Storm tide threat in Queensland: History, prediction and relative risks

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Glossary

AHD (Australian Height Datum)
This datum has been adopted by the National Mapping Council as the datum to which all vertical control for mapping is to be referred. It is approximately equivalent to Mean Sea Level (MSL).

Ambient pressure
The MSL atmospheric pressure surrounding, but not affected by, a tropical cyclone.

Astronomical tide
The periodic rising and falling of the oceans, resulting from the gravitational attraction of the moon, sun and other astronomical bodies acting upon the rotating Earth. Although the accompanying horizontal movement of the water resulting from the same cause is also sometimes called the 'tide', it is preferable to designate the latter as the tidal current, reserving the name astronomical tide for the vertical movement.

Bathymetry
The measurement of depths of water in oceans, seas and lakes; also information derived from such measurements.

Continental shelf
The zone bordering a continent and extending from the tidal low water mark to a depth where there is a marked or rather steep descent toward greater depths.

Coriolis effect
The influence of the Earth's rotation that causes winds to circulate in a clockwise direction around low pressure systems in the southern hemisphere.

El Niño — southern oscillation
Large-scale natural fluctation in the global climate system that occurs irregularly and involves a close coupling of the oceans and atmosphere.

HAT (Highest Astronomical Tide)
The highest level that can be predicted to occur under average meteorological conditions and any combination of astronomical conditions. These levels will not be reached every year, HAT generally occurring at any one location once every 18.6 years.

Inverse barometer effect
The proportional rise in water level due to the hydrostatic pressure deficit beneath a tropical cyclone. The pressure deficit is the difference between the MSL ambient pressure and the MSL pressure at the centre of the tropical cyclone. The local magnitude of the rise in elevation is approximately 10mm per 1hPa of pressure deficit.

Long-wave motion
A class of surface disturbances of the sea surface whose characteristic wavelength (distance between consecutive peaks or troughs) is such that the resulting motion can be considered as nearly-horizontal in form. Long waves include the astronomical tide, storm surge and tsunamis.

Radius of maximum winds
The distance from the centre of a tropical cyclone, where winds are calm, to the point where the surface wind speeds are greatest (at the position of maximum radial pressure gradient).

Return period
Also known as average recurrence interval or ARI. The return period of an event, normally expressed in years, is the average time between successive events of equal or greater magnitude. The actual time between such events may be greater or less than this period due to the randomness of the process. The inverse of the return period is the average annual probability of exceedance, which remains constant from one year to the next, regardless of whether a given event has or has not occurred.

Sea
That portion of wave motions on the sea surface that are generated by local winds and are still in a state of absorbing the energy of the wind, which leads to a growth in wave energy.

Spring tidal range
The difference in height between MHWS (mean high water springs) and MLWS (mean low water springs). MHWS is the long term average of the heights of two successive high waters during those periods of 24 hours (approximately once per fortnight) when the range of tide is greatest, at full and new moon. MLWS is the long-term average value of two successive low waters over the same period as defined for MHWS.

Storm surge
A rise above normal water level on the open coast due to the combined effects of surface wind stress and atmospheric pressure fluctuations caused by severe weather events (e.g. tropical cyclones).

Storm tide
The combined action of storm surge and astronomical tide.

Swell
That portion of wave motions on the sea surface that have travelled away from the area of wave generation and become characteristically more regular, of longer period and with flatter crests.

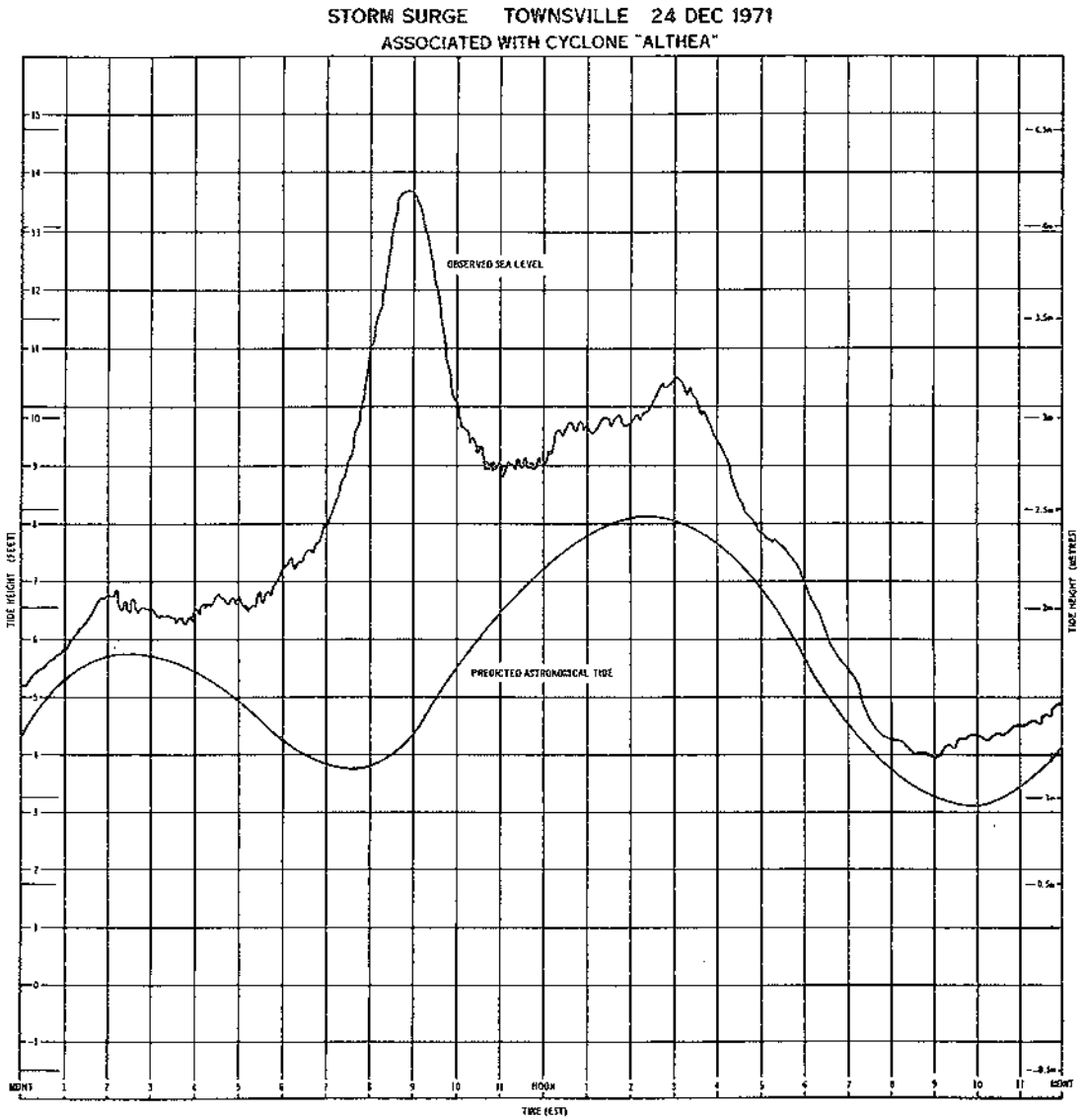
Tropical cyclone
Also known as a hurricane or typhoon. An intense, large-scale low-pressure storm system of tropical origin with cyclonically rotating mean winds at the sea surface (clockwise in the southern hemisphere) in excess of gale force (63km/hr, 34kt, or 17.5m/s).

Tsunami
Japanese for harbour wave. A transient long-period wave typically caused by an underwater disturbance such as an earthquake, volcanic eruption or landslide. Tsunami can travel very long distances across oceans and affect remote coasts, often being amplified as they enter shallow waters and are capable of significant inundation. Tsunami are sometimes incorrectly termed tidal waves.

Wave runup
The rush of water up against a structure or beach on the breaking of a wave. The amount of runup is the vertical height above still-water level to which the rush of water reaches. In the present report, runup is measured from the quasi-steady wave setup level.

Wave setup
A quasi-steady super-elevation of the water surface due to the onshore mass transport of water caused entirely by the action of breaking waves. Wave setup is sometimes included in calculations of wave runup.

Illustrations from Bureau of Meteorology (1972), report by Director of Meteorology on Cyclone Althea; photograph of Townsville foreshore attributed to A. Trotter.



1 Introduction

This report summarises present knowledge of the potential threat posed by storm tides along the Queensland coast.

As single catastrophic events, extreme storm tides generated by tropical cyclones (hurricanes or typhoons) are responsible for the Earth's largest known loss of human life. The Bangladesh cyclone of 1970 is estimated to have drowned more than 300 000 inhabitants (Frank and Hussain, 1971). More than 30 000 hurricane deaths this century have been reported in the Caribbean, as well as almost 15 000 in the United States (Sheets, 1994), the majority due to the direct effects of the associated storm tide. The greatest US disaster occurred in 1900 at Galveston, Texas, where more than 6000 people were drowned. Nearly 2000 US lives were also lost in 1893 and again in 1928. In terms of life and economic loss, tropical cyclones far exceed the impact of earthquakes worldwide. In Australia, we have thankfully not experienced such devastating losses as a result of storm tide, but the potential exists and the likelihood increases as the population increases along the coastal margin.

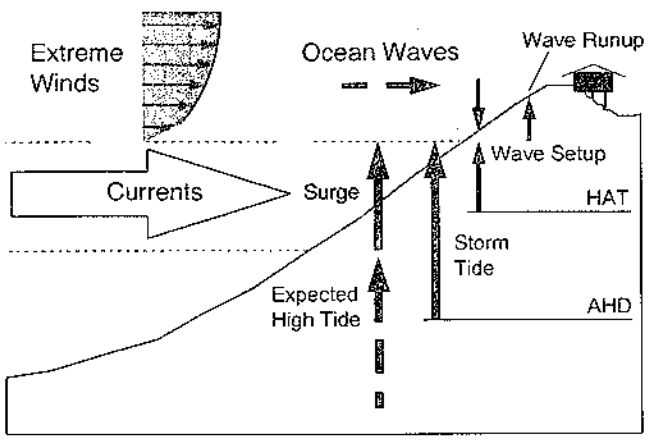
This report provides an overview of the problems associated with storm tides, an introduction to the physical mechanisms at work, an historical perspective and a summary of results from some of the numerous technical studies done to date. Aspects explored include coastal zone planning and infrastructure design, and community forecasting, including shelter and evacuation issues. Data from existing studies is examined in terms of its currency, accuracy and applicability and recommendations for on-going or updated analyses and research are presented.

Although no new analyses are presented here, the appendices contain detailed results from past studies and form the basis of an historical record of storm tide phenomena for the Queensland coast. A glossary of technical terms is included for reference.

2 Definitions

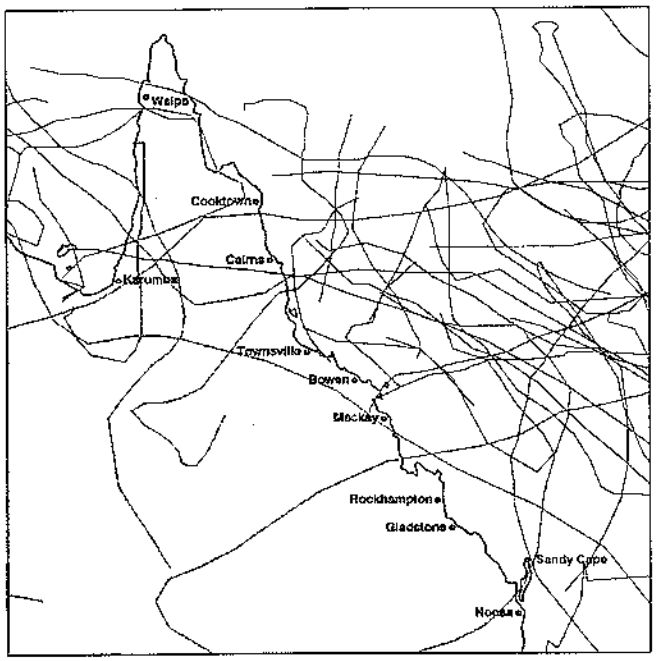
A storm tide is the effect on coastal water levels of a storm surge combining with the normally occurring astronomical tide (see fig.1). The storm surge (or, more correctly, meteorological tide), is an atmospherically forced ocean response, caused by extreme surface winds and low surface pressures associated with severe and/or persistent offshore weather systems. At exposed beachside areas, an additional localised increase in water level can occur due to the effects of breaking wave setup, and wave runup can also cause severe erosion above the storm tide level.

Figure 1. Components of total water level during a storm surge event



In Queensland, the tropical cyclone represents the principal threat to life and property in respect of storm surge. Figure 2 shows the incidence of tropical cyclones off the Queensland coast during the month of January since 1959. Other intense large-scale weather systems are also capable of producing storm surges, but their effects are less significant and are generally limited to the south-east corner of the state.

Figure 2. Cyclone tracks for January since 1959



The term 'storm tide' correctly conveys the sense of a prolonged and, generally, gradual increase in coastal water levels, followed by a similar decline after the event has passed. While the increase is, at times, quite rapid (e.g. several metres in one hour), there is a low likelihood of the spontaneous rise in levels conveyed by popular views of tidal waves or tsunamis associated with earthquakes. A storm surge can influence normal water levels for several hundred or even thousands of kilometres along a coastline, but peak and potentially destructive surge levels are associated with the region of maximum wind speeds. Typically, relative to the centre of a tropical cyclone, this is 50–100km in diameter. Because of the co-incidence of severe winds and surge, any population evacuation needs to be signalled well clear of the onset of destructive winds.

Many factors influence the potential for serious storm tide events at a particular coastal site. Prime factors in determining the potential surge level are intensity of the tropical cyclone, its proximity to a site and the coastal characteristics of that site. Local astronomical tide characteristics are then important in determining the final storm tide level. A large tidal range adds a degree of chance that a surge impact may be mitigated if it occurs at a low tidal level. The critical storm tide level is that which exceeds the Highest Astronomical Tide (HAT) at any location. HAT is determined by the periodic motions of the sun and the moon and occurs at any location every 18.6 years, although levels very close to HAT may frequently happen at other times. Along the Queensland coast, HAT levels typically vary between 0.5m and 1m above the mean high water spring tide value (or 'high tide'). Throughout this report, storm tide levels are given relative to Australian Height Datum (AHD), which is approximately at mean sea level, or, in some cases, relative to HAT, which can vary from 1m to more than 4m above AHD depending on location.

Associated with a storm surge will be the familiar ocean waves (sea and swell) also derived from severe winds. These waves are an intrinsic effect of the surge-generating mechanism, but are largely non-interacting with the surge. As water levels rise, due to the combined effects of surge and tide, ocean waves can travel atop the storm tide to attack coastal structures or cause severe coastal erosion at elevations not normally reached in common storm events.

As well as attacking the coast, the ocean wave energy can create an additional local build-up of water near the coastline where the waves break. This additional (generally small) increase in water level is referred to as 'wave setup'. A very localised effect, differing from one beach or bay to another, it can be significant in certain circumstances, especially on offshore islands.

Wave runup on beaches by individual waves can also cause overtopping of dunes and severe erosion at heights above the storm tide and wave setup levels.

3 Historical record

The first recorded instance of a significant storm tide in Queensland is the 3.1m surge in 1884 at Bowen, although Green Island, near Cairns, was reputedly overtopped by waves in 1858. Various authors have scanned both the historical literature and the record of tidal anomalies over a number of years (e.g. Whittingham, 1958; Holthouse, 1971; Harvey, 1974; and Nelson, 1975). Much of the earliest data was collected by Whittingham, and remains in unpublished form with the Bureau of Meteorology in Brisbane. From these and many more recent records, the present study has amassed approximately 70 known instances of tropical cyclone-related storm surge events along the Queensland coast, affecting some 150 locations. These are presented in Appendix 1, where some 70 percent of events are classed as minor in terms of surge height (≤1m). However, a number represent quite significant surge events and 15 are definitely known to have resulted in the exceedance of HAT levels at a particular site by more than 0.5m, posing a potential threat to the community. At least nine cyclones have produced storm tide levels of 2m or more above HAT.

Undoubtedly, many more severe events occurred unnoticed along the sparse northern coastline prior to the early 1900s. The Gulf of Carpentaria has figured in a number of the more severe storm tide episodes. Steadily increasing settlement of the northern coastal margin is a significant factor in the increasing storm tide threat to Queensland communities.

Table 1 lists some of the more notable events, including the infamous Bathurst Bay event of 1899, when a pearling fleet sheltering near Princess Charlotte Bay, 200km north of Cooktown, was devastated and 300 people killed. The estimate of approximately 14m stands from the literature, but is not easily supported by technical analysis. Regardless, it is clear that a quite severe surge event occurred at this site.

During the 1918 cyclone at Mackay (Harbours and Rivers Dept, 1918), a 3.7m surge combined with a high tide to enter the town, reaching levels of 5.4m AHD and inundating parts up to 2m above HAT. More recently, the 2.9m Althea surge at Townsville in 1971 luckily coincided almost exactly with low tide, so that storm tide levels were only about 0.5m above HAT (Stark, 1972). Nevertheless, large sections of The Strand seawall (see page 3 photograph) were destroyed and waves entered properties at Pallarenda.

Table 1. Some notable storm surges in Queensland

Year	Place	Event	Est. central pressure (hPa)	Surge ht (m)
1884	Bowen		-	3.1=
1887	Burketown		-	5.5=
1896	Townsville	*Sigma*	-	>2
1899	Bathurst Bay	*Mahina*	914	14=
1918	Mackay		935	3.7=
1918	Innisfail		928	>3=
1920	Cairns		988	>1.5=
1923	Albert River	*Douglas Mawson*	974	>3=
1934	Port Douglas		968	>1.8
1948	Bentinck Is		996	>3.7
1964	Edward R.	Dora	974	5?
1971	Inkerman Station	Fiona	960	>4
1971	Townsville	Althea	952	2.9=
1971	Edward R.	Fiona	960	3
1972	Fraser Is	Daisy	959	3?=
1976	Burketown	Ted	950	4.6?=
1978	Weipa	Peter	980	1.2=
1987	Karumba	Jason	970	2
1989	Ayr	Aivu	935	3.2=
1995	Karumba	Warren	980	1.5
1996	Gilbert River	Barry	950	>4?=

(= exceeded HAT)

4 Current knowledge of risk

The historical rarity of severe storm tides along the Queensland coast, and more particularly at any specific location, means basic statistical methods using measured water level data are not suitable for estimating long-term risk. Methodologies developed since the late 1970s (outlined below), which combine complex numerical and statistical modelling, have provided a robust scientific basis for making long-term predictions. Figure 3 shows the location of the major regional studies presently available, the majority of which have been commissioned by the Beach Protection Authority (BPA).

Figure 3. Location of major storm surge studies in Queensland

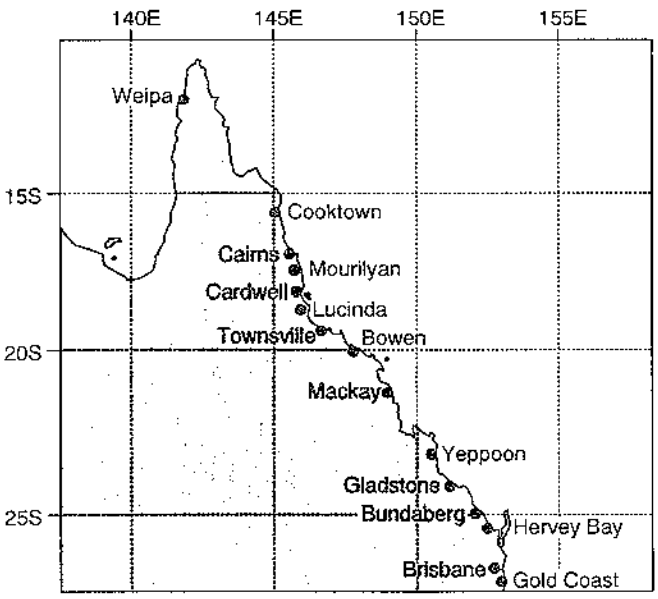
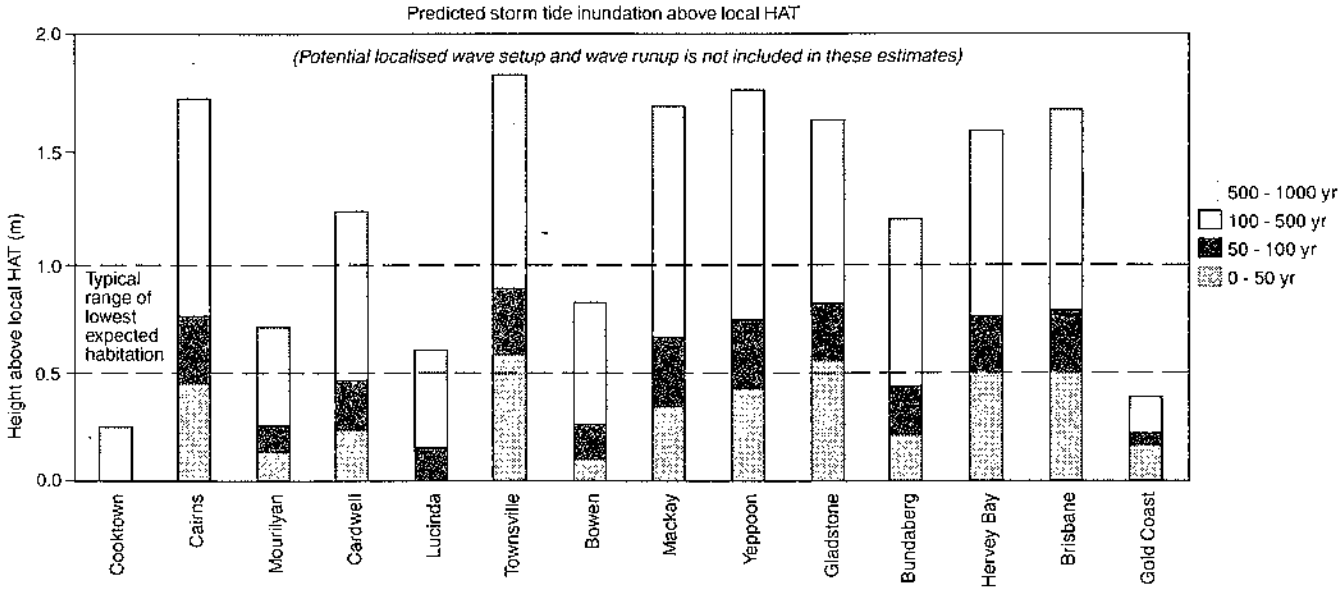


Figure 4 summarises the presently predicted inundation risk for these major coastal centres of Queensland. The results are presented as the predicted level of inundation above the local HAT (maximum tidal level) for a range of return periods. For example, the 500-year return period inundation level is expected to be equalled or exceeded at least once on average in any period of 500 years of observations. This means that there is a 63 percent chance of reaching or exceeding the 500-year level in any 500-year period.

Figure 4. Summary of the predicted storm tide inundation risk at major population centres in Queensland based on present studies (after Harper 1996b).



Another way of expressing this same level of risk is that there is a 10 percent chance of exceeding the 500-year return period level in any 50-year period. This level of risk has been discussed with regard to new urban and residential development along the Queensland coast in the Coastal Protection Strategy Green Paper (Queensland Government, 1991). Another example of an acceptable risk level in common use is the standard engineering wind loading code AS1170.2 (Standards Australia, 1989) which considers a 1000-year return period for tropical cyclone-induced wind loads on all types of structures.

Figure 4 also shows that risk is predicted to vary greatly between coastal centres. Taking the +0.5m to +1.0m above HAT level as a typical lowest-built-level range for more recent permanent habitation or infrastructure, only Cooktown, Lucinda and the Gold Coast are below this range at the 500-year return period risk level. By contrast, the areas of Cairns, Cardwell, Townsville, Mackay, Yeppoon, Gladstone, Hervey Bay and Brisbane are all susceptible to inundation at or above the +1m level with a return period of between 100 and 500 years.

Estimates suggest Townsville has the highest likelihood of significant inundation, followed by Yeppoon and Cairns, with only slightly lesser risks for Mackay, Brisbane, Gladstone and Hervey Bay. Wave setup of approximately 0.5m could be an additional factor for some beachside suburbs at these sites. The following sections explain the basis for these predictions and explore their technical aspects.

5 Storm tide generation

The discussion of storm tide generation here relates only to tropical cyclones, but mechanisms are similar for other severe weather systems that can influence water levels in south-east Queensland (such as large-scale easterly trough lows). A tropical cyclone (or hurricane or typhoon) is defined as a non-frontal cyclonically rotating (clockwise in the southern hemisphere) low pressure system, below 1000hPa and of tropical origin, in which 10-minute mean wind speeds exceed gale force (63km/hr, 34kt or 17.5m/s).

The highly organised structure of the near-surface wind field and atmospheric pressure forcing in a tropical cyclone, together with forward motion of the system, results in a complex and transient long-wave motion of the underlying ocean.

This motion initially lags behind the moving cyclone (due to the effect of mass inertia) but can then travel large distances along a coastline before gradually decaying over time. Complex coastal bathymetry can significantly interact with the storm surge, affecting both its generation and propagation in a region. This report does not consider the possible interaction of freshwater flooding concurrent with storm tides.

5.1 Surface pressure forcing

Tropical cyclones exist within a nearly symmetric radial sea surface pressure field, which has its minimum surface pressure in the centre of the cyclone eye. Beyond the eye the atmospheric pressure rapidly increases, the rate of increase being a maximum at the so-called radius of maximum winds, and then gradually rising to meet the surrounding environmental pressure some hundreds of kilometres beyond the centre. Figure 5 presents an example of the radial surface pressure and gust wind speed profiles during a severe Category 5 tropical cyclone. (See table 2 where the Bureau of Meteorology category scale is indicated relative to peak gust wind speeds; the US category scale is different.) Note that peak gust wind speeds can be greater than mean winds by approximately 40 percent, but it is the mean wind strength that generates the storm surge.

Figure 5. Example radial pressure and mean wind speed profiles in a severe Category 5 tropical cyclone

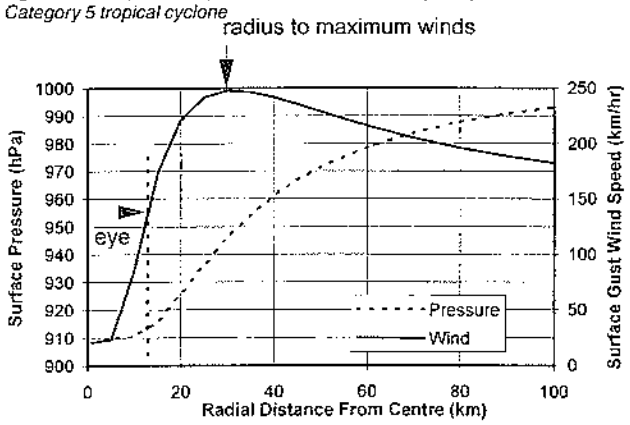


Table 2. Cyclone severity categories (Davidson, 1996b)

Category	Strongest Gust (km/h)
1	Less than 125
2	125–170
3	170–225
4	225–280
5	More than 280

The relative pressure deficit at the centre of the cyclone induces a super-elevated mound of water — historically termed 'the inverse barometer effect' — which is broadly a mirror image of the pressure profile itself. The local magnitude of the rise in elevation is approximately 10mm per 1hPa of pressure deficit relative to the ambient pressure.

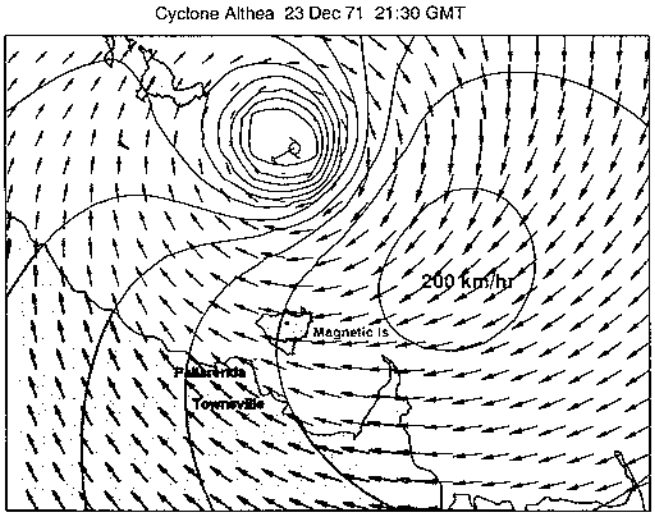
For the example in fig.5, assuming a typical 1010hPa ambient pressure, the central pressure of 910 hPa would produce a maximum pressure-induced surge component of about 1m directly below the eye of the cyclone in deep water, decreasing further away from the centre. Islands with narrow continental shelves and in deep water away from the coast normally only experience the static effects of the pressure-induced surge. In such situations, wave-induced setup may represent the highest component of increased water levels. In shallow waters, the pressure surge component interacts with the bathymetry and coastal forms, and may become dynamically amplified at the coastline to levels approximately twice the offshore levels (Sobey et al., 1977).

5.2 Surface wind shear

In contrast, the influence of the severe surface wind shear on surge levels is confined largely to the shallower waters of the continental shelf. The wind-induced surge component is depth-dependent, increasing with decreasing ocean depth and normally responsible for the greater proportion of surge height at the coastline. Flat, shallow continental shelf regions therefore generate larger surges than narrow, steep shelf regions.

In the southern hemisphere, winds circulate clockwise around a low pressure system. Figure 6 presents a numerical model's view of the windfield surrounding Althea a few hours before it crossed the coast to the north of Townsville. This circulation initially causes an alongshore flow (northwards in the east coast context) as the cyclone approaches the coast. This is gradually supplanted by a severe onshore flow of water on the left-hand side of the cyclone (observer moving with storm) where the winds are greatest due to forward speed effects combining with the extreme circular vortex winds. The magnitude of the surge then depends largely on particular coastal forms, which may either amplify or diminish the piling up of water against the coast.

Figure 6. A numerical model depiction of Althea's windfield (after Harper 1996b)



5.3 Track and other effects

Sobey et al. (1977) present a series of basic sensitivity tests derived from numerical hydrodynamic modelling of storm surges, which consider the relative influence of such factors as intensity, scale radius, angle of the track to the coast, speed of forward motion, coastal forms and bathymetry. Basic findings from those tests are outlined below.

Storm surge magnitude can be regarded as directly proportional to the cyclone intensity for a given coastal site, over the range of intensities likely to be experienced at that site. It can be highly site-specific due to local factors. The relative horizontal scale (e.g. diameter) of the cyclone is also important in determining the length of affected coastline and, below a certain minimum size, may reduce the potential peak surge, again dependent on local effects.

In general, the highest surge will be generated for the case of a coast-crossing cyclone, although a parallel moving system close to the radius of maximum winds can produce an equivalent surge in a straightline (idealised) ocean basin. In practice, coastal forms such as bays, capes and offshore islands often reduce the influence of the parallel case and increase the influence of the coast-crossing situation. Inertial effects also make it difficult for a system that forms close to land to generate a large surge.

Speed of forward motion can also affect the peak surge, tending to increase with fast-moving cyclones. Theoretically, a resonance situation is possible between the forward speed and the surge generation process, but this requires particularly special conditions in time and space. While some interaction between the astronomical tide and the generation of the surge does occur, usually its effect is quite small, and so the linear addition of storm surge and astronomical tide levels can often be assumed.

Interested readers should see Sobey et al. (1977) or Harper and McMonagle (1985), where more specific details of potential alongshore and offshore surge profiles may be found. Detailed technical presentations may also be found, for example, in Bode and Sobey (1984) and Bode and Hardy (1996).

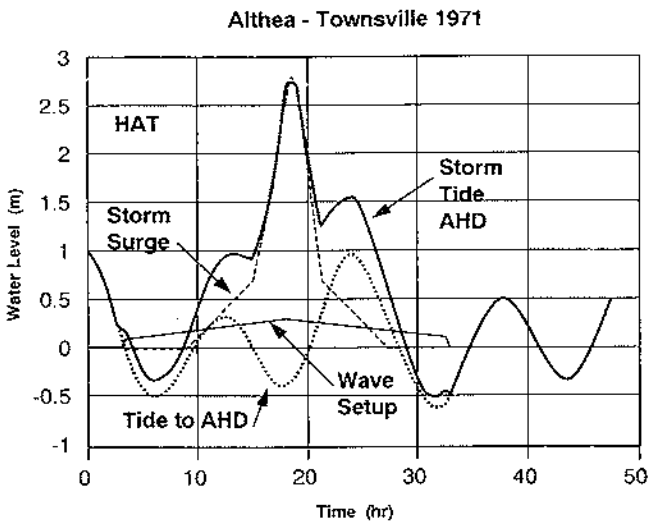
6 Example Storm Tide

The surge and resulting storm tide generated by tropical cyclone Althea at Townsville in December 1971 are a good example of a classical storm surge scenario. In this example, the storm tide is reconstructed by way of a numerical representation of its various components.

Figure 7 presents a schematic of the time history of variation in ocean water levels during the passage of Althea. The predicted astronomical tide is indicated at the base of the graph, which then represents the possible wave setup component of water level over the period of cyclone passage, and finally a schematic of the 2.9m surge itself. Together, these components yield the upper line of total storm tide levels, basically as recorded on the tide gauge at Townsville harbour, peaking at 2.6m AHD.

The critical relative phasing between the surge and the tide is instrumental in determining whether a surge will be a minor inconvenience or a potential major disaster. In this case, the peak surge arrived near the time of low tide and the resulting storm tide only exceeded local HAT by about 0.5m at Townsville. However, surveys of coastal damage in the region indicate that higher surge levels up to 1m above HAT probably occurred further north (Stark, 1972). Had the cyclone passed six hours later, peak water levels could have been up to 2m above HAT at Townsville, representing a major community disaster.

Figure 7. Schematisation of the Althea storm tide (after Harper 1996b)



7 Regional variation in risk

From the previous example it can be seen that storm tides result from a number of quite complex mechanisms, which often act over different time and space scales, and can interact in specific ways depending on the exact situation. To see the underlying patterns that combine to produce a state-wide variation in storm tide threat, such as that depicted in fig.4, one must consider major factors on an individual basis. Qualitative aspects of these variations are discussed below.

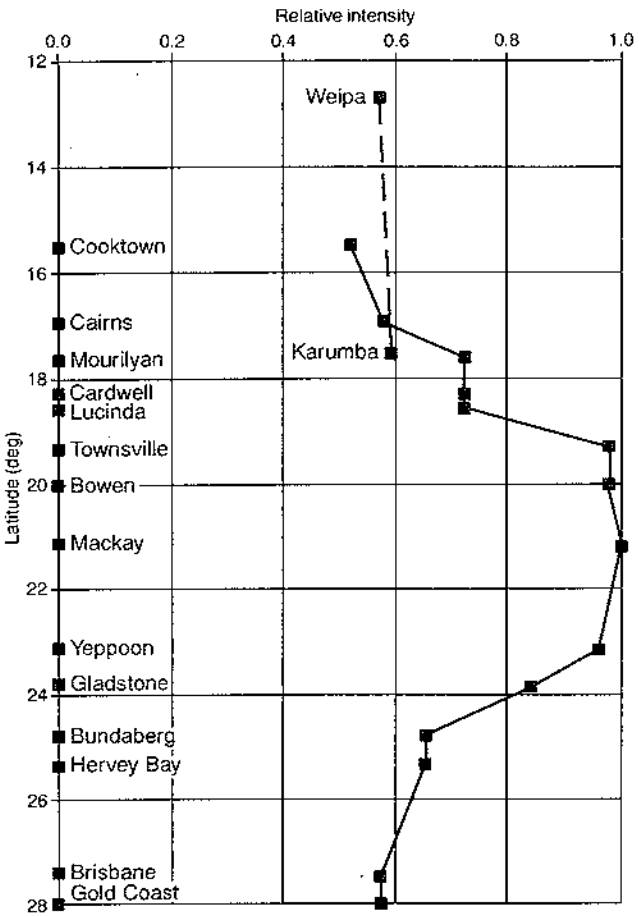
7.1 Variation in cyclone intensity

This is perhaps the most obvious of all the factors affecting storm tide risks. Put simply, a low likelihood of cyclones occurring in a particular area will lead to a low risk of severe storm tides in that area. By examining the historical record of cyclone tracks and their estimated intensities, statistical analyses can be undertaken which expose the underlying function of risk that exists along the Queensland coast, usually in terms of the return period of a given central pressure within a given region. This variation in risk has been normalised and is shown in fig.8, derived predominantly from Harper (1985). It shows, in a relative way, that the risk rises north from the Queensland-New South Wales border, peaking between Yeppoon and Townsville and declining towards Cape York.

A primary indicator of potential cyclone intensity is the near-surface ocean temperature which, in current climate at least, is known to be influential above the critical value of 26°C. While sea surface temperature tends to rise towards the equator, there is not a continual rise in cyclone risk northwards because of a number of other physical features and limits. Firstly, tropical cyclones cannot form within approximately 5 degrees of the equator because of the low Coriolis effect — the influence of the earth's rotation, which causes winds to circulate in a clockwise direction around low pressure centres in the southern hemisphere. Secondly, as a rule, tropical cyclones move polewards throughout their life. This, combined with the influence of New Guinea to the north east of Cape York, appears to limit opportunities for development and cyclone movement in the far north.

The more open Western Pacific regions spawn the majority of cyclones which, by the time they have moved westwards towards the Queensland coast, have also moved southwards as a general rule to below latitude 18° (e.g. Cardwell). Recurving of the cyclone path often then follows under the influence of the prevailing westerlies over the continent, causing many cyclones to effectively travel nearly parallel to the Queensland coast at certain stages of their life.

Figure 8. Variation in intensity of tropical cyclones



7.2 Coastal crossings

This is closely related to the preceding section due to the preferred angles of approach at various latitudes. Because of the trapping effects of reefs, bays and headlands, the coast-crossing cyclone is likely to generate a more significant storm surge than a parallel-to-coast cyclone, which must pass close to the coast without weakening to have a similar effect. Figure 9 summarises the relative coast-crossing occurrence along the Queensland coast, which can be seen to follow a somewhat similar response to the intensity variation.

7.3 Site-specific characteristics

The relative importance of coastal characteristics at specific sites is addressed in fig.10. This reflects the relative propensity to amplify or diminish a storm surge as a result of factors such as the width, depth and slope of the continental shelf, the scale of bays, headlands and islands or the possible influence of extensive reef areas. This shows a sometimes very localised variation, with areas such as Hervey Bay, Cardwell and Townsville showing high risk due to local large-scale bay effects.

Weipa and Karumba are especially prone because of their extensive shallow water regions, while the Gold and Sunshine Coasts are protected due to the narrow continental shelf. Within Moreton Bay, Brisbane is at higher risk than the adjacent open coast. Areas north of Mourilyan are protected by the effect of a narrowing shelf. The Great Barrier Reef also has some influence, principally in retarding the passage of large swell waves. Note that, because site conditions can change significantly along the coast, strict interpolation of fig.10 is not reliable.

Figure 9. Variation in coast crossing frequency

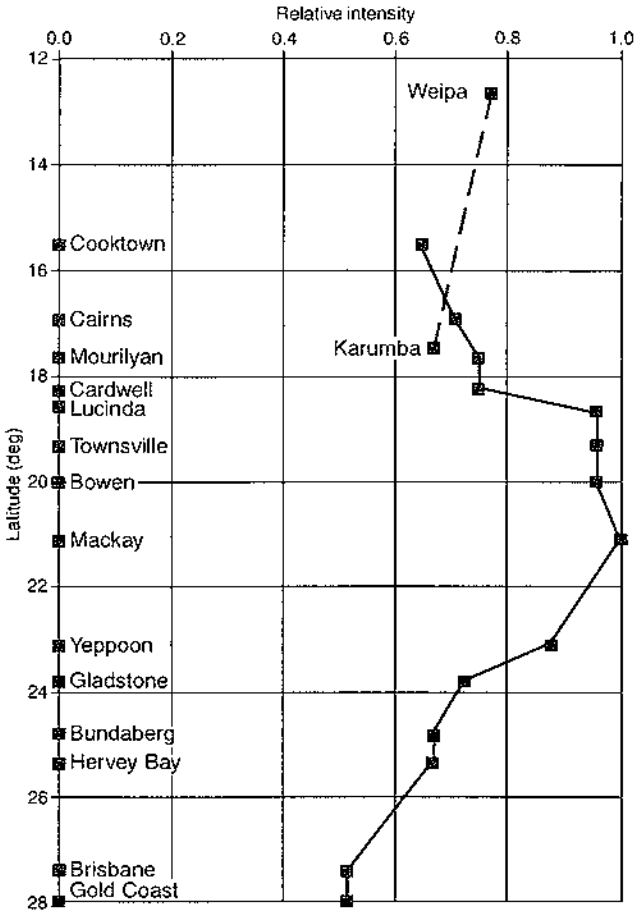
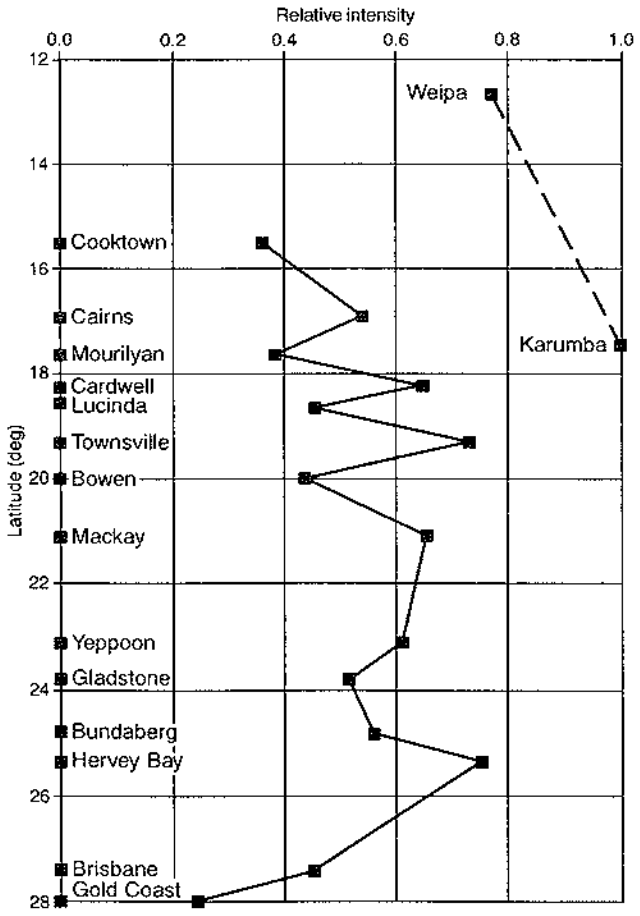


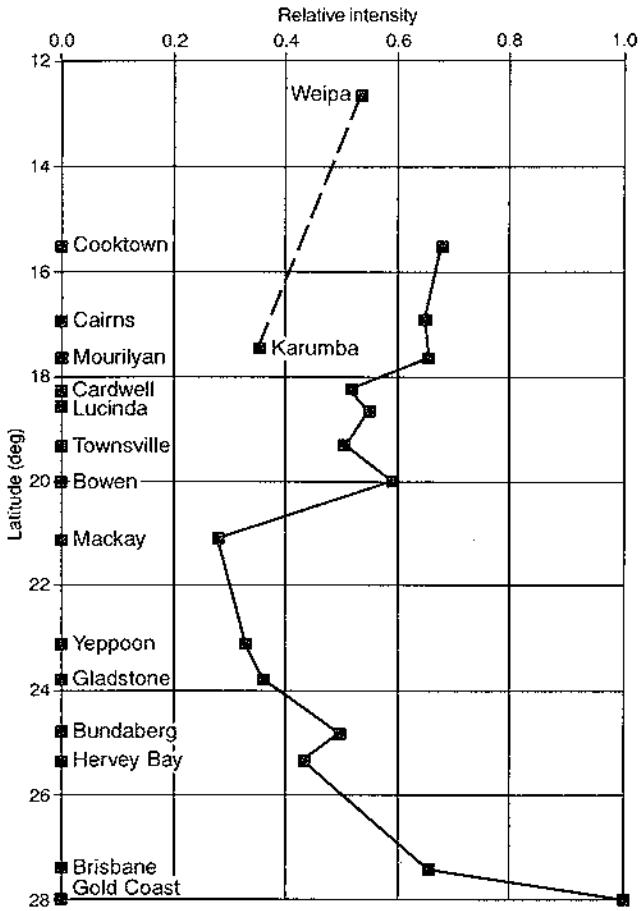
Figure 10. Variation in surge responsiveness along the coast (interpolation between sites is not reliable)



7.4 Role of the astronomical tide

Since the total storm tide level is strongly influenced by the state of the tide, it follows that locations with a large tidal range will provide a degree of statistical variability, which can serve to reduce the likelihood of a severe storm tide inundation. Figure 11 shows relative storm tide vulnerability along the coast arising from specific tidal characteristics. The inverse of the spring tidal range in metres (Queensland Transport, 1995) is used here as a suitable normalising indicator.

Figure 11. Variation in storm tide vulnerability due to tidal range



The Gold Coast, with its low tidal range, has a relatively increased vulnerability to storm tide inundation compared with, for example, Mackay, where the tidal range is quite high. While there is a degree of interaction between surge magnitude and tide level (due to the overall depth effect) it can generally be considered as a separate, independent effect.

8 Planning vs forecasting

In their investigations of long-term water levels in various coastal communities, all studies reported on here have focused on planning, rather than forecasting (e.g. BPA, 1979;1984;1989b). This approach has proved important to the engineering design of ports and harbours, near-coast developments and other infrastructure and services. It has also been used in deciding matters such as erosion set-back distances and land-use rezoning applications.

Much can still be done in terms of investigating surge propagation in estuaries and coastal river systems and the potential for specific localised dune breaches and inundation. Another area requiring research is the direct impact of overland flooding and wave attack on domestic and commercial construction.

The US experience (FEMA, 1985; 1986; 1988a;b) shows that effective planning and building design procedures can be put in place to safeguard life and property and also to gain access to insurance cover against storm tide for beachside residents — an advantage not presently available in Australia. Smith and Greenaway (1994) have estimated, for example, a repeat of the 1918 storm tide at Mackay could produce residential and commercial losses in the order of $160M and long-term average damage levels may be as high as $8M per year for Mackay alone.

A forecasting approach has a different emphasis, concentrating on immediate community safety. This is the statutory role of the Bureau of Meteorology which, under established State Counter Disaster Organisation arrangements (SCDO, 1994), advises of an impending storm tide threat. To date, the forecasting methodology has necessarily been limited to simplified analytical techniques. However, significant improvements to the present forecasting schemes are presently underway as a part of the Tropical Cyclone Coastal Impacts Program (TCCIP, 1996). It is expected that these studies will ultimately meet or exceed the detail embodied in the earlier engineering analyses described here, but with a focus on the forecasting problem.

Each tropical cyclone season brings with it the potential for a serious storm tide incident somewhere along the Queensland coast, even though the probability of a storm tide actually occurring at one specific location is quite low. For example, a Category 4 cyclone is likely to occur near the Queensland coast approximately once every 15 years, with the potential to produce a 4m surge at some locations if it crosses the coast. A 3.5m surge could be produced by an Althea-like cyclone, which occurs every 5 years on average. Forecasting must then deal with the uncertainty surrounding each and every potential storm tide event.

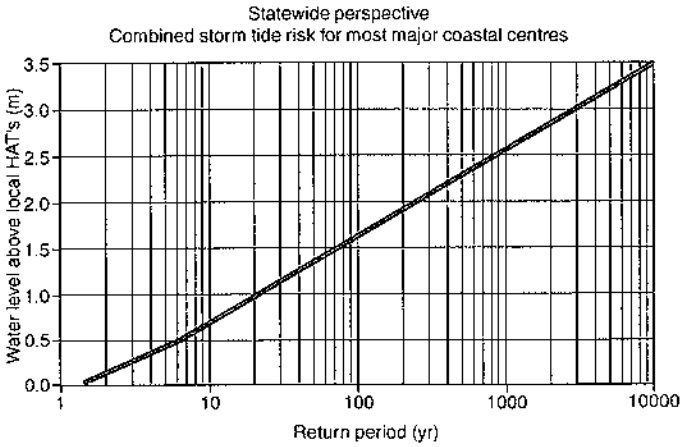
All the preceding components of storm tide sensitivity at any particular coastal site come into play in a forecast scenario. Factors such as the intensity of the cyclone and its possible track are clearly most important in determining whether a particular community is likely to be affected. Forecast track positional error, for example, shows a decreasing trend over the past 10 years from 150km to 94km for a 12-hour forecast (Davidson, 1996a), but this still presents considerable uncertainty relative to a specific coastal community.

Ultimately, however, the most critical element that determines whether a relatively minor annoyance or a major disaster threatens is the phasing of any storm surge with the tide. Therefore, the compounding uncertainties inherent in forecasting the erratic movement of tropical cyclones means that a forecasting scheme is dutybound to provide a conservative estimate of total storm tide levels, at least on a timescale necessary for any type of mass community evacuation. It is quite possible for a surge of, say, 3.5–4.5m generated by a Category 4 cyclone to coincide with the top of a spring tide to produce a combined water level of 2.5 to 3.5m above HAT. Such an event would be rare, having an annual probability of exceedance of less than 0.01 percent (more than 1 in 10 000 years) for one particular town. However, *evacuation* of coastal areas threatened by storm tides of this magnitude can be expected to occur much more often than once in 10 000 years, given that any cyclone may threaten several towns and the uncertainty of whether or not the cyclone will coincide exactly with high tide.

Therefore, site-specific surge inundation risks such as those presented in fig.4 must be combined to determine the total community risk. This has been done in fig.12, showing that the 0.5m inundation event has an average return period of approximately 6 years for at least one of the major coastal centres, and the 1.0m inundation event is likely to occur every 20 years on average.

On this basis, extreme storm tides causing dangerous levels of inundation are not particularly rare events in Queensland. As settlement of the coastal margins increases, the likelihood of such events will similarly increase.

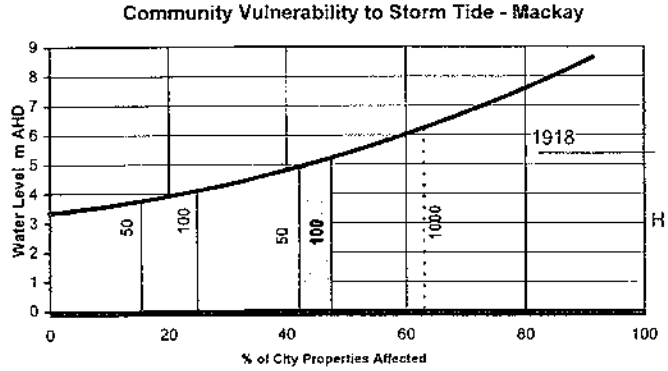
Figure 12. Example of community vulnerability (after Harper 1996b)



Therefore, in preparing for statewide disasters, the site-specific surge inundation risks (such as those presented in fig.4) must be combined to determine the total community risk. This has been in fig.12, showing that the 0.5m inundation event has an average return period of approximately six years for at least one of the major coastal centres, and the 1.0m inundation event is likely to occur every 20 years on average. On this basis, extreme storm tides causing dangerous levels of inundation are not particularly rare in Queensland. As settlement of the coastal margin increases, the likelihood of such events will also increase.

In spite of uncertainty surrounding specific scenarios, the analyses summarised here can be used to good advantage in emergency planning. They provide an overall perspective of the inundation risks along the coast, and highlight the most sensitive aspects of the problem in each of the major coastal centres. For example, planning can be directed towards the highest risk zones in the first instance. This means initially addressing inundation issues at the shortest return period elevations in each location, because they represent a more likely outcome, notwithstanding the forecast elevations on the day. Specific community vulnerability studies are presently part of the TCCIP (1996) investigations. Figure 13, using contemporary dwelling data from Smith and Greenaway (1994) for Mackay, shows how the statistical water level predictions (Harper, 1985) might interact with the distribution of property elevations in a particular region. Some 40 percent of the City of Mackay can be seen to be within the 500-year return period storm tide range.

Figure 13. Combined statewide risk of storm tide inundation for the major coastal centres in Queensland



It is impractical to plan for worst case scenarios involving coincidence of HAT with a fast-moving Category 5 cyclone crossing at the worst possible location. However, it is prudent to allow for a specific very low probability event that could put many lives at risk. On this basis, fig.13 also indicates the predicted 10 000-year return period event (based on the studies simulating 15 000 years of possible scenarios). The 10 000-year return period is commonly accepted worldwide as the probability level to which it is deemed practical to ensure human life can be protected (Louisse and Kulk, 1990). In the case of Mackay, this level would affect about 63 percent of all dwellings. By comparison, the 2m inundation above HAT experienced during the 1918 cyclone corresponds to a 2000-year return period using these figures. Demographic studies presently underway for other coastal cities will be able to provide similar information to fig.13. For example, large areas of the Cairns, Townsville and Hervey Bay suburban regions are potentially within similar hazard zones. Using preliminary property data from Granger (1996) it can be inferred that, at approximately the 500 year return period, Cairns has twice as many vulnerable properties than Mackay, three times more than Hervey Bay, five times more than Townsville and ten times more than Gladstone.

Disaster preparedness planning will also highlight issues such as vehicular access limitations or other constraints, and the possible need for vertical evacuation shelters or refuges in some situations. If planning is staged on the basis of likely risk, prospects of surviving any storm tide threat should improve.

9 Details of existing studies

Prior to tropical cyclone Althea's effect on Townsville in 1971 (Stark, 1972), no detailed studies had considered the risk arising from storm surge in Australia. Althea's impact spurred a significant period of research and investigation into all matters of tropical cyclone threat.

In 1975, the BPA supported a specific program of research with the Department of Civil and Systems Engineering at the James Cook University of North Queensland in Townsville. This research led to a successful generalised numerical hydrodynamic model capable of estimating peak surge levels for any coastal location in Queensland (Sobey et al., 1977). The BPA also began addressing the need for a state-wide automatic surge monitoring system, which now covers some 30 locations. Techniques were also developed to address the issue of statistical interaction of the surge and tide.

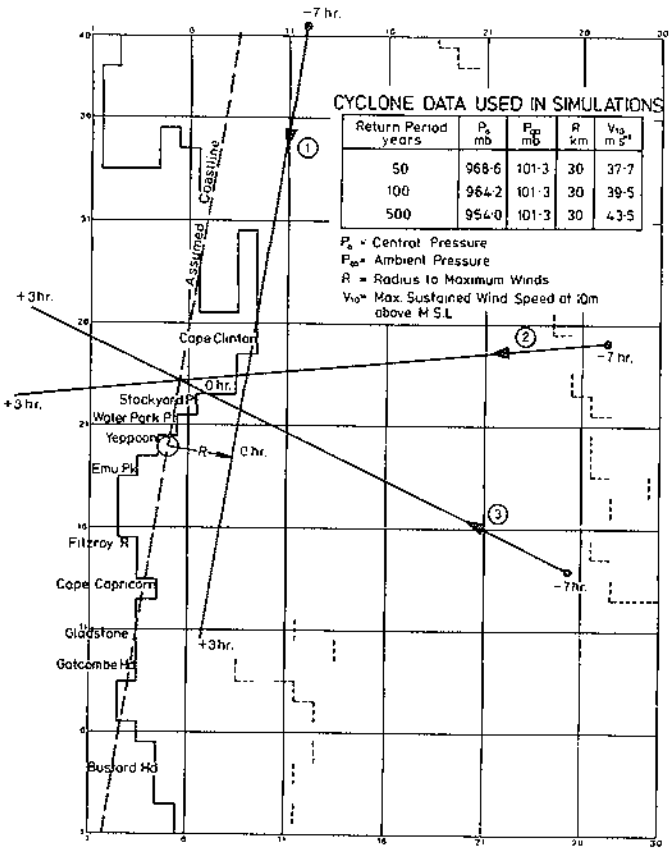
9.1 James Cook University surge studies 1975–1977

This was the first application of sophisticated numerical hydrodynamic modelling of storm surge undertaken in Australia and remains the most comprehensive for the Queensland coastline. It involved basic research into representing tropical cyclones, storm surge development and propagation mechanisms, and numerical experimentation on the various sensitivities embodied in the process (Sobey et al., 1977). From this work, a generalised two-dimensional numerical model named SURGE was developed (Harper et al., 1977a), which was tested against the Althea storm surge, and used as the basis for a series of studies at 10 separate regional centres along the Queensland coastline (Harper et al., 1977b):

- Weipa
- Cooktown
- Cairns
- Innisfail
- Ingham
- Townsville
- Bowen
- Mackay
- Rockhampton
- Gold Coast

These studies were deterministic; reports estimated the highest storm surge values possible at each location, given a particular set of cyclone parameters. Due to computer limitations at the time, this meant only a discrete number of possible cyclone scenarios could be considered at each site. This resulted in three separate approach tracks (1, 2 and 3), each with three separate cyclone intensities, totalling nine simulations per site (see fig.14). The influence of astronomical tides was not considered in these studies, all simulations being undertaken for the case of mean water level and with a fixed model spatial resolution of 5 nautical miles.

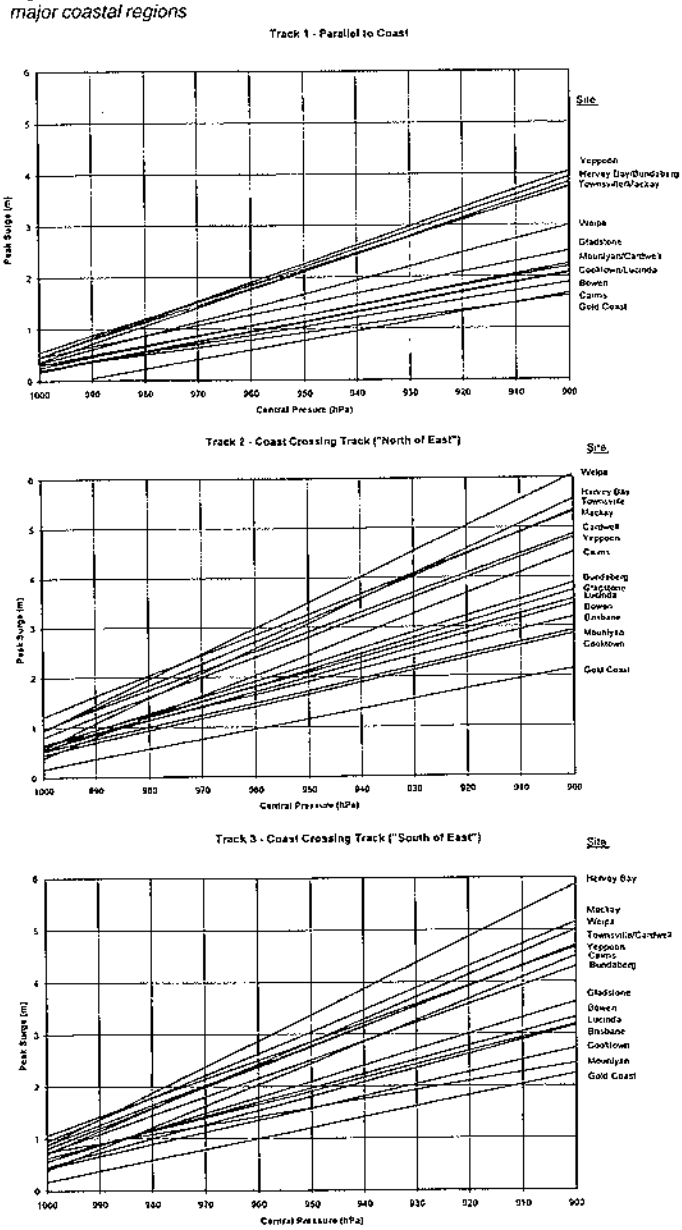
Figure 14. Example of SURGE model tracks for Yeppoon



In spite of the necessarily limited modelling scope, essential characteristics had already been identified from the research studies, namely that the peak surge occurs approximately at the position of the radius to maximum winds of the cyclone and approximately at the time of landfall, or closest passage, and that surge level is essentially a linear function of cyclone intensity. The test cyclone tracks were then located to pass one radius of maximum winds to the north (east coast) or south (west coast) or seawards (parallel case) to ensure the potential for creating the maximum possible surge for a given intensity at the site in question. Due to a lack of information (which still largely persists to this day), the radius of maximum winds in all cases was set at 30km, considered a mean value for the Australian region. The cyclone intensities were carefully chosen on the basis of a regional statistical analysis of available Bureau of Meteorology records (1907–1972), such that nominal values of the 50-year, 100-year and 500-year return period central pressures were used in the modelling, concentrating on the range of likely threats in each region. The forward speed of all model cyclones was conservatively set at 28km/hr, representing the mean of the fastest speeds of individual cyclones from the historical data.

From these studies, the first essential prediction of along-coast sensitivity to storm surge generation could be assessed, incorporating the potential influence of such factors as the Great Barrier Reef and other major coastal forms and islands. The results from these reports are summarised in fig.15, showing the predicted peak surge at each of the major locations as a function of cyclone central pressure prior to landfall and for each of the approach directions modelled. The relationships are shown here in an extrapolated manner and the interested reader should refer to the original studies where the actual modelled cyclone intensity ranges are described in detail. In addition, the indicated range of central pressures down to 900hPa has varying applicability along the coast and is unlikely to be attained, for example, south of the Hervey Bay region.

Figure 15. Predicted peak storm surge vs central pressure for major coastal regions



9.2 James Cook University Statistical Studies 1976–1977

While the above numerical model studies were being completed, other developments occurred in the statistical combination of surge and tide levels based on Monte Carlo methods. This was pioneered by Stark (1976) for the Rosslyn Bay boat harbour, which was heavily damaged by cyclone David. The emerging statistical model was named SATURN (Surge And Tide Using Random Numbers). A follow-up study by Harper and Stark (1977) considered the combination of tide and surge water levels for Townsville.

A more detailed and specific storm surge modelling study was then undertaken for Cairns by Sobey et al. (1979a) for the Naval patrol boat base in Trinity Inlet. This incorporated overland flooding in the surge calculations for the first time. The results from this and the earlier Cairns modelling were then adopted by Stark (1979) to prepare statistical water levels on behalf of Cairns City Council. An unpublished prediction of storm tide statistics at Weipa was also carried out for Comalco Limited (Sobey et al., 1979b).

9.3 Cameron McNamara and Partners 1976

At around the time the James Cook University statistical studies began, consulting engineers Cameron McNamara and Partners undertook other studies for Mackay (Irish, 1976a) and Farnborough Beach (Irish, 1976b), near Yeppoon. These studies did not involve numerical hydrodynamic modelling but were based on published empirical surge estimation methods. However, allowance for the statistical tidal variation was included. These site-specific studies cannot be easily compared with the more detailed numerical analyses that followed.

9.4 Blain, Bremner and Williams Pty Ltd 1979–1983

After working with Stark on the Rosslyn Bay investigation, consulting engineers Blain Bremner and Williams Pty Ltd saw the potential of the method for coastal engineering design problems, and further developed the statistical water level methodology as a modelling package. McMonagle (1979) applied it first to the new Brisbane airport development using (limited) modelled surge elevations provided through the Danish Hydraulic Institute, and then McMonagle (1980) to a study of the Gladstone region. The latter study included a series of deterministic surge predictions using the SURGE model. The same methodology was later applied to northern New South Wales coastal water levels by McMonagle (1981) and developed further for Half Tide Tug Harbour near Hay Point (Harper, 1983a) and also Darwin (Harper, 1983b).

9.5 Beach Protection Authority 1985

The BPA, recognising the importance of converting the 1977 deterministic storm surge studies into fully statistical estimates of storm tide, first commissioned Blain Bremner and Williams Pty Ltd to undertake a series of studies for the following primary coastal locations (Harper, 1985):

- Cooktown
- Mourilyan
- Lucinda
- Townsville
- Bowen
- Mackay
- Yeppoon
- Surfers Paradise

These locations paralleled the studies of Harper et al. (1977b) with the exception of Weipa and Cairns, but no additional numerical storm surge modelling was specified as part of this work. The earlier deterministic model results (Harper et al., 1977b) were therefore parameterised and included in a more sophisticated statistical model termed SATSIM (Surge And Tide Simulation), which was capable of generating statistical water level predictions for up to 10 locations simultaneously, linked to a central target site. In practice, up to five or six secondary sites were included at each location, resulting in storm tide statistics being produced for 50 separate locations along the coastline between Cooktown and Surfers Paradise. The (previously unmodelled) surge response needed for the secondary sites was derived by analysing the alongshore response to the case of the parallel moving (Track 1) cyclones. Tide characteristics were factored using range ratios from the target site, which was often a standard port. The study also produced estimates of the persistence of the storm tide above given levels, affecting the structural design of such elements as breakwaters and the degree of coastline erosion likely to be experienced.

In the same year, consultants Lawson and Treloar Pty Ltd (Treloar, 1985) were commissioned to undertake a study of the Hervey Bay region, which involved both deterministic storm surge modelling and storm tide statistical analysis. This study applied a technical methodology similar to the Blain Bremner and Williams and James Cook University studies for the other sections of the coast.

Later, a further study specifically for Cardwell was commissioned from consultants Rust PPK Pty Ltd (formerly Blain Bremner and Williams Pty Ltd). This study produced two reports (McMonagle, 1995a;b) based on the previous methodologies; the first designed to complement the existing Harper et al. (1977b) series for deterministic storm surge and the second to add to the Harper (1985) series of storm tide statistics.

9.6 James Cook University 1987–1993

In response to growing awareness of climate change and potential for sea level rise, commercially funded studies were commissioned for development projects in the Cairns region through the Department of Civil and Systems Engineering at James Cook University (Hardy et al., 1987a;b). These investigations were based on the Joint Probability Method, a variation on the Monte Carlo methodology of Harper et al. (1985). Later studies (Mason et al., 1992) also included the broader Marlin Coast for Cairns City Council (formerly Mulgrave Shire Council), and the Cairns casino development site (Hardy and Mason, 1993). Advances in computational power at this time allowed surge modelling to a finer horizontal scale than the original 1977 studies and highlighted the potential for additional local surge amplification within Trinity Inlet. Wave setup was also included in these analyses, with offshore wave conditions predicted by a separate spectral wave model. All of these studies also included additional information on the possible effects of sea level rise due to climate change.

9.7 Summary predictions

Figure 16 presents a summary of the predicted risks of storm tide events for more than 70 locations along the Queensland coast relative to AHD. Plotted values are from Appendix 2, based on the studies by Mason et al. (1992), Hardy et al. (1987a), McMonagle (1979, 1980), Harper (1985), Treloar (1985) and McMonagle (1995b). These represent the most complete spatial coverage and consistent methodology.

The risk levels shown are for the 50-year, 100-year, 500-year, 1000-year and 10 000-year return period of combined surge and tide, but exclude potential localised wave setup and runup effects. Mason et al. (1992) and Hardy et al. (1987a) included wave setup; accordingly their predictions have been nominally lowered here on a log-linear basis from 0.0m at the 10-year return period to 0.5m at the 10 000-year return period level. This provides some consistency with other data. Note that no values are presently available for the Gulf of Carpentaria, although it is known to be an area of significant storm tide risk. The local HAT line is also indicated for comparison since its variability along the coast is a significant component in the overall storm tide inundation risk. It should be noted that AHD (Australian Height Datum) is approximately equal to the local Mean Sea Level (MSL).

Figure 17 shows exactly the same data but adjusted to be relative to local HAT, indicating the predicted level of inundation above highest tide levels (functionally equivalent to the summary values in fig.4 for the major centres only). The Capricorn coast near Yeppoon (Emu Park) exhibits the highest regional storm tide inundation risk overall. Next highest is the Halifax Bay region (Black River) near Townsville, followed by Sarina Inlet south of Mackay and the Hervey Bay region. Townsville is next, then Cairns, Mackay and Brisbane (Moreton Bay), Dunk and Bedarra Islands, Cardwell and Bundaberg. Significantly lower inundation risks are indicated at Bowen, followed by Mourilyan, Lucinda, Cooktown and finally the Gold Coast (deemed representative of the Sunshine Coast also). Interpolation between sparsely located points is not valid. Consult Appendix 2 for details of all available sites and recommended allowances for wave setup.

10 Future studies

Preceding sections demonstrate that a significant investment in research into and analysis of the storm tide problem has occurred in Queensland over the past 20 years. Nevertheless, it is possible to identify a number of areas where improvements could be made if further studies were to be undertaken, or to justify more studies in the future. These can be grouped into categories, as is done below.

Figure 16. Predicted storm tide levels to AHD

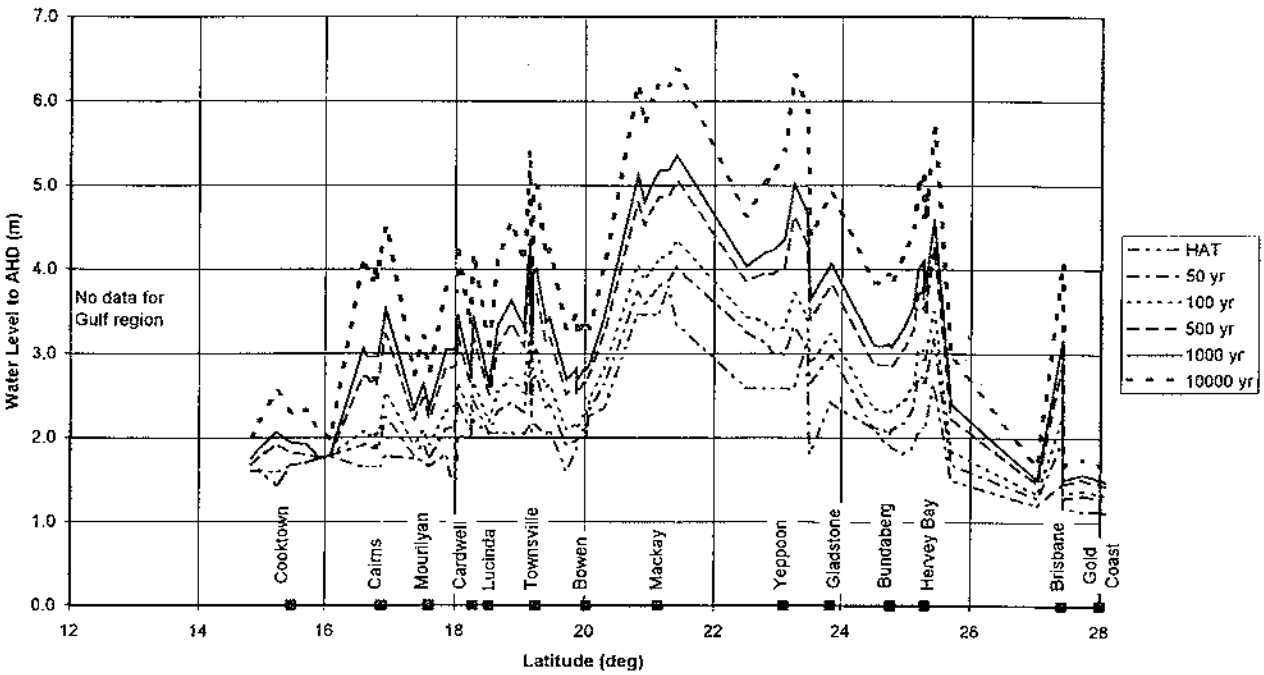
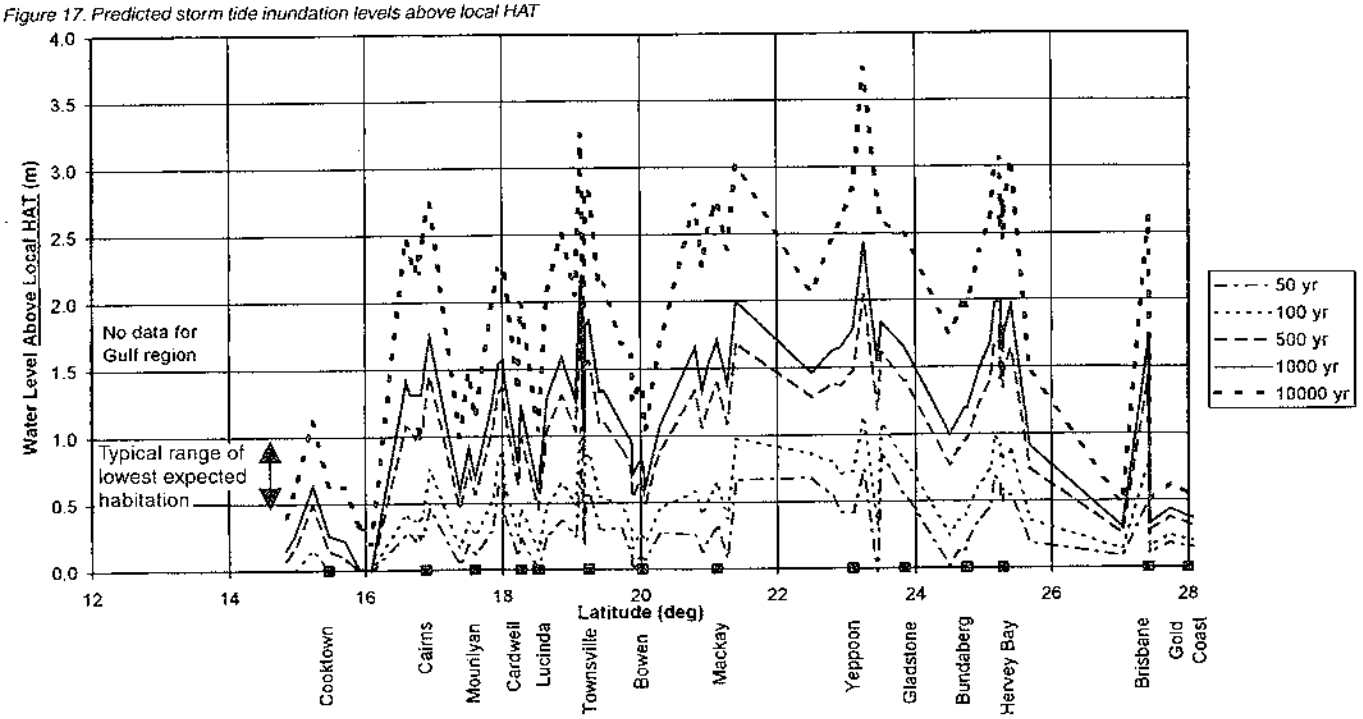


Figure 17. Predicted storm tide inundation levels above local HAT



Note: Interpolation of the above figures is not recommended. See Appendix 2 where all values are presented. Data do not include potential localised wave setup or wave runup effects compared to the detailed hydrodynamic models which followed and significantly increased the likely accuracy of surge estimates at specific sites.

10.1 Spatial coverage

While the existing studies are reasonably comprehensive, some locations may require reworked or additional studies, especially as numbers of permanent inhabitants and visitors increase in risk-prone areas. The Whitsunday region, for example, has not been a focus for any previous work, but the Bureau of Meteorology is currently investigating this area for the BPA as part of the TCCIP research project. The Gulf of Carpentaria is a significant storm tide risk region likely to experience development pressures, but is not covered by the present series of detailed statistical studies. The Gulf region also presents a number of specific modelling challenges because of its shallow near-closed form, complex tides, a questionable cyclone statistical record and sparsely instrumented coastline. Moreton Bay is in need of a more detailed study. It is also important that any future studies of new sites match statistically with the existing studies or that all sites be re-analysed in a consistent manner.

10.2 Basic methodology

Methodologies for storm surge analyses have changed gradually since the mid-1970s. For example, the early empirical analyses and assessments cannot be readily compared to the detailed hydrodynamic models that followed, which offered significantly more accurate surge estimates for specific sites.

Likewise, improved models of the tropical cyclone wind field are now available, which will create slightly different surge responses for the same set of parameters. Numerical hydrodynamic models of surge have also progressed during this period, with cleaner open boundary conditions, better seabed bottom friction formulations and allowance for overland flow. Two-dimensional (depth integrated) modelling may now be replaced by three-dimensional modelling, which permits a more realistic treatment of the bed friction interaction. Access to increased computational power also allows finer-scale representation of coastal forms, wider parameter ranges, greater numbers of scenarios, modelling over longer periods and potential for including simultaneous tide, wave and current effects.

Taken separately, each of the above advances is unlikely to represent major shifts in predicted water levels compared with the existing studies. This is because their impacts are essentially of second order in the overall force balances and scales of motion that govern storm surge behaviour. Taken together, and in specific locations along the coast, it is possible that some quite significant differences could arise which might impact emergency responses.

10.3 Cyclone data

The earliest statistical studies were limited to the cyclone details published by Coleman (1972) and Lourensz (1981). For example, Sobey et al. (1977) used data over the period 1907 to 1972, but this was used only for the selection of appropriate central pressure return periods for deterministic modelling. McMonagle (1979, 1980) used 1909–10 to 1974–75 data based on Lourensz (1977); Harper et al. (1985) included data from 1939–40 to 1979–80; and Treloar (1985) included data from 1909–10 to 1983–84, all of which directly impact the estimation of the resulting storm tide levels. Following work by Holland (1981) it is now generally acknowledged that cyclone data in the Australian region can only be regarded as reasonably reliable since 1959–60, when the first satellite surveillance commenced. The ability to revise older cyclone data and more easily examine measured wind and pressure data has enabled the historical track details to be enhanced in some cases.

10.4 Climate change scenarios

The impact of climate change and El Niño episodes on the tropical cyclone hazard must also now be considered in storm surge studies. With the exception of the later work on Cairns (e.g. Hardy et al., 1987a) where climate change scenarios were considered in the discussion, all of the existing studies assume a static mean sea level based on present climate conditions. If sea levels rise, existing predictions will need to be adjusted to compensate for the rising base water level. If greenhouse events alter the climatology of cyclone occurrence and severity, then the statistics themselves will need to be re-evaluated. Hence, the impact of the changing statistical data set and scenarios of climate change or sea level rise could only be assessed by reworking present water level predictions.

10.5 Measured data on storm tides

At the time of the Sobey et al. (1977) studies, cyclone Althea represented the only useful data set for calibration of numerical models of cyclone-generated storm surge in the Australian region. Since that time, a number of other significant surges have occurred or been found to have occurred (e.g. Tracy in Darwin, Ted at Burketown, Jason at Karumba, Orson at Dampier, Aivu near Ayr). Numerical models tested against these later occurrences will yield more accurate estimates of storm surge and provide better insight into the potential interaction between surge, tides and waves.

Long-term measurements of water level, wind, waves and wave setup must continue and be expanded to ensure the capture of rare extreme natural events such as storm surge. Recent trends for economic justification of such programs (as argued in Gordon, 1993) can seriously underestimate and neglect the fundamental worth and benefit of data that can rarely be measured twice in a lifetime of monitoring. Numerical and statistical model development relies intrinsically on measured data for calibration and verification of predictions. In particular, wind data should be used as a verification technique in future analyses to provide confidence in the assumed statistical climatology.

10.6 Wave setup, runup and inundation

Existing studies cover large sections of coast and, commensurate with the scale of the storm surge itself, do not address fine-scale details at many coastal sites. These include the local effect of wave setup, runup and overland flooding — all of which can have significant counter-disaster ramifications. With the exception of Harper (1983a), Hardy et al. (1987 a,b) and Mason et al. (1992), none of the existing studies described here includes explicit ocean wave modelling in the estimation of wave-induced setup. Only Sobey et al. (1979a) considers overland flooding. Techniques required for detailed wave modelling were only emerging during this period (e.g. Sobey and Young, 1986) and the computational overheads made large-scale wave modelling time-consuming and expensive for practical application. Accordingly, no coastal sites have had a detailed setup analysis performed but nominally recommended values are available.

Similar arguments apply in the case of overland flooding. At present, it must be (conservatively) assumed that inland flooding will occur equal to the predicted water level at the coast. Wave runup calculations are straightforward but would only be practical when undertaken for specific localised shoreline conditions. Likewise, analyses may be required to calculate wave crest heights in respect of nearshore structures that are likely to be sensitive to underfloor wave impact effects.

Any future studies should include reasonably detailed simultaneous wave modelling of selected sites of high vulnerability or significance. Overland flooding, especially in association with wave transmission and damage, is an area requiring further studies. In the US, for example, standardised techniques have been adopted for calculating variation in storm tide and wave height levels as energy propagates inland from the coast (FEMA, 1988a;b). This approach could be updated for Australian conditions. Future studies should also ensure that the respective components of extreme water level (tide, surge, setup and runup) are separately as well as jointly reported.

10.7 Non-cyclonic storm tide influences

Significant non-cyclonic weather events such as monsoonal surges or deep extra-tropical systems are capable of producing smaller but often more prolonged increases in coastal water levels. These may be responsible for more frequent episodes where the elevation of water levels reaches or just exceeds HAT, and their effects (with the exception of the Gold Coast region), are not accounted for in the results of the present studies. Because of their longer duration and potential linkage to episodes of heavy rain, such events are more likely to coincide with periods of high catchment runoff and, in some low-lying coastal areas, will tend to be associated with local minor flooding. The available Gold Coast analyses include an allowance for easterly trough low weather systems, based on the climatological analysis in McMonagle (1981) where the northern New South Wales coastline was examined in some detail. Future studies may consider the effect which these low impact but higher frequency events might have on the overall statistics of water level variation.

11 Conclusions and recommendations

Considerable work has been done over the past 27 years since cyclone Althea raised awareness of the storm tide threat in Queensland. Much is now known of at least the theoretical potential of these severe events in terms of annual risks along most of the Queensland coast and also on an individual cyclone basis. Detailed studies to date have concentrated on long-term planning issues and subsequent engineering design issues, which ultimately address and underscore public safety issues. Although planning legislation in Queensland does not yet include explicit storm surge considerations, this power is within the jurisdiction of local government.

Armed only with the present information, it is possible to undertake more detailed assessments of individual coastal communities at risk. This could take the form of specific design and planning rules covering such factors as better mapping, land-use zoning, structural design requirements, shelter or refuge requirements, evacuation routing and coastal protection works. With this type of approach, it should ultimately be possible to make available insurance cover against storm tide damage for responsible beachside residents who meet requisite design standards.

The forecasting of storm tides has undoubtedly improved with the increased access to data and refining of cyclone prediction techniques over the years, but is only now beginning to take full advantage of more detailed methods of water level estimation. The counter disaster role is expanding due to the increasing settlement of the coastal margins, especially in northern Queensland, and will require increasingly more accurate and timely information in preparing for possible civilian evacuations.

The majority of storm tide studies for Queensland were completed approximately 12 years ago and some aspects date to the late 1970s. They were performed subject to practical computing limits at the time, as well as the statistical cyclone record of the day. Techniques and capabilities have advanced and the statistical record has been extended significantly since that time. Coastal development pressures have created more and greater potential exposure to storm tide threats. As a result, there is an emerging and relatively strong case for a comprehensive reassessment of storm tide risks along the entire Queensland coast. The opportunity now also exists for greater integration of the diverse service requirements of engineering, planning and counter-disaster measures.

The vast majority of analysis and modelling capability needed to undertake such a reassessment is readily available at present, but some specific areas would benefit from further research and development. These include a need for more practical methods for representing wave, current and surge interaction, localised wave setup, overtopping and transmission through community areas. Also, the likely behaviour of domestic and commercial structures in the event of surge inundation has not yet been fully examined in Australia as it has in the US.

In addition to specific research and development, storm tide prediction will also benefit from on-going basic research into cyclone structure and behaviour and the likely impact of climate change on frequency, intensity and mean sea level. Finally, long-term data measurement programs of water levels, winds, waves and wave setup will continue to be essential adjuncts to the quest for increased knowledge, planning and preparedness for storm tide hazards throughout Queensland.

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Appendix 1 — Recorded cyclone-related storm surges and storm tides in Queensland

Date	Place	Event	Reference central pressure (hPa)	Storm surge (m)	Storm tide level	Inundation above HAT (m) (m AHD)	Reference
1858	Green Is		?	?	2?	"awash"	Jones (1976)
30-Jan-1884	Bowen		"hur"	3.1?	?		Harvey (1974)
04-Mar-1887	Albert R Heads		"cyc"	5.5?	7.8	5.1	Harbours and Rivers Dept (1918)
08-Jun-1891	Brisbane		?	?	1.8	0.3	Queensland Transport (1995)
19-Feb-1894	Brisbane		"cyc"	?	1.6	0.2	"
26-Jan-1896	Townsville	Sigma	"hur"	>2?	4?	2?	Holthouse (1971)
05-Mar-1899	Bathurst Bay	Mahina	914	13.7?	13?	11?	Whittingham (1958)
09-Mar-1903	Cairns	Leonta	965<	?	2+?	0.7	Gourlay and Hacker (1981)
27-Jan-1910	Cairns		"hur"	?	2+?	0.7	"
21-Jan-1918	Mackay		935	3.7	5.4	2	Harbours and Rivers Dept (1918)
9-Mar-1918	Innisfail		928	>3	3.9	2.3	"
04-Feb-1920	Cairns		988	>1.5	2.5?	0.7?	Jones (1976)
30-Mar-1923	Albert R Heads	Douglas Mawson	974	>3	5?	2.3?	Whittingham (1968)
16-Jun-1928	Brisbane		?	?	1.7	0.2	Queensland Transport (1995)
05-Feb-1931	Brisbane		982	>0.9	?	?	McKay (1959)
01-Feb-1934	Brisbane		?	1.2	?		Callaghan (1996)
11-Mar-1934	Port Douglas		968	>1.8	?	?	Moorhouse (1936)
03-Apr-1941	Cairns		1002	>0.5	?		Harvey (1974)
17-Mar-1945	Cairns		994	>0.8	?	?	"
02-Mar-1946	Cairns		982	>0.7	?		"
23-Jan-1947	Brisbane		?	>0.5	?		McKay (1959)
12-Jan-1948	Cairns		995?	>0.5	?		Harvey (1974)
28-Jan-1948	Brisbane		?	?	1.8	0.3	Queensland Transport (1995)
23-Feb-1948	Bentinck Is		996	>3.7	4.7?	3.2?	Tyndale (1962)
02-Mar-1949	Gladstone		988	>1.2	2.2	0.2	Harvey (1974)
15-Jan-1950	Cairns		994	0.5	?		"
18-Jan-1950	Brisbane		?	?	1.8	0.3	Queensland Transport (1995)
21-Feb-1954	Coolangatta		973	>1?	2?	?	Callaghan (1996)
1954	Mackay			0.5?			McKay (1959)
07-Mar-1955	Mackay			0.5?			"
05-Mar-1956	Townsville	Agnes?	961	0.8	?		Harvey (1974)
"	Mackay	"	"	1.4	?		"
17-Feb-1957	Brisbane	Clara?	943?	>0.5	?		McKay (1959)
01-Apr-1958	Bowen		968	>1?	?		Holthouse (1971)
1958	Mackay			0.5?			McKay (1959)
16-Feb-1959	Mackay			0.5?			"
31-Dec-1962	Brisbane		978	0.8	?		Bureau of Meteorology (1965)
11-Jan-1964	Karumba	Audrey	984	1.5	?		Bureau of Meteorology (1966)
03-Feb-1963	Edward River	Dora	974	5?	?	?	"
05-Dec-1964	Inkerman Station	Flora	992	?			Bureau of Meteorology (1968)
07-Dec-1964	Palm Island	"	996	0.6			"
27-Jan-1967	Mackay	Dinah	945	0.3			Irish (1976b)
29-Jan-1967	Lady Elliot Is	"	"	?		"awash"	Bureau of Meteorology (1969)
"	Bundaberg	"	"	0.7			Beach Protection Authority (1989)
"	Bundaberg	"	"	0.4			Irish (1976b)
"	Brisbane	"	"	0.2			"
"	Moreton Bay	"	"	0.5?			Callaghan (1996)
"	Broadwater	"	"	1.5?			"
14-Mar-1967	Cairns	Elaine	996	0.5	?		Harvey (1974)
16-Feb-1971	Cardwell	Gertie	988	0.6			Bureau of Meteorology (1973)
15-Feb-1971	Townsville	"	"	0.3			"
"	Mackay	"	983	0.3			"
"	Lindeman Is	"	"	0.6			Harvey (1974)
19-Feb-1971	Aurukun	Fiona	960	0.9			Bureau of Meteorology (1973)
"	Inkerman Station	"	>4?	?	?	"	
21-Feb-1971	Gladstone	"	995	0.6			"
24-Dec-1971	Cairns	Althea	952	0.5	0.7		Stark (1972) due Hopley
"	Mourilyan	"	"	0.8	1.1		"

Date	Place	Event	Reference central pressure (hPa)	Storm surge (m)	Storm tide level	Inundation above HAT (m) (m AHD)	Reference
24-Dec-1971	Lucinda	Althea	952	0.9	1.5		Stark (1972) due Hopley
"	Toolakea	"	"	3.6?	3.3?	1.1?	"
"	Townsville	"	"	2.9	2.6	0.4	"
"	Bowen	"	"	1.2	1.3		"
"	Mackay	"	"	0.9	1.9		"
11-Feb-1972	Fraser Island	Daisy	959	3?	?	?	Bureau of Meteorology (1975)
"	Bribie Island	"	"	0.8?			"
"	Tweed Heads	"	"	0.6?			"
02-Apr-1972	Port Alma	Emily	985	0.6	1.4		Stark (1972) due Hopley
"	Gladstone	"	"	0.9	2.2		"
"	Bundaberg	"	"	0.9	1.5		"
"	Tannum Sands		"	"	0.9?		"
"	Bustard Head	"	"	1.8?			"
"	Agnes Water	"	"	1.5?			"
"	Heron Island	"	"	1.2?			"
04-Mar-1973	Cape Flattery	Madge	997	1?			Harvey (1974)
"	Cooktown	"	"	1?			"
"	Cairns	"	"	0.4	?		"
19-Dec-1973	Cairns	Una	985	0.4			Hopley (1974)
"	Mourilyan	"	"	0.5			"
"	Lucinda	"	"	0.5			"
"	Townsville	"	"	0.5			"
"	Bowen	"	"	0.7			"
"	Mackay	"	"	0.4			"
24-Jan-1974	Mackay	Wanda	995	0.5			Hopley and Harvey (1974a)
"	Port Alma	"	"	0.3			"
"	Gladstone	"	"	0.3			"
"	Bundaberg	"	"	0.2			"
"	Noosa	"	"	0.6			"
"	Mooloolaba	"	"	0.3			"
"	Brisbane	"	"	0.6			"
"	Broadwater	"	"	0.3			"
06-Feb-1974	Cairns	Pam	965	0.3			Hopley and Harvey (1974b)
"	Mackay	"	"	0.2			"
07-Feb-1974	Noosa	"	"	0.4			"
"	Mooloolaba	"	"	0.4			"
"	Brisbane	"	"	0.7	1.9	0.4	"
"	Broadwater	"	"	0.6			"
"	Kirra	"	"	0.4			"
06-Mar-1974	Mackay	Zoe	968	0.6			Hopley and Harvey (1974c)
09-Mar-1974	Gladstone	"	"	0.4			"
"	Bundaberg	"	"	0.4			"
12-Mar-1974	Mooloolaba	"	"	0.4			"
"	Caloundra	"	"	1			"
"	Brisbane	"	"	0.7			"
"	Broadwater	"	"	0.5			"
19-Jan-1976	Townsville	David	961	0.3	2.1		Beach Protection Authority (1976)
"	Bowen	"	"	0.4	2.1		"
"	Mackay	"	"	0.6	3.5		"
"	Sandy Point	"	"	1.2?	2.7?		Beach Protection Authority (1979)
"	Rosslyn Bay	"	"	1.2	2.7		Irish (1976b)
19-Dec-1976	Albert River	Ted	950	4.6?	6.3?	3.6?	Victory and Davis (1996)
"	Burketown	"	"	3?	3.2?	?	"
"	Karumba	"	"	2	3.6		"
"	Mornington Is	"	"	1.7?	1.8?		"
31-Dec-1978	Weipa	Peter	980	1.2	2.3	0.6	Beach Protection Authority Storm Surge Gauge Data
01-Mar-1979	Mackay	Kerry	995	0.7			Oliver and Walker (1979)
14-Feb-1981	Burnett Heads	Cliff	985	0.5			Beach Protection Authority (1989b)
"	Urangan	"	"	0.6			"
Apr-1982	Weipa	Dominic	950	1			Callaghan (1996)
"	Karumba	"	"	1.5			"

Date	Place	Event	Reference central pressure (hPa)	Storm surge (m)	Storm tide level	Inundation above HAT (m) (m AHD)	Reference
31-Jan-1986	Cairns	Winifred	957	0.5			Beach Protection Authority (1986)
01-Feb-1986	Clump Point	"	"	1.8	1.7		"
"	Mourilyan	"	"	1	1.4		"
"	Cardwell	"	"	1.2	1.7		"
01-Feb-1986	Lucinda	Winifred	957	0.5			Beach Protection Authority (1986)
13-Feb-1987	Weipa	Jason	970	0.6	1.5		Beach Protection Authority (1987)
"	Karumba	"	"	2	3.1		"
28-Feb-1988	Townsville	Charlie	972	0.4			Beach Protection Authority (1988)
"	Abbot Point	"	"	0.4			"
29-Feb-1992	Bowen	"	"	0.5			"
"	Shute Harbour	"	"	0.6			"
01-Mar-1988	Mackay	"	"	0.6			"
04-Apr-1989	Molongle Creek	Aivu	935	3.2?	3.7?	1.7?	Bowen Shire Council (1989)
"	Bowen	"	"	1.2	2.3		Beach Protection Authority (1989a)
15-Dec-1989	Gilbert River	Felicity	965	2.4?	?		Callaghan (1996)
24-Dec-1990	Port Douglas	Joy	940	0.5			Beach Protection Authority (1996b)
08-Jan-1992	Karumba	Mark	980	0.8			BPA Storm Surge Gauge Data
13-Jan-1992	Caloundra	Betsy	980	0.4			Beach Protection Authority (In preparation)
14-Jan-1992	Urangan	"	"	0.6			"
15-Mar-1992	Gladstone	Fran	980	0.8			Beach Protection Authority (In preparation)
16-Mar-1992	Burnett Heads	"	"	1	2.1	0.2	"
16-Mar-1992	Urangan	"	"	0.7	2.2		"
17-Mar-1992	Mooloolaba	"	"	0.4			"
25-Dec-1992	Weipa	Nina	975	0.7	3.2		Beach Protection Authority (1996a)
17-Mar-1993	Boreen Point	Roger	985	0.5			Beach Protection Authority (In preparation)
17-Mar-1993	Munna Point	"	"	0.6	0.9		"
17-Mar-1993	Gold Coast Seaway	"	"	0.7	1.3		"
19-Jan-1994	Hay Point	Rewa	970	0.5			Beach Protection Authority (In preparation)
06-Mar-1995	Karumba	Warren	980	1.5	3.8		Beach Protection Authority (In preparation)
06-Mar-1995	Mornington Is	"	"	?		1?	"
06-Jan-1996	Weipa	Barry	950	0.6	1.5		Beach Protection Authority (In preparation)
06-Jan-1996	Staaten River	"	"	3.7?			"
06-Jan-1996	Gilbert River	"	"	4.5?	6?	3.4?	"
07-Jan-1996	Karumba	"	"	0.7	2.2		"
09-Mar-1996	Weipa	Ethel	980	1.2	3.6	0.3	Beach Protection Authority (In preparation)

Notes:

- *The above data set should not be regarded as a complete time history of all storm surges along the Queensland coast. The record is biased towards centres of population where data has been available for analysis, or eyewitness reports.*
- *An effort has been made to locate and cite the original or earliest easily recoverable reference.*
- *Surges listed may not be the maximum levels for any particular event. Wherever possible, accurately measured levels from tide or storm surge gauges have been used. Debris estimates are included for some specific events where the maxima is thought to have occurred between instrumented sites.*
- *? = value is unknown, unreliable or an estimate only.*
- *The quoted reference central pressure relates to the intensity most closely associated with the generation of the indicated storm surge, and may not be the minimum central pressure for each event.*
- *Early reference central pressures are from Visher and Hodge (1925) or Lourensz (1981) where appropriate.*
- *Minor adjustments have been made for some tide gauge datum shifts and changing HAT over time.*
- *Not all surges in south-east Queensland are related specifically to a tropical cyclone.*
- *References attributed to McKay (1959) are predominantly from Harvey (1974) and have not been able to be fully substantiated (library searches have been unsuccessful in locating the original McKay material).*

Appendix 2 — Detailed tropical cyclone storm tide risk along the Queensland coast

Predictions listed by latitude		Storm tide relative to AHD					Extra wave setup allowance	Storm tide relative to HAT				
		50 year m	100 year m	500 year m	1000 year m	10 000 year m	m	50 year m	100 year m	500 year m	1000 year m	10 000 year m
Harper (1985)	Lookout Point	1.6	1.6	1.7	1.8	2.0	0.3	0.0	0.0	0.1	0.2	0.4
"	Cape Flattery	1.6	1.6	1.8	1.9	2.2	0.2	0.0	0.0	0.2	0.3	0.6
"	Cape Bedford	1.4	1.6	1.9	2.1	2.5	0.3	0.0	0.1	0.5	0.6	1.1
"	Cooktown	1.7	1.7	1.8	1.9	2.3	0.2	0.0	0.0	0.1	0.3	0.6
"	Thomas Point	1.7	1.7	1.8	1.9	2.3	0.2	0.0	0.0	0.1	0.2	0.6
"	Bloomfield River	1.8	1.8	1.8	1.8	2.1	0.3	0.0	0.0	0.0	0.0	0.3
"	Cape Tribulation	1.8	1.8	1.8	1.8	2.0	0.3	0.0	0.0	0.0	0.0	0.2
Mason et al. (1992)	Oak Beach	1.9	2.1	2.7	3.1	4.1	0.5*	0.3	0.4	1.1	1.4	2.5
"	Wangetti Beach	1.9	2.0	2.7	3.0	4.0	0.5*	0.3	0.4	1.1	1.3	2.3
"	Ellis Beach	1.9	2.0	2.6	3.0	3.9	0.5*	0.2	0.4	1.0	1.3	2.2
"	Palm Cove	1.9	2.0	2.7	3.0	4.0	0.5*	0.3	0.4	1.1	1.3	2.3
"	Clifton Beach	1.9	2.0	2.7	3.0	4.0	0.5*	0.3	0.4	1.1	1.3	2.3
"	Kerarra Beach	1.9	2.0	2.6	3.0	3.9	0.5*	0.2	0.4	1.0	1.3	2.2
"	Trinity Beach	1.9	2.0	2.6	3.0	3.9	0.5*	0.2	0.4	1.0	1.3	2.2
"	Trinity Park	1.9	2.0	2.7	3.0	4.0	0.5*	0.3	0.4	1.1	1.3	2.3
"	Yorkeys Knob	1.9	2.0	2.7	3.0	4.0	0.5*	0.3	0.4	1.1	1.3	2.3
"	Holloways Beach	1.9	2.1	2.7	3.1	4.1	0.5*	0.3	0.4	1.1	1.4	2.5
"	Machans Beach	1.9	2.1	2.8	3.1	4.2	0.5*	0.3	0.5	1.2	1.5	2.6
Hardy et al. (1987a)	Cairns	2.2	2.5	3.2	3.5	4.5	0.5*	0.5	0.8	1.4	1.7	2.7
Harper (1985)	Rocky Point	1.8	1.9	2.2	2.3	2.8	0.3	0.0	0.2	0.5	0.6	1.0
"	Flying Fish Point	1.9	2.1	2.5	2.6	3.2	0.3	0.2	0.4	0.7	0.9	1.5
"	Mourilyan	1.8	1.9	2.2	2.3	2.8	0.3	0.1	0.3	0.6	0.7	1.1
McMonagle (1995b)	Clump Point	2.1	2.3	2.8	3.0	3.8	0.3	0.3	0.5	1.0	1.2	2.0
"	Dunk Island	2.1	2.3	2.8	3.0	3.7	0.2	0.6	0.8	1.3	1.5	2.2
"	Bedarra Island	2.2	2.4	2.9	3.1	3.7	0.2	0.7	0.9	1.4	1.6	2.2
"	Tully Heads	2.4	2.6	3.2	3.4	4.2	0.2	0.4	0.6	1.2	1.4	2.2
"	NE Hinchinbrook Is	2.1	2.3	2.6	2.8	3.3	0.3	0.1	0.3	0.6	0.8	1.3
"	Cardwell	2.4	2.7	3.2	3.4	4.2	0.1	0.2	0.5	1.0	1.2	2.0
Harper (1985)	Lucinda	2.1	2.2	2.5	2.6	3.1	0.2	0.0	0.1	0.5	0.6	1.0
"	Allingham	2.3	2.5	3.1	3.3	4.1	0.2	0.3	0.5	1.0	1.3	2.1
"	Crystal Creek	2.4	2.7	3.3	3.6	4.6	0.3	0.4	0.6	1.3	1.6	2.5
"	Leichhardt River	2.3	2.5	3.1	3.3	4.1	0.3	0.3	0.5	1.0	1.3	2.1
"	Magnetic Is (N)	2.7	3.0	3.7	4.0	5.1	0.2	0.6	0.9	1.6	1.9	3.0
"	Black River	2.9	3.2	4.0	4.3	5.4	0.2	0.7	1.1	1.8	2.2	3.3
"	Magnetic Is (E)	2.7	3.0	3.7	4.0	5.1	0.4	0.6	0.9	1.6	1.9	3.0
"	Cape Cleveland	2.2	2.4	2.9	3.1	3.8	0.5	0.2	0.4	0.8	1.0	1.7
"	Pallarenda	2.7	3.0	3.7	4.0	4.9	0.3	0.5	0.8	1.5	1.8	2.8
"	Townsville	2.7	3.0	3.7	4.0	5.0	0.2	0.6	0.9	1.6	1.9	2.8
"	Combe Creek	2.4	2.6	3.1	3.4	4.2	0.2	0.3	0.5	1.1	1.3	2.1
"	Alva Beach	2.4	2.6	3.2	3.4	4.2	0.5	0.3	0.5	1.1	1.3	2.1
"	Cape Upstart	1.9	2.1	2.5	2.7	3.3	0.5	0.3	0.5	0.9	1.1	1.7
"	Elliot River	2.0	2.2	2.6	2.8	3.5	0.5	0.1	0.3	0.8	1.0	1.6
"	Abbot Point	2.0	2.1	2.5	2.7	3.2	0.4	0.0	0.2	0.5	0.7	1.2
"	Queens Beach	2.1	2.2	2.6	2.8	3.4	0.3	0.1	0.2	0.6	0.8	1.4
"	Bowen	2.1	2.3	2.6	2.8	3.4	0.2	0.1	0.3	0.6	0.8	1.4
"	George Point	2.3	2.5	2.8	2.9	3.3	0.3	0.1	0.2	0.5	0.6	1.0
"	Shutehaven	2.6	2.8	3.2	3.4	4.0	0.1	0.3	0.5	0.9	1.1	1.7
"	St Helens Beach	3.7	4.0	4.8	5.1	6.2	0.3	0.3	0.6	1.3	1.7	2.7
"	Cp Hillsborough	3.6	3.9	4.5	4.8	5.7	0.4	0.1	0.4	1.1	1.3	2.3
"	Shoal Point	3.7	4.0	4.7	5.0	6.0	0.5	0.2	0.5	1.2	1.5	2.6

Predictions listed by latitude		Storm tide relative to AHD					Extra wave setup allowance	Storm tide relative to HAT				
		50 year m	100 year m	500 year m	1000 year m	10 000 year m	m	50 year m	100 year m	500 year m	1000 year m	10 000 year m
"	Slade Point	3.7	4.1	4.8	5.1	6.1	0.5	0.3	0.6	1.3	1.6	2.7
"	Mackay	3.8	4.1	4.9	5.2	6.2	0.5	0.3	0.7	1.4	1.7	2.8
"	Hay Point	3.9	4.2	4.9	5.2	6.2	0.3	0.1	0.4	1.1	1.4	2.4
"	Sarina Inlet	4.0	4.3	5.0	5.4	6.4	0.3	0.7	1.0	1.7	2.0	3.0
"	Cape Clinton	3.3	3.4	3.9	4.0	4.6	0.5	0.7	0.9	1.3	1.5	2.1
"	Stockyard Point	3.1	3.4	4.0	4.2	5.0	0.5	0.5	0.8	1.4	1.6	2.5
"	Water Park Point	3.0	3.3	3.9	4.2	5.2	0.5	0.4	0.7	1.4	1.6	2.6
"	Yeppoon	3.0	3.3	4.0	4.4	5.4	0.3	0.4	0.7	1.5	1.8	2.8
"	Emu Park	3.3	3.7	4.6	5.0	6.3	0.4	0.7	1.1	2.0	2.4	3.7
"	Cattle Point	3.1	3.5	4.3	4.7	5.9	0.1	0.0	0.3	1.2	1.5	2.8
"	Cape Capricorn	2.7	2.9	3.4	3.6	4.4	0.5	0.8	1.1	1.6	1.8	2.6
McMonagle (1980)	Gladstone	3.0	3.2	3.8	4.1	4.9	0.3*	0.5	0.8	1.4	1.6	2.5
Treloar (1985)	Baffle Creek	2.1	2.3	2.9	3.1	3.8	0.5*	0.0	0.2	0.8	1.0	1.7
"	Kolan River	2.1	2.3	2.9	3.1	3.8	0.5*	0.1	0.4	0.9	1.1	1.9
"	Moore Park	2.0	2.3	2.9	3.1	3.9	0.5*	0.1	0.4	0.9	1.2	2.0
"	Bundaberg	2.1	2.3	2.9	3.1	3.8	0.5*	0.2	0.4	1.0	1.2	1.9
"	Elliot Heads	2.2	2.4	3.0	3.3	4.2	0.5*	0.4	0.6	1.2	1.5	2.4
"	Woodgate	2.3	2.6	3.3	3.6	4.5	0.5*	0.4	0.7	1.4	1.7	2.6
"	Burrum Heads	2.7	3.0	3.7	4.0	5.0	0.5*	0.7	1.0	1.7	2.0	3.0
"	Toogoom	2.7	3.0	3.8	4.1	5.2	0.5*	0.6	0.9	1.7	2.0	3.1
"	Point Vernon	2.7	2.9	3.5	3.8	4.6	0.5*	0.5	0.8	1.4	1.7	2.5
"	Scarness	2.7	3.0	3.6	3.9	4.9	0.5*	0.6	0.9	1.5	1.8	2.7
"	Urangan Jetty	2.6	2.9	3.5	3.7	4.6	0.5*	0.5	0.7	1.3	1.6	2.4
"	Urangan Harbour	2.7	3.0	3.7	3.9	4.9	0.2*	0.5	0.8	1.5	1.7	2.7
"	Bingham	3.2	3.5	4.3	4.6	5.7	0.0*	0.5	0.9	1.6	2.0	3.0
"	Tuan	1.7	1.9	2.2	2.4	3.0	0.0*	0.2	0.4	0.7	0.9	1.5
Harper (1985)	Cape Moreton	1.3	1.3	1.5	1.5	1.7	0.7	0.1	0.1	0.3	0.3	0.5
McMonagle (1979)	Brisbane	2.0	2.2	2.9	3.2	4.1	0.3*	0.5	0.8	1.4	1.7	2.6
Harper (1985)	Point Lookout	1.3	1.3	1.5	1.5	1.7	0.7	0.1	0.2	0.3	0.3	0.5
"	Jumpinpin	1.3	1.4	1.5	1.6	1.8	0.7	0.2	0.2	0.4	0.4	0.6
"	Surfers Paradise	1.3	1.3	1.5	1.5	1.7	0.7	0.2	0.2	0.3	0.4	0.5
"	Point Danger	1.3	1.3	1.4	1.5	1.6	0.7	0.2	0.2	0.3	0.4	0.5

Notes:

- *The predictions represent the potential impact on coastal water levels due to tropical cyclones only (except for the Gold Coast). No allowance is included for any potential mean sea level rise due to climate change.*
- *The above levels do not include breaking wave setup or runup. If available, a recommended additional wave setup allowance is given. In other cases a nominal allowance is indicated by *. Runup is site-specific.*
- *Other severe weather events such as monsoonal surges or deep extra-tropical systems are capable of producing smaller but often more prolonged increases in coastal water levels. A quoted storm tide level relative to HAT of 0.0 indicates that the predicted cyclone-induced level alone is actually below the peak tide level.For consistency with the other data, predictions for Cairns and district (Hardy et al. 1987a) and Mason et al. (1992) have been reduced log-linearly from 0.0m at 10 years up to 0.5m at the 10 000 year level as a nominal allowance for the estimated wave setup component included in those analyses.*
- *When comparing these levels with those in the original references, the possibility of historical changes to HAT at some locations (due to longer tidal records being available for analysis), should be considered.*
- *McMonagle (1995b) supersedes Harper (1985) in respect of predicted levels at Clump Point, Hull Heads and Cardwell.*

Storm tide threat in Queensland: History, prediction and relative risks

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Disclaimer

While data in this report were collected, processed and compiled with reasonable care, the accuracy and reliability of this information are not guaranteed in any way by the Beach Protection Authority. Neither the Queensland Government nor the Authority accepts liability for any decision or actions taken on the basis covered by this report.

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Glossary

AHD (Australian Height Datum)
This datum has been adopted by the National Mapping Council as the datum to which all vertical control for mapping is to be referred. It is approximately equivalent to Mean Sea Level (MSL).

Ambient pressure
The MSL atmospheric pressure surrounding, but not affected by, a tropical cyclone.

Astronomical tide
The periodic rising and falling of the oceans, resulting from the gravitational attraction of the moon, sun and other astronomical bodies acting upon the rotating Earth. Although the accompanying horizontal movement of the water resulting from the same cause is also sometimes called the 'tide', it is preferable to designate the latter as the tidal current, reserving the name astronomical tide for the vertical movement.

Bathymetry
The measurement of depths of water in oceans, seas and lakes; also information derived from such measurements.

Continental shelf
The zone bordering a continent and extending from the tidal low water mark to a depth where there is a marked or rather steep descent toward greater depths.

Coriolis effect
The influence of the Earth's rotation that causes winds to circulate in a clockwise direction around low pressure systems in the southern hemisphere.

El Niño — southern oscillation
Large-scale natural fluctation in the global climate system that occurs irregularly and involves a close coupling of the oceans and atmosphere.

HAT (Highest Astronomical Tide)
The highest level that can be predicted to occur under average meteorological conditions and any combination of astronomical conditions. These levels will not be reached every year, HAT generally occurring at any one location once every 18.6 years.

Inverse barometer effect
The proportional rise in water level due to the hydrostatic pressure deficit beneath a tropical cyclone. The pressure deficit is the difference between the MSL ambient pressure and the MSL pressure at the centre of the tropical cyclone. The local magnitude of the rise in elevation is approximately 10mm per 1hPa of pressure deficit.

Long-wave motion
A class of surface disturbances of the sea surface whose characteristic wavelength (distance between consecutive peaks or troughs) is such that the resulting motion can be considered as nearly-horizontal in form. Long waves include the astronomical tide, storm surge and tsunamis.

Radius of maximum winds
The distance from the centre of a tropical cyclone, where winds are calm, to the point where the surface wind speeds are greatest (at the position of maximum radial pressure gradient).

Return period
Also known as average recurrence interval or ARI. The return period of an event, normally expressed in years, is the average time between successive events of equal or greater magnitude. The actual time between such events may be greater or less than this period due to the randomness of the process. The inverse of the return period is the average annual probability of exceedance, which remains constant from one year to the next, regardless of whether a given event has or has not occurred.

Sea
That portion of wave motions on the sea surface that are generated by local winds and are still in a state of absorbing the energy of the wind, which leads to a growth in wave energy.

Spring tidal range
The difference in height between MHWS (mean high water springs) and MLWS (mean low water springs). MHWS is the long term average of the heights of two successive high waters during those periods of 24 hours (approximately once per fortnight) when the range of tide is greatest, at full and new moon. MLWS is the long-term average value of two successive low waters over the same period as defined for MHWS.

Storm surge
A rise above normal water level on the open coast due to the combined effects of surface wind stress and atmospheric pressure fluctuations caused by severe weather events (e.g. tropical cyclones).

Storm tide
The combined action of storm surge and astronomical tide.

Swell
That portion of wave motions on the sea surface that have travelled away from the area of wave generation and become characteristically more regular, of longer period and with flatter crests.

Tropical cyclone
Also known as a hurricane or typhoon. An intense, large-scale low-pressure storm system of tropical origin with cyclonically rotating mean winds at the sea surface (clockwise in the southern hemisphere) in excess of gale force (63km/hr, 34kt, or 17.5m/s).

Tsunami
Japanese for harbour wave. A transient long-period wave typically caused by an underwater disturbance such as an earthquake, volcanic eruption or landslide. Tsunami can travel very long distances across oceans and affect remote coasts, often being amplified as they enter shallow waters and are capable of significant inundation. Tsunami are sometimes incorrectly termed tidal waves.

Wave runup
The rush of water up against a structure or beach on the breaking of a wave. The amount of runup is the vertical height above still-water level to which the rush of water reaches. In the present report, runup is measured from the quasi-steady wave setup level.

Wave setup
A quasi-steady super-elevation of the water surface due to the onshore mass transport of water caused entirely by the action of breaking waves. Wave setup is sometimes included in calculations of wave runup.