the seabed and coastline over the area of the proposed numerical modelling systems. Charts 818, 819, 820, 822 and 4602 were used. This data was digitised to provide a digital terrain model, from which the numerical surge and wave model grids were prepared.

Additionally, Council provided land survey charts (hard copy and/or digital) to describe land levels in some low lying coastal and estuarine regions of the study area. That data was used to provide back-beach area slopes and land level indications. There are no large coastal lakes or lagoons in the area.

4.2 Tidal Information

Tides in this region are predominantly semi-diurnal. Therefore there are two high and two low tides each day. The most representative sites are Bowen and Abbot Point, for which tidal planes are presented in Table 1.

Table 1 – Tidal Information

Tide	Tide Level (m LAT)	
	Bowen	Abbot Point
Highest Astronomical Tide (HAT)	3.73	3.6
Mean High Water Springs (MHWS)	2.77	2.69
Mean High Water Neaps (MHWN)	2.16	2.07
Mean Sea Level (MSL)	1.72	1.67
Mean Low Water Neaps (MLWN)	1.39	1.29
Mean Low Water Springs (MLWS)	0.78	0.67

This information is presented in The Official Tide Tables & Boating Safety Guide (2001), prepared by the Department of Transport, Queensland. All data is to Chart Datum which is Lowest Astronomical Tide (LAT). Datum AHD is 1.78m above Chart Datum at Bowen and 1.63m above Chart Datum at Abbot Point, which is a Standard Port.

4.3 Wave Data

The Beach Protection Authority (BPA) recorded wave data at their Abbot Point site between May, 1977 and August, 1979 in a depth of 12m at 19°52'S; 148°06'E. The highest wave height (Hs) recorded at this installation was 2.2m during cyclone Kerry in March, 1979. In general, two records, each of 20 minutes duration, were made each day in analogue form. Hence it is possible that peak storm wave conditions were not recorded.

In the Bowen Region, wave data was collected between September, 1978 and November, 1984 in a depth of 20m at 148°16'E; 19°56'S. The highest wave height (Hs) recorded was 2.2m in February, 1981 during cyclone Freda. In general, two records, each of 20 minutes duration, were made each day until November, 1981. Thereafter, four records were taken each day, thereby increasing the likelihood that peak storm conditions would be identified.

Council advised that Cyclone Dawn, which occurred in March 1976, had caused damage at Bowen. Cyclone Dawn crossed the coast near Cape Upstart and tracked inland of Bowen, refer Appendix A. No wave data was recorded at Bowen, but Queensland EPA advise that wave data recorded at Mackay and Townsville did not exceed about 2m, refer Appendix A. It is likely that similar wave heights occurred in the Bowen area.

4.4 Cyclone Data

Cyclone track data was required to describe the characteristics of historical cyclones that have affected the Bowen Shire coastal region. Although some data was held in L&T archives, the Bureau of Meteorology advised that all data is now available from their web site in digital form. This data was down loaded for this study. Additionally, cyclone impacts in Queensland have been discussed with Mr Jim Davidson and Mr Jeff Callaghan of the Bureau of Meteorology and data presented in the Bureau's Impacts report (circa 2002) has been provided and assisted this study.

Generally, cyclone track data has improved in quality since about 1960 when satellite imagery and over-the-horizon radar sampling provided better records of important parameters. However, events occurring since 1955, and which have had a significant effect in the study area, have been included.

Table 2 lists all cyclones included in this investigation that have occurred since 1955, and which have passed close by the study area. Those cyclone tracks are plotted in Figure 7.

Table 2 – Cyclones Affecting Bowen Shire Council Since 1955

No	Cyclone Number	Cyclone Name	1st Day Cyclone is in Zone of Influence	Representative Central Pressure in Zone of Influence (hPA)	Distance of Simplified Track to Site (km)	Average Forward Velocity of Simplified Cyclone Track (m/s)
South East Population Cyclones						
1	248		20/1/1956	996	-43	11
2	628		15/2/1956	1003	252	3.7
3	259 (642)		21/12/1956	998	-115	14
4	640		10/01/1957	994	-60	11.7
5	264		7/2/1957	960	380	2.1
6	278		20/1/1959	980	388	11.3
7	286		27/12/1959	994	128	5.8
8	293		5/1/1961	993	85	5.7
9	301		4/3/1961	990	282	9.1
10	304		22/12/1961	1000	201	4.3
11	310		29/12/1961	999	350	10.9

No	Cyclone Number	Cyclone Name	1st Day Cyclone is in Zone of Influence	Representative Central Pressure in Zone of Influence (hPA)	Distance of Simplified Track to Site (km)	Average Forward Velocity of Simplified Cyclone Track (m/s)
12	649		14/1/1963	1001	171	2.5
13	334	Gertie	15/3/1964	999	222	3.3
14	338	Flora	8/12/1964	996	137	3.4
15	341	Judy	30/1/1965	990	316	7.7
16	360	Elaine	16/3/1967	996	307	9.4
17	562		6/12/1967	1003	390	5.9
18	397	Gertie	14/2/1971	983	43	5.6
19	399	Fiona	20/2/1971	995	-137	7.7
20	435	Wanda	20/1/1974	1002	243	3.1
21	447	Gloria	16/1/1975	986	239	3.2
22	468	Dawn	4/3/1976	995	-17	7.6
23	470	Waterea	27/4/1976	978	175	10.6
24	475	June	17/1/1977	994	397	3.2
25	476	Keith	31/1/1977	994	-43	3.6
26	482	Otto	9/3/1977	987	-21	4.4
27	492	Hal	9/4/1978	994	29	4.9
28	496	Kerry	1/3/1979	994	68	4.7
29	897	Paul	6/1/1980	995	-73	9.6
30	898	Ruth	11/2/1980	1003	248	6.5
31	523	Freda	27/2/1981	982	342	7.8
32	720	Des	15/1/1983	999	363	4.4
33	700	Grace	11/1/1984	990	312	3.7
34	702	Ingrid	6/4/1984	1000	286	3.2
35	706	Lance	20/3/1985	995	371	4.3
36	725	Pierre	23/1/1986	986	103	8.3
37	743	Vernon	29/12/1988	992	214	8.2
38	771	Delilah	29/12/1989	997	278	3.2
39	775	Felicity	16/12/1989	999	333	7.5
40	776	Ivor	23/3/1990	999	-20	3.7
41	835	Celeste	26/1/1996	965	34	5.1
42	858	Justin	23/3/1997	999	128	3.5
43	865	Katrina	19/1/1998	980	365	3.5

No	Cyclone Number	Cyclone Name	1st Day Cyclone is in Zone of Influence	Representative Central Pressure in Zone of Influence (hPA)	Distance of Simplified Track to Site (km)	Average Forward Velocity of Simplified Cyclone Track (m/s)
South West Population Cyclones						
44	243		7/3/1955	965	-235	5.2
45	600		11/3/1955	992	-230	5.1
46	253 (597)		6/3/1956	961	13	2.8
47	637		19/2/1958	994	64	4.4
48	272		1/4/1958	968	11	6.5
49	280		16/2/1959	948	34	3.2
50	647		7/3/1960	1000	160	2.4
51	652		25/3/1963	1002	171	4.3
52	376	Bridget	26/1/1969	1002	256	1.8
53	383	Ada	18/1/1970	962	-64	1.9
54	405	Althea	22/12/1971	952	196	5.4
55	431	Una	18/12/1973	985	149	4.2
56	434	Vera	17/1/1974	996	60	5.3
57	437	Yvonne	9/2/1974	995	155	5.3
58	461	David	19/1/1976	961	-248	4.6
59	495	Gorden	11/1/1979	1001	-64	4.4
60	899	Simon	23/2/1980	955	-320	2.4
61	718	Dominic	13/4/1982	1002	282	9.5
62	721	Elinor	1/3/1983	980	-265	3.6
63	744	Winifred	31/1/1986	957	320	4
64	762	Charlie	27/2/1988	972	55	3.1
65	770	Aivu	3/4/1989	945	77	5.1
66	790	Joy	25/12/1990	980	128	2.5
67	857	Gillian	11/2/1997	995	201	4.9
68	859	Ita	24/2/1997	994	124	6.4
69	885	Tessi	1/4/2000	980	167	5.4

4.5 Storm Surge Data

Calibration of the proposed storm surge model provides confidence in simulated storm surge results. Only two severe surge events (the 1958 Cyclone and Cyclone Aivu) were identified in this area between 1955 and the present time. Prior to this time data is less reliable. They were both south-west tracking cyclones. However, cyclone Celeste, which occurred in January, 1996, with a south-eastward track, caused a storm surge of 0.4m at Bowen and this cyclone was included also in the calibration process.

Recorded water levels and predicted tide data for Aivu and Celeste are presented in Figures 8 and 9. No time series data was available for the 1958 Cyclone.

This data was provided by the Department of Transport, Queensland and was used for model calibration/verification.

4.6 On-Shore Survey Data

The following survey data was used during the study for on-shore areas:

- Aerial Laser Survey Data (ALS)
  In the early stages of the project, it was identified that the existing topographic mapping data was limited in accuracy and detail. Preliminary mapping of the storm tide inundation identified the limitations of this dataset. It was therefore decided to obtain new topographic data along the coastal area and over the lower reaches of the Don River floodplain.

  The Bowen township and Queens Beach areas were flown at an appropriate level to provide an average point spacing of 1.3m and an accuracy of 0.15m. Whilst the remaining coastal areas, Don River and Euri Creek floodplains were flown to provide data with an average point spacing of 2.3m and to an accuracy of 0.35m. This ALS data has been used as the basis for the flood modelling and mapping tasks.

- Road structure details from Main Roads
  The Department of Main Roads supplied road structure drawings for the Bruce Highway crossing of the Don River. These drawings were used to provide details for inclusion in the MIKE 21 hydraulic model of the Don River.

- Rail structure details from Queensland Rail
  Drawings showing details of the rail crossing over the Don River were obtained from Queensland Rail. These drawings were used to provide details for inclusion in the MIKE 21 hydraulic model of the Don River.

- Topographic and infrastructure details from Council
  Council supplied details of the major infrastructure within the shire including roads, water and sewer mains, cadastral boundaries and aerial photographs. As well being used to in the risk assessment on-site work this data was also used to verify levels and assess potential areas of flood inundation.

4.7 Other Data

During the study, Ms Trinity Graham and Dr Doug Treloar conducted separate site inspections where they visited Council and investigated the study area. Some of the key activities that were undertaken during this site visit included:

- Meeting with Mr Graeme Hawes at Council to ascertain what data Council had available for use in the study;
- Thorough inspection of all of the areas at risk;
- Examination of breakout channels from the Don River and coastal foreshore areas; and
- Determination of required extent of ALS data.

The Bureau of Meteorology (BoM) kindly supplied a copy of their Don River URBS hydrologic model for use in this project. This model has been developed by the BoM to allow flood forecasting to occur based on real-time rainfall data. The model has been calibrated to a number of flood events and it was hoped that this study would assist in confirming the accuracy of the rating curves used, particularly for large events.

5. Study Approach

The purpose of this study was to develop detailed storm tide statistics at 25 selected sites within Council's area of responsibility. These sites were:

- Sinclair Bay;
- White Cliffs;
- Heronvale;
- Brisk Bay;
- Adelaide Point;
- Edgecumbe Bay (2);
- Bowen (4);
- Kings Beach (2);
- Cape Edgecumbe;
- Queens Beach (4);
- Abbot Point (3);
- Salisbury;
- Cape Upstart (2); and
- Gumlu (Molongle Creek).

There are two basic approaches that can be adopted. They are:

- Hindcast historical cyclone events using actual cyclone tracks and tides; or

- Analyse the historical cyclone track data to develop a parametric description of variables such as central pressure, track direction and distance from the Bowen area in terms of probabilities of occurrence. This task is followed by a series of cyclone simulations that provide basic time series of surge, wave and wind data, for example. These time series are then used in a Monte Carlo analysis in which cyclones are generated according to the parameterised cyclone wave climate. Estimated parameters for each simulated cyclone event are determined by interpolation/extrapolation from the base simulation results.

Both approaches produce time series of parameters that are subjected to extremal and correlation analyses. However, the Monte Carlo approach lends itself to the preparation of data covering much longer periods of time, and because ARI up to about 10,000 years were required for this study, the Monte Carlo procedure was adopted. All water level recurrence statistics were based on a 10,000 years period of simulations.

6. Cyclone Data Analysis

6.1 General

The Monte Carlo procedure required that a range of cyclone simulations be undertaken to provide basic time series input data for interpolation/extrapolation. As part of this process it was necessary to describe each simulated cyclone in a general way, choosing the principal parameters - track direction, distance from the Bowen area, central pressure and forward speed, based on historical cyclone data.

In this analysis only those cyclones affecting the area over the 46 years period from 1955 to 2002 were considered. Based on previous experience, only those cyclones passing within a defined zone of influence were included in parameter analyses. This zone of influence was chosen on the basis of those cyclone tracks that might produce the highest storm surges along the Bowen Shire coast. For this study the zone of influence was defined as being the area between latitudes 17ºS and 23ºS and longitudes 145°15'E and 151°15'E. Figure 7 shows the tracks of the selected cyclones. Details are presented in Table 2, Section 4.4. Bowen is located at 20°01'S 148°15'E.

6.2 Track Direction

An inspection of the available cyclone track data led to the decision to adopt two direction categories:

- From north-east to south-west (south-westward); and
- From north-west to south-east (south-eastward).

These are generally equivalent to coast crossing and coast parallel tracks, respectively. The selection basis is related to cyclone track direction in the Bowen region. Although many cyclones do not wholly fit these descriptions, each of the 69 identified cyclones could be placed satisfactorily into one of these two direction categories.

On this basis, (43/69 =) 62% of cyclones were classified as south-westward and (26/69 =) 38% south-eastward.

6.3 Track Distance

Due to the clockwise rotating windfield structure of a cyclone, track location relative to the coastline is an important issue when determining the impact a cyclone will have on a coastal location. For example, a south-westward moving cyclone that crosses the coast to the north of this region will cause a strong storm surge to occur due to onshore winds as the cyclone crosses the coast, whereas a south-westward tracking cyclone crossing to the south of the site will cause offshore winds that push water away from the coastline. For cyclones of similar central pressure and forward speed, the inverse barometer effect and the strength of the cyclonic winds in the study region are proportional to the distance the cyclone is from the site. Wind direction is also dependent on track location, and for cyclones that pass within approximately 40km of the site, full reversal of wind direction will occur as the cyclone passes the site.

This parameter is more complex than one might expect because it is interlinked with central pressure and location north or south, east or west of the Bowen Shire. This issue is also related to the clockwise rotating windfield structure of cyclones. For example, within the adopted 6 of latitude/longitude extent from the Bowen Shire region, the lowest central pressure may not occur when the cyclone is closest to the Bowen Shire. Second, a cyclone passing 100km north of the Bowen Shire region may cause greater surge in the study region than a similar cyclone passing 100km to the south. The differences in outcome also depend on regional and local seabed topography.

For this study, track distance was defined by simplifying each cyclone track into a linear track and determining the radial distance from this track to Bowen. If a cyclone significantly changed intensity as it passed through the selected zone of influence, the distance to the most intense section of the cyclone track was chosen.

For shore crossing (south-westward) cyclones, tracks that passed north of the site were defined as positive distances; those that crossed to the south were defined with negative track distances. Similarly, for shore parallel (south-eastward) cyclone tracks, those that passed offshore of the site were defined as being positive while those that travelled over land (west of the coastline) were defined as being negative. These parameters are described in Appendix B.

6.4 Forward Speed

Forward speed may influence cyclone surge in two ways. First, the cyclonic winds may be increased by this speed on the south-eastern side of the cyclone and decreased on the north-western side. Second, when forward speed is close to the celerity of long waves, a resonance state can develop which causes an increased surge. Windfield changes would also affect waves near the Bowen Shire coast.

Average forward speeds were estimated in the region near the Bowen Shire. The results are presented in Appendix B, separately for south-westward and south-eastward tracking cyclones.

6.5 Cyclone Central Pressure

Central pressure is the cyclone parameter that has the dominant impact on wind speed. Representative cyclone central pressures that were assessed to have had the most significant impact on the site were determined in the Bowen Shire region and analysed separately for all cyclones and also for the south-westward and south-eastward tracking cyclones. Results are presented in Table 3.

Table 3 – Analysis of Cyclone Central Pressures for Selected Populations of Historical Cyclones

Return Period (years)	SW Population		SE Population		All Cyclones Since 1955	
	CP (hPa)	95% CL (hPa)	CP (hPa)	95% CL (hPa)	CP (hPa)	95% CL (hPa)
5	975	10	986	5	971	7
10	963	14	981	6	962	10
20	952	19	976	8	954	12
50	939	25	969	11	943	15
100	928	30	964	12	935	17
500	904	41	952	16	916	22
Data Points	43		26		69	
Years of Analysis	46		46		46	

The results show that south-westward tracking cyclones (coast crossing) are generally more severe than coast parallel cyclones; for the less frequently occurring cyclones. Note that Walsh and Ryan (2000) advise that present climate change investigations show that there is unlikely to be an increase in coast crossing cyclone severity.

These parameters were used to define 54 basic cyclone simulations used to prepare time series data for the Monte Carlo analyses. They are presented in Table 4. Six additional cyclones were included to describe the effect of the radius to maximum winds and astronomical tide level on surge height.

Table 4 – Parameters Adopted for Basic Cyclone Runs

Run No	Track Direction	Track Distance (km)	Vf (m/s)	CP (hPa)
1	SW	100	4	950
2	SW	100	4	970
3	SW	100	4	990
4	SW	100	8	950
5	SW	100	8	970
6	SW	100	8	990
7	SW	40	4	950
8	SW	40	4	970
9	SW	40	4	990
10	SW	40	8	950
11	SW	40	8	970
12	SW	40	8	990
13	SW	-40	4	950
14	SW	-40	4	970
15	SW	-40	4	990
16	SW	-40	8	950
17	SW	-40	8	970
18	SW	-40	8	990
19	SW	-40	4	950
20	SW	-100	4	970
21	SW	-100	4	990
22	SW	-100	8	950
23	SW	-100	8	970
24	SW	-100	8	990
25	SE	150	6	950
26	SE	150	6	970
27	SE	150	6	990
28	SE	150	12	950
29	SE	150	12	970
30	SE	150	12	990
31	SE	75	6	950
32	SE	75	6	970
33	SE	75	6	990

Run No	Track Direction	Track Distance (km)	Vf (m/s)	CP (hPa)	
34	SE	75	12	950	
35	SE	75	12	970	
36	SE	75	12	990	
37	SE	-75	6	950	
38	SE	-75	6	970	
39	SE	-75	6	990	
40	SE	-75	12	950	
41	SE	-75	12	970	
42	SE	-75	12	990	
43	SE	-150	6	950	
44	SE	-150	6	970	
45	SE	-150	6	990	
46	SE	-150	12	950	
47	SE	-150	12	970	
48	SE	-150	12	990	
49	SE	0	6	950	
50	SE	0	6	970	
51	SE	0	6	990	
52	SE	0	12	950	
53	SE	0	12	970	
54	SE	0	12	990	
55	SE	0	6	950	Radius to Max. Winds = 30km
56	SE	0	6	950	Radius to Max. Winds = 20km
57	SE	0	6	950	Radius to Max. Winds = 10km
58	SE	0	6	970	Water Level = MSL
59	SE	0	6	970	Water Level = MSL+1.0m
60	SE	0	6	970	Water Level = MSL-1.0m

The basis for selection of these simulation cyclones was their overall representation of severe, but not extremely rare cyclones. Because of the limited number of these basic runs, it was important that a reliable basis for describing the parameters of the greatest number of simulated cyclones was developed.

6.6 Greenhouse Related Climate Change Issues

At the commencement of the study, two documents provided the information most relevant to this matter. They were:

- Climate Change in Queensland under Enhanced Greenhouse Conditions, Second Annual Report (1998-1999) prepared by CSIRO Atmospheric Research; and
- Walsh, K.J.E. and Ryan, B.F (2000): Tropical cyclone intensity increase near Australia as a result of climate change. Journal of Climate, Vol.13.

The (1998-1999) CSIRO report is now superseded by the (1999-2000) report.

The main issues are:

- What is the likely magnitude of change, if any, in MSL over a 50 years planning period (say)?
- What is the likely change in cyclone occurrence frequency, if any?
- What is the likely change in cyclone intensity, if any?

6.6.1 MSL Rise

The issue of MSL rise is addressed by Walsh and Ryan (2000). Walsh is also an author of the CSIRO reports and this matter does not appear to be addressed in the (1999-2000) CSIRO report. The increase in MSL advised is 0.2m over 50 years. A range of 0.1m to 0.4m was advised in the CSIRO (1998-1999) report as part of discussions on storm surge analyses for Cairns. This is supported by IPCC (2001).

From discussions with Council, it is understood that at present no MSL rise over the next 50 years has been adopted. A figure of 0.2m for the next 50 years is advised. This parameter would need to be re-assessed on a decadal basis, or as substantial new information became available. This is consistent with basic hydrodynamics and recommendations in CSIRO (1999-2000).

6.6.2 Cyclogenesis Changes

Section 3 of CSIRO (1999-2000) addresses the likely (though not definite) changes in cyclone activity in the Queensland region. This CSIRO report also discusses the Monte Carlo procedure, which is consistent with the overall approach adopted for this study.

Parameters proposed by CSIRO for inclusion in the Monte Carlo analysis are central pressure, radius to maximum winds, forward speed and coast parallel and coast crossing cyclones. CSIRO have analysed data for the Hervey Bay region using a regional extent similar, but not identical, to that adopted for this study. There is no definitive basis for this choice, both are realistic; the basic assumption being that cyclone parameters within the adopted region are similar throughout the adopted region. Note that CSIRO's main purpose in their Section 3 was to examine design wind speeds over land and cyclone filling was also considered by them.

6.6.3 Extreme Event Analysis

Although CSIRO discuss frequency of cyclone occurrence on the basis of coast parallel and coast crossing cyclones, they do not appear to describe cyclone intensity recurrence in terms of these separate populations, see Figure 3.5 of CSIRO (1999-2000).

CSIRO (1999-2000) adopt the Generalised Pareto Distribution (GPD) to describe the frequency of recurrence of cyclones with specific central pressures. CSIRO choose the GPD rather than the more common Extreme Value Type 1 (EXV1) distribution (termed Gumbel by CSIRO) because the GPD has an upper limit extreme value. They also state, incorrectly in our view, '...that the GPD also has an advantage over the Gumbel distribution in that all available data are used to fit the distribution rather than just the extreme value within a specified time interval'. That statement is correct only when annual minimum central pressures are used, for example, in a Gumbel analysis procedure. Using the EXV1 (same theoretical formulation as Gumbel) though, all data is used in either the Method of Moments, Least Squares or Maximum Likelihood Method. Moreover, there is the issue of adopting a physically realistic minimum central pressure. CSIRO do not specify how this should be done, or whether they did for the CSIRO (1999-2000) report. However, their Figure 3.5 implies a minimum central pressure of about 940hPa for the Hervey Bay region.

For this study a minimum central pressure of 920hPa was adopted for present day cyclone simulations.

6.6.4 Forward Speed

This study has analysed cyclone forward speed in a manner very similar to that applied by CSIRO. However, the parameters have been developed separately for coast parallel and coast crossing cyclones for this study. The probability density function was described as a cumulative frequency distribution, refer Appendix B, and sampled using random numbers within the Monte Carlo analysis.

6.6.5 Radius to Maximum Winds (Rm)

CSIRO (1999-2000) propose 30km. Note that cyclone Dinah probably had an Rm closer to 40km, based on cyclone track data for that event and wind data recorded at Sandy Cape at the northern end of Fraser Island. A radius of 40km was used for this study. Additionally, the sensitivity of the results to choice of Rm was examined.

6.6.6 Direction of Approach

A similar procedure for approach direction has been followed in this study. However, a theoretical distribution was not fitted to the data, as was adopted by CSIRO, but rather a cumulative probability distribution based on the actual occurrences was used, refer Appendix B.

Distance from the Bowen area was also included in this study using a statistical description.

6.6.7 Changes in Cyclogenesis

Estimated changes in cyclone intensity are summarised in Table 3.4 of CSIRO (1999-2000). For the Queensland region, cyclone central pressures are likely to reduce by 5hPa, on average, over the next 50 years.

The CSIRO (1999-2000) report discusses the point that cyclones with central pressures greater than 985hPa may not change, whereas cyclones more intense than 985hPa may increase in intensity by more than the average 5hPa.

For this study, two Monte Carlo analyses were undertaken. They were:

- An analysis based on existing cyclone data, to which could be added 0.2m (to be confirmed) for projected MSL rise over the next 50 years.

- An analysis based on an average increase in cyclone intensity of 5hPa, to which could be added 0.2m for projected MSL rise over the next 50 years.

7. Storm Surge Modelling

7.1 Model Set-up

The numerical current and storm surge model applied to this investigation was the Delft3d hydrodynamic modelling system. This system provides a third order finite difference solution to the equations of mass and momentum conservation. It uses an alternating direction, implicit solution scheme.

The model has been applied to many investigations throughout Australia by L&T. It includes tidal and wind forcing, wetting and drying and turbulence model eddy viscosity terms. The model also includes spatially variable bed friction. Roughness height was set to be a Mannings 'n' of 0.025. There is generally not a large area of hinterland inundation. The model also has a range of other modules, such as an advection-dispersion module, which can be operated in parallel with the hydrodynamic module.

Wind set-up develops across the near shore area as the result of interfacial shear between the wind and sea surface and the consequent onshore currents. The Coriolis acceleration acting on northward flowing coastal currents may also cause a storm surge component. Set-up is inversely proportional to water depth, directly proportional to fetch and proportional to the square of wind speed. A large area model was established to ensure physically realistic development of these currents and set-up. This model area extended north to Townsville, south to Mackay and seaward beyond the 200m depth. Grid sizes vary from about 100m near the coastline to 8km offshore and at the northern and southern ends of the model. Figure 10 shows the extent of the Delftd3d model used in this investigation.

Two other features of the model were important to this study. First, the model has an advanced curvilinear grid system. This grid system enables preparation of a grid that better follows the natural curvature of the coastline. Preparation of the grid in curvilinear form reduces the so-called stair-case problem of fixed grid size rectangular grids, which tend to falsify bed friction along narrow waterways that are not closely aligned with the grid. It also allows fine grid resolution in these narrow waterways and near the coastline, whilst allowing a coarser grid further away where high resolution is not required.

Second, a cyclone passing to the north of Bowen will drive water southward into the Port Denison area where some flow constriction will occur. When this happens there will be a natural tendency for some back-flow near the seabed to occur, as well as horizontally at different locations. This flow structure can be described better by three-dimensional modelling, which also allows better application of wind stress to the water column.

Wind fields were computed from the available historical cyclone track data for model calibration/verification and from idealised cyclone track data for the basic Monte Carlo simulations. The wind and pressure fields were prepared using the Holland wind model developed for the Bureau of Meteorology. This model is considered to provide the most realistic description of cyclonic windfields for the Australian region.

7.2 Model Verification

Three cyclones were selected for model verification. They were the so-called Bowen cyclone in 1958 and Cyclones Aivu and Celeste in April, 1989 and January, 1996, respectively. Peak surge for the Bowen cyclone was about 1.5m at Bowen. For Aivu, peak surge was about 1.2m at Bowen and occurred at a tidal level of about 0.5m AHD, refer Figure 8. Peak surge was only 0.4m during Cyclone Celeste and occurred near MSL at Bowen, refer Figure 9.

Figures 11, 12 and 13 show that the modelled surge peak was reproduced well for these cyclones. Figure 14 shows the extent of storm surge in the Bowen region near the time of peak surge during Cyclone Aivu.

The outcome of the calibration task shows that the model system can be used confidently to predict cyclone surge in the Bowen region.

8. Monte Carlo Procedure

8.1 Analysis Processes

Previous sections have discussed the fifty-four basic model cyclone surge simulations that were undertaken. These results provided time series of cyclone surge over 72 hour periods at intervals of 0.5 hours.

In reality cyclone central pressures will vary considerably and coastline crossing may be any distance from the Bowen region, or cyclones may run parallel to the coast, offshore or inland of the Bowen region. Furthermore, the phases of peak surge relative to high and low water of the astronomical tides will be random.

Extreme water levels could be determined from very long term tidal records, which would include cyclone occurrences, but these are not available for the Bowen region. A practical alternative is to perform a Monte Carlo modelling exercise.

Monte Carlo modelling requires the generation of a large number of simulated cyclone events. These simulated cyclones are generated by randomly selecting parameters from distributions created by analysing historical cyclones, which have affected the area. Because the historical data showed that south-westward tracking cyclones exhibited different characteristics to the south-eastward moving cyclones, they were considered separately. Distributions of historical cyclone parameters for characteristics including distance to landfall, forward speed and central pressure were developed for both cyclone data populations, refer Appendix B and Table 4.

Sixty-nine cyclones were defined as being significant cyclonic events occurring in the region since 1955. This means that the average inter-arrival time of cyclones that affect the Bowen region is 0.67 years, that is, more than one each cyclone season. Of these, 62% will be coast-crossing (south-westward) while 38% will be coast-parallel (south-eastward) tracking cyclones. Coast crossing cyclones are normally marginally more severe than coast parallel cyclones in this region. Figure 15 describes the cyclone tracks used to prepare the basic simulation results.

Once track direction has been selected, a simulated cyclone is then given other cyclone parameters. Track distance from the Bowen region and forward speed were selected using random numbers to select values from the distribution of cyclone parameters, refer Appendix B.

Central pressures were determined independently by sampling randomly and fulfilling the central pressure versus probability of non-exceedance distributions determined from the cyclone data. This was done using the analytical expressions (Extreme Value Type 1) representing the best fit to the data. They are:

- South-westward Cyclones
  $0.0683 \times (p - 987.1) = -\ln(-\ln P)$
  $P = 1-(1/\lambda R)$
  $\lambda = 0.5652$

- South-eastward Cyclones
  $0.1391 \times (p - 996.6) = -\ln(-\ln P)$
  $P = 1-(1/\lambda R)$
  $\lambda = 0.93478$

Where,

R is average recurrence interval (years)
λ is average number of cyclones per year
p is cyclone central pressure (hPa)
P is probability of non-exceedance

Central pressures higher than 1001hPa were discarded and another choice made. These events were not considered to be cyclones. Similarly, central pressures lower than 920hPa were discarded. This is a slightly arbitrary choice, but is lower than any cyclone that has affected the area and recognises that sea temperatures limit the possible central pressure. Long term mean atmospheric pressure was adopted to be 1010hPa. These modelling processes were checked by calculating the average recurrence interval relationship(s) of simulated central pressures. The agreement was good.

Because the hydrodynamic model was set-up to calculate storm surge only, suitable time-series of tide elevations were required to allow the calculation of total water elevations (storm tide) during the simulated cyclones. Nineteen years of astronomical tides at half-hourly intervals were predicted using the so-called Canadian tidal package (Foreman, 1977) and tidal constants for Abbot Point and Bowen provided in Australian National Tide Tables, 2002. This period of time allows for recession of the lunar nodes along the plane of the ecliptic and the associated changes in tidal range.

No other suitable tidal station exists south of Bowen and close to Greta Creek. Therefore Bowen tides were used for Bowen and locations south of Bowen, whereas tidal interpolation was used for locations between Bowen and Abbot Point. Beyond Abbot Point the Abbot Point tides were applied.

Random numbers were used to select a time series of tidal levels from any one of the nineteen years and any of the months between December and May, the typical cyclone season for this area. In this manner the correct arrival time structure was formed and cyclone arrival times and tides varied randomly.

Random numbers were used to select other cyclone parameters based on distributions of historical cyclones in the region of influence, see Appendix B. Once all the parameters (track direction, minimum track distance to site, forward speed and central pressure) of each simulated cyclone were determined, time series of storm surge were interpolated from the fifty-four basic simulation runs. Total water level (storm tide) for the event was then calculated by adding the storm surge time-series to the randomly selected time series of tidal levels.

In addition to the basic fifty-four simulations undertaken to provide input to the Monte Carlo analyses, it was important to test the sensitivity of the analyses to tide levels and radius to maximum wind speed. Wind set-up is inversely proportional to water depth.

Figure 16 compares the results for three values of Rm – 10km, 20km, 30km and 40km. The track selected for this comparison was south-east with 0km track distance from the coastline. This track will typically cause the greatest storm surge in the Bowen region. The simulation was undertaken with a central pressure of 950hPa. The results show that for this site Rm can be important. The greatest surge was caused by an Rm of 40km, which was adopted for this study.

Storm surge (wind set-up component) is dependent on water depth. Therefore, in the very near shore region, where tide range has a significant influence on water depth, it is an important issue. However, in the Monte Carlo based analysis, the basic simulations were undertaken at MSL, the most common tide level. This means, in a simple topographical region, that surges occurring at high tide would be over-estimated, whereas those occurring near low tide would be underestimated, to some extent. Figure 17 compares surge time series at Bowen for three tide levels adopted for describing the effect of tide level on storm surge – MSL-1.0m, MSL and MSL+1.0m. The result is consistent with the concepts discussed above and shows that the effect is in the order of 10%. Those results were applied on a site specific basis to the Monte Carlo procedure, adjusting the basic-run surge results according to each simulated tide.

8.2 Results

Simulations of 10,000 years were undertaken and the simulated time series of results stored. Monte Carlo simulation results were analysed by ranking them in terms of peak event storm tide and then undertaking an Extreme Value Type 1 Analysis using the method of moments.

The outcome of the analyses is presented in Table 5 in terms of datum AHD. Locations of output points in Table 5 are shown in Figure 18. Water levels are presented for the 50 years average recurrence interval (ARI) and longer. No Greenhouse related MSL rise has been included. Time series plots of combined astronomical tide and storm surge water level for Cyclones Aivu and Althea are shown in Figures 19 and 20. The time series provide a basis for assessment of inundation times and for assessment of inland flows. Storm tide is dominated by the astronomical tide and peak water levels caused by cyclone surge will persist only for durations up to six hours.

Table 5 – Peak Storm Tide at Selected Locations Excluding Greenhouse Related Climate Change

Location	ARI Water Levels (m AHD)				
	50 year	100 year	500 year	1,000 year	10,000 year
Molongle Creek	2.62	2.91	3.50	3.75	4.56
Cape Upstart (North)	2.28	2.51	2.98	3.17	3.80
Cape Upstart (South)	2.37	2.62	3.11	3.32	3.99
Salisbury	2.52	2.79	3.34	3.57	4.32
Abbot Point (North)	2.30	2.54	3.02	3.22	3.88
Abbot Point	2.12	2.31	2.70	2.86	3.40
Abbot Point (South)	2.41	2.67	3.2	3.42	4.14
Between Abbot Point /Queens Beach	2.33	2.56	3.04	3.24	3.90
Queens Beach (North)	2.39	2.62	3.09	3.29	3.94
Queens Beach (Centre)	2.36	2.59	3.06	3.26	3.90
Queens Beach (South)	2.30	2.51	2.95	3.14	3.74
Cape Edgecumbe	2.30	2.51	2.94	3.12	3.71
Kings Beach (North)	2.36	2.58	3.05	3.24	3.87
Kings Beach (South)	2.39	2.62	3.09	3.29	3.94

Location	ARI Water Levels (m AHD)				
	50 year	100 year	500 year	1,000 year	10,000 year
Bowen (North)	2.47	2.72	3.23	3.44	4.14
Bowen Breakwater	2.50	2.76	3.28	3.50	4.22
Bowen Wharf	2.51	2.77	3.3	3.52	4.24
Bowen (South)	2.54	2.81	3.35	3.58	4.32
Edgecumbe Bay (N1)	2.64	2.93	3.51	3.75	4.55
Edgecumbe Bay (N2)	2.52	2.78	3.32	3.54	4.27
Adelaide Point	2.48	2.73	3.25	3.46	4.17
Brisk Bay	2.52	2.77	3.3	3.51	4.22
Heronvale	2.61	2.88	3.44	3.67	4.44
White Cliffs	2.56	2.83	3.37	3.60	4.34
Sinclair Bay	2.25	2.43	2.82	2.97	3.49

Previous studies have shown that at more frequent ARI (eg 20 year), high water levels are more likely to be produced by high astronomical tides together with other meteorological events such as east coast lows, rather than cyclone storm surge.

The highest storm tides generally occur at Molongle Creek and Edgecumbe Bay and there are significant variations in design water levels amongst the sites within the study area. Some of this variation is caused by the slightly lower tides at Abbot Point. A comparison between these results and those of Blain, Bremner and Williams (1985), shows that the levels presented in this report are generally higher, being only 0.1m greater at Abbot Point, but about 0.3m higher at Bowen. This outcome has most likely been the result of the finer grid applied to this study and the greater resolution of embayments, for example Edgecumbe Bay.

Table 6 presents equivalent results for the case where central pressures have been reduced by 5hPA in order to represent possible Greenhouse related climate change cyclonic response. No MSL rise has been included.

Table 6 – Peak Storm Tide at Selected Locations Including Greenhouse Related Climate Change to Cyclone Central Pressure, but not to MSL

Location	ARI Water Levels (m AHD)				
	50 year	100 year	500 year	1,000 year	10,000 year
Molongle Creek	2.74	3.03	3.62	3.86	4.67
Cape Upstart (North)	2.37	2.59	3.06	3.26	3.89
Cape Upstart (South)	2.46	2.70	3.18	3.39	4.05
Salisbury	2.63	2.89	3.43	3.65	4.38
Abbot Point (North)	2.41	2.65	3.16	3.36	4.05
Abbot Point	2.19	2.39	2.79	2.96	3.50
Abbot Point (South)	2.52	2.78	3.31	3.53	4.25
Between Abbot Point /Queens Beach	2.43	2.77	3.16	3.37	4.05

Location	ARI Water Levels (m AHD)				
	50 year	100 year	500 year	1,000 year	10,000 year
Queens Beach (North)	2.48	2.71	3.20	3.40	4.06
Queens Beach (Centre)	2.46	2.69	3.17	3.37	4.03
Queens Beach (South)	2.38	2.60	3.06	3.24	3.86
Cape Edgecumbe	2.38	2.59	3.03	3.22	3.82
Kings Beach (North)	2.45	2.67	3.15	3.34	3.98
Kings Beach (South)	2.48	2.72	3.20	3.40	4.06
Bowen (North)	2.57	2.82	3.35	3.57	4.28
Bowen Breakwater	2.60	2.87	3.40	3.62	4.35
Bowen Wharf	2.62	2.88	3.42	3.64	4.38
Bowen (South)	2.65	2.93	3.49	3.72	4.48
Edgecumbe Bay (N1)	2.77	3.06	3.66	3.91	4.72
Edgecumbe Bay (N2)	2.64	2.91	3.46	3.69	4.44
Adelaide Point	2.59	2.85	3.39	3.61	4.34
Brisk Bay	2.64	2.90	3.44	3.66	4.39
Heronvale	2.74	3.02	3.60	3.84	4.62
White Cliffs	2.71	2.98	3.53	3.76	4.52
Sinclair Bay	2.35	2.54	2.94	3.10	3.65

9. Wave Set Up

9.1 General

Wave setup is caused by the conservation of wave momentum flux in the surf zone, Goda (2000). The shoreward decrease in wave height in the breaker zone leads to a gradient in wave radiation stresses and a consequent increase in the 'still water level' in the shoreward direction. Wave grouping causes some fluctuations in this still water level. At the breaker line there is a setdown.

This shoreward increase in water level is called wave set-up and it increases non-linearly in the shoreward direction. It is greatest at the shoreline and is additional to storm tide.

Wave set-up depends upon 'near shore' wave height. Five historical cyclone events were selected for this investigation. They were:

- Kerry (1979);
- Watorea (1976);
- Celeste (1996);
- Aivu (1989); and
- Althea (1971).

These cases were selected because offshore wave heights were expected to be high and they represented different offshore wave directions.

9.2 Wave Modelling

The first step in this investigation was to set up an offshore wind/wave model based on the second generation wind/wave modelling system, ADFA1, developed by Dr Ian Young of the Australian Defence Force Academy. The model is based on a numerical solution of the Radiative Transfer Equation and is applicable in water of any depth. It predicts the evolution of the directional wave energy spectrum as a result of the processes of wind energy transfer, propagation, refraction, shoaling, bed friction, white capping, nonlinear wave-wave inter-action and depth limited wave breaking. Output from the model includes significant wave height, dominant wave direction and spectral peak wave period at selected grid points.

The wind/wave model was established on a 5km computational grid width an origin at 23°S:148°30' E. The model extended northward to approximately 20° S and eastward to approximately 154° E. A time step of 7.5 minutes was adopted to ensure physically realistic wave propagation and growth. The frequencies selected for spectral description ranged from 0.03Hz to 0.423Hz - a total of fifteen frequencies being used. Directional resolution was based on sixteen divisions of the compass. The Holland wind model, developed by the Australian Bureau of Meteorology for tropical regions of Australia, was used to calculate cyclone wind fields from the cyclone track parameters. The model extent and spatial resolution are considered more than adequate for the description of peak storm wave conditions arising from tropical cyclones. Generally, little wave energy propagates through the Great Barrier Reef and wave generation occurs within the reef lagoon for waves affecting this shoreline.

In addition to this regional model, two finer grid (150m) SWAN wave models were established for the inshore area. The models were orientated at 30°, which is approximately perpendicular to the coastline in the Bowen region. Two model grids were required to cover the extent of coastline with appropriate spatial resolution and to avoid model edge effects. The SWAN model is part of the Delft3d system and was developed at the Delft Technical University. It includes natural bathymetry, offshore wave input (parametric or spectral), wind input, refraction, shoaling, bed friction, full frequency-direction wave propagation, white-capping, wave/current interaction and solutions to third order. Fine grids can be nested within coarser outer grids. The model system is considered to be one of the most reliable. Output from the ADFA1 model was used as boundary input data for the SWAN wave propagation model, which transferred offshore waves to the nearshore region extending along the coastline from Greta Creek to Wangaratta Creek.

Output locations from the SWAN model were located in approximately 5m of water depth at each of the study sites. Figure 21 shows the southern region SWAN model for the study area, together with example output for Cyclone Kerry.

Using a surf zone model with beach profiles estimated from Bowen Shire Council survey data and site photographs, wave set-up was calculated using SWAN model output as input in water depths of about 5m, where wave set-up is negligible. Wave set-up was calculated following the procedures developed by Goda (2000). In general, wave set-up is approximately 10% of the nearshore significant wave height at this site. The relationship depends on seabed slopes and wave period.

These linked ADFA1 and SWAN wave models are hereinafter referred to as the wave model system.

9.3 Model Verification

In order to verify the wave model system, output for Cyclone Kerry was compared to peak wave conditions recorded at the Abbot Point Waverider Buoy and provided by the BPA. Additionally, the daily synoptic charts prepared by the Bureau of Meteorology were inspected to estimate offshore wave direction. Peak recorded conditions occurred on 2 March 1976. They were:

- Hs = 2.2 m;
- Tp = 7.4 s;
- Direction ESE (estimated by EPA).

Modelled results for Cyclone Kerry were as follows:

- Hs = 2.2 m;
- Tp = 6.5 s;
- Direction = 43°.

This verification indicates good agreement between modelled results and recorded data for this event, within the range of data available, and gives confidence in the modelling system to predict wave parameters reliably for this location. Figure 21 shows the peak wave conditions in the Bowen Shire area during Cyclone Kerry.

9.4 Results

Results from the wave modelling, as described above, are presented in Table 7. As can be seen from these results, the nearshore wave height (5m depth) is typically only 2m with wave direction between 45° and 90° at peak wave conditions in this study area. This seems low, but is the outcome of wave propagation across extensive, shallow seabed areas and fetch limitations caused by The Great Barrier Reef.

Table 7 – Wave Modelling Results at 5m AHD Depth Approximately

Cyclone Event	Wave Model (offshore) Output			Inshore Location	SWAN (inshore) output		
	Hs (m)	Tp (s)	Direction		Hs (m)	Tp (s)	Direction (°)
Aivu	5.8	10.1	77	Abbot Bay	2.1	10.7	55
				Abbot Point	2.4	10.7	63
				Queens Beach (N)	2.3	10.7	66
				Queens Beach (C)	2.2	10.7	53
				Queens Beach (S)	2.2	10.7	46
				Kings Beach	2.6	10.7	69
				Bowen	1.7	4.5	110
				Edgecumbe Bay (N)	1.9	5.7	84
				Heronvale	2.4	6.5	58
				Sinclair Bay	1.9	10.7	46
	6	9.4	42	Molongle Creek	2.2	9.5	28
				Cape Upstart (N)	1.9	9.5	0
				Cape Upstart (S)	3.5	9.5	52
				Abbot Bay	2.1	9.5	40
				Abbot Point	2.3	9.5	40
				Queens Beach (N)	2.3	9.5	46
				Queens Beach (C)	2.3	9.5	38
				Queens Beach (S)	2.4	9.5	32
				Kings Beach	2.6	9.5	45
				Bowen	1.1	4.5	75
				Edgecumbe Bay (N)	1.7	5.1	59
				Heronvale	2.7	9.5	36
				Sinclair Bay	2.1	9.5	12
	7.4	11.8	90	Molongle Creek	2.2	5.1	70
				Cape Upstart (N)	1.6	12.1	38
				Cape Upstart (S)	3.7	12.1	80

Cyclone Event	Wave Model (offshore) Output			Inshore Location	SWAN (inshore) output		
	Hs (m)	Tp (s)	Direction		Hs (m)	Tp (s)	Direction (°)
Althea	4.8	9.1	80	Abbot Bay	2	9.5	51
				Abbot Point	2.3	9.5	63
				Queens Beach (N)	2.2	9.5	65
				Queens Beach (C)	2.1	9.5	51
				Queens Beach (S)	2.1	9.5	42
				Kings Beach	2.4	9.5	65
				Bowen	1.2	4	109
				Edgecumbe Bay (N)	1.4	5.1	84
				Heronvale	2	9.5	56
				Sinclair Bay	1.3	9.5	49
	6	10.8	93	Molongle Creek	1.6	10.7	70
				Cape Upstart (N)	1.1	10.7	35
				Cape Upstart (S)	3.53	10.7	79
Celeste	3.5	7	76	Molongle Creek	1.4	4	63
				Cape Upstart (N)	0.8	8.4	47
				Cape Upstart (S)	2.8	7.4	77
				Abbot Bay	2	7.4	53
				Abbot Point	2.1	7.4	67
				Queens Beach (N)	2.2	7.4	66
				Queens Beach (C)	2.1	7.4	51
				Queens Beach (S)	2	7.4	43
				Kings Beach	2.3	7.4	68
				Bowen	1.2	4	103
				Edgecumbe Bay (N)	1.4	5.1	84
				Heronvale	1.9	5.1	59
				Sinclair Bay	1.2	4	59

Cyclone Event	Wave Model (offshore) Output			Inshore Location	SWAN (inshore) output		
	Hs (m)	Tp (s)	Direction		Hs (m)	Tp (s)	Direction (°)
Kerry	2.4	6.5	45	Molongle Creek	1.3	6.5	27
				Cape Upstart (N)	0.8	6.5	3
				Cape Upstart (S)	2.2	6.5	58
				Abbot Bay	1.9	6.5	40
				Abbot Point	1.9	6.5	48
				Queens Beach (N)	2.1	6.5	50
				Queens Beach (C)	2	6.5	40
				Queens Beach (S)	2.1	6.5	32
				Kings Beach	2.1	6.5	48
				Bowen	0.6	3.1	90
				Edgecumbe Bay (N)	0.9	4	70
				Heronvale	1.6	6.5	40
				Sinclair Bay	1.1	6.5	24
Watorea	1	3.9	115	Molongle Creek	0.3	2.1	110
				Cape Upstart (N)	0.2	1.9	147
				Cape Upstart (S)	0.5	3.5	106
				Abbot Bay	0.3	2.7	88
				Abbot Point	0.5	4	88
				Queens Beach (N)	0.4	3.5	92
				Queens Beach (C)	0.3	2.7	83
				Queens Beach (S)	0.3	3.5	84
				Kings Beach	0.5	3.1	108
				Bowen	0.4	2.7	122
				Edgecumbe Bay (N)	0.4	3.1	100
				Heronvale	0.4	2.7	103
				Sinclair Bay	0.2	1.9	101

Wave set-up analysis for these peak inshore wave conditions and subsequent extremal analysis leads to the estimated wave set-up heights presented in Table 8.

Table 8 – Estimated Wave Set-up

Location	ARI Set-up Heights (m)				
	50	100	500	1000	10000
Molongle Creek	0.3	0.3	0.4	0.4	0.4
Cape Upstart (North)	0.3	0.3	0.4	0.4	0.4
Cape Upstart (South)	0.2	0.2	0.2	0.2	0.2
Salisbury	0.3	0.3	0.4	0.4	0.4
Abbot Point (North)	0.3	0.3	0.4	0.4	0.4
Abbot Point	0.3	0.3	0.4	0.4	0.4
Abbot Point (South)	0.3	0.3	0.4	0.4	0.4
Between Abbot Point/ Queens Beach	0.3	0.3	0.4	0.4	0.4
Queens Beach (North)	0.3	0.3	0.4	0.4	0.4
Queens Beach (Centre)	0.3	0.3	0.4	0.4	0.4
Queens Beach (South)	0.3	0.3	0.4	0.4	0.4
Cape Edgecumbe	0.3	0.3	0.4	0.4	0.4
Kings Beach (North)	0.3	0.3	0.4	0.4	0.4
Kings Beach (South)	0.3	0.3	0.4	0.4	0.4
Bowen (North)	0.2	0.3	0.3	0.3	0.3
Bowen Breakwater	0.2	0.3	0.3	0.3	0.3
Bowen Wharf	0.2	0.3	0.3	0.3	0.3
Bowen (South)	0.2	0.3	0.3	0.3	0.3
Edgecumbe Bay (N1)	0.2	0.3	0.3	0.3	0.3
Edgecumbe Bay (N2)	0.2	0.3	0.3	0.3	0.3
Adelaide Point	0.4	0.5	0.6	0.6	0.6
Brisk Bay	0.4	0.5	0.6	0.6	0.6
Heronvale	0.4	0.5	0.6	0.6	0.6
White Cliffs	0.4	0.5	0.6	0.6	0.6
Sinclair Bay	0.2	0.3	0.4	0.4	0.4

These are the wave set-up heights occurring jointly with storm tide at the specified ARI.

9.5 Inclusion of Wave Set-up in Water Level Statistics

In order to include wave set-up in total water level in a manner that is fully physically realistic, it would be necessary to undertake a detailed joint occurrence study of cyclone surge and wave set-up using historical storms so that relative phasing and duration were explicitly included. Such a study would also be best undertaken together with rainfall/runoff modelling so that fresh water flows in the principal estuaries were included also.

This study has shown that offshore wave direction does not have a major influence on nearshore wave heights and set-up, at least over the commonly occurring wave directions. Wave set-up heights are to be added to the storm tide statistics of Tables 5 and 6 at the specified ARI, except for locations on the frontal dune, where wave runup (which implicitly includes wave set-up) is added instead, see Section 10.

Note that peak storm wave heights for storms of 20 or more years ARI will not vary greatly and that peak wave set-up for those events will be similar. It is also unlikely that peak wave set-up will occur at the same time as peak storm tide. The wave set-up heights presented in Section 9.4 reflect that characteristic.

10. Property Design Water Levels

In respect to suitable design water levels for coastal property in the study area, it is recommended that the 100 years ARI storm tide is the appropriate design level. This level should include the possible Greenhouse related MSL rise of 0.2m; that is, 0.2m should be added to the 100 year ARI water levels given in Table 4. Wave set-up for 100 years ARI is 0.3m, refer Section 9.4, but is included in wave runup, see below.

For coastal sites it is also necessary to include wave runup for habitable and commercial floor levels of buildings in order to prevent ocean inundation. Wave runup is difficult to assess because it depends on seabed slope near the breaker line. Based on survey data provided by Bowen Shire Council, the foreshore slope at Queens Beach South, for example, including the design storm tide, is about 1:25. However, it could be steeper if wave action is causing rapid sand transport offshore and an erosion escarpment forms in the back-beach area.

Previous studies have found the relationship of Holman (1986) to be realistic for runup calculation on natural and near-natural shoreline areas. It is:

- $R2 = (5.2\beta + 0.2)Hs$

Where,

R2 is the wave runup height exceeded by only 2% of waves
β is bottom slope near the Still Water Line.
Hs is significant wave height in 5 to 6m depth

From Section 9.4 the nearshore wave height (5m depth) is typically only 2.5m at peak wave conditions in this study area. The outcome then is that a realistic 'estimate' of R2 is 2m. This includes wave set-up implicitly. Note that:

- Wave set-up is manifested as a relatively steady increase in water level that occurs at the coastline and can propagate into bays and creeks. It varies over times in the order of hours. Hence it should be included in the boundary time series input to inundation modelling.

- Wave runup is what one sees at the beach when a wave breaks and rushes up the beach face. It varies metres over times of a few seconds. It is only important at the coastline, unless it causes significant overtopping and filling of the area behind the beach. This can lead to a drainage problem if the water can not escape back to the beach.

On this basis, floor levels for coastline sites should be set at 2m above the 100 year ARI water level for the specific locations indicated in Table 5, plus 0.2m MSL rise and 0.3m freeboard. The definition of a coastline site is a little unclear, but applies to all properties on the frontal dune. At Queens Beach South, for example, design level is 5.0 mAHD.

Table 9 presents estimated wave runup values for the Bowen coastline.

Table 9 – Estimated Wave Runup

Location	ARI Runup Heights (m)				
	50	100	500	1000	10000
Molongle Creek	1.8	1.8	1.8	1.8	1.8
Cape Upstart (North)	1.5	1.5	1.5	1.5	1.5
Cape Upstart (South)	2.0	2.0	2.0	2.0	2.0
Salisbury	2.0	2.0	2.0	2.0	2.0
Abbot Point (North)	1.5	1.5	1.5	1.5	1.5
Abbot Point	2.0	2.0	2.0	2.0	2.0
Abbot Point (South)	2.0	2.0	2.0	2.0	2.0
Between Abbot Point/ Queens Beach	2.0	2.0	2.0	2.0	2.0
Queens Beach (North)	2.0	2.0	2.0	2.0	2.0
Queens Beach (Centre)	2.0	2.0	2.0	2.0	2.0
Queens Beach (South)	2.0	2.0	2.0	2.0	2.0
Cape Edgecumbe	2.0	2.0	2.0	2.0	2.0
Kings Beach (North)	2.0	2.0	2.0	2.0	2.0
Kings Beach (South)	2.0	2.0	2.0	2.0	2.0
Bowen (North)	1.0	1.0	1.0	1.0	1.0
Bowen Breakwater	1.0	1.0	1.0	1.0	1.0
Bowen Wharf	1.0	1.0	1.0	1.0	1.0
Bowen (South)	1.0	1.0	1.0	1.0	1.0
Edgecumbe Bay (N1)	1.0	1.0	1.0	1.0	1.0
Edgecumbe Bay (N2)	1.5	1.5	1.5	1.5	1.5
Adelaide Point	1.8	1.8	1.8	1.8	1.8
Brisk Bay	1.8	1.8	1.8	1.8	1.8
Heronvale	1.8	1.8	1.8	1.8	1.8
White Cliffs	1.8	1.8	1.8	1.8	1.8
Sinclair Bay	1.0	1.0	1.0	1.0	1.0

Where properties are 'back' from the shoreline, waves may overtop the back-beach area and propagate in-land; for an unspecified distance, but in the order of 100m. Therefore for a property about 100m inland, built on a land level of 2.3m AHD, at Queens Beach South, for example, storm tide plus 0.2m MSL rise and 0.3m wave set-up would lead to a water depth of 0.7m (3.0-2.3m AHD). Wave heights at the site might then be 0.6 x water depth ≅ 0.4m (based on work by Nelson (1983) on depth limited waves with flat bed slopes) with wave runup of 0.2m. Floor levels would then need to be at 3.5m AHD to prevent inundation, (including a freeboard of 0.3m).

Estimated design floor levels for frontal dune and hinterland sites are presented in Table 10. Note that for hinterland sites, no attenuation of the storm tide has been included. It is understood that Bowen Shire Council intend undertaking additional investigations to quantify that process.

Table 10 – Design Levels for Properties Affected By Storm Surge

Location	Design Levels (m AHD)	
	Coastal Site	Wave Overtopping affecting Inland Site*
Molongle Creek	5.2	4.0
Cape Upstart (North)	4.5	3.4
Cape Upstart (South)	5.1	3.6
Salisbury	5.3	3.9
Abbot Point (North)	4.5	3.4
Abbot Point	4.8	3.1
Abbot Point (South)	5.2	3.7
Between Abbot Point/ Queens Beach	5.1	3.6
Queens Beach (North)	5.1	3.6
Queens Beach (Centre)	5.1	3.6
Queens Beach (South)	5.0	3.5
Cape Edgecumbe	5.0	3.4
Kings Beach (North)	5.1	3.6
Kings Beach (South)	5.1	3.6
Bowen (North)	4.2	3.7
Bowen Breakwater	4.3	3.9
Bowen Wharf	4.3	3.9
Bowen (South)	4.3	3.9
Edgecumbe Bay (N1)	4.4	4.0
Edgecumbe Bay (N2)	4.8	3.9
Adelaide Point	5.0	3.7
Brisk Bay	5.1	3.9
Heronvale	5.2	4.0
White Cliffs	5.1	3.9
Sinclair Bay	3.9	3.3

** - Based on a land level of RL 2.3 m AHD.*

11. Storm Surge/Flooding Inundation

Having predicted storm tide levels and wave set-up along the coastline, it was then appropriate to determine resulting inundation of inland areas. In general, this is not simply a matter of adopting the storm tide level at the coast and projecting it inland at a constant level. There are numerous physical features that would influence the inland propagation of an elevated storm tide, and it was important to take these into consideration. In addition, the township of Bowen and the Queens Beach area are particularly susceptible to inundation from Don River flood events and the potential impact of combined storm surge and freshwater events needed to be considered.

To assist in the prediction of inland inundation and to assess the potential interaction between storm tide and freshwater events, a two-dimensional MIKE 21 hydrodynamic model was developed. The following sections detail the development of the Don River hydraulic model and its use for estimation of inundation associated with freshwater and/or storm tide events. Also documented is the mapping of storm tide inundation for the remainder of the Bowen Shire coastline.

11.1 Don River Hydraulic Modelling

The nature of the Don River floodplain terrain meant that modelling using MIKE 21 was deemed more appropriate for accurately determining flood and/or storm tide inundation. During previous flood events the river has broken out at several locations with flood waters then follow gullies or old channels within the floodplain area. This wide spread flow with multiple breakouts is best represented by a 2-dimensional hydraulic model. Therefore modelling for this investigation was undertaken using the Danish Hydraulic Institute's ("DHI") MIKE 21 package. MIKE 21 is a comprehensive modelling system for two dimensional free surface flows where stratification can be neglected. MIKE 21 simulates the water level variations and flows in response to a variety of forcing functions in floodplains, lakes, estuaries, bays and coastal areas. The water levels and flows are resolved on a rectangular grid covering the area of interest when provided with the bathymetry (topography), bed resistance coefficients, wind field, hydrographic boundary conditions etc.

A MIKE 21 generated model has only three calibration factors, namely bed resistance, wind friction and momentum dispersion. Using these factors alone, calibration of a model is normally quite easy. In practice, the calibration of a model depends far more on the accuracy of the data, eg topography and boundary conditions. It should be noted that wind friction has not been considered in this investigation.

The MIKE 21 data requirements for this project included the following:

- Basic Model Parameters
  - Model grid size and extent;
  - Time step and length of simulation; and
  - Type of output required and its frequency.
- Topography
- Calibration Factors
  - Bed resistance; and
  - Momentum dispersion coefficients.
- Initial Conditions
  - Water surface level; and
  - Flux densities in x and y directions.
- Boundary Conditions
  - Water levels or flow magnitude; and
  - Flow direction.

The ALS data was entered into the terrain modelling package '12D' to form a digital terrain model ("DTM") of the Don River floodplain. A Digital Elevation Model ("DEM") was extracted from this data for input into the MIKE 21 Comet River model. The topography and area covered by the MIKE 21 model is presented in Figure 23. The area covered is approximately 18km by 17.2 km and due to this large size it was necessary to adopt a grid spacing of 20 metres to give an acceptable run time for model runs.

Roughness values were determined using information gained from the site inspection, photographs of the creek and aerial photography. Roughness values in 2-dimensional hydraulic models are generally slightly lower than those used in 1-dimensional models (eg MIKE 11) as losses due to factors other than friction are accounted for in 2-dimensional modelling, whereas they are lumped into the friction loss in 1-dimensional modelling.

The Bruce Highway bridge crossing and the rail bridge crossing were both included in the MIKE 21 model using details obtained from Drawings supplied by DMR and QR respectively.

11.2 MIKE 21 Model Calibration

A review of existing reports and discussion with Council Officers, indicated that the best dataset available for a historical Don River flood event was for the January 1980 event. Peak flood levels and inundation extents were well mapped for this event and it is one of the largest event to have occurred, as shown in the Figure in Appendix C. It was therefore decided to adopt this event as the primary MIKE 21 model calibration event.

In order to determine appropriate inflow for the MIKE 21 model, the BoM's URBS hydrologic model of the Don River catchment was sourced. The Don River URBS model has been developed by BoM for flood forecasting purposes and has been calibrated to a number of historical storm events ranging in size and duration. BoM's concerns with the current model include the high continuing loss rate required to achieve calibration and the uncertainty of the upper stages of the current rating curve used for the Bowen Pump Station gauge. It was hoped that through the hydraulic modelling to be undertaken that both of these aspects could be confirmed and/or refined. The layout for the URBS model is shown in Figure 22.

Discussions with BoM, suggested that the February 1991 event would be ideal as a second calibration event as it was of a medium size. However as for all other recent events, with the exception of the stream gauge levels, minimal additional recorded flood level data is available to assist in the calibration process. Therefore at this stage the calibration process has focussed on the 1980 event.

Table 11 presents the URBS model parameters used by BoM to calibrate the URBS model for the 1980 and 1991 events. Also presented are the peak levels and discharge estimates.

Table 11 – BoM URBS Model Calibration Parameters

Parameter	1980 Event	1991 Event
Alpha	0.1	0.08
Beta	2.5	2.5
M	0.7	0.7
Initial Loss (mm)	70	25
Continuing Loss (mm/hr)	8.5	8
Gauge Peak Level (mAHD)	12.007	10.307
MIKE 21 Model Inflow (m^3/s)	9696	2946

The peak discharges detailed in Table 11, were used as inflows to the MIKE 21 model and a series of calibration runs undertaken. The MIKE 21 model runs were all undertaken steady state (ie peak discharge only). Initially these runs involved adjusting the model roughness values to determine the sensitivity of model results to this parameter. It was apparent from these initial runs that adjustment of the model inflow and/or topography would be necessary to achieve an acceptable match to the recorded flood levels (ie the range of level variation from the roughness adjustments was insufficient to match recorded levels). A summary of the roughness values adopted is presented below:

- River bed – 0.025
- Overbank – 0.06 to 0.1 (allowing for variation in ground cover)
- Urban Areas – 0.15

The 1980 calibration results using the BoM parameters and the above roughness estimates are presented in Figure 24a. The peak tide level recorded during the 1980 event was 2.5m AHD, however it is unlikely to have occurred at the same time as the peak of the flood event due to the longer response time for the Don River catchment. The peak storm tide level would coincide with landfall of the cyclone, but the peak discharge from runoff on the catchment is likely to occur later once the entire catchment responds, approximately 6 to 12 hours. Therefore this 1980 calibration run was undertaken using a MHWS tailwater level of 1.0m AHD.

The peak water levels resulting from this run were generally higher than those recorded and the model showed areas inundated that were recorded as being dry. Preliminary discussions with Council Officers indicated that there may have been substantial filling of the creek bed with sand during smaller flood events since the 1980 event and that this may have been up to 5 metres in depth. Further model runs were then undertaken with the river bed lowered by 5m. In order to achieve a reasonable calibration, it was necessary to lower the continuing loss rate used in the URBS model to 6mm/hr giving a new peak discharge for the 1980 event of 10,235m^3/s. The results of this calibration run are presented in Figure 24b. The tidal level adopted in this run was also raised to 2.0m AHD, to improve the calibration in the lower reaches. It can be seen that the peak water levels predicted are close to the recorded levels in the majority of areas but may be slightly low in the lower reaches. Also the dry areas match that recorded much better than the previous run results.

For both runs presented, the breakout from the Don River via Bell's Gully and the Webster Brown wall area, is limited and this is due to the fact that the ALS based topography includes the improvement works that have been carried out in these area to contain flood waters. To improve the calibration in these areas, it will be necessary to obtain details of ground levels prior to the works being undertaken to allow the topography to be adjusted.

Following completion of the above model runs, discussions were held with Mr Barry Menzies from Council, who advised that filling of the river channel by 5m has not occurred. This was confirmed by comparing the channel cross-sections shown on the QR and DMR bridge drawings with that obtained from the recent ALS data. In total there may be a variation of up to 1m in levels between 1970 and present day. However it is unclear how much erosion occurs in the river channel during flood events of varying sizes and how this may impact upon peak flood levels. The outcomes of the analysis undertaken to date can be summarised as:

- There has been some minor increase in bed levels due to accumulation of sand since the 1980 event but this may be less than 1m in depth;
- The depth of scour that may occur in the river channel during flood events is unknown;
- Works that have taken place since the 1980 event on the floodplain and along the river channel need to be identified and taken into account in the topography used for the 1980 calibration runs;
- The continuing loss rate used as the main calibration parameter in the URBS hydrologic model cannot be fixed at this stage until the topographic issues are resolved; and
- As there is only good recorded data for one recent historical flood event, it is hard to accurately calibrate the hydraulic model to just one event.

In summary the capacity of the river has a significant impact upon peak flood levels in the floodplain and therefore it is necessary to try improve knowledge of the channel levels at the time of the 1980 event. This includes consideration of the sediment movement during such an event.

For the following design event and storm tide runs, the current topography has been used with the adopted roughness values detailed above. The inflows to the MIKE 21 model are based on average parameters as advised by BoM, which were derived from consideration of a number of historical flood events and which are shown in Table 12. In order to be conservative at this stage an initial loss rate of 0mm has been adopted – this can be revised in later model runs.

Table 12 – Adopted URBS Model Parameters for Design Event Runs

Parameter	Value
Alpha	0.11
Beta	2.5
M	0.7
Initial Loss (mm)	0
Continuing Loss (mm/hr)	8.5
100 year ARI Peak Discharge (m^3/s)	7797
20 year ARI Peak Discharge (m^3/s)	4936

11.3 Storm Tide Event Model Runs

The MIKE 21 model was run with the downstream boundary set to represent the storm tide levels associated with the following return periods:

- 50 years;
- 100 years;
- 1,000 years; and
- 10,000 years.

The downstream boundary condition consisted of the storm tide levels (taken from Table 5) plus the wave setup data. Wave setup values were added to the storm surge levels as per the values presented in Table 8. These combined levels were then applied to the downstream boundary for each event.

A series of plans have been prepared presenting the estimated inundation associated with each of these events. The linkages between these plans is presented in Figure 25.

Figure 26 presents the 50 and 100 year ARI storm surge inundation and Figure 27 presents the estimated inundation under the 1,000 year and 10,000 year ARI storm surge events. In all nine separate plans make up each figure as demonstrated in Figure 25.

It should be noted that the new ALS topography does not cover all plans. Where the ALS data is unavailable the older topographic data has been used. Where the greyscale photography is shown the ALS data is available, beyond the limits of the photograph the data resorts to the older topographic data. The older topographic data is limited in some areas and therefore makes it difficult to present the predicted flood inundation (eg Figures 26-1 Upstart Bay and Figure 26-2 Cape Upstart). It may be appropriate to exclude these drawings from the Final Report.

The potential impact of storm tide on population and infrastructure is discussed in detail in the Section 12 onwards.

11.4 Don River Design Event Model Runs

Two design events have been run using the MIKE 21 model. These are the 20 and 100 year ARI design events. Peak discharges were obtained from the URBS model using the parameters detailed in Table 12 above. The current topography (ie based on the ALS data) has been used and a tidal level of 1.0m AHD adopted (MHWS).

The peak flood levels resulting from these events are presented in Figures 30 and 31 for the 20 and 100 year ARI events respectively.

11.5 Combined Flood and Storm Tide Events

When in flood the Don River has a significant impact upon Bowen as access to the Bruce Highway is cut under large events. There is significant potential for a storm tide event to occur at the same time as a Don River flood event. In order to assess the likelihood for such an occurrence it would be necessary to undertake a joint probability analysis examining historical stream gauging, rainfall and tidal gauge information.

In order to gain an appreciation of the potential impact under joint events the following combinations have been modelled using the MIKE 21 hydraulic model:

- Figure 32 – Don River 20 year ARI event plus 100 year ARI storm surge event; and
- Figure 33 – Don River 100 year ARI event plus Highest Astronomical Tide (HAT).

From previous storm surge studies along the Queensland Coast it has been noted that generally East Coast Lows tend to produce higher storm surge levels at lower return periods and that the 20 year ARI level is close to HAT as adopted above.

12. Factors Affecting Flood Hazard

As discussed in SCARM (2000), factors affecting flood hazard can be grouped into four broad categories:

- Flood behaviour (ie severity, depth, velocity, rate of rise, duration);
- Topography (ie evacuation routes, islands);
- Population at risk (ie number of people and developments, type of land use, flood awareness); and
- Emergency management (ie forecasting/warning, response plans, evacuation plans, recovery plans).

It is appropriate to make comment upon all of these issues in general terms, before proceeding on to the specific hazard assessment.

12.1 Flood Behaviour

In accordance with risk management guidelines, this study has assessed and quantified the full range of potential storm tides, from the 50 year ARI event to the extreme 10,000 year ARI event (Probable Maximum Surge).

The rate of rise of ocean level associated with a storm surge is dependent on many factors, as discussed in Sections 6 and 9. Irish (1977) reported an indicative storm surge hydrograph based on Queensland data. Close to landfall or close to the coast water levels gradually increase, followed by a rapid rise to peak water level and an equally rapid fall, and then gradual decay. However, storm tide is dominated by the astronomical tide and peak water levels caused by cyclone surge will persist only for durations up to six hours.

The total time of inundation of any particular area is not only dependant on the time the peak surge is sustained, but on the local drainage features once the ocean level has dropped. For example, in many of the residential areas, the inundation time will be dictated by the time the local underground pipe network takes to drain the excess water. It is considered reasonable therefore to assume a total time of inundation of somewhere between 12 and 24 hours.

The hazard posed by the flood waters themselves is directly related to the depth of storm tide flooding and the velocity of the flow. SCARM (2000) presents a series of hazard categories related to the depth and velocity of flow, and the relative evacuation time. Whilst the latter factor will only be known by the counter-disaster managers, this report assigns an initial hazard assessment based on the first two factors, with the understanding that this will be adjusted at a later time. Depth of inundation maps have been prepared in critical areas, based on the following depth ranges:

- 0 to 0.3m (nominal low hazard);
- 0.3 to 0.6m (nominal medium hazard);
- 0.6 to 1.2m (nominal high hazard); and
- >1.2m (nominal extreme hazard).

Adjustments based on velocity of flow are made in individual locations as appropriate.

Hazard maps have been prepared for the Bowen Shire coastline under the 100 year ARI Storm Surge event and the 10,000 year ARI Storm Surge event. These are presented in Figure 28 for the 100 year ARI event and Figure 29 for the 10,000 year ARI event.

12.2 Topography

The availability of effective access routes from flood-prone areas and developments can directly influence the resulting hazard when a flood occurs. Specific comment on access and evacuation are provided in Section 13.

12.3 Population at Risk

The degree of hazard and social disruption varies with the size of the population at risk. An estimate of the total population at risk (PAR) at critical locations has been made (refer Section 13).

The flood awareness of the population is typically related to past experiences with flooding, and regular public awareness campaigns.

13. Risk to Population and Infrastructure

13.1 Population at Risk

For the purposes of this risk/hazard assessment, all critical areas (ie areas inundated under the 10,000 year ARI storm tide event) have been examined. At this stage, this assessment has focussed upon Bowen and Queens Beach but can be extended to other nominated coastal communities. Note that some inundated areas have been excluded from consideration, including:

- Land currently undeveloped, hence not filled to above flood level; and
- Parks and environmental areas.

An attempt has been made to quantify the potential population at risk (PAR) within each zone, based on recent aerial photography supplied by Council (exact date unknown), DCDB and Australian Bureau of Statistics 2001 Census data. The methodology involved a count of all properties (residential and commercial/industrial) from the DCDB, cross-checked against aerial photography, to provide the basis number of properties affected. The ABS data was used to provide average numbers of persons per household. The combination of these two figures provides an indicative population figure for each zone. Table 13 below provides a summary of this data and the PAR.

Table 13 – PAR Per Zone

Zone	Approximate No of Properties[1]	Ave Household Size[2]	Estimated PAR[3]
Bowen	770 Residential 14 Commercial/Industrial 1 Caravan Park	2.6	2002
Queens Beach	922 Residential 5 Commercial/Industrial 4 Caravan Parks	2.6	2398
		Total Population At Risk	4400

Notes 1. Count based on DCDB and aerial photography where available (not verified on site).
2. Source – Australian Bureau of Statistics – 2001 Census data.
3. Estimated PAR based on residential dwellings only.
4. Does not include persons residing in units.
5. Does not include persons residing in units or shops.

13.2 Risk to Infrastructure

13.2.1 General

Horseshoe Bay, Rose Bay and Flagstaff Hill may become completely isolated during a storm surge, due to inundation of Horseshoe Bay Road, Rose Bay Road and Peter Wyche Drive. These communities could not expect external assistance during an event and would need to be evacuated before significant sea level rise occurred as all of Queens Bay and Queens Beach may become inundated. The storm surge would also inundate the city to Williams Street. The City of Bowen would become isolated during a surge event due to the Bruce Highway being inundated.

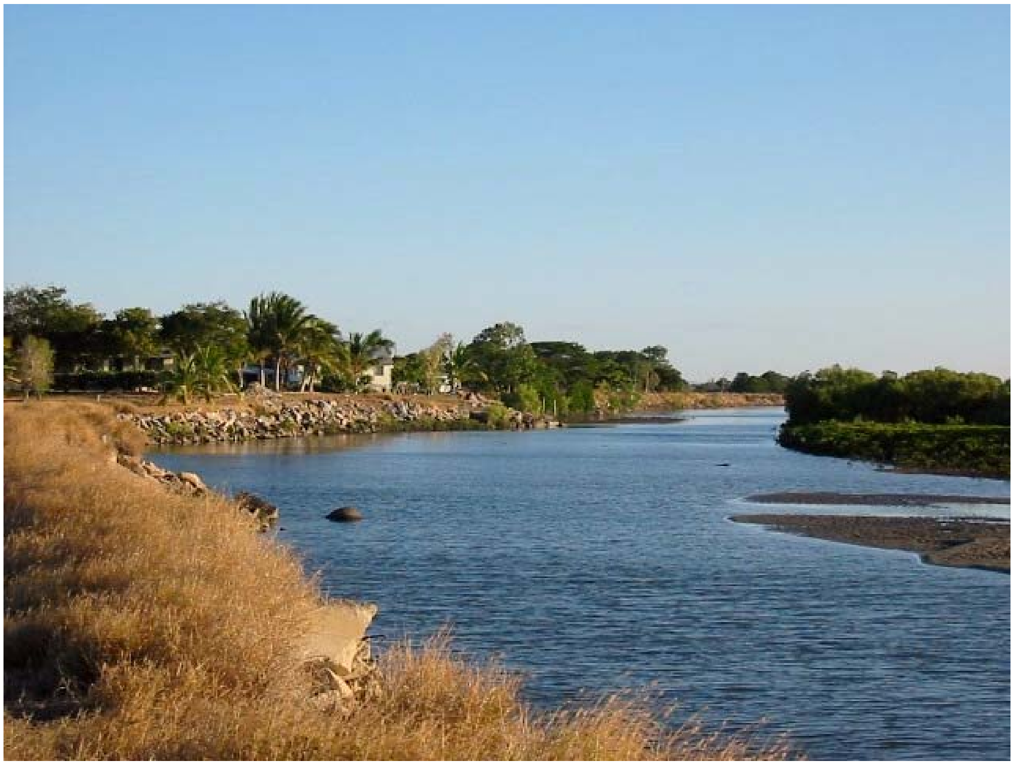

Plate 1: Don River, north end of Queens Beach

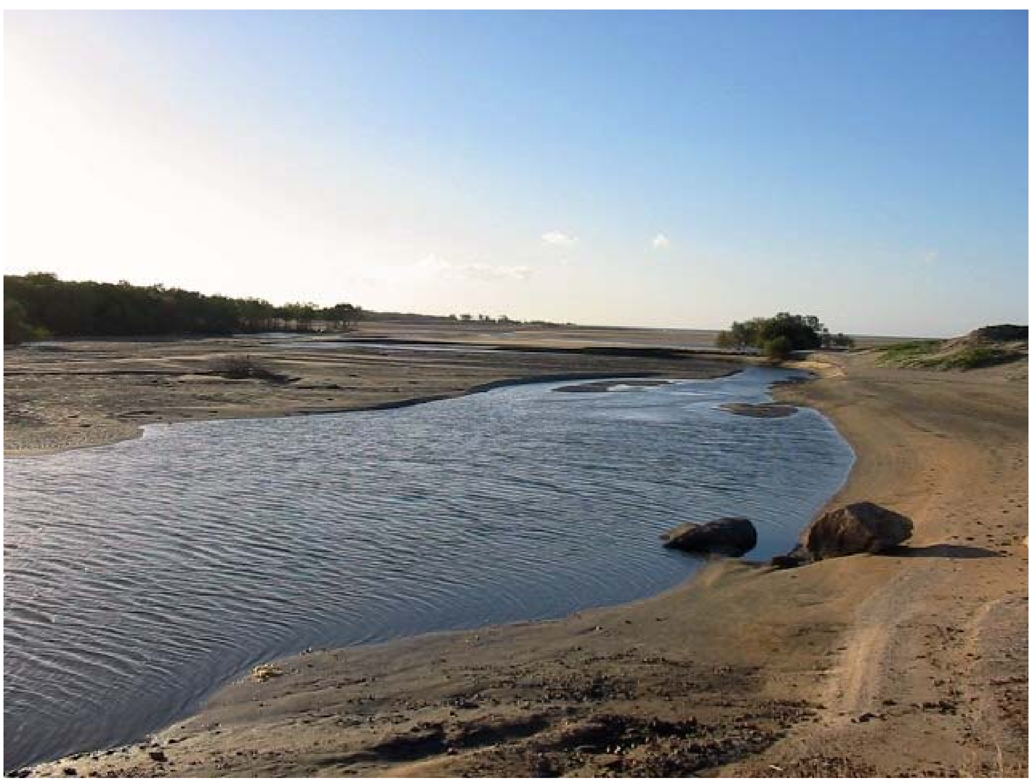

Plate 2: Don River Mouth, north end of Queens Beach

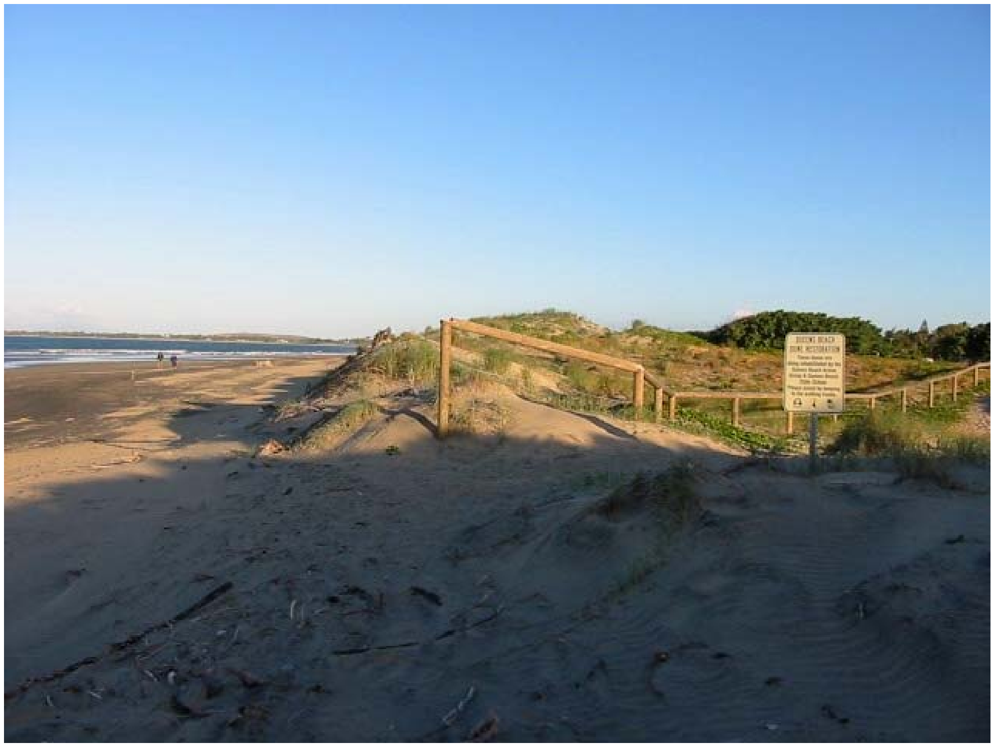

Plate 3: Queens Beach Frontal Dune

13.2.2 Roads

Inundation of roads is most likely to occur as a result of backflow of tidal water through the existing open and underground stormwater drainage networks. Flow velocities are expected to be minimal, possibly in the order of 0.5m/s, and scour of road pavements or footpaths is therefore unlikely to be a source of major road infrastructure damage. Long term inundation of roads and footpaths (approximately 12 hours) may allow the underlying road pavements and subgrade to become waterlogged, resulting in a softening of the pavement structure. The pavement should return to pre-inundation strengths when the underlying pavement and subgrade has sufficiently dried. This may take some time after the surface water has receded.

When the inundation has receded it is recommended that vehicular use on recently inundated roads be restricted to single axle vehicles and emergency vehicles. Heavy or commercial vehicles, not required for emergency access, should be prevented from travelling on the affected roads until the pavements have regained sufficient strength. This time can vary considerably and is particularly dependent on the type of subgrade material. It is therefore recommended that Council engineers be consulted before unrestricted access is permitted.

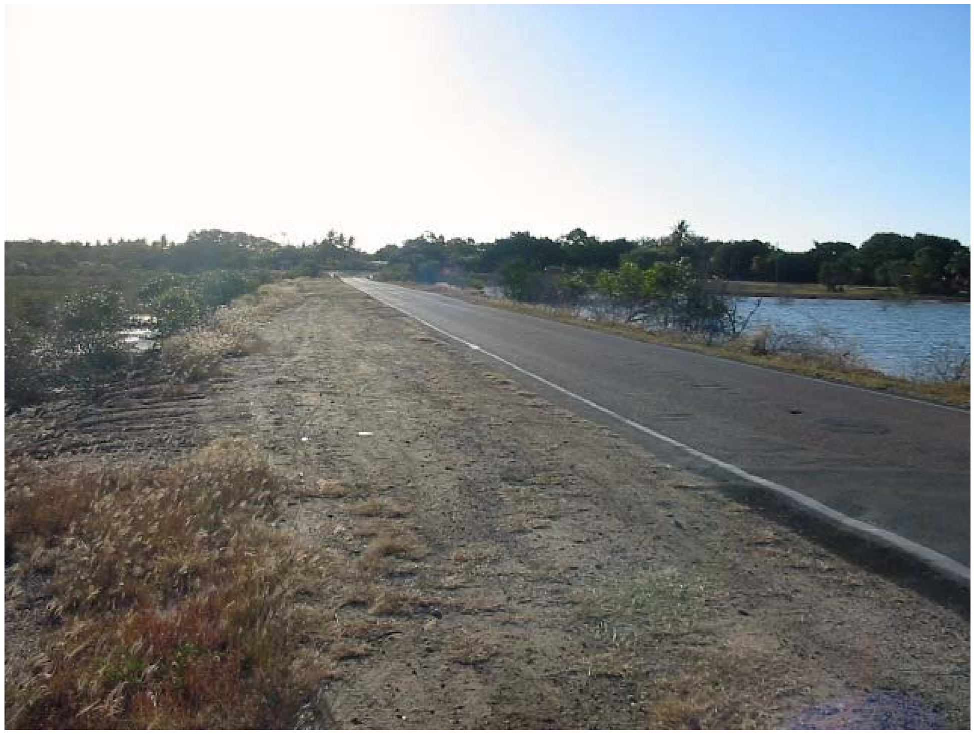

Plate 4: Rose Bay Road near Horseshoe Bay Road

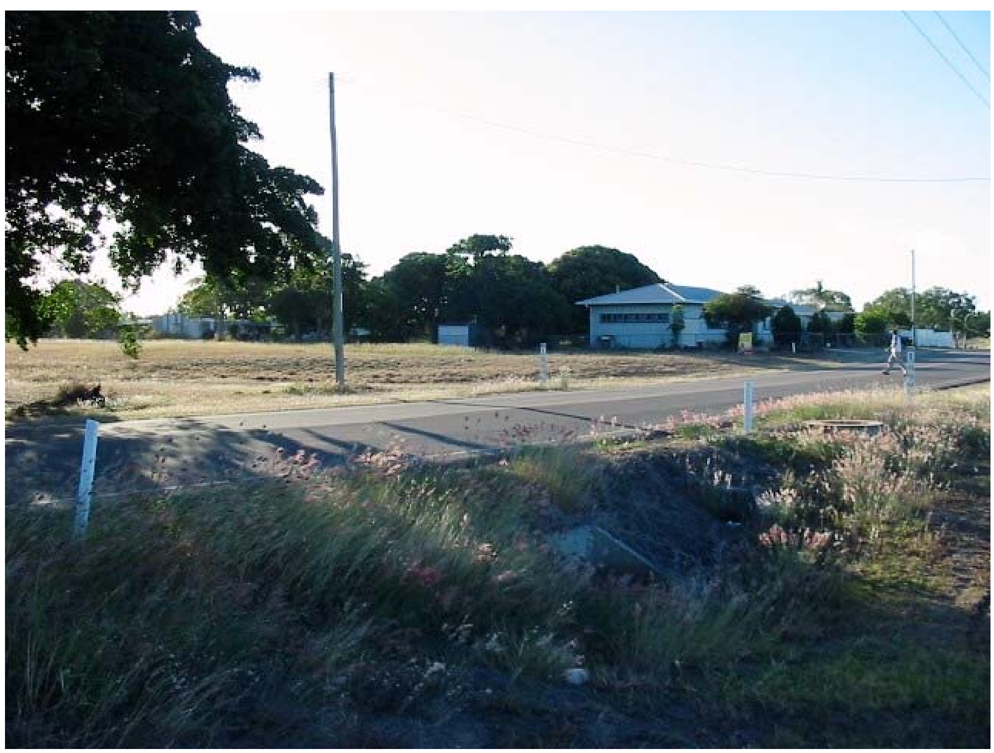

Plate 5: Floodway at Soldiers Road

Plate 6: Floodway Argyle Park just south of Emmerson Drive

13.2.3 Sewer

During wet weather, sewerage inflows tend to increase dramatically due to illegal stormwater connections and groundwater ingress. It could be expected that this would also be the case during periods of surge inundation.

The majority of Bowen is sewered with the area around the airport having individual septic systems. Some damage to these individual septic systems due to seawater ingress or flotation of septic tanks can be expected. Seawater ingress would stop or hinder treatment of sewage in the tank, and result in release of essentially untreated waste into adsorption trenches in saturated ground. Septic systems are typically private infrastructure (except for public toilets) but release of sewage has major public health implications.

The sewage treatment plant is located at Flagstaff Hill. The plant will become isolated and inundated during a surge event. A new STP location is currently being considered. The new plant should be located where it is not affected by storm surge or stormwater inundation.

Plate 7: Sewerage Treatment Plant

Of more concern would be the numerous sewerage pump/lift stations throughout the lower lying areas subject to inundation. There are 32 sewage pump stations/lift stations within the city of Bowen. The Main Sewage Pump Station is located at the intersection of Hay Street and George Street.

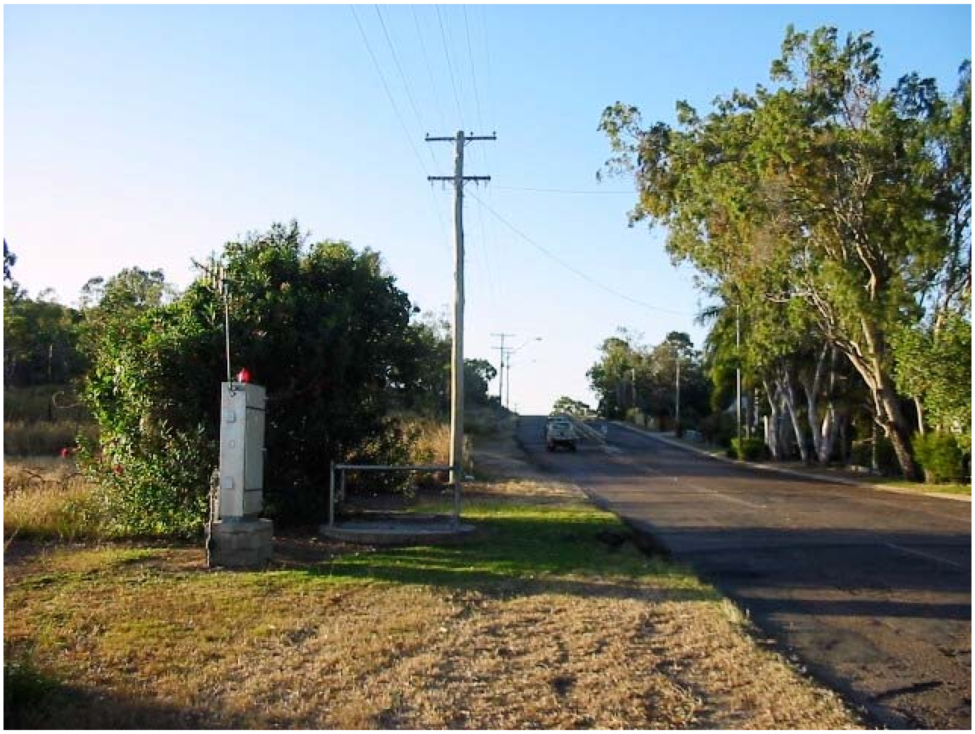

Plate 8: Sewage Pump Station in low lying area on Mt Nutt Road

The pump station overflow systems would also be inundated, allowing salt water to enter the pump well. If the pumps remain in service, the shock loading from salt water influx could result in a complete loss of biological treatment performance at the sewage treatment plant. Following this shock loading, the quality of treatment plant outfall would initially have pathogen and pollutant levels similar to that of raw sewage. This would gradually return to normal levels after treatment bacteria have fully re-established, (ie perhaps after six to twelve weeks of operation).

The pumps rely on electrical power, which may be interrupted during the inundation and could result in the overflow of raw sewage into waterways. Power supply to the pump stations is sourced via overhead transformers and is no greater risk from inundation than general power supply failure (see Section 13.2.5). Switch boards and motor control cabinets are generally located at or near ground level and may require maintenance or replacement following seawater inundation.

13.2.4 Water Supply

Water to supply to Bowen via trunk main from Proserpine to a reservoir on Bowen Hill. Water is reticulated from the reservoir.

There are some above ground creek crossings and these may be at risk.

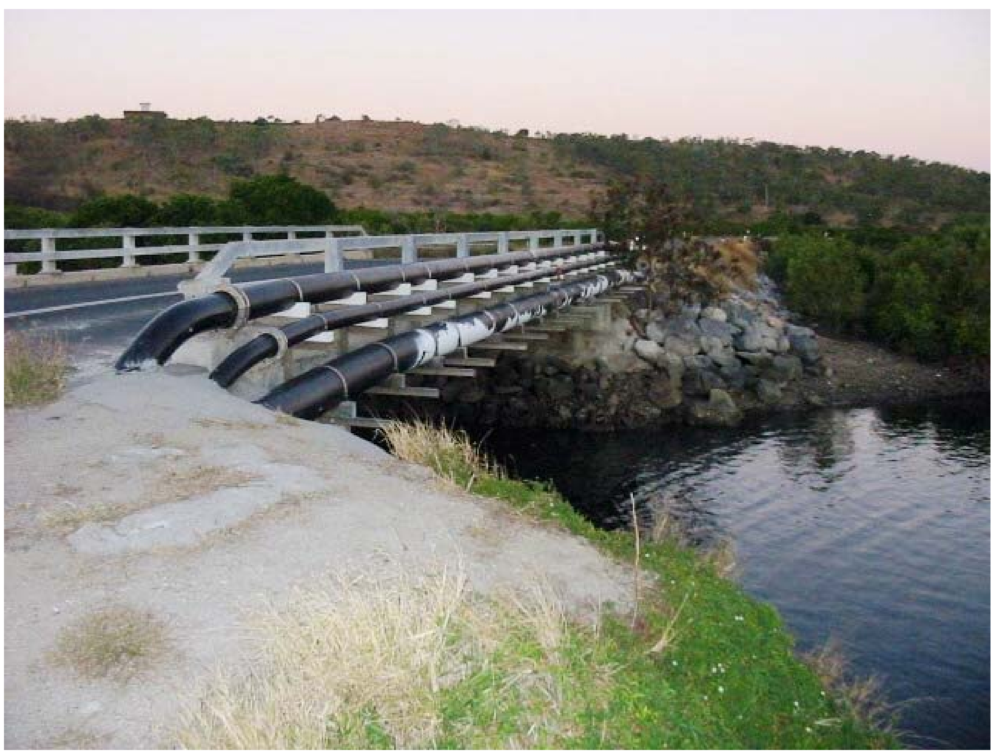

Plate 9: Tidal Crossing to Flagstaff Hill and STP

13.2.5 Electrical and Communications

General

Electricity is supplied to Bowen from Proserpine. The electrical infrastructure in Bowen is overhead and is owned by Ergon.

Telstra owns the underground communication infrastructure.

Communications

The Telstra infrastructure is all underground reticulation. The system is therefore designed and installed to be robust against the ingress of water. The pit and conduit system is regularly inundated with water as part of the natural storm water dissipation. The cables and cable joints used are grease filled which can be submerged in low level water with no adverse affects. The cable connection pillars, which are located above ground, are also sealed and positively pressurised to prevent the ingress of water, however are not submersible.

The weak links are Telstra RIM's and exchanges. The RIM's are electronic devices installed in suburban areas in a weatherproof housing. The housings are not generally located above the storm surge level and are not designed for submersion.

The loss of a RIM will cause a local loss of communications restricted to the general area of the RIM. The loss of an exchange will cause a loss of all communications connected to the exchange. This will have affected a larger area of population and rectification will not be possible until the water level returns to normal. There is no life threatening implications associated with communications other than disconnection of local electrical power supplies.

The telephone exchange for Bowen is located near Livingstone and Kennedy Street. It is not at risk from a surge event.

Electrical Supply

The Ergon infrastructure is overhead reticulation. The overhead reticulation is suitably segregated from the rising water by virtue of being located well above ground level. The poles supporting the cables are able to withstand minor water flow around the base of the pole. Susceptible points in this system are locations where overhead and underground reticulation is joined at connection boxes. The location and height above ground of connection boxes is currently under review by Ergon.

The underground reticulation is robust against water due to the inherent resistance required for underground installations. The weak points are ground mounted and low level equipment, which is not water proof. These include house meter panels, distribution pillars, padmount transformers and 11kV Ring Main Units (RMU). Ergon has a series of cascading protection, which includes meter panels protected at distribution pillars protected at the transformer protected at the RMU protected at the zone substation. As the protection trip proceeds from meter panel to substation a greater area is affected by a loss of power. Power will not be able to be returned until the water level lowers and new equipment is installed. In the case of transformers and RMU's this may take 2 to 3 weeks for supply and installation.

There is potential loss of life situations if the electricity is not shut off prior to water levels rising. The speed at which water rises and warnings, which may be available will play an important role in assisting Ergon in the maintenance and safety of the network. However, the protection settings are generally set to provide power shutoff in less than 1 second.

13.2.6 Other Infrastructure

The hospital, ambulance, fire and police stations are located above the surge levels. There are three retirement villages at risk from tidal surge effects. Also at risk is the Golf Club. Queens Beach School and the TAFE College are at risk from surge events. The Bowen High School is above the surge level.

Plate 10: Ambulance Station, John Street

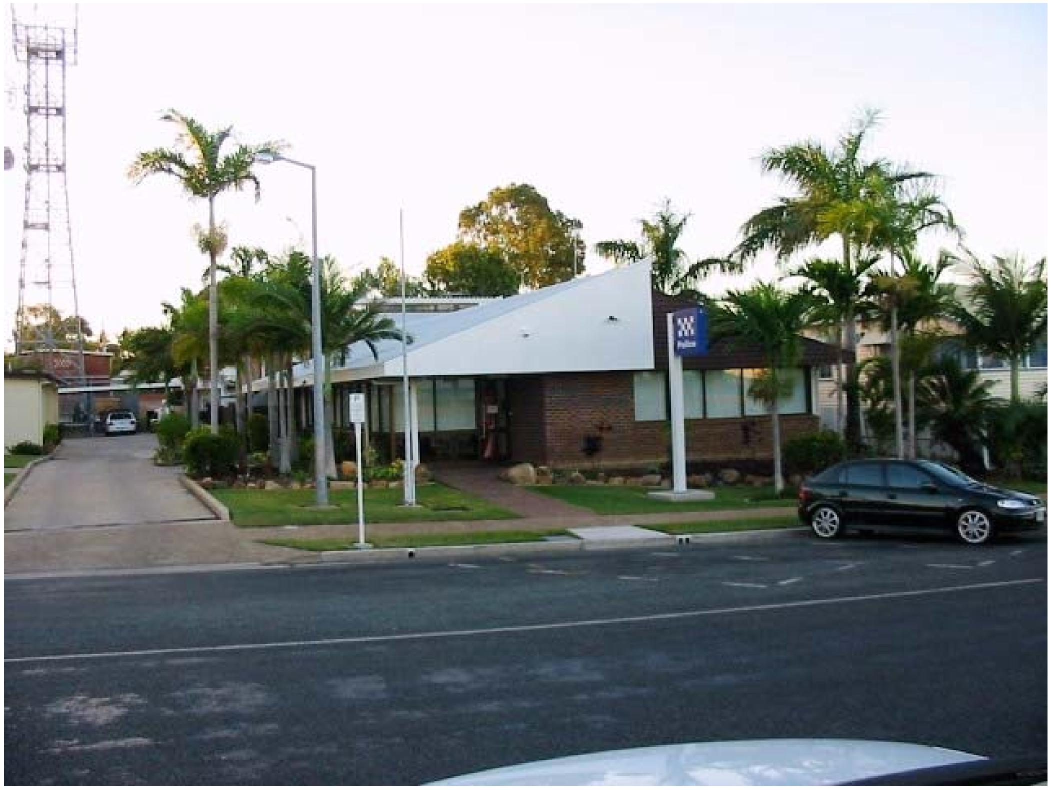

Plate 11: Police Station Williams Street

13.3 Storm Surge Risk Assessment

As outlined in Section 12, depth of inundation maps have been prepared for critical areas, based on increments outlined in SCARM (2000). Figures 26 and 27 present the inundation mapping for the full range of storm tide events considered. Figure 28 presents the depth mapping for the 100 year ARI storm surge event and Figure 29 presents the depth mapping for the 10,000 year ARI storm tide event. A review of hazard at each of the communities is provided below:

Bowen

Under the 100 year ARI event, some inundation of Bowen occurs along the foreshore and back towards the junction of Dalrymple and Leichhardt Streets. Shallow to medium inundation of Santa Barbara Parade occurs and increases towards the Hay Street end of town. Denison Park is completely inundated and this spreads to inundate up to Powell and Herbert Streets. George Davidson Park is also completely inundated, as are a number of neighbouring properties.

Access to town is cut on Don Street with at least 1.2m across the roadway. Access may be possible by Woodlands/Richmond Road though localised inundation of the roadway may occur from adjacent flowpaths and limit accessibility.

Under the 10, 000 year ARI event inundation of Bowen substantially worsens with both main access roads into town cut by deep water. Inundation of the majority of Dalrymple Street occurs with deep (>1.2m) inundation extending up to Powell Street. Inundation of the other areas discussed above deepens and extends further into the town.

Queens Beach/Queens Bay

Under the 100 year ARI event, Queens Beach properties are generally dry, however the Wangaratta Golf Course is substantially inundated. Properties bordering the golf course in Queens Bay are also inundated. Queens Bay is almost isolated by inundation. Properties along Tollington and Queens Road are inundated and this access way cut. The Tafe College is also inundated by up to 0.6m of water.

Access would not be possible by Tollington Road but may be possible by Mt Nutt Road as long as there is no local flooding also occurring.

Under the 100 year ARI Queens Beach and Queens Bay are almost all completely inundation and isolated by deep water. Early evacuation of these areas would be essential.

It should be noted that the above review considers storm tide only and does not include the impact of local or regional runoff from rainfall events. These impacts would significantly increase the risk to residents if considered in conjunction with the storm tide impacts.

Summary

A summary of the hazard ratings for each area and ARI is provided in Table 14. The worst hazard rating for each area has been used.

Table 14 – Initial Hazard Estimates

Area	Storm Tide ARI	
	100 year	10,000 year
Bowen township	High	Extreme*
Queens Beach	Medium*	Extreme
Queens Bay	High	Extreme

** Indicates hazard would be negligible or may be lessened once alternative flood free access is open*

It should be noted that the hazard estimates presented in Table 14 are initial estimates only based on the mapping produced. The hazard classifications should be confirmed by the counter-disaster managers, taking into account local knowledge and emergency procedures.

13.4 Joint Storm Tide and Don River Flooding Risk Assessment

Figures 32 and 33 present the estimated inundation associated with the combined storm tide and freshwater flooding events that have been modelled. Figure 32 presents a 20 year ARI Don River event combined with the 100 year ARI storm tide event. Figure 33 presents the 100 year ARI Don River event combined with a sea level of HAT of 1.95m AHD.

Figure 32 shows that, on the Don River floodplain, the extent of inundation under the 20 year ARI Don River event with the 100 year ARI storm tide event, is fairly similar to the Don River 20 year ARI event in isolation. The inundation extent in the urban areas is similar to that discussed above for the 100 year ARI storm tide event. Closer examination of the model results shows that flood levels increase by between 0.2 and 0.4m in the flooded area to the south of Bowen and across the lower reaches of the Don River floodplain. Access to the township would be an issue with the Bruce Highway cut by floodwaters.

Figure 33 shows that the Don River flood inundation is generally similar to that predicted for the Don River 100 year ARI event in isolation. This appears to be due to the fact that the large flood flow is dominating flood levels rather than the HAT tide level. Closer examination of the model results shows that flood levels increase by up to 0.08m in the flooded area to the south of Bowen and across the Don River floodplain.

There is some minor inundation of Bowen and Queens Bay urban areas but it is expected that this impact would not hinder movement around the town and would be short lived. The main difficulty is access to the town is cut by the Don River flooding and there is a reasonable likelihood of damage to the highway and/or railway as portions of these structures are overtopped.

14. Emergency Management

The latest version of the Bureau of Meteorology's "Tropical Cyclone Storm Tide Warning-Response System" was obtained and reviewed. A summary of the information that will be provided to Council in the event of a storm tide emergency is shown in Table 15.

Table 15 – Sequence of Events (in the ideal case) (BoM, 2003)

Time before 100km/h wind gusts on Coast	Warning	Comments
24 hours	Preliminary Storm Tide Warning	12 hours to Standby time
18 hours	Preliminary Storm Tide Warning	Standby time is confirmed or revised
12 hours	Storm Tide Warning	Standby time with first estimate of Storm Tide height
9 hours	Storm Tide Warning	Earliest likely evacuation authorised
6 hours	Storm Tide Warning	
3 hours	Storm Tide Warning	
ZERO hours	Storm Tide Warning	Evacuation completion deadline
Plus 3 hours	Storm Tide Warning	
Plus 3 to 6 hours		Landfall of cyclone centre
Plus 6 hours	Final Storm Tide Warning	

Evacuations should commence as early as possible as cyclone landfall also coincides with the most destructive winds, and it is difficult to evacuate during such conditions. If not already in place, a comprehensive evacuation plan should be prepared in consultation with the Shire Counter Disaster Committee (CDC). This plan should take into account:

- Population characteristics;
- Evacuations centres;
- Evacuation routes and their immunity;
- Evacuation personnel and resources available;
- Evacuation time estimates; and
- Public announcement methods.

The evacuation procedures should be documented and included in the Shire Counter Disaster Plan.

DES, BoM and Emergency Management Australia (EMA) have recently produced the "National Storm Tide Mapping Model for Emergency Response". This document contains a standard mapping approach that ties evacuation areas to the BoM cyclonic storm tide warning system. Mapping produced using this model is critical to the evacuation plan and should be produced as a matter of priority.

15. Recommended Further Work

This Study has quantified and highlighted the risks posed to Bowen Shire from storm surge flooding and Don River flooding, however there are some critical issues that remain outstanding, including:

- Further refinement and calibration of the MIKE 21 hydraulic model of the Don River to improve the model accuracy and reliability, and the rating curve used by BoM for flood forecasting purposes;
- Collation of additional flood levels and information for specific storm events to improve the MIKE 21 model calibration;
- The need to confirm the potential transportation of sand in the Don River during flood events;
- The need for preparation of an evacuation plan for select communities, eg Bowen and Queens Beach;
- The need for the initial hazard estimates presented in Table 14 to be reviewed by counter-disaster managers and adjusted based on evacuation times;
- The need for further consideration of freshwater flooding occurring jointly with storm surge; and
- The need for consideration for treatment options.

As discussed in SCARM (2000), the study area is subjected to both rainfall and storm surge flooding, and both these flood-producing mechanisms can and do occur at the same time. If flooding is caused by heavy rainfall and storm surge combined, the question arises of how severe will be the resultant flood for example, for rainfall severity of 100 year ARI and storm surge severity of 20 year ARI. If both effects are caused by the same storm, the more extreme severity is chosen as representative of the resultant flood severity (ie 100 year ARI for the above example). However, heavy rainfalls and storm surge may not be generated by the same storm, and even if they are, the relative severity of each effect may be independent of the other.

A review of the typical time of concentration for the small coastal creek catchments along the Bowen Shire coastline indicates that the response time for the coastal creeks is short and therefore it is feasible that freshwater peak discharges could coincide with peak storm surge levels. However due to the low density of population in these areas, this short-lived impact may not create a significant risk to the residents.

A Don River flood event, however, has a significant potential to impact on the local communities at Queens Beach and Bowen, and the associated Don River floodplain area. Flooding of the Don River in conjunction with a storm tide event has been considered in this study by examining two combinations of storm tide and freshwater events.

This arbitrary choice of combination of freshwater events and storm surge events may be producing results of unknown quality, hence have an unknown impact on Council's counter-disaster plans. It is recommended that Council considers a joint probability study to actually quantify this critical issue. This study should also examine the joint probability of wave setup with surge, to allow more realistic combination estimates to be made. Once this study is completed, inundation plans and the hazard assessment would need to be reviewed.

This report has focussed on analysing and evaluating risks posed to the Bowen Shire coastline from storm surge, but has not considered any risk treatment options. Council will need to review all possible treatment options in the light of this report. It may be that some relatively simple structural measures could remove flood risk in some areas (eg flood flaps on stormwater outlets to prevent surge inundation of local roads, raising of some low points on access roads etc).

In addition, the information collected in this report should be used to update or produce evacuation plans for the townships of Bowen and Queens Beach, and any other selected communities at risk.

A final issue to note is the impact that sea-level rise would have on the existing inundation plans. Council should closely monitor predictions of sea-level rise with time, and review the impacts on the inundation plans accordingly.

16. Conclusions

This report describes the data, methods and results of the investigation into storm tide levels along the Bowen Shire coastline. In addition, flood modelling of the Don River has been undertaken and this report details the analysis and results of this work.

An analysis of historical cyclones that have affected the area was undertaken. Only cyclones recorded since 1955 were included. That data was analysed to provide statistical descriptions of the principal cyclone parameters. At total of 69 historical cyclones were identified within a selected area.

Numerical storm surge and wave models were set up using bathymetric data prepared from available charts. The surge model was validated using historical storm surge data provided by the Department of Transport. Numerical simulations of fifty-four selected base cyclones were undertaken. A further six sensitivity simulations were undertaken to describe the effects of tide level and radius to maximum winds. They provided time series of storm surge over periods of seventy-two hours at half hourly intervals. Those simulations provided basic data for cyclone surge descriptions used in a Monte Carlo analysis, together with the analysed historical data.

Cyclones and astronomical tides over a period of ten thousand years were simulated. The resulting storm tide time series were analysed using the Extreme Value Type 1 distribution to provide peak storm tide levels at selected average recurrence intervals. Other meteorological events such as East Coast Lows may also cause elevated ocean levels, but have not been investigated.

Wave setup was also investigated and likely water level increments determined. In addition, wave runup heights, which implicitly include wave setup, were determined specifically for locations along the beach frontal dune. Design levels for different locations in the coastal region that might be affected by storm tide have been provided for an example site. A procedure for undertaking similar calculations for other sites has been prepared.

The peak storm tide levels presented in Table 5 do not include an increment for possible MSL rise or for increased cyclogenesis caused by Climate Change. This may be 0.2m by 2048 (CSIRO, 2000).

Wave setup increments are to be added to peak storm design surge levels, other than for frontal dune sites where wave runup is to be included.

A detailed MIKE 21 hydraulic model of the Don River has been developed and calibration against the 1980 historical flood event attempted. Further refinement of the MIKE 21 model parameters, including topography and inflows from the URBS hydrologic model, is required to achieve a satisfactory calibration. This process should include consideration of the potential movement of sediment in the river during flood events.

Mapping of the predicted storm tide inundation and flood inundation for the 20 and 100 year ARI design events has been prepared. Combined storm tide and freshwater events are currently being considered and will also be mapped. The mapping including freshwater events will need to be reviewed when calibration of the MIKE 21 hydraulic model is refined.

The storm tide mapping shows that Queens Beach and Bowen are at a high to extreme level of risk from storm tide events. Substantial inundation of Queens Beach and Queens Bay occurs during extreme events, with localised inundation Bowen occurring during most events. Isolation of all areas occurs under extreme events, with some key roadways cut during smaller events. It will be important to evacuate Queens Beach and Queens Bay early to avoid residents being trapped when roadways are cut. There are high areas within Bowen that residents can be relocated to during events.

This study has quantified the storm surge risk along the Bowen Shire coastline and assessed potential impacts in terms of flood inundation and flood hazard.

In summary, the overall risks appear manageable with good counter disaster planning. There are a couple of areas that would require evacuation under the more extreme storm tides, however the majority of coast is generally immune from surges up to 100 year ARI (ie typical flood immunity standards), with localised inundation of some areas. Isolation of areas, such as Keppel Sands, would need to be specifically addressed. Approximately 18 hours advanced warning would be given by BoM to allow time for evacuation.

It is important for Council to obtain an accurate picture of the joint probability of flooding combined with storm surge.

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Appendix A

Observed Wave Data for Cyclone Dawn

Appendix B

Analysed Historical Cyclone Data

Appendix C

1980 Calibration Event – Recorded Flood Levels