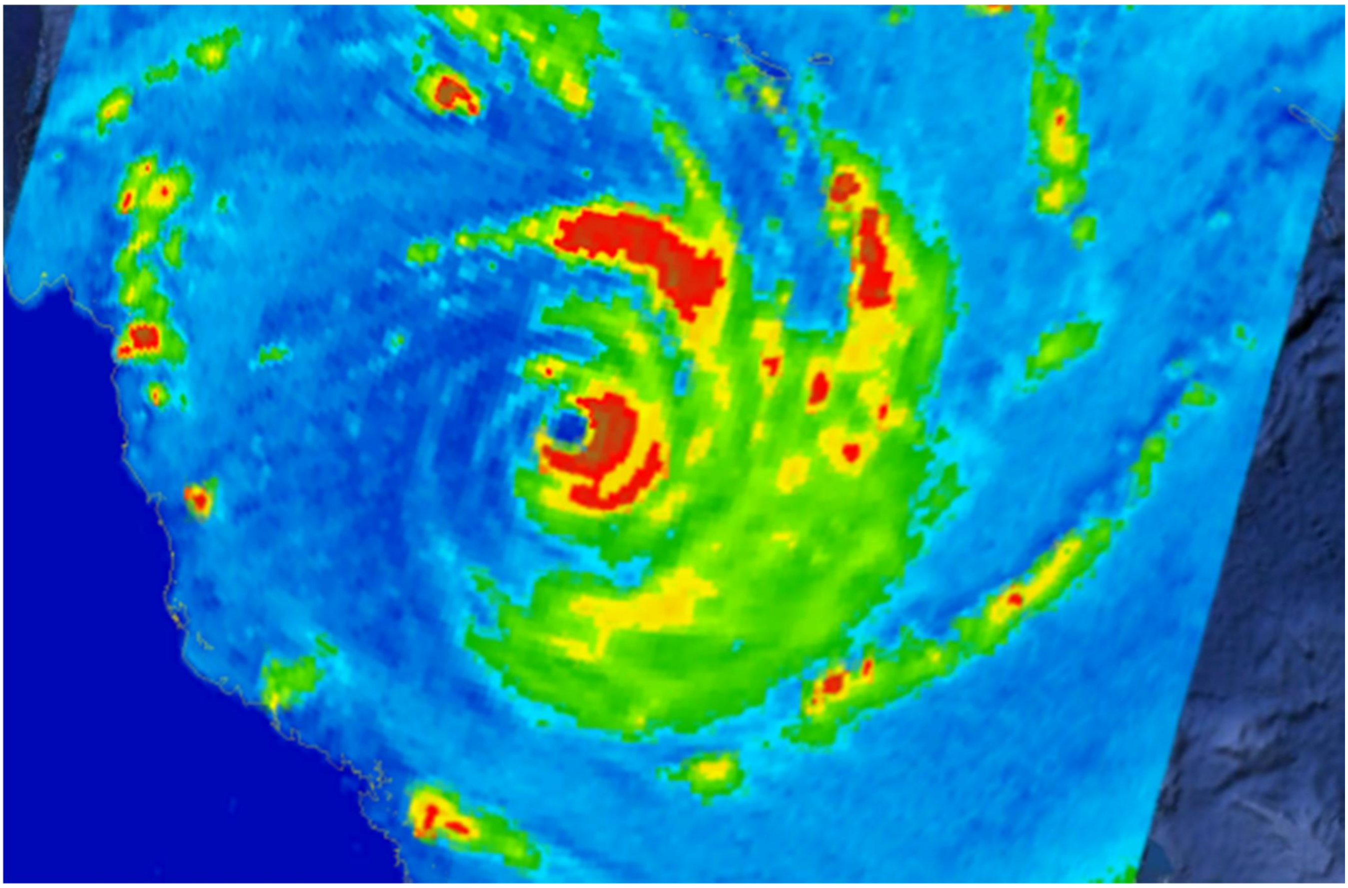

Department of Science, Information Technology, Innovation and the Arts

NDRP Storm Tide Hazard Interpolation Study

Report

June 2014

FOREWORD

The Department of Science, Information Technology, Innovation and the Arts (DSITIA) through the support of a Natural Disaster Resilience Program (NDRP) grant has commissioned GHD Pty Ltd to develop consistent 'state-wide' levels to provide statistical return period storm tide levels to inform the Queensland Natural Disaster Risk Register. The resultant maps represent a first pass broad scale approach to identifying the relative likelihood of specific communities and public infrastructure to be subjected to storm tide inundation. These maps are intended to inform disaster management and should not be used in place of local government mapping for other purposes, such as land use planning, that may be of higher accuracy and detail.

The principal requirement of this study was to identify, based on a consistent methodology using data from existing studies, the Average Recurrence Interval (ARI, or Return Period event) for a range of ocean water levels for each coastal LGA area. The minimum ARI levels required are the 20, 50, 100, 500, 1,000 and 10,000 y ARI events, plus the estimated Theoretical Maximum Storm Tide (TMST) level. The methodology was developed to amalgamate and normalise numerous independent storm tide studies of varying modelling approaches through a standardised approach based on technical recommendations provided in the *Queensland climate change and community vulnerability to tropical cyclones: ocean hazards assessment - stage 1* (Harper, 2001). The resulting consistent set of storm tide statistics were then mapped based on GIS 'bath-tub' inundation techniques for the open coast. The Storm Tide Hazard Probability Mapping project supports the Queensland Natural Disaster Risk Register by providing a state-wide assessment of storm tide that integrates local government modelling of storm tide with other state data sets to provide a consistent basis for comparison of risks between different local governments along the Queensland coastline.

USER ACKNOWLEDGEMENT

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Cover Image: Microwave image of Tropical Cyclone Yasi approaching the QLD Coastline. US Naval Research Laboratory (2012)

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1. Introduction

1.1 Background

The Department of Science, Information Technology, Innovation and the Arts (DSITIA) requires provision of information on the risk of storm tide hazards across the State that will identify the relative likelihood of specific communities being subjected to dangerous inundation events. Such events would be those that require, for example, community evacuation on the one hand or a move towards planning interventions to mitigate the identified emergency risk. Such a product would also be an adjunct to the real time inundation warnings available from the Bureau of Meteorology and assist in placing any forecast threat into a statistical or likelihood context.

1.2 Purpose

The principal requirement of this study is to identify, based on a consistent methodology using data from existing studies, the Average Recurrence Interval (ARI, or Return Period event) for a range of ocean water levels for each coastal LGA area. The minimum ARI levels required are the 20, 50, 100, 200, 500, 1,000 and 10,000 y ARI event, plus the estimated Theoretical Maximum Storm Tide (TMST) level. The methodology adopted has been developed based on the following philosophy:

- Provide a statistically consistent set of ARI levels for the Queensland open coast
- Where possible use all available study information
- Follow the technical recommendations in:
  - Harper B.A. (ed.), (2001) Queensland climate change and community vulnerability to tropical cyclones - ocean hazards assessment - stage 1 (aka the “QCC” studies); and
  - GHD/SEA (2007) South east Queensland storm tide review – recommendations for modelling, risk assessment and mitigation strategies.

1.3 Dune Crest and Beach Slope Assessment

Additionally, a detailed dune crest and beach slope assessment has been completed to support State-wide storm tide prediction modelling. This work has been included as Appendix J.

1.4 Scope

Key outputs of the study include:

- An overview of historically significant storm tide events affecting the Queensland coast;
- Provision of the 20, 50, 100, 200, 500, 1,000 and 10,000 y ARI events, plus the estimated Theoretical Maximum Storm Tide (TMST) levels for the Queensland open coast;
- Review of 23 separate storm tide studies and extraction of results;
- Development of an agreed approach to derive and document a consistent set of storm tide levels;
- Report on the significance of gaps that remain along the coast; and
- Provision of GIS layers containing the final consistent ARI and TMST datasets.

1.5 Acknowledgements

It is acknowledged that this work has been partially funded by the Australian Government National Disaster Resilience Program (NDRP).

GHD would like to acknowledge Mr Lou Mason from the Australian Maritime College in Launceston for his assistance, particularly his in-kind contribution of the previously unpublished 10,000 y ARI results from the Hardy et al. (2004).

GHD would also like to acknowledge the input of the project Technical Review Group (TRG) comprising the following members:

- Crispin Smythe (Sunshine Coast Regional Council)
- Derek Todd (DEHP)
- Dorean Erhart (LGAQ)
- John Arrowsmith (DCS/EMQ)
- Kevin Chetwynd (DSITIA)
- Robert Preston (DCS)
- Robert Schwartz (DSITIA)
- Sel Sultmann (DEHP)
- Wes Bailey (Townsville Regional Council)

1.6 Definitions

All severe weather systems are capable of producing a storm surge, which can increase coastal and ocean water levels for periods of several hours to days and significantly affect over 1,000 km of coastline (Harper 2001). Tropical cyclones (TCs) are the most damaging wind and storm surge events in northern Australia, but their greatest impacts are typically limited to within 100 km of the centre and last for less than 12 hours. Meanwhile, the more common and regular tropical monsoon and at higher latitudes Extra-tropical storm systems such as East Coast Lows (ECL) may have an extended (time and space) influence but normally at a magnitude lower than that from a severe tropical cyclone. The combination of these events with the astronomical tide in areas that are low-lying and susceptible to inundation can be very significant.

The storm surge (or meteorological tide), is an atmospherically forced ocean response caused by the high surface winds and low surface pressures associated with severe and/or persistent offshore weather systems. An individual storm surge is measured relative to the tide level at the time. It is generated by the combined action of the severe surface winds (tropical cyclone winds circulate clockwise around a storm centre while strong monsoon winds tend to be more frontal in nature), generating ocean currents, and the decreased atmospheric pressure, causing a local rise in sea level (the so-called inverted barometer effect). When a severe tropical cyclone crosses the coast, the strong winds perpendicular to the coastline are responsible for the greater proportion of the surge (also called wind setup).

The total seawater level experienced at a coastal, ocean or estuarine site during the passage of a severe large scale ocean storm (e.g. TC, ECL or monsoonal depression) will be made up of relative contributions from a number of different effects, as depicted in Figure 1-1. The combined or total water level is then termed the storm tide, which is an absolute vertical level, referenced in this report to Australian Height Datum (AHD).

1.6.1 Components of a Storm Tide

It is important to understand the different water level components that can comprise the *Total Storm Tide* at a specific site. These effects can vary throughout any given region in both time and space and depending on the local physical conditions. With reference to the definition sketch in Figure 1-1:

(a) The Astronomical Tide

This is the regular periodic variation in water levels due to the gravitational effects of the moon and sun, which can often be predicted with generally very high accuracy at any point in time (past and present) where sufficiently long and precise measurements are available.

In practice, the analysis of tides often also includes non-astronomical components that are persistent and have a fixed periodicity. This includes components such as the radiation tide which is driven by the daily solar cycle and the annual tide created by seasonal variations in wind and atmospheric pressure.

The highest expected tide level at any location is termed the Highest Astronomical Tide (HAT) and occurs theoretically once each 18.6 y period, although at some sites tide levels similar to HAT may occur several times per year or even be exceeded due to atmospheric influences.

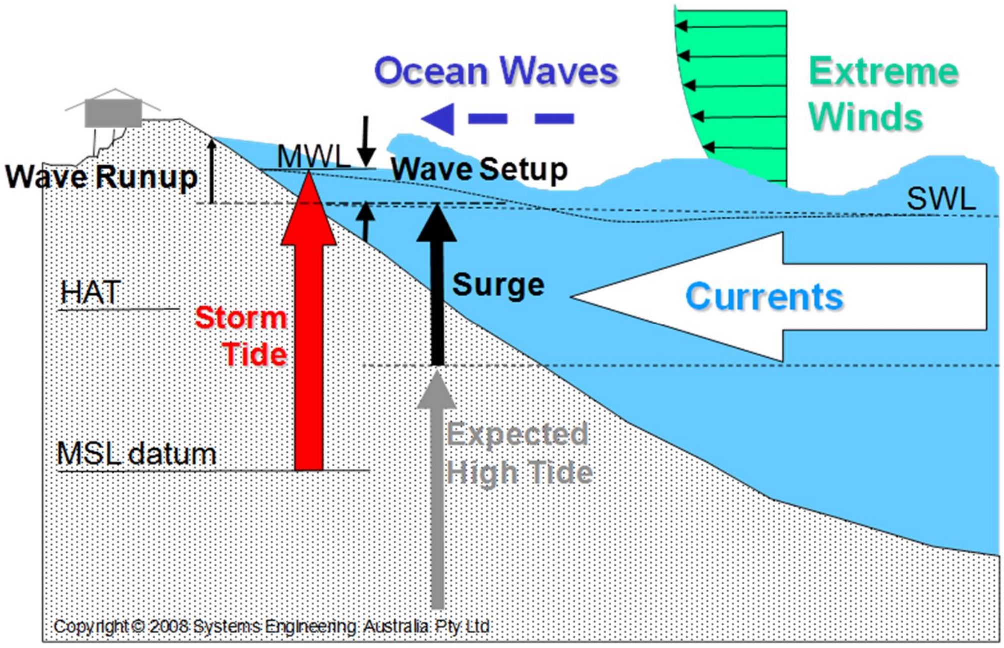


Figure 1-1 Water level components of an extreme storm tide (after Harper 2001)

(b) Storm Surge

By some definitions, the storm surge is simply the difference between the expected (predicted) astronomical tide and the actual (measured) average sea level at some point in time and space. This difference is typically termed the “residual” water level variation. However, because of non-linear interactions in some situations, the residual often does not fully represent the incident non-astronomical wave-form.

As previously introduced, the storm surge is perhaps best referred to as the meteorological tide because it is the combined result of atmospheric pressure gradients and wind shear stress acting on the underlying ocean. While these influences are universally active everywhere, and are present at many time and space scales (e.g. refer (f) later), the effects are significantly greater during the enhanced forcing provided by weather events colloquially called storms.

The storm surge manifests as a long period “wave” capable of sustaining above-normal or below-normal water levels over a number of hours. The wave travels with and ahead of the storm system and may be amplified as it progresses into shallow waters or is confined by coastal features. The magnitude of the surge can be affected by many factors such as storm intensity, size, speed and angle of approach to the coast and the coastal bathymetry (undersea depths). The storm surge will add to the normally expected tide over a large area, combining to produce the so-called “still water level” or SWL. This is the highest water level at a point on the shoreline if short period wind-wave action were ignored.

(c) Breaking Wave Setup

Severe wind fields also create abnormally high sea conditions and extreme waves may propagate large distances from the centre of a storm as ocean swell. As the waves enter shallower waters they refract and steepen under the action of shoaling until their stored energy is dissipated by wave breaking either offshore in shallow regions or at a beach or reef. Through the continuous action of many breaking waves, shoreward water levels can rise above the still-water level (SWL), creating a locally higher “mean water level” (MWL) at the shore.

This increase in water level immediately after wave breaking is known as “breaking wave setup” and applies to most natural beaches and reefs. Seawards of the breaker zone there is also a region of minor wave setdown. Importantly, wave setup needs some type of a vertical barrier that will act to sustain the water level gradient that balances the incoming wave momentum. Accordingly, wave setup generally is not expected to be significant in harbours or navigable river mouths (due to an absence of breaking processes) or protected swampy lands (due to precedent wave dissipation). The presence of irregular (i.e. 2-D) natural banks and channels can also act to dissipate the products of wave setup on natural beaches and generate so-called rip current circulations.

(d) Breaking Wave Runup

Notwithstanding wave setup, there will remain some residual energy in the form of individual waves that will generate intermittent vertical runup and may cause localised impacts and erosion at elevations above that of the nominated storm tide (MWL) level. These effects can only be accurately estimated with specific information about the land-sea interface, which may even be changing in time as the storm tide increases in height. This would include the slope of the shoreline, the porosity, vegetation and the incident wave height and period.

(e) Overland Inundation and Wave Penetration

When normally dry, relatively flat nearshore land becomes inundated during a severe storm tide episode, the sea begins to quickly flood inland as an intermittent “wave front”, driven by the initial momentum of the surge, products of wave setup and runup and the local surface wind stress. This flow then reacts to the local ground contours and the encountered hydraulic roughness due to either natural vegetation or housing and other infrastructure. It will continue inland until a dynamic balance is reached between the applied hydraulic gradients, wind stress and the land surface resistance or until it becomes constrained by elevation and creates ponding etc. As the storm surge abates or the tide reduces, an ebb flow is created which is commonly responsible for much of the observed coastline scouring after such extreme inundation events.

(f) Other Effects on Sea Level

There remain other related phenomena that can also have an effect on the local ocean water level. These include annual and inter-annual variations in the sea level caused by large scale wind-forced ocean currents and their associated temperature changes. For example, these effects are relatively large contributors to sea level variability in the Gulf of Carpentaria on an annual basis and are also present at Mackay due to the persistent SE Trade Winds. In addition, there exist episodic, low amplitude, long period shelf waves that can propagate large distances and affect the predicted tidal elevation over periods of several days.

Finally, where there is a high exposure to large swell waves, the wave setup effect can be further modulated by unsteady “surf beat” or infra-gravity waves and some communities may be affected by localised stormwater and/or river runoff in specific situations.

1.6.2 Water Level Components not Considered in this Study

With reference to the above definitions, the following potential effects on local coastal water levels are not included in this study:

- Episodic low amplitude long period shelf waves not directly related to the local or regional meteorological forcing
- Breaking wave runup
- Overland inundation and wave penetration
- Wave grouping (infra-gravity) effects
- Fluvial flooding
- Stormwater or local flash flooding due to rainfall events.

1.6.3 Average Recurrence Interval Concepts

The present study reports its findings in terms of statistical Average Recurrence Intervals (ARIs). It is important to understand that an ARI (or Return Period) is simply the expected average elapsed time in years between equalling or exceeding a specified event level. This concept does not guarantee that the nominated event’s ARI number of years will have elapsed before such an event occurs again. In fact, the probability of experiencing the “n” year ARI event within any consecutive period of “n” years is approximately 64%, i.e. more likely than not. For example, the 100 y and 1,000 y ARI events could both occur in the same year or one might occur twice in the same year, etc. Appendix A provides more explicit advice on the choice of ARIs in the context of encounter probability.

1.6.4 Historically Significant Storm Tide Events

As first collated in Harper (1999) and later updated in Harper (2001), there have been a number of significant storm tide events in the recorded history of Queensland. This summary record has been further updated here (Table 1) to include the most recent ex *TC Oswald* event in Moreton Bay in January 2013, which in association with minor flood runoff in the Brisbane River, caused inundation in parts of Brisbane City. Each event has its highest recorded water level only. The estimated probability of exceedance of some of the more reliable historical events is discussed later in Section 7.3.

The table provides an entry for every known event thought to have exceeded HAT. The storm surge magnitude (m) is a measure of intensity of the storm event but depends on the distance of the site away from the track. The storm tide level is the absolute tide+surge level (m AHD) either as measured by a tide gauge or often only estimated (perhaps by debris lines that may include wave effects). The final column shows the water level relative to HAT, which would be the more visible impact of the event for residents. The more significant events, either because of magnitude or impact, are shown in **bold**. Events that occurred prior to the mid-1970s (prior to the State Government expanded gauged network) or impacted very remote areas, are suitably labelled to indicate a high degree of uncertainty in the indicated values. On the one hand some of the very earliest reports almost certainly overstate the impacts, while in other cases, water levels may well have exceeded the indicated levels at other locations but were not observed.

Table 1 Notable historical storm tide events reported in Queensland

Date	Place	Event	Storm Surge (m)	Storm Tide Level (m AHD)	Inundation Above HAT (m)
1858	Green Is	unnamed	?	2?	"awash"
04-Mar-1887	Albert R Heads	**unnamed**	5.5?	7.8?	5.1?
08-Jun-1891	Brisbane	unnamed	?	1.8	0.3
19-Feb-1894	Brisbane	unnamed	0.6	1.6	0.2
26-Jan-1896	Townsville	**Sigma**	>2?	4?	2?
05-Mar-1899	Bathurst Bay	**Mahina**	13.7??	13?	11??
09-Mar-1903	Cairns	**Leonta**	?	2+?	0.7
27-Jan-1910	Cairns	**unnamed**	?	2+?	0.7
21-Jan-1918	Mackay	**unnamed**	3.8	5.5	2
10-Mar-1918	Mission Beach	**unnamed**	>7??	8??	3.5??
04-Feb-1920	Cairns	**unnamed**	>1.5	2.5?	0.7?
30-Mar-1923	Albert R Heads	**Douglas Mawson**	>3	5?	2.3?
16-Jun-1928	Brisbane	unnamed	?	1.7	0.2
11-Mar-1934	Cape Tribulation	**unnamed**	>9??	>7??	>6??
17-Mar-1945	Cairns	unnamed	>0.8	?	?
28-Jan-1948	Brisbane	unnamed	0.5	1.8	0.3
23-Feb-1948	Bentinck Is	**unnamed**	>3.7	4.7?	3.2?
02-Mar-1949	Gladstone	unnamed	>1.2	2.2	0.2
18-Jan-1950	Brisbane	unnamed	0.6	1.8	0.3
21-Feb-1954	Coolangatta	unnamed	>1?	2?	?
03-Feb-1964	Edward River	Dora	5?	?	?
29-Jan-1967	Brisbane Bar	**Dinah**	0.4	1.6	0.2
19-Feb-1971	Inkerman Station	Fiona	>4?	?	?
24-Dec-1971	Townsville	**Althea**	2.9	2.6	0.4
11-Feb-1972	Fraser Island	Daisy	3?	?	?
07-Feb-1974	Brisbane	Pam	0.7	1.9	0.4
19-Dec-1976	Albert River	**Ted**	3.0?	5.2?	2.4?
31-Dec-1978	Weipa	Peter	1.2	2.3	0.6
26-Apr-1989	Beachmere	Charlie	0.6	1.5	0.2
04-Apr-1989	Molongle Creek	**Aivu**	2.7?	3.1?	1.1?
16-Mar-1992	Burnett Heads	Fran	1	2.1	0.2
06-Jan-1996	Gilbert River	**Barry**	4.5?	6?	3.4?
09-Mar-1996	Weipa	Ethel	1.2	3.6	0.3
08-Mar-1997	Cairns	Justin	0.7	1.9	0.2
04-Jan-2002	Weipa	Bernie	0.64	1.67	0.04
12-Mar-2003	Weipa	Craig	1.05	1.80	0.17
07-Feb-2005	Karumba	Harvey	0.45	2.79	0.19
10-Mar-2005	Night Island	**Ingrid**	1.15	1.80	1.19
20-Mar-2006	Clump Point	**Larry**	2.3	2.6	0.7
13-Jan-2009	Townsville	**Charlotte**	0.7	2.6	0.4
08-Feb-2009	Townsville	Ellie	0.3	2.5?	0.3?
09-Mar-2009	Rosslyn Bay	Hamish	0.7	2.7	0.2
21-Mar-2010	Laguna Marina	**Ului**	2.5	3.9	0.4
03-Feb-2011	Cardwell	**Yasi**	5.3	4.5	2.2
28-Jan-2013	Brisbane	**ex TC Oswald**	0.9	1.8	0.2

2. Methodology Overview

The following section provides brief overview of the key analysis steps undertaken. Further detail of each component is provided in Chapters 4, 5 and 6.

1. **Theoretical Maximum Storm Tide (TMST):** Outline the method and modelling undertaken to provide TMST estimates for the entire Queensland open coastline.
2. **Study Review:** Collate and review all relevant studies. Based on this review assign a score that can be used to differentiate each study in the following analysis.
3. **Gap Analysis:** Extract available *Tide plus Surge* and *Total Storm Tide* data from each report. Assess data availability and potential gaps in both ARI and geographical terms along the QLD coast.
4. **Study Merging:** Normalise and combine each storm tide study into a consistent Queensland wide dataset.
5. **Results:** Detail of key project GIS and tabulated outputs.

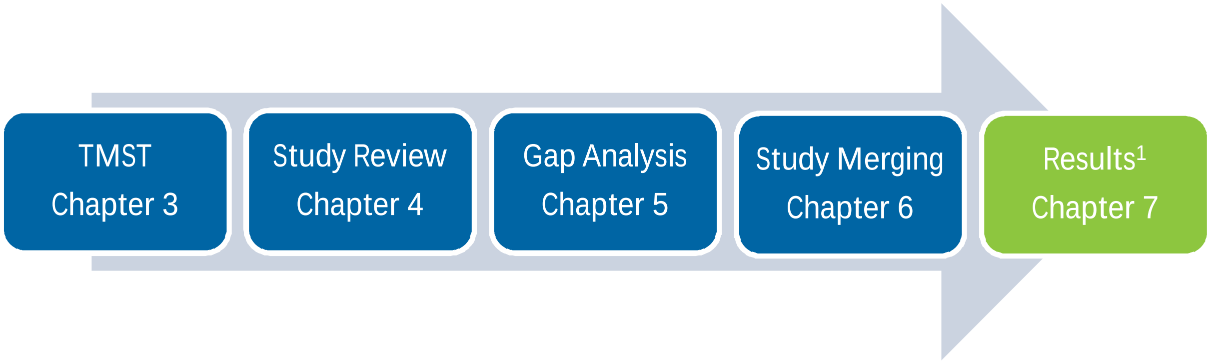


Figure 2-1 Overview of study methodology[1]

One component of the project scope of work was to advise the TRG on the benefits and dis-benefits of incorporating wave setup, runup and the so – called 'freeboard' into this scale of analysis. The inclusion/omission of each of these components is detailed below:

- **Wave Setup:** With the exception of the Queensland Climate Change Stage 3 (Hardy et al, 2004), all storm tide studies completed for the Queensland coast have included estimates of breaking wave setup components. As wave setup can represent a sustained contribution to total water levels in the active wave zone (nominally within 200 m from the coastline) these estimates have been included in the *Total Storm Tide* estimates herein.
- **Wave Runup:** As detailed in Section 1.6.1 (d) wave runup varies on a wave to wave basis and is highly dependent on local beach characteristics. While some of the available studies have provided statistical wave runup estimates (and some have combined runup with setup estimates) none have done so at a resolution and scale deemed reliable enough for application to the entire Queensland coast. Accordingly wave runup estimates have not been included in this compilation.
- **Freeboard:** The purpose of a "freeboard" allowance is to address the uncertainty and inaccuracies in the estimate of storm tide levels across the floodplain. In effect, freeboard acts as a factor of safety for a given location to try and ensure that a particular nominal event level can be defended. However freeboard is not a concept suited to statistical analysis or risk assessment and so it has not been included in the estimates herein.

[1] The dune crest and beach slope methodology and results have been included in Chapter 7.

3. Theoretical Maximum Storm Tide (TMST)

The "theoretical maximum storm tide" considers what upper limit of storm surge magnitude might be physically possible through a combination of specifically extreme storm parameters, without regard to their likely joint probability or overall probability of occurrence, and then combines that resulting magnitude with the Highest Astronomical Tide. The resulting water level can then be regarded as representing a "theoretical upper limit" to possible storm tide levels and statistically approximates an infinitely long ARI estimate[2]. While this seems straightforward, the selection of the "extreme parameters" still requires significant subjective judgement. The parameters of interest in the context of a standard Holland parametric wind and pressure model, as described in Harper (2001), and their typical influence on the resulting storm surge magnitude are summarised in the following Table:

Parameter	Symbol	Indicative Range	Effect of Increasing |Latitude|	Impact Maximised When
Central Pressure	p_c	990 to 880 hPa	increases	lowest
Radius to Maximum Winds	R	5 to 100 km	increases	largest
Peakedness Parameter	B	0.8 to 2.5	decreases	largest[3]
Speed of Forward Movement	V_{fm}	0 to 10 m/s	increases	largest[4]
Track	θ_{fm}	180 to 290 deg	decreases	coast perpendicular (typically)

It can be noted that in the Queensland setting, all the above parameters exhibit a significant variation with latitude (assumed here increasing from north to south) and the likely ranges were investigated in Harper (2004a) in association with Bureau of Meteorology (BoM) personnel.

3.1.1 Parameter Selection

The method adopted here extends that first developed by Harper (2007) – an analysis undertaken for the EPA to help determine "safe" elevations for planned storm surge shelters along the Queensland coast. This method utilised the BoM Parametric Storm Surge Model (BPSSM) that was manually applied in-house and provided a series of discrete estimates along the coastline targeted at the major population areas, which were then smoothed to simplify the

[2] This contrasts with the concept of the "probable maximum storm tide" (PMST) that has an estimated finite but very low probability of exceedance. With state-of-the-art simulations extending out to 50,000 y the PMST has traditionally been assigned a nominal estimated ARI of 10,000 y to be representative of a very rare event. However, with increasing experience of severe events accumulating over time the 100,000 y event may be more appropriate to use as the PMST.

[3] This is a general statement that may not be the case in individual situations due to the relationship between B and R in the Holland model. This has been partly addressed here by adopting a more sophisticated "double Holland" wind field modelling approach.

[4] Typically there will be a specifically resonant forward speed applicable to a particular situation and there are physical limits to the speed of a storm system and its ability to maintain intensity.

results. The parameter selections were made using the climatology summary provided in Harper (2004a), which was used as the basis for the original BPSSM development. Because access to the BPSSM is not available to GHD and a more detailed along-coast assessment was intended, the present methodology builds on this approach by undertaking discrete hydrodynamic modelling using the MMUSURGE hydrodynamic model (upon which the BPSSM was developed). A series of hypothetical storm tracks have been constructed, each of 36 h duration, approximately perpendicular to the coastline, spaced every 50 km apart from near Byron Bay in NSW and north to Torres Strait (being approximately 100 storm tracks). The highest peak storm surge values generated at each modelled location from all tracks on the adopted B grid resolution (2.8 km) have then been extracted and combined with the DSITIA-provided "HAT thread". These have then been merged with the Gulf of Carpentaria TMST estimates (GHD/AMC 2013), which have a similar basis but were extracted from SATSIM parametric models rather than MMUSURGE simulations. Figure 3-1 provides an overview of the "B grids" utilised in Harper (2004a), with B1 to B9 and A1 to A4 being used in the present analysis.

It can be noted that "breaking wave setup" is not specifically calculated in this assessment as the associated necessary spectral wave modelling would represent a very significant additional modelling step that is not possible within the study budget and timeframe. Instead, the nominal recommendations of Harper (2007) for wave setup have been adopted with appropriate blending and interpolation. This has the effect of significantly increasing MMUSURGE-derived TMST levels only in those areas that are exposed to deepwater wave conditions (e.g. south of Hervey Bay). In other areas its impacts will generally be insignificant in situations where surge+tide inundation is the overwhelming impact.

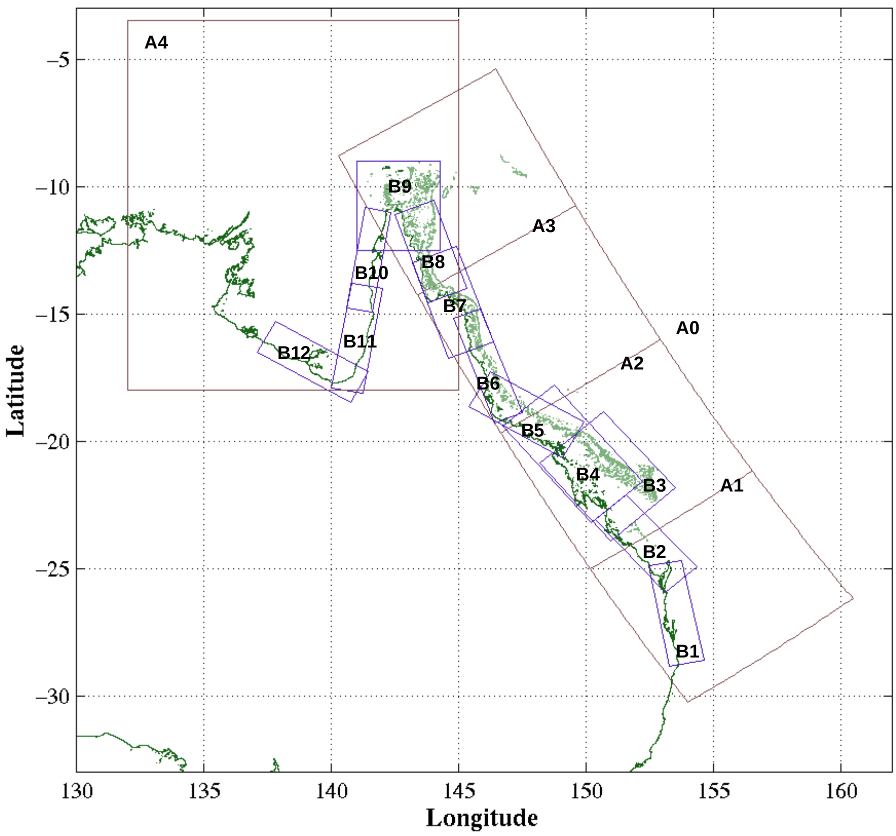


Figure 3-1 Storm surge model A and B domains for the Queensland coast (after Harper 2004a)

The individual storm tracks spaced 50 km apart follow an approach similar to that shown below for the B5 model domain, which indicates the series of tracks used specifically for the original MMUSURGE-BPSSM development, whose spacing varied as shown. Points along the coastline are at the domain resolution of 2.8 km, which is deemed adequate for obtaining estimates of the TMST.

Table 2 below summarises the TMST storm parameters used in each model grid, which is based on a “double-Holland” tropical cyclone wind and pressure model (e.g. McConochie et al. 2004) to provide a more realistic outer wind profile compared with the earlier BPSSM analyses. The parameters used within each model region comprise the present climate Maximum Potential Intensity (MPI) expressed as a pressure deficit (Δp), the “inner” Holland profile upper (+σ) standard deviation estimates of R, B and V_{fm} as proposed in Harper (2004a), and the “Outer” profile parameters that have been fixed for the whole coastline. Also shown are the model simulation track times that have been applied.

Table 2 Adopted TMST tropical cyclone parameters

	Trackr	MPI	Inner (+ Sigma)			Outer			Track Times		
Grid	θfm	Δp	R	B	Vfm	Δp2	R2	B2	buildup	duration	after land
	deg	hPa	km	-	m/s	hPa	km	-	h	h	h
1	260	90	75	1.3	8	10	150	1.0	12	36	18
2	230	110	60	1.4	8	10	150	1.0	12	36	18
3	230	120	55	1.5	8	10	150	1.0	12	36	18
4	230	125	50	1.6	8	10	150	1.0	12	36	18
5	210	125	45	1.7	8	10	150	1.0	12	36	18
6	250	125	35	1.8	8	10	150	1.0	12	36	18
7	250	125	25	2.0	8	10	150	1.0	12	36	18
8	250	125	25	2.1	8	10	150	1.0	12	36	18
9	270	125	20	2.4	8	10	150	1.0	12	36	18

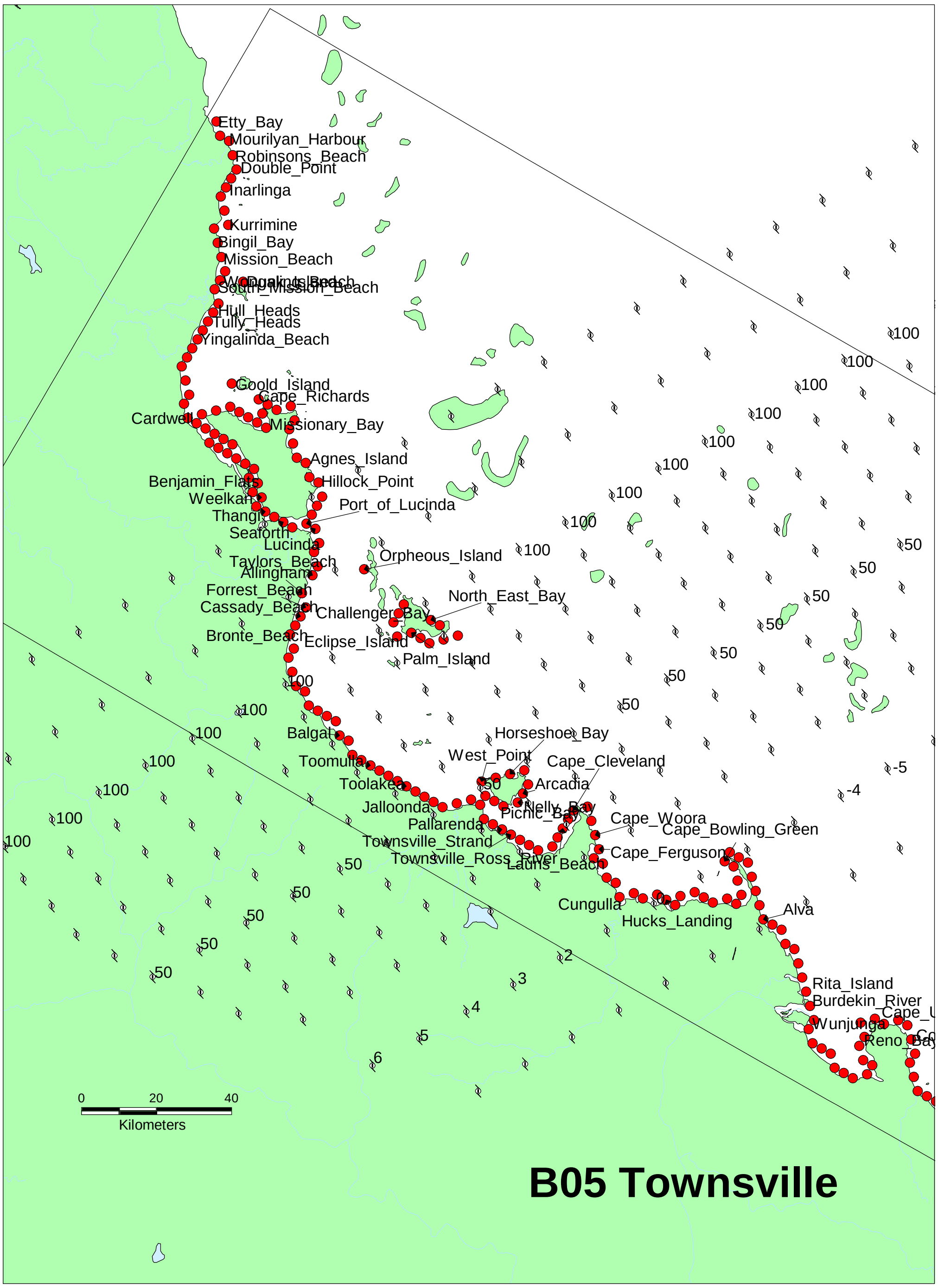


Figure 3-2 Example MMUSURGE storm tracks for the Townsville region used in the development of the BPSSM that illustrate the TMST approach.(after Harper 2004)

3.1.1 TMST Estimates

A comparison of the newly developed levels and the work of Harper (2007) is presented in Figure 3-3. Visual inspection provides a reasonable match between the two datasets at the sites modelled during the 2007 study given the differing methodologies adopted.

The resulting 1280 TMST point estimates for the Qld coast are presented in Figure 3-4 and indicate water levels ranging from approximately 3 mAHD in the lieu of Bribie Island up to 15 mAHD in the Gulf of Carpentaria and St Lawrence regions. The Qld mean TMST is approximately 7.5 m AHD.

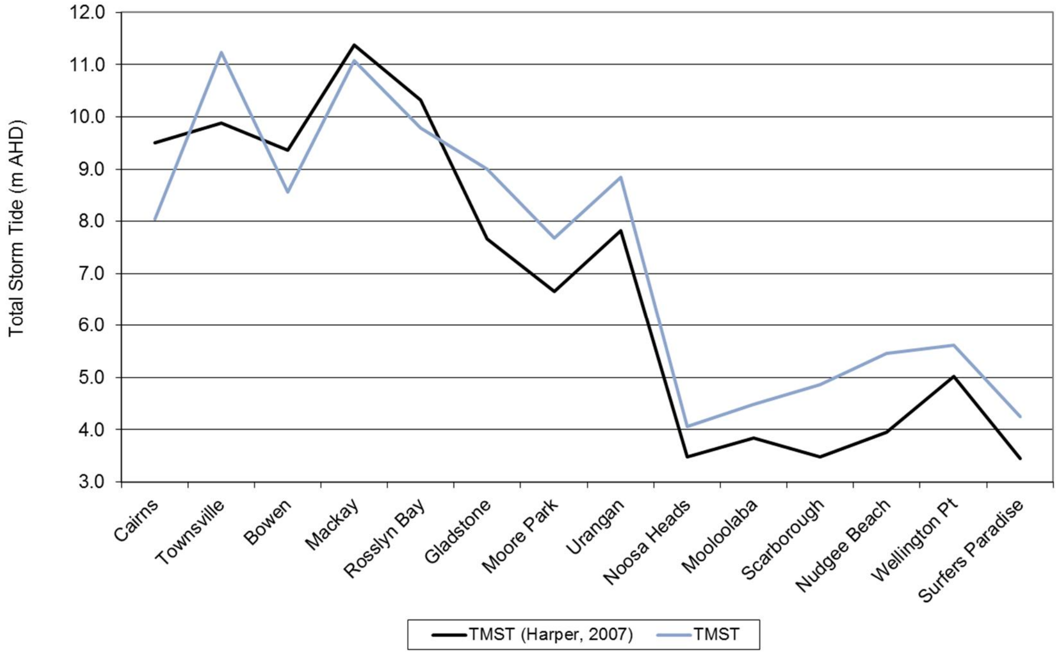
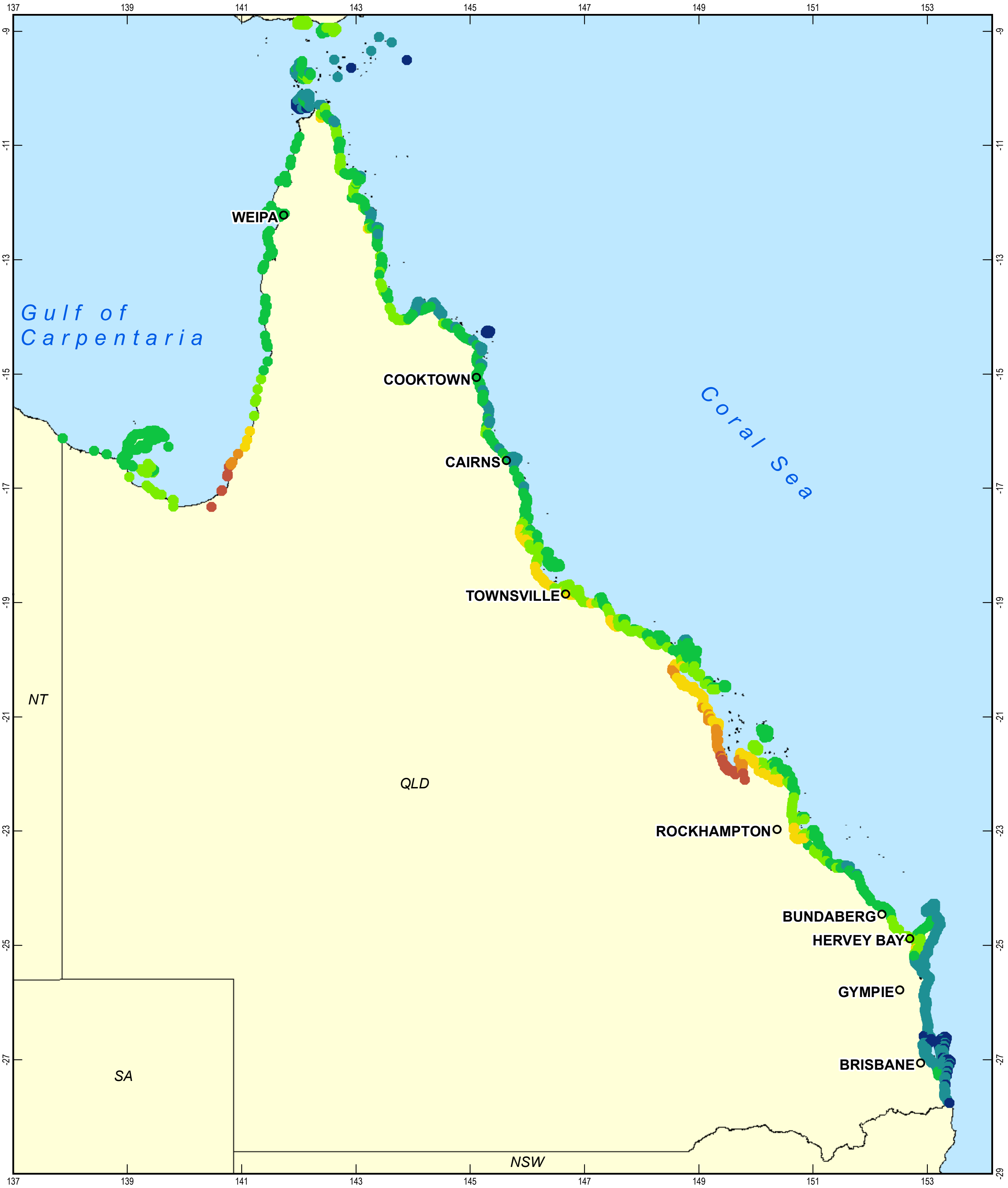


Figure 3-3 Comparison of Harper (2007) estimates (black) and the GHD (2013) results (blue).



LEGEND

Locality	Water Elevation (m AHD)	8.01 - 10.00
	<4.00	10.01 - 12.00
	4.01 - 6.00	12.01 - 14.00
	6.01 - 8.00	>14

1:10,000,000 @ A4

0 1 2

Decimal Degrees
Horizontal Datum: GDA 1994
Grid: GCS GDA 1994

N

Department of Community Safety
NDRP Storm Tide Hazard Interpolation Study

Job Number 41-25509
Revision A
Date 19 Aug 2013

Theoretical Maximum Storm Tide Levels

Figure 3-4

G:\41\25509\GIS\Maps\Deliverables\4125509_008_RevA.mxd

145 Ann Street Brisbane QLD 4000 Australia T 61 7 3316 3000 F 61 7 3316 3333 E bnemail@ghd.com W www.ghd.com

Data source: DNRM - Locality/2010; ESRI - Mainland/2007; GHD - Water Elevation/2013. Created by: LS

4. Study Review

4.1 Report Collation

During the course of the project, over 40 separate studies were made available by DSITIA including those within the Queensland Government Storm Tide Information Resource (STIR) and others sourced directly from respective local Councils. Only the more recent post-2001 studies were used, resulting in a total of 23 separate studies, with the expectation that these studies might have adopted the State Government and Bureau of Meteorology sanctioned Harper (2001) recommendations. A detailed bibliography is provided in the report references section.

It is noted that at the time of writing a number of these reports were still in draft phase:

- Sunshine Coast Storm Tide Study – Storm Tide Definition; and
- Bundaberg Coastal Storm Tide Study

It is expected that the results of these studies should be finalised within a number of months. If significant changes are made to these draft results it is recommended that the updated storm tide levels be incorporated into an amended version of this report.

It is acknowledged that a nation-wide storm tide study has also been recently completed by the ACECRC, Haigh, et al. (2012). During the project a number of attempts were made to access this dataset in order to provide an additional baseline dataset. Unfortunately this data was not made available and as such the reliability of these estimates remains unknown.

4.2 Review

A systematic review of each storm tide study was completed based on a methodology developed during the South east Queensland storm tide review – recommendations for modelling, risk assessment and mitigation strategies (GHD/SEA 2007), termed the SEQDMAG report. Key study components for review included:

- Tropical Cyclone climatology;
- Windfield modelling;
- Hydrodynamic modelling;
- Statistical modelling;
- ARI and wave setup/runup provision.

Appendix B provides a detailed summary of the storm tide study review scoresheet which, has been designed to reflect elements from the essential aspects of the Preferred Practice Methodology from the SEQDMAG report.

Scoring of the studies is presented within a professional context, noting that the scope, timing and budget of investigations often has a controlling impact on the content of the final reports that have been made available for this review. Estimation of extreme events such as storm tide remains a very difficult and complex process that demands a high level of disclosure of methods and assumptions in order to demonstrate confidence in the predictions. *Consequently, reports that appear incomplete or void of essential detail have been marked down*.

The scoring process is imperfect, unavoidably subjective in many areas and, is not intended to reflect badly on the good intentions or capabilities of the respective consultants and/or their LGA clients. Rather, the scoring is designed to provide a consistent framework for inter-comparison of the various scopes, methods and outcomes in the context of a complete and comprehensive storm tide risk scope of work.

Due to the large variation in climate change assumptions, particularly mean sea level allowances within the various reports it was decided by the SAG that future climate would not form a component of this study.

Each study has been scored out of a maximum available 70 points across five categories as shown in Figure 4-1.

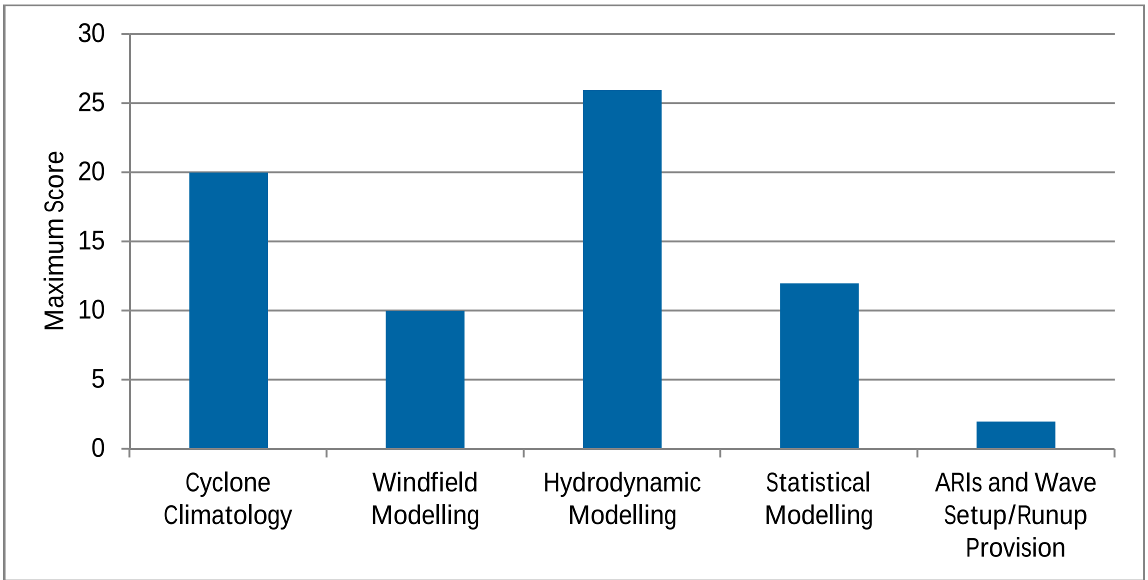


Figure 4-1 Maximum Possible Score for each Review Component

Based on the review scores summarised in Figure 4-2 and the detailed scoring provided in Appendix B the following can be observed:

- Generally, each of the studies scores well on the hydrodynamic component; and
- The variation in scores between studies can be largely attributed to differences in TC climatology and windfield modelling.

It is noted that the methodology employed for the Draft Sunshine Coast Storm Tide study is different in that tidal residual analysis has been used rather than the QCC study recommended TC windfield and hydrodynamic modelling simulation. As the scoring method adopted here is based on the SEQDMAG approach, the Sunshine Coast study has been scored somewhat lower than if a traditional storm tide study had been completed.

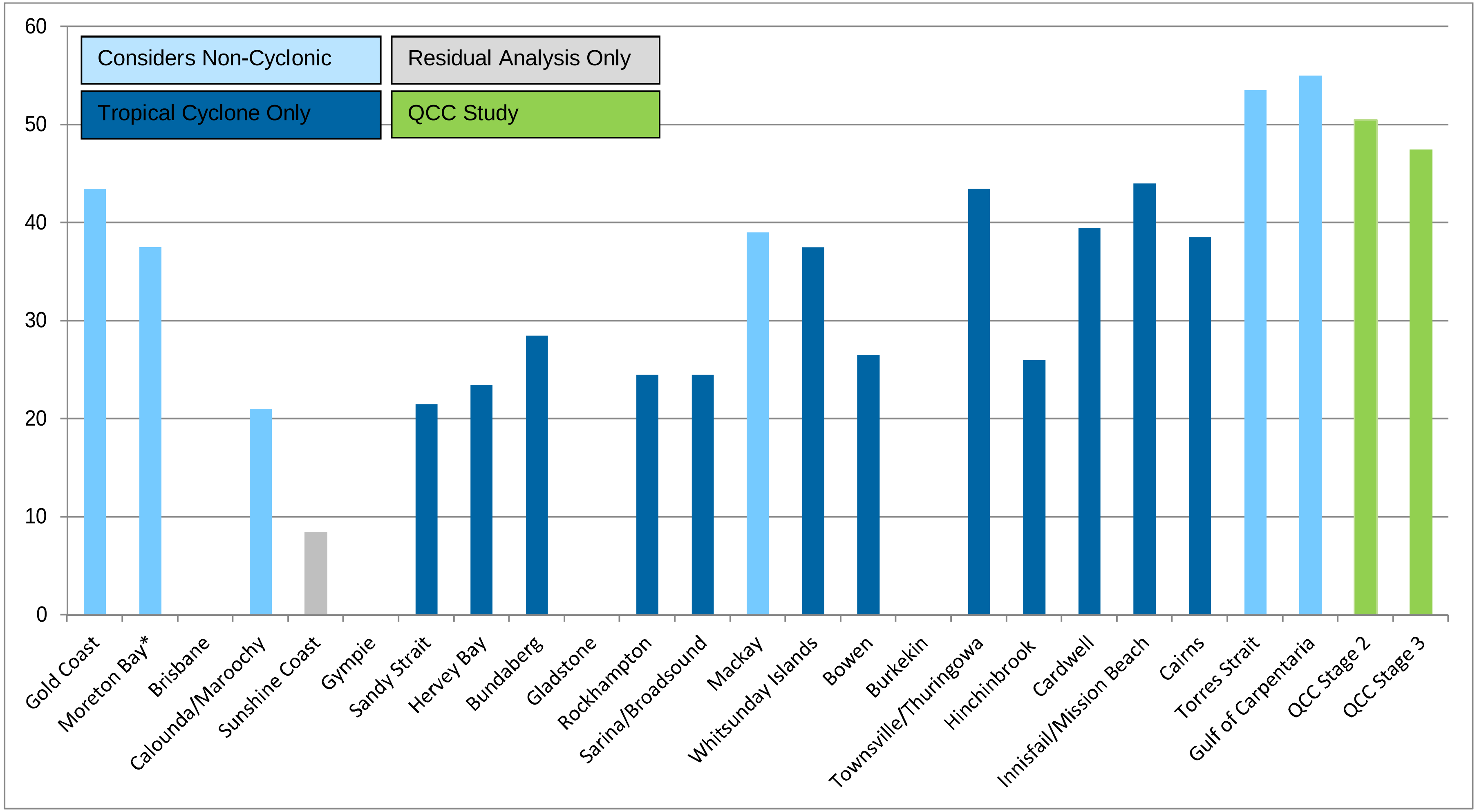


Figure 4-2 Storm tide review study scores.

* Moreton Bay represents the Moreton/Redland/Logan Studies.

Note: The Bundaberg study has had scores deducted due to the high ARI data being below HAT.

5. Gap Analysis

5.1 Data Extraction

Tabulated *Tide plus Surge* and wave setup estimates from each of the 23 studies were extracted and input into a GIS environment. Appendix C Figure C1, C2 and C3 provide an overview of the data extracted from each study.

HAT estimates have been extracted for each point based on the DSITIA provided HAT GIS layer. An exception to this is in the Torres Strait where HAT values have been based on those reported in SEA/AMC (2011)[5].

5.2 Non-Cyclonic/Cyclonic Statistical Blending

As highlighted in Figure 4-2 the Gold Coast, Moreton/Redland, Maroochy/Caloundra, Sunshine Coast, Mackay, Torres Strait and Gulf of Carpentaria studies all provided both cyclonic and non-cyclonic storm tide estimates. The latter class of estimates includes events being caused by large-scale synoptic disturbances such as the Monsoon Trough, deep Monsoonal Lows, East Coast Lows/Extra-Tropical Hybrid systems or coastally trapped waves. The influence of such weather systems can have a significant contribution to water levels below the 200 y ARI along the majority of the QLD coast north from Hervey Bay. South of Hervey Bay, on the Gold and Sunshine Coast, non-cyclonic events can influence estimated water levels out to the 1,000 y ARI.

The combined extreme water level risk due to each of the independent non-cyclonic and cyclonic events provided in the Gulf of Carpentaria, Torres Strait and Gold Coast studies have been statistically combined[6] using the method outlined in Gomes and Vickery (1977) as follows:

$$R = \left[\frac{1}{Rtc} + \frac{1}{Rnc} - \frac{1}{Rtc * Rnc} \right]^{-1}$$

Where:

Rtc = the ARI of the cyclonic water level

Rnc = the ARI of the non-cyclonic water level

As the Moreton/Redland/Logan Study, Maroochy/Caloundra and Mackay studies provided separate tropical cyclone and non-cyclonic estimates the results from these studies have also been combined in a manner consistent with the above.

The sequence in which statistical combination has taken place in the study normalisation process is detailed further in Section 6.1.1.

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[5] This is because this study relied on previously unavailable tidal plane information and the storm tide estimates are linked to its tidal description. It also provided HAT estimates over a wider area than the DSITIA values and was otherwise reasonably consistent with those. In any case the HAT values are used only to assist in the ARI interpolation.

[6] It can be noted that several studies did not correctly combine the independent cyclonic and non-cyclonic event sets and recommended instead choosing the higher event set. This advice can lead to significant errors in ARI estimates in certain situations.

5.3 ARI Gap Analysis

5.3.1 Review of Study ARIs

A comprehensive review of the ARIs reported by each study was undertaken as provided in Table 3. The table highlights the focus of many studies on the 50, 100, 500, 1000 and 10,000 y ARIs, such that these ARIs were addressed in 18, 22, 20, 19 and 20 of the studies respectively.

5.3.1 ARI Interpolation

As highlighted by Table 3 not all studies include the ARIs required by the scope of work (i.e. 20, 50, 100, 200, 500, 1,000 and 10,000 y ARI), particularly the 20 y ARI which, has only been assessed in 8 of the 23 studies.

Tide plus Surge Only Log-Linear Interpolation

To 'infill' data at missing ARIs a log-linear interpolation has been undertaken for each and every point provided in Figure C1. Where required ARI levels have been outside the available data range, values have been log-linear extrapolated. An example highlighting the outcomes of log-linear interpolation is provided in Figure 5-1. The red crosses indicate the available data as extracted from a given study at point X. The black triangles indicate where water level data has been interpolated at the 20, 200 and 2,000 y ARIs

Following log-linear interpolation each of the required ARI levels have been plotted as a function of coastline distance from the NT/QLD border. These coastal long sections are provided in Appendix D.

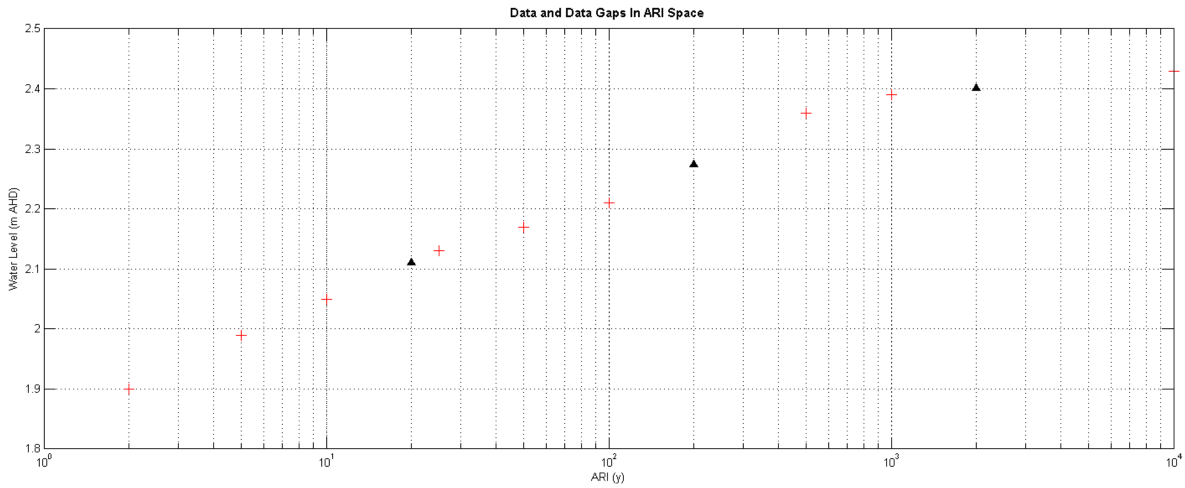

Figure 5-1 Example of log-linear ARI interpolation at Point X

Table 3 Study ARI Gap Analysis

Study	ARI Event													Count
	2	5	10	20	25	50	100	200	500	1,000	2,000	5,000	10,000	
Gold Coast	X	X		X		X	X	X	X		X		X	9
Logan/Redland				X		X	X			X			X	5
Brisbane														NA
Moreton Bay				X		X	X			X			X	5
Caloundra				X		X	X		X	X			X	6
Maroochy				X		X	X		X	X			X	6
Noosa														NA
Sunshine Coast				X		X	X		X	X				5
Gympie														NA
Sandy Strait						X	X		X	X			X	5
Hervey Bay							X		X	X			X	4
Bundaberg			X	X		X	X	X	X	X	X	X	X	10
Gladstone														0
Capricorn						X	X		X				X	5
Isaac (Sarina/Broadsound)						X	X		X				X	5
Mackay			X	X		X	X	X	X	X	X	X	X	10
Whitsunday Islands		X	X		X	X	X		X	X			X	8
Bowen						X	X		X	X			X	5
Burdekin														NA
Townsville						X	X		X	X			X	5
Hinchinbrook						X	X		X	X			X	5
Cardwell							X	X	X	X			X	6
Innisfail/Mission Beach		X	X		X	X	X		X	X			X	8
Cairns							X	X	X	X			X	5
Torres Strait	X	X	X		X	X	X		X	X			X	9
Gulf of Carpentaria						X	X	X	X	X			X	6
QCC Stage 2							X		X	X				3
QCC Stage 3			X	X		X	X	X	X	X			X	8
Count	2	4	5	8	3	18	22	6	20	19	3	2	20	

Total Storm Tide Log-Linear Interpolation/Extrapolation

To ‘infill ‘data for *Total Storm Tide* estimates a similar process to that provided in Figure 5-1 was completed however, interpolation was undertaken of the wave setup component from each study. To obtain the interpolated *Total Storm Tide* estimates the following was applied:

$$Total\ \ Storm\ \ Tide(m\,AHD) = TPS`(m\,AHD) + WS`(m)$$

Where:

TPS‘ = Log-linear interpolated/extrapolated *Tide plus Surge* estimates

WS‘ = Log-linear interpolated/ extrapolated wave setup potential component estimates

Following log-linear interpolation each of the 20, 50, 100, 200, 500, 1,000 and 10,000 y ARI event levels have been plotted as a function of coastline distance from the NT/QLD border. These coastal long sections are provided in Appendix E.

Wave setup potential here refers to an estimated wave setup elevation above the stillwater *Tide plus Surge* level without regard to the local dune crest height, which would otherwise convert the wave setup volume into a wave overtopping volume.

5.4 Geographic Gap Analysis

The point mapping (Appendix C) and water level long sections as provided in Appendix D and Appendix E highlight a number of spatial gaps along the Queensland coast where limited data is available. These include:

- North of Cairns to Torres Strait
- Burdekin (no ARI estimates were available)
- St Lawrence to Yeppoon
- Gladstone
- Tin Can Bay, Cooloola Cove (Gympie Regional Council)
- Brisbane

Fortunately a number of these spatial gaps exist in locations where there are limited population centres or emergency service assets. The exceptions to this are at Gladstone and Brisbane which, although not covered by a Council-specific storm tide study, are represented by the QCC Study Stage 3 but at a limited resolution and with no consideration of wave setup effects.

Only a preliminary storm tide study using a simplified methodology was available for the communities of Rainbow Beach, Cooloola Cove and Tin Can Bay for the Gympie Regional Council. This was not deemed sufficiently consistent with the approaches of Harper (2001) and has been omitted from the current analysis.

It is noted that for the regions mentioned above, spatial interpolation has not been completed to ‘infill’ the gaps based on results from adjacent studies. This is as storm tide levels are highly dependent on coastal morphology. Should estimates be required for regions outside the existing study extents, it is recommended that a formal study be conducted.

5.1 Tidal Datum Review

To assess whether any significant amendments to mean sea level had been made by MSQ over the past 10 y a review of the stated mean sea level datums was undertaken. Where available, mean sea level estimates from each study was compared to the published (MSQ 2013) tidal planes (refer Appendix F).

Based on this available data, mean sea level datums have typically not changed more than ± 0.1 m. These differences are deemed negligible when considering the significant variability in each study's tidal prediction assumptions. Although a valuable reference, these differences have not been applied to standardise the studies to 2013 mean sea level values.

6. Study Merging

This chapter details the methodology by which each study along the Queensland coast has been merged and normalised to provide one consistent *Tide plus Surge* and *Total Storm Tide* dataset for the whole coastline for each of the required ARIs.

6.1 Normalisation Methodology

The overlay of all storm tide studies as a function of ARI and coastline chainage from the NT border (as provided in Appendix D and Appendix E) has highlighted the differences in *Tide plus Surge* and *Total Storm Tide* estimates between each of the different studies. These differences are a product of slightly differing climatology, wind field, hydrodynamic and statistical modelling methodologies. As can be observed, these differing approaches have resulted in a number of large water level 'steps' at the study boundaries for a given ARI.

In order to provide a consistent basis for comparing storm tide hazard along the Queensland coast a study 'normalisation' approach has been developed and agreed with the project TRG. Key steps involved in the method are detailed as follows:

1. For each study and ARI the available *Tide plus Surge* study data points (Appendix D) have been spatially triangulated to create a continuous water level surface for each study extent.
2. At each QCC point within a given study extent, *Tide plus Surge* levels have been extracted from the surfaces developed in Step 1. It is noted that because the QCC data points are typically located in very close proximity to study points there is limited error introduced due to interpolation.
3. Following Step 2 we now have both levels from Study X and the QCC study for a given ARI. Based on these results a 'normalisation ratio' or shift factor can be calculated.

Figure 6-1 below provides an example of how the normalisation ratio can be applied.

The top panel shows results from Study X at high resolution along the coast compared with the more sparsely reported[7] QCC values. For this example study, the resulting levels for a given ARI are higher than the QCC values, although this difference varies along the coastline within the extent of Study X, e.g. for points A, B and C, Study X is 1.1 (10%), 1.2 (20%) and 1.5 (50 %) times higher than the QCC values respectively.

The normalisation process is illustrated in the lower panel of Figure 6-1. Study X at points A, B and C have been shifted by the 10, 20 and 50% to align with the QCC reported values. In the regions between points A and B and also between B and C, the normalisation ratios have been spatially interpolated (linear triangulation) and applied to Study X.

By using this approach, assessed statistical biases due to study methodology are removed while maintaining the deterministic surge variability along the coast, for example keeping higher surge levels in bays and lower surge levels at headlands as predicted by hydrodynamic modelling.

[7] Although the QCC studies were completed on a high resolution grid only a selection of model points were reported.

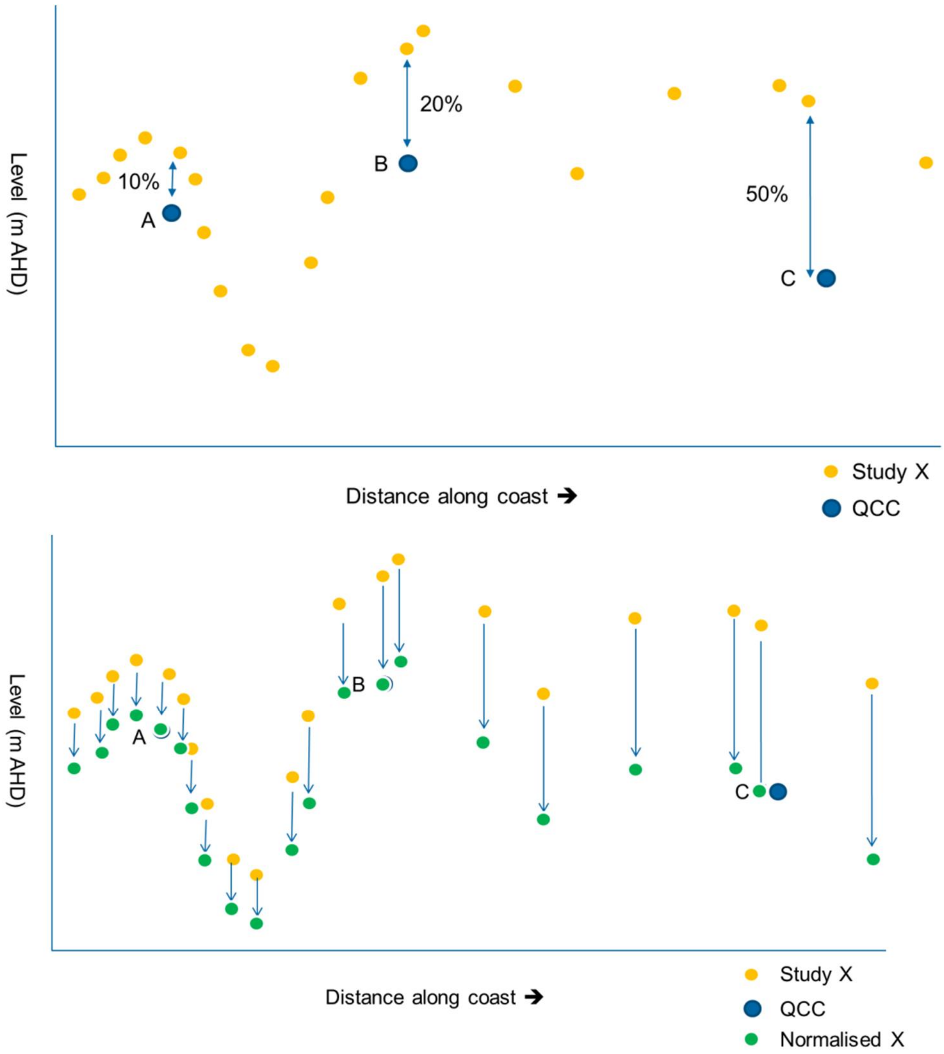

Figure 6-1 Study normalisation method. Note the 10, 20 and 50 % values represent the normalisation ratio.

6.1.1 Why Normalise to the QCC Studies?

The QCC studies completed between 2001 and 2004 (Harper 2001; Hardy et al. 2004a,b; Harper 2004b) confirmed best practice TC storm tide methodologies in a number of technical areas and proposed options for future studies to address both the needs of planning and emergency response, within a perspective of potentially changing climate. These methodologies were sanctioned by State Government and the Bureau of Meteorology.

A principal feature of the predictive aspects of the QCC studies (Hardy et al. 2004a,b) was that a simulated TC track climatology was utilised, based on previous work by James and Mason (2005). The advantages of this approach were that a "seamless" climatology was developed for all areas of the coast without reliance on assumptions of fixed track, speed, direction or intensity. In addition all hydrodynamic modelling was undertaken using a consistent approach and to a high technical standard. This seamless climatology avoids problems inherent in other discrete statistical descriptions that focus on one region at a time and assume constant parameter behaviour within that region. **Even if each discrete study used the same set of climate assumptions, there would be stepped changes evident at the boundaries between regions. In fact, because each non-QCC study has used slightly different parameters this is likely the main reason for differences in estimated ARI values as one moves along the coast.** This is further exacerbated by differences in other assumptions internal to the wind modelling process, where not all studies have confirmed that they followed the recommendations in Harper (2001). Also, notwithstanding that this is a very specialised area of knowledge, each consultant chose their parameter limits based on their own experience. In summary, a major reason for differences between studies is not the hydrodynamic modelling, but rather the assumptions made in regard to the tropical cyclone climate that dictates the probability estimate.

This is not to say that the circa-2001 QCC studies can never be improved upon. For example following the tropical cyclone intensity review work that was done for Western Australia (Harper et al. 2008), a review of Queensland's tropical cyclone climatology is overdue and would likely have a significant impact on risks in some regions. Until that is done, the existing QCC study TC climatology is the most appropriate for the present study. Unfortunately the QCC studies did not include non-cyclonic storm tide events, which are still important at low ARIs in all areas and increasingly tend to dominate TC events south of Hervey Bay.

6.2 Normalisation Framework

A consistent and transparent method has been applied in the normalisation of all study data for Queensland. This section details the rules or framework that has been applied to produce each of the 20, 50, 100, 500, 1000 and 10000 y ARIs *Tide plus Surge* and *Total Storm Tide* estimates.

6.2.1 *Tide plus Surge* Normalisation

Tide plus Surge normalisation to the QCC levels has been completed consistently with the methods outlined in Section 5.3.1 with the exception of the following:

- **Gold Coast:** The Gold Coast study with the inclusion of statistically blended non-cyclonic/cyclonic estimates is deemed more reliable than the QCC for this region. The cyclonic-only estimates are also noted to be consistent with the QCC Stage 3 results. As such the Gold Coast study results have been adopted with no normalisation conducted.
- **Moreton Bay, Sunshine Coast and Mackay:** The Moreton/Redland/Logan, Caloundra/Maroochy and Mackay Studies have included both cyclonic and non – cyclonic *Tide plus Surge* estimates. For each of these studies the following sequence of processing steps has been completed:
  - Extraction of reported cyclonic-only estimates
  - Normalisation of cyclonic-only estimates to QCC cyclonic-only estimates
  - Statistical blending of normalised cyclonic-only estimates and study non-cyclonic estimates using the Gomes and Vickery method outlined in Section 5.2.
- **Sunshine Coast** (Aurecon, 2012): The residual analysis methodology undertaken for this study differs from the majority of contemporary studies undertaken for the Qld coast. No normalisation was conducted because the statistical extrapolation approach is deemed to unrealistically overestimate the storm tide hazard at large ARIs. Given that the study scope was tasked at providing return periods of 1000 y or less, this impact may have been limited.
- **Torres Strait and Gulf of Carpentaria:** The studies undertaken for this region are outside the QCC study coverage and also have been undertaking using a state of the art methodology. As such the study results are 'as-is' and no normalisation has been completed.

6.2.2 Correction of *Tide plus Surge* below HAT

Following each of the steps outlined above any water level estimates below HAT have been removed. This can occur for studies that have not included non-cyclonic estimates in their methodologies.These values have been replaced by log-linear interpolating required water levels between HAT to the next available water level above HAT. An example of this process is provided in Figure 6-2.

The top panel provides non-normalised study data as detailed in Section 5.3.1. The red crosses in the middle panel show the *Tide plus Surge* estimates at the same location following normalisation to the QCC levels. At this location the normalisation process has resulted in the increase of *Tide plus Surge* levels by approximately 0.5 m at the 1000 y Return Period. Levels at other Return Periods have also increased by varying amounts. It is noted that the 20 and 25 y Return Period levels remain below HAT.

In the bottom panel of Figure 6-2 all *Tide plus Surge* levels (red crosses) below HAT have been log linear interpolated between HAT at the 1 year ARI and the next available ARI water level above HAT, in this instance the 50 y ARI.

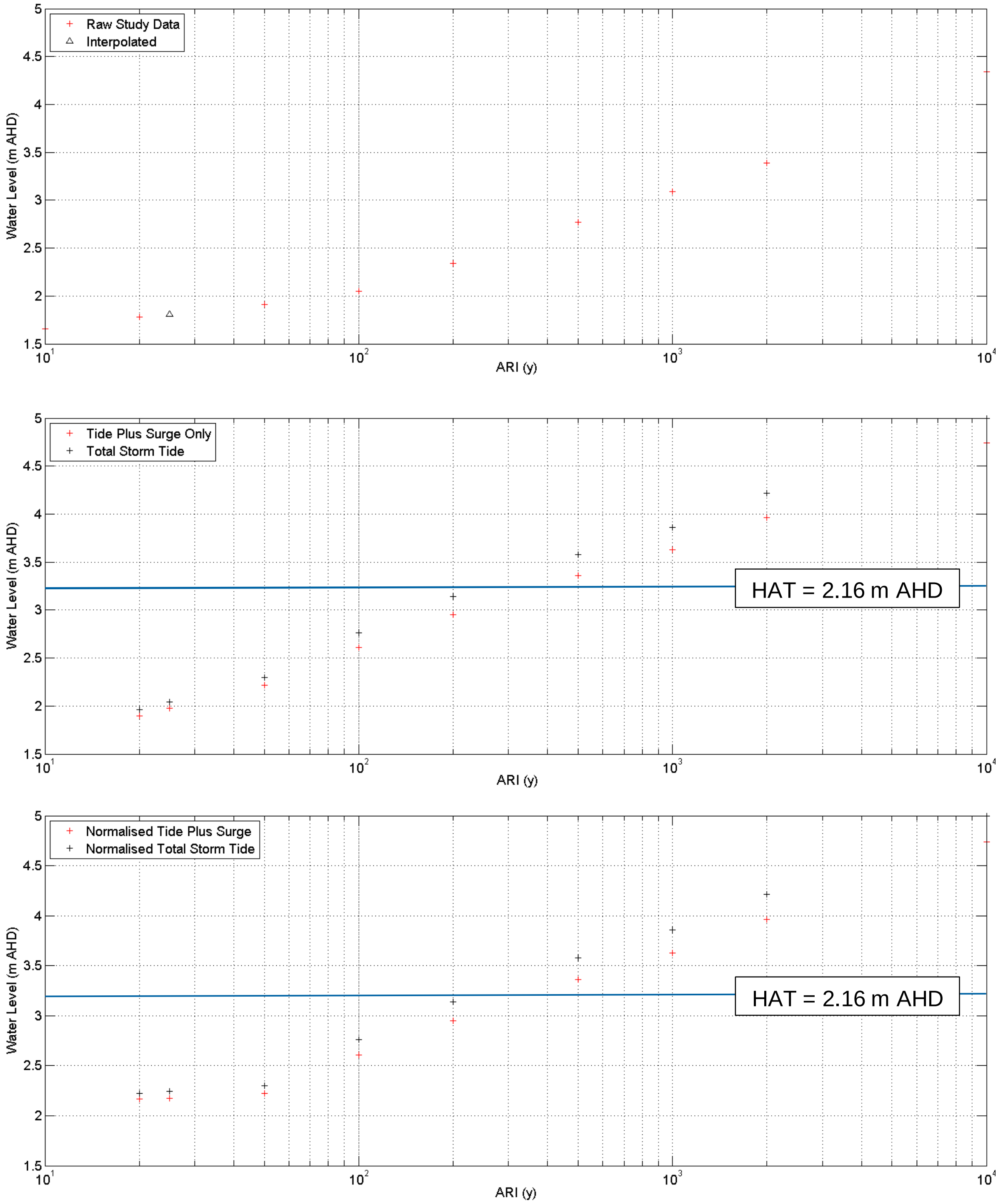

Figure 6-2 Example of normalisation process in ARI space

6.2.3 Wave Setup and *Total Storm Tide* Normalisation

Total Storm Tide estimates have been calculated by adding wave setup components (refer Section 5.3.1) from each study to the normalised *Tide plus Surge* level for each ARI of interest as derived using the methodology detailed in Section 6.1.1 . For locations where

- For the Sunshine Coast, wave setup estimates from the QCC Stage 2 study (Hardy et al. 2004a) have been applied to the Caloundra, Maroochy and Sunshine Coast studies in preference to the local studies. This preference is based on the more statistically rigorous and consistent QCC wave modelling and wave setup methods. It is noted that the wave setup values from the QCC study are also representative of observed wave setup values for the Gold Coast beaches (Hanslow and Nielsen, 1993);
- In regions where only the QCC Stage 3 study was available, only *Tide plus Surge* levels have been provided as the QCC Stage 3 study did not investigate wave setup.

An example of the added wave setup potential to provide *Total Storm Tide* levels is provided in the middle and bottom panels (refer black crosses) of Figure 6-2.

6.3 Geographical Merging of Normalised Studies

For a number of locations there exist multiple storm tide estimates for a given location, typically at the northern and southern boundaries of each study. Within these regions of LGA overlap, the normalised water level results were filtered based on the decision matrix provided in Table 4 below.

Table 4 Decision Matrix for Study Overlap Regions

Study 1	Study 2	Retained	Details
Gold Coast	Redland/ Logan	Redland/ Logan	Overlapping points at very northern boundary or Gold Coast Study. Redland Study more focused on Moreton Bay
Moreton Bay	Caloundra	Moreton Bay	Highest Review Score
Sunshine Coast	Maroochy	Maroochy	Highest Review Score
Sunshine Coast	Caloundra	Caloundra	Highest Review Score
Sunshine Coast	QCC Stage 2	Sunshine Coast	Although Sunshine Coast likely conservative has included non-cyclonic events.
Hervey Bay	QCC Stage 2	QCC Stage 2	Highest Review Score
Mackay	Sarina	Mackay	Highest Review Score
Mackay	Whitsunday	Mackay	Highest Review Score
Bowen	Whitsunday	Whitsunday	Highest Review Score
Cardwell	Innisfail	Cardwell	Overlapping points at southern boundary of the Innisfail study. Cardwell study more focused on Cardwell region
Cairns	Innisfail	Innisfail	Highest Review Score
QCC Study 3	All	All	Where no studies available QCC Stage 3 data retained otherwise Study X retained.

7. Results

This chapter discusses the results of the storm tide hazard interpolation and also the method and results used to develop the dune crest and beach slope dataset.

7.1 Results

This section provides the *Tide plus Surge* and *Total Storm Tide* level results following the process outlined in Chapter 6. These final study results are presented as a series of maps, tables and long section plots including:

- Appendix G Figures G1 and G3 provide the spatial distribution of the final *Tide plus Surge* datasets along the coast south of Port Douglas. Figures G2 and G4 provide the distribution of *Total Storm Tide* levels.
- Appendix H provides coastal long sections of the final *Tide plus Surge* only levels for the east coast south of Port Douglas.
- Appendix I provides coastal long sections of the *Total Storm Tide* levels for the east coast south of Port Douglas.
- Table 5 provides statistics for each study and ARI based on the difference between the resulting *Tide plus Surge* estimates and the raw study cyclonic *Tide plus Surge* estimates. Columns marked by NA (not applicable) indicate where a given ARI was not used from that study. Highlighted in blue, yellow and green are ARIs where the mean shift has exceeded 0.25 m:
  – Blue where levels have been reduced by more than 0.25 m,
  – Yellow where they have been raised by more than 0.25 m; and
  – Green indicating where levels have been raised by more than 0.25 m due to the statistical combination of cyclonic only and non-cyclonic only estimates as detailed in Section 5.2.

7.2 Discussion

Review of Table 5 indicates a number of interesting trends as follows:

- By considering non-cyclonic events, water levels below the 500 y ARI are increased for the Caloundra, Maroochy and Mackay;
- For studies south of Capricorn there are relatively small differences between the QCC and other studies. An exception to this trend is at Bundaberg where estimates for lower ARIs are on average increased by up to 0.37 m.
- For a number of the North QLD studies including Capricorn, Bowen, Hinchinbrook and Cardwell there is a tendency for the 500 and 1000 ARI to be 0.3 – 1.1 m higher than the QCC estimates.
- Within North QLD, at the 10,000 y ARI event, the QCC *Tide plus Surge* levels tend to be between 0.4 and 1.1 m lower than the study estimates.

The reasons for expecting significant differences in ARI estimates across the range of studies examined was discussed in Section 6.1.1. Accordingly the relative age of any particular study has no specific bearing on its suitability and some studies also may contain errors. The identified trend of differences away from the QCC study in northern regions may relate to increasing storm MPI tending to exaggerate the methodology differences.

Table 5 QCC Normalised Statistics vs the Original Study Results by ARI Event (Normalised – Original (m))

Study	20 y		50 y		100 y		500 y		1,000 y		10,000 y	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Gold Coast	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Logan/Redland	-0.06	0.09	-0.02	0.11	0.02	0.12	NA	NA	0.08	0.13	0.05	0.14
Moreton Bay	-0.06	0.09	-0.02	0.11	0.02	0.12	NA	NA	0.08	0.13	0.05	0.14
Caloundra	0.43	0.09	0.34	0.09	0.23	0.11	0.07	0.18	0.03	0.19	0.05	0.13
Maroochy	0.43	0.03	0.40	0.05	0.33	0.05	0.21	0.08	0.18	0.09	0.14	0.10
Sunshine Coast	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Sandy Strait	NA	NA	0.06	0.09	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Hervey Bay	NA	NA	NA	NA	-0.34	0.12	-0.09	0.15	0.03	0.17	0.41	0.25
Bundaberg	0.37	0.10	0.28	0.13	0.29	0.36	0.17	0.58	0.10	0.59	-0.17	0.68
Capricorn	NA	NA	-0.37	0.08	-0.61	0.04	-0.75	0.05	-0.74	0.06	0.06	0.04
Isaac (Sarina/Broadsound)	NA	NA	0.26	0.09	-0.03	0.16	-0.48	0.23	-0.50	0.24	-0.42	0.26
Mackay	NA	NA	0.50	0.12	0.39	0.16	-0.15	0.17	-0.41	0.15	-0.65	0.20
Whitsunday Islands	NA	NA	0.03	0.12	-0.10	0.12	-0.29	0.12	-0.29	0.14	-0.16	0.21
Bowen	NA	NA	-0.33	0.09	-0.49	0.10	-0.62	0.15	-0.64	0.17	-0.39	0.27
Townsville	NA	NA	0.10	0.05	0.09	0.04	-0.03	0.11	-0.22	0.19	-1.11	0.64
Hinchinbrook	NA	NA	0.01	0.07	-0.14	0.08	-0.32	0.07	-0.37	0.07	-0.48	0.15
Cardwell	NA	NA	NA	NA	-0.16	0.08	-0.69	0.06	-0.83	0.08	-1.04	0.10
Innisfail/Mission Beach	NA	NA	0.19	0.03	0.20	0.04	0.10	0.09	0.03	0.12	-0.44	0.46
Cairns	NA	NA	NA	NA	0.08	0.05	-0.28	0.14	-0.68	0.20	-0.37	0.64
Torres Strait	NA	NA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gulf of Carpentaria	NA	NA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
QCC Stage 2	NA	NA	NA	NA	0.00	0.02	0.00	0.00	0.00	0.00	NA	NA
QCC Stage 3	0.08	0.11	0.03	0.09	0.02	0.07	0.00	0.00	0.00	0.00	0.00	0.00

7.3 Historical Perspective

The list of historical storm tide events presented earlier in Section 1.6.4 has been considered here in compiling an indication of the likely probability of exceedance of some of the more reliably recorded storm tide events. Table 6 shows 13 events since 1918 for which the approximate ARI has been assessed from the combined study results. These are deliberately approximate to avoid focus on a specific ARI, which can give an unreasonable implication of precision. This is because firstly, many of the actual water levels are uncertain both in datum and in terms of the actual contributions from tide, surge, wave setup or runup and sometimes local flooding. This applies even for a recent event like TC *Yasi* at Cardwell, where even though there is good instrumentation in terms of a storm tide gauge, there remains the possibility that breaking wave setup contributed some component to the recorded (nominally) *Tide plus Surge* levels. Secondly, the risk curves are relatively flat in probability space and so small differences in reported water level can result in large shifts in the estimated ARI. Nevertheless the summary shows that from a State-wide perspective there is a wide range of experience over the past 100 years. This illustrates how the risk of events that individually seem unlikely at any specific location (which is what the point-based risk curves developed here address) can quickly accumulate over a much larger area. This is because, at a certain spatial scale, the probabilities of exceedance at individual points along the coastline become independent of each other and the risks of exceedance at that scale must then be summed.

Table 6 Approximate ARI assigned to a selection of historical storm tide events.

Date	Place	Event	Storm Tide Level m AHD	Average Recurrence Interval y
21-Jan-1918	Mackay	unnamed	5.5	~10,000
23-Feb-1948	Bentinck Is	unnamed	4.7?	~1,000
29-Jan-1967	Brisbane Bar	Dinah	1.6	~20
24-Dec-1971	Townsville	Althea	2.6	~200
19-Dec-1976	Albert River	Ted	5.2?	~500
04-Apr-1989	Molongle Creek	Aivu	3.1?	~700
06-Jan-1996	Gilbert River	Barry	6?	~10,000
10-Mar-2005	Night Island	Ingrid	1.80	~100
20-Mar-2006	Clump Point	Larry	2.6	~1,000
13-Jan-2009	Townsville	Charlotte	2.6	~200
21-Mar-2010	Laguna Marina	Ului	3.9	~500
03-Feb-2011	Clump Point Cardwell	Yasi	2.4 4.5	~1,000 ~3,000
28-Jan-2013	Brisbane	ex TC Oswald	1.8	~100

7.4 Limitations

7.4.1 HAT Thread

In locations where tidal planes are rapidly varying such as the Whitsundays it is possible that lower ARI estimates have been truncated by the HAT estimates provided by the DSITIA HAT thread. For these areas the assigned HAT value should be compared with available data to determine the reliability of the data point.

7.4.2 Dune Crest Assumption[8]

The *Total Storm Tide* levels provided in the Townsville, Innisfail and Whitsunday reports make allowance for wave setup limiting following dune crest overtopping. In these regions normalised *Tide plus Surge* levels will monotonically increase with increasing ARI however, due to the wave setup component being linked to actual dune crests, this may not be the case for *Total Storm Tide* estimates. If *Total Storm Tide* levels are important for mapping purposes it is recommended that further work be undertaken to limit wave setup estimates once dune overtopping has been realised.

7.4.3 Non-Cyclonic Estimates

As many studies north of the Sunshine Coast have not completed non –cyclonic estimates, care should be taken in interpreting risk between study areas for ARIs below 200 y. For example it is likely that studies with cyclonic only modelling will have underestimated storm tide levels below the 200 y ARI.

7.5 GIS Deliverables

Key study outputs include a consolidated set of GIS points indicating *Tide plus Surge* only and *Total Storm Tide* levels for the Queensland coast. These points, combined with Queensland Government provided topographic data have formed the basis for detailed inundation mapping providing estimated water levels, depths and extents. The following sections provide an overview of the GIS mapping methodology completed and the provided mapping deliverables.

7.5.1 Storm Tide Mapping

Storm tide mapping has been completed for the 20, 50, 100, 200[9], 500, 1000 and 10000 y ARIs plus the TMST event using a suite of GHD developed GIS tools that are run within the ESRI ArcGIS environment. Key steps in the surface development process include:

Tide plus Surge Only Mapping

- Storm tide point data is used to interpolate/extrapolate levels to the extent of a provided Digital Elevation Model (DEM).
- The user has the capability to add ‘barrier/break lines’ to provide further control over the interpolation. Barrier lines have been used in areas such as key coastal islands, coastal spits (such as within the Gold Coast Broadwater) and prominent headlands to reduce interpolation through these features.

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[8] Although included in this report for completeness, the extraction of dune crest and slope information was conducted on a separate contract with DSITIA which occurred after the development of Storm Tide Mapping. As such, the dune crest information was not available at the time of study normalisation and has not been used to limit total storm tide levels.

[9] The 200 y ARI was an additional mapping scope item and not been detailed in this report. The development of levels associated with the 200 y ARI is consistent with those outlined in Chapter 5-6. The 200 y ARI levels have been included in the provided GIS deliverables.

- The tool outputs water level and depth rasters at an agreed resolution (10 m) and also polygon extents for each ARI considered.
- It is noted that this method is essentially the so-called 'bathtub' mapping and has reduced accuracy in resolving hydraulic gradients as you move away from the coast and or available data points.

Total Storm Tide Mapping

- For regions likely to be affected by wave setup, the approximate position of the frontal dune has been digitised based on available aerial photography and where possible, this location has been verified based on provided topographic data.
- Total storm tide levels have been mapped within a region 200 m adjacent to the digitised coastline with *Total Storm Tide* levels mapped directly on the coastline linearly decreasing to *Tide plus Surge* only levels at the edge of the nominal wave runup zone.

Please note that for the TMST mapping, only the *Total Storm Tide* levels have been mapped and represent the upper limit of ocean surges for each of the regions considered.

7.5.2 Storm Tide Hazard Deliverables

Accompanying this report are a series of ArcGIS geodatabases that include the GIS points, barrier lines and water level, depth rasters and inundation extents as detailed in Table 7.

Table 7 GIS Deliverables

Folder/Geodatabase	Details
BarrierLines.gdb	Theoretical Maximum Storm Tide and Tide Plus Surge/Total Storm Tide points used for interpolation. Theoretical Maximum Storm Tide and Tide Plus Surge/Total Storm Tide barrier lines used for interpolation.
Central.gdb	Water level (m AHD), Depth (m) and Flood extent layers for the 20, 50, 100, 200, 500, 1000, 10000 y ARIs and TMST for the central grid region.
South.gdb	Water level (m AHD), Depth (m) and Flood extent layers for the 20, 50, 100, 200, 500, 1000, 10000 y ARIs and TMST for the southern grid region.
\North Note this folder contains 11 separate geodatabases for each community within the northen DEM region.	Water level (m AHD), Depth (m) and Flood extent layers for the 20, 50, 100, 200, 500, 1000, 10000 y ARIs and TMST for the northern grid region.

8. Conclusion

The Department of Science, Information Technology, Innovation and the Arts requires the provision of statistically consistent storm tide levels across the State. The information will inform risk assessments that include storm tide hazards to identify the relative likelihood of specific communities being subjected to these natural hazards.

This study has identified, based on a transparent methodology using data from 23 separate existing studies, a set of consistent 20, 50, 100, 200, 500, 1,000 and 10,000 y ARIs plus the estimated Theoretical Maximum levels. The intention of this dataset is to assist DSITIA with State-wide emergency response planning and disaster management.

Additionally, a detailed dune crest and beach slope assessment has been completed to support State-wide storm tide prediction modelling. Notably, this work was an additional item completed under the NDRP contract and is largely independent of the Storm Tide Hazard Interpolation Study. For completeness, this work has been included as Appendix J.

A geographical gap analysis has been completed and for the majority of the Queensland coast there are limited data gaps in regions of high population or emergency service assets. Notable exceptions include Brisbane, Gympie and Gladstone where is it is recommended that a contemporary storm tide study should be undertaken based on the recommendations outlined in Harper (2001) and GHD/SEA (2007).

Results have been presented in a series of formats including mapping, tables and coastal long sections. Key deliverables for the project include GIS shape file and raster datasets containing *Tide plus Surge* and *Total Storm Tide* estimates respectively.

The study has highlighted the variability in project methodologies and resulting water level estimates with respect to the accepted baseline Queensland Climate Change Stage 2 and 3 studies (QCC). Comparison of each study has revealed the following trends:

- For studies south of Capricorn there are relatively small differences between the QCC and other studies. An exception to this trend is at Bundaberg where estimates for lower ARIs are on average increased by up to 0.37 m;
- For a number of the North QLD studies including Capricorn, Bowen, Hinchinbrook and Cardwell there is a tendency for the 500 and 1000 ARI to be 0.3 – 1.1 m higher than the QCC estimates; and
- Within North QLD, at the 10,000 y ARI the QCC *Tide plus Surge* levels tend to be between 0.4 and 1.1 m lower than the study estimates

To reduce this variability and provide greater certainty for emergency response, long-term planning and coastal management, there is significant merit in undertaking an updated study[10] for the entire Queensland east coast that would build on the original landmark QCC study initiatives and address both cyclonic and non-cyclonic estimates. This would complement the increased standard achieved for the more recently completed studies for the Gulf of Carpentaria and Torres Strait.

[10] As detailed in Section 3.1, the levels from a recently completed nation-wide study by Haigh et al. (2012) was unavailable during the project and as such the reliability of the reported levels has not been assessed.

9. References

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Appendices

Appendix A – Return Period Concepts

A1 - General

This study has presented its analyses of risk in terms of the so-called Return Period (or Average Recurrence Interval ARI). The return period is the “average” number of years between successive events of the same or greater magnitude. For example, if the 100-year return period storm tide level is 3.0 m AHD then on average, a 3.0 m AHD level storm tide or greater will occur due to a single event once every 100 years, but sometimes it may occur more or less frequently than 100 years. It is important to note that in any “N”-year period, the “N”-year return period event has a 64% chance of being equalled or exceeded. This means that the example 3.0 m storm tide has a better-than-even chance of being exceeded by the end of any 100-year period. If the 100-year event were to occur, then there is still a finite possibility that it could occur again soon, even in the same year, or that the 1000 year event could occur, for example, next year. Clearly if such multiple events continue unchecked then the basis for the estimate of, say, the 100 year event might then need to be questioned, but statistically this type of behaviour can be expected.

A more consistent way of considering the above (NCCOE 2004) is to include the concepts of “design life” and “encounter probability” which, when linked with the return period, provide better insight into the problem and can better assist management risk decision making. These various elements are linked by the following formula (Borgman 1963):

$$T = -N / \ln[1 - p]$$

Where p = encounter probability 0 □ 1

N = the design life (years)

T = the return period (years)

This equation describes the complete continuum of risk when considering the prospect of at least one event of interest occurring. More complex equations describe other possibilities such as the risk of only two events in a given period or only one event occurring.

Figure S.1 illustrates the above equation graphically. It presents the variation in probability of at least one event occurring (the encounter probability) versus the period of time considered (the design life). The intersection of any of these chosen variables leads to a particular return period and a selection of common ARIs is indicated. For example, this shows that the 200-year return period has a 40% chance of being equalled or exceeded in any 100-year period.

The level of risk acceptable in any situation is necessarily a corporate or business decision. Figure A.1, is provided to assist in this decision making process by showing a selection of risk options. For example, accepting a 5% chance of occurrence in a design life of 50 years means that the 1000-year return period event should be considered. A similar level of risk is represented by a 1% chance in 10 years. By comparison, the 100 year return period is equivalent to about a 10% chance in 10 years. AS1170.2 (Standards Australia 2002), for example, dictates a 10% chance in 50 years criteria or the 500-year return period as the minimum risk level for wind speed loadings on engineered structures.

A2 - References

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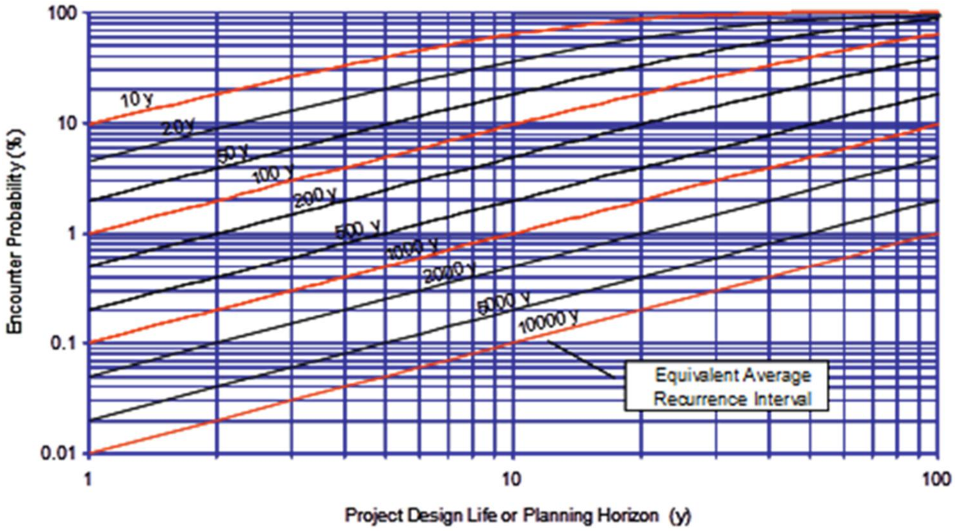


Figure A.1 Relationship between Return Period and Encounter probability

Appendix B – Study Review Results

ID	Category / Element	Score			Gold Coast	ogan/Redland/Moreton B	Brisbane	Calounda/Maroochy	Sunshine Coast	Sandy Strait
		✗	✓	✓✓	GHD	Cardno	NA	Marooհcy	Aurecon	GHD
		0	1	2	2012	2009	NA	2003-2005	2012	2011
1	**Climatological Analysis**									
1.01	Are the relevant storm surge producing events identified?	No	Yes	Comprehensive	1	1	NA	1	1	0.5
1.02	Are all datasets clearly defined and referenced?	No	Yes	Fully disclosed	1.5	1.5	NA	1	0.5	1
1.03	Has Bureau of Meteorology advice been obtained?	Not stated	Yes	Done in conjunction	1	1	NA	1	0	0.5
1.04	Have temporal and spatial distributions of storm populations been determined?	No	Basic	Comprehensive	1.5	0.5	NA	1	0	0
1.05	Have scale and speed distributions of storm populations been determined?	No	Basic	Comprehensive	1.5	0.5	NA	0.5	0	0.5
1.06	Has the intensity of storm populations been determined?	No	Basic	Comprehensive	2	2	NA	1	0	0.5
1.07	Have synoptic scale interactions been considered?	No	Basic	Comprehensive	0	0	NA	0	0	0
1.08	Is parameterisation of the storm set explained and justified?	No	Basic	Comprehensive	2	2	NA	0.5	0	0.5
1.09	Are inter-annual or inter-decadal variabilities discussed or considered?	No	Yes	Comprehensive	1	0	NA	0	0	0
1.1	Is potential enhanced Greenhouse climate change considered?	No	MSL, track, intensity only	MSL, track, intensity, freq	2	1	NA	0.5	1	1
2	**Numerical Modelling - Atmospheric**									
2.01	Are the atmospheric models adequately disclosed and described?	No	Basic	Comprehensive	2	0.5	NA	0	0	0
2.02	Are critical coefficients and assumptions relevant to this study disclosed?	No	Yes	Comprehensive	1.5	0.5	NA	0	0	0
2.03	Are example modelled storm systems provided and explained?	No	Basic	Comprehensive	2	1.5	NA	0	0	0
2.04	Are the models shown to be calibrated and/or verified in similar contexts?	No	Yes	Insitu	1	0.5	NA	0	0	0
2.05	Does the model consider overland decay or land interactions where relevant?	No	Basic	Comprehensive	0	0	NA	0	0	0
3	**Numerical Modelling - Oceanic / Hydrodynamic**									
3.01	Has suitably accurate bathymetric data been obtained?	No	Yes	Collected or enhanced	1	1	NA	1	0	1
3.02	Has suitably accurate land elevation data been obtained?	No	Yes	Collected or enhanced	1	1	NA	1	0	1
3.03	Do model extents and resolutions satisfy QCC recommendations?	No	Yes	Exceed	2	2	NA	1	0	2
3.04	Are the hydrodynamic models adequately disclosed and described?	No	Basic	Comprehensive	2	2	NA	1	0	1
3.05	Are critical coefficients and assumptions relevant to the study disclosed?	No	Yes	Comprehensive	1	1	NA	1	0	1
3.06	Are example model outputs provided and explained?	No	Basic	Comprehensive	2	1.5	NA	1	0	1
3.07	Are the models shown to be calibrated and/or verified in similar contexts?	No	Yes	Insitu	0.5	1	NA	1.5	0	1
3.08	Is surge-tide interaction considered?	No	Yes	Modelled	1	1	NA	0	0	2
3.09	Is storm tide coincident with surface waves modelled?	No	Yes	Comprehensive	0	1	NA	0	0	0
3.1	Is surge-wave interaction considered?	No	Yes	Comprehensive	1	2	NA	0	0	0
3.11	Is potential enhanced Greenhouse climate change considered?	No	MSL or CycGen only	Interactions	2	1	NA	1	1	2
3.12	Is freshwater river inflow considered?	No	N/A	Yes	0	0	NA	1.5	0	0
3.13	Is morphological modification considered?	No	N/A	Yes	0	0	NA	0	0	0
4	**Statistical Modelling**									
4.01	What is the basis of the statistical method?	Bayesian	MCM/JPM	EST or similar	1	1	NA	1	1	0
4.02	Are statistics derived from parameterised or full model representations?	Interpolated	Parametric	Full models	1	1	NA	0	0	0
4.03	Does the simulation period adequately cover the required ARI estimates?	No	Extrapolation	Yes	2	2	NA	1	2	1
4.04	How are the various storm population risks considered?	Separate	Envelope	Comprehensive	2	1	NA	0	0	0
4.05	Is coupled tide, surge and wave modelling represented?	Uncoupled	Surge + tide	Surge + tide + waves	1	1.5	NA	0.5	0	1
4.06	Is there sensitivity testing of model assumptions?	No	Yes	Comprehensive	1	1	NA	0	0	0
5	**ARIs and Wave Setup/Runup**									
5.01	Does the study provide storm tide estimates on an ARI basis?	No	Yes	Additional	1	1	NA	1	1	1
5.02	Is wave setup or runup included in the estimates?	No	Setup	Setup and runup	1	2		1	1	2
	Total Elements Scored	**Max Score=**		**Total Score=**	**43.5**	**37.5**	**0**	**21**	**8.5**	**21.5**

NDRP Storm Tide Hazard Interpolation Study

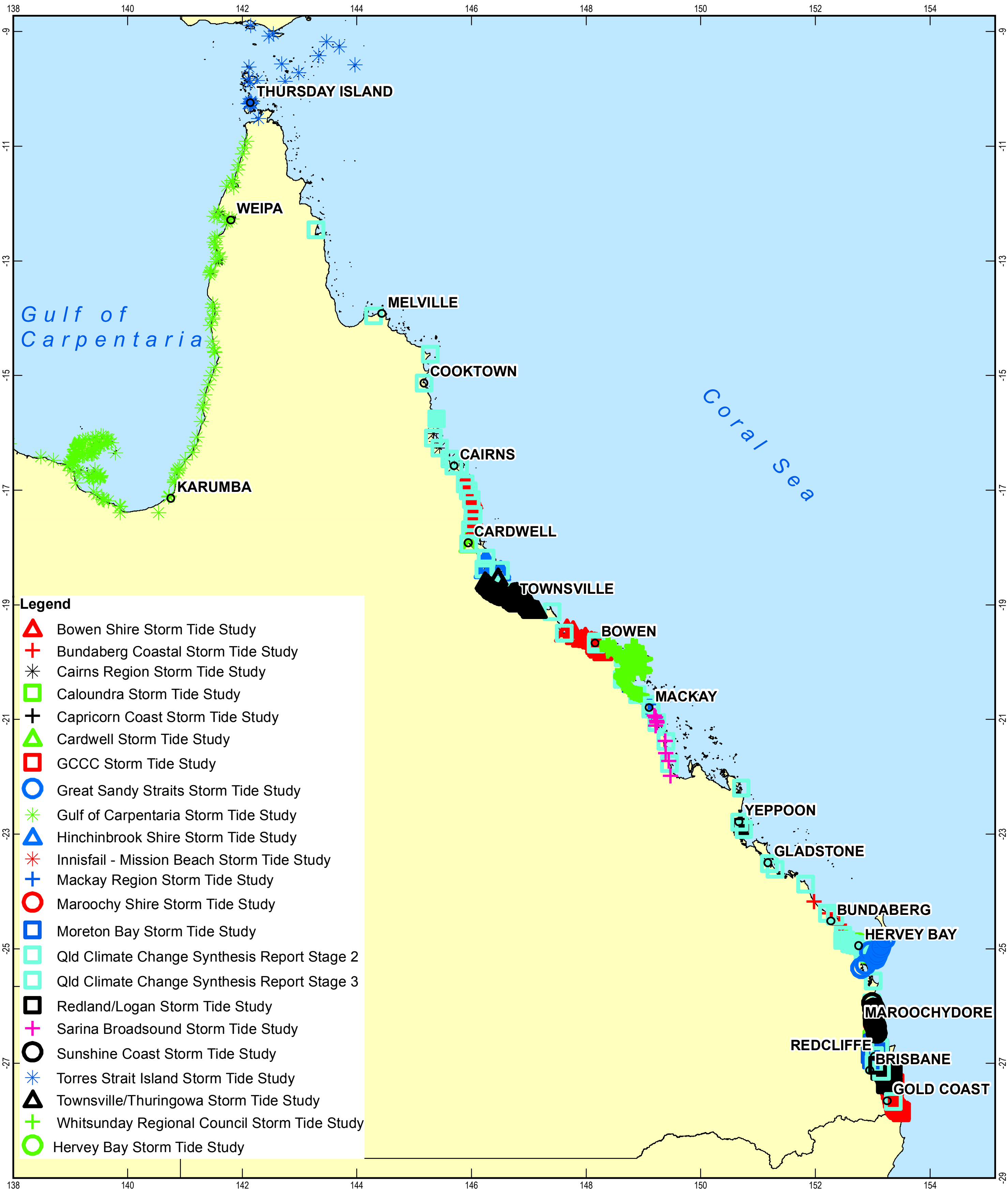
Appendix B - Study Review

ID	Category / Element	Score ✗ 0	Score ✓ 1	Score ✓✓ 2	Hervey Bay L&T 2002	Bundaberg WBM/BMT 2012	Gladstone NA NA	Rockhampton CW and L&T 2003	Sarina/Broadsound WS Group, CW & L&T 2003	Mackay WBM/BMT 2012
1	**Climatological Analysis**									
1.01	Are the relevant storm surge producing events identified?	No	Yes	Comprehensive	1	2	NA	1	1	2
1.02	Are all datasets clearly defined and referenced?	No	Yes	Fully disclosed	1	1.5	NA	1	1	1.5
1.03	Has Bureau of Meteorology advice been obtained?	Not stated	Yes	Done in conjunction	1	1	NA	1	1	1
1.04	Have temporal and spatial distributions of storm populations been determined?	No	Basic	Comprehensive	1	1.5	NA	1	1	1.5
1.05	Have scale and speed distributions of storm populations been determined?	No	Basic	Comprehensive	0.5	1.5	NA	0.5	0.5	1.5
1.06	Has the intensity of storm populations been determined?	No	Basic	Comprehensive	1	2	NA	1	1	2
1.07	Have synoptic scale interactions been considered?	No	Basic	Comprehensive	0	0	NA	0	0	0
1.08	Is parameterisation of the storm set explained and justified?	No	Basic	Comprehensive	1	1	NA	1	1	1
1.09	Are inter-annual or inter-decadal variabilities discussed or considered?	No	Yes	Comprehensive	0	0	NA	0	0	0
1.1	Is potential enhanced Greenhouse climate change considered?	No	MSL, track, intensity only	MSL, track, intensity, freq	0.5	1	NA	0.5	0.5	1
2	**Numerical Modelling - Atmospheric**									
2.01	Are the atmospheric models adequately disclosed and described?	No	Basic	Comprehensive	0	2	NA	0	0	2
2.02	Are critical coefficients and assumptions relevant to this study disclosed?	No	Yes	Comprehensive	0	1.5	NA	0	0	1.5
2.03	Are example modelled storm systems provided and explained?	No	Basic	Comprehensive	0	2	NA	0	0	2
2.04	Are the models shown to be calibrated and/or verified in similar contexts?	No	Yes	Insitu	0	1	NA	0	0	1
2.05	Does the model consider overland decay or land interactions where relevant?	No	Basic	Comprehensive	0	0	NA	0	0	0
3	**Numerical Modelling - Oceanic / Hydrodynamic**									
3.01	Has suitably accurate bathymetric data been obtained?	No	Yes	Collected or enhanced	1	1	NA	1	1	1
3.02	Has suitably accurate land elevation data been obtained?	No	Yes	Collected or enhanced	1	1	NA	1	1	1
3.03	Do model extents and resolutions satisfy QCC recommendations?	No	Yes	Exceed	2	2	NA	2	2	2
3.04	Are the hydrodynamic models adequately disclosed and described?	No	Basic	Comprehensive	1	2	NA	1	1	2
3.05	Are critical coefficients and assumptions relevant to the study disclosed?	No	Yes	Comprehensive	1	1.5	NA	1	1	1.5
3.06	Are example model outputs provided and explained?	No	Basic	Comprehensive	1	1	NA	1	1	1
3.07	Are the models shown to be calibrated and/or verified in similar contexts?	No	Yes	Insitu	1.5	1	NA	1.5	1.5	1
3.08	Is surge-tide interaction considered?	No	Yes	Modelled	1	0	NA	1	1	0
3.09	Is storm tide coincident with surface waves modelled?	No	Yes	Comprehensive	0	0	NA	0	0	0
3.1	Is surge-wave interaction considered?	No	Yes	Comprehensive	0	0	NA	0	0	0
3.11	Is potential enhanced Greenhouse climate change considered?	No	MSL or CycGen only	Interactions	1	2	NA	1	1	2
3.12	Is freshwater river inflow considered?	No	N/A	Yes	0	2	NA	0	0	2
3.13	Is morphological modification considered?	No	N/A	Yes	0	0	NA	0	0	0
4	**Statistical Modelling**									
4.01	What is the basis of the statistical method?	Bayesian	MCM/JPM	EST or similar	1	1	NA	1	1	1
4.02	Are statistics derived from parameterised or full model representations?	Interpolated	Parametric	Full models	0.5	1	NA	0.5	0.5	1
4.03	Does the simulation period adequately cover the required ARI estimates?	No	Extrapolation	Yes	1	2	NA	1	1	2
4.04	How are the various storm population risks considered?	Separate	Envelope	Comprehensive	0	0	NA	0	0	0
4.05	Is coupled tide, surge and wave modelling represented?	Uncoupled	Surge + tide	Surge + tide + waves	0.5	0	NA	0.5	0.5	0
4.06	Is there sensitivity testing of model assumptions?	No	Yes	Comprehensive	1	0	NA	1	1	0.5
5	**ARIs and Wave Setup/Runup**									
5.01	Does the study provide storm tide estimates on an ARI basis?	No	Yes	Additional	1	1	NA	1	1	1
5.02	Is wave setup or runup included in the estimates?	No	Setup	Setup and runup	1	2		2	2	2
	Total Elements Scored	**Max Score=**		**Total Score=**	**23.5**	**38.5**	**0**	**24.5**	**24.5**	**39**

ID	Category / Element	Score			Whitsunday Islands	Bowen	Burkekin	Townsville/Thuringowa	Hinchinbrook	Cardwell
		✗	✓	✓✓	GHD/SEA	CW and L&T	Maunsell/DHI	GHD/SEA	Maunsell/L&T	WBM
		0	1	2	2003	2004	2003	2007	Jul-03	2008
1	**Climatological Analysis**									
1.01	Are the relevant storm surge producing events identified?	No	Yes	Comprehensive	1	1	NA	2	1	2
1.02	Are all datasets clearly defined and referenced?	No	Yes	Fully disclosed	1	1	NA	1	0.5	1.5
1.03	Has Bureau of Meteorology advice been obtained?	Not stated	Yes	Done in conjunction	1	1	NA	1	1	1
1.04	Have temporal and spatial distributions of storm populations been determined?	No	Basic	Comprehensive	1.5	1	NA	2	1	1.5
1.05	Have scale and speed distributions of storm populations been determined?	No	Basic	Comprehensive	1.5	0.5	NA	1.5	0.5	0.5
1.06	Has the intensity of storm populations been determined?	No	Basic	Comprehensive	2	1	NA	2	1	2
1.07	Have synoptic scale interactions been considered?	No	Basic	Comprehensive	0	0	NA	0	0.5	0
1.08	Is parameterisation of the storm set explained and justified?	No	Basic	Comprehensive	2	1	NA	2	0.5	1
1.09	Are inter-annual or inter-decadal variabilities discussed or considered?	No	Yes	Comprehensive	1	0	NA	1	0	0
1.1	Is potential enhanced Greenhouse climate change considered?	No	MSL, track, intensity only	MSL, track, intensity, freq	2	0.5	NA	2	1.5	1
2	**Numerical Modelling - Atmospheric**									
2.01	Are the atmospheric models adequately disclosed and described?	No	Basic	Comprehensive	2	0	NA	2	0	2
2.02	Are critical coefficients and assumptions relevant to this study disclosed?	No	Yes	Comprehensive	2	0	NA	2	0	1.5
2.03	Are example modelled storm systems provided and explained?	No	Basic	Comprehensive	1	0	NA	2	0	2
2.04	Are the models shown to be calibrated and/or verified in similar contexts?	No	Yes	Insitu	0.5	0	NA	1	0	1
2.05	Does the model consider overland decay or land interactions where relevant?	No	Basic	Comprehensive	0	0	NA	0	0	0
3	**Numerical Modelling - Oceanic / Hydrodynamic**									
3.01	Has suitably accurate bathymetric data been obtained?	No	Yes	Collected or enhanced	1	1	NA	1	1	1
3.02	Has suitably accurate land elevation data been obtained?	No	Yes	Collected or enhanced	1	1	NA	1	1	1
3.03	Do model extents and resolutions satisfy QCC recommendations?	No	Yes	Exceed	1	2	NA	2	2	2
3.04	Are the hydrodynamic models adequately disclosed and described?	No	Basic	Comprehensive	2	1	NA	2	1	2
3.05	Are critical coefficients and assumptions relevant to the study disclosed?	No	Yes	Comprehensive	1	1	NA	1.5	0	1.5
3.06	Are example model outputs provided and explained?	No	Basic	Comprehensive	1	1	NA	1	1	2
3.07	Are the models shown to be calibrated and/or verified in similar contexts?	No	Yes	Insitu	1	1.5	NA	1	0.5	1
3.08	Is surge-tide interaction considered?	No	Yes	Modelled	1	1	NA	1	1	0
3.09	Is storm tide coincident with surface waves modelled?	No	Yes	Comprehensive	0	0	NA	0	0	0
3.1	Is surge-wave interaction considered?	No	Yes	Comprehensive	1	0	NA	1	0	0
3.11	Is potential enhanced Greenhouse climate change considered?	No	MSL or CycGen only	Interactions	2	1	NA	2	1.5	2
3.12	Is freshwater river inflow considered?	No	N/A	Yes	0	2	NA	0	1.5	2
3.13	Is morphological modification considered?	No	N/A	Yes	0	0	NA	0	0	0
4	**Statistical Modelling**									
4.01	What is the basis of the statistical method?	Bayesian	MCM/JPM	EST or similar	1	1	NA	1	1	1
4.02	Are statistics derived from parameterised or full model representations?	Interpolated	Parametric	Full models	1	0.5	NA	1	0.5	1
4.03	Does the simulation period adequately cover the required ARI estimates?	No	Extrapolation	Yes	2	1	NA	2	2	2
4.04	How are the various storm population risks considered?	Separate	Envelope	Comprehensive	0	0	NA	0	0	0
4.05	Is coupled tide, surge and wave modelling represented?	Uncoupled	Surge + tide	Surge + tide + waves	0	0.5	NA	0	0.5	0
4.06	Is there sensitivity testing of model assumptions?	No	Yes	Comprehensive	1	1	NA	1.5	1	1
5	**ARIs and Wave Setup/Runup**									
5.01	Does the study provide storm tide estimates on an ARI basis?	No	Yes	Additional	1	1	NA	2	1	1
5.02	Is wave setup or runup included in the estimates?	No	Setup	Setup and runup	1	2		1	2	2
	Total Elements Scored	Max Score=		Total Score=	37.5	26.5	0	43.5	26	39.5

ID	Category / Element	Score × 0	 ✓ 1	 ✓✓ 2	Innisfail/Mission Beach GHD/SEA 2009	Cairns WBM/BMT 2009	Torres Strait SEA/AMC 2011	Gulf of Carpentaria GHD/AMC 2012	QCC Stage 2 2004	QCC Stage 3 2004
1	**Climatological Analysis**									
1.01	Are the relevant storm surge producing events identified?	No	Yes	Comprehensive	2	2	2	2	1	1
1.02	Are all datasets clearly defined and referenced?	No	Yes	Fully disclosed	1	1.5	1	1.5	1.5	1.5
1.03	Has Bureau of Meteorology advice been obtained?	Not stated	Yes	Done in conjunction	1	1	1.5	1	2	2
1.04	Have temporal and spatial distributions of storm populations been determined?	No	Basic	Comprehensive	2	1.5	2	2	2	2
1.05	Have scale and speed distributions of storm populations been determined?	No	Basic	Comprehensive	2	1.5	2	2	2	2
1.06	Has the intensity of storm populations been determined?	No	Basic	Comprehensive	2	2	2	2	2	2
1.07	Have synoptic scale interactions been considered?	No	Basic	Comprehensive	0	0	1	1	0	0
1.08	Is parameterisation of the storm set explained and justified?	No	Basic	Comprehensive	2	1	2	2	2	2
1.09	Are inter-annual or inter-decadal variabilities discussed or considered?	No	Yes	Comprehensive	1	0	1	1	1	1
1.1	Is potential enhanced Greenhouse climate change considered?	No	MSL, track, intensity only	MSL, track, intensity, freq	2	1	2	2	2	2
2	**Numerical Modelling - Atmospheric**									
2.01	Are the atmospheric models adequately disclosed and described?	No	Basic	Comprehensive	2	2	2	2	2	2
2.02	Are critical coefficients and assumptions relevant to this study disclosed?	No	Yes	Comprehensive	2	1.5	2	2	2	2
2.03	Are example modelled storm systems provided and explained?	No	Basic	Comprehensive	2	2	2	2	2	2
2.04	Are the models shown to be calibrated and/or verified in similar contexts?	No	Yes	Insitu	1	1	2	2	2	2
2.05	Does the model consider overland decay or land interactions where relevant?	No	Basic	Comprehensive	0	0	1	1	0	0
3	**Numerical Modelling - Oceanic / Hydrodynamic**									
3.01	Has suitably accurate bathymetric data been obtained?	No	Yes	Collected or enhanced	1	1	2	1	1.5	1.5
3.02	Has suitably accurate land elevation data been obtained?	No	Yes	Collected or enhanced	1	1	1	1.5	0	0
3.03	Do model extents and resolutions satisfy QCC recommendations?	No	Yes	Exceed	2	2	1	1	1	1
3.04	Are the hydrodynamic models adequately disclosed and described?	No	Basic	Comprehensive	2	2	2	2	2	2
3.05	Are critical coefficients and assumptions relevant to the study disclosed?	No	Yes	Comprehensive	1.5	1.5	2	2	2	2
3.06	Are example model outputs provided and explained?	No	Basic	Comprehensive	1	2	2	2	2	2
3.07	Are the models shown to be calibrated and/or verified in similar contexts?	No	Yes	Insitu	1	1	1	1.5	2	2
3.08	Is surge-tide interaction considered?	No	Yes	Modelled	1	0	2	2	0	0
3.09	Is storm tide coincident with surface waves modelled?	No	Yes	Comprehensive	0	0	0	0	0	0
3.1	Is surge-wave interaction considered?	No	Yes	Comprehensive	1	0	1	1	1	0
3.11	Is potential enhanced Greenhouse climate change considered?	No	MSL or CycGen only	Interactions	2	2	2	2	2	2
3.12	Is freshwater river inflow considered?	No	N/A	Yes	0	0	0	0	0	0
3.13	Is morphological modification considered?	No	N/A	Yes	0	0	0	0	0	0
4	**Statistical Modelling**									
4.01	What is the basis of the statistical method?	Bayesian	MCM/JPM	EST or similar	1	1	2	2	2	2
4.02	Are statistics derived from parameterised or full model representations?	Interpolated	Parametric	Full models	1	1	2	2	2	2
4.03	Does the simulation period adequately cover the required ARI estimates?	No	Extrapolation	Yes	2	2	2	2	2	2
4.04	How are the various storm population risks considered?	Separate	Envelope	Comprehensive	0	0	2	2	2	2
4.05	Is coupled tide, surge and wave modelling represented?	Uncoupled	Surge + tide	Surge + tide + waves	0	0	0	1.5	1.5	1
4.06	Is there sensitivity testing of model assumptions?	No	Yes	Comprehensive	1.5	1	1	1	1.5	1.5
5	**ARIs and Wave Setup/Runup**									
5.01	Does the study provide storm tide estimates on an ARI basis?	No	Yes	Additional	2	1	1	1	1	1
5.02	Is wave setup or runup included in the estimates?	No	Setup	Setup and runup	1	2	2	2	1.5	0
	Total Elements Scored	**Max Score=**		**Total Score=**	**44**	**38.5**	**53.5**	**55**	**50.5**	**47.5**

Appendix C – Existing Data Extent



Note: This figure shows all study data points (Total Storm Tide and Tide Plus Surge).

Paper Size A4

0 50 100 200 300 400

Kilometers

Horizontal Datum: GDA 1994

Grid: GCS GDA 1994

N

Department of Community Safety

NDRP Storm Tide Hazard Interpolation Study

Existing Study Data

Queensland Wide

Job Number 41-25509

Revision A

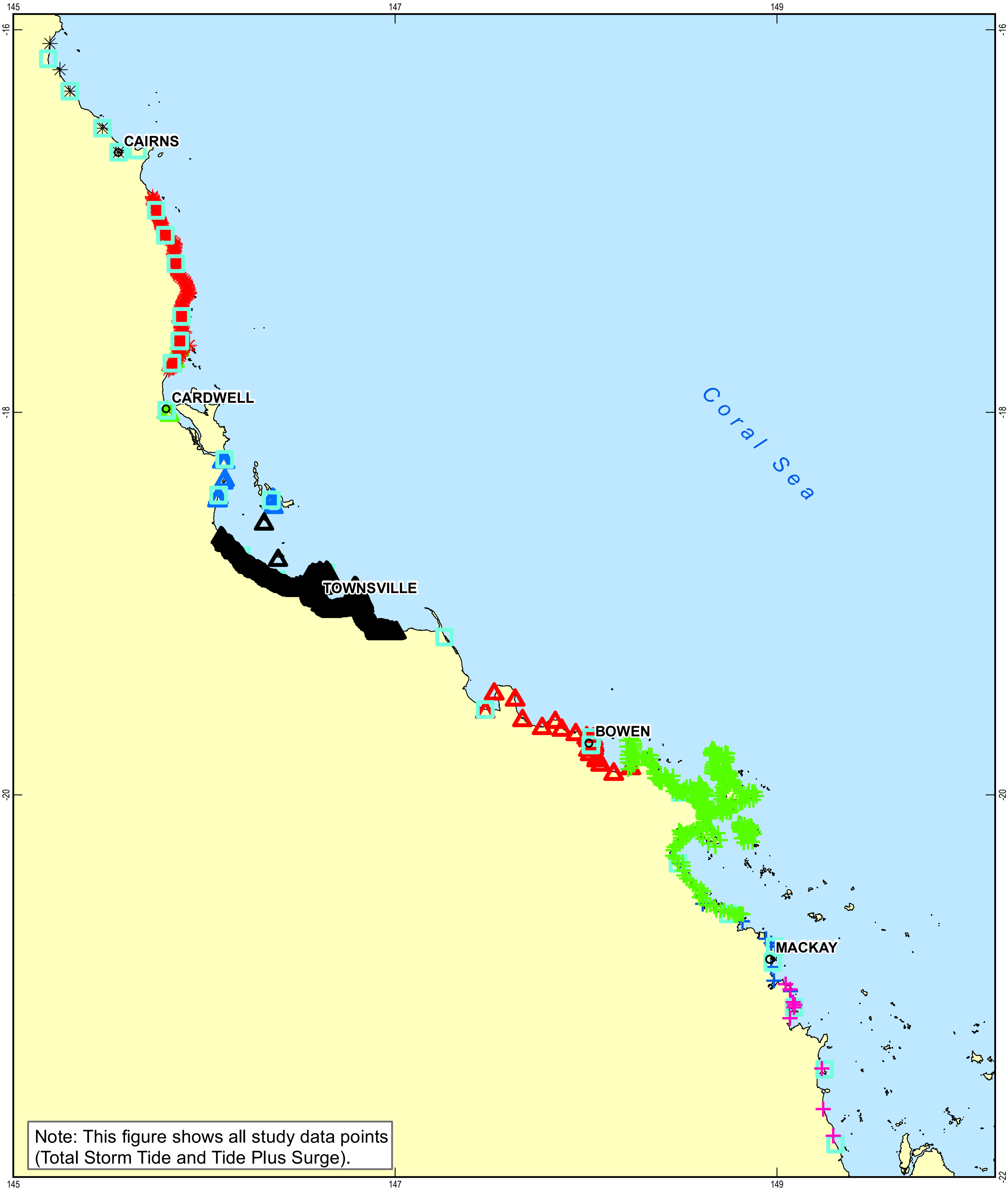
Date 10 May 2013

Figure C1

145 Ann Street Brisbane QLD 4000 Australia T 61 7 3316 3000 F 61 7 3316 3333 E bnemail@ghd.com W www.ghd.com

G:\41\25509\GIS\Maps\Deliverables\4125509_001_RevA.mxd

Data source: Geoscience Australia, Created by:IBotev



Legend

- Bowen Shire Storm Tide Study
- Cairns Region Storm Tide Study
- Cardwell Storm Tide Study
- Hinchinbrook Shire Storm Tide Study
- Innisfail - Mission Beach Storm Tide Study
- Mackay Region Storm Tide Study
- Qld Climate Change Synthesis Report Stage 3
- Sarina Broadsound Storm Tide Study
- Townsville/Thuringowa Storm Tide Study
- Whitsunday Regional Council Storm Tide Study

Paper Size A4

0 12.5 25 50 75 100

Kilometers

Horizontal Datum: GDA 1994
Grid: GCS GDA 1994

N

Department of Community Safety
NDRP Storm Tide Hazard Interpolation Study

Job Number	41-25509
Revision	A
Date	10 May 2013

Existing Study Data
Port Douglas to St. Lawrence

Figure C2

145 Ann Street Brisbane QLD 4000 Australia T 61 7 3316 3000 F 61 7 3316 3333 E bnemail@ghd.com W www.ghd.com

G:\41\25509\GIS\Maps\Deliverables\4125509_002_RevA.mxd

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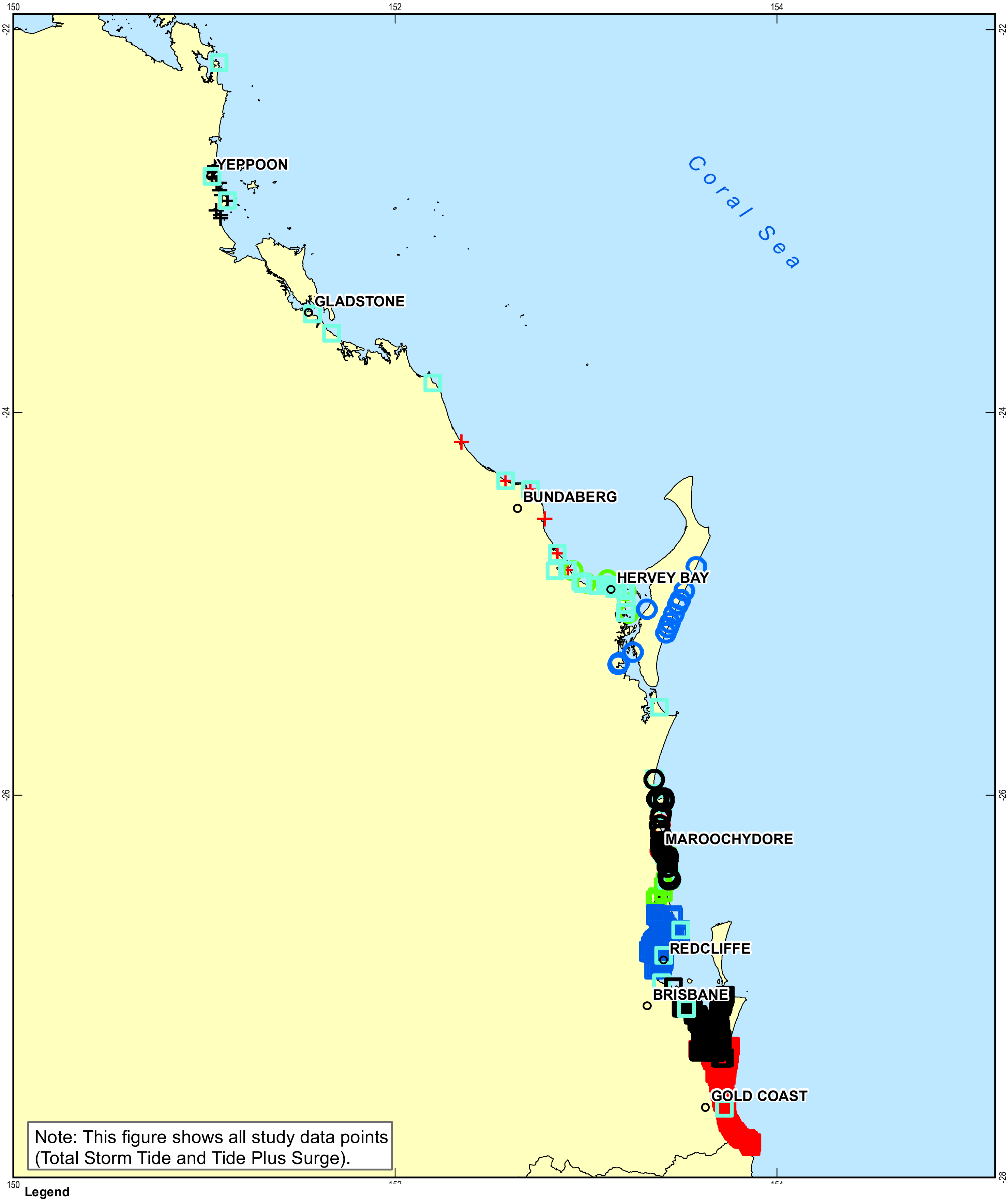


Legend

- Bundaberg Coastal Storm Tide Study
- Caloundra Storm Tide Study
- Capricorn Coast Storm Tide Study
- GCCC Storm Tide Study
- Great Sandy Strait Storm Tide Study
- Maroochy Shire Storm Tide Study
- Moreton Bay Storm Tide Study
- Qld Climate Change Synthesis Report Stage 2
- Qld Climate Change Synthesis Report Stage 3
- Redland/Logan Storm Tide Study
- Sunshine Coast Storm Tide Study
- Hervey Bay Storm Tide Study

Paper Size A4
0 12.5 25 50 75 100
Kilometers
Horizontal Datum: GDA 1994
Grid: GCS GDA 1994

N

Department of Community Safety
NDRP Storm Tide Hazard Interpolation Study

Job Number 41-25509
Revision A
Date 10 May 2013

Existing Study Data
St Lawrence to Point Danger

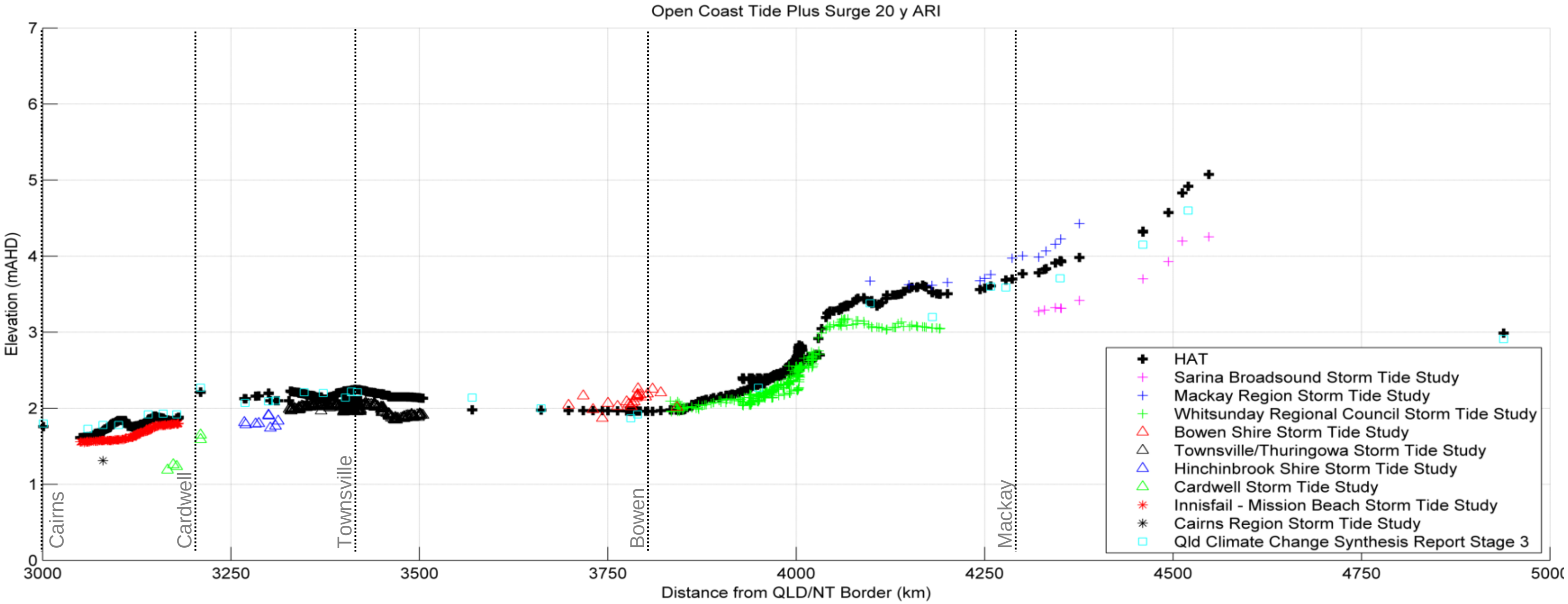
Figure C3

145 Ann Street Brisbane QLD 4000 Australia T 61 7 3316 3000 F 61 7 3316 3333 E bnemail@ghd.com W www.ghd.com

G:\41\25509\GIS\Maps\Deliverables\4125509_003_RevA.mxd

Data source: Geoscience Australia, Created by:IBotev

Appendix D – Non-Normalised *Tide plus Surge* Coastal Long Sections



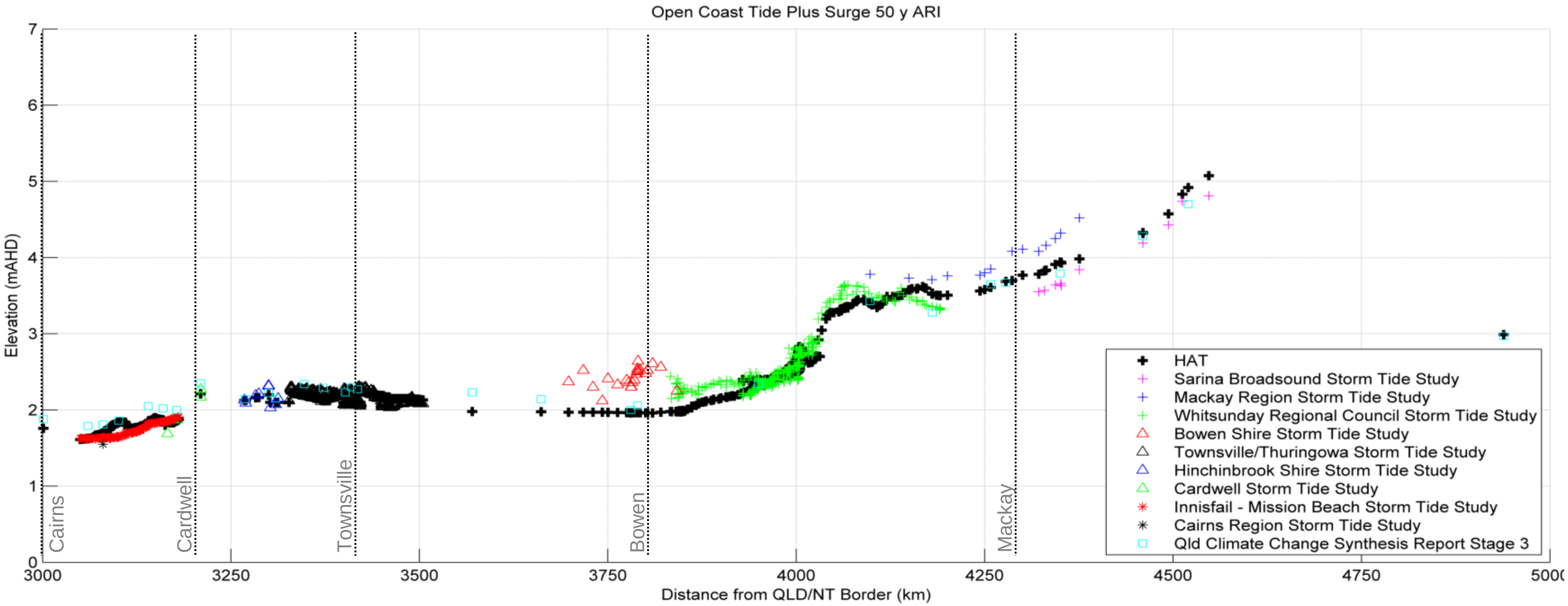


Figure – D1. 20 y (top) and 50 y (bottom) ARI Non-Normalised Tide plus Surge Estimates (Cairns to St. Lawrence).

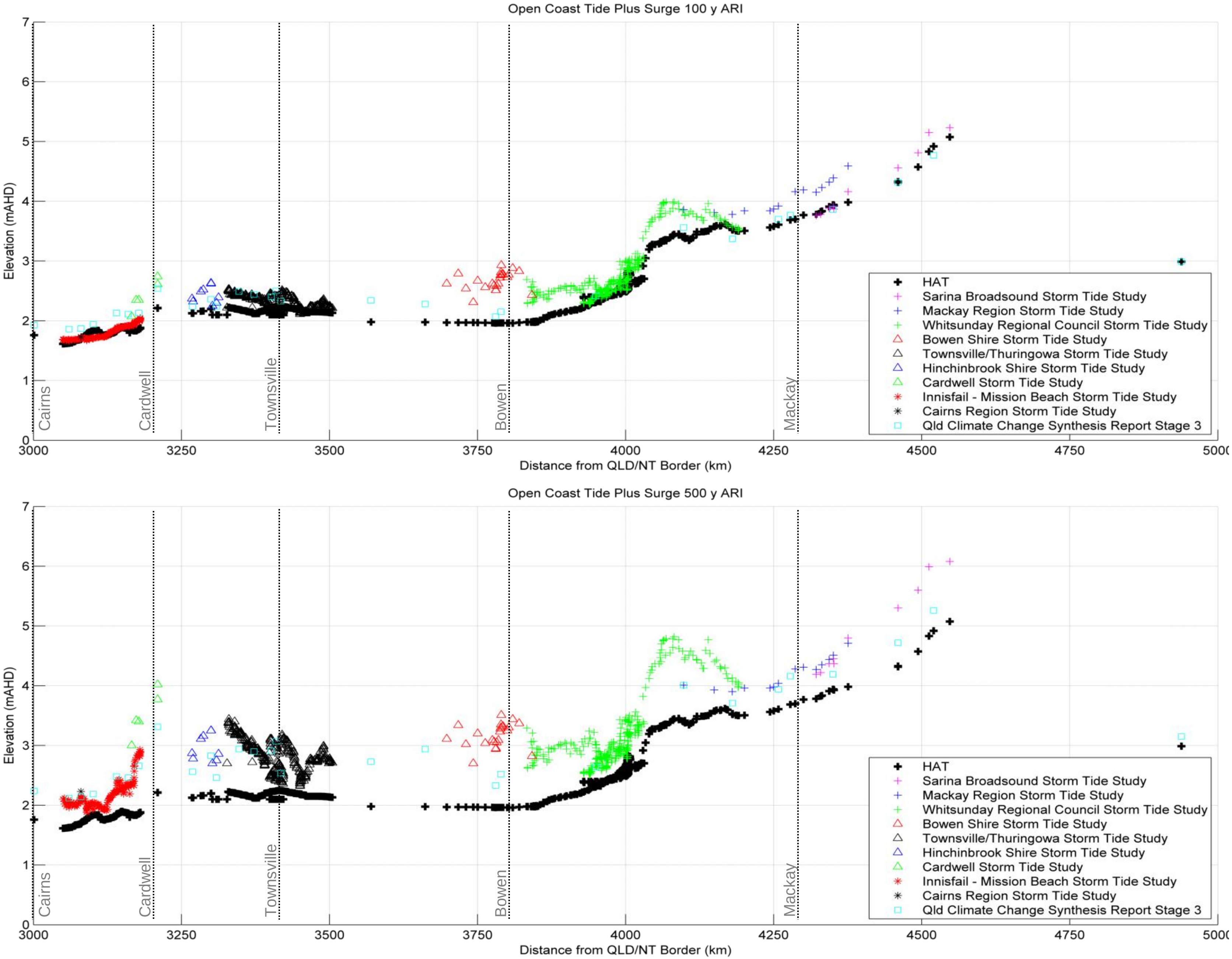


Figure – D2. 100 y (top) and 500 y (bottom) ARI Non-Normalised Tide plus Surge Estimates (Cairns to St. Lawrence).

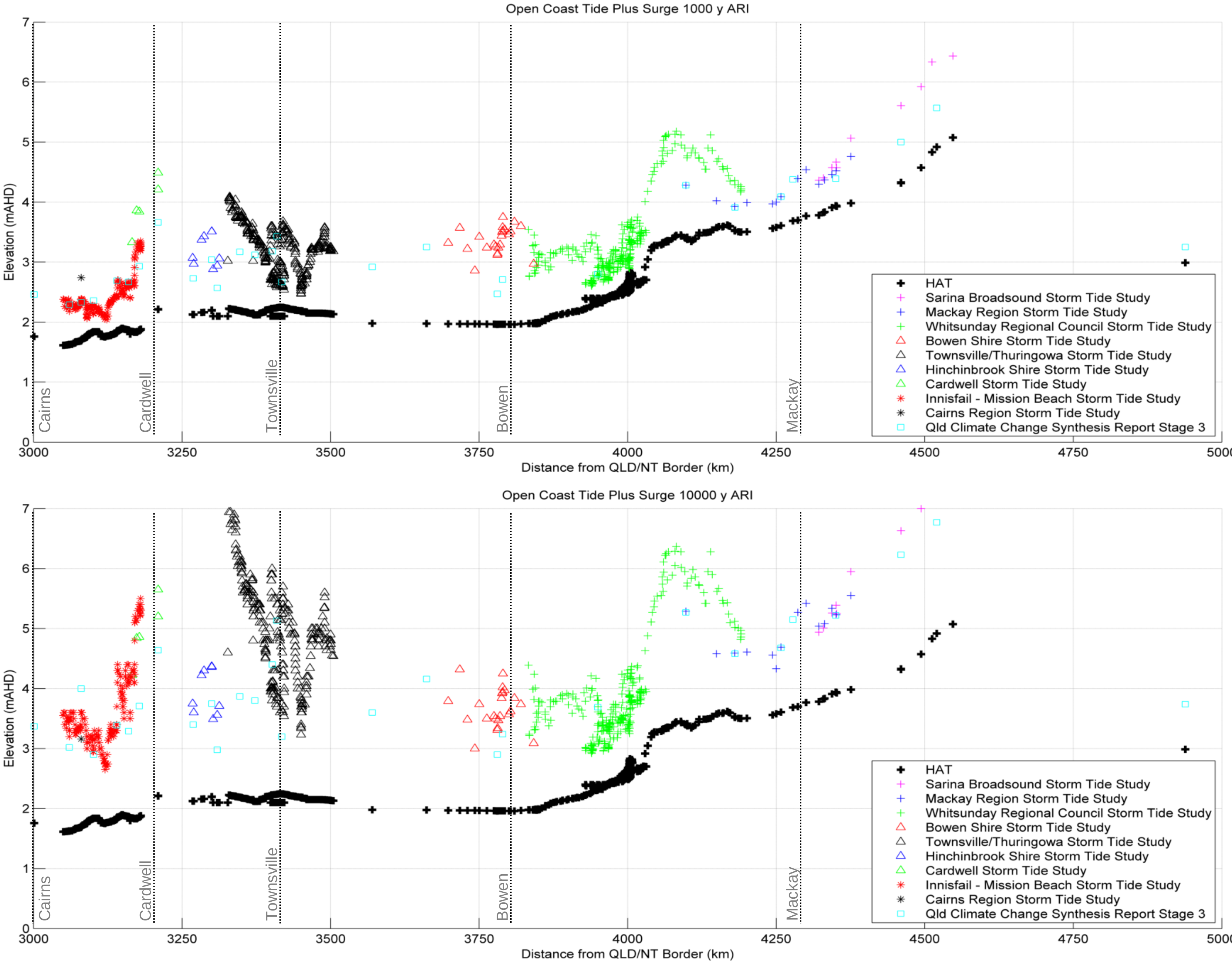


Figure – D3. 1000 y ARI (top) and Probable Maximum (bottom) Non-Normalised Tide plus Surge Estimates (Cairns to St. Lawrence).

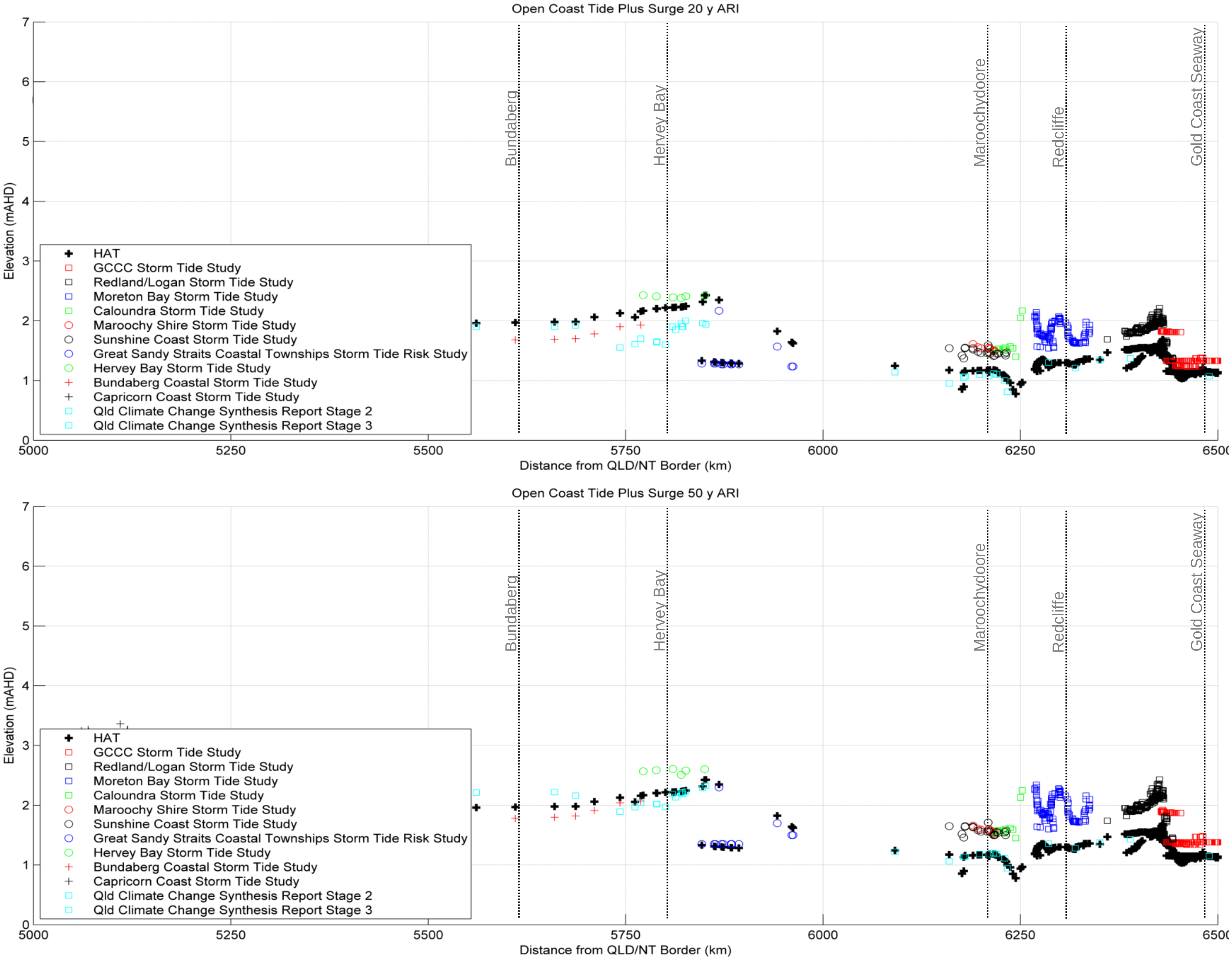


Figure – D4. 20 y (top) and 50 y (bottom) ARI Non-Normalised Tide plus Surge Estimates (St. Lawrence to Point Danger).

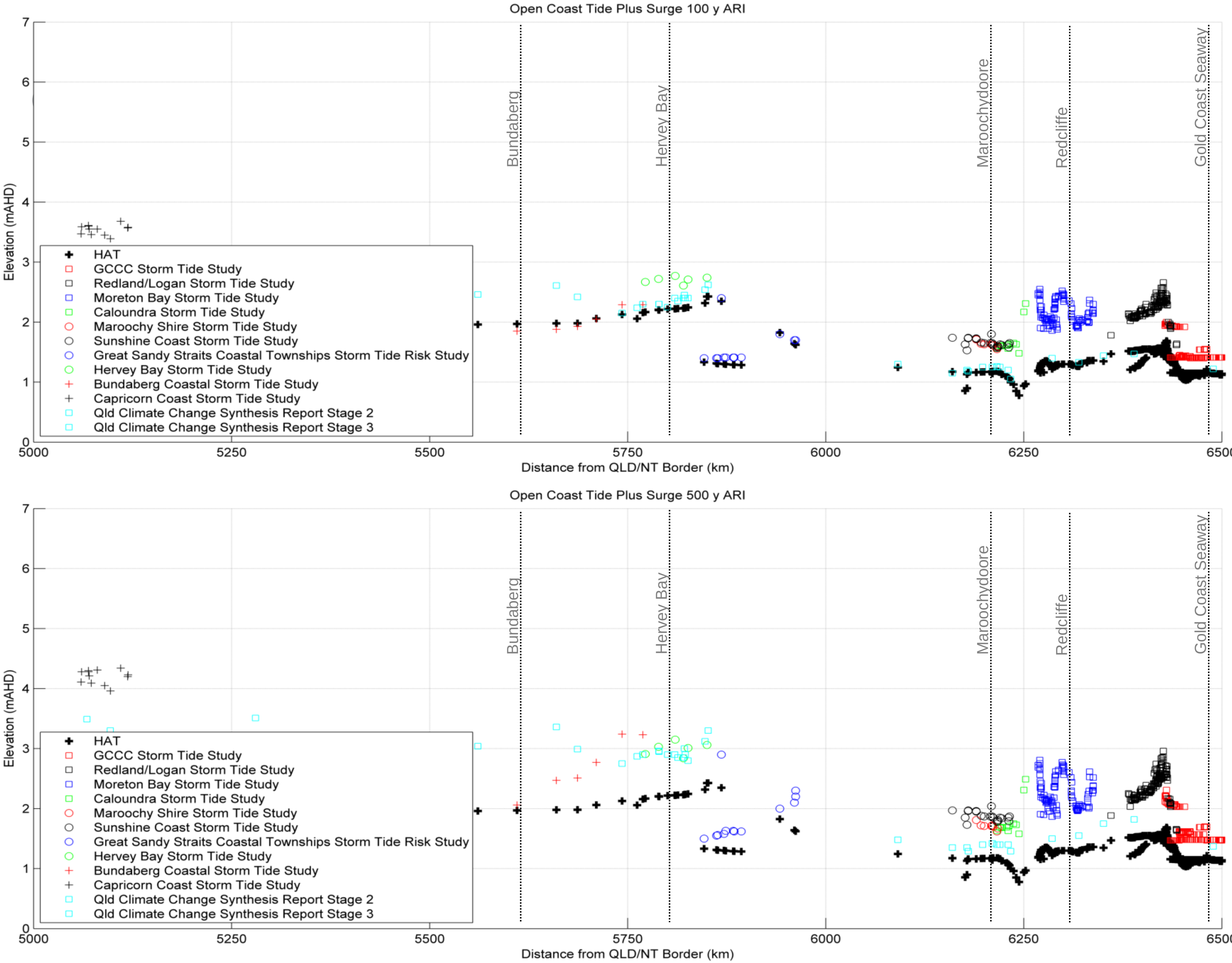


Figure – D5. 100 y (top) and 500 y (bottom) ARI Non-Normalised Tide plus Surge Estimates (St. Lawrence to Point Danger).

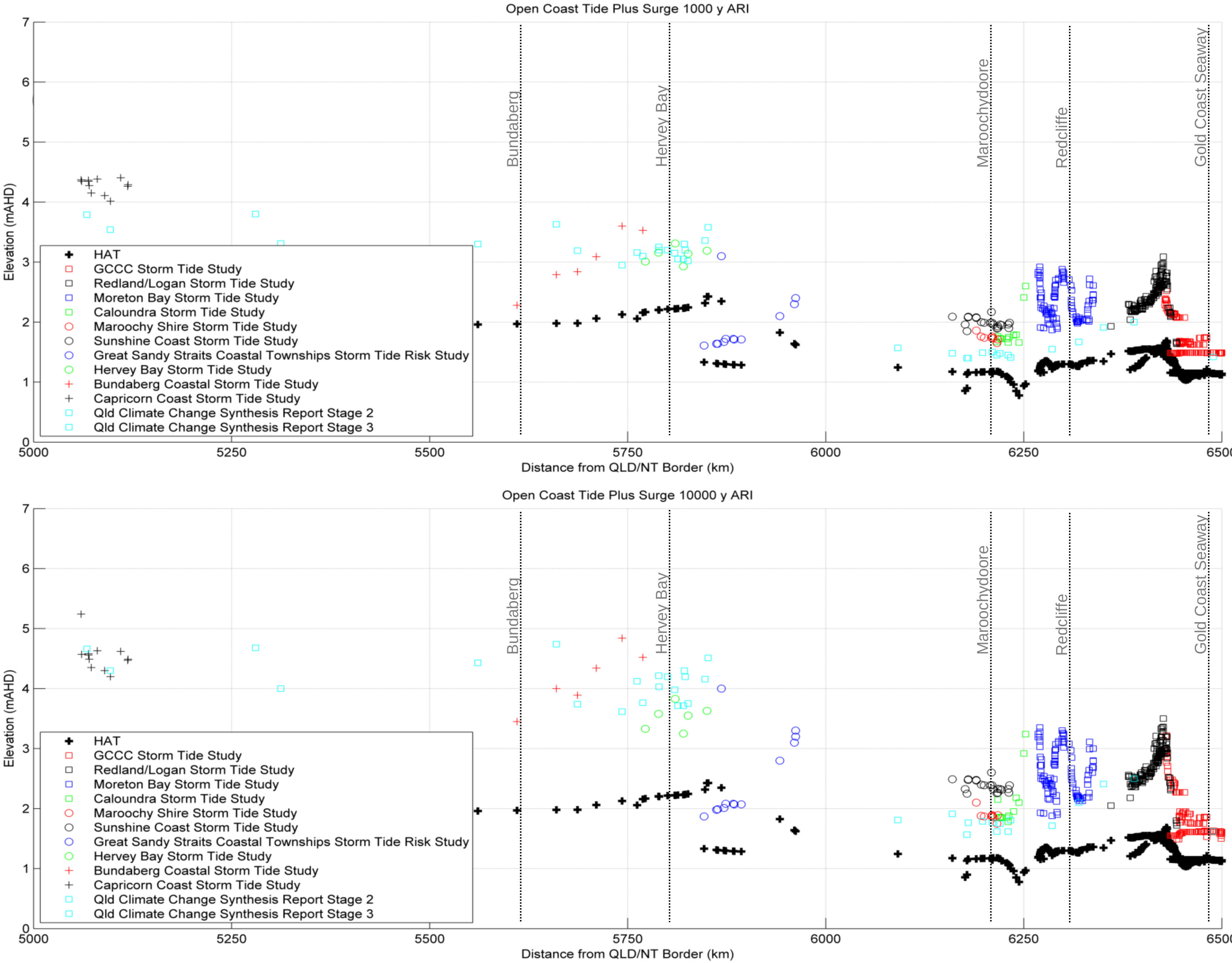


Figure – D6. 1000 y ARI (top) and Probable Maximum (bottom) Non-Normalised Tide plus Surge Estimates (St. Lawrence to Point Danger)

Appendix E – Non-Normalised *Total Storm Tide* Coastal Long Sections

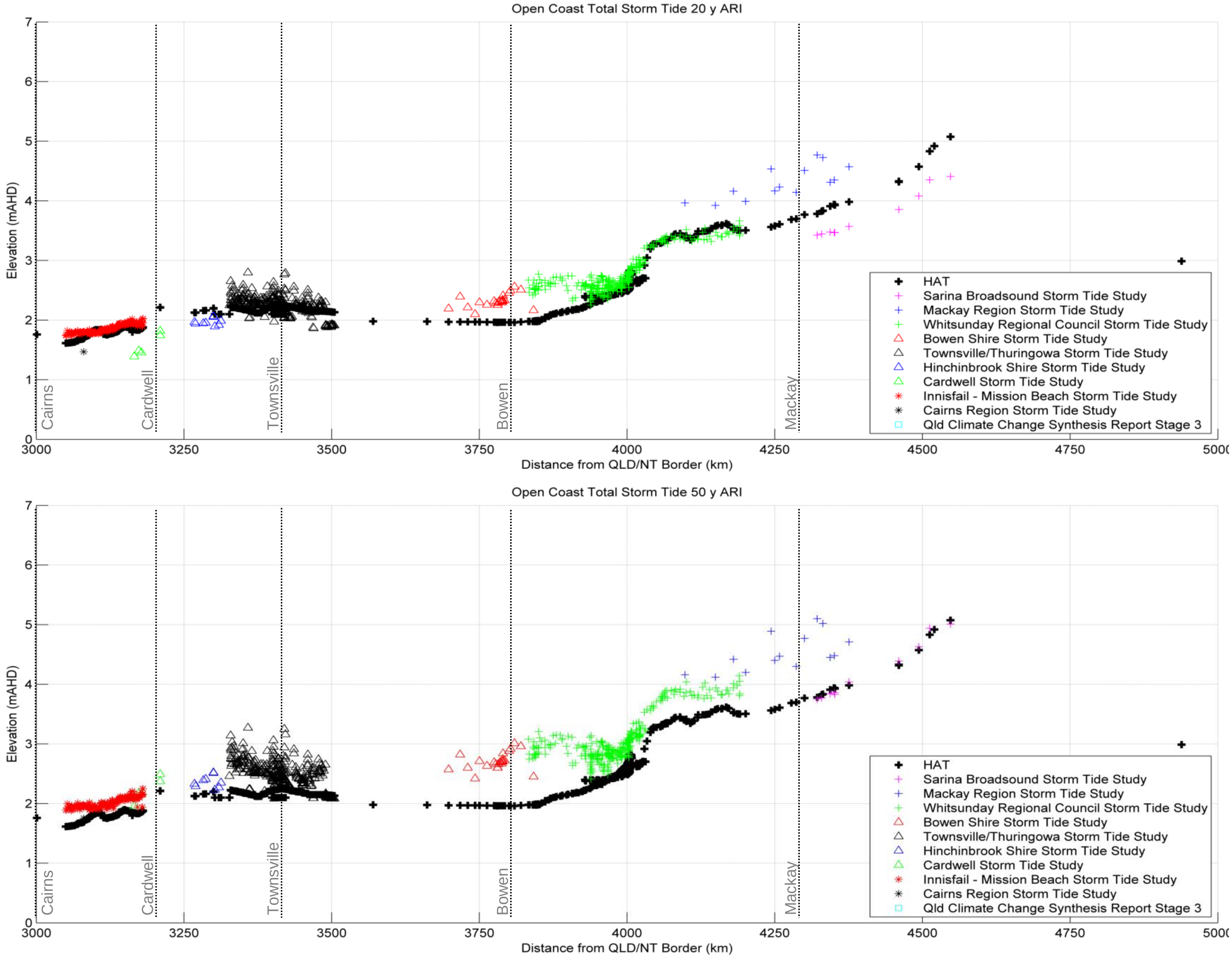


Figure – E1. 20 y (top) and 50 y (bottom) ARI Non-Normalised Total Storm Tide Estimates (Cairns to St. Lawrence).

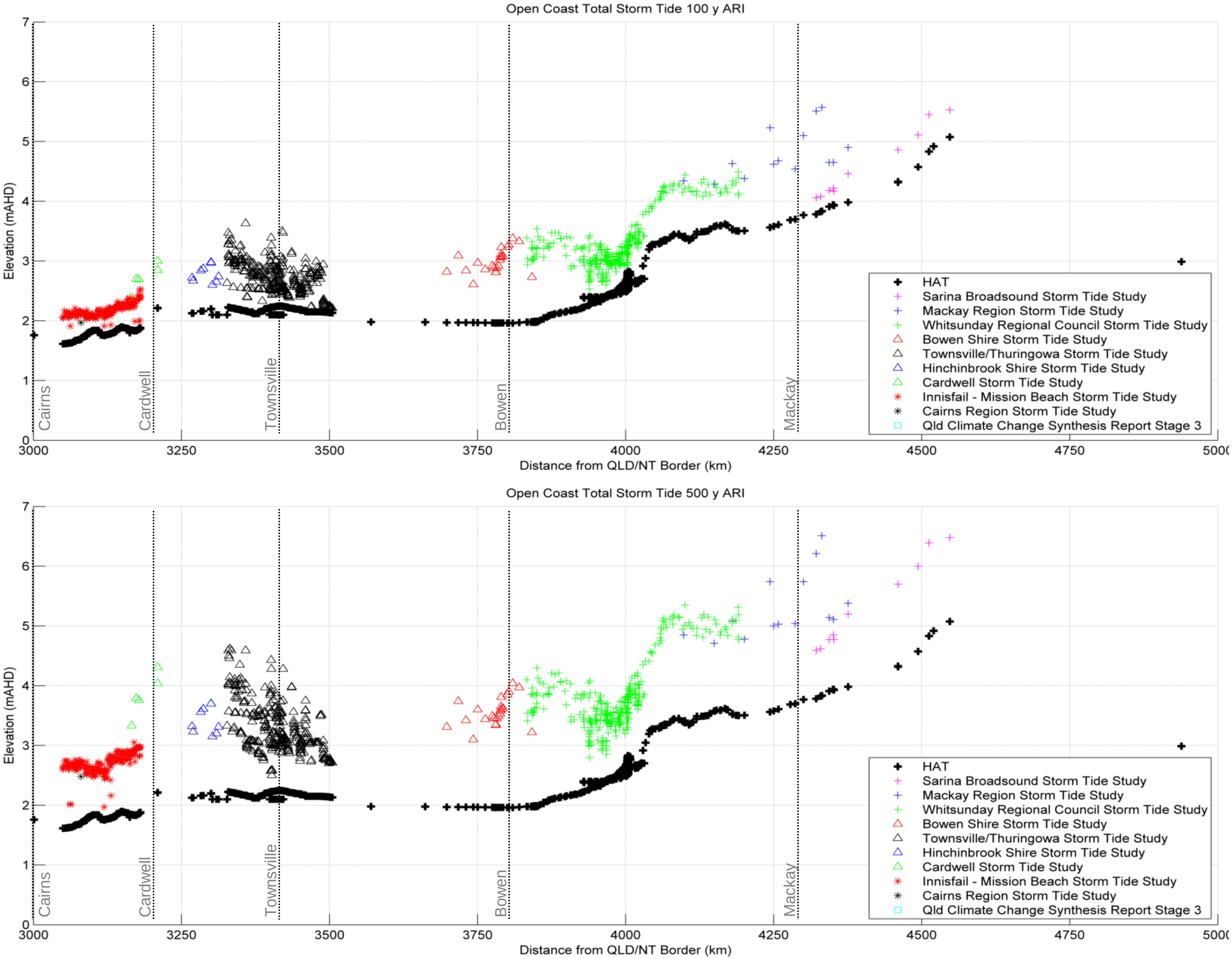


Figure – E2. 100 y (top) and 500 y (bottom) ARI Non-Normalised Total Storm Tide Estimates (Cairns to St. Lawrence).

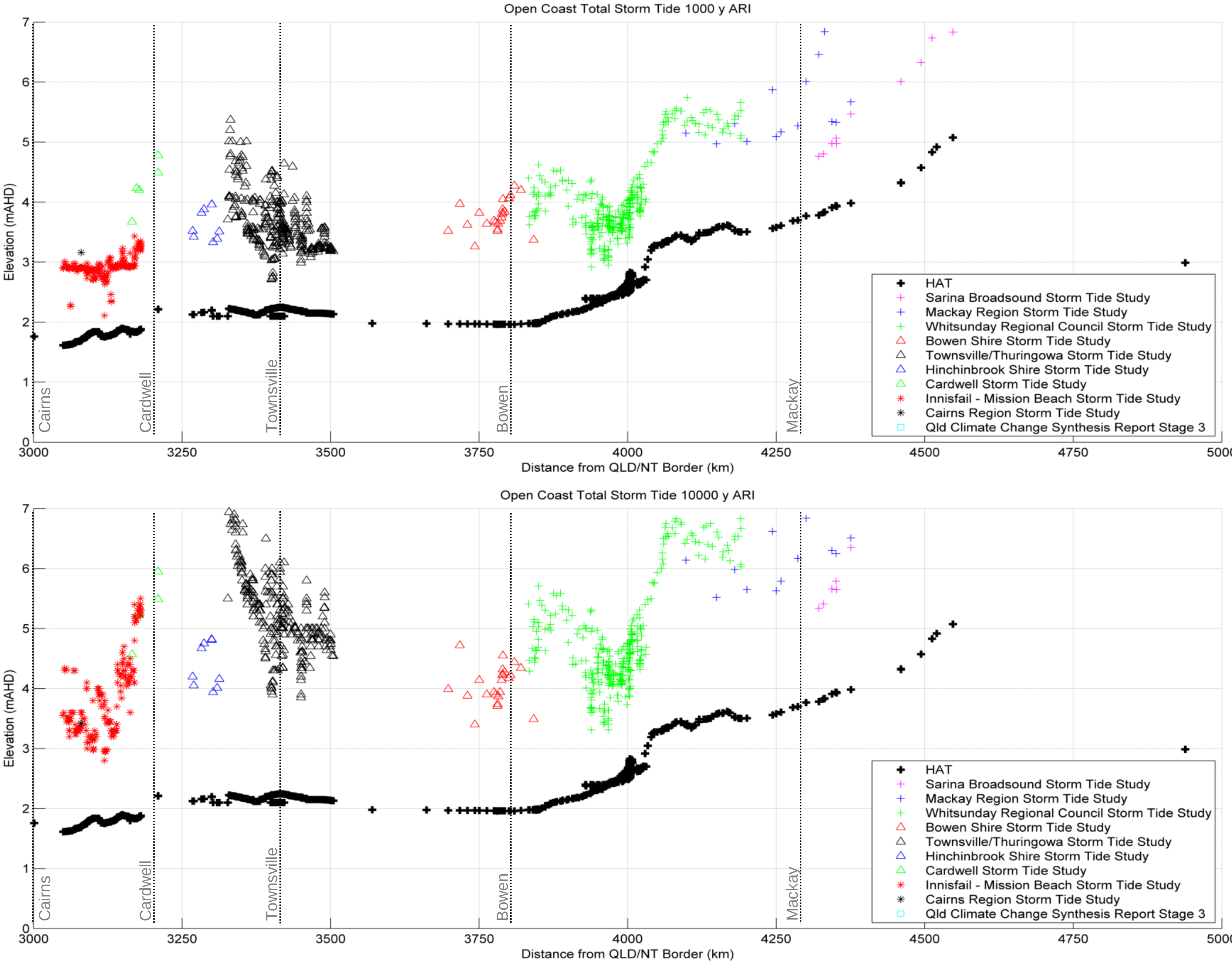


Figure – E3. 1000 y ARI (top) and Probable Maximum (bottom) Non-Normalised Total Storm Tide Estimates (Cairns to St. Lawrence).

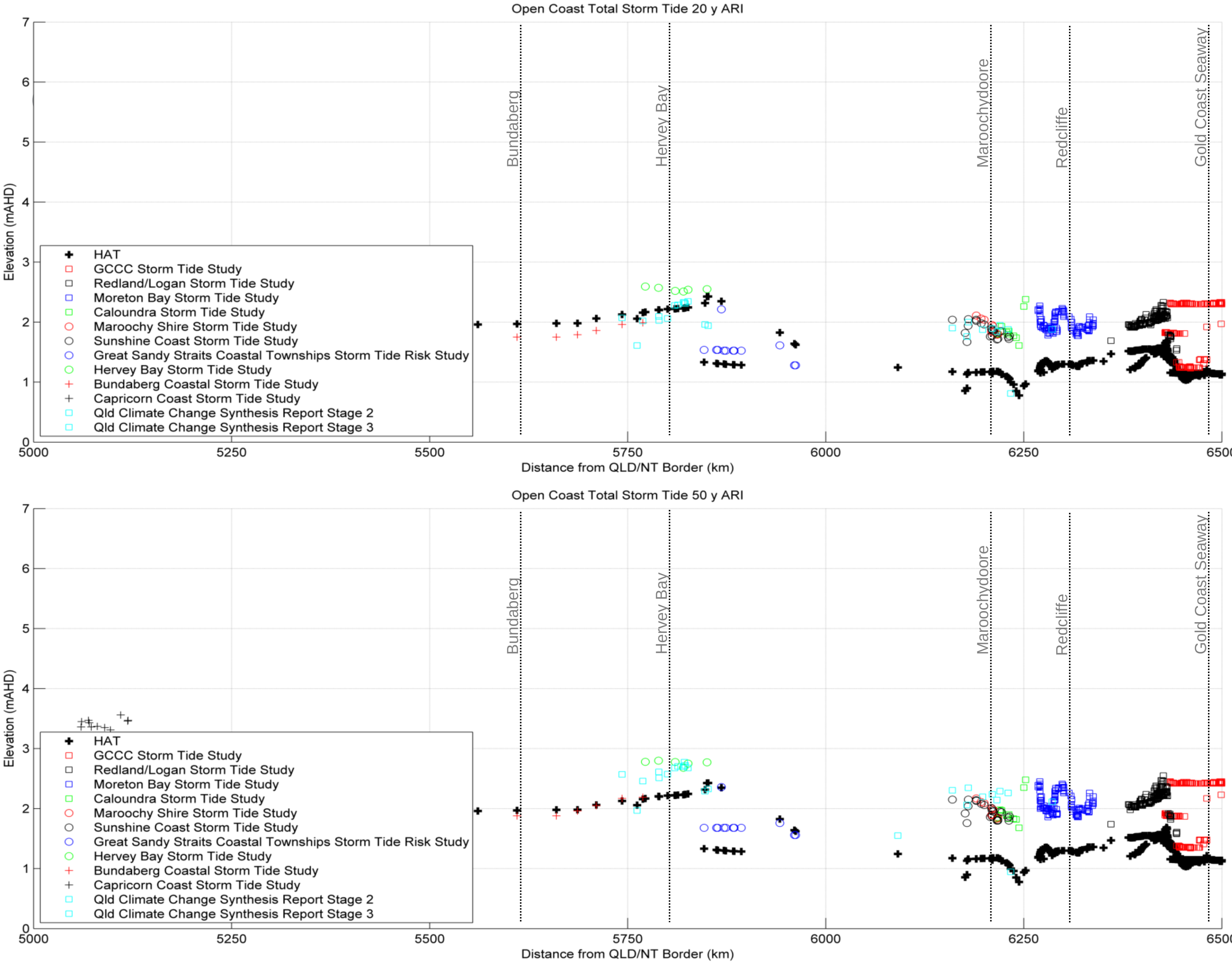


Figure – E4. 20 y (top) and 50 y (bottom) ARI Non-Normalised Total Storm Tide Estimates (St. Lawrence to Point Danger).

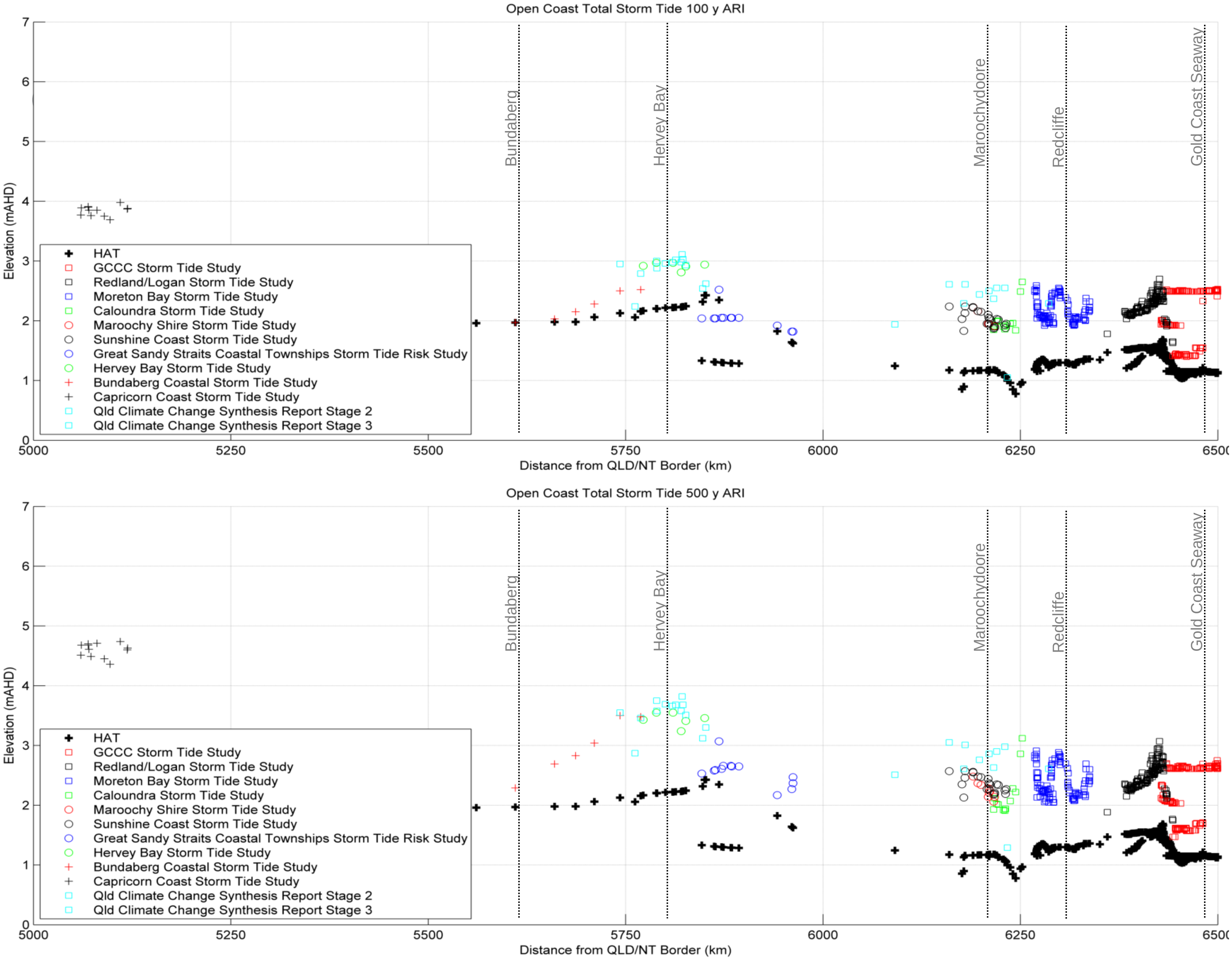
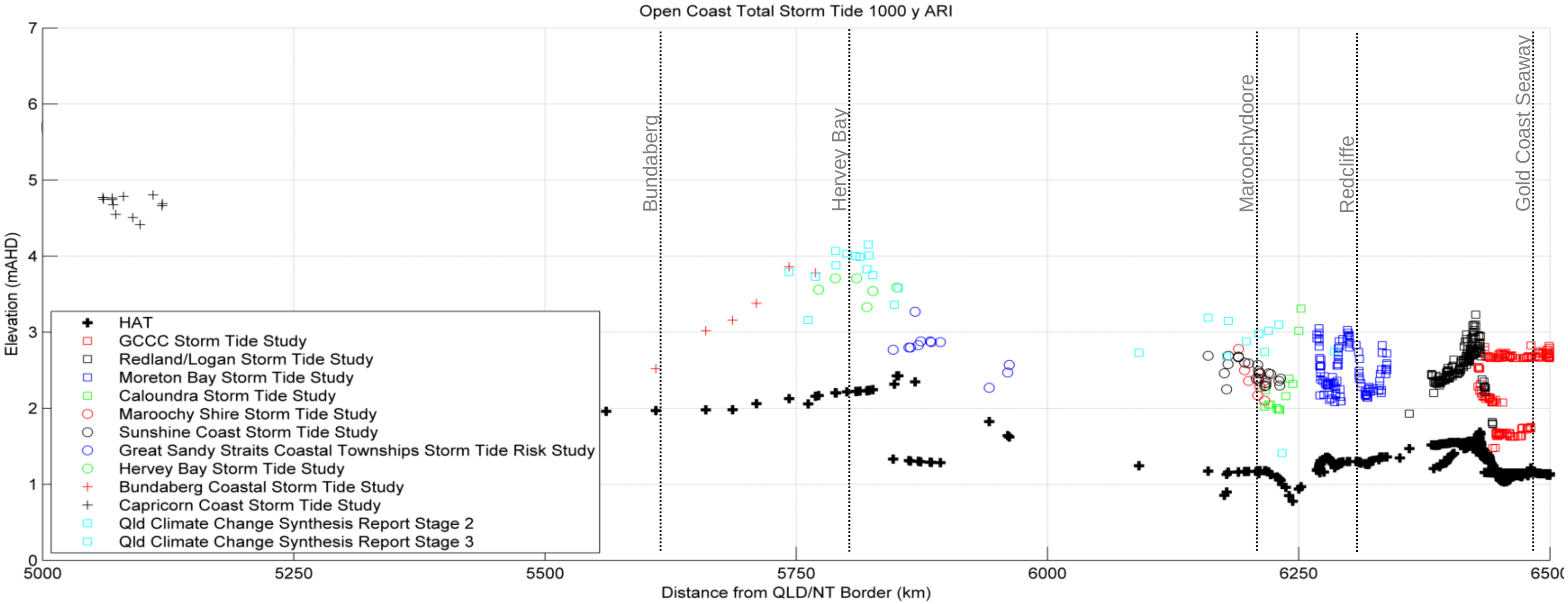


Figure – E5. 100 y (top) and 500 y (bottom) ARI Non-Normalised Total Storm Tide Estimates (St. Lawrence to Point Danger).



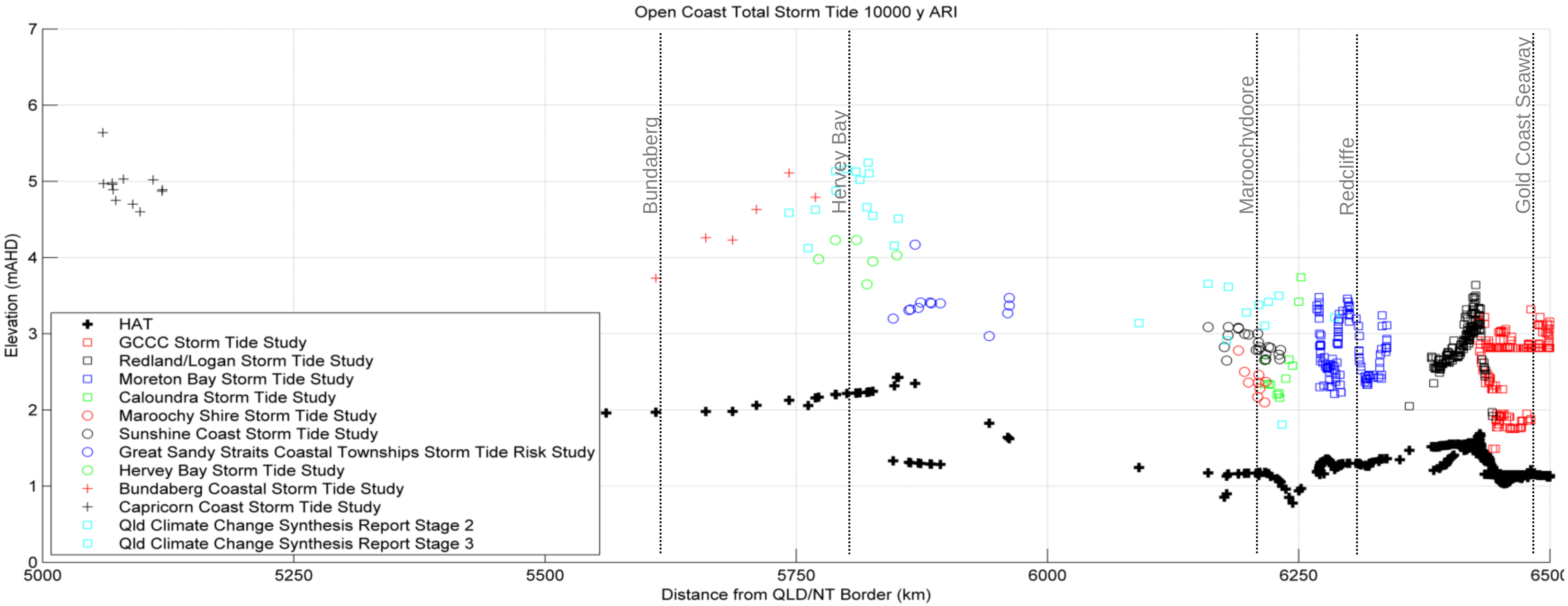


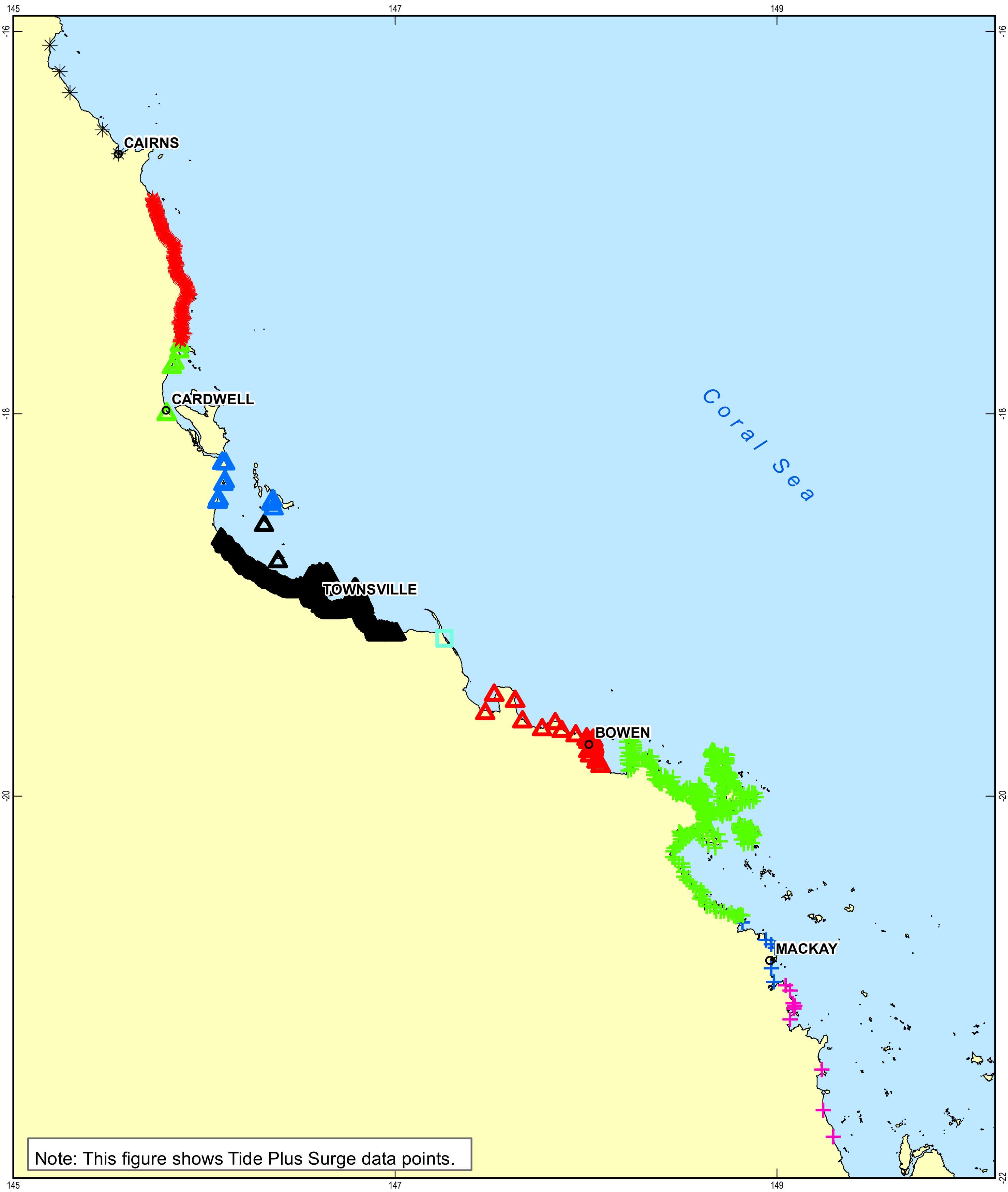
Figure – E6. 1000 y ARI (top) and Probable Maximum (bottom) Non-Normalised Total Storm Tide Estimates (St. Lawrence to Point Danger)

Appendix F – Mean Sea Level Datum Comparisons

Study	Location	Mean Sea Level from Study (m AHD)	Mean Sea Level from MSQ 2013 (m AHD)	Difference : MSQ – Study (m)
Hinchinbrook	Lucinda Offshore	-0.05	-0.05	0.00
Maroochy Shire	Mooloolaba	-0.10	-0.03	0.07
	Caloundra Head	-0.10	-0.04	0.06
Bowen	Bowen	-0.06	-0.02	0.04
	Abbot Point	0.04	0.06	0.02
Capricorn Coast	Rosslyn Bay	0.00	0.06	0.06
Isacc (Sarina Broadsound)	Hay Point	0.00	0.03	0.03
Fraser Coast (Hervey Bay)	Burrum Heads	0.10	-0.04	-0.14
	Urangan	0.10	0.05	-0.05
	Bingham	0.10	0.00	-0.10
Gold Coast	Gold Coast Seaway	0.00	0.00	0.00
Sunshine Coast	Noosa Head	-0.04	-0.04	0.00
	Mooloolaba	-0.03	-0.03	0.00
	Caloundra Head	-0.04	-0.04	0.00
Whitsunday Islands	Shute Harbour	0.00	0.03	0.03
Townsville	Townsville Harbour	0.00	0.08	-0.02
QCC Stage 3	stn 066003A	0.05	0.05	0.00
	Cairns	0.04	0.06	0.02
	stn 056012A	0.04	0.06	0.02
	Cairns	0.04	0.06	0.02
	flying fish point	0.06	0.06	0.00
	stn 036007A	0.06	0.06	0.00
	clump point	0.06	0.05	-0.01
	stn 035012A	0.08	0.08	0.00
	stn 062006A	0.03	0.05	0.02
	lucinda	0.03	0.05	0.02
	townsville	0.08	0.08	0.01
	jaloonda	0.05	0.00	-0.05
	magnetic island arcadia	0.07	0.07	0.00
	townsville	0.08	0.08	0.01
	cape ferguson	0.07	0.07	0.00
	abbott point	0.04	0.06	0.02
	bowen	-0.03	-0.02	0.02
	stn 030016A	0.05	0.00	-0.05
	laguna quays	-0.02	-0.07	-0.04
	halliday bay	0.02	0.02	0.00
	mackay	0.06	0.08	0.02
	hay point	0.00	0.03	0.03
	rosslyn bay	0.01	0.06	0.05
	auckland point	0.05	0.07	0.02

	agnes waters	-0.01	-0.01	0.00
	bundaberg	0.01	0.03	0.01
	noosa head	-0.06	-0.04	0.02
	stn048002A	-0.06	-0.06	0.00
	cabbage tree creek	-0.12	-0.12	0.00
	stn 007204A	-0.07	-0.07	0.00
	snapper rocks	-0.01	-0.01	0.00

Appendix G – Interpolated Data Extents



Legend

- Bowen Shire Storm Tide Study
- Cairns Region Storm Tide Study
- Cardwell Storm Tide Study
- Hinchinbrook Shire Storm Tide Study
- Innisfail - Mission Beach Storm Tide Study
- Mackay Region Storm Tide Study
- Qld Climate Change Synthesis Report Stage 3
- Sarina Broadsound Storm Tide Study
- Townsville/Thuringowa Storm Tide Study
- Whitsunday Regional Council Storm Tide Study

Paper Size A4

0 12.5 25 50 75 100

Kilometers

Horizontal Datum: GDA 1994
Grid: GCS GDA 1994

N

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Queensland Government

Australian Government Attorney-General's Department

Department of Community Safety
NDRP Storm Tide Hazard Interpolation Study

Job Number	41-25509
Revision	A
Date	10 May 2013

Normalised Tide Plus Surge Data
Port Douglas to St. Lawrence

Figure G1

145 Ann Street Brisbane QLD 4000 Australia T 61 7 3316 3000 F 61 7 3316 3333 E bnemail@ghd.com W www.ghd.com

G:\41\25509\GIS\Maps\Deliverables\4125509_004_RevA.mxd

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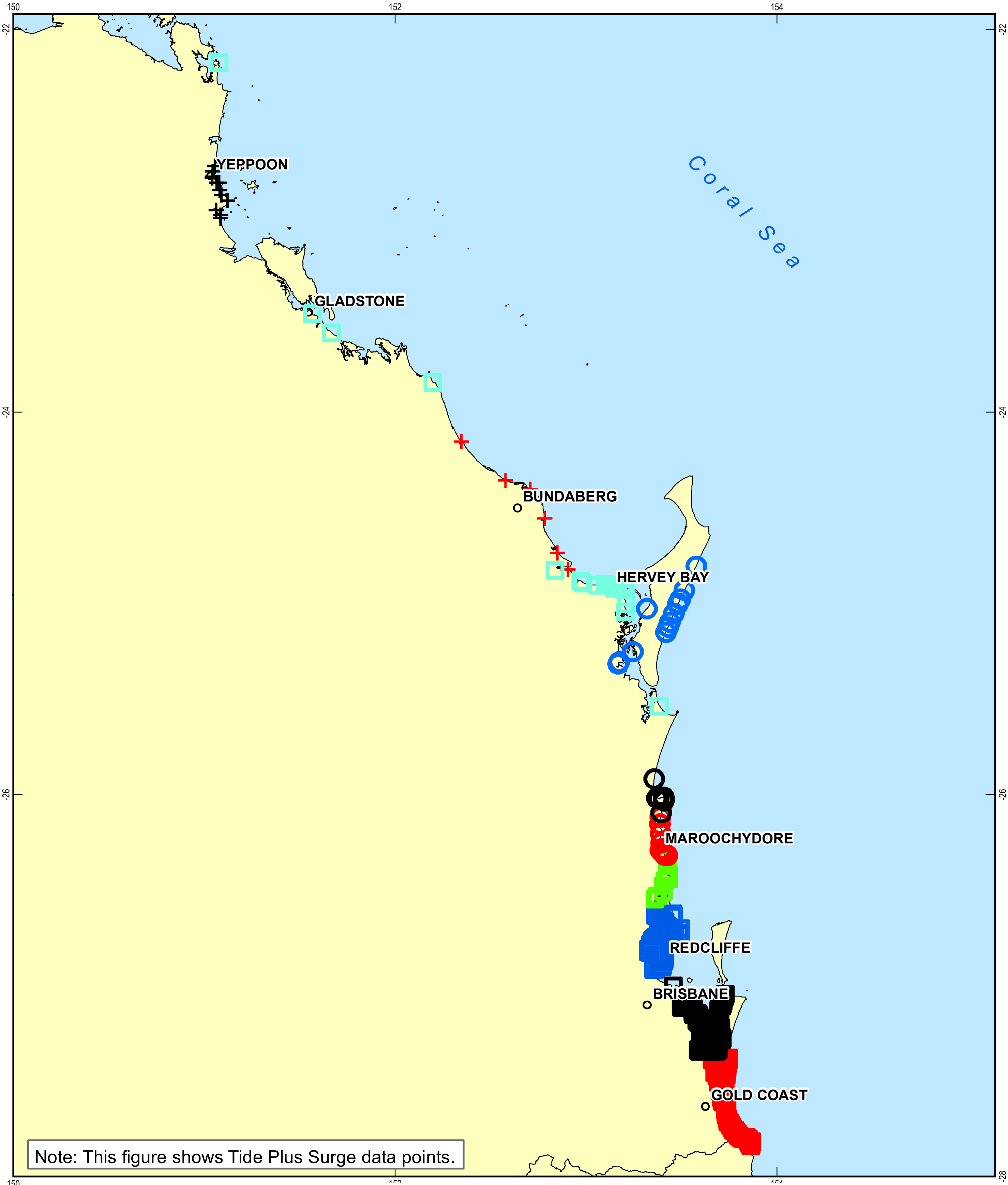

Legend

- Bundaberg Coastal Storm Tide Study
- Caloundra Storm Tide Study
- Capricorn Coast Storm Tide Study
- GCCC Storm Tide Study
- Great Sandy Strait Storm Tide Study
- Maroochy Shire Storm Tide Study
- Moreton Bay Storm Tide Study
- Qld Climate Change Synthesis Report Stage 2
- Qld Climate Change Synthesis Report Stage 3
- Redland/Logan Storm Tide Study
- Sunshine Coast Storm Tide Study

Paper Size A4

0 12.5 25 50 75 100

Kilometers

Horizontal Datum: GDA 1994
Grid: GCS GDA 1994

N

Department of Community Safety
NDRP Storm Tide Hazard Interpolation Study

Job Number 41-25509
Revision A
Date 10 May 2013

Normalised Tide Plus Surge Data St Lawrence to Point Danger

Figure G2

145 Ann Street Brisbane QLD 4000 Australia T 61 7 3316 3000 F 61 7 3316 3333 E bnemail@ghd.com W www.ghd.com

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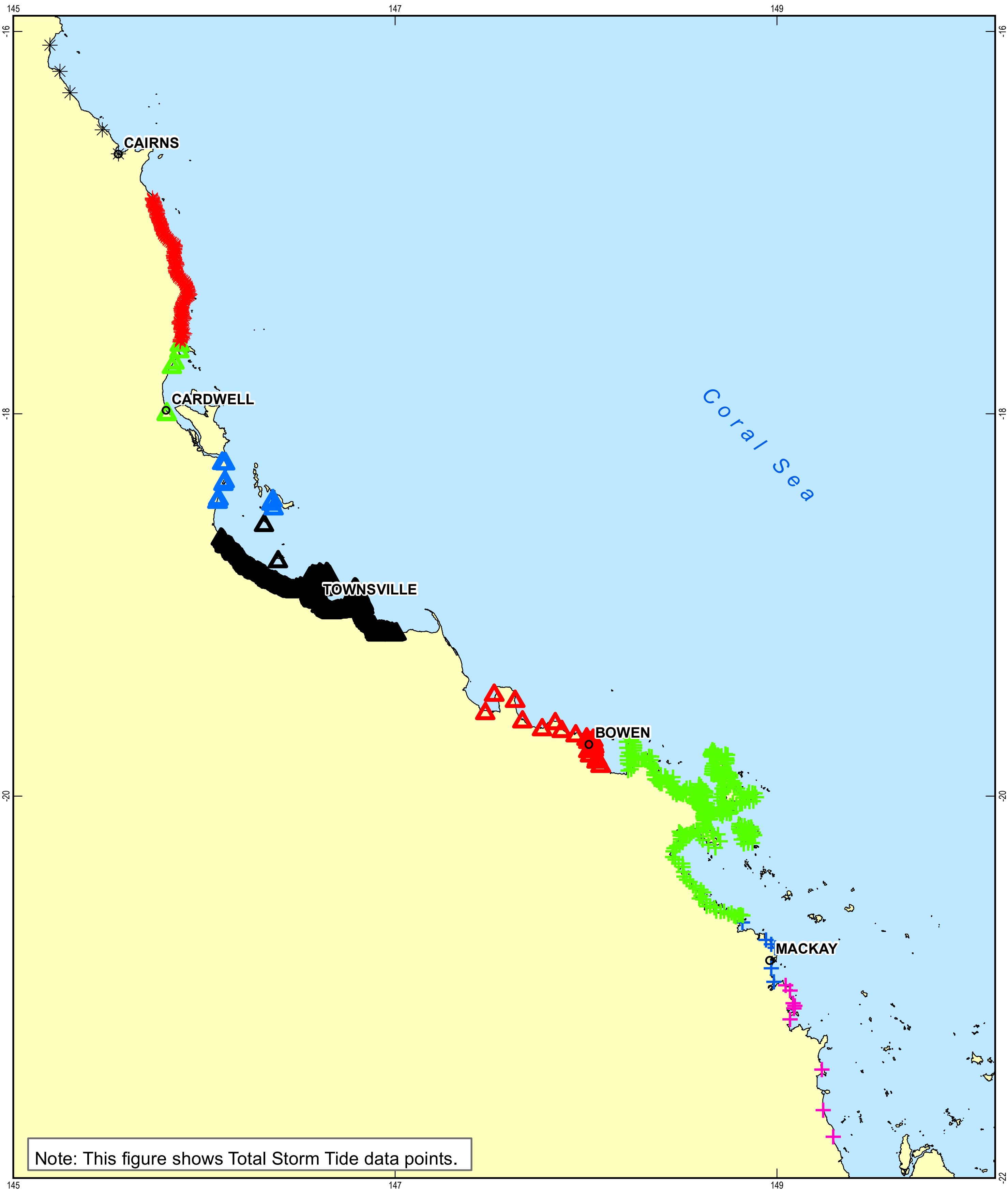

Legend

- Bowen Shire Storm Tide Study
- Cairns Region Storm Tide Study
- Cardwell Storm Tide Study
- Hinchinbrook Shire Storm Tide Study
- Innisfail - Mission Beach Storm Tide Study
- Mackay Region Storm Tide Study
- Sarina Broadsound Storm Tide Study
- Townsville/Thuringowa Storm Tide Study
- Whitsunday Regional Council Storm Tide Study

Paper Size A4

0 12.5 25 50 75 100

Kilometers

Horizontal Datum: GDA 1994
Grid: GCS GDA 1994

N

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Australian Government
Attorney-General's Department

Department of Community Safety
NDRP Storm Tide Hazard Interpolation Study

Job Number	41-25509
Revision	A
Date	10 May 2013

Normalised Total Storm Tide Data
Port Douglas to St. Lawrence

Figure G3

145 Ann Street Brisbane QLD 4000 Australia **T** 61 7 3316 3000 **F** 61 7 3316 3333 **E** bnemail@ghd.com **W** www.ghd.com

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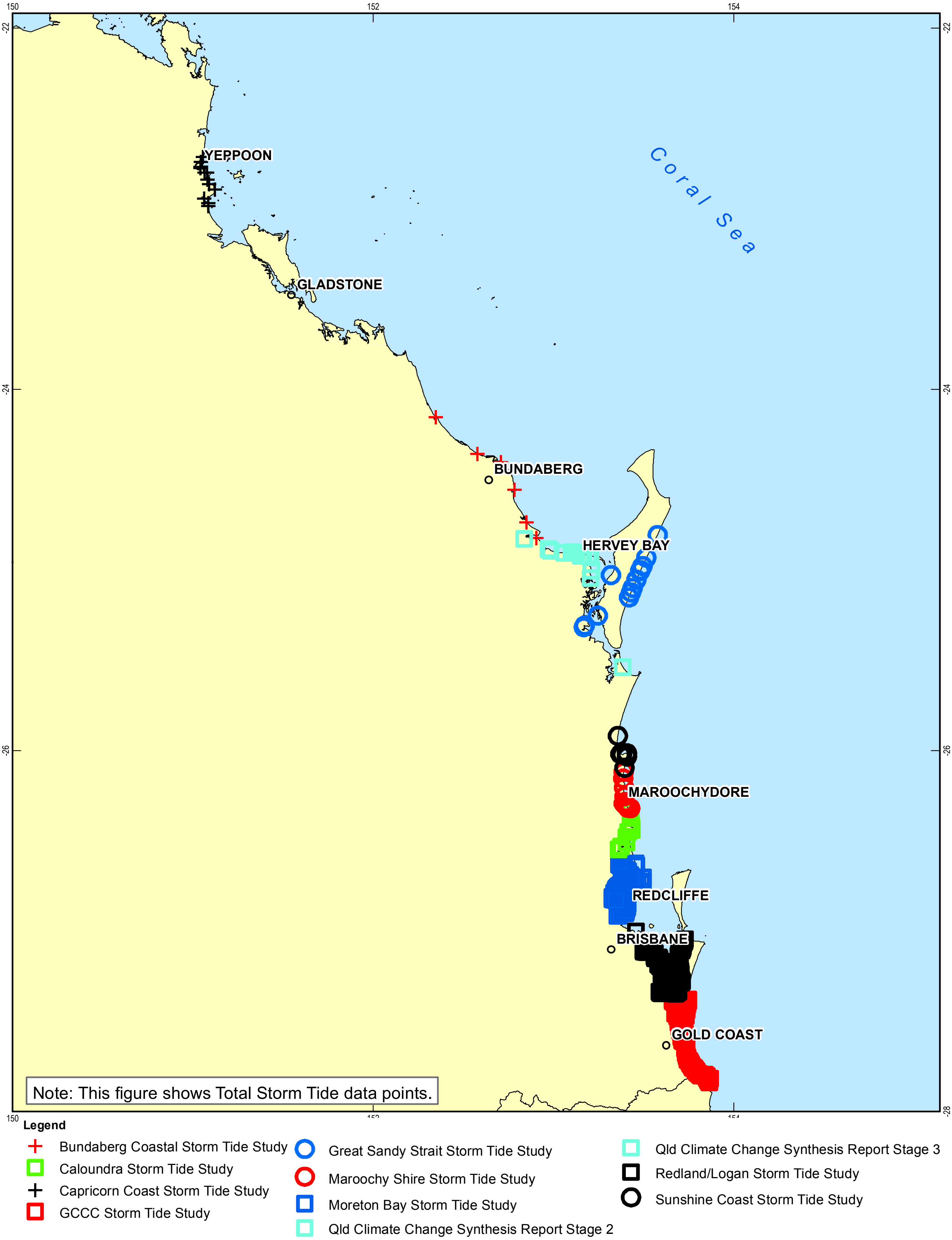

Department of Community Safety
NDRP Storm Tide Hazard Interpolation Study

Job Number	41-25509
Revision	A
Date	10 May 2013

Normalised Total Storm Tide Data
St Lawrence to Point Danger

Figure G4

145 Ann Street Brisbane QLD 4000 Australia T 61 7 3316 3000 F 61 7 3316 3333 E bnemail@ghd.com W www.ghd.com

G:\41\25509\GIS\Maps\Deliverables\4125509_007_RevA.mxd

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Appendix H – Normalised *Tide plus Surge* Coastal Long Sections

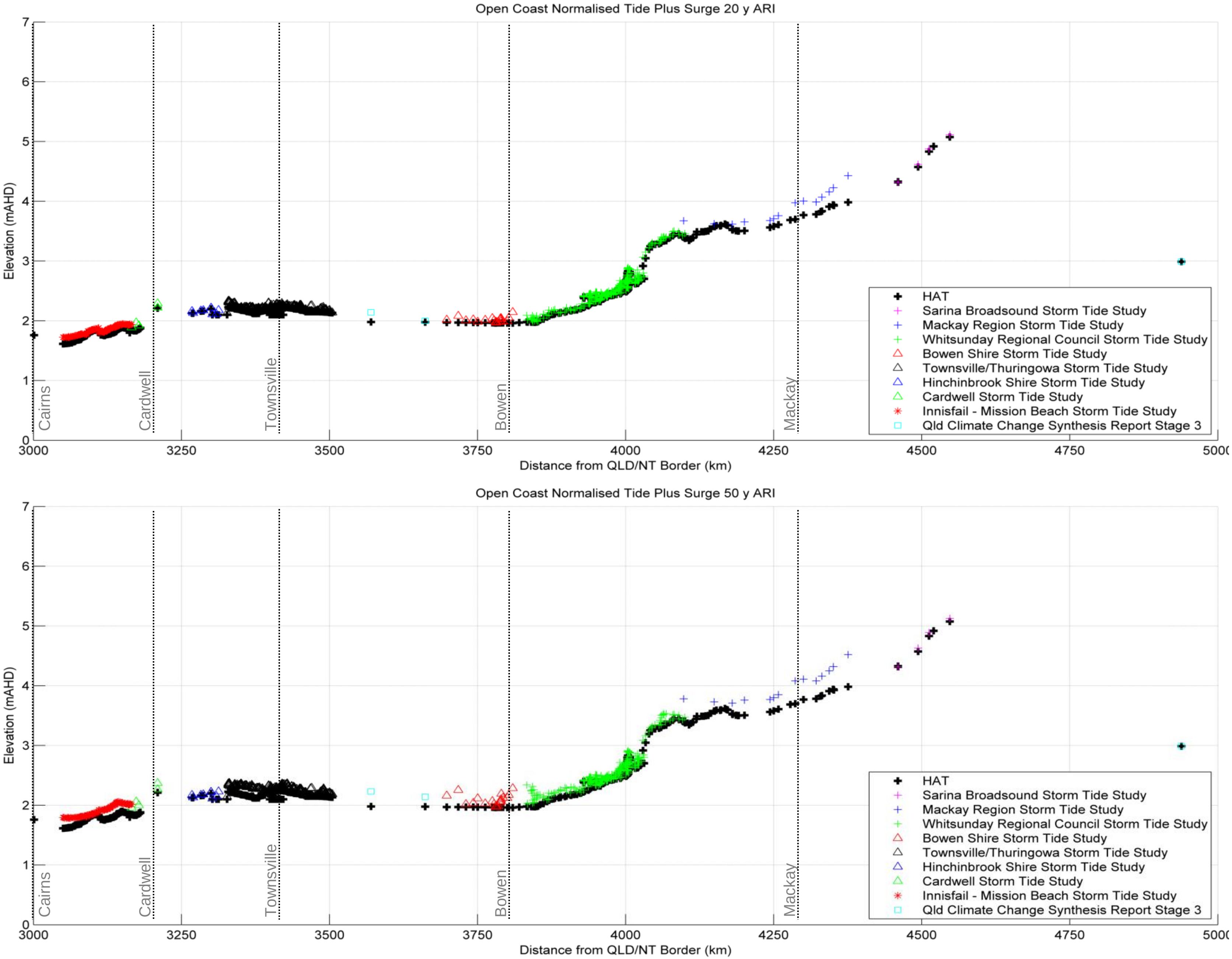


Figure – H1. 20 y (top) and 50 y (bottom) ARI Normalised Tide plus Surge Estimates (Cairns to St. Lawrence).

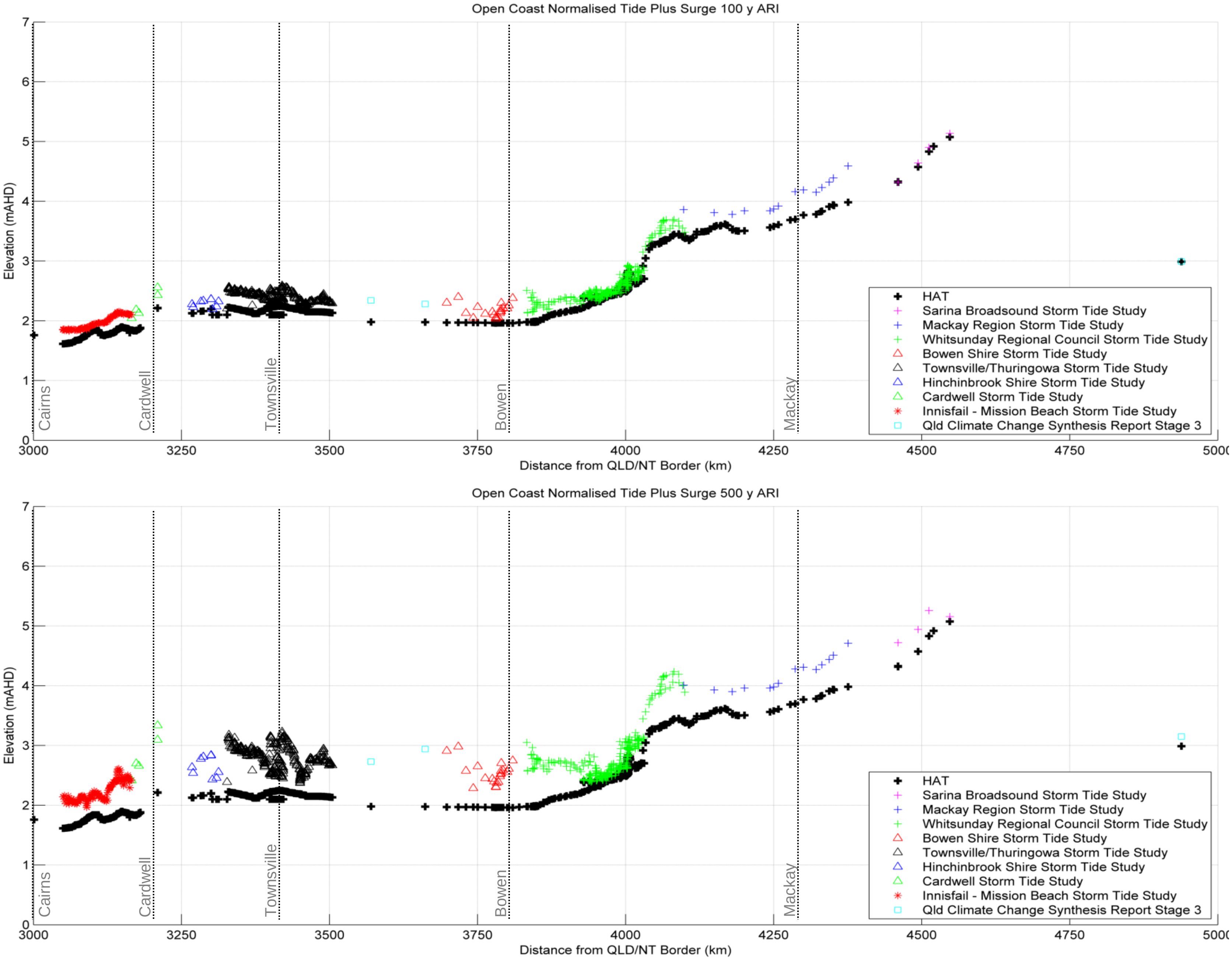


Figure – H2. 100 y (top) and 500 y (bottom) ARI Normalised Tide plus Surge Estimates (Cairns to St. Lawrence).

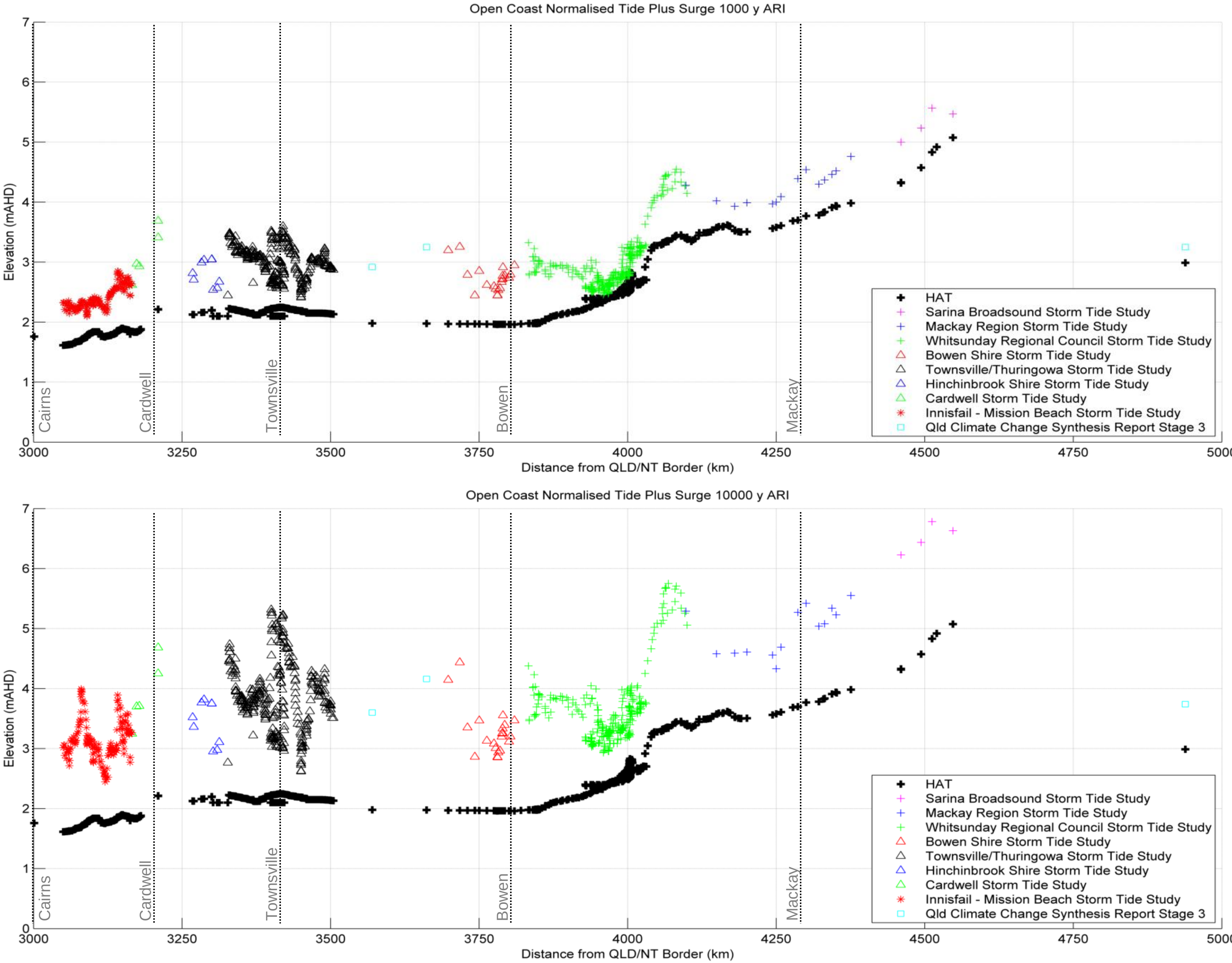
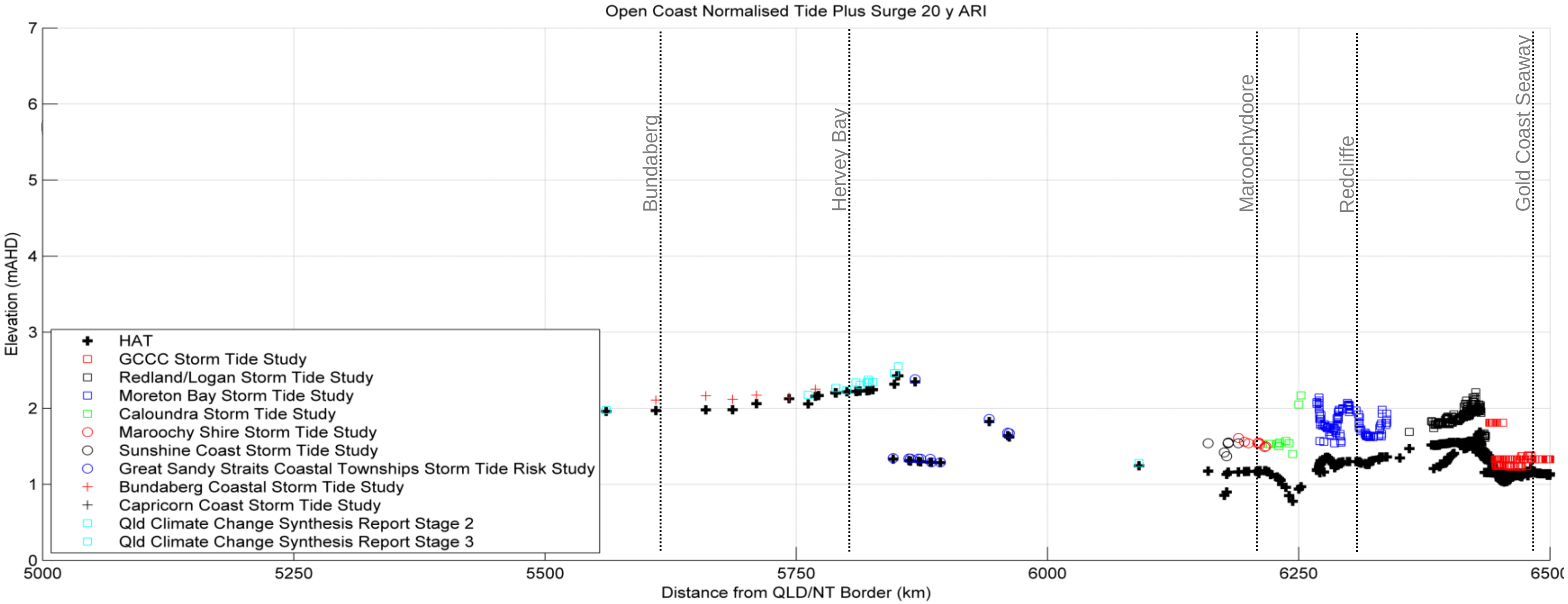


Figure – H3. 1000 y ARI (top) and Probable Maximum (bottom) Normalised Tide plus Surge Estimates (Cairns to St. Lawrence).



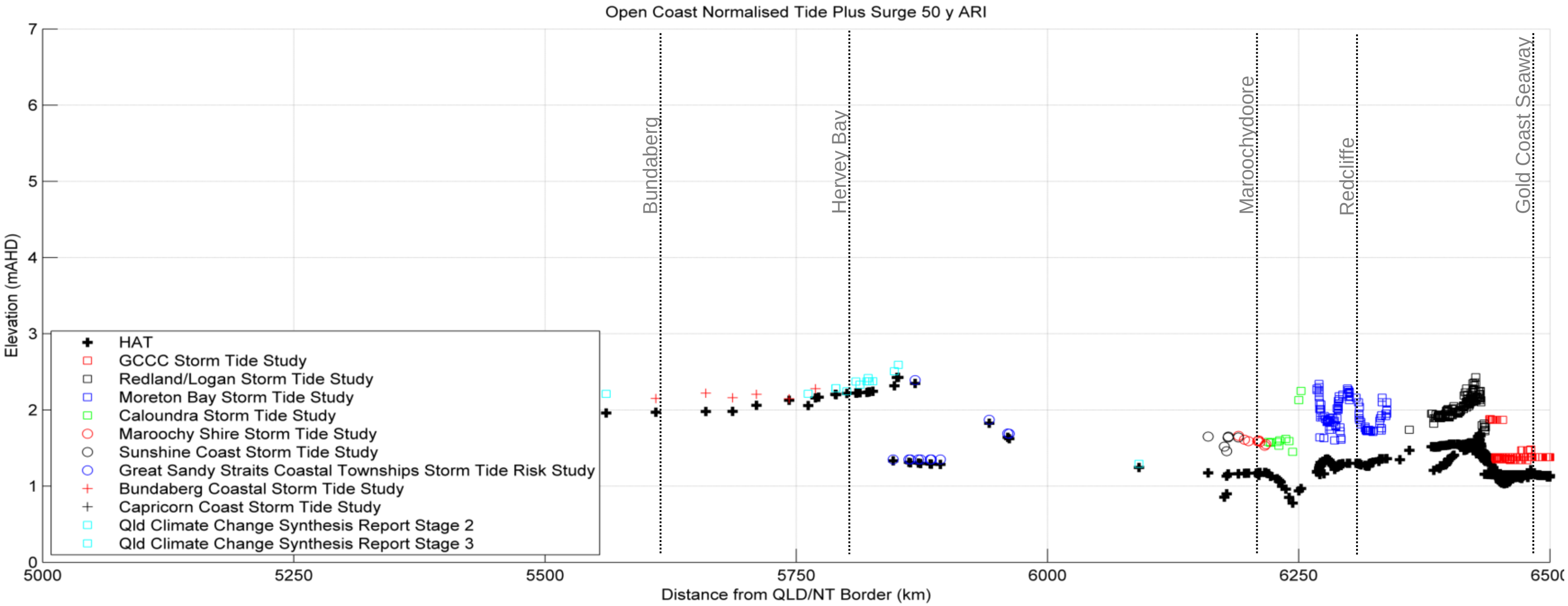


Figure – H4. 20 y (top) and 50 y (bottom) ARI Normalised Tide plus Surge Estimates (St. Lawrence to Point Danger).

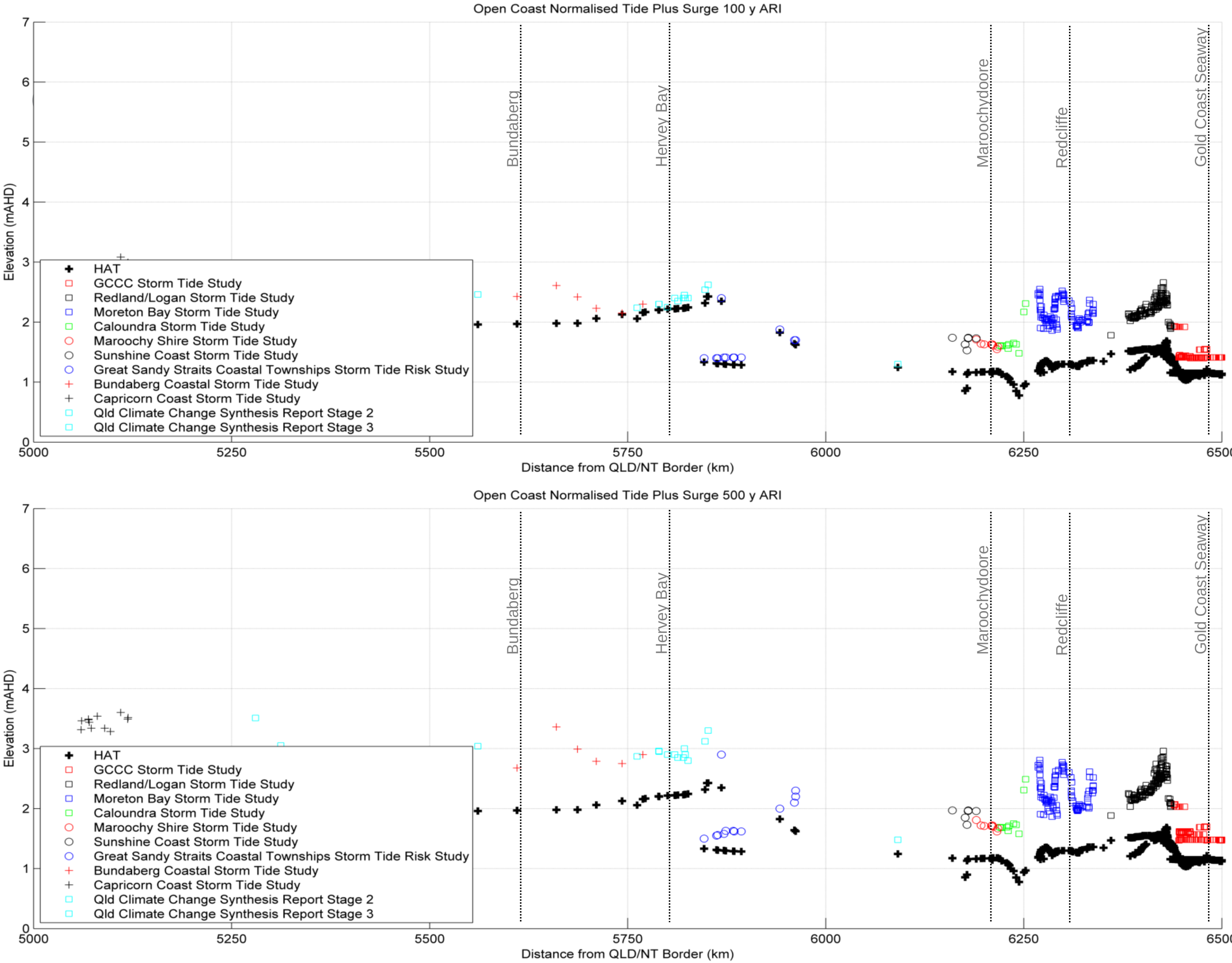
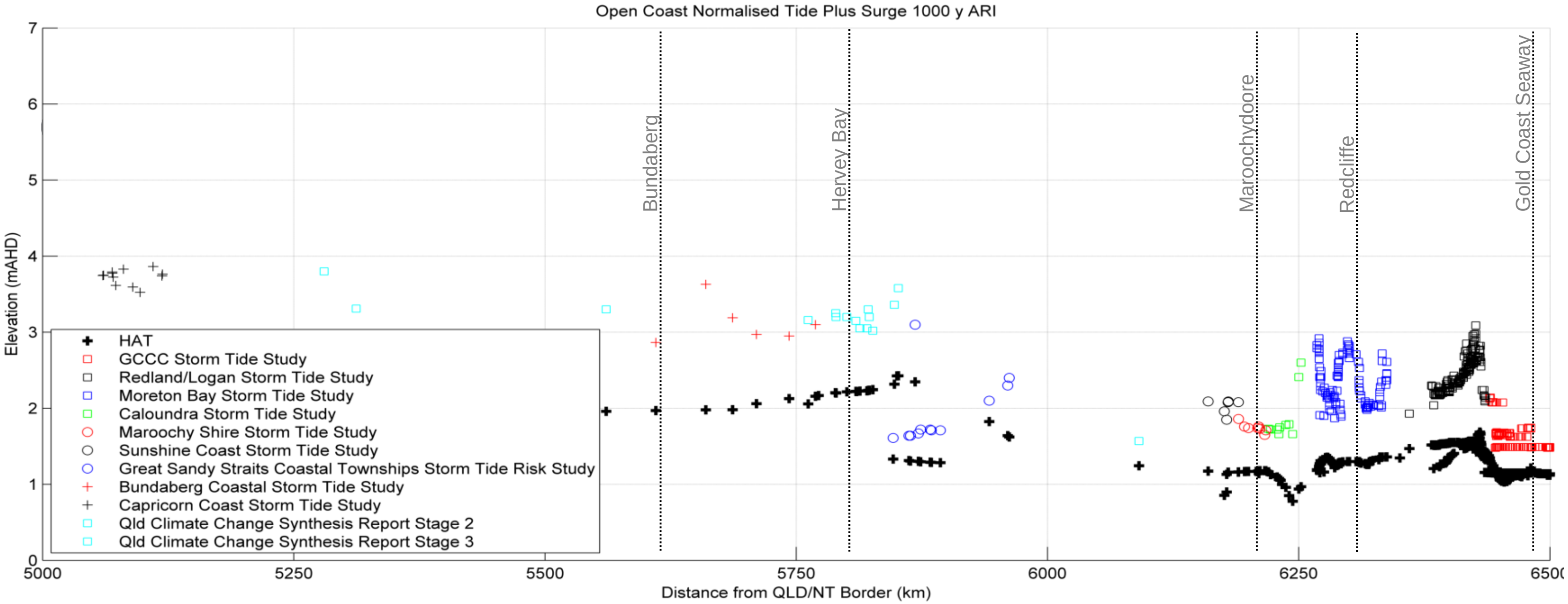


Figure – H5. 100 y (top) and 500 y (bottom) ARI Normalised Tide plus Surge Estimates (St. Lawrence to Point Danger).



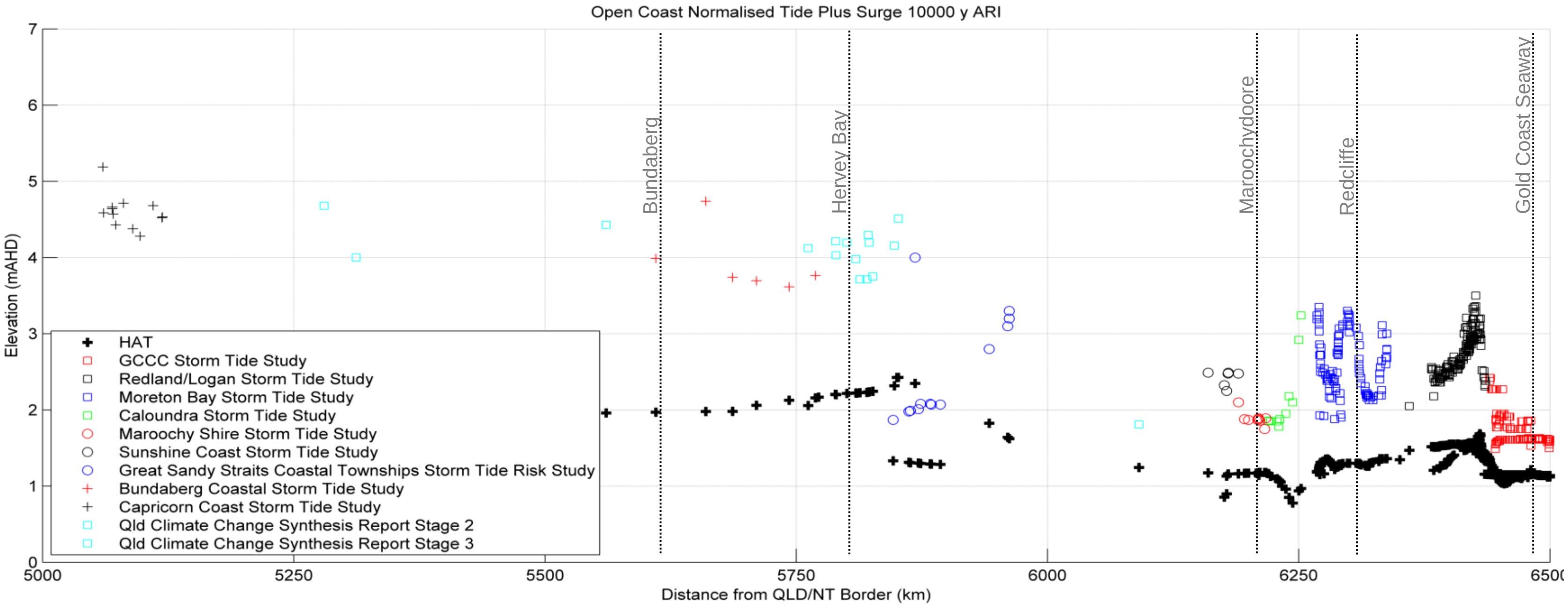
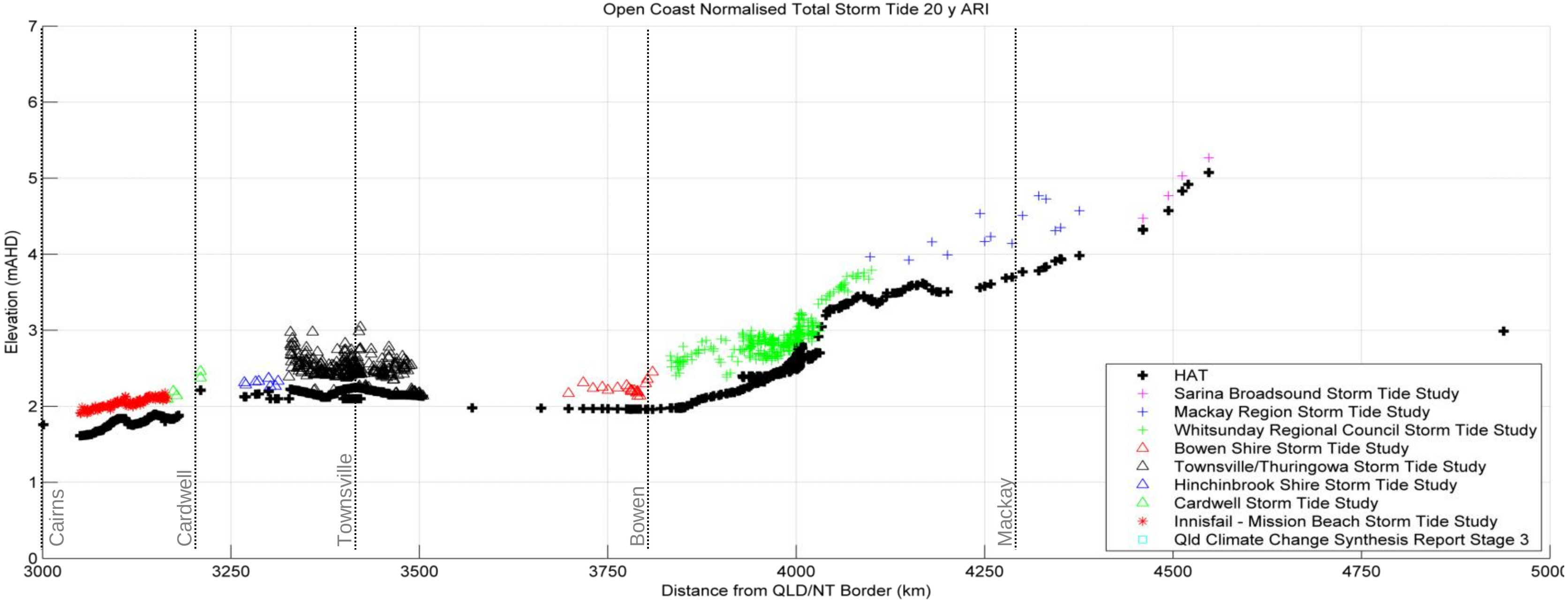


Figure – H6. 1000 y ARI (top) and Probable Maximum (bottom) Normalised Tide plus Surge Estimates (St. Lawrence to Point Danger)

Appendix I – Normalised *Total Storm Tide* Coastal Long Sections



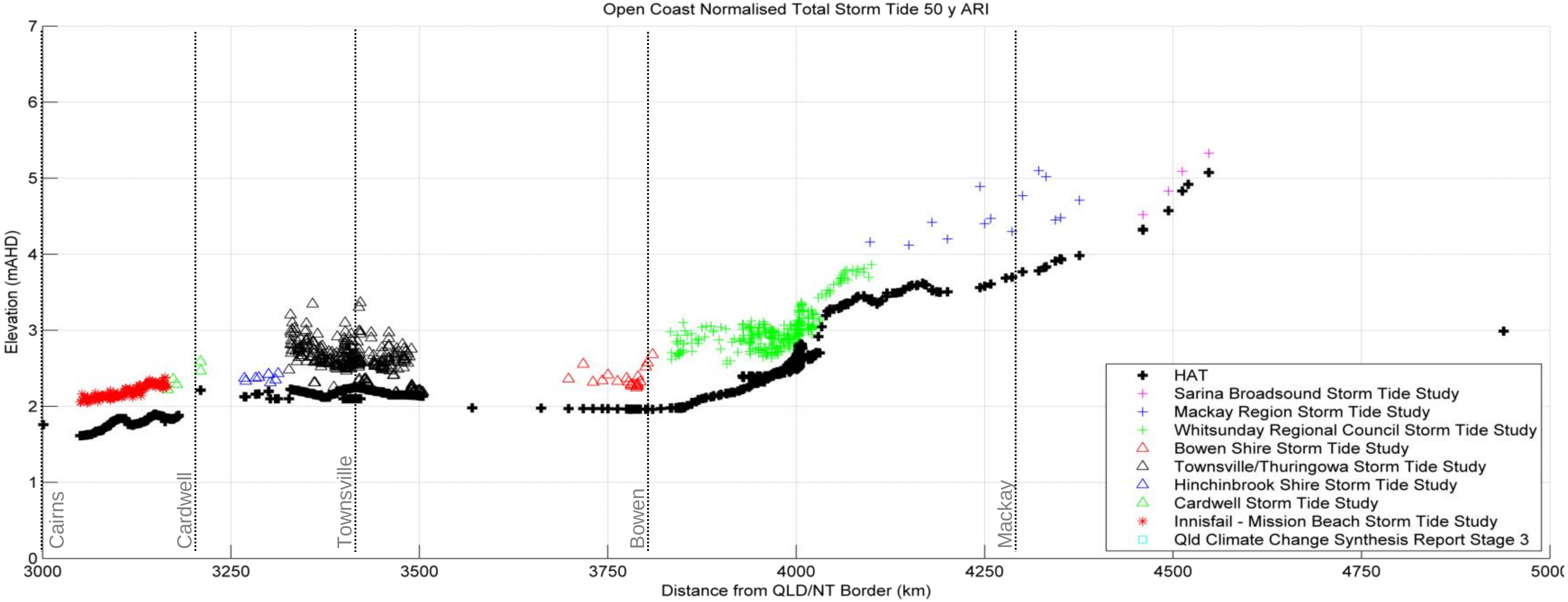


Figure – I1. 20 y (top) and 50 y (bottom) ARI Normalised Total Storm Tide Estimates (Cairns to St. Lawrence).

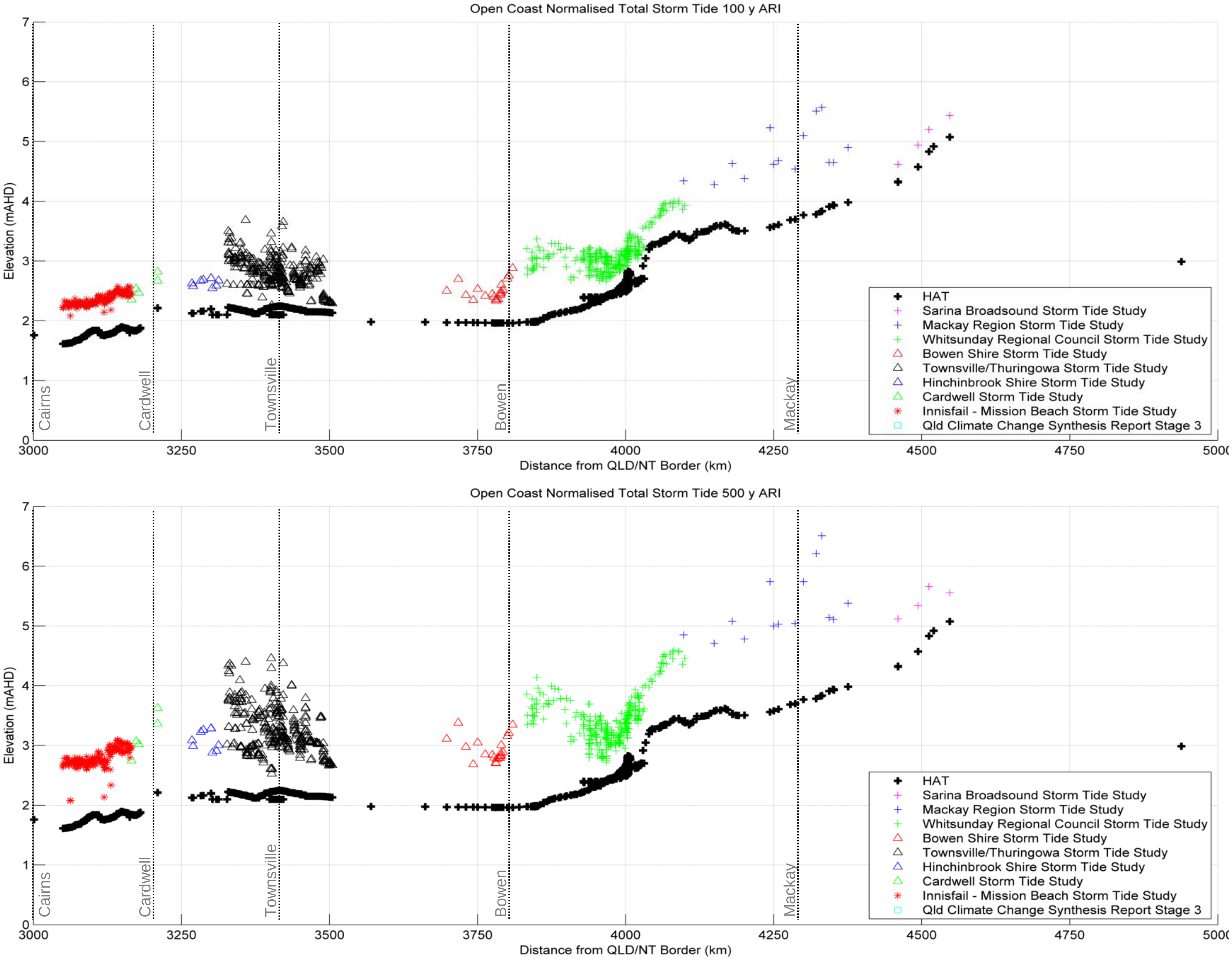


Figure – I2. 100 y (top) and 500 y (bottom) ARI Normalised Total Storm Tide Estimates (Cairns to St. Lawrence).

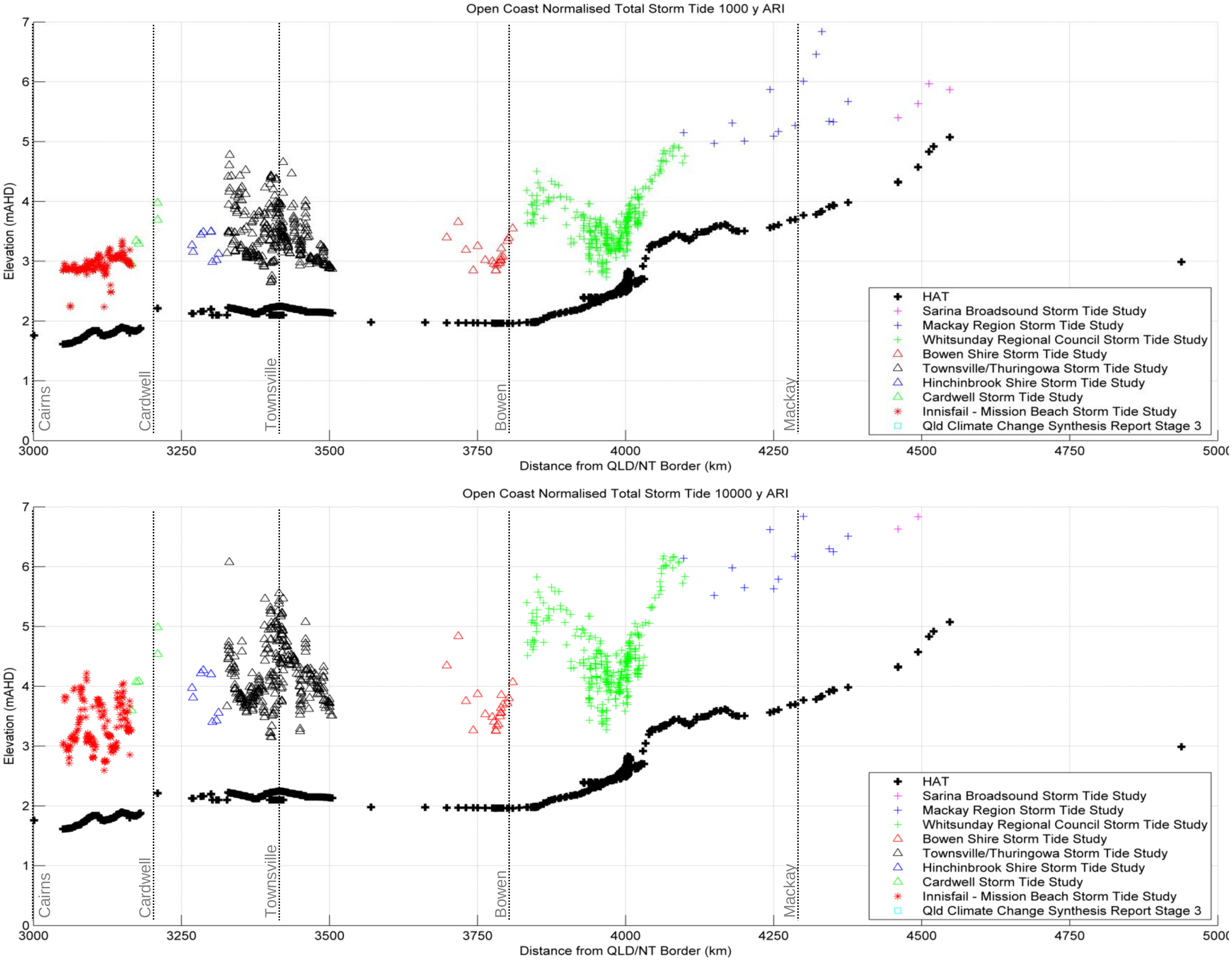


Figure – I3. 1000 y ARI (top) and Probable Maximum (bottom) Normalised Total Storm Tide Estimates (Cairns to St. Lawrence).

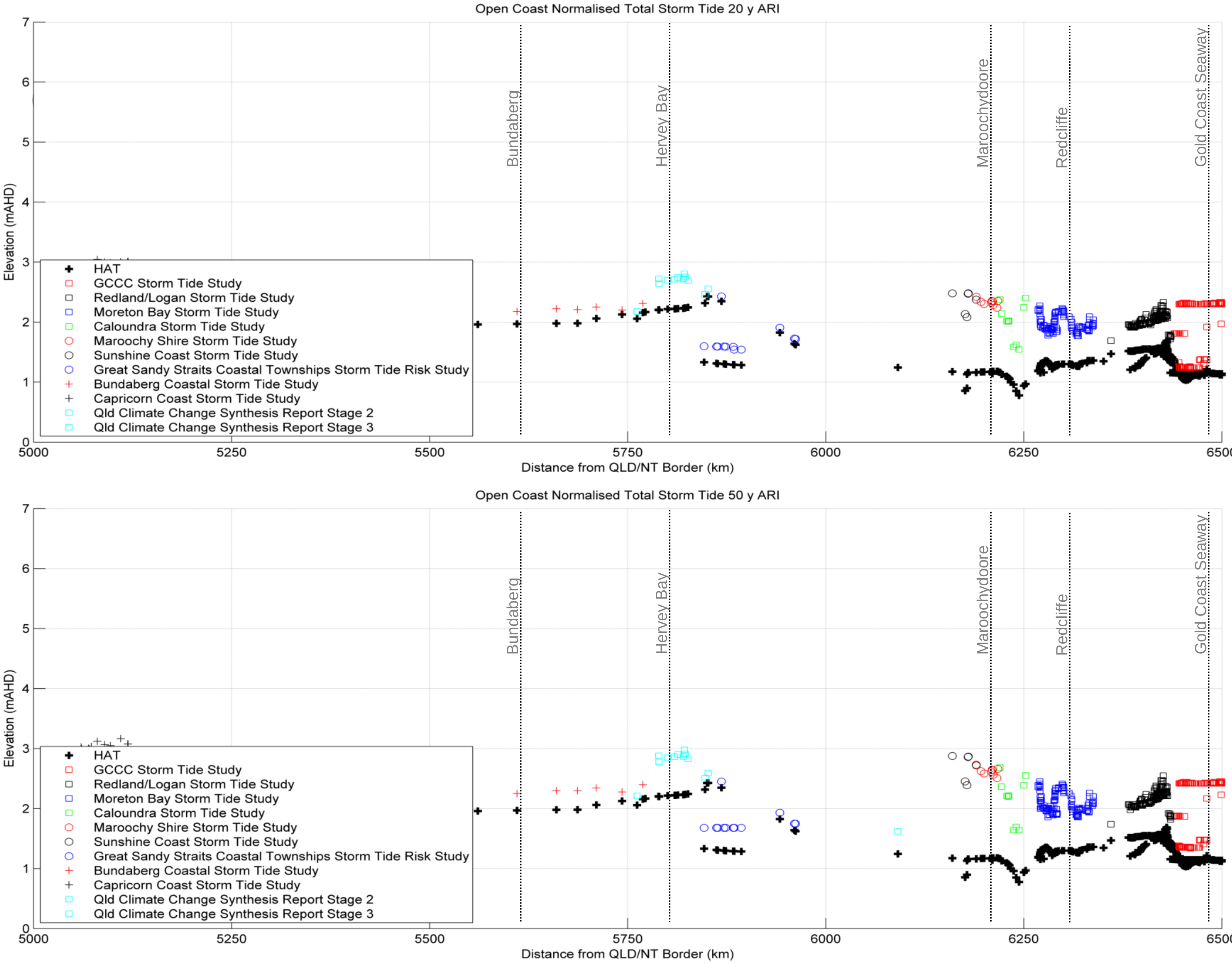


Figure – I4. 20 y (top) and 50 y (bottom) ARI Normalised Total Storm Tide Estimates (St. Lawrence to Point Danger).

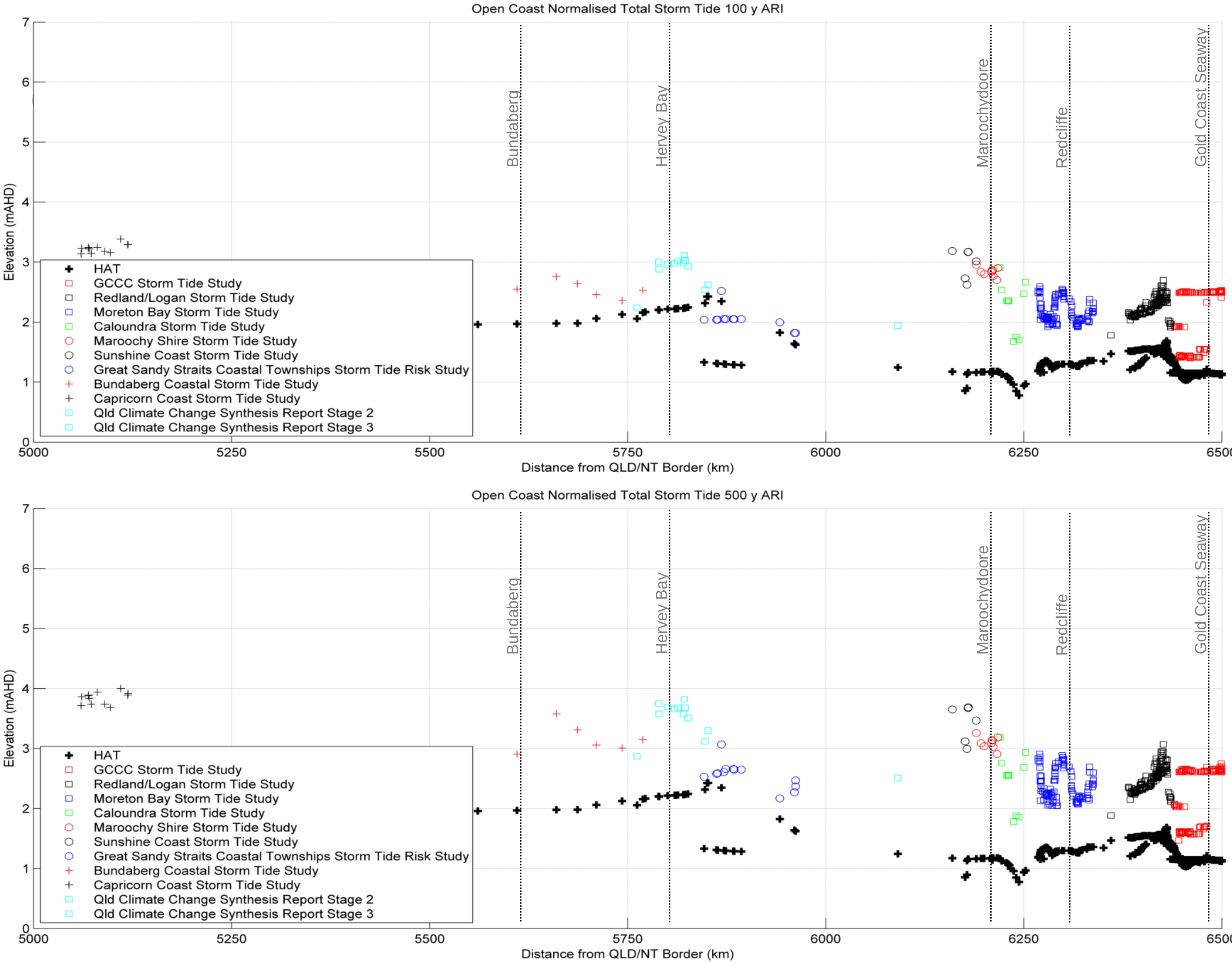


Figure – I5. 100 y (top) and 500 y (bottom) ARI Normalised Total Storm Tide Estimates (St. Lawrence to Point Danger).

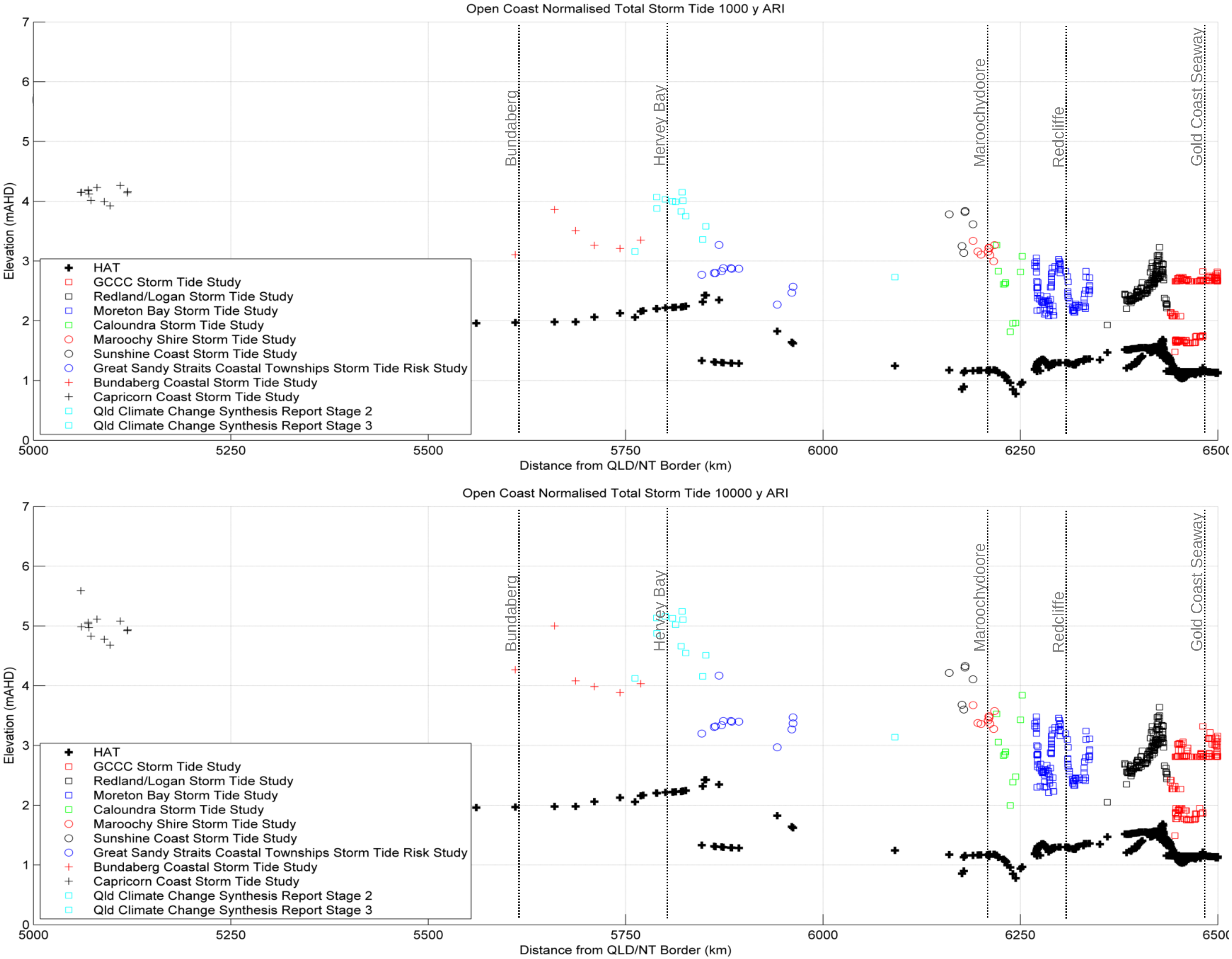


Figure – I6. 1000 y ARI (top) and Probable Maximum (bottom) Normalised Total Storm Tide Estimates (St. Lawrence to Point Danger)

Appendix J – Dune Crest and Beach Slope Assessment

Purpose

This assessment has been completed to provide dune crest and beach slope information for state-wide storm tide prediction modelling. The outputs form key input parameters required for the estimation of wave setup.

Methodology

Beach slope and dune crest information has been extracted from 5 m LiDAR DEM information provided by the State. The methodology has been developed based on the *'Advice for Assigning SEAtide Dune Crests and Beach Slopes (SEA, 2014).*

Dune Crest Extraction

To determine approximate beach dune crest levels a total of 629 cross sections have been manually identified at representative sites spanning the east coast and Torres Strait. In populated regions, cross sections have been extracted at a maximum distance of 1-2[11] km apart while in regions of limited population cross sections have been extracted at intervals of approximately 5-10 km apart. The State Infrastructure Planning Cadastral Dataset has been used to determine the extent of populated regions.

The offshore limit of each cross section has been defined by the LiDAR ocean interface or the 0 m AHD contour. Onshore the cross section has been carefully selected to ensure that only the frontal dune has been sampled. An example cross section from the Gold Coast is provided in Figure J1.

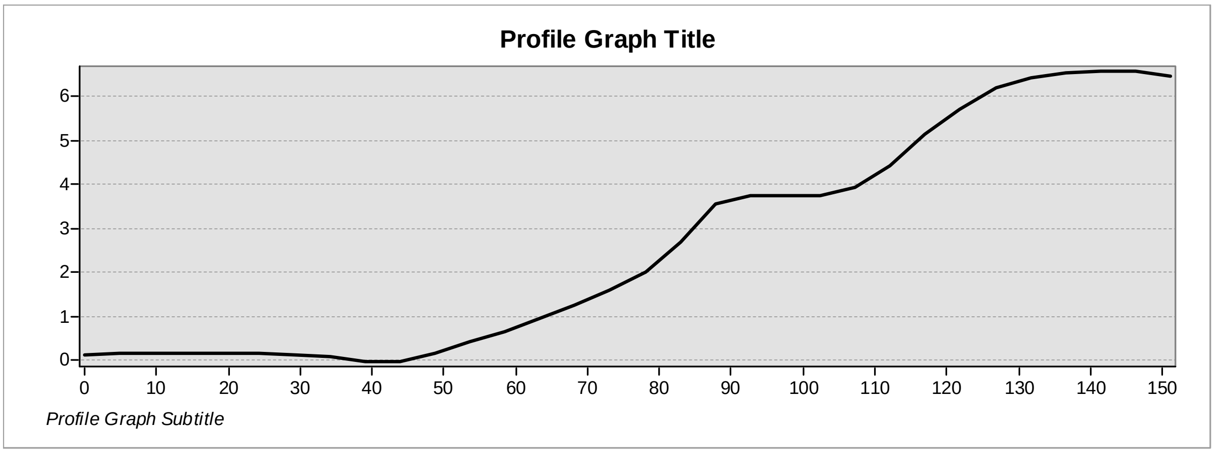


Figure J1 Example beach cross section. In this case the offshore cross section extent will be limited to approximately chainage 40 m. The dune crest for this location is at chainage 140 m of approximately 6.8 m AHD.

Beach Slope Calculation

For each cross section the average beach slope between 0 m AHD (or lowest cross sectional elevation above 0 m AHD) and the Highest Astronomical Tide (HAT) has been calculated. This process is shown via Figure J2. Key steps include:

[11] Where possible, cross sections have been assigned immediately adjacent to offshore storm tide points.

- At each cross section HAT has been determined based on the DSITIA provided HAT gridded GIS raster for the QLD coast;
- The average slope (r) has been calculated based on the region from 0 m AHD to HAT.
- The calculated beach slopes via LiDAR have been verified against available DSIITA beach profile information at a number of locations. The calculated and measured beach slopes provide a surprisingly good level of agreement of on average ± 2 °.

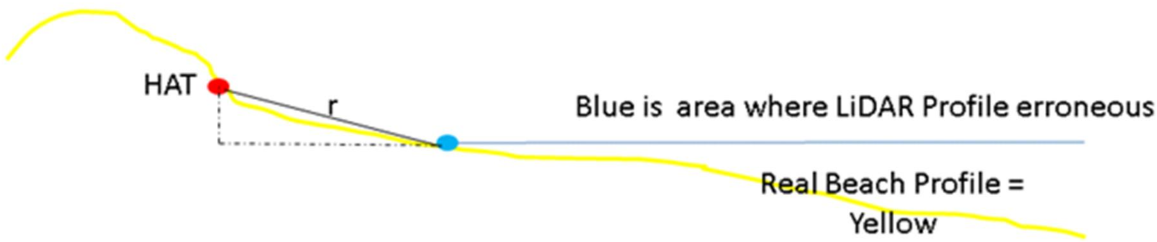


Figure J2 Beach Slope Calculation Method

Assignment of Beach Slope and Dune Crest to Storm Tide Points

Slope and dune crest information from each of the 629 discreet cross sections has been interpolated onto two 1 km x 1 km grids. This grid allowed assignment dune crest and beach slope information to be assigned at all required offshore storm tide points.

Assignment of Headland/Cliff, Mangrove and Coral Cays

Regions of headland/cliff, mangrove and offshore coral cays have been identified using available aerial photography and the provided DEM. In these areas dune crest and slope information has been manually overwritten as per the requirements of the project brief. The values for each coastline type is provided in Table J1.

Table J1 Headland/Cliff, Mangrove and Coral Cays

Coastline Type	Dune Crest (m AHD)	Slope (Degrees)
Headland/Cliff	10	20
Mangrove	0	0
Coral Cay	HAT*	0
Beach	As calculated	As calculated

*Note: If the specified point was outside the DSITIA HAT raster layer the dune crest value at a specified point of null or -9999 has been assigned.

9.1 References

SEA (2014) Advice for Assigning SEAtide Dune Crests and Beach Slopes. Systems Engineering Australia, Feb, 8pp.

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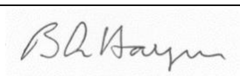
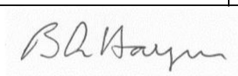
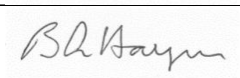
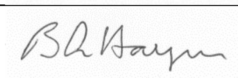
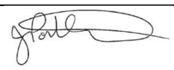
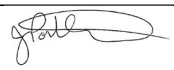
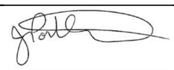
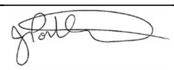
Document Status

Rev No.	Author	Reviewer		Approved for Issue		
		Name	Signature	Name	Signature	Date
1	M.Smith	B.Harper		B.Harper		14/05/13
2	M.Smith B.Harper	B.Harper		B.Harper		13/08/13
3	M.Smith	J.Postlethwaite		J.Postlethwaite		06/03/2014
4	M.Smith	J.Postlethwaite		J.Postlethwaite		12/06/2014

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