ASSOCIATION OF BAYSIDE MUNICIPALITIES

Final Report | 2015

Port Phillip Bay
Managing Better Now program

REPORT 03

PORT PHILLIP BAY SEA LEVEL

This report has been prepared by Cardno Victoria Pty Ltd for the Association of Bayside Municipalities as part of the Managing Better Now program.

ASSOCIATION OF BAYSIDE MUNICIPALITIES

The Association of Bayside Municipalities represents the ten councils with frontage to Port Phillip Bay. As coastal councils we are acutely aware of the need to protect and manage Port Phillip Bay for our local communities, and for the benefit of all Victorians, tourists and the unique ecosystems it supports.

As the appointed Committee of Management for much of the Port Phillip Bay coast, councils play a vital role in the environmental management of Port Phillip Bay, as the foreshore manager, strategic land use planning authority; asset manager; and service provider to Parks Victoria or other Committees of Management, and more.

The ABM vision is a healthy Port Phillip Bay that is valued and cared for by all Victorians.

ABM MEMBER COUNCILS:

ACKNOWLEDGEMENTS

The Association of Bayside Municipalities acknowledges funding from Member councils and state government to enable the Managing Better Now program. Thank you to the staff from ABM Member Councils and Melbourne Water for providing technical input and feedback on the reports.

The Association of Bayside Municipalities recognising the substantial support from Cardno in preparing the reports, and presenting the outputs and recommendations over many years.

EXECUTIVE SUMMARY

The *Managing Better Now* program is an initiative of the Association of Bayside Municipalities.

Launched in 2013, the program aimed to better understand the dynamics and coastal processes of Port Phillip Bay using data modelling and analysis to:

- Improve knowledge of coastal processes in Port Phillip Bay, and their effects on vulnerable sections of the coast.
- Understand present and future risks and hazards.
- Inform the management of coastal processes impacting Port Phillip Bay 'now' and into the future.
- Contribute to a future coastal hazard assessment for Port Phillip Bay.

Outputs from the Managing Better Now program are designed to support better decision making, clearer investment, management and planning by ABM Member Councils and other bay stakeholders in:

- beach protection,
- local coastal hazard and risk assessment,
- foreshore and infrastructure management,
- maintenance planning and response to weather extremes, and
- coastal climate adaptation.

Using a 'step by step' approach, the program was undertaken in phases with work proceeding as funding and resources were secured.

Phases 1 and 2 examined the programs, strategies and approaches used to manage the coastline, beaches and immediate foreshore areas, identifying gaps in knowledge. Phases 3, 4 and 5 gathered existing information and invested in data modelling and analysis of new essential data, mapping and modelling – compiling a series of reports aimed at better understand the dynamics of Port Phillip Bay.

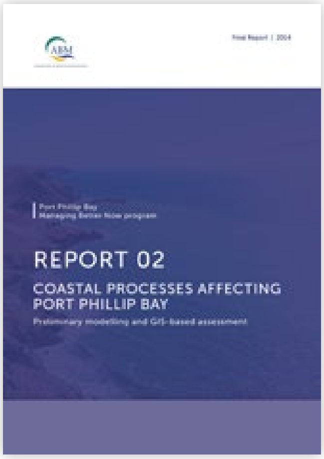
As coastal mangers, the ABM recognises the importance of using the best available information, and values working in partnership to improve understanding of the processes and systems affecting Port Phillip Bay

The following reports comprise the Managing Better Now series, and are available on the ABM website at www.abm.org.au.

REPORT **Snapshots**

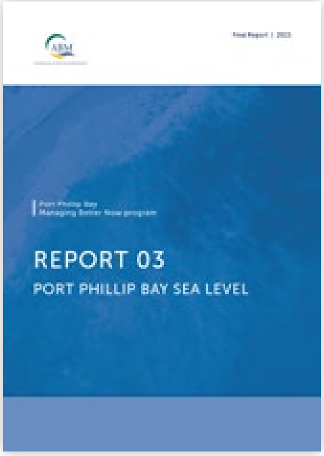
Report #1: Coastal Processes Affecting Port Phillip Bay - preliminary data collection and gap analysis

Identification of existing spatial and non-spatial information to inform a coastal hazard assessment. This included spatial data layers, over 200 technical reports, images and 60 strategies and plans relevant to Port Phillip Bay. More than 200 GIS data layers were identified and stored on an online GIS portal, made available to ABM councils.



Report #2: Coastal Processes Affecting Port Phillip Bay – preliminary modelling and mapping of coastal asset location and proximity to the Port Phillip Bay shoreline; and GIS-based assessment of width and volume of erodible land along Port Phillip Bay.

- **Part 1:** Preliminary modelling and mapping of coastal asset location and proximity to the Port Phillip shoreline. Purpose of this study was to use readily available spatial information layers identified in Report 1 to locate and map coastal assets at a bay-wide scale, and improve understanding of the proximity of assets to the Port Phillip Bay shoreline. This work was not intended to be a comprehensive study or replace a local hazard study. It provided a demonstration of the type of analysis that can be undertaken using readily available spatial data layers, informing local studies by individual coastal land managers such as the effects of coastal storms on sections of shoreline, the effects of coastal inundation on parts of the coast, the quality of drainage networks and associated infrastructure to model water flow, availability of information for assets of significance, their values, etc.
- **Part 2:** Spatial Analysis of area (width) and volume of erodible land along Port Phillip Bay. Three methodologies were used to demonstrate the calculation of area and volume of sand between the mean sea level (taken as the shoreline) and three different landward extents. The landward extents are based on existing infrastructure such as roads or houses; horizontal distances (eg, within 5 metres, 10 metres, etc.); or vertical elevation (eg, 0.5 metres, 1.0 metres, etc.) from the shoreline. Information about physical processes or hazards, including sediment transport rates, wave impacts, shoreline erosion rates or other such information was not available. The approach used is of generic and demonstrative nature and can be applied around Port Phillip Bay; and substantially enhanced if coupled with information about coastal processes and coastal hazard information.



Report #3: Port Phillip Bay Sea Level

Analysis of existing historical sea level data for Port Phillip Bay measuring sea levels over an extended period at multiple locations. Data was collected from Port of Melbourne Corporation, National Tidal Centre, Victorian Regional Channel Authority and Melbourne Water. Data was subjected to extreme value analysis to develop values for sea level with Annual Exceedance Probabilities at 1%, 2%, 5% and 10% (corresponding to Annual Recurrence Intervals of 100, 50, 20 and 10 years).

The results are intended to support the setting of values for planning and design, not replace decisions made by the appropriate responsible authorities. Results may be useful in establishing regional variations; undertaking assessments of the appropriate values in setting planning benchmarks and design criteria; investigating potential risks; supporting planning, design and assessment of future coastal vulnerability considering climate change.

Report #4: Port Phillip Bay Wave Climate

Wave modelling for the whole of Port Phillip Bay using a tested and consistent approach. The modelling incorporated annual and seasonal occurrence of wave conditions, highlighting the marked seasonal variability in wave conditions over Port Phillip Bay resulting from seasonal wind changes. The longshore component of wave power was also computed for the entire shoreline providing insights into the annual and seasonal variability of potential sediment transport around Port Phillip Bay.

Modelling results can be used to understand phenomena observed on a specific beach, or to review broad bay-wide scale processes.

In addition to the data presented in the report, detailed frequency of occurrence matrices for each of the 248 data extraction points have been provided as tables which can be accessed via a Geographic Information System. Contact the ABM for further information.

Report #5: Port Phillip Bay Storm Bite Analysis

Building on the previous studies of waves and sea levels in Port Phillip Bay, this project modelled likely volumes and extent of storm bite erosion on 20 beach profiles in Port Phillip Bay between Little River and Sorrento, under varying storm conditions. Results inform changes in beach profile following an individual storm event, and the magnitude of the storm event.

This report provides a first-pass risk assessment of coastal erosion that can be used to identify and prioritise areas of concern; focus more detailed studies on areas of intolerable risk level; and to understand what level of coastal erosion might be expected in a ‘typical’ or an ‘extreme’ storm event.

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Glossary

Abbreviation	Definition
ABM	Association of Bayside Municipalities
AEP	Annual Exceedance Probability: the likelihood that the given level will be exceeded by the stated probability in any one year.
AHD	Australian Height Datum The Australian Height Datum is a geodetic datum for altitude measurement in Australia, "In 1971 the mean sea level for 1966-1968 was assigned the value of zero on the Australian Height Datum at thirty tide gauges around the coast of the Australian continent"
ARI	Average Recurrence Interval: the average interval (in years) between recurrences of an exceedance of the given level.
Astronomical tides	The fall and rise of sea levels caused by the gravitational effects of the Earth, Sun and Moon, without any atmospheric influences.
BoM	Bureau of Meteorology
CD	Chart Datum The datum to which soundings on a chart are referenced. It is usually taken to correspond to a low-water elevation.
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Fetch	The maximum distance over water that winds of a constant speed and direction can generate waves. Areas such as Port Phillip Bay are defined as fetch-limited meaning that wave heights will always be restricted by the area over which wind can blow.
HAT	Highest Astronomical Tide The highest level which can be predicted to occur under average meteorological conditions
High tide	Term used by Adams (1987) for what is called a storm tide in this report
High water	Maximum height reached by a rising tide.
MHHW	Mean Higher High Water: the average over a number f years (ideally 18.6 years) of the level of the higher of the high tides in each day. Similarly for other tidal planes.
MSL	Mean sea level (see Section 2.4 for a discussion)
MW	Melbourne Water

NTC	National Tidal Centre (within the Bureau of Meteorology
PoMC	Port of Melbourne Corporation
Storm surge	A combination of barometric set up, wind set-up, and coastal trapped-waves leading to an increase in sea level above the predicted tide.
Storm tide	The highest level measured by a tide gauge during a storm event, the combined effect of the storm surge and astronomical tide (based on hourly values)
UTC	Coordinated Universal Time (French: Temps Universel Coordonné, UTC) is the primary time standard by which the world regulates clocks and time. For most purposes, UTC is used interchangeably with Greenwich Mean Time (GMT), but GMT is no longer precisely defined by the scientific community.
VRCA	Victorian Regional Channels Authority

01. Introduction

This reports aims to improve understanding of the impacts of sea level rise in Port Phillip Bay. Through analysis of existing historical sea level data for Port Phillip Bay the project measured sea levels over an extended period at multiple locations. Where appropriate, data was also subjected to extreme value analysis to develop values for sea level with Annual Exceedance Probabilities at 1%, 2%, 5% and 10% (corresponding to Annual Recurrence Intervals of 100, 50, 20 and 10 years).

The scope of work set out to:

- determine 1% AEP sea levels for Port Phillip Bay based on measured data;
- compare with values from previous work; and
- recommend values for use at locations around the bay for planning and design purposes.

Results support the setting of values for planning benchmarks, design criteria or investigating potential risks. They do not replace decisions made by the appropriate responsible authorities. Results may be useful in establishing regional variations; undertaking assessments of the appropriate values in setting planning benchmarks and design criteria; investigating potential risks; supporting planning, design and assessment of future coastal vulnerability considering climate change.

1.1. Qualifications

This report and analysis has relied on data provided by others. No independent checks on the accuracy or validity of these data have been undertaken other than those available in published documents and internal consistency checks. The sources are reputable and presumed to have carried out quality control checks prior to providing the data to this study.

The sea level provided as chart datum was converted to Australian Height Datum (AHD) based on the information provided by the sources. Investigation of the reliability of this adjustment is beyond the scope of this report and relies on internal comparisons and checks.

02. Background

2.1. Available Data

Sea level data within Port Phillip Bay has been obtained from four sources; Port of Melbourne Corporation (PoMC), National Tidal Centre (NTC). Victorian Regional Channel Authority (VRCA) and Melbourne Water (MW).

PoMC maintains permanent acoustic tide gauges at Queenscliff, Williamstown, Hovell Pile and West Channel Pile. The PoMC gauges use acoustic sensors in stilling wells and record 6-minute average sea levels. There is also a tide gauge on Fawkner Beacon, however this is a free-air acoustic gauge without a stilling well and the data are less reliable for extreme levels. The data from this site has not been included in the analysis. Data from the PoMC gauges are held by the National Tidal Centre (NTC) within the Bureau of Meteorology (BoM).

Tide gauges are maintained by VRCA for the Port of Geelong. Two main gauges were used as part of the project, the gauge at Shell refinery (Geelong) and, Point Richards. Hourly sea level data at Geelong was used from 1965 to 2006. Six-minute sea level data was obtained from 2006 to the end of 2013. Six-minute sea level data from the Point Richards gauge are available from 2005 to 2013.

Melbourne Water maintains tide gauges located at St Kilda and Patterson River which provide six-minute sea level data. The data from St Kilda are available from 1977 to 2013 and Patterson River from 1993 to 2013, the latter gauge data has not been included in the analysis because of its location inside the river.

The sea level data obtained from PoMC, VRCA and NTC are relative to chart datum (CD) and have been corrected to Australian Height Datum (AHD). Melbourne Water data are recorded relative to AHD

The list of the tide gauges used in the study, with the operator, datum, location and data period are listed in Table 1. The location of tide gauge is presented in Figure 1.

Table 1: Tide gauges used in the analysis

Tide Gauges/Stations	Owner/ Operator	Datum	Location		Data Period
			Latitude	Longitude	
Queenscliff	PoMC	CD	-38.2713	144.6640	1992-2013
Hovell Pile	PoMC	CD	-38.3272	144.8987	1991-2013
West Channel Pile	PoMC	CD	-38.1930	144.7567	2009-2013
Breakwater Pier, Williamstown	PoMC	CD	-37.8643	144.9179	1966-2013
Geelong	VRCA	CD	-38.0920	144.3933	1965-2013
Point Richards Beacon	VRCA	CD	-38.0859	144.6414	2005-2013
St Kilda	MW	AHD	-37.8720	144.9746	1977-2013

Figure 1: Location of tide gauges used in the analysis.

2.2. Astronomical Tides

The astronomical tides are the variation in sea level caused by the gravitational effects of the moon and the sun and their movements relative to the earth. These are well known and are able to be predicted with high accuracy into the foreseeable future.

The tides in the Port Phillip Bay are semi diurnal with a diurnal inequality. This means that there are, in general, two high tides and two low tides per tidal day and there is a difference in height between successive high or low tides.

The astronomical tides can be described by a set of tidal planes and the values for Williamstown and Geelong, taken from the Victorian Tide Tables (PoMC, 2014), are shown in Table 2. Values are provided relative to both CD and AHD.

Table 2: Tidal planes for Williamstown and Geelong (Inner Harbour) (PoMC, 2014)

Tidal Level	Williamstown			Geelong	
	m, AHD	m, CD		m, AHD	m, CD
Highest recorded sea level (Storm tide)	1.33 (1874-2012)	1.85		1.13 (1965-2012)	1.71
Highest Astronomical Tide (HAT)	0.52	1.04		0.66	1.24
Mean Higher High Water (MHHW)	0.42	0.94		0.42	1.00
Mean Lower High Water (MLHW)	0.12	0.64		0.12	0.70
Australian Height Datum (AHD) Approximately Mean Sea Level, (MSL)	0.000	0.524		0.000	0.580
Mean Higher Low Water (MHLW)	-0.08	0.44		-0.08	0.50
Mean Lower Low water (MLLW)	-0.38	0.14		-0.48	0.10
Lowest Astronomical Tide (LAT)	-0.48	0.04		-0.580	0.000
Chart Datum	-0.524	0.000		-0.580	0.000

2.3. Non-tidal Sea level Variations

In addition to variations in sea level caused by the astronomical tides, there are variations due to meteorological effects on the ocean surface. Wind blowing over the surface of the water causes a change in level with, for example, water "piling up" against the coast to which the wind is blowing. Atmospheric pressure leads to changes in sea level with high pressure lowering the sea level and low pressure resulting in an increase in sea level. This is called the inverse barometric effect. These changes in level can cause very long period waves to move across the ocean and, in particular, along the edge of continents where they interact with the continental shelf to form "shelf waves". There are a number of types and propagation modes for such waves and all involve a variation in sea level at the coast. The effects of shelf waves will be felt in the bay even though the waves themselves may be formed by a weather system a great distance away. Since all these mechanisms combine to make up the water-level variations other than the astronomical tides, they have been grouped under the term storm surge in this report since their combined effect will be greatest during a storm event.

The changes in sea level caused by these phenomena have a time scale similar to those of meteorological systems, which is a number of days. Due to the longer time scale, in contrast to the astronomical tides, the sea level in the Bay is able to adjust to be the same as that in Bass Strait for storm surges. Lawson & Treloar (2004) demonstrated that storm surges are almost uniform from Lorne, in Bass Strait, to Queenscliff, at the entrance to the bay, through to Williamstown in the North of the Bay. This shows that the constrictions of the Entrance and the south of the bay region do not have any effect on the level of storm surges.

The longest period (slowest) variations in sea level have time scales of many years and include sea level variations due to climate cycles and climate changes, both over geologic time and the more recently observed man-induced changes.

The combination of storm surge and astronomical tide, which is what is recorded by a tide gauge, is known as a storm tide. It is storm tides which lead to coastal inundation during storm events.

2.4. Terminology

It is important to understand the terminology used when discussing sea level. Terms have been defined in the glossary as discussed above, but further explanation is warranted.

The term "mean sea level" has historically been used for the "long-term" average of recordings of sea level from tide gauges. However, in recent years, with the recognition of changes attributed to climate change, it has become apparent that a more precise definition is required. In essence, any use of the term "mean sea level" should be accompanied by a timeframe over which the mean is applied and a reference to the time at which it refers. Thus the term can be used for an annual mean for a given year, the average of the sea level measurements over a given calendar year. It is also possible to calculate the mean over an extended period, relative to a given year by "detrending" the measured data, or removing the effects of sea level rise relative to that year.

In a similar fashion, reference to storm tides (or high sea level events) can consider the data "as-recorded" or can have the effects of sea level rise removed so as to allow comparison of the storm-tide alone, without the impact of the change in annual mean sea level over time.

The usage of the terms below should be obvious from the context or mentioned explicitly.

In this report, the term "tide" or "high tide" is used to refer to the astronomical tide unless stated otherwise. The term "storm tide" is the combination of the astronomical tide and storm surge and is used for the high sea levels recorded during storm events, but excluding the effects of wind-generated waves.

03. Previous Studies

3.1. Background

There have been a number of previous studies or publications that have presented sea levels which have been, or could be, used for design and planning purposes. These studies vary in approach and intent. They are briefly described below with any significant assumptions and a summary of their findings. These findings can then be compared with the results of the present study and used in a final recommendation for sea levels for design and planning purposes around Port Phillip Bay.

3.2. Adams (1987)

Adams (1987) states the purpose of his report "*is to determine,*

- *The true tide level during the November – December 1934 flood,*
- *What effect the tide had on the flood levels in the Yarra River downstream of Spencer Street,*
- *The frequency distribution for high tides."*

In this context, Adams term "high tides" corresponds with "storm tides".

Adams discusses in some detail the various tide gauge and survey datums which contribute to the definition of the sea levels in a common (AHD) datum. He also considers the accuracy and validity of the different sources of data.

Based on data from1874 to 1939 and 1944 to 1985, Adams used a log-normal annual series and partial series to derive levels for a range of return periods and "Adopted Levels" were selected from the analysis results and rounded to the nearest 0.05 m AHD. His results are shown in Table 3.

Table 3: Summary of Adams (1987) storm tide levels for Williamstown

Return Period	Calculated Levels (Log-normal)		Adopted Levels
	Annual Series	Partial Series	
years	m AHD	m AHD	m AHD
200	1.33	n/a	n/a
100	1.28	1.32	1.30
50	1.23	1.27	1.25
20	1.20	1.21	1.20
10	1.09	1.14	1.15
5	1.02	1.07	1.10
2	0.89	0.98	1.00
1	n/a	0.89	0.90

3.3. McInnes, et al. (2009)

McInnes et al. *"provides data and information about the potential extent of extreme sea levels under a range of sea level rise scenarios."*

McInnes et al. did not undertake any analysis of measured data in its own right to provide water levels for planning and inundation. All the results presented by McInnes et al. are from numerical models, both for storm surge and tides, and thus the combination to yield storm tides. They use measured data to identify periods of storm surge and for comparison of the modelled tidal constituents with those from measurements.

McInnes et al. combine the storm surge and tidal elevation using the peak level from the surge (that is the highest level of the storm surge from the model) and the modelled tide at the time of the peak surge. This does not allow for the possibility of a near-peak sea level from a storm surge combining with a high tide to yield a higher combined sea level than the peak of the surge and tide at the time of that peak. This may not have a significant effect at the 1% AEP level, but may be important at more frequent events such as 10% or 20% AEP.

Table 4 presents a summary of the results of McInnes et al. for present day (1990 mean sea level) storm tide extreme levels at a range of frequencies of occurrence and including the 95% confidence interval (taken from Table 6 of McInnes et al.).

Table 4: Summary of present day (1990) storm tide levels in m AHD (from McInnes et al., 2009)

Location	ARI / AEP			
	10 yr / 10%	20 yr / 5%	50 yr / 2%	100 yr / 1%
Point Lonsdale	1.16 ± 0.26	1.27 ± 0.26	1.35 ± 0.26	1.41 ± 0.27
Queenscliff	1.04 ± 0.28	1.12 ± 0.28	1.20 ± 0.28	1.23 ± 0.28
Geelong	0.91 ± 0.09	0.98 ± 0.09	1.03 ± 0.10	1.06 ± 0.10
Werribee	0.94 ± 0.09	1.00 ± 0.09	1.07 ± 0.09	1.09 ± 0.09
Williamstown	0.96 ± 0.09	1.03 ± 0.09	1.09 ± 0.09	1.12 ± 0.10
St Kilda	0.99 ± 0.09	1.05 ± 0.09	1.12 ± 0.10	1.15 ± 0.10
Aspendale	0.98 ± 0.09	1.05 ± 0.09	1.11 ± 0.10	1.14 ± 0.10
Frankston	0.98 ± 0.09	1.05 ± 0.09	1.11 ± 0.10	1.15 ± 0.10
Mornington	0.97 ± 0.09	1.04 ± 0.09	1.10 ± 0.10	1.14 ± 0.10
Rosebud	0.93 ± 0.09	0.99 ± 0.09	1.06 ± 0.10	1.09 ± 0.10
Rye	0.89 ± 0.09	0.95 ± 0.09	1.01 ± 0.10	1.04 ± 0.10
Sorrento	0.85 ± 0.09	0.91 ± 0.09	0.96 ± 0.10	1.00 ± 0.10

In commentary on these values, McInnes et al. note the following (page 34 of their report)

"There is a strong gradient in storm tide return levels just inside the entrance to Port Phillip Bay as the tides are strongly attenuated by the narrow entrance. We note that the 95% confidence intervals for Point Lonsdale and Queenscliff, which are located in this area of strong gradient, are particularly large. This is due to poorer agreement between simulated and observed tidal constituents in this area than elsewhere in the bay and suggests that the modelled results are less reliable in this area. The storm tide return levels presented in this study for this area differ quite substantially from those presented by McInnes et al. (2009), who sourced tidal constituent data from tide gauge observations."

The reference to McInnes et al (2009) in this quotation is not clear as the references list several possible sources.

3.4. Melbourne Water (2012)

Melbourne Water (2012) are guidelines for use *"in assessing development proposals for areas within the Port Phillip and Western Port Region affected by tidal inundation and flooding associated with predicted sea level rise"*.

The guidelines state that the flood level for 2010 for Port Phillip Bay for a 100 year ARI event is 1.6 m AHD. For the redevelopment of existing buildings or new buildings within existing development zones, Melbourne Water also require a 600 mm freeboard above the relevant flood level.

The basis for Melbourne Water's levels is stated as:

A Bay level of 1.52m AHD was "recorded" at Williamstown during the 1934 flood event. This level was accepted by the Melbourne and Metropolitan Board of Works, (MMBW) and was rounded up to 1.6m AHD as a starting water level for flood modelling on various waterways.

A further study was undertaken by the MMBW Hydrology and Flood Warning Unit in 1987. Tide levels during November to December 1934 - flood high tide frequency analysis found that the maximum level at Williamstown in the 1934 flood event was more likely to have been 1.33m AHD. As part of the same study, the frequency analysis of tide charts determined the flood level for a 100 year average recurrence interval (ARI) event to be 1.3m AHD.

In 2009, Melbourne Water completed a frequency analysis study of all available data for St Kilda Marina. Using 31 years of available data, this study found that a reasonable flood level for a 100 year ARI event to be 1.4m AHD. This analysis included a July 2004 recorded still tide level of 1.29m AHD.

Melbourne Water's existing 100 year flood level of 1.6m AHD provides a minor allowance for wave action.

3.5. PoMC Tide Tables.

The PoMC Tide Tables (89th Edition, 2014) report the "highest recorded tide" (storm tides in the terminology of this report) for a number of locations based on varying lengths of record. These values are shown in Table 5.

Table 5: Highest recorded storm tides from PoMC Tide tables (2104)

Location	Length of record	Highest recorded tide	
		(m AHD)	Date
Point Lonsdale	1962-2012	1.30	4/7/1981
Williamstown	1874-2012	1.33	30/11/1934
Geelong	1965-2012	1.13	5/7/2011

3.6. Canute

The Antarctic Climate and Ecosystems Cooperative Research Centre http://www.acecrc.org.au/ has a system called Canute which provides values for sea level at various probabilities and sea level rise scenarios. The web site states:

"Canute provides estimates of the likelihood of future flooding from the sea. By combining two uncertainties (the frequency of present storm surges and the uncertainty of future sea level rise) into a single likelihood, a statistically robust prediction is generated.

The storm-tide data used in this analysis was provided by numerical modelling performed by the University of Western Australia. The simulations were adjusted to provide consistency with observations from 29 tide-gauges provided by the Australian National Tidal Centre. The modelled results and observations have been validated to yield data which is of the best quality that is practically achievable at this time, although some unresolved errors may remain. Note, this data currently does not include the impact of tropical cyclones."

Values are given for sites where tide gauges are located as well as a large number of model output points. The results from the two computations vary slightly for the same locations. Values have been extracted from Canute (read from graphs of sea level probability). The results, in Table 6 are for mean sea level at the 2000 level. Geelong tide gauge outputs are labelled as "Suspect Data". Tide gauge data from Williamstown and Geelong are available, but St Kilda is only available as modelled outputs.

Table 6: Values for sea level (m AHD) for sites in Port Phillip Bay from Canute

Location	ARI / AEP	
	10 yr / 10%	100 yr / 1%
Geelong (TG)	1.00	1.09
Williamstown (Model)	1.05	1.21
Williamstown (TG)	1.01	1.08
St Kilda (Model)	1.12	1.27
Queenscliff (Model)	1.19	1.33
Point Lonsdale (TG)	1.23	1.34

04. Data Processing

4.1. Processing Steps

The aim of the data processing and analysis is to generate values for sea level for extreme events, that is the levels having an Annual Exceedance Probability (AEP) of 1%, 5%, 10% and 20%. This corresponds to an Annual Recurrence Interval (ARI) of 100, 20, 10 and 5 years respectively. AEP is the preferred terminology as it portrays the risk of the event in a clearer way and this will be the terminology used in the report.

Data is available as both one-hourly values and six-minute values. For the purposes of coastal inundation, one-hourly values are more appropriate (supported by Paul Davill, NTC, pers. comm.). Six-minute values are likely to vary from one station to another due to differences in the detailed characteristics of the stilling wells and also due to the precise location of the tide gauge with respect to local seiching (oscillations of the water surface within harbours, basins, etc). Also, inundation levels and extents will not be controlled by high frequency variations in sea level other than for locations very close to the sea in limited circumstances. For these reasons and also that much of the data is only available as hourly values this study uses hourly values and the resulting sea levels are hourly average values.

The data processing steps are set out in Figure 2.

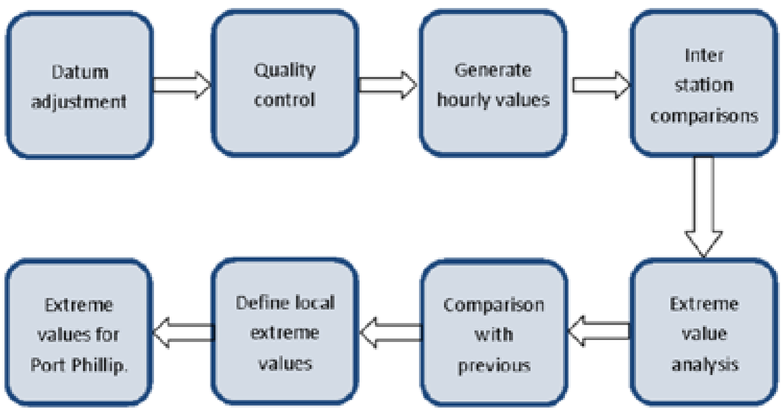


Figure 2: Steps in data processing

4.2. Datum Conversion

All data sourced from PoMC, NTC and VRCA were converted from CD to AHD. Datum conversion values were obtained from the PoMC document "OP101-03_gaugeSensors_PoMC_reference.doc", in which chronological information on gauge datum is documented. The datum information prior to 1991 was based on Stewart (1983). Sea level data from Melbourne Water at St Kilda was provided in AHD. A summary of datum conversion values from CD to AHD is given in Table 7.

Table 7: Tide-gauge datum conversion from Chart Datum to Australian Height Datum

Time Period	Station					
	Williamstown	Geelong	Point Richards	Queenscliff	West Channel Pile	Hovell Pile
Before 1 Jan. 1970	-0.466					
After 31 Dec 1969	-0.524					
July1991-7 Jun1993	-0.526					
After 7 Jun1993	-0.524					
Before1 Jan 1998		-0.441				
After 1 Jan 1998		-0.580				
All			-0.524			
Before 1 Jan 1996				-0.784		
After 1 Jan 1996				-0.625		
All					-0.524	-0.524

4.3. Quality Control

The percentage of valid data in each year has been identified. The percentage of valid data is important to identify so that only valid years of data are included in the extremal analysis. That is, if within 30 years of data 5 years contained a large number of missing values, the extremal analysis would be undertaken based on 25 years of data not 30.

The first step in the data quality control is plotting of all data and visual identification and removal of obvious errors such as spikes, "flat-line" or outliers. Since all data comes from third parties it was anticipated that internal procedures would have identified such errors and no obvious errors were identified during this process. Data were then inspected in more detail and compared with that from other stations for the same period.

4.3.1. Williamstown

Measured sea level data at Williamstown is available from 1966 to 2013. Earlier data is available and has been analysed by Adams (1987), but is not available in digital form from NTC. Prior to July 1991, sea level was recorded using a chart recorder and digitised manually to provide hourly values. Prior to and including 1972, the data were extracted manually from the charts in units of tenths of a foot (30.5 mm) and converted to centimetres in the digital database. From 1973 to June 1978, data was recorded in decimetres (100 mm). This resulted in a significant loss of resolution as shown in Figure 4. From July 1978, data was measured in centimetres from the charts until the installation of a digital Sutron Logger at Breakwater Pier in 1991. From July 1991 sea level has been recorded in millimetres at six-minute intervals. NTC have filled gaps in the record with readings from Victoria Dock while this tide gauge was operating.

Data from Williamstown are provided by NTC in UTC.

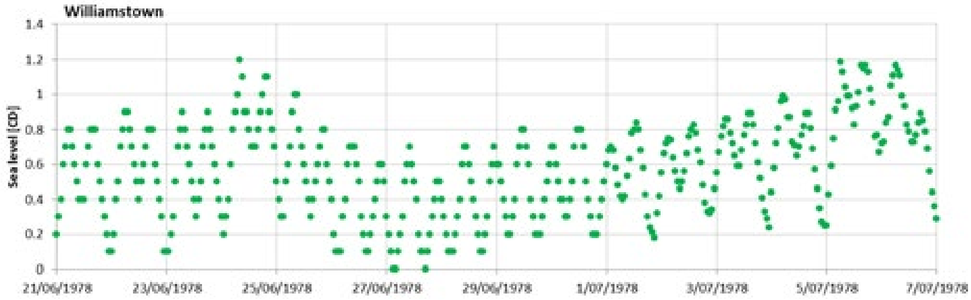


Figure 3: Data from Williamstown during 1978, measured in decimetres from chart records, note the loss of resolution.

The percentage of valid data at Williamstown from 1965 to 2013 is over 90% for the whole 48 years. The highest number of days missing is 59 days in 2007. Data return from all stations is discussed further below.

4.3.2. St Kilda

Data at St Kilda has been recorded from 1977 to 2013. From the 37 years of data less than 5% of data is missing. Data is provided as six-minute values with a resolution of 1 mm and is recorded in local time.

Due to the proximity of the Williamstown and St Kilda tide gauges, it is expected that the sea level will be very similar at these two sites with possible exceptions during storm events when the St Kilda sea level may become elevated, especially during westerly winds. This provides a ready check on the quality of the data from the two sites. The correspondence of the two gauges from 1977 to 2013 has been investigated by subtracting the hourly data at St Kilda from that at Williamstown at corresponding times and this difference has been plotted in Figure 5.

Figure 5 shows that in each year from October to March, which corresponds approximately to the change to daylight saving time in Victoria, the difference between the two sites increases. This has been found to be due to the St Kilda data being recorded in Local Time. However, inspection of the data found that the daylight saving time appears to be manually adjusted as the times are not related to the specific timing of daylight saving as specified on the BoM website. The record also shows that the record was maintained in Eastern Standard Time (AEST) from 2009. The timing difference was confirmed by comparison with data recorded at Geelong. It was found that Geelong and Williamstown are recorded in the same constant time zone, but that St Kilda varies.

The circled points in Figure 5 show apparent changes in the datum at one of the tide gauges. Again, checks against Geelong suggest that the change is at St Kilda. Figure 5 also suggests significant periods of very large differences due to causes other than natural phenomena. Without supporting meta-data for St Kilda, which may exist, but was not provided with the data, it is very difficult to correct the St Kilda data by removing poor-quality data points. The St Kilda data was therefore retained in the processing, but the resulting values are not considered reliable.

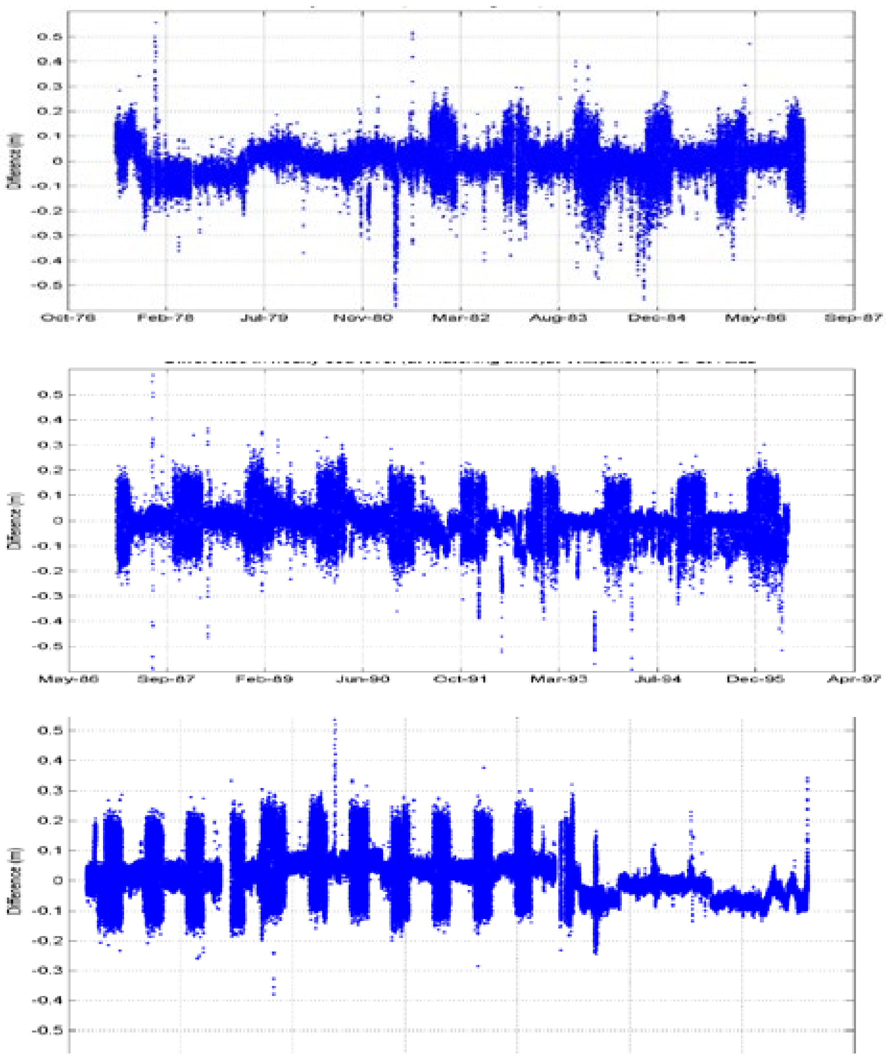


Figure 4: Difference in hourly sea levels between Williamstown and St Kilda.

4.3.3. Geelong

The longest data set available at the time of the study are from Geelong, from 1965 to 2013 or 49 years. There are gaps and some years have very little data, for example there are no data for 1968. Overall there is about 16% of data missing from the whole 49 years excluding 1968.

4.3.4. Point Richards

The recorded sea level at Point Richards is only available for 9 years with 99% of valid data available for years excluding 2005 for which there is no data. Due to the short time period no extreme value assessment was undertaken as reliable assessment of a 1% AEP requires at least 30 years of data.

4.3.5. Queenscliff

From the 22 years available, the number of missing days at Queenscliff is around 6% excluding 1992 where there is no data and 2002 when about 60% of the data are missing.

4.3.6. West Channel Pile

At West Channel Pile, sea level data were available from 1991 to 2013. The number of missing days is less than 20% in the available years. There are no data from January to May 1992. .

4.3.7. Hovell Pile

At Hovell Pile, 93% of valid data is available for a period of 23 years. Data for the first half of the year 1991 is missing

4.3.8. Summary

The amount of quality-controlled data available for analysis from all stations is shown in Figure 6. The details are provided in Appendix A.

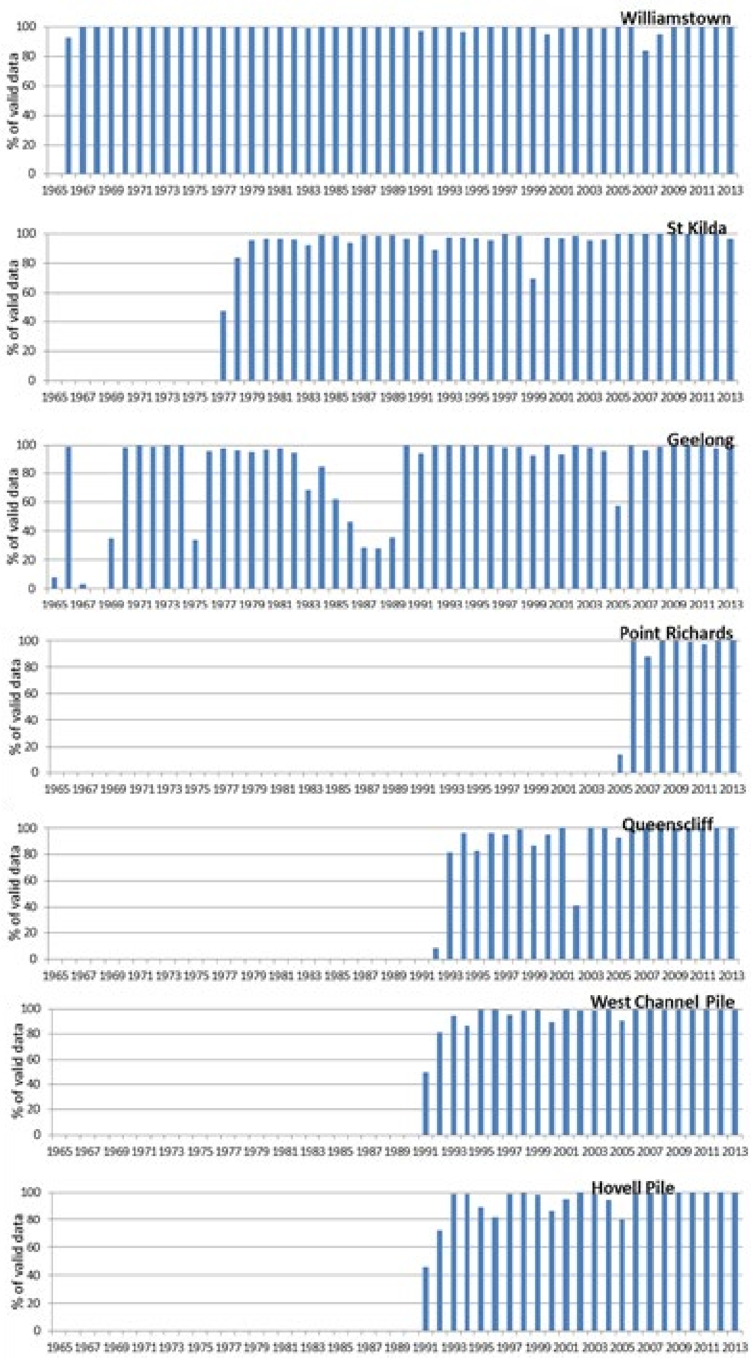


Figure 5: Percentage of valid data in each year at all stations.

4.4. Generate Hourly Values

As noted above, it was decided to use hourly values of sea level as the basis for extreme value analysis rather than six-minute values. There are two reasons for this, one is to maximise the available data as six-minute values are not available for years prior to 1992 for many stations. The second reason is hourly values are considered to represent the variability which is appropriate for inundation modelling and higher frequency variability is not significant. This assumption could be checked by detailed inundation modelling, however, this is beyond the scope of this investigation.

In order to obtain hourly values from six-minute recordings, it is necessary to smooth the data using a low-pass filter to avoid aliasing (sampling of peaks and troughs in the high-frequency variability if hourly values are simply sub-sampled from the six-minute data). All six-minute data was smoothed using the filters recommended by Godin (1972) and then subsampled to hourly values. The filters were based on running means which are simple to apply and maximise the data available after filtering. During periods of calm weather, the six-minute and hourly values are very similar, however more high frequency variability is apparent during storm conditions.

The impact of short-period oscillations during storm events was further investigated by plotting data from both St Kilda and Williamstown. The six-minutes and hourly sea level at both locations from storms in November 1994 and April 2009 are presented in Figure 7.

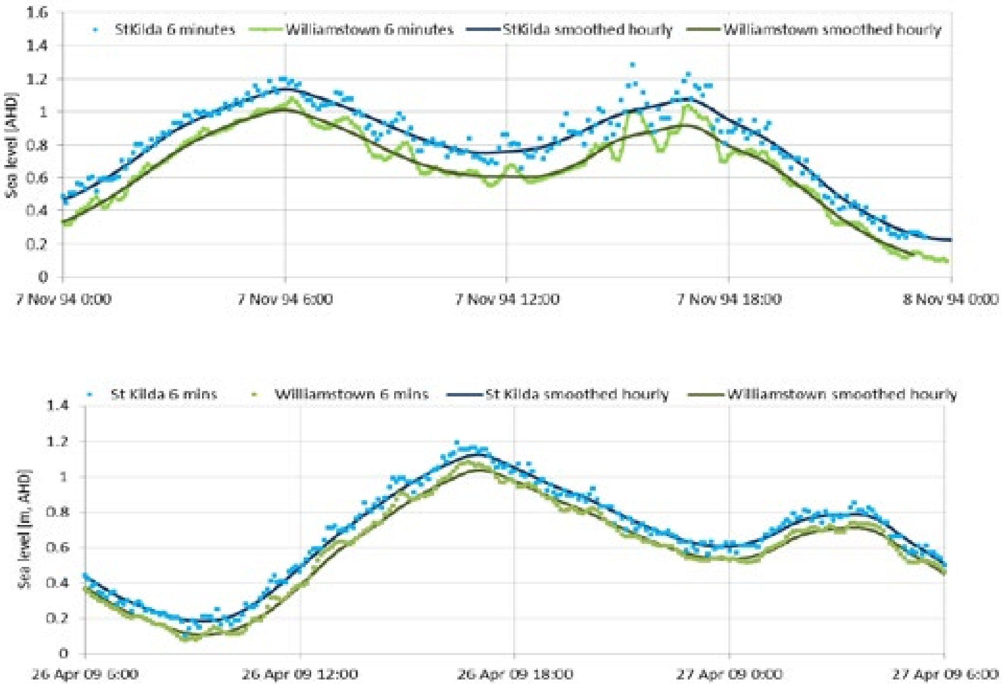


Figure 6: Six-minute and hourly smoothed sea levels from St Kilda and Williamstown for two significant storm events.

Both Williamstown and St Kilda six-minute data show high-frequency variability during storm events and these are largely coherent at the two sites indicating a regional phenomenon, although the St Kilda data appear to have slightly more variability. The smoothed hourly values are very similar at the two stations with the exception of a datum difference, which in fact allows the two sets of data to be seen separately. It is believed that the datum at St Kilda is questionable and the difference between the locations in the two time periods varies.

4.5. Inter-station Comparisons

In order to detect any inconsistency in the data from year to year and with neighbouring stations, yearly summary statistics of the sea level records and correlation among the stations were made. The variability from year to year of the available sea level data was examined by producing yearly arithmetic mean, maximum, minimum, fifth highest value, fifth lowest value, and 90th, 50th and 10th percentile of the smoothed hourly data at each tide gauge. The yearly values for individual stations for all parameters are presented in Appendix A.

Differences in yearly mean sea levels between stations were examined to detect any datum shifts, brought about by such things as change in tide gauge configuration or physical height of the sea level sensors. The annual mean sea levels are shown in Figure 8.

As expected, the yearly mean sea level at Williamstown and St Kilda are centred about zero. However, the mean at Geelong (top panel in Figure 8) shows a drop after 1997. It is most likely that datum conversion value -0.441 m (Table 7) from 1965 to 1997 was not correct. The data during that period was thus adjusted down by 0.139 m to match the value -0.580 m used in the following years. The corrected mean is plotted in the bottom panel in Figure 8. This is the only correction applied to the data.

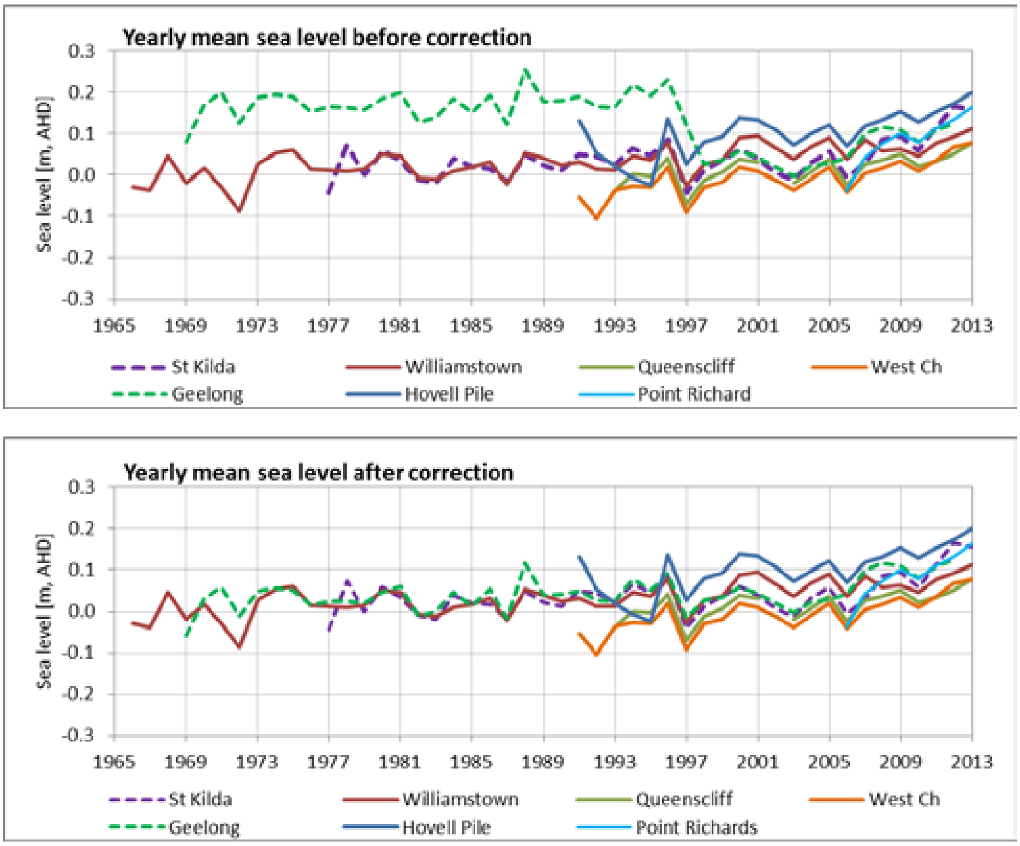


Figure 7: Yearly mean sea level (smoothed hourly data) at all tide gauges/stations; [bottom panel] after correction of datum at Geelong

Other statistical checks are provided by considerations of the annual maximum, minimum and fifth lowest sea levels, which are plotted in Figure 9.

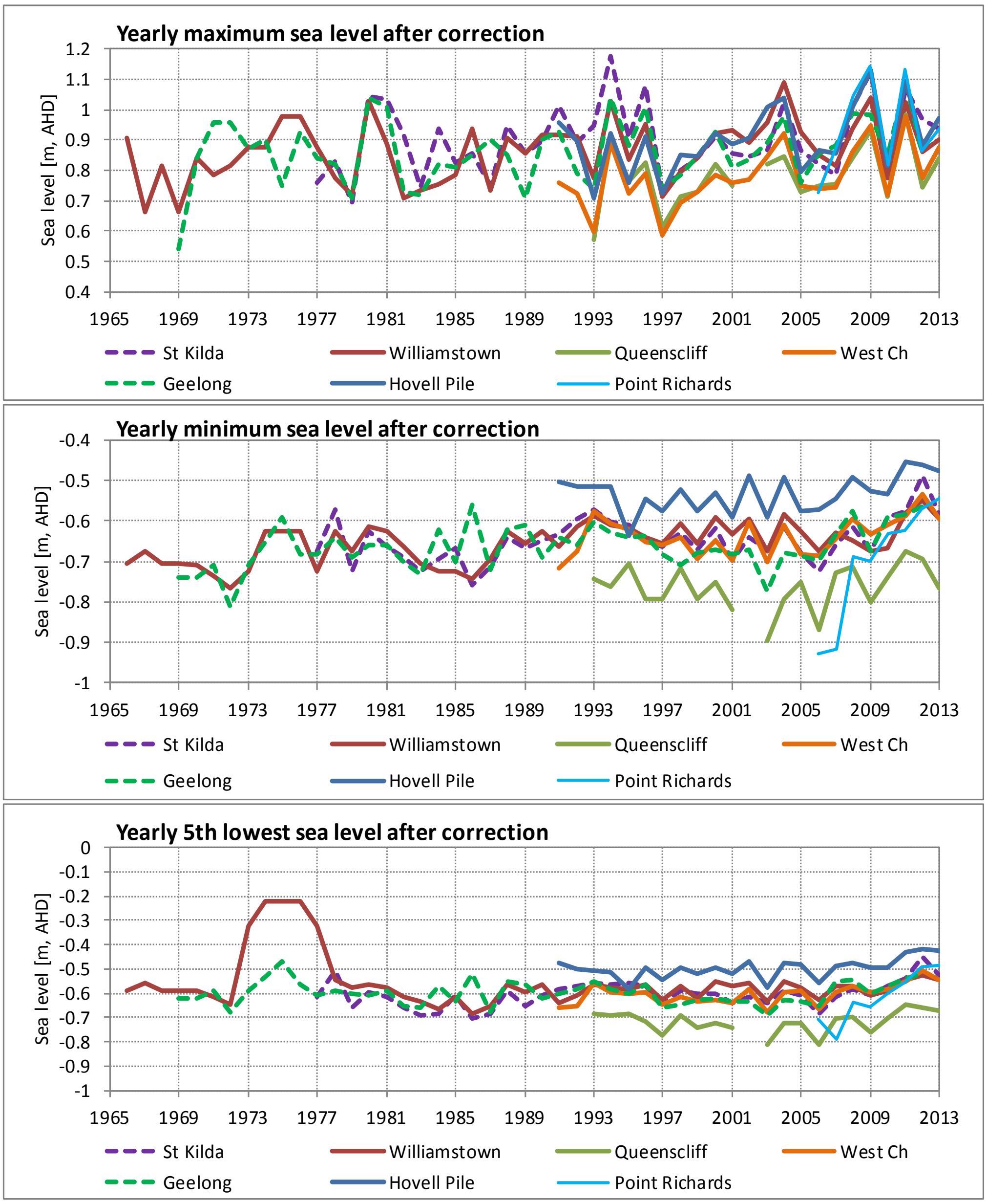


Figure 8: Annual maximum, minimum and fifth lowest hourly sea level from all stations after adjustment of datum at Geelong.

Whilst the maximum and minimum sea levels from Williamstown between 1973 and 1978, as plotted in Figure 9, are reasonably consistent in comparison to other gauges, this was the period when data was only recorded to the nearest decimetre (100 mm). The errors introduced by this reduced resolution become apparent in the record in the fifth lowest value as plotted in Figure 9. All the statistical measures should be consistent across all stations.

Hovell Pile also appears to be higher (upper panel, Figure 8) in the mean values. This was also identified in the minima except in the years 1994 and 1995 (Figure 9). Although the maximum fits well with other stations, this indicates that there may be an uncertainty in the Hovell Pile datum or possibly some unknown natural phenomenon. The datum conversion value -0.524 m, based on the PoMC document (Section 4.2 above), was applied to Hovell Pile data from 1991 to 2013. However, the PoMC document also states that there is some variability in the gauge benchmark, but it is assumed that this has been correctly applied to the measured data.

The reasons for the lower minimum sea levels at Queenscliff are not clear, but may be related to the greater range in the tides at that site.

It appears there may have been some movement in the pile on which the Point Richards gauge was mounted.

At most of the stations the highest recorded sea levels occurred on 26th April 2009, when an intense low-pressure weather system brought severe weather across Melbourne in addition to storm surge in Bass Strait and Port Phillip Bay. However, at Williamstown higher sea levels were recorded during a storm surge on 19th June 2004 and at St Kilda on 7th November 1994 (noting the uncertainty in datum at St Kilda).

Whilst it is difficult to identify any trend over time from the data in Figure 9, examination of the annual mean sea level from the three stations with the longest records does allow identification of a trend in mean sea level. The yearly mean values at Williamstown, St Kilda and Geelong are plotted in Figure 9 along with the trend lines (where *x* in the trend equation is the calendar year, e.g. 1994).

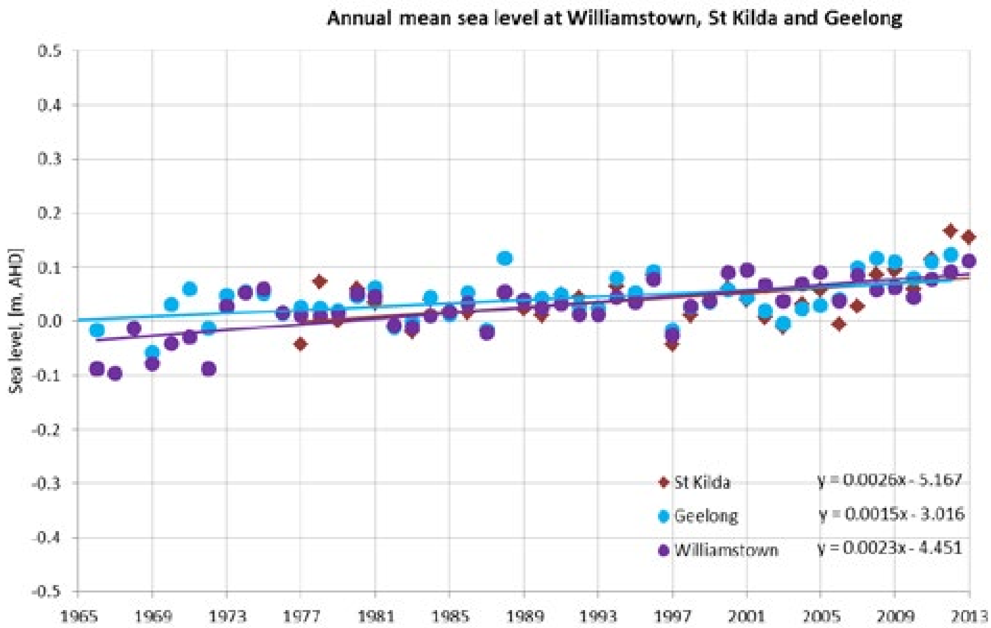


Figure 9: Annual mean sea level with trend at Williamstown, St Kilda and Geelong

Note that in Figure 9 the trend lines for Williamstown and St Kilda are almost indistinguishable. In broad terms, sea level has been rising at Williamstown at about 2.3 mm per year over the last 48 years, 2.6 mm per year at St Kilda over the last 37 years and 1.5 mm per year at Geelong over the last 48 years, but there are many other variations which make this signal hard to identify precisely. There also appears to be an issue with the datum at St Kilda in 2012 and 2013.

05. Extreme Value Analysis

5.1. Extreme Value Methodology

For the purpose of planning and engineering design, storm surge or storm tide levels are commonly expressed in terms of return periods. A return period or Average Recurrence Interval (ARI) is defined as the average number of years between events that exceeds a particular level. Therefore a 100 year ARI sea level is the sea level that is exceeded on average once every 100 years. In other words, the 100 year ARI sea level has Annual Exceedance Probability (AEP) of 1%, this means that there is a 1% chance (i.e. a 1 in 100 chance) of the event being equalled or exceeded in any one year. Similarly 1 in 50 year ARI is equivalent to 2% AEP, 1 in 20 year ARI to a 5% AEP. AEP is preferred to ARI because it highlights the fact that the issue at hand is a risk of occurrence.

The length of sea level records from the tide gauges around Port Phillip Bay varies from 22 to 48 years. Extreme value analysis was performed using a Weibull distribution where the maximum likelihood parameter estimation method was applied. In essence, the extreme value analysis involves fitting a probability distribution to the highest values in the available data for each station; that is, a mathematical description of the likelihood of a given value being exceeded at that site. This distribution can then be used to determine the value likely to be exceeded for any given probability. By considering how well the distribution fits the measured data, a confidence interval can be defined, which is the range within which the actual value lies to within a 95% probability. Technically, the confidence interval was determined through a robust bootstrap data resampling approach. A peak-over-threshold selection criterion which selected an average of one to two events per year was adopted and the threshold for an "extreme event" was adjusted to minimise the error in the fit of the probability distribution. An event was defined as an episode during which the daily maximum values exceeded the set threshold. As the non-tidal sea level variability scale ranges from five to seven days, five days was adopted as the duration of an event to ensure only independent events were selected with a single value assigned to each event. This criterion ensures that all data included in the analyses are independent extremes.

An alternative approach to determining extreme storm tides is to separate the storm surge signal by removing the astronomical tides and then carry out the extreme value analysis on the storm surge and use a Monte Carlo approach to recombine the storm surge with the tides. This approach has not been adopted in this study because of the difficulty of separating the storm surge from the astronomical tides. In Bass Strait and Port Phillip Bay, storm surges are often accompanied by a phase shift in the astronomical tide (McInnes and Hubbert, 2003). This means that subtraction of the predicted astronomical tide from the recorded sea level does not isolate the storm surge, but includes the effects of this phase shift. Alternative filtering techniques can be used, but this is more complex and requires correction for the effects of the filters. The validity of the adopted approach is considered below.

5.2. Results of Analysis

The extremal analysis was performed on the hourly sea level at all stations. The 10%, 5%, 2% and 1% AEP sea level heights for Williamstown, St Kilda, Geelong, Queenscliff, Hovell Pile and West Channel Pile are presented in Table 8. The 95% confidence limits indicate the accuracy of the predicted extreme sea level. It can be seen that the longer the data record the more accurate the extreme event analysis. When shorter records are used to determine longer return period predictions the uncertainty limits are often increased.

Table 8: Results of extreme value analysis on measured data for storm tides in Port Phillip Bay including 95% confidence limits.

Location	ARI / AEP			
	10 yr / 10%	20 yr / 5%	50 yr / 2%	100 yr / 1%
Williamstown	0.99 ± 0.04	1.03 ± 0.04	1.08 ± 0.05	1.12 ± 0.06
St Kilda	1.05 ± 0.04	1.10 ± 0.06	1.15 ± 0.07	1.19 ± 0.08
Geelong	0.99 ± 0.04	1.02 ± 0.05	1.07 ± 0.06	1.10 ± 0.07
Queenscliff	0.91 ± 0.05	0.95 ± 0.06	1.00 ± 0.07	1.04 ± 0.08
Hovell Pile	0.92 ± 0.05	0.97 ± 0.07	1.03 ± 0.08	1.08 ± 0.09
West Channel Pile	0.91 ± 0.05	0.95 ± 0.06	1.01 ± 0.07	1.05 ± 0.08

The results in Table 8 have been calculated on the measured sea levels assuming a constant mean level. That is, no allowance has been made for sea level rise. Since it is known (Figure 9) that there has been a change in the mean sea level over the period of the data, the analysis was repeated using data with the mean sea level trend removed. For the data from Williamstown, St Kilda and Geelong, the equations for the sea level trend in Figure 9 were used to adjust the measurements to sea level in 1990. The values before 1990 were increased slightly and values after 1990 were decreased by an amount depending on the time difference from 1990. The results of the extreme value analysis on the de-trended data are shown in Table 9.

Table 9: Results of extreme value analysis on measured data for storm tides in Port Phillip Bay using data with mean sea level trends removed to yield values for 1990.

Location	ARI / AEP			
	10 yr / 10%	20 yr / 5%	50 yr / 2%	100 yr / 1%
Williamstown	0.98 ± 0.03	1.01 ± 0.04	1.06 ± 0.05	1.09 ± 0.06
St Kilda	1.04 ± 0.05	1.09 ± 0.06	1.14 ± 0.07	1.18 ± 0.08
Geelong	0.98 ± 0.04	1.01 ± 0.05	1.05 ± 0.05	1.08 ± 0.06

As might be expected, removal of mean sea level rise results in a small reduction in the storm tide levels. The changes are small, the largest being 30 mm and most 10-20 mm.

As a check on the validity of the analysis methodology, the extreme values for Williamstown was computed using only the available data between 1991 and 2013, that is the same data period as is available for the PoMC stations in the south of the bay. The results are shown in Table 10.

Table 10: Comparison of extreme values for Williamstown using all available data (1966-2013) and a shorter period (1991-2013)

Data period	ARI / AEP			
	10 yr / 10%	20 yr / 5%	50 yr / 2%	100 yr / 1%
1966-2013	0.99 ± 0.04	1.03 ± 0.04	1.08 ± 0.05	1.12 ± 0.06
1991 - 2013	0.97 ± 0.04	1.01 ± 0.05	1.07 ± 0.06	1.11 ± 0.07

The values in Table 10 show that the values from the shorter period are slightly lower than those from the full period. This is not unexpected as the long data period allows more likelihood of a storm surge coinciding with a high tide and this is one of the limitations of the methodology adopted. However the differences are well within the confidence limits of the analysis.

A visual comparison of the results of the analysis without any adjustment for sea level rise is shown in Figure 10.

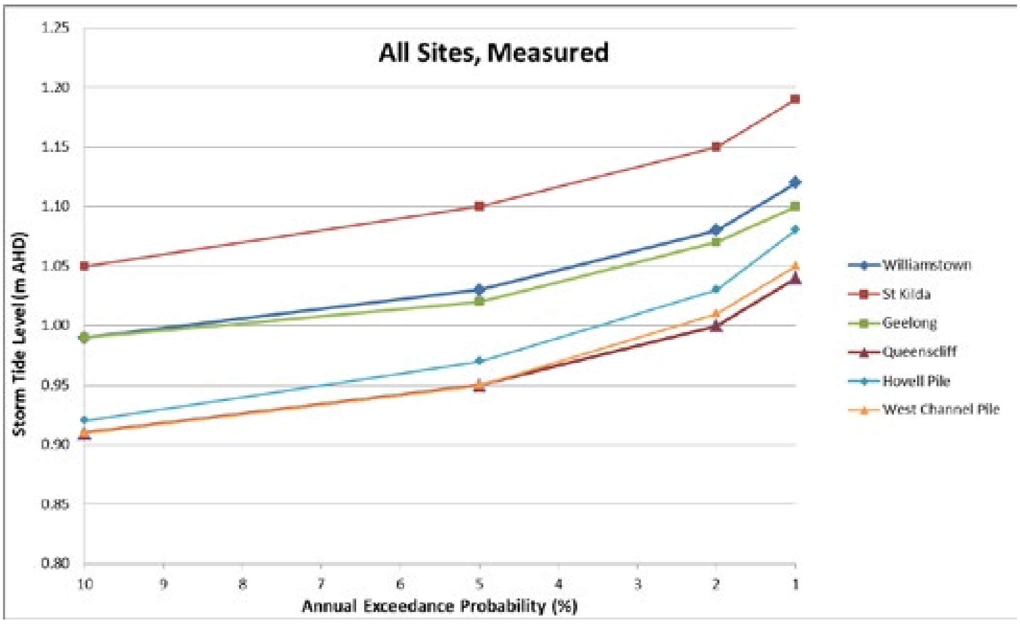


Figure 10: Results of extreme value analysis on measured data for storm tides in Port Phillip Bay (no adjustment for sea level rise)

There are differences in the levels shown in Figure 10 for the various stations. St Kilda stands out as separate from all other locations and this is likely to be due to uncertainty in the datum for this gauge. This is reinforced by the fact that the difference between the values for Williamstown and St Kilda are virtually constant over the full range of AEP values calculated. If the difference was due to a difference in phenomena, it would be expected that there would be a change in difference in level between the two stations for different AEP values. This is the case for the differences between Geelong and Williamstown where the two stations are identical at the 10% AEP level, but Williamstown values increase faster than Geelong as the AEP decreases.

The three stations in the southern portion of Port Phillip Bay, Queenscliff, Hovell Pile and West Channel Pile have very similar values at the 10% AEP level, but Hovell Pile increases at a faster rate than the other two stations as the AEP decreases. This may be due to the more exposed location of Hovell Pile. The differences may also be a response to local wind setup within Port Phillip Bay. As noted above, the shorter data record available for analysis may also lead to slightly lower values, but this effect is not sufficient to account for the differences observed.

It is also of note that, with the exception of St Kilda, the values from all stations for a given AEP value differ by 0.08 m or less.

5.3. Comparison with Previous Results

5.3.1. Williamstown

The sea levels from Williamstown for all the previous studies discussed in Chapter 2 have been plotted against the relevant AEP along with the computed values from this study, both the values as measured (“Williamstown”) and those with sea level rise removed (“Williamstown DT”). Where confidence limits are available (this study and McInnes, 2009), these are indicated by a plus or minus sign. The values from Melbourne Water (2012) and the highest recorded sea level have been plotted as points at the 1% AEP level. The results are shown in Figure 11.

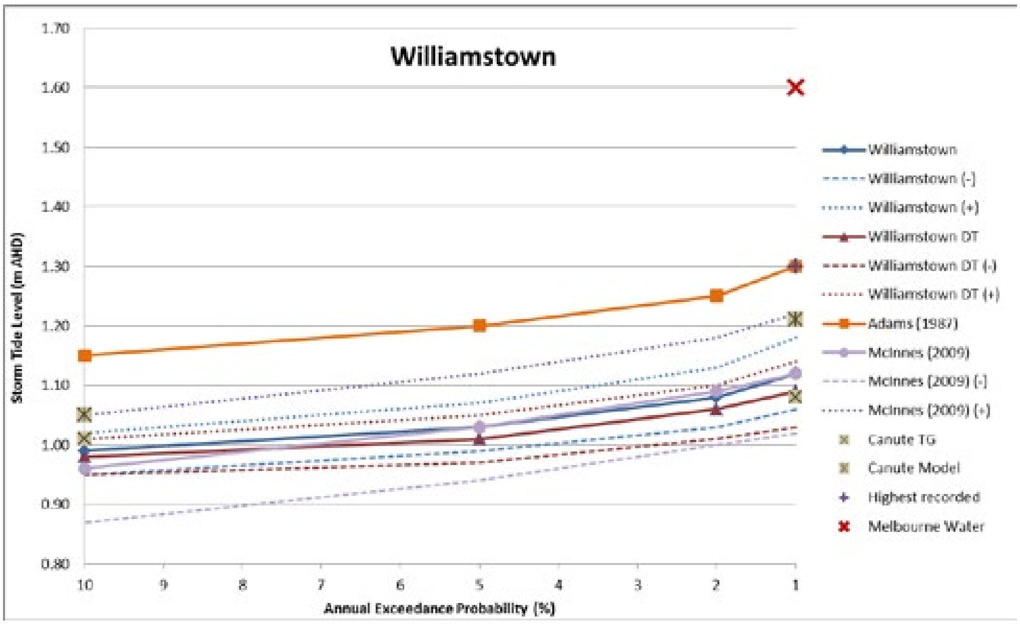


Figure 11: Storm tide levels for Williamstown from all sources used in this study (see text for details).

The following points arise from Figure 11:

1. There is very close agreement between the results of this study (with and without detrending) and McInnes (2009), in particular there is very large overlap between the areas covered by the confidence limits.
2. The values of Adams (1987) are outside the confidence limits of the more recent studies. This may be due to differences in analysis methodology, but another significant factor is likely to be the manner in which the extreme values are determined. Adams used values extracted from graphical records. A comparison of values listed in Adams (1987) with the hourly values for the same events taken from the data provided by NTC (Appendix A) shows that Adams' values are always higher than the NTC data, in some cases by up to 0.15 m.
3. The values from the Canute model are higher than those from this study and from McInnes (2009).
4. The value used by Melbourne Water (2012) is much higher than values from all other sources.

5.3.2. St Kilda

The sea levels from St Kilda for all the previous studies discussed in Chapter 2 have been plotted against the relevant AEP along with the computed values from this study, both the values as measured ("St Kilda") and those with sea level rise removed ("St Kilda DT"). Where confidence limits are available (this study and McInnes, 2009), these are indicated by a plus or minus sign. The values from Melbourne Water (2012) have been plotted as points at the 1%AEP level. The results are shown in Figure 12.

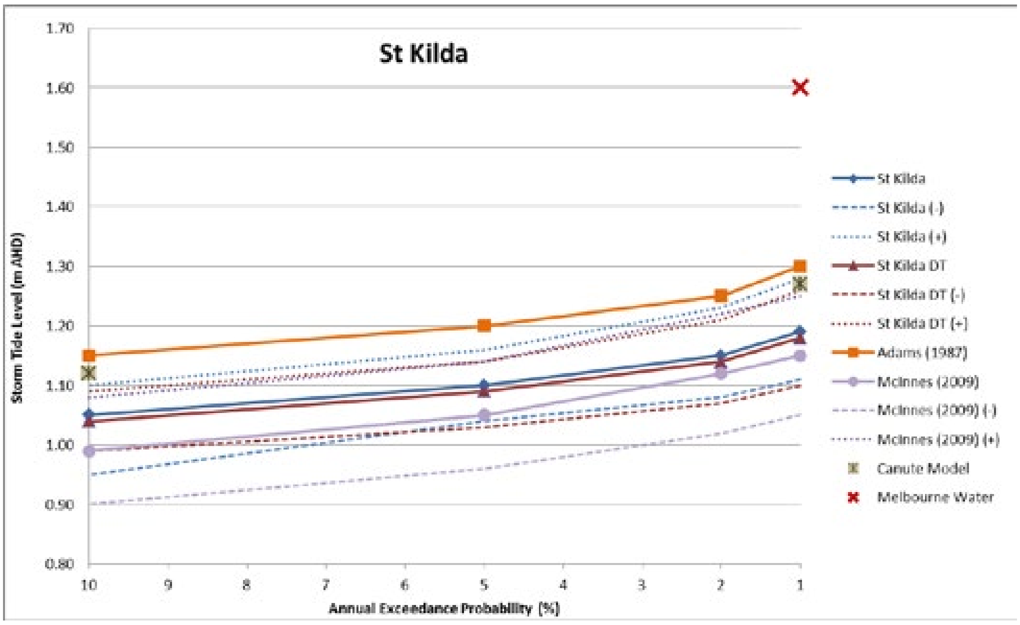


Figure 12: Storm tide levels for St Kilda from all sources used in this study (see text for details).

The following points arise from Figure 12:

5. There is very close agreement between the results of this study (with and without detrending) and McInnes (2009). In particular there is very large overlap between the areas covered by the confidence limits. There is a small offset between the measured data and McInnes (2009) which corresponds to the higher values from the measured data at St Kilda noted in Figure 10.
6. Whilst Adams (1987) used data from the Williamstown tide gauge, it is appropriate to compare his values with those from St Kilda. The values of Adams (1987) are outside the confidence limits of the more recent studies. Similar comments to those in the previous section are relevant.
7. The values from the Canute model are higher than those from this study and from McInnes (2009).
8. The value used by Melbourne Water (2012) is much higher than values from all other sources.

5.3.3. Geelong

The sea levels from Geelong for all the previous studies discussed in Chapter 2 have been plotted against the relevant AEP along with the computed values from this study, both the values as measured ("Geelong") and those with sea level rise removed ("Geelong DT"). Where confidence limits are available (this study and McInnes, 2009), these are indicated by a plus or minus sign. The values from Melbourne Water (2012) have been plotted as points at the 1% AEP level. The results are shown in Figure 13.

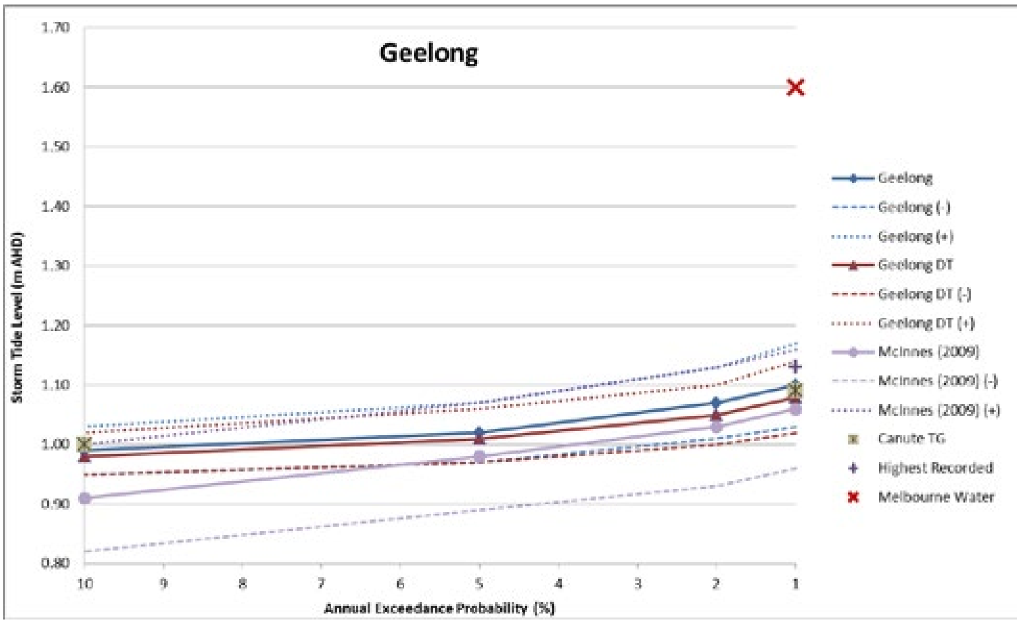


Figure 13: Storm tide levels for Geelong from all sources used in this study (see text for details).

The following points arise from Figure 13:

1. There is very close agreement between the results of this study (with and without detrending) and McInnes et al. (2009). In particular there is very large overlap between the areas covered by the confidence limits. There is a larger difference at higher frequency events (10% AEP) with McInnes (2009) indicating lower levels. This is thought to arise from the methodology used to combine the storm surge and astronomical tides in the modelling study of McInnes et al.
2. The highest recorded value is slightly above the calculated 1%AEP value based on the recorded data, but within the confidence limits.
3. The values from the Canute analysis of the tide gauge are very close to those from this study.
4. The value used by Melbourne Water (2012) is much higher than values from all other sources, although Melbourne Water is not the Catchment Management Authority for most of the area near Geelong and thus this value may have limited applicability. (The Corangamite CMA uses values from McInnes et al. (2009) for planning purposes unless better information is available).

5.3.4. Summary

A summary of the results presented in this section is shown in Table 11. A list of the highest 20 storm tides in the measured data record at each site and comparable AEP levels for each site based on the measured data (not detrended) is included in Appendix B.

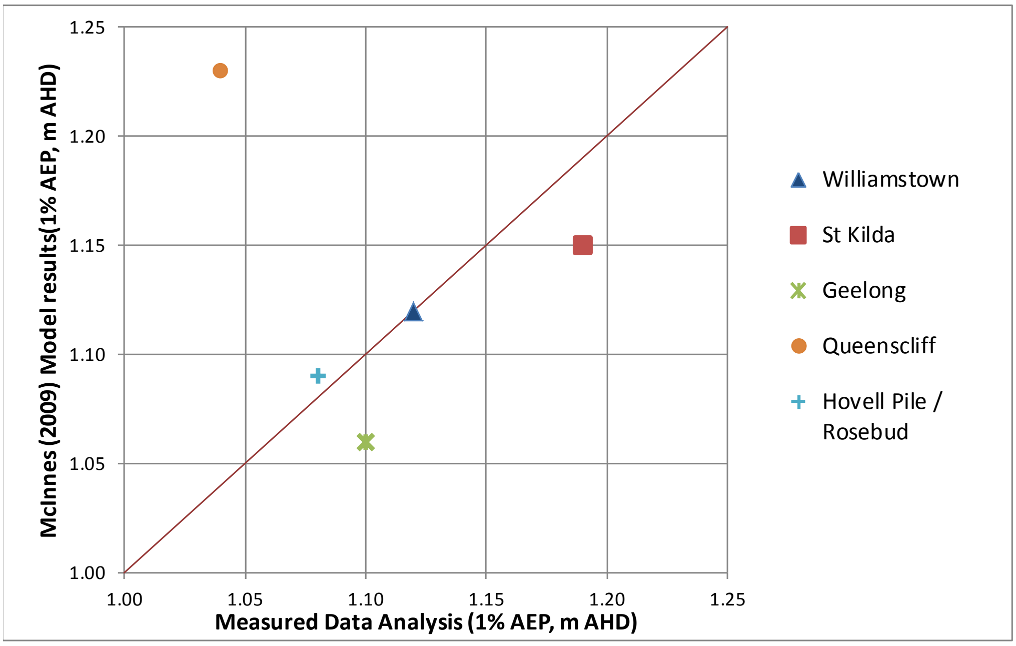
Table 11: Summary of storm-tide levels (m AHD)

AEP	ARI (yr)	Cardno This study	Cardno DT This study	McInnes et al. (2009)	Adams (1987)	Canute TG	Canute model	Melbourne Water (2012)
Williamstown								
1%	100	1.12 ± 0.06	1.09 ± 0.06	1.12 ± 0.10	1.30	1.08	1.21	1.6
2%	50	1.08 ± 0.05	1.06 ± 0.05	1.09 ± 0.09	1.25	-	-	
5%	20	1.03 ± 0.04	1.01 ± 0.04	1.03 ± 0.09	1.20	-	-	

10%	10	0.99 ± 0.04	0.98 ± 0.03	0.96 ± 0.09	1.15	1.01	1.05	
St Kilda								
1%	100	1.19 ± 0.08	1.18 ± 0.08	1.15 ± 0.10	-	-	1.27	1.6
2%	50	1.15 ± 0.07	1.14 ± 0.07	1.12 ± 0.10	-	-	-	
5%	20	1.10 ± 0.06	1.09 ± 0.06	1.05 ± 0.09	-	-	-	
10%	10	1.05 ± 0.04	1.04 ± 0.05	0.99 ± 0.09	-	-	1.12	
Geelong								
1%	100	1.10 ± 0.07	1.08 ± 0.06	1.06 ± 0.10	-	1.09	-	
2%	50	1.07 ± 0.06	1.05 ± 0.05	1.03 ± 0.10	-	-	-	
5%	20	1.02 ± 0.05	1.01 ± 0.05	0.98 ± 0.09	-	-	-	
10%	10	0.99 ± 0.04	0.98 ± 0.04	0.91 ± 0.09	-	1.00	-	
Queenscliff								
1%	100	1.04 ± 0.08	-	1.23 ± 0.28	-	-	1.33	
2%	50	1.00 ± 0.07	-	1.20 ± 0.28	-	-	-	
5%	20	0.95 ± 0.06	-	1.12 ± 0.28	-	-	-	
10%	10	0.91 ± 0.05	-	1.04 ± 0.28	-	-	1.19	
Hovell / Rosebud								
1%	100	1.08 ± 0.09	-	1.09 ± 0.10	-	-	-	1.6
2%	50	1.03 ± 0.08	-	1.06 ± 0.10	-	-	-	
5%	20	0.97 ± 0.07	-	0.99 ± 0.09	-	-	-	
10%	10	0.92 ± 0.05	-	0.93 ± 0.09	-	-	-	

5.4. Modelled and measured values around Port Phillip Bay

It has been noted in the previous sections that there is generally close agreement between the results of the analysis of the measured data from this study and the modelled results from McInnes et al. (2009). Whilst there are limited additional opportunities to compare results, Figure 14 directly compares the 1% AEP values from this study with those of McInnes et al. (2009).



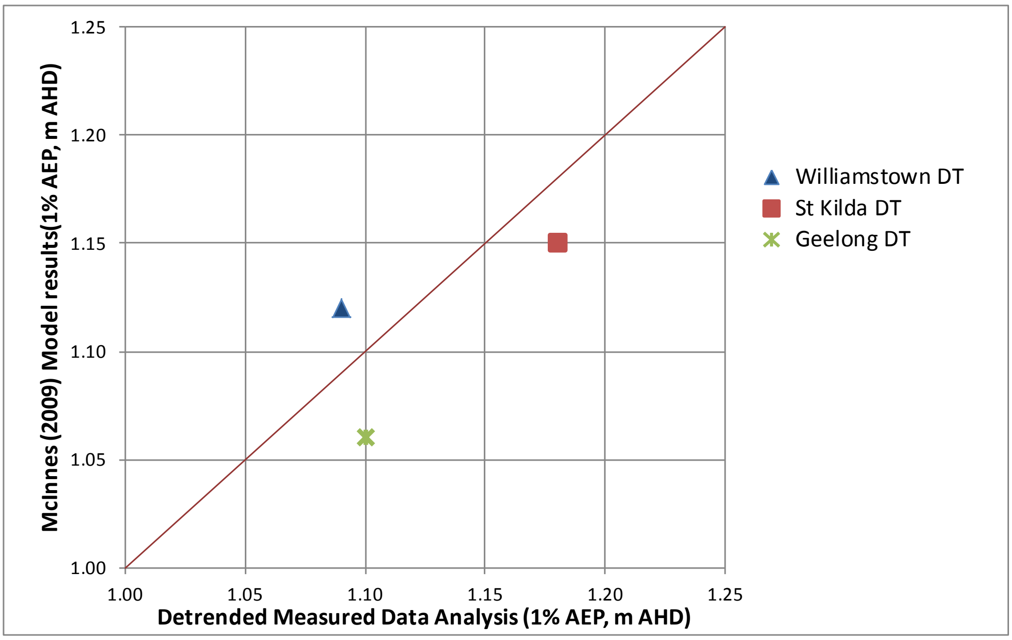


Figure 14: Comparison of sea levels for 1% AEP from the measured data and McInnes et al. (2009) modelled results.

The following points arise from Figure 14:

1. The values at Williamstown for the measured data are identical and very close for the detrended data.
2. The value from measured data at St Kilda is higher than the McInnes (2009) modelled value, but this may be associated with the uncertainty in the datum of the measurements.
3. Values at Geelong are close
4. The value from the Hovell Pile measurements is very close to that from the model at Rosebud which is nearby on the coast.
5. At Queenscliff, the modelled value is significantly higher and this may be associated with the difficulty of modelling the tides at Queenscliff due to the large tidal gradients in the vicinity of Port Phillip Heads. McInnes (2009) noted that the model values in this area may be less reliable.

06. Conclusions and Recommendations

6.1. Conclusions

1. For the purposes of this investigation, a difference between analysis results of 0.05 m or greater is considered significant, based on the confidence limits of the analysis of measured data.
2. There is close agreement between the results of the extreme value analysis of measured data and the model results from McInnes et al. (2009), especially at Williamstown, Geelong and Hovell Pile/Rosebud.
3. The measured data from St Kilda are not as reliable as data form other sites due to undocumented datum shifts.
4. The modelled results from Queenscliff (McInnes et al, 2009) are significantly different to those obtained from analysis of the measured data.
5. Allowance for sea level rise in the analysis of measured data has no significant impact on the results, but will need to be considered in the future.
6. The results of Adams (1987) are different to those from the analysis of measured data and the modelled data of McInnes et al. (2009).
7. The values adopted by Melbourne Water (2012) are significantly higher than the results of either the analysis of measured data or the modelled data of McInnes et al. (2009).
8. The values provided by the Canute system are variable and differ from the analysis of measured data and the modelled data of McInnes et al. (2009).

6.2. Recommendations

1. Sea levels for planning and design purposes for inundation should be based on hourly values derived from smoothed higher frequency (six-minute) values. The impact of this recommendation could be checked by detailed inundation modelling, however, this is beyond the scope of this investigation.
2. For locations in Port Phillip Bay north of the Great Sands (such as a line from Rosebud to St Leonards), the present day (1990) sea levels determined by McInnes et al. (2009) should be used to provide existing (1990) conditions to support planning and design and for risk assessment purposes. These values are recommended due to the spatial coverage they afford and the level of agreement with the analysis of measured data.
3. For locations south of the Great Sands, in particular west of Rosebud on the Mornington Peninsula, further investigations are required to determine the spatial variation and match results from measured data with model results.
4. The measured data from St Kilda should be treated with caution due to changes in the timing and apparent periodic apparent datum shifts.
5. The data record from all stations should be maintained and accurate records of repeated surveys of datums and instrument checks also be maintained.
6. Measured sea levels should be detrended and the probability distribution of storm tides based on 1990 mean sea level determined. This will provide a basis for assessing storm events without the compounding impact of sea level rise which can be included separately.
7. Careful review of values to be used for setting planning benchmarks be undertaken including a consideration of the need for and amount of any allowance for freeboard.

07. References

Adams, J. R., 1987. *Tide levels during November-December 1934 flood and high tide frequency analysis for Williamstown*. Hydrology and Flood Warning Unit, Melbourne and Metropolitan Board of Works.

Godin, G., 1972. *The Analysis of Tides*. Liverpool University Press.

Lawson & Treloar, 2004. *PoMC Channel Deepening, Hydrodynamics, Sediment Transport and Water Quality Modelling*. Report prepared for Port of Melbourne Corporation by Lawson and Treloar Pty Ltd. Report Rm2045.J5372

McInnes, K.L., and Hubbert, G.D., 2003: *A numerical modeling study of storm surges in Bass Strait*. Aust. Met. Mag. 52, 143-156.

McInnes, K.L., O'Grady, J. and Macadam, I. 2009. *The Effect of Climate Change on Extreme Sea Levels in Port Phillip Bay*. Report by CSIRO Marine and Atmospheric Research for the Department of Sustainability and Environment, Victoria.

Melbourne Water, 2012. *Planning for sea level rise, Assessing development in areas prone to tidal inundation from sea level rise in the Port Phillip and Westernport Region*.

PoMC 2014. *Victorian Tide Tables*. Port of Melbourne Corporation.

Stewart, D., 1983. *Hobson's Bay and Yarra River tides and datum with particular reference to the record tide of 30 November 1934*. (Appendix 5 in Adams, 1987)

08. Appendices

Appendix A - Statistics of sea level at all stations

RESULTS FROM ANALYSIS OF SEA LEVEL OBSERVATIONS AT WILLIAMSTOWN (M AHD)

Year	No of Hourly data	No of missing days	5th Highest	5th Lowest	Mean	Max	Min	Percentiles		
								90th	50th	10th
1965										
1966	8110	27	0.636	-0.644	-0.088	0.846	-0.764	0.206	-0.094	-0.404
1967	8760	0	0.486	-0.614	-0.096	0.606	-0.734	0.176	-0.094	-0.404
1968	8771	1	0.636	-0.644	-0.012	0.756	-0.764	0.296	-0.004	-0.344
1969	8760	0	0.486	-0.644	-0.078	0.606	-0.764	0.206	-0.064	-0.404
1970	8760	0	0.664	-0.646	-0.041	0.784	-0.766	0.234	-0.036	-0.346
1971	8760	0	0.664	-0.616	-0.029	0.784	-0.736	0.264	-0.036	-0.346
1972	8784	0	0.634	-0.646	-0.088	0.814	-0.766	0.204	-0.096	-0.406
1973	8760	0	0.476	-0.324	0.027	0.876	-0.724	0.376	0.076	-0.324
1974	8760	0	0.476	-0.224	0.053	0.876	-0.624	0.376	0.076	-0.224
1975	8760	0	0.576	-0.224	0.060	0.976	-0.624	0.376	0.076	-0.224
1976	8784	0	0.576	-0.224	0.015	0.976	-0.624	0.276	-0.024	-0.324
1977	8760	0	0.476	-0.324	0.012	0.876	-0.724	0.376	-0.024	-0.324
1978	8760	0	0.686	-0.544	0.010	0.776	-0.624	0.296	-0.004	-0.314
1979	8760	0	0.636	-0.574	0.014	0.716	-0.674	0.316	0.016	-0.304
1980	8774	0	0.956	-0.564	0.051	1.026	-0.614	0.356	0.056	-0.254
1981	8759	0	0.796	-0.574	0.046	0.886	-0.624	0.356	0.046	-0.284
1982	8760	0	0.636	-0.614	-0.008	0.706	-0.664	0.286	-0.004	-0.314
1983	8670	4	0.656	-0.634	-0.011	0.736	-0.704	0.286	-0.004	-0.324
1984	8784	0	0.706	-0.664	0.010	0.756	-0.724	0.316	0.016	-0.314
1985	8760	0	0.696	-0.614	0.018	0.786	-0.724	0.326	0.026	-0.314
1986	8760	0	0.786	-0.684	0.032	0.936	-0.744	0.336	0.036	-0.284
1987	8730	1	0.686	-0.654	-0.022	0.736	-0.694	0.286	-0.014	-0.344
1988	8784	0	0.806	-0.564	0.054	0.906	-0.624	0.376	0.056	-0.284
1989	8760	0	0.746	-0.594	0.040	0.856	-0.654	0.346	0.046	-0.284
1990	8760	0	0.796	-0.564	0.024	0.916	-0.624	0.336	0.036	-0.294
1991	8493	11	0.842	-0.639	0.032	0.915	-0.664	0.342	0.036	-0.284
1992	8753	1	0.813	-0.608	0.013	0.910	-0.615	0.327	0.015	-0.312
1993	8750	0	0.669	-0.564	0.013	0.773	-0.589	0.317	0.018	-0.305
1994	8461	12	0.972	-0.578	0.045	1.028	-0.612	0.362	0.045	-0.279
1995	8760	0	0.781	-0.584	0.036	0.833	-0.619	0.356	0.034	-0.289
1996	8784	0	0.882	-0.565	0.079	0.951	-0.641	0.392	0.081	-0.244

1997	8760	0	0.642	-0.625	-0.026	0.714	-0.656	0.261	-0.020	-0.326
1998	8758	0	0.762	-0.573	0.027	0.795	-0.607	0.324	0.032	-0.281
1999	8760	0	0.781	-0.623	0.037	0.838	-0.656	0.342	0.041	-0.279
2000	8347	18	0.877	-0.549	0.089	0.922	-0.591	0.405	0.093	-0.241
2001	8685	3	0.833	-0.572	0.095	0.930	-0.633	0.397	0.103	-0.226
2002	8735	1	0.842	-0.560	0.067	0.889	-0.594	0.389	0.066	-0.264
2003	8685	3	0.896	-0.633	0.038	0.956	-0.676	0.363	0.041	-0.296
2004	8685	4	0.912	-0.553	0.069	1.087	-0.585	0.368	0.078	-0.261
2005	8760	0	0.792	-0.576	0.089	0.925	-0.624	0.400	0.101	-0.242
2006	8760	0	0.789	-0.630	0.038	0.848	-0.674	0.335	0.050	-0.287
2007	7343	59	0.765	-0.570	0.084	0.815	-0.628	0.404	0.090	-0.245
2008	8349	18	0.917	-0.573	0.058	0.937	-0.649	0.365	0.066	-0.267
2009	8760	0	0.888	-0.610	0.063	1.038	-0.674	0.384	0.067	-0.275
2010	8745	1	0.722	-0.588	0.045	0.777	-0.667	0.353	0.052	-0.284
2011	8760	0	0.889	-0.546	0.079	1.025	-0.581	0.387	0.083	-0.244
2012	8784	0	0.805	-0.524	0.092	0.862	-0.550	0.389	0.101	-0.225
2013	8760	0	0.821	-0.545	0.111	0.900	-0.596	0.425	0.115	-0.208

RESULTS FROM ANALYSIS OF SEA LEVEL OBSERVATIONS AT GEELONG (M AHD)

Year	No of Hourly data	No of missing days	5th Highest	5th Lowest	Mean	Max	Min	Percentiles		
								90th	50th	10th
1966	724	335								
1967	8677	3	0.719	-0.621	-0.016	0.839	-0.741	0.319	-0.011	-0.351
1968	297	353								
1969	0	366								
1970	3082	237	0.409	-0.621	-0.058	0.539	-0.741	0.259	-0.041	-0.411
1971	8617	6	0.689	-0.621	0.031	0.839	-0.741	0.349	0.049	-0.321
1972	8760	0	0.779	-0.591	0.059	0.959	-0.711	0.409	0.079	-0.291
1973	8725	2	0.809	-0.681	-0.012	0.959	-0.811	0.319	-0.011	-0.381
1974	8760	0	0.749	-0.591	0.048	0.869	-0.711	0.379	0.049	-0.291
1975	8760	0	0.779	-0.531	0.055	0.899	-0.651	0.379	0.049	-0.291
1976	2970	241	0.599	-0.471	0.052	0.749	-0.591	0.379	0.049	-0.291
1977	8434	15	0.719	-0.561	0.014	0.929	-0.681	0.349	0.019	-0.321
1978	8571	8	0.719	-0.611	0.025	0.839	-0.681	0.349	0.029	-0.321
1979	8421	14	0.729	-0.591	0.024	0.819	-0.641	0.349	0.029	-0.311
1980	8326	18	0.659	-0.601	0.019	0.709	-0.691	0.349	0.024	-0.321
1981	8492	12	0.849	-0.611	0.046	1.039	-0.661	0.369	0.049	-0.281
1982	8583	7	0.869	-0.591	0.060	1.009	-0.661	0.389	0.059	-0.291
1983	8307	19	0.679	-0.651	-0.011	0.729	-0.701	0.309	-0.001	-0.341
1984	5999	115	0.629	-0.661	-0.001	0.719	-0.731	0.319	0.009	-0.341
1985	7434	56	0.739	-0.571	0.045	0.819	-0.621	0.369	0.049	-0.301
1986	5433	139	0.709	-0.631	0.012	0.809	-0.701	0.339	0.019	-0.341
1987	4073	195	0.719	-0.521	0.054	0.849	-0.561	0.369	0.059	-0.281
1988	2483	262	0.709	-0.681	-0.016	0.899	-0.721	0.309	-0.011	-0.371
1989	2444	264	0.749	-0.551	0.116	0.849	-0.621	0.459	0.124	-0.241
1990	3120	235	0.619	-0.561	0.039	0.709	-0.611	0.369	0.049	-0.301
1991	8760	0	0.769	-0.621	0.042	0.899	-0.691	0.369	0.049	-0.301

1992	8268	21	0.809	-0.601	0.050	0.929	-0.641	0.379	0.049	-0.291
1993	8784	0	0.749	-0.581	0.027	0.789	-0.661	0.359	0.029	-0.311
1994	8760	0	0.649	-0.551	0.024	0.739	-0.601	0.349	0.029	-0.311
1995	8760	0	0.889	-0.581	0.079	1.039	-0.631	0.409	0.079	-0.261
1996	8735	1	0.804	-0.602	0.052	0.879	-0.640	0.386	0.053	-0.295
1997	8784	0	0.888	-0.563	0.091	1.010	-0.635	0.423	0.095	-0.250
1998	8609	6	0.651	-0.659	-0.016	0.738	-0.683	0.303	-0.017	-0.344
1999	8679	3	0.760	-0.647	0.026	0.782	-0.711	0.347	0.031	-0.313
2000	8128	26	0.769	-0.630	0.035	0.843	-0.680	0.365	0.040	-0.304
2001	8784	0	0.837	-0.621	0.058	0.927	-0.671	0.392	0.066	-0.290
2002	8204	23	0.779	-0.636	0.044	0.811	-0.683	0.362	0.051	-0.291
2003	8760	0	0.797	-0.633	0.020	0.836	-0.671	0.352	0.024	-0.325
2004	8612	6	0.839	-0.689	-0.004	0.889	-0.774	0.330	0.004	-0.358
2005	8415	15	0.799	-0.630	0.022	0.975	-0.679	0.345	0.030	-0.324
2006	5049	155	0.696	-0.631	0.029	0.759	-0.685	0.361	0.039	-0.319
2007	8731	1	0.774	-0.653	0.041	0.853	-0.696	0.352	0.052	-0.299
2008	8453	13	0.849	-0.552	0.099	0.882	-0.632	0.429	0.106	-0.246
2009	8687	4	0.896	-0.544	0.116	0.988	-0.577	0.436	0.124	-0.224
2010	8760	0	0.917	-0.605	0.109	0.981	-0.673	0.447	0.116	-0.247
2011	8760	0	0.778	-0.572	0.080	0.843	-0.591	0.412	0.085	-0.270
2012	8735	1	0.924	-0.539	0.110	1.093	-0.583	0.433	0.112	-0.233
2013	8625	7	0.787	-0.518	0.123	0.851	-0.566	0.440	0.132	-0.216

RESULTS FROM ANALYSIS OF SEA LEVEL OBSERVATIONS AT ST KILDA (M AHD)

Year	No of Hourly data	No of missing days	5th Highest	5th Lowest	Mean	Max	Min	Percentiles		
								90th	50th	10th
1977	4105	194	0.721	-0.611	-0.043	0.760	-0.675	0.273	-0.044	-0.369
1978	7350	59	0.752	-0.508	0.072	0.831	-0.570	0.368	0.074	-0.224
1979	8368	16	0.657	-0.657	0.000	0.694	-0.725	0.308	0.002	-0.313
1980	8453	14	0.991	-0.593	0.059	1.045	-0.624	0.371	0.061	-0.260
1981	8446	13	0.894	-0.615	0.035	1.034	-0.663	0.367	0.036	-0.305
1982	8374	16	0.743	-0.658	-0.011	0.916	-0.692	0.290	-0.006	-0.324
1983	8076	29	0.698	-0.689	-0.019	0.746	-0.725	0.286	-0.008	-0.341
1984	8693	4	0.851	-0.684	0.040	0.936	-0.693	0.357	0.047	-0.291
1985	8615	6	0.769	-0.607	0.021	0.824	-0.666	0.342	0.028	-0.317
1986	8213	23	0.784	-0.706	0.016	0.857	-0.757	0.320	0.025	-0.306
1987	8654	4	0.685	-0.681	-0.017	0.751	-0.714	0.291	-0.012	-0.339
1988	8636	6	0.876	-0.587	0.048	0.947	-0.642	0.371	0.050	-0.286
1989	8662	4	0.766	-0.651	0.023	0.854	-0.667	0.331	0.028	-0.295
1990	8439	13	0.789	-0.606	0.012	0.895	-0.647	0.333	0.013	-0.318
1991	8693	3	0.955	-0.585	0.050	1.014	-0.634	0.366	0.048	-0.272
1992	7833	40	0.843	-0.572	0.044	0.891	-0.597	0.387	0.043	-0.290
1993	8525	10	0.764	-0.554	0.024	0.946	-0.574	0.334	0.027	-0.291
1994	8511	10	1.097	-0.563	0.065	1.173	-0.603	0.385	0.059	-0.259
1995	8474	12	0.880	-0.558	0.046	0.905	-0.609	0.375	0.041	-0.284
1996	8372	17	0.975	-0.572	0.086	1.079	-0.649	0.406	0.086	-0.242
1997	8718	2	0.665	-0.641	-0.042	0.727	-0.665	0.241	-0.039	-0.336

1998	8621	6	0.757	-0.590	0.011	0.800	-0.629	0.300	0.014	-0.294
1999	6088	111	0.759	-0.602	0.036	0.841	-0.670	0.337	0.038	-0.277
2000	8538	10	0.865	-0.599	0.062	0.912	-0.619	0.387	0.065	-0.272
2001	8469	12	0.803	-0.639	0.039	0.858	-0.696	0.335	0.048	-0.280
2002	8624	6	0.790	-0.617	0.007	0.844	-0.640	0.323	0.008	-0.316
2003	8339	18	0.815	-0.640	-0.011	0.868	-0.670	0.306	-0.008	-0.337
2004	8430	15	0.844	-0.588	0.031	1.021	-0.615	0.328	0.040	-0.297
2005	8749	0	0.763	-0.611	0.057	0.865	-0.680	0.368	0.068	-0.274
2006	8747	1	0.751	-0.684	-0.006	0.822	-0.723	0.292	0.006	-0.331
2007	8753	0	0.720	-0.613	0.028	0.783	-0.661	0.350	0.034	-0.304
2008	8774	0	0.981	-0.584	0.086	1.007	-0.614	0.395	0.095	-0.237
2009	8706	2	0.963	-0.610	0.094	1.127	-0.675	0.421	0.097	-0.247
2010	8760	0	0.764	-0.569	0.060	0.798	-0.593	0.374	0.068	-0.279
2011	8760	0	0.944	-0.537	0.115	1.070	-0.575	0.432	0.120	-0.215
2012	8784	0	0.912	-0.451	0.166	0.966	-0.490	0.470	0.176	-0.155
2013	8426	14	0.868	-0.529	0.156	0.935	-0.585	0.478	0.161	-0.172

RESULTS FROM ANALYSIS OF SEA LEVEL OBSERVATIONS AT QUEENSCLIFF (M AHD)

Year	No of Hourly data	No of missing days	5th Highest	5th Lowest	Mean	Max	Min	Percentiles		
								90th	50th	10th
1992	727	336								
1993	7121	68	0.543	-0.686	-0.039	0.573	-0.745	0.264	-0.017	-0.379
1994	8405	15	0.879	-0.688	0.001	0.910	-0.764	0.316	0.018	-0.354
1995	7220	64	0.716	-0.687	-0.002	0.764	-0.706	0.327	0.015	-0.366
1996	8449	14	0.780	-0.717	0.041	0.827	-0.791	0.354	0.062	-0.310
1997	8335	18	0.542	-0.773	-0.070	0.614	-0.794	0.222	-0.045	-0.407
1998	8669	4	0.672	-0.693	-0.013	0.712	-0.718	0.286	0.009	-0.358
1999	7583	49	0.696	-0.739	0.007	0.728	-0.792	0.314	0.028	-0.340
2000	8322	19	0.760	-0.724	0.039	0.818	-0.750	0.361	0.061	-0.321
2001	8746	1	0.713	-0.743	0.032	0.749	-0.818	0.326	0.062	-0.312
2002	3621	214								
2003	8749	0	0.787	-0.810	-0.020	0.822	-0.896	0.307	0.003	-0.391
2004	8742	2	0.753	-0.720	0.008	0.845	-0.792	0.306	0.038	-0.351
2005	8123	27	0.682	-0.721	0.038	0.730	-0.753	0.346	0.066	-0.321
2006	8733	1	0.694	-0.810	-0.024	0.751	-0.869	0.273	0.007	-0.385
2007	8760	0	0.709	-0.705	0.027	0.752	-0.728	0.348	0.051	-0.331
2008	8757	1	0.808	-0.694	0.037	0.840	-0.715	0.340	0.067	-0.314
2009	8760	0	0.857	-0.760	0.051	0.931	-0.800	0.377	0.072	-0.318
2010	8758	0	0.683	-0.705	0.022	0.713	-0.740	0.338	0.048	-0.345
2011	8760	0	0.834	-0.648	0.034	0.983	-0.676	0.346	0.058	-0.326
2012	8759	1	0.689	-0.662	0.051	0.744	-0.694	0.359	0.079	-0.303
2013	8759	0	0.799	-0.674	0.078	0.842	-0.765	0.406	0.100	-0.282

RESULTS FROM ANALYSIS OF SEA LEVEL OBSERVATIONS AT HOVELL PILE (M AHD)

Year	No of Hourly data	No of missing days	5th Highest	5th Lowest	Mean	Max	Min	Percentiles		
								90th	50th	10th
1991	4034	197	0.895	-0.478	0.130	0.958	-0.504	0.445	0.127	-0.183
1992	6350	101	0.837	-0.501	0.054	0.895	-0.515	0.346	0.055	-0.247
1993	8653	4	0.684	-0.506	0.021	0.710	-0.515	0.306	0.021	-0.273
1994	8659	4	0.895	-0.511	-0.008	0.921	-0.517	0.279	-0.012	-0.303
1995	7841	38	0.709	-0.581	-0.024	0.759	-0.637	0.265	-0.026	-0.320
1996	7197	66	0.885	-0.496	0.136	0.909	-0.546	0.423	0.139	-0.162
1997	8650	5	0.667	-0.544	0.026	0.724	-0.575	0.287	0.030	-0.249
1998	8733	1	0.799	-0.493	0.080	0.849	-0.524	0.349	0.082	-0.202
1999	8624	6	0.797	-0.520	0.092	0.844	-0.576	0.374	0.094	-0.197
2000	7598	49	0.836	-0.497	0.139	0.922	-0.530	0.437	0.144	-0.167
2001	8339	18	0.846	-0.520	0.134	0.887	-0.593	0.404	0.142	-0.153
2002	8758	0	0.874	-0.470	0.108	0.908	-0.489	0.411	0.106	-0.194
2003	8657	4	0.910	-0.576	0.073	1.006	-0.592	0.387	0.068	-0.237
2004	8290	21	0.882	-0.475	0.098	1.038	-0.491	0.369	0.106	-0.201
2005	6982	74	0.759	-0.478	0.121	0.795	-0.578	0.409	0.128	-0.183
2006	8758	0	0.804	-0.555	0.070	0.867	-0.571	0.343	0.081	-0.227
2007	8760	0	0.794	-0.487	0.120	0.858	-0.546	0.440	0.120	-0.192
2008	8757	1	0.966	-0.476	0.133	1.009	-0.494	0.411	0.140	-0.161
2009	8760	0	1.010	-0.497	0.153	1.129	-0.528	0.459	0.153	-0.164
2010	8758	0	0.792	-0.494	0.128	0.815	-0.533	0.418	0.135	-0.183
2011	8760	0	0.978	-0.431	0.153	1.094	-0.455	0.436	0.156	-0.145
2012	8784	0	0.815	-0.419	0.173	0.883	-0.461	0.451	0.181	-0.121
2013	8734	1	0.900	-0.426	0.199	0.973	-0.476	0.510	0.196	-0.103

RESULTS FROM ANALYSIS OF SEA LEVEL OBSERVATIONS AT WEST CHANNEL PILE (M AHD)

Year	No of Hourly data	No of missing days	5th Highest	5th Lowest	Mean	Max	Min	Percentiles		
								90th	50th	10th
1991	4337	184	0.693	-0.658	-0.054	0.761	-0.717	0.255	-0.055	-0.367
1992	7183	67	0.674	-0.654	-0.104	0.722	-0.673	0.187	-0.103	-0.403
1993	8258	21	0.574	-0.557	-0.036	0.597	-0.578	0.244	-0.033	-0.322
1994	7589	49	0.806	-0.595	-0.026	0.889	-0.608	0.246	-0.025	-0.313
1995	8685	3	0.693	-0.602	-0.030	0.726	-0.621	0.264	-0.032	-0.328
1996	8723	3	0.769	-0.594	0.020	0.789	-0.653	0.309	0.022	-0.279
1997	8333	18	0.486	-0.645	-0.091	0.589	-0.661	0.165	-0.087	-0.363
1998	8670	4	0.651	-0.616	-0.029	0.693	-0.639	0.241	-0.026	-0.310
1999	8709	2	0.668	-0.637	-0.018	0.727	-0.694	0.261	-0.017	-0.309
2000	7890	37	0.704	-0.625	0.019	0.782	-0.648	0.315	0.025	-0.285
2001	8760	0	0.700	-0.637	0.009	0.760	-0.698	0.278	0.018	-0.279
2002	8642	5	0.729	-0.582	-0.012	0.768	-0.601	0.290	-0.012	-0.312
2003	8667	4	0.758	-0.681	-0.038	0.847	-0.701	0.271	-0.041	-0.347
2004	8784	0	0.784	-0.593	-0.010	0.922	-0.612	0.261	0.000	-0.311
2005	7934	34	0.658	-0.588	0.019	0.748	-0.682	0.308	0.025	-0.287
2006	8760	0	0.687	-0.663	-0.041	0.738	-0.686	0.231	-0.029	-0.341

2007	8760	0	0.681	-0.598	0.006	0.742	-0.643	0.303	0.009	-0.301
2008	8757	1	0.832	-0.571	0.018	0.862	-0.596	0.295	0.026	-0.276
2009	8724	2	0.864	-0.593	0.034	0.948	-0.634	0.338	0.036	-0.283
2010	8760	0	0.674	-0.581	0.009	0.718	-0.612	0.302	0.016	-0.302
2011	8760	0	0.879	-0.553	0.035	0.979	-0.587	0.322	0.038	-0.261
2012	8757	1	0.730	-0.506	0.067	0.776	-0.534	0.350	0.071	-0.227
2013	8733	1	0.798	-0.543	0.078	0.874	-0.596	0.382	0.079	-0.222

RESULTS FROM ANALYSIS OF SEA LEVEL OBSERVATIONS AT POINT RICHARDS (M AHD)

Year	No of Hourly data	No of missing days	5th Highest	5th Lowest	Mean	Max	Min	Percentiles		
								90th	50th	10th
2005	1237	313								
2006	8718	2	0.657	-0.706	-0.038	0.727	-0.929	0.243	0.243	-0.363
2007	7699	44	0.803	-0.786	0.043	0.880	-0.915	0.388	0.388	-0.315
2008	8750	1	0.971	-0.640	0.075	1.044	-0.687	0.398	0.398	-0.267
2009	8752	0	1.003	-0.655	0.102	1.143	-0.700	0.450	0.450	-0.259
2010	8682	3	0.807	-0.598	0.079	0.819	-0.629	0.415	0.415	-0.281
2011	8532	10	0.990	-0.552	0.112	1.130	-0.623	0.439	0.439	-0.234
2012	8773	0	0.824	-0.489	0.134	0.865	-0.571	0.439	0.439	-0.193
2013	8760	0	0.898	-0.484	0.163	0.937	-0.542	0.487	0.487	-0.163

Appendix B - Twenty highest storm tide levels at all stations

Williamstown			St Kilda			Geelong		
Rank	Date	m AHD	Rank	Date	m AHD	Rank	Date	m AHD
1% AEP		1.12	1% AEP		1.19	1% AEP		1.10
#	24/06/2014 04:00	1.10	1	6/11/1994 7:00	1.17	1	5/07/2011 8:00	1.09
1	19/06/2004 7:00	1.09	2% AEP		1.15	2% AEP		1.07
2% AEP		1.08	2	26/04/2009 7:00	1.13	2	29/06/1980 6:00	1.04
2	26/04/2009 7:00	1.04	5% AEP		1.10	3	27/05/1994 7:00	1.04
5% AEP		1.03	3	26/05/1994 17:00	1.10	5% AEP		1.02
3	6/11/1994 20:00	1.03	4	9/02/1996 21:00	1.08	4	3/08/1996 8:00	1.01
4	29/06/1980 6:00	1.03	5	5/07/2011 8:00	1.07	5	4/07/1981 7:00	1.01
5	5/07/2011 8:00	1.03	10% AEP		1.05	6	6/11/1994 20:00	1.01
6	26/05/1994 17:00	1.00	6	29/06/1980 6:00	1.05	7	21/06/2011 10:00	0.99
10% AEP		0.99	7	9/05/1981 9:00	1.03	10% AEP		0.99
7	25/05/1975 16:00	0.98	8	19/06/2004 7:00	1.02	8	2/07/2008 5:00	0.99
8	1/08/1976 9:00	0.98	9	7/08/1991 12:00	1.01	9	1/07/2009 12:00	0.98
9	6/06/2003 11:00	0.96	10	2/07/2008 5:00	1.01	10	19/06/2004 6:00	0.98
10	4/08/1996 9:00	0.95	11	17/04/1996 17:00	1.00	11	4/05/1971 12:00	0.96
11	1/07/2008 3:00	0.94	12	21/06/2011 9:00	0.98	12	30/06/1972 8:00	0.96
12	25/04/1986 6:00	0.94	13	2/07/2009 12:00	0.97	13	26/08/2009 9:00	0.95
13	9/02/1996 20:00	0.93	14	4/12/2012 21:00	0.97	14	14/08/2013 10:00	0.94
14	18/08/2001 5:00	0.93	15	8/01/1994 1:00	0.95	15	1/08/1976 9:00	0.93
15	2/07/2009 12:00	0.93	16	6/06/1988 10:00	0.95	16	7/08/1991 13:00	0.93
16	2/02/2005 19:00	0.93	17	12/06/1993 11:00	0.95	17	21/07/2000 9:00	0.93
17	28/05/2000 12:00	0.92	18	7/09/2012 9:00	0.95	18	18/07/1974 15:00	0.90
18	27/06/1990 8:00	0.92	19	15/08/1991 8:00	0.94	19	15/07/1987 9:00	0.90
19	7/08/1991 12:00	0.92	20	26/03/1984 23:00	0.94	20	27/06/1990 9:00	0.90
20	4/07/1992 8:00	0.91						
#	recent storm event							

Queenscliff		
Rank	Date	m AHD
1% AEP		1.04
2% AEP		1.00
1	5/07/2011 6:00	0.98
5% AEP		0.95
2	26/04/2009 5:00	0.93
3	26/05/1994 15:00	0.91
10% AEP		0.91
4	6/11/1994 18:00	0.88
5	2/07/2009 10:00	0.88
6	21/06/2011 7:00	0.86
7	19/06/2004 4:00	0.84
8	18/08/2013 11:00	0.84
9	1/07/2008 1:00	0.84
10	26/08/2009 7:00	0.83
11	4/08/1996 7:00	0.83
12	6/06/2003 8:00	0.82
13	21/07/2000 7:00	0.82
14	5/07/2013 11:00	0.80
15	15/05/2009 8:00	0.78
16	24/06/1994 4:00	0.78
17	13/07/1995 15:00	0.76
18	4/05/2007 5:00	0.75
19	20/04/2006 8:00	0.75
20	7/01/1994 22:00	0.75

Hovell Pile		
Rank	Date	m AHD
1% AEP		1.08
#	24/06/2014 05:00	1.03
2% AEP		1.03
1	26/04/2009 7:00	1.02
2	5/07/2011 8:00	0.98
5% AEP		0.97
3	19/06/2004 7:00	0.93
4	6/11/1994 20:00	0.92
10% AEP		0.92
5	26/05/1994 17:00	0.91
6	2/07/2009 12:00	0.90
7	1/07/2008 4:00	0.90
8	6/06/2003 10:00	0.90
9	21/06/2011 9:00	0.87
10	18/08/2013 13:00	0.86
11	7/08/1991 11:00	0.86
12	26/08/2009 8:00	0.83
13	15/05/2009 10:00	0.81
14	21/07/2000 9:00	0.81
15	3/08/1996 8:00	0.80
16	13/06/2002 8:00	0.80
17	5/07/2013 3:00	0.80
18	4/07/1992 8:00	0.79
19	7/01/1994 23:00	0.79
20	5/07/2002 12:00	0.78
#	recent storm event	

West Channel Pile		
Rank	Date	m AHD
1% AEP		1.05
2% AEP		1.01
1	5/07/2011 8:00	0.98
5% AEP		0.95
2	26/04/2009 7:00	0.95
3	19/06/2004 7:00	0.92
10% AEP		0.91
4	6/11/1994 20:00	0.89
5	21/06/2011 9:00	0.88
6	18/08/2013 12:00	0.87
7	1/07/2009 11:00	0.87
8	1/07/2008 3:00	0.86
9	6/06/2003 10:00	0.85
10	7/08/1991 11:00	0.84
11	26/08/2009 8:00	0.80
12	4/07/1992 9:00	0.80
13	5/07/2013 3:00	0.79
14	3/08/1996 8:00	0.79
15	21/07/2000 9:00	0.78
16	7/09/2012 9:00	0.78
17	13/06/2002 7:00	0.77
18	15/05/2009 10:00	0.77
19	18/08/2001 4:00	0.76
20	27/06/1990 9:00	0.90

Date of Event (UTC)	Williamstown		St Kilda		Geelong		Hovell Pile		West Channel Pile		Queenscliff	
	Rank	m AHD	Rank	m AHD	Rank	m AHD	Rank	m AHD	Rank	m AHD	Rank	m AHD
4/05/1971	-	-	-	-	11	0.96	-	-	-	-	-	-
30/06/1972	-	-	-	-	12	0.96	-	-	-	-	-	-
18/07/1974	-	-	-	-	18	0.90	-	-	-	-	-	-
25/05/1975	7	0.98	-	-	-	-	-	-	-	-	-	-
1/08/1976	8	0.98	-	-	15	0.93	-	-	-	-	-	-
29/06/1980	4	1.03	6	1.05	2	1.04	-	-	-	-	-	-
9/05/1981	-	-	7	1.03	-	-	-	-	-	-	-	-
4/07/1981	-	-	-	-	5	1.01	-	-	-	-	-	-
26/03/1984	-	-	20	0.94	-	-	-	-	-	-	-	-
25/04/1986	12	0.94	-	-	-	-	-	-	-	-	-	-
15/07/1987	-	-	-	-	19	0.90	-	-	-	-	-	-
6/06/1988	-	-	16	0.95	-	-	-	-	-	-	-	-
27/06/1990	18	0.92	-	-	20	0.90	-	-	-	-	-	-
7/08/1991	19	0.92	9	1.01	16	0.93	11	0.86	10	0.84	-	-
15/08/1991	-	-	19	0.94	-	-	-	-	-	-	-	-
4/07/1992	20	0.91	-	-	-	-	18	0.79	12	0.80	-	-
12/06/1993	-	-	17	0.95	-	-	-	-	-	-	-	-
7-8/01/1994	-	-	15	0.95	-	-	19	0.79	20	0.75	20	0.75
26/05/1994	6	1.00	3	1.10	3	1.04	5	0.91	-	-	3	0.91
24/06/1994	-	-	-	-	-	-	-	-	-	-	16	0.78
6/11/1994	3	1.03	1	1.17	6	1.01	4	0.92	4	0.89	4	0.88
13/07/1995	-	-	-	-	-	-	-	-	-	-	17	0.76
9/02/1996	-	-	4	1.08	-	-	-	-	-	-	-	-
9/02/1996	13	0.93	-	-	-	-	-	-	-	-	-	-
17/04/1996	-	-	11	1.00	-	-	-	-	-	-	-	-
3-4/08/1996	10	0.95	-	-	4	1.01	15	0.80	14	0.79	11	0.83
28/05/2000	17	0.92	-	-	-	-	-	-	-	-	-	-
21/07/2000	-	-	-	-	17	0.93	14	0.81	15	0.78	13	0.82
18/08/2001	14	0.93	-	-	-	-	-	-	19	0.76	-	-
13/06/2002	-	-	-	-	-	-	16	0.80	17	0.77	-	-
5/07/2002	-	-	-	-	-	-	20	0.78	-	-	-	-
6/06/2003	9	0.96	-	-	-	-	8	0.90	9	0.85	12	0.82
19/06/2004	1	1.09	8	1.02	10	0.98	3	0.93	3	0.92	7	0.84
2/02/2005	16	0.93	-	-	-	-	-	-	-	-	-	-
20/04/2006	-	-	-	-	-	-	-	-	-	-	19	0.75
4/05/2007	-	-	-	-	-	-	-	-	-	-	18	0.75
1/07/2008	11	0.94	10	1.01	8	0.99	7	0.90	8	0.86	9	0.84
26/04/2009	2	1.04	2	1.13	-	-	1	1.02	2	0.95	2	0.93
15/05/2009	-	-	-	-	-	-	13	0.81	18	0.77	15	0.78
1/07/2009	15	0.93	13	0.97	9	0.98	6	0.90	7	0.87	5	0.88
26/08/2009	-	-	-	-	13	0.95	12	0.83	11	0.80	10	0.83
21/06/2011	-	-	12	0.98	7	0.99	9	0.87	5	0.88	6	0.86

5/07/2011	5	1.03	5	1.07	1	1.09	2	0.98	1	0.98	1	0.98
7/09/2012	-	-	18	0.95	-	-	-	-	16	0.78	-	-
4/12/2012	-	-	14	0.97	-	-	-	-	-	-	-	-
5/07/2013	-	-	-	-	-	-	17	0.80	13	0.79	14	0.80
14/08/2013	-	-	-	-	14	0.94	-	-	-	-	-	-
18/08/2013	-	-	-	-	-	-	10	0.86	6	0.87	8	0.84
24/06/2014	*	1.10	-	-	*	0.98	*	1.03	-	-	-	-

* recent storm event so not ranked

LEGEND

Events that were

greater than 1% AEP
between 1 - 2% AEP
between 2 - 5% AEP
between 5 - 10% AEP

Appendix C -

Table 12: Summary of storm-tide levels (m AHD)

AEP	ARI (yr)	Cardno This study	Cardno DT This study	McInnes et al. (2009)	Adams (1987)	Canute TG	Canute model	Melbourne Water (2012)
Williamstown								
1%	100	1.12 ± 0.06	1.09 ± 0.06	1.12 ± 0.10	1.30	1.08	1.21	1.6
2%	50	1.08 ± 0.05	1.06 ± 0.05	1.09 ± 0.09	1.25	-	-	
5%	20	1.03 ± 0.04	1.01 ± 0.04	1.03 ± 0.09	1.20	-	-	
10%	10	0.99 ± 0.04	0.98 ± 0.03	0.96 ± 0.09	1.15	1.01	1.05	
St Kilda								
1%	100	1.19 ± 0.08	1.18 ± 0.08	1.15 ± 0.10	-	-	1.27	1.6
2%	50	1.15 ± 0.07	1.14 ± 0.07	1.12 ± 0.10	-	-	-	
5%	20	1.10 ± 0.06	1.09 ± 0.06	1.05 ± 0.09	-	-	-	
10%	10	1.05 ± 0.04	1.04 ± 0.05	0.99 ± 0.09	-	-	1.12	
Geelong								
1%	100	1.10 ± 0.07	1.08 ± 0.06	1.06 ± 0.10	-	1.09	-	
2%	50	1.07 ± 0.06	1.05 ± 0.05	1.03 ± 0.10	-	-	-	
5%	20	1.02 ± 0.05	1.01 ± 0.05	0.98 ± 0.09	-	-	-	
10%	10	0.99 ± 0.04	0.98 ± 0.04	0.91 ± 0.09	-	1.00	-	
Queenscliff								
1%	100	1.04 ± 0.08	-	1.23 ± 0.28	-	-	1.33	
2%	50	1.00 ± 0.07	-	1.20 ± 0.28	-	-	-	
5%	20	0.95 ± 0.06	-	1.12 ± 0.28	-	-	-	
10%	10	0.91 ± 0.05	-	1.04 ± 0.28	-	-	1.19	
Hovell / Rosebud								
1%	100	1.08 ± 0.09	-	1.09 ± 0.10	-	-	-	1.6
2%	50	1.03 ± 0.08	-	1.06 ± 0.10	-	-	-	
5%	20	0.97 ± 0.07	-	0.99 ± 0.09	-	-	-	
10%	10	0.92 ± 0.05	-	0.93 ± 0.09	-	-	-	

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