Water Research Laboratory

Generic Design Coastal Erosion Volumes and Setbacks for Australia

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by
A Mariani, T D Shand, J T Carley, I D Goodwin, K Splinter, E K Davey, F Flocard and I L Turner

UNSW
THE UNIVERSITY OF NEW SOUTH WALES

Water Research Laboratory
University of New South Wales
School of Civil and Environmental Engineering

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1. Introduction

1.1 Background

Coastal zones in Australia are subject to increasing pressure due to rapid growth in use and development. It was estimated that 86% of the Australian population lives within 50 kilometres from the coastline (RAC, 1993). Australian communities, infrastructure and assets located in proximity to the shoreline and mean sea level are therefore extremely vulnerable to coastal inundation and beach erosion.

The Australian coast is subject to a spatially and seasonally varied mean wave climate periodically affected by large wave events such as those which occurred in 1899 in Queensland (*Cyclone Mahina*), 1974 in NSW (*'Sygna Storm'*) and Darwin (*Cyclone Tracy*), 1999 in Western Australia (*Cyclone Vance*) and in 2008 in NSW (the *'Pasha Bulker Storm'*). These large wave events, particularly when they coincide with high water levels, may cause widespread beach erosion resulting in damage to private and public property and infrastructure. Additionally, future sea level rise (SLR) due to a warming global climate is anticipated to cause additional erosion/recession as coastlines respond and find new equilibrium positions.

1.2 Setback Components

All state government policies in Australia endorse the determination of coastal hazard setback lines to guide the planning and management of the coastal zone. While terminology and the requirement for consideration (or not) varies between jurisdictions, the components for coastal setbacks can be defined as:

- S1: Allowance for short term storm erosion (storm demand);
- S2: Allowance for ongoing underlying recession;
- S3: Allowance for recession due to future sea level rise (SLR);
- S4: Allowance for beach rotation;
- S5: Allowance for dune stability (Zone of Reduced Foundation Capacity - ZRFC as defined by Nielsen et al. 1992); and
- FS: A factor of safety that may apply to none, one, more than one, or all of the above components.

Inundation presents a separate hazard and is beyond the scope of this report.

1.3 Scope of Works and Report Structure

The Water Research Laboratory (WRL) of the University of New South Wales was commissioned by the Antarctic Climate & Ecosystems Cooperative Research Centre (ACE-CRC) to provide "*Generic Design Coastal Erosion Volumes and Setbacks for Australia*".

The Antarctic Climate & Ecosystems Cooperative Research Centre (ACE-CRC), in partnership with the Department of Climate Change and Energy Efficiency, has developed a sea level calculator (http://slr.sealevelrise.info) to assist coastal managers in assessing the level of future risk under conditions of a rising sea level and to plan accordingly. This web tool allows the estimate of ocean water levels (excluding local wave setup and runup) at 29 locations around Australia (for which there is good existing sea-level data) based on a future greenhouse gas emission scenarios and average recurrence interval (ARI), or annual exceedance probability (AEP).

Consistent with the sea level calculator tool, the scope of the present investigation is to provide numerical model predictions of coastal erosion volumes and setbacks at selected representative open coast, sandy beaches along the Australian coastline. Also, for a range of extreme storm events allow the assessment of storm erosion vulnerability on a regional level and provision of a range of storm erosion volumes along the Australian coastline and recession due to sea level rise. The erosion and recession predictions will be implemented in a web tool analogous to the sea level calculator tool.

This was achieved by completing the following tasks:

1. Description of policies or common practice for each state;
2. Parameterisation of important variables;
3. Estimation of extreme water levels around Australia using the ACE-CRC sea level calculator and other available literature sources;
4. Estimation of extreme storm wave parameters around Australia based on available literature and new analysis by WRL;
5. Development of synthetic design storms;
6. Development of realistic generic coastal types;
7. Review literature on storm clustering;
8. Establishment and implementation of the storm erosion model XBeach; and
9. Production of a lookup table of design erosion volumes and setbacks.

Following this introduction, **Section 2** summarises the policies and common practice for the assessment of coastal erosion in each state of Australia. **Section 3** describes environmental conditions around the Australian Coast including fundamental coastal types, mean and extreme wave and water level conditions and future sea level rise scenarios. **Section 4** describes the beach response modelling including a review of the underlying physical processes and the various models commonly used, a description of the XBeach model used within this study, presentation of boundary conditions and model scenarios, results of calibration and results of scenario modelling around the Australian Coastline. From the modelling predictions, lookup tables are derived for use within an erosion prediction toolbox. **Section 5** describes coastal response to sea level rise including a review of the various modelling approaches that have been commonly used, the retreat model adopted within this study and results for various SLR scenarios on different coastal types.

1.4 Significance of Study

The ACE-CRC Sea Level Calculator has provided a simple tool for determining the probability of water level exceedance for a given timeframe and specified sea level rise scenario at a number of Australian locations. The results of this study are intended **to provide similar first-order estimations of the erosion volumes and setback distances due to SLR that could be expected for different coastal types around Australia**.

1.5 Project Limitations

The main limitations of this study are related to the paucity of data. While state-of-the-art statistical methods and numerical modelling were applied to estimate erosion volumes and setback distances, available data related to (i)the input beach bathymetries at different locations and (ii)the forcing conditions (extreme waves and water levels) limit the domain of applicability of the study. **Detailed site-specific studies by qualified practitioners using the most**

recently available data should always be undertaken for local-scale planning and coastal hazard assessment.

The assumptions and limitations applicable to the analysis and the data used in this study are described below. **Results reported herein should always be interpreted and utilised within these assumptions and limitations.**

1.5.1 Beach Profiles and Bathymetric Data

Model output validation

Bathymetric and topographic data for several locations along the Australian coastline were obtained from as many available and reliable sources as practicable. However, field datasets incorporating the pre- and post-storm bathymetry required for model validation are scarce. Model validation for this project was therefore limited to specific beach types and wave/water level conditions, which do not cover the range of beach morphologies and hydrodynamic conditions that occur along the Australian coastline. Additionally, undertaking specific model calibration for each study site was both infeasible and out of the present scope of works; the purpose of the project being to apply the numerical model XBeach as a generic erosion model to in excess of 100 locations along the Australian coastline. No validation of the model outputs was, nor could be, undertaken at any beach assessed in this study. The validity of the model predictions therefore rely entirely on the transferability of the implemented model from one beach site to the other.

Representative beach profiles

Representative ("proxy") beach profiles selected from the ones made available for this study were used at locations where no bathymetric data was provided. Beach profiles should be taken for a range of pre- and post-storm conditions at any site where hazard setback lines are to be incorporated in LEP (Local Environmental Plan) planning regulations. Although the representative profiles were carefully selected considering both morphological and hydrodynamic factors, the model outputs at these locations need to be considered only as broad approximation and subject to detailed site specific investigations.

1.5.2 Boundary Wave and Water Level Conditions

Wave and water level conditions relied on statistical extreme wave and water level analyses. There is uncertainty in extreme value analysis due to the accuracy and completeness of original data, particularly in cyclonic regions where a number of more detailed wave and storm tide studies have been undertaken for private organisations.

Boundary wave conditions were set in deep water and, unless otherwise stated, assumed a linear, two-dimensional transformation to the shoreline. In reality, this is rarely the case and wave energy is often focussed, diverged and dissipated by various bathymetric and topographical features such as reefs and headlands. Wave dissipation over reefs was not implemented in the model and wave direction was always (conservatively) assessed as perpendicular to the coast. Model predictions need to be considered as inherently conservative based on the selection of events and combinations of driving parameters. This conservatism is considered appropriate for first-order assessment and regional-scale planning.

1.5.3 *Beach Erosion and Setbacks*

Beach erosion volumes and setbacks were estimated applying state-of-the-art beach response numerical models tempered with engineering judgement. However, limited data was available to verify the model output and the model predictions were validated only at specific sites where field datasets incorporating pre- and post-storm measurements were available. Model predictions are appropriate for the assessment of relative beach vulnerability to storm erosion and general regional variability of storm impacts.

Only unconsolidated sandy beaches exposed to moderate to high wave energy were considered for this assessment. The presence of hard rock substrate within the beach was not considered neither was fine cohesive sediments. Within the model XBeach, numerical modelling was undertaken in profile mode, therefore only cross-shore sediment transport processes were considered. Alongshore variability and processes such as longshore currents were not considered. However, dune and beach erosion during extreme storm events is mainly a cross-shore process and the model output data provides realistic estimates of storm impact on beaches. The effect of seawalls in limiting the erosion was not considered in the modelling.

1.5.4 *Future Shoreline Recession*

Future shoreline recession as a result of sea level rise was estimated by providing active slopes ("Bruun factors") for the application of the Bruun Rule (1962, 1983 and 1988). The limitations of this methodology are well recognised (Ranasinghe et al., 2007) and were taken into consideration. However, no robust and scientifically recognised alternative currently exists and the application of the Bruun Rule is currently supported by several State Government Policies (DECCW, 2010).

2. Australian Policies and Practice

2.1 Introduction

The following section summarises Australian policies and practice with regard to determining coastal setbacks. This information is with regard to erosion and recession setbacks and does not include the inundation hazard. There are numerous caveats and qualifications within the documents referenced. The reader should refer to the original source documents before basing any decision on the information presented below.

The relevant documents and policies are often contentious and have diverging views among stakeholders. This often results in long policy development times, draft documents being available for public consultation, and sometimes abandoned or discontinued policies. Only policies finalised at the time of writing (June 2012) have been included below.

Engineers Australia's NCCOE (2004) has published the document "Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering" which also provides valuable guidance. These guidelines are undergoing revision at the time of writing this report and an updated version should be available before the end of 2012. For recent changes in legislation and policies for coastal management and planning, reference should be made to Gates and Cox (2012).

While it has no jurisdictional power, the Commonwealth adopted a sea level rise of 1.1 m in its 2011 national coastal vulnerability assessment.

2.2 Queensland

The following information is provided from the Queensland Department of Environment and Resource Management (DERM). The Queensland Coastal Plan (DERM, 2012a) came into effect from 3 February 2012. It replaced the State Coastal Management Plan (DERM, 2001) and associated regional coastal management plans. The Queensland Coastal Plan was prepared under the Coastal Protection and Management Act 1995. It includes a state planning policy under the Sustainable Planning Act 2009.

The Queensland Coastal Plan has two parts:

- State Policy for Coastal Management; and
- State Planning Policy 3/11: Coastal Protection (SPP).

The Coastal Protection and Management Act 1995 defines *coastal hazard* as "erosion of the foreshore or inundation" (page 120). DERM (2012a) lists the following coastal hazards:

- Coastal erosion;
- Storm tide inundation; and
- Permanent inundation from sea-level rise.

SPP 3/11 has the following stipulations:

- It applies to building work within 500 m of the coastline (Clause B.8).
- A sea level rise of 0.8 m by 2100 (Section 2.1).

Coastal building lines are defined in the Coastal Protection and Management Act 1995 (s. 66) and declared under the Coastal Protection and Management Regulation 2003. They can only be declared in a coastal management district.

For storm tide assessment (inundation), the guidance shown in Table 2.1 is provided (Table 3.2 of SPP 3/11). Design sea level rise for planning is shown in Table 2.2 (Table 3.3 of SPP 3/11). The policy also provides different suggested ARI/AEPs for differing development types.

Table 2.1 Planning Periods for Queensland Development

Development type	Planning period
Short-term tourist accommodation	40 years
Residential dwelling, excluding unit blocks of 7+	50 years
Residential dwelling unit blocks of 7+	60 years
Industrial building	40 years
Commercial building (retail)	40 years
Commercial building (multiple storeys)	60 years

Table 2.2 Design Sea Level Rise for Queensland Coastal Planning

Year of end of planning period	Projected sea level rise (m)
2050	0.3
2060	0.4
2070	0.5
2080	0.6
2090	0.7
2100	0.8

An Annex to SPP 3/11 is entitled Queensland Coastal Hazards Guideline (DERM, 2012b). This guideline provides the following Eqn. 2-1 for calculating setbacks:

$$E = [(N \times R) + C + S] \times (1 + F) + D \qquad (2\text{-}1)$$

Where:
E = erosion prone area width (metres)
N = planning period (years)
R = rate of long-term erosion (metres per year)
C = short-term erosion from the 'design' storm or cyclone (metres)
S = erosion due to sea-level rise (metres)
F = factor of safety (0.4 has been adopted)
D = dune scarp component to allow for slumping of the erosion scarp (metres)

DERM (2012b) stated: *"In the above equation, the values of R, C, S and D can be determined for individual beaches based on collected data and site specific modelling or profile response. The choice of values for N and F, as well as the specifications of the storm used to determine C, are more subjective decisions that require reliance on accepted practices."*

Suggested techniques and common practice for the components in DERM (2012b) are:

Planning period: as per Table 2.1 and Table 2.2 above;

Ongoing underlying recession: Aerial photos, photogrammetry or surveys;

Storm erosion: Consider "acceptable" community risk, which is generally 100 year ARI. On wave dominated beaches (e.g. Gold Coast), 100 year ARI waves and "moderate" storm surge water levels can be combined. On tide dominated beaches, 20 year ARI waves can be combined with 100 year ARI water levels. The use of a single event may not account for clustering of storms, but this is somewhat offset by the use of a factor of safety (see below). The policy suggests either a simple geometric translation model such as Vellinga (1983) or mid complexity 1D models such as SBEACH. The policy acknowledges that professional engineering judgement is required.

Erosion due to sea level rise: The policy suggests the use of the Bruun Rule for this component. It does not provide any guidance to its application on the open coast. On moderate energy tide dominated beaches, it suggests use of the upper beach face slope in the Bruun Rule calculation rather than the tidal flats slope. In low energy estuaries, it stated that the sea level response is expected to be dominated by inundation, and recommends against the Bruun Rule on these coasts.

Factor of Safety: A factor of safety of +40% is applied to the above setback calculations. This is somewhat subjective but comparable to many other engineering calculations.

Dune Scarp Component: This component is required to be considered. The factor of safety is not applied to this component and no specific technique is recommended for its calculation. Suitable techniques (e.g. Nielsen et al, 1992) are well known to coastal engineers and geotechnical engineers practising on the coast.

The erosion prone area is taken to be the greater of:

- 40 m from present HAT line;
- A distance calculated as per Equation 2.1, using the present HAT line or the dune vegetation line.

2.3 New South Wales

The following coastal hazards in NSW are listed in the Coastline Management Manual (NSW Government, 1990):

- Beach Erosion;
- Shoreline Recession;
- Coastal Entrance Hazard;
- Sand Drift (wind blown);
- Coastal Inundation;
- Slope and Cliff Instability;
- Stormwater Erosion; and
- Climate Change.

A sea level rise policy statement (DECCW NSW, 2009) lists the following benchmarks:

- 2050: up to 0.4 m; and
- 2100: up to 0.9 m.

On the open coast, design storm erosion is usually calculated from the statistics published by Gordon (1987). These statistics were derived from photogrammetry and surveys, in particular following the May-June 1974 storms, including the *Sygna storm*. The statistics of Gordon are often supplemented with erosion models such as SBEACH and compared to photogrammetric data. On more sheltered beaches, those without photogrammetry, or where gaps (2 to 20 years) in photogrammetry prevent direct measurement, erosion models such as SBEACH are commonly used.

Ongoing underlying recession is usually estimated from photogrammetry. Where littoral drift transport differentials exist, numerical shoreline evolution models have also been used to supplement this analysis.

On sand dunes, slope instability is assessed with the methodology of Nielsen et al (1992). This method contains a factor of safety of +50% in the angle of repose of sand. It is noted, however, that many published "coastal hazard lines" do not include the allowance for the "stable foundation zone" as it is highly dependent on dune elevation and sand characteristics, which often vary substantially alongshore.

Additional recession due to sea level rise is generally assessed with the Bruun Rule, although alternative models such as the Cowell (1992 and 1995) *Shoreface translation model* and techniques such as those presented in Patterson (2009) and Huxley (2009) have been used. The NSW Government (2010) "Coastal Risk Management Guide: Incorporating sea level rise benchmarks in coastal risk assessments" suggests the use of the Bruun Rule, with the Hallermeier (1978, 1981 and 1983) outer closure depth. Most practitioners consider a range of techniques for assessing closure depth, including Hallermeier inner and outer depths, and sediment boundaries, with the adopted value relying on engineering judgement.

The other hazards listed in the NSW Coastline Management Manual are beyond the scope of this report, but it is noteworthy that the manual recognises that erosion may be locally increased due to stormwater outlets and may be unrelated to waves near unstable coastal entrances.

2.4 Tasmania

The Tasmanian State Coastal Policy 1996 and the State Coastal Policy Validation Act 2003 define the coastal zone as being within 1 km of the high water mark. A draft revision of this policy has been produced and discontinued. A state sea level rise policy has not yet been published but has been reported to be a high priority (Lord and Gordon, 2011).

Section 1.4 of the State Coastal Policy regarding coastal hazards includes:

> *"1.4.1. Areas subject to significant risk from natural coastal processes and hazards such as flooding, storms, erosion, landslip, littoral drift, dune mobility and sea level rise will be identified and managed to minimise the need for engineering or remediation works to protect land, property and human life.*
>
> *1.4.2. Development on actively mobile landforms such as frontal dunes will not be permitted except for works consistent with Outcome 1.4.1.*
>
> *1.4.3. Policies will be developed to respond to the potential effects of climate change (including sea-level rise) on use and development in the coastal zone."*

No guidance is provided regarding the estimation of these hazards. A major study by Sharples (2006) identified potentially erosion prone land on a first pass state wide basis. Later studies by Sharples et al. (2009) provided a "smartline" of potentially erosion prone land based on landforms and geology. This was undertaken for the Commonwealth and used a sea level rise of 1.1 m by 2100 and a Bruun Rule factor of 100.

Some council planning schemes stipulate that coastal setbacks for development be calculated by a practising engineer or coastal scientist. To date, assessments for local councils (e.g. Carley et al., 2008) have relied on contemporary coastal engineering techniques using parameters and techniques (e.g. sea level rise, erosion modelling and recession estimates) comparable to other states and suggested in NCCOE (2004).

2.5 Victoria

The Victorian Coastal Strategy (VCS, 2008) stated that sea level rise of at least 0.8 m by 2100 should be used for coastal planning. Furthermore, development proponents should "allow for the combined effects of tides, storm surges, coastal processes and local conditions such as topography and geology when assessing risks and impacts associated with climate change".

A series of planning notes and guidelines are available which state the need to consider the following components in setbacks:

- Storm erosion;
- Ongoing underlying recession; and
- Recession due to sea level rise.

No specific techniques are recommended to estimate values for these components.

The experience of the authors is that storm erosion in Victoria is usually estimated by coastal engineers using numerical models such as SBEACH. Underlying recession is usually estimated by mapping the vegetation line from aerial photos dating back to the 1940s and/or photogrammetry. Recession due to sea level rise is estimated using the Bruun Rule. Ranasinghe et al (2011) stated that common practice in Victoria was for the closure depth in Bruun Rule calculations to be estimated from SBEACH modelling.

2.6 South Australia

Coastal setbacks are covered in the "Coast Protection Board Policy Document: Revised 20 January 2012" which refers to the "CPB [Coast Protection Board] Policy on Coast Protection and New Coastal Development including Hazard Standards, Sea Level Rise, and Protection Funding" (1991).

The sea level rise component of the above policy is to plan for sea level rise of:

- 2050: 0.3 m; and
- 2100: 1.0 m.

The above values need to also consider local land subsidence (or uplift).

The 2012 and 1991 policies recognise that setbacks need to consider storm erosion, ongoing underlying recession and recession due to sea level rise, but recommended or suggested methods are not provided.

The documents state that "insofar as staff resources and funding permits" the CPB will assist local councils with studies, but development proponents must undertake their own studies.

A comprehensive survey program has been undertaken for Adelaide's beaches. This allows direct measurements of storm erosion and recession in the most developed locations. Some studies have supplemented these with numerical modelling such as SBEACH. Such models are used away from areas of intensive data collection.

2.7 Western Australia

Coastal setbacks are covered in the policy: Statement Of Planning Policy No. 2.6 State Coastal Planning Policy prepared under section 5AA of the Town Planning And Development Act 1928. At the time of writing (June 2012) the latest version was dated 19 May 2006. A revision of this document is currently in draft format.

For sandy coasts, the policy considers three setback components for 100 year planning period, namely:

- S1: Acute erosion (extreme storm sequence);
- S2: Historic trend (erosion or accretion); and
- S3: Distance to allow for sea level change.

S1 (acute erosion) is to be calculated using a model such as SBEACH with three back to back design storms to account for storm sequencing/clustering. In the absence of such modelling an allowance of 40 m is to be made.

S2 (historic trend) is to be based on at least 40 years monitoring (e.g. aerial photos). On "stable" shores a minimum allowance of 20 m is required unless it can be demonstrated that the area is accreting, in which case the allowance can be zero.

S3 (distance to allow for sea level change) is set to 38 m, which is based on a sea level rise projection of 0.38 m and a Bruun factor of 100. A position statement and technical guide by the WA Planning Commission has adopted a sea level rise of 0.9 m by 2110, which would increase the S3 component to 90 m if the reasoning of the 2006 document is continued, but a revision of SPP 2.6 has not yet been finalised.

2.8 Northern Territory

The Northern Territory Government published Northern Territory Climate Change Policy 2009, which acknowledges the threat of rising sea levels and the need to consider climate change in planning. However, the Northern Territory has no formal sea level rise policy. Lord and Gordon (2011) reported that values consistent with Queensland have been used in practice. No formal policies exist regarding coastal setbacks. Due to the generally low wave energy and the potential for cyclonic surges, inundation is likely to be a greater coastal hazard than erosion/recession.

2.9 Summary of Australian Policy and Practice

A summary of Australian Policy and Practice is provided in Table 2.3. It can be seen that all states with developed policies acknowledge the need to consider storm erosion, ongoing recession and recession due to sea level rise. Projected sea level rise benchmarks are within 0.1 m of each other. There are differences in the suggested or recommended method of calculating storm erosion, however, all methods require coastal engineering experience and judgement. No states consider beach rotation in formal policies, but it is acknowledged by practitioners in site specific studies, and sometimes accounted for by adopting "conservative" values for other parameters.

Only two states (QLD and NSW) routinely consider dune stability in setback calculations. Only Queensland has an explicit factor of safety incorporated into its setback calculation. In other states, this is managed by adopting "conservative" values for other parameters. In NSW, the Nielsen et al. (1992) dune stability model has a factor of safety of +50% in the dune stability component referred to as S5 in this report.

Table 2.3 Summary of Australian Policy and Practice for Coastal Setbacks (erosion and recession, not inundation)

State	Sea level rise (m)							Storm erosion	Ongoing underlying recession	Recession due to sea level rise	Beach rotation	Dune stability	Factor of safety	SLR policy comment	Setback policy comment
	2050	**2060**	**2070**	**2080**	**2090**	**2100**	**2110**	***S1***	***S2***	***S3***	***S4***	***S5***	***FS***		
QLD	0.3	0.4	0.5	0.6	0.7	0.8	-	Suggests Vellinga, SBEACH or equivalent	Aerial photos, photogrammetry or surveys suggested	Bruun Rule. Closure depth method not specified. Upper beach face slope suggested for moderate energy beaches	Not specified	Required but method not specified	40% on S1, S2, S3	SLR policy is explicit and allows for a range of planning periods	Setback policy is explicit but leaves some estimates to engineering judgment
NSW	0.4	-	-	-	-	0.9 (a)	-	Gordon erosion statistics, supplemented with photogrammetry &/or numerical models	Generally photogrammetry	Bruun Rule. Closure depth by Hallermeier outer is suggested, but most practitioners use Hallermeier inner or sediment boundaries	Not specified but usually covered in conservative S1 estimate	Nielsen et al. (1992)	Nil, but "conservative" values adopted for S1, S2, S3. Nielsen model has 50% on S5	SLR policy is explicit and allows for a range of planning periods	Setback policy relies on engineering judgment but accepted practice is quite consistent
VIC	-	-	-	-	-	0.8 (b)	-	Not specified, usually SBEACH or equivalent	Aerial photos or photogrammetry	Not specified, but most practitioners use SBEACH closure depth	Not specified	Not specified	-	SLR policy is explicit and only for 2100	Setback policies not explicit – generally left to engineering judgment
TAS	(c)	-	-	-	-	(c)	-	Not specified	Not specified	Not specified	Not specified	Not specified	-	SLR policy not yet published. In practice, values from nearby states are adopted	Setback policy not yet published. Relies on engineering judgment where invoked
SA	0.3	-	-	-	-	1.0	-	Not specified, usually SBEACH or surveys	Not specified, generally aerial photos, surveys, photogrammetry	Not specified but Bruun Rule usually applied	Not specified	Not specified, but judgment allowance has been used	-	SLR policy is explicit and allow for a range of planning periods. 200 year period for major development	S1 to S3 are listed to consider but techniques are not specified. Relies on judgment of practitioners

State	Sea level rise (m)							Storm erosion	Ongoing underlying recession	Recession due to sea level rise	Beach rotation	Dune stability	Factor of safety	SLR policy comment	Setback policy comment
	2050	**2060**	**2070**	**2080**	**2090**	**2100**	**2110**	***S1***	***S2***	***S3***	***S4***	***S5***	***FS***		
WA	-	-	-	-	-	-	0.9	Use of SBEACH or equivalent with 3x design storms. 40 m if modelling not done	Aerial photos, photogrammetry or surveys suggested. Minimum 20 m unless demonstrated to be accreting	Standard distance of 38 m by 2100, which equates with 0.38 m SLR and Bruun factor of 100. Policy using 0.9 m SLR not yet finalised for setbacks.	Not specified. Considered in site specific assessments	Not specified	Nil, but "conservative" values adopted for S1, S2, S3.	Policies are quite explicit	Setback policy is explicit but leaves some estimates to engineering judgment
NT	(c)	-	-	-	-	(c)	-	Not specified	Not specified	Not specified	Not specified	Not specified	-	SLR policy not yet published. In practice, values from nearby states are adopted	Setback policy not yet published. Relies on engineering judgment where invoked.

Notes:

a: "Up to"

b: "At least"

c: In practice, values from nearby states are adopted in the absence of formal policy

3. Environmental Conditions

3.1 Introduction

The vulnerability of an unconsolidated (sandy) shoreline to erosion during a storm event or series of events is dependent on the characteristics of both the beach system and the storm system(s) acting on that beach. Storm characteristics including the wave height and period, and storm duration influence the total energy available to act upon the beach. Water level, influenced by both astronomical tide and meteorological systems, affects the amount of wave energy able to reach the upper beach and mobilise sediment. Likewise, near-shore morphology influences cross-shore energy distributions and the upper beach geometry, and sediment characteristics influence the susceptibility of the beach to erosion. The combination of these parameters dictate the magnitude of coastal erosion volumes and the setback distances required.

This section discusses the various Australian Coastal Types including both nearshore and offshore morphology, sediment characteristics and typical seasonal and storm-induced change. The Australian wave climate including storm climatology and extreme values are discussed along with present and future extreme water level distributions.

3.2 Australian Coastal Types

3.2.1 Overview

As part of the First Pass National Assessment of Coastal Vulnerability, a broad typology of coastal types was completed. SMARTLINE, as the classification scheme was called (Sharples et al., 2009), broadly defines the Australian coast into types based on the geological substrate and broad geomorphology, e.g. cliffed vs. sandy coast. Coastlines can then be segregated into regional mega-compartments that are representative of integrated morphologies and intra-compartment sediment transport connectivity. Further, compartments can then be subdivided into a continuum of beach types based on a morphodynamic response to wave climate (Wright et al., 1984).

The latter approach was applied to sandy and reef coasts to produce a beach typology for Australia (Short, 2006) that also has global applicability. The Short (2006) beach typology is an extension of previous versions, and now provides 15 different types spanning, wave-dominated beaches (Figure 3-1), tide-modified beaches (Figure 3-2), and tide-dominated beaches (Figure 3-3). Wave dominated and tide-dominated beaches are characteristic of southern and northern Australia respectively. Tide modified beaches primarily occur in north Western Australia, Northern Territory, and eastern Cape York Peninsula (Short and Woodroffe, 2009).

For each beach type, the linear to curved morphology found offshore in the surf zone is reflected in the beach berm and backshore (foredune) morphology. For example, a Type 3 Rhythmic Bar and Beach has a morphodynamic relationship between the surf zone, beach and backshore where the location and width of rip cells can control the spatial variability in storm beach and dune erosion. It is important to note that this typology is restricted to the beach and surf zone, comprising the upper shoreface, and does not include differentiation based on sand grain size, although the tide-dominated types do relate to a fining of sediment size. However, there is considerable spatial variability in the slope of the lower shoreface (extending out to wave base) and the inner shelf slope. Typically, the inner shelf slope is steeper (flatter) in Southern (Northern) Australia.

We consider that the Short (2006) beach type classification is suitable to apply in the allocation of beach types around Australia for the purpose of storm beach modelling, since the latter is applied principally to upper shoreface profiles. The sediment grain size varies between beach types and beach gradient, such that the lower energy beach types comprise coarser sediments on the beach face and berm due to the lack of offshore breaking wave energy, while the higher energy beach types comprise finer sediments on the beach face and berm, due to the dissipation of breaking wave energy offshore. In reality, differing beach types occur in a spatial and temporal continuum. Storm events drive a transformation in beach type due to the co-adjustment of beach and surf zone morphology to re-establish dynamic equilibrium with the higher wave power. Hence an erosionary sequence is described by a transition from reflective (Type 6) to dissipative (Type 1) sequence, while an accretionary sequence involves the opposite.

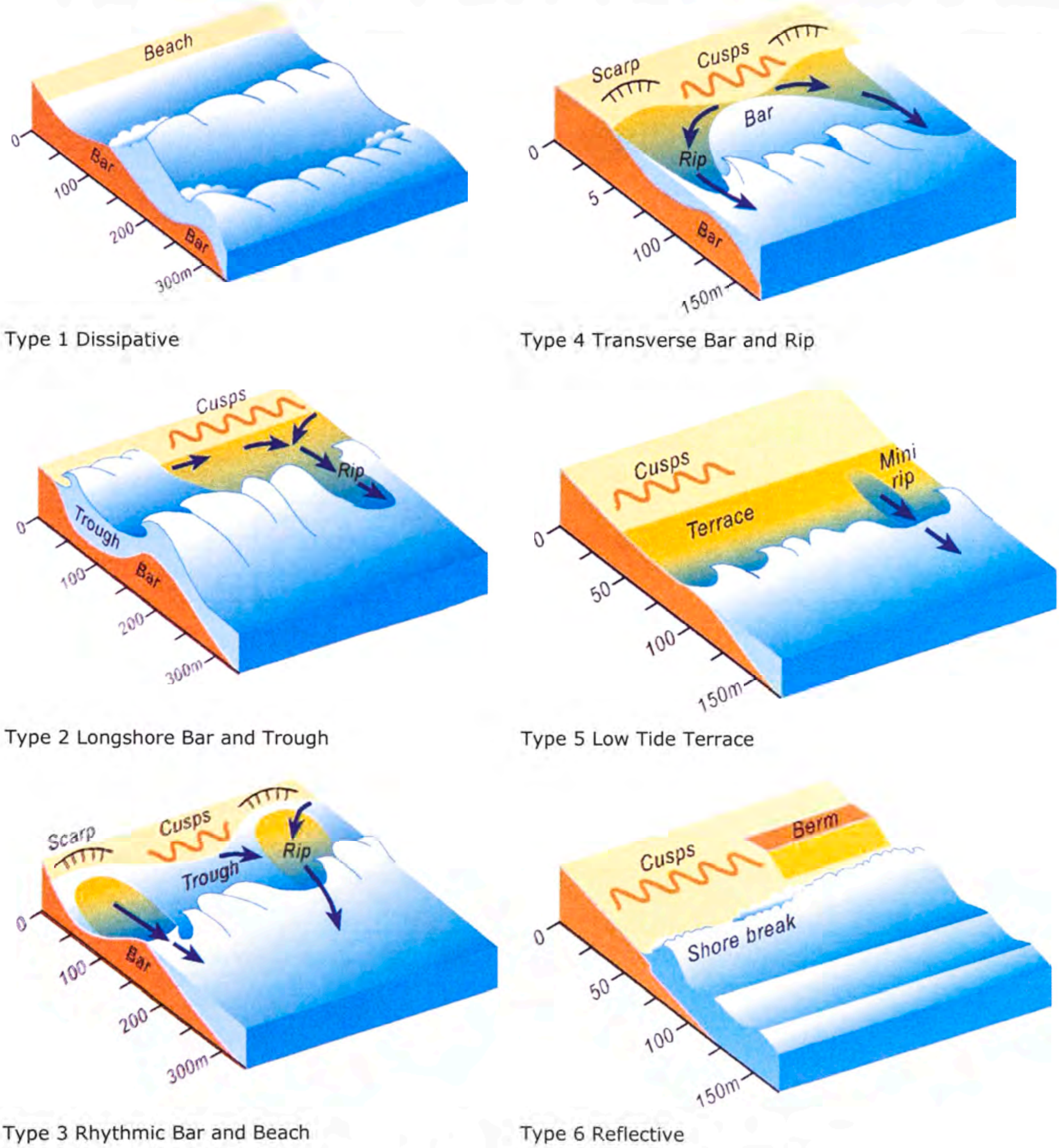
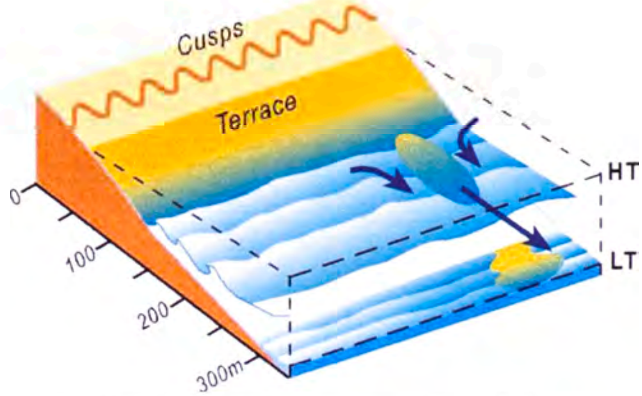
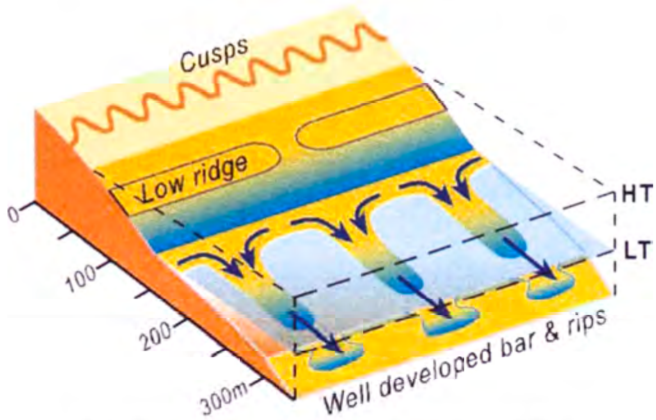


Figure 3-1 Wave Dominated Beach Types (after Short, 2006)

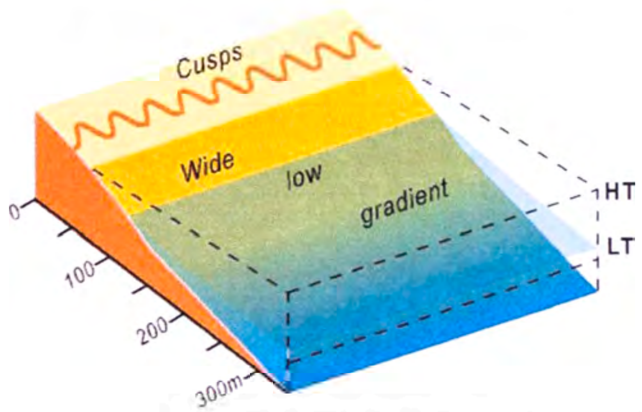
The Short (2006) beach types have previously been shown to change during a storm event, where the beach type transforms during the storm erosion phase to the next highest energy type during a storm event (day), as sand is transported offshore. During the subsequent recovery or accretion phase the beach type transforms to the next lower energy type at a typical rate of one type per few days (Wright et al., 1984). On multi-barred beaches, there is a cross-shore continuum of surf zone types, similar to the spatial continuum along the beach.



Type 7 Reflective + Low Tide Terrace



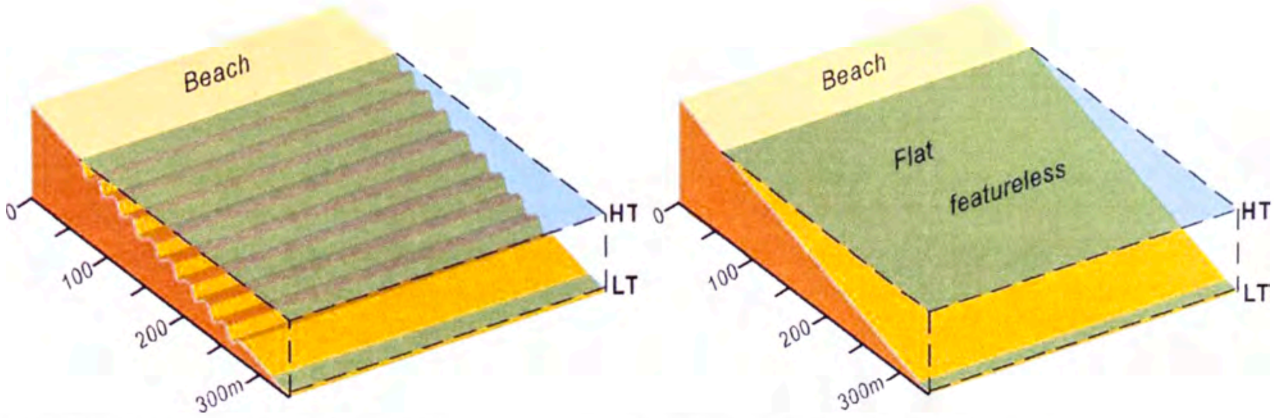
Type 8 Reflective + Low Tide Bars and Rips



Type 9 Ultradissipative

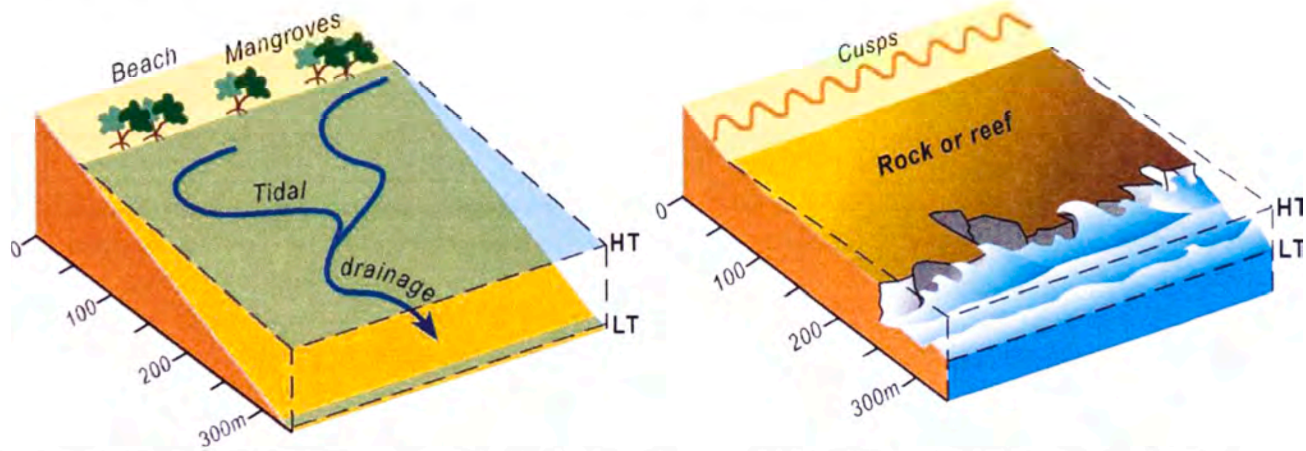
Figure 3-2 Tide-modified Beach Type (after Short, 2006)

For example on a double barred surf zone, the beach may be Type 4, Transverse Bar and Rip, the first bar would be Type 3 Rhythmic Bar and Beach, and the second bar offshore would be Type 2, Longshore Bar and Trough (Short, 1999). The temporal changes are driven by changes in prevailing wave conditions, whilst the spatial changes are driven by changes in both wave climate and sediment characteristics (Short, 1999).



Type 10 Beach + Ridged Sand Flats

Type 11 Beach + Sand Flats



Type 12 and 13 Beach + Tidal Sand/Mud Flats

Type 14 and 15 Reflective + Rock/Reef Flat

Figure 3–3 Tide Dominated Beaches (Type 10 to 13) and Beaches with Rock or Reef Flats (Type 14 and 15) (after Short, 2006)

3.2.2 Representative Beach Profile Data

For the purpose of this project, WRL collected beach profile data for in excess of 50 beaches along the Australian coastline. Data was made available by a number of sources, which are acknowledged and listed below:

- Department of Transport WA;
- Department of Environment and Resource Management QLD;
- Coastal Observation Program (COPE) QLD;
- Department of Environment and Natural Resources SA;
- Tasmanian Shoreline Monitoring and Archiving (TASMARC) project, TAS;
- Office of Environment and Heritage NSW;
- Andy Short (personal communication);
- WRL of University of New South Wales;
- Northern Territory Government; and
- Department of Sustainability and Environment VIC.

The data obtained consisted of:

- LIDAR survey;
- Photogrammetry;
- Digital Elevation Model (DEM);
- Eco-sounding survey;
- GPS-RTK survey; and
- Argus, video imaging.

Profile data mostly related to the sub-aerial beach, with detailed surveys of the surfzone and nearshore bathymetry available at few locations. Where necessary, data was initially complemented with nearshore bathymetry derived from the analysis of bathymetric charts (Australian Bathymetry and Topography Grid, GeoScience Australia). However, the accuracy of the Geoscience bathymetric data proved inadequate for the purposes of this study. The modelling significantly under-predicted storm erosion at some locations where the Geoscience data was utilised as shown in Appendix C. Consequently, higher quality survey data was collected (for some sites) from several sources and additional modelling was undertaken with the improved bathymetric data. WRL undertook long term averaging of the profiles at locations where good temporal coverage was available such as long-term photogrammetric datasets (sub-aerial beach only). As per Nielsen et al. (1992), beach profiles related to extremely depleted beach states were excluded from the averaging. Single profiles were analysed at locations where historical datasets were not available.

Locations of the beach profile data available for this study are shown in Fig 3-4. Table 3.1 lists the beach locations, the data type available (long term weighted average or single profile) and the dominant beach type at each location as per Short (2006). Main characteristics and plots of the available beach profiles are presented in Appendix A. It is important to note that the beach types associated with each location do not exclude the possibility of other beach types at that location. As explained in Section 3.2.1, the beach type refers to a particular state of the beach at a point in time and migration through different beach types during a single or a succession of storm events is expected.

While good spatial coverage was available for the south and east Australian coast, including South Australia, Tasmania, Victoria, New South Wales and Queensland, data for the west and north coast (Western Australia and Northern Territory) was more limited. However, the areas characterised by significant coastal development were covered. These areas are likely to be the most severely impacted during extreme storm events due to the presence of significant public and private assets built in proximity to the eroding shoreline.

1. Kingscliff Beach, NSW
2. Byron Bay, NSW
3. Stockton Beach, NSW
4. Wamberal (1), NSW
5. Wamberal (2), NSW
6. Narrabeen (Malcolm St), NSW
7. Narrabeen (Narrabeen St), NSW
8. Adam's Beach, TAS
9. Roches Beach, TAS
10. Seaspray, VIC
11. Gunnamatta Beach, VIC
12. St Kilda (Elwood), VIC
13. Lorne, VIC
14. Port Fairy, VIC
15. Discovery Bay (4), VIC
16. Discovery Bay (3), VIC
17. Discovery Bay (2), VIC
18. Discovery Bay (1), VIC
19. Goolwa, SA
20. Semaphore Park, SA
21. Esperance, WA
22. Mandurah, WA
23. North Fremantle, WA
24. Brighton Beach, WA
25. Port Denison, WA
26. Point Samson, WA
27. Mindil Beach, NT
28. Vesty's Beach, NT
29. Casuarina Beach, NT
30. Cairns, QLD MU 245
31. Cairns, QLD MU 235
32. Cairns, QLD MU 224
33. Cairns, QLD MU 216
34. Cairns, QLD MU 26
35. Cairns, QLD MU 12
36. Cairns, QLD MU 11
37. Cairns, QLD MU 8
38. Mackay, QLD 235
39. Mackay, QLD 179
40. Mackay, QLD 155
41. Mackay, QLD 130
42. Mackay, QLD 122
43. Mackay, QLD 104
44. Hervey Bay, QLD 108
45. Hervey Bay, QLD 104 (end)
46. Hervey Bay, QLD 104 (start)
47. Hervey Bay, QLD 100
48. Hervey Bay, QLD Shell14
49. Narrowneck, QLD
50. Kirra, QLD

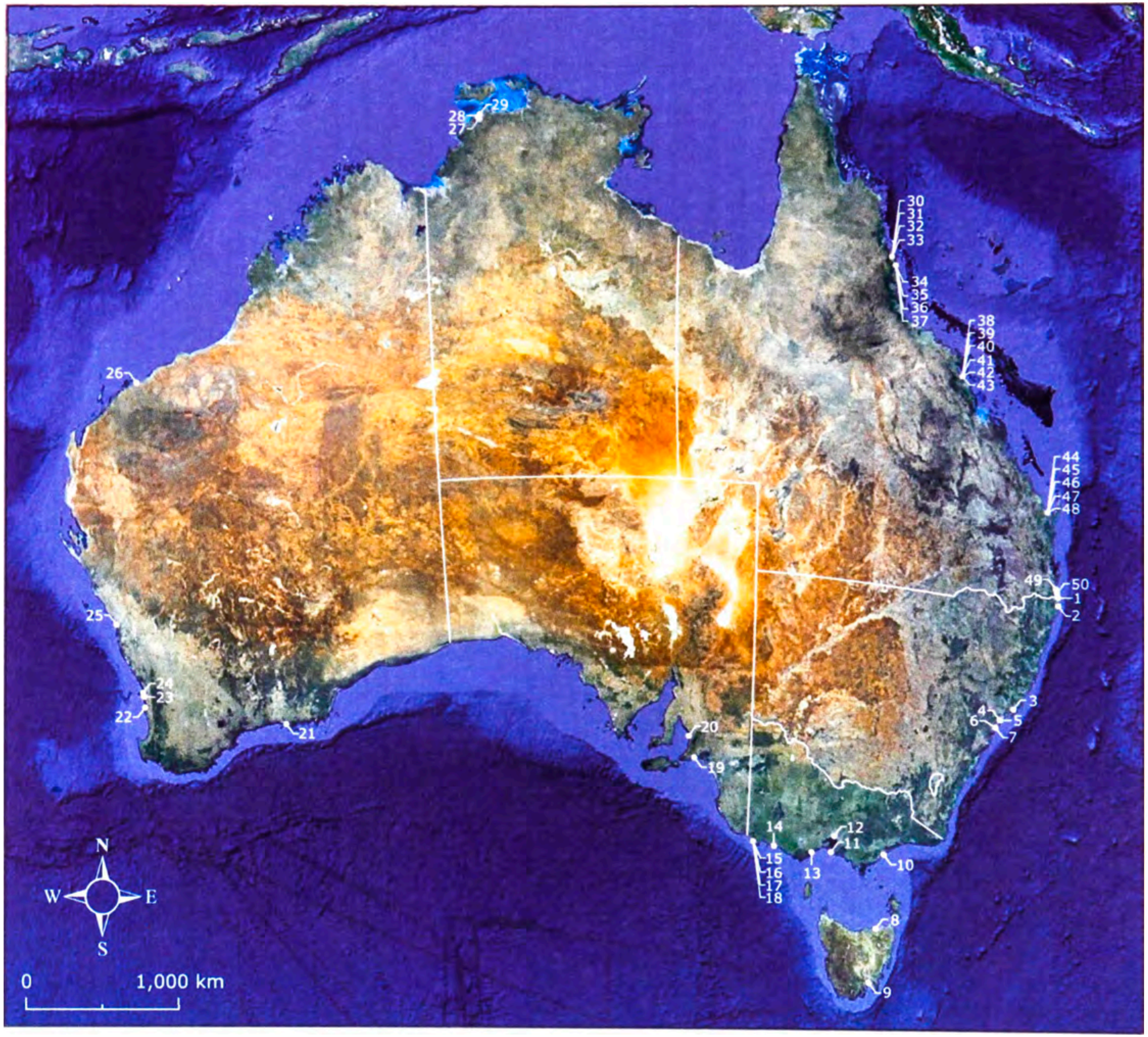


Figure 3–4 Location of Representative Profiles

Table 3.1 List of Beach Profile Locations and Relevant Beach Type

State	Beach Location	Data Type ([1]average/single profile)	[2]Beach Type
QLD	Gold Coast, Kirra	Long term average	Type 3
QLD	Gold Coast, Narrowneck	Long term average	Type 2
QLD	Hervey Bay (3 locations)	Long term average	Type 10, 11 and 12
QLD	Cairns (8 locations)	Long term average	Type 8 and 9
QLD	Mackay (6 locations)	Long term average	Type 10 to 13
NT	Casuarina Beach, Darwin	Long term average	Type 10 and 11
NT	Vestey's Beach, Darwin	Long term average	Type 7 and 8
NT	Mindil Beach, Darwin	Long term average	Type 12 to 14, 16
WA	Point Samson	Single Profile	Type 1 and 2
WA	Port Denison	Single Profile	Type 5
WA	Brighton Beach, Perth	Single Profile	Type 5 and 6
WA	North Fremantle, Perth	Single Profile	Type 4
WA	Mandurah	Single Profile	Type 4
WA	Esperance	Single Profile	Type 4
SA	Adelaide, Semaphore Park	Three year average	Type 7
SA	Goolwa	Long term average	Type 2
VIC	Discovery Bay (4 locations)	Single Profile	Type 1, 2 and 3
VIC	Port Fairy	Single Profile	Type 4
VIC	Lorne	Single Profile	Type 9
VIC	Port Phillip Bay (St Kilda)	Single Profile	Type 6
VIC	Gunnamatta Beach	Single Profile	Type 2
VIC	90 miles beach, Seaspray	Single Profile	Type 2
TAS	Roches Beach	Long term average	Type 7 and 8
TAS	Adam's Beach - Bridport	Long term average	Type 5 and 6
NSW	Narrabeen (two locations)	Long term average	Type 3
NSW	Wamberal	2012 average of monthly data	Type 4 and 5
NSW	Stockton Beach, Newcastle	Long term average	Type 6
NSW	Byron Bay	Long term average	Type 4
NSW	Kingscliff	Long term average	Type 4

Notes: (1) Profiles associated with a particularly depleted beach state, e.g. after a significant storm, were not considered in the averaging (Nielsen et al. 1992)

(2) Beach types relate to the dominant beach types in each location, which does not exclude the occurrence of other beach types

3.3 Wave Climate

3.3.1 Australian Wave Climatology

The Australian continent extends from southern mid-latitudes to tropics in the north and, as a result, the wave climatology affecting Australia's coastal margins varies both spatially and temporally with distinct climatic processes dominating different regions. The coastal margin is exposed to waves generated within two oceans and three adjacent seas.

The southern part of Australia receives persistent moderate to high wave energy from mid-latitude low pressure systems centred within the Southern Ocean at between 50 and 60° S latitude (Short and Woodroffe, 2009) with large wave events occurring intermittently as these low pressure systems intensify and/or extend further north towards the coastline. These large wave events are more frequent during winter months as the subtropical high pressure belt moves north and subsequently allows the northern migration of mid-latitude lows (Lemm *et al.* 1999). These systems have long westerly fetches and propagation paths from west to east. The resulting wavetrains have mean peak periods exceeding 12 to 14 s at Cape Sorell and Cape de Couedic (Short and Woodroffe, 2009).

The uniform nature of the climatic system responsible for both the mean and extreme wave climate results in a near unidirectional wave climate along the southern continental margin. A numerical analysis by Hemer *et al.* (2007) showed waves in southern Australia generally to arrive from the SSW to WSW with seasonal variation of less than 10° S and similarly small variation in the direction of large (>99th percentile) wave events.

While a portion of this south-west directed wave energy reaches the Australian East Coast, the majority of the east coast's wave energy is generated within the Coral Sea and Tasman Sea window (Short and Trenaman, 1992). Storm climatology along the NSW and southern Queensland coast has been described by PWD (1985 and 1986), Short and Trenaman (1992), Lord and Kulmar (2000), Allen and Callaghan (2001) and Speer *et al.* (2009) among others with Shand *et al.* (2010) classifying storm waves along the NSW coast according to eight synoptic types.

Major storm events in northern NSW and southern Queensland were found to be a mixture of tropical cyclones, tropical lows and easterly trough lows while in the mid NSW coast, major storm events also included inland trough lows and southern secondary lows. In the south of NSW, extreme waves are caused by a combination of easterly trough lows, inland and continental lows and southern secondary lows. Tropical cyclones and lows are restricted to December to April with most occurring between January and March. Easterly trough lows are concentrated between April and August. On the east coast, wave direction was found to be highly variable depending on season and particular storm type (Shand *et al.* 2010).

The synoptic storm types, which affect NSW, are also generally appropriate for south-east Queensland. In contrast, northern Queensland and the northern Australian coastal margin is subject to typically small to moderate waves caused by north-west monsoons affecting north-west exposed locations, trade winds affecting areas exposed to the south-east, particularly in summer and sea breezes also during the summer months.

In northern Australia large waves are generally induced only by infrequent tropical cyclones (Short and Woodroffe, 2009) between December and March. Cyclone frequency, intensity and track have received significant attention with extensive studies by Lourensz (1977 and 1981) forming the basis of the Bureau of Meteorology *Tropical Cyclones Historical Archive* and Harper (1998) describing a number of subsequent studies. Figure 3–5 shows the average annual occurrence of tropical cyclones between 1996 and 2006. Cyclones generated within the Coral Sea are observed to generally track south-west towards northern Queensland and cyclones generated within the Arafura and Timor seas typically track south-west across the top of the Northern Territory and north-west Western Australia. Numerical models show wave direction at the coast during large wave events to be typically south-east in the northern Queensland region and Northern Territory and south-west to west off north-west Western Australia (Hemer *et al.* 2007).

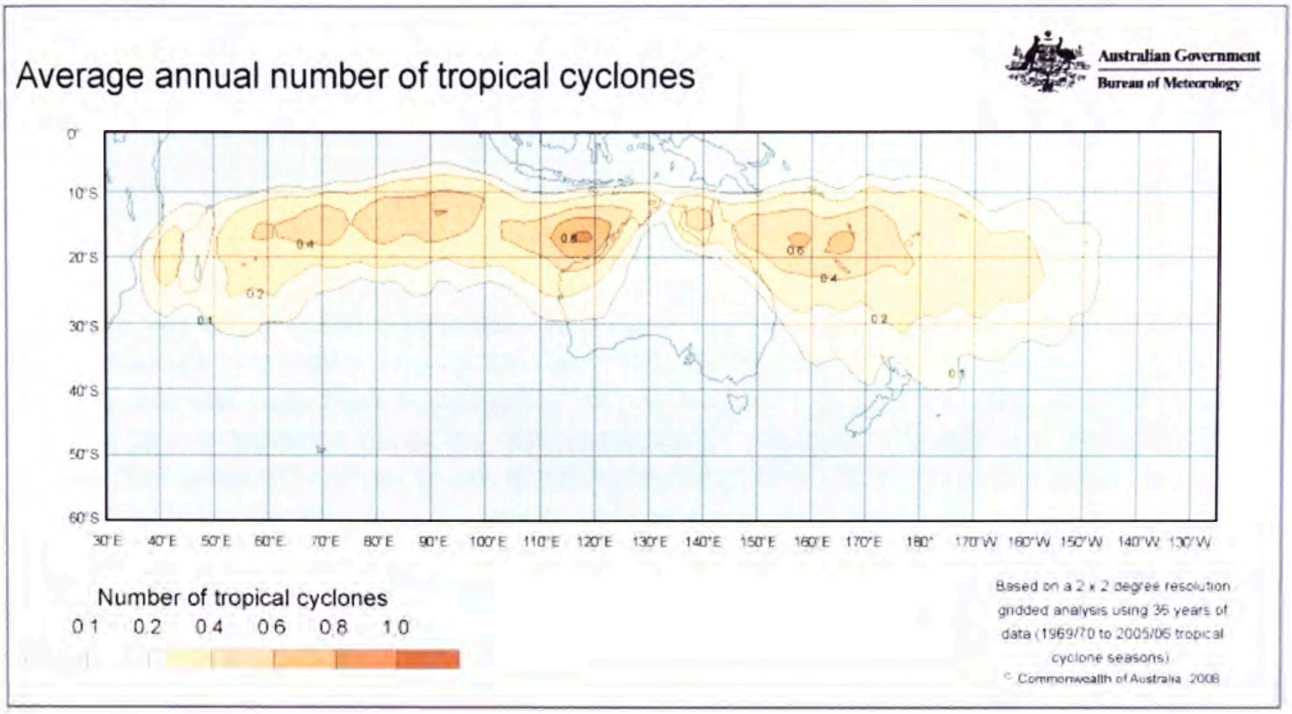


Figure 3-5 Mean Tropical Cyclone Frequency in Australia (source: BoM, 2008)

The south-western Australian coastline is subject to high wave energy from mid-latitude lows centred within the Southern Ocean, particularly during the winter months when the low-pressure band moves north (Lemm *et al.* 1999) but is also subject to smaller sea breeze-induced waves during the summer months and tropical cyclones in the northern regions during summer. This sea breeze component can be important along the coast as an extensive network of offshore reefs extend some 600 km along the south-west Australian coastline, which attenuate large amounts of the incident swell energy (Pattiaratchi *et al.* 1997). Extreme wave events, however, are generally caused by intense mid-latitude lows in the southern regions of Western Australia; and by a combination of large northerly propagating swell from such events and tropical cyclones along the mid-Western Australian coastline. Variation in mean and extreme wave direction is small with waves typically arriving from the SSW to WSW (Hemer *et al.* 2007).

Mean wave climate derived by Hemer *et al.* (2007) using the NOAA Wavewatch III (NWW3) numerical hindcast dataset (1997 - 2009) is presented within Figure 3-6. Results show the southern margins to be exposed to highest wave energy with mean significant wave height of up to 3.5 to 4 m along the Tasmanian West coast and Western Australian south-west coast. Mean wave climate is reduced to the north as distance from the dominant generation zone increases and the wave mean climate drops substantially north of Exmouth and in Northern Territory as land-mass sheltering blocks waves energy from the dominant south-westerly direction. These numerical results are generally higher than wave buoy-derived values presented in Shand et al. (2010) with mean significant wave height found to range from 1.6 m along the Australian south-east coast, up to 3 m along the southern coast and reducing slightly to 2.3 m with distance up the Australian south-west coast.

3.3.2 Extreme Wave Climate

The identification and analysis of large events observed within a historical record allows quantification of extreme event and, using appropriate extreme value analysis, characterisation of large, low probability wave events. These low probability events are generally described by either their average recurrence interval, which describes the average time interval between events exceeding a particular magnitude, or by their annual exceedance probability. The AEP describes the probability of an event, which exceeds a particular magnitude occurring in any given year. The relationship between average recurrence interval and annual exceedance probability is near reciprocal, and given by Eqn. 3-1.

$$AEP = 1 - e\left(\frac{-1}{ARI}\right) \quad (3\text{-}1)$$

While the use of particular terminology to describe extreme events is somewhat arbitrary, the use of average recurrence interval has been criticised for being *"sometimes misinterpreted as implying that the associated magnitude is only exceeded at regular intervals, and that they are referring to the elapsed time to the next exceedance"* (Australian Rainfall and Runoff, IE Aust., 1987). The probability of an event of particular magnitude (AEP) occurring within a specified timeframe (TL) is given by Eqn. 3-2 and presented within Table 3.2.

$$P(Z) = 1 - (1 - AEP)^{T_L} \quad (3\text{-}2)$$

Table 3.2 Probability of Event Occurrence within a Specified Timeframe

Event Average *Recurrence Interval* (ARI; Years)	**Probability of event occurrence within**					
	1 year	5 years	10 years	20 years	50 years	100 years
1	0.63	0.99	1.00	1.00	1.00	1.00
5	0.18	0.63	0.86	0.98	1.00	1.00
10	0.10	0.39	0.63	0.86	0.99	1.00
50	0.02	0.10	0.18	0.33	0.63	0.86
100	0.01	0.05	0.10	0.18	0.39	0.63
1,000	0.00	0.00	0.01	0.02	0.05	0.10

Sources of wave data, which may be used in extreme value analysis, include instrumentally measured wave conditions, numerically and/or analytically forecast or hindcast conditions or visually observed wave conditions (shore- or ship-based). These data sources each possess certain advantages and disadvantages.

Advantages of instrumentally measured data are that they are accurate and continuous. Disadvantages include that data is spatially discrete, which, in areas subject to small-scale storm systems such as tropical cyclones can lead to buoys missing the peak of (or the entire) event. Additionally, data is relatively expensive to obtain and deployments around the Australian coastline have been limited with the majority of buoys deployed along the south and western coasts having between 5 and 15 years of data, while the older New South Wales and Queensland buoy networks have between 10 and 30 years of data.

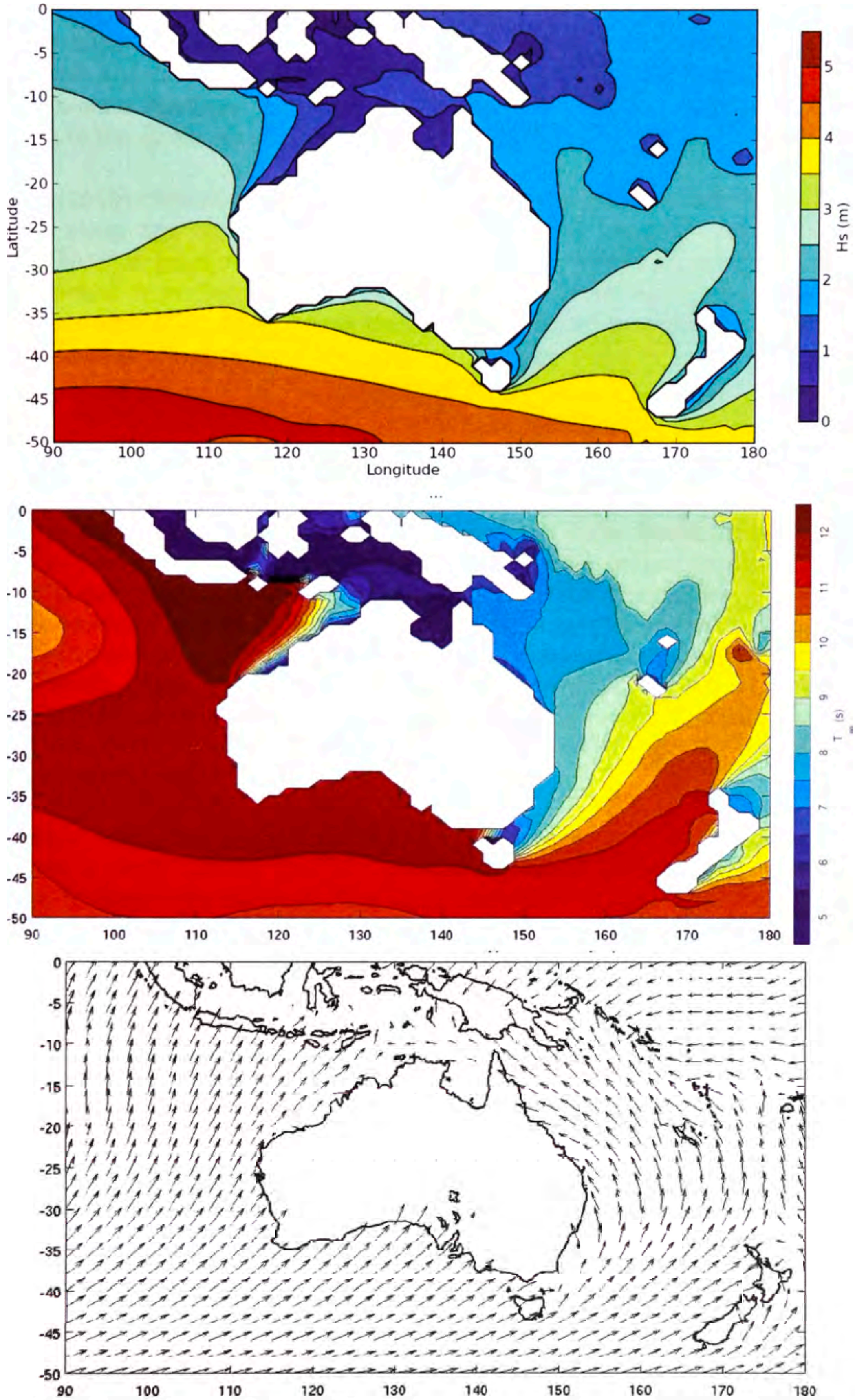


Figure 3-6 Long-term mean significant wave height (A), mean wave period (B) and mean wave direction (C) around Australia based on NWW3 model (1997 – 2007) (source: Hemer *et al.*, 2007)

Many extreme value analyses of wave buoy records have been undertaken, e.g. Reid and Fandry (1994 - Cape Sorell), Lemm *et al.* (1999 – Rottnest Island), Lord and Kulmar (2000 – NSW buoys) and Allen and Callaghan (2000 – Brisbane). Hemer et al. (2007) analysed data from 27 wave buoys around Australia to derive 25, 50 and 100 year ARI significant wave heights corresponding to the storm peak (1 hour exceedance H_s).

Shand et al. (2010) derived extreme values for durations between 1 and 144 hours for nine wave buoys along the NSW coast to investigate longer duration extreme events and Shand et al. (2011) expanded this detailed assessment to a further six buoys around Australia. Additionally, Shand et al (2011) calculated the total cumulative storm energy for each storm event (Eq 3-3: Harley *et al.* 2009), which is expressed in MJ/m^2 and provides a measure of total energy occurring over the duration of the event.

$$E = \frac{1}{16}\rho g \Delta t \sum_{i=1}^{N} H_s^2 \tag{3-3}$$

Where N is the number of data points in the storm event, ρ is the density of sea water, g is the acceleration due to gravity, Δt is the temporal resolution of the dataset and H_s is the significant wave height at each time interval. This measure of total storm energy was found to provide a reasonable measure of erosive potential by a single storm event (Mendoza and Jimenez, 2006) and was found by Ilich et al. (2009) to provide a better measure of erosive capacity for storms in Western Australia than the peak significant wave height or maximum water level. Shand et al. (2011) undertook an extreme value analysis using this total storm energy parameter (Table 3.4) and, using the results, derived Synthetic Design Storm time series which are further discussed in the following section.

Numerically and analytically-derived datasets have the advantage of being relatively cheaper to setup and run, of being spatially extensive and continuous (i.e. do not contain gaps in data due to instrument failure or maintenance). Disadvantages include reliance on the accuracy of forcing parameters (i.e. wind fields) and of the model formulation itself. These require extensive calibration and validation, which have often shown under-prediction of extremes, particularly in tropical cyclone-dominated regions where the spatial scale of global models is often insufficient to adequately resolve the small-scale tropical cyclone systems and the model physics is often similarly inadequate. Caires and Sterl (2005) undertook a global assessment of extreme wave height using the ERA-40 numerical hindcast dataset. The numerical data was found to under- predict large wave heights when compared to northern hemisphere wave buoys and a global correction was applied based on a linear relationship to the return value estimates.

Hemer *et al.* (2007) derived extreme wave height values around Australia using the C-ERA-40 numerical hindcast (1957 – 2002) and NOAA WavewatchIII (NWW3, 1997 – 2009) numerical forecasts (i.e. Figure 3–7). While values were typically in reasonable agreement with buoy-derived values in regions below around 30° latitude (attributed to the generally larger scale of storm-systems), derived 100 year ARI significant wave heights reduced to between 3 to 4 m in sheltered northern locations. This is significantly less than estimated by specialist cyclonic-analysis such as Dexter and Watson (1975) and Hardy *et al.* (2003).

Dexter and Watson (1975) undertook a numerical assessment of extreme wave heights in the Australian tropics using extreme wind velocities, cyclone occurrence frequency and fetch length to derive significant wave height for recurrence intervals of 50, 100 and 200 years at 70 locations north of 30° S and from this produced wave height isopleth charts of the Australian tropics (Figure 3–8). Results of their analysis show 100 year ARI significant wave heights of around 8 m on the eastern Queensland coast, 7 m along the northern coasts and up to 11 or 12 m along parts of north-west Western Australia. Hardy et al. (2003) numerically simulated over 6,000 tropical cyclone events to produce the Great Barrier Reef Wave Atlas, which gives spatial maps of significant wave height for average recurrence intervals of 20 to 1,000 years for over the Great Barrier Reef region between Gladstone and Cape Grenville. An example of 100 year ARI wave heights is shown within Figure 3–9.

Of note, the wide and very flat continental shelf off many parts of northern Australia limit the maximum nearshore wave height due to bed friction and depth-limited wave breaking (Nelson, 1987). Wave energy reaching and able to erode the backshore is therefore critically influenced by coincident water level with offshore wave height playing a lesser role by contributing to wave setup.

While a number of more detailed studies have been undertaken, some including joint-probabilistic studies of wave height and water level, they have often been undertaken for private clients with results unpublished. A more comprehensive summary of previous studies of extreme wave analyses around Australia is presented in Shand et al. (2011) and summarised in Table 3.3.

A coherent Australian extreme wave climate has been derived using primarily the buoy assessments of Hemer et al. (2007), Shand et al. (2010, 2011) and the Qld EPA (2006), supplemented by the analytical and numerical assessments of Dexter and Watson (1974), Harper et al. (1993), Hardy et al. (2004), Hemer et al. (2007), a number of unpublished private metocean studies in tropical cyclonic regions and analysis of numerical wave data from the NWW3 dataset.

Maps showing adopted peak (1 hour) significant wave height and cumulative storm energy (MJ/m^2) around Australia for a 100 year ARI events are shown within Figure 3–10 and Figure 3–11. Note that values in north-west Western Australia may be larger offshore, however, the very wide and shallow continental shelves result in significant offshore energy losses. Values presented here are those assumed for 20 m water depth.

Table 3.3 Summary of Australian Extreme Wave Analyses (non-exhaustive)

Location	Study	Data source	Finding
Australia-wide	Dexter and Watson (1975)	Numerically synthesised cyclone events	Assessment used extreme wind velocities, cyclone occurrence frequency and fetch length to derive significant wave height for recurrence intervals of 50, 100 and 200 years. Results given as isopleth charts and tables for 70 locations north of 30° latitude.
	Alves and Young (2003)	Satellite Altimeter Data (6.5 years , 1986 - 1995)	100 year ARI extreme wave heights were derived globally at resolution between 2°x2° and 4°x4° using different extreme value analysis methods. Results compared with a number of buoys located in the northern hemisphere.
	Caires and Sterl (2005)	ERA-40 numerical hindcast (1957 - 2002)	Derived global 100 year ARI estimates of H_s based on the Corrected ERA-40 hindcast dataset at 1.5° x 1.5° resolution. In the Australian region estimated 100 year ARI wave heights increased with distance north. However, the resolution of the model limits the inclusion of tropical cyclones and yields the estimates questionable in regions where tropical cyclones dominate the extreme wave climate.
	Hemer *et al.* (2007)	Wave buoys Australia wide, several numerical forecasts and hindcast datasets, altimeter and visual observation	Data from 25 wave buoys analysed and compared with C-ERA-40 numerical hindcast (1957 – 2002), NOAA WavewatchIII (1997 – 2009) and AusWAM (1994 – 2009) numerical forecasts, Satellite Altimeter (1985 – 2006) and BoM visual observations (SEASTATE) data (1960 – 2009). Summary of Australian wave climate given including yearly and monthly mean wave height, period and direction for each individual buoy, numerical and altimeter data. Extreme value analysis of buoy and regional numerical data undertaken for 25, 50 and 100 year ARI events.
	Shand *et al.* (2011)	Nine wave buoys around Australia	Wave statistics, long-term trends and extreme analysis of wave heights and total storm energy assessed. Synthetic design storms derived for each buoy for 1, 10, 50 and 100 year ARI events.
Western Australia	Harper *et al.* (1993)	North Rankin 'A' platform north of Dampier	Analysis of local buoy and wind data and numerical simulation of Tropical Cyclone Orson, a category 5 cyclone which crossed land west of Karratha April 23, 1989. Maximum observed Hs was 8.8 m, although buoy records ceased before the storm peak. Numerical hindcast showed Hs = 11 m, with Tp = 16 s. Peak wave heights relatively short with Hs > 3 m for less than 1.5 days.
	Lemm *et al.* (1999)	Rottnest Island wave buoy (1994 - 1996)	Extreme value analysis of 2.5 years of Rottnest Island wave buoy data with 1 and 100 year ARI events estimated at 6.7 m and 9.8 m respectively.
	Anonymous	Varied	A number of confidential studies undertaken for private industry by a range of organisations.
South Australia	Riedel and MacFarlane (1999)	Hindcast from local wind data	1 to 100 year ARI wave heights at Adelaide estimated ranging from 2.1 to 3.4 m.
Tasmania	Reid and Fandry (1994)	Cape Sorell (1985 - 1993), Cape Grim (1991 - 1992) Wedge Island (1993) buoys	Analysed 8 years of wave buoy data from Cape Sorell and shorter (<1 year) records from Cape Grim and Wedge Island. 100 year ARI significant wave heights of between 12.8 and 15.7 m were estimated for Cape Sorell using a Gumbel or FT-1 Distribution with the variation in derived height due to the selected fitting type.
	Carley *et al.* (2007)	Cape Sorell (1985 – 1993; 1998 - 2004) and Wedge Island (1993) wave buoys	Analysed 15 years of wave buoy data from Cape Sorell and less than 1 year of data from Wedge Island. Estimated a 100 year ARI significant wave height of 13 m at Cape Sorell and 9 m at Wedge Island using a PoT method and Gumbel or FT-1 Distribution.

Location	Study	Data source	Finding
New South Wales	Lawson and Abernethy (1974)	Botany Bay wave buoy (1971 – 1973)	Evaluated three years of wave data to derive exceedance statistics. Due to the short record length, ARI type statistics were not derived.
	Blain, Bremner and Williams Pty Ltd. and Lawson and Treloar Pty Ltd (PWD, 1985; 1986)	Variety, generally visual reported and analytically forecast/ hindcast (1880 – 1985)	Evaluated historical storm events between 1880 and 1985. Proxy wave heights were assigned based on historical charts, weather bulletins and reports, newspapers and other studies and theses; and extreme wave heights derived for the north, mid-north, central and south coast sectors. Derived extreme wave heights generally increased from south to north, with the derived 100 year ARI significant wave height on the north coast estimated at between 12.27 and 12.55 m depending on the selection of extreme value distribution.
	Willoughby (1995)	Botany Bay (1971 – 1995)	Presents wave and storm persistence statistics derived from 24 years of wave data from the Botany Bay wave buoy. 100 year ARI wave height estimated at 8.3 m (95% CI ±1 m).
	Lord and Kulmar (2000)	Byron Bay (1976 – 1999), Sydney (1987 – 1999) and Eden (1978 – 1999) wave buoys	Evaluation of extreme wave heights for events of between 1 and 24 hours duration. The 100 year ARI, 1 hour significant wave height was found to be 7.8 m for Byron Bay, 8.6 m for Sydney and 9.3 m for Eden. This indicated a reverse spatial trend from the PWD (1985; 1986) studies.
	You (2007)	Sydney wave buoy (1988 - 2006)	Examined the fit of nine extreme value distributions to long term wave data (1988 to 2006) for the Sydney wave buoy. Found the FT-1 (or Gumbel) and Weibull distributions provided the best fit, with derived 100 year ARI significant wave heights of 8.62 and 8.61 m respectively.
	Shand *et al.* (2010)	Eight NSW Buoys (between 1971 and 1987 - 2009); numerical forecast/ hindcast datasets.	Analysed wave buoy data for nine locations along the NSW Coast and south-east Queensland to derive extreme wave heights for Average Recurrence Intervals (ARI) of between 1 and 100 years for storm durations of between 1 hour and 6 days. Extreme wave heights were typically largest in central NSW and smaller to the north and south with one hour exceedance, 100 year ARI wave height found to range from 9.1 m at Botany Bay to 7.6 m at Byron Bay. Effect of direction on derived extremes also assessed. Compared results with those derived from numerical datasets (ERA-40 and NWW3) with variable levels of agreement.
Queensland	Allen and Callaghan (2000)	Brisbane wave buoy (1976 - 1997)	Describe storm climatology in the south-east Queensland region and undertake separate extreme value analyses for tropical cyclone, east coast low and combined storm events. Results for the combined assessment range from 5.02 m for a 2 year ARI event to 7.75 m for a 100 year ARI event.
	Hardy *et al.* (2003)	Numerically synthesised storm events	Over 6,000 tropical cyclone events numerically simulated using synthesised wind fields and the WAM wave model. Extreme value analysis undertaken to produce the Great Barrier Reef Wave Atlas (James Cook University Marine Modelling Unity, 2006) which gives spatial maps of significant wave height for average recurrence intervals of 20 to 1,000 years for over the Great Barrier Reef region between Gladstone and Cape Grenville.
	EPA (2006) Mackay Coast Study	Mackay wave buoy (1984 – 2006); Numerical Hindcast	Present 2 year ARI H_s = 3.4 m; 10 year ARI H_s = 4.2 m; 50 year ARI H_s = 4.9 m; 100 year ARI H_s = 5.2 m
	Anonymous	Varied	A number of confidential studies undertaken for private industry by a range of organisations.
Northern Territory	Harper (2010)	Numerical Hindcast	Numerical hindcast of Tropical Cyclone Tracey, a small but intense tropical cyclone that made landfall at Darwin on 24 December, 1974. Maximum storm wave Hs north of Darwin harbour entrance was hindcast at 8 m.

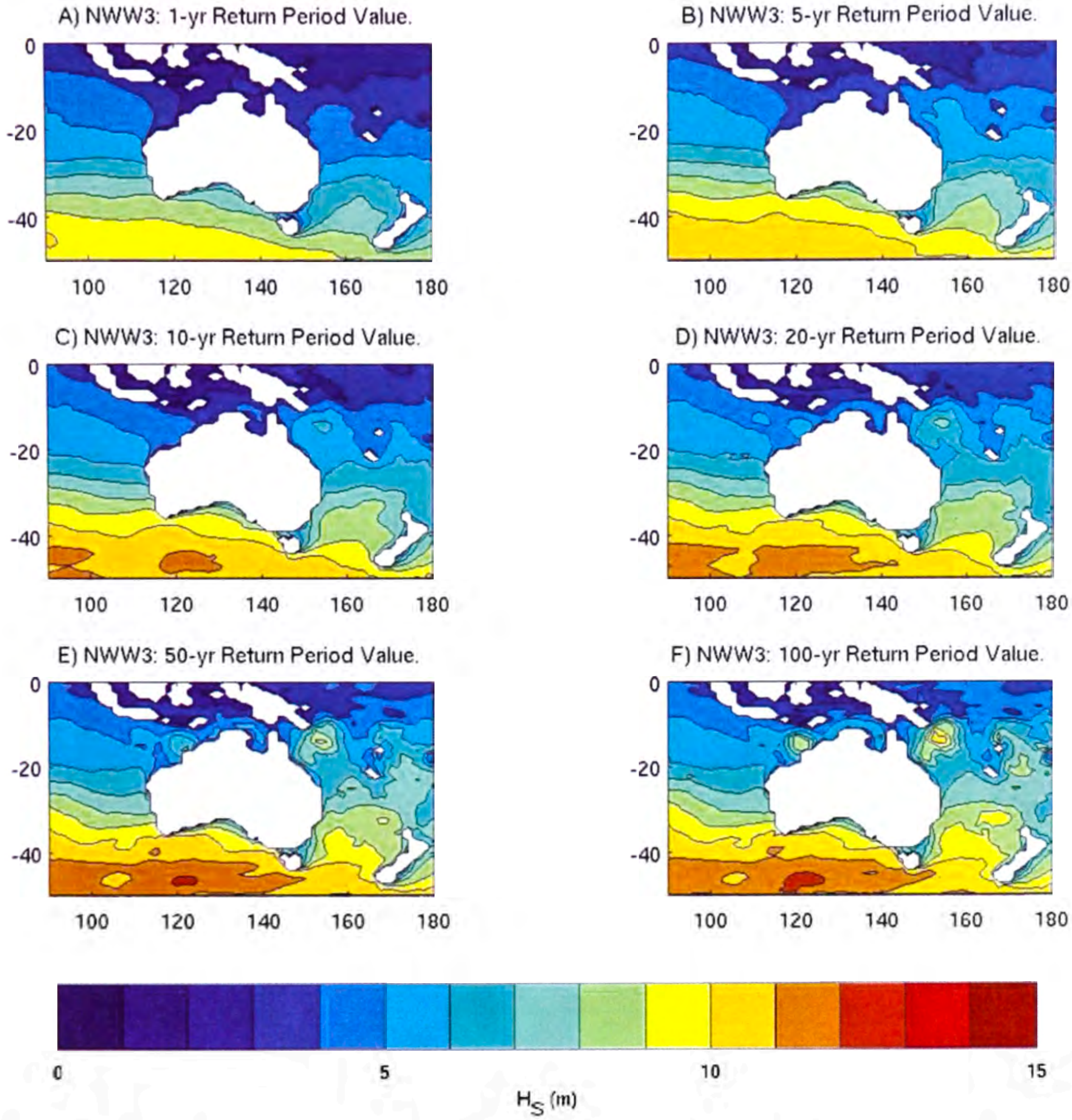


Figure 3–7 N-year Return Average Recurrence Intervals Determined From NWW3 Numerical Datasets (Source: Hemer et al., 2007)

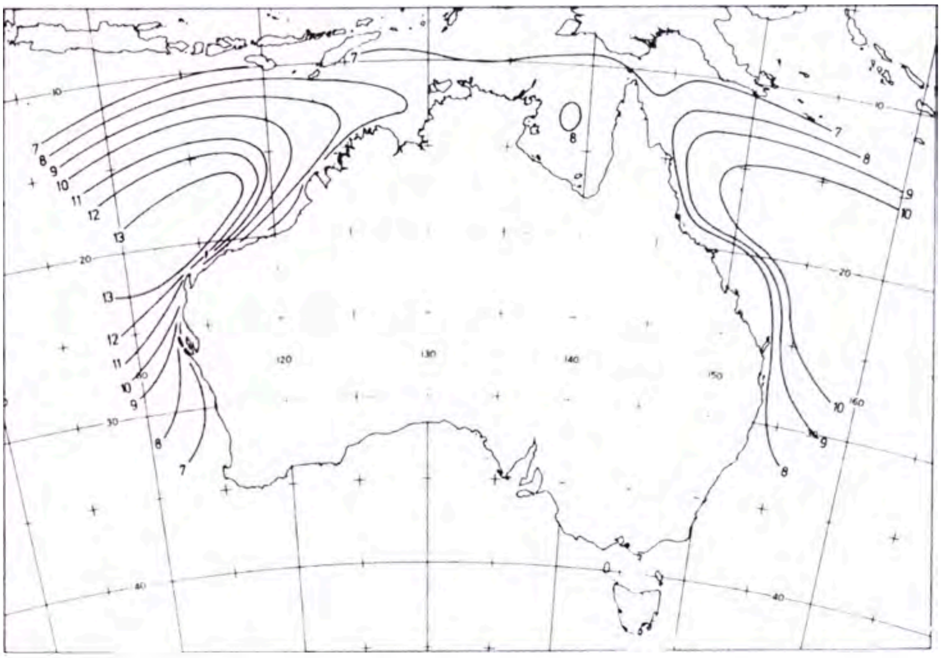


Figure 3-8 Isopleths of Extreme Significant Wave Height (m) for 100 year ARI Event and Average Cyclone Radius of 30 km (source: Dexter and Watson, 1975)

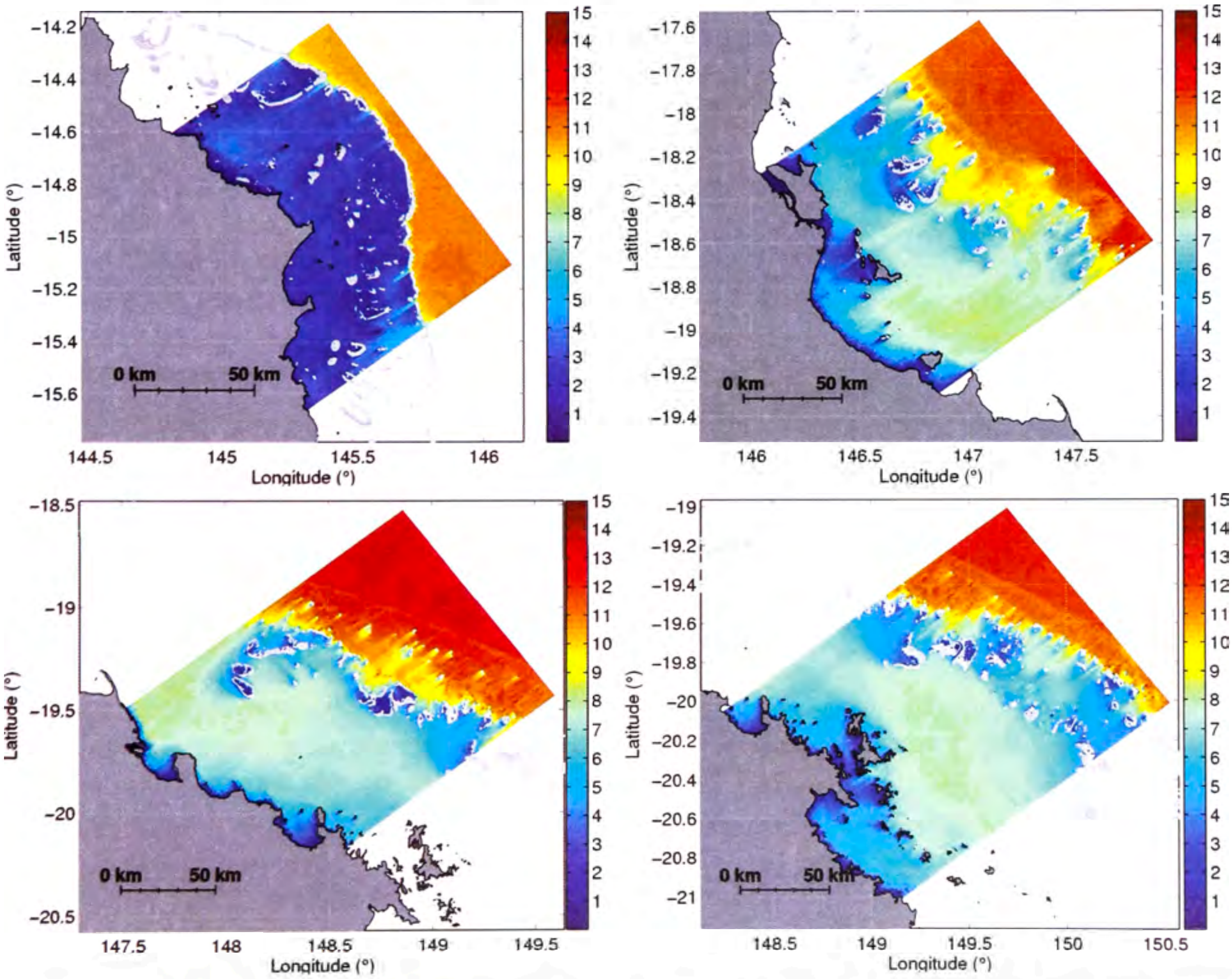


Figure 3-9 100 year ARI significant wave height (m) for Cape Melville to Cooktown (A), Cardwell to Townsville (B), Ayer to Bowen (C) and Bowen to Mackay (D). (source: Hardy et al., 2004)

Table 3.4 Summary of One Hour Exceedance Hs with 90% Confidence Limits (after Shand et al., 2011)

Buoy	1 year ARI		10 year ARI		100 year ARI	
	H_s (m) (90% CI)	Cumulative Energy (MJh/m^2)	H_s (m) (90% CI)	Cumulative Energy (MJh/m^2)	H_s (m) (90% CI)	Cumulative Energy (MJh/m^2)
Brisbane	5 (4.8,5.2)	0.85 (0.72,0.98)	6.6 (6.3,6.9)	1.85 (1.54,2.16)	8.1 (7.6,8.6)	3.03 (2.5,3.56)
Botany Bay	5.7 (5.5,5.9)	0.82 (0.74,0.9)	7.5 (7.2,7.8)	1.53 (1.37,1.69)	9.1 (8.7,9.5)	2.29 (2.05,2.53)
Eden	5.4 (5.2,5.6)	0.73 (0.66,0.8)	7.0 (6.7,7.3)	1.32 (1.18,1.46)	8.7 (8.2,9.2)	1.92 (1.72,2.12)
Cape Sorell	8.6 (8.3,8.9)	2.36 (2.09,2.63)	10.8 (10.2,11.4)	4.13 (3.61,4.65)	12.9 (12.1,13.7)	5.93 (5.16,6.7)
Cape d Cou	7.1 (6.8,7.4)	1.67 (1.42,1.92)	8.4 (8,8.8)	2.85 (2.39,3.31)	9.6 (9,10.2)	4.03 (3.36,4.7)
Cape Nat	7.5 (7.2,7.8)	2.06 (1.75,2.37)	8.9 (8.5,9.3)	3.64 (3.05,4.23)	10.1 (9.6,10.6)	5.23 (4.34,6.12)
Rottnest	6.9 (6.6,7.2)	1.63 (1.35,1.91)	8.5 (8.1,8.9)	3.24 (2.62,3.86)	10 (9.4,10.6)	5.04 (4.04,6.04)
Jurien Bay	6.2 (6,6.4)	1.23 (1.09,1.37)	7.5 (7.1,7.9)	2.02 (1.76,2.28)	8.6 (8.1,9.1)	2.78 (2.42,3.14)

3.3.3 Storm Clustering

Extreme value analysis provides an average recurrence interval for events of a particular magnitude and is based on an assumption of sample independence, yet clustering of storm events is frequently noted (i.e. McGrath 1968, Foster *et al.* 1975; Kemp and Douglas, 1981; Allen and Callaghan, 1997 and 2000; Callaghan *et al.* 2009, Harper *et al.* 2007). Clustering is the result of a persistence in the ocean-atmosphere synoptic conditions that are conducive to storm formation. The seasonal clustering of storms is linked to the seasonal fluctuations in the large-scale circulation; for example, tropical cyclones in summer, East Coast Cyclones in autumn and early winter, and intensification of mid-latitude cyclones in winter. However, this seasonal clustering of storms is a strong characteristic on the annual wave climatology and reflects the ARI range of < 1 year to 5 years. To the contrary, extreme or 'explosive' storm events have an ARI of > 5 years and are linked to the modes of decadal to multi-decadal climate variability. Analysis of the instrumental observations over the past century indicates a tendency for extreme storms to occur in a sequence or clusters within a month to few months. In northern Australia increased frequency or clustering of Tropical Cyclones has been noted to occur during the La Nina or positive phase of the ENSO (El Niño/La Niña - Southern Oscillation) mode (Hopkins and Holland, 1997) with the more extreme storms occurring in the strongest La Nina summers or during persistent biennial La Nina events such as 2010-2012. Similarly in late summer and autumn, the persistence of the inland trough across Australia to the Tasman Sea, or a strengthened subtropical anticyclone over the northern Tasman Sea is a precondition for clustering of East Coast Cyclones.

Whilst there appears to be an increasing understanding of the synoptic and statistical relationship between tropical cyclones, or East Coast Cyclones and ENSO on sub-decadal time scales, it is becoming clearer that decadal to multi-decadal variability enhances the risk of extreme storm events. In the Australian region the two phenomena that may enhance risk are the Interdecadal Pacific Oscillation (IPO) (15 to 35 year periodicity) and the Southern Annular Mode (SAM) (11 to 23 year periodicity). The IPO modulates the background sea surface temperature (SST) and sea level pressure (SLP) anomalies over the subtropical to mid-latitude Pacific, whilst the SAM modulates the intensity and track of the mid-latitude cyclones. Storm clustering off Western Australia may also be a function of climate connections between the Atlantic Multi-Decadal Oscillation (AMO) (50 to 80 year periodicity) and the eastern Indian Ocean sector (Baines and Folland, 2009). Recent research by Goodwin et al. (in press) indicates that extreme storm clustering on the east coast, for example, 1890's, 1950's 1970's and 2010's is related to the phase changes in the IPO and SAM, and/or the coupling of the multi-decadal modes, e.g. IPO and AMO. Speer et al. (2010) find a similar association with the IPO and SAM for eastern Australian rainfall variability. Goodwin et al. (in press) also show that there is considerable centennial variability between decadal vs. multi-decadal cyclicity in climate variability. Hence, the associated storm clusters can include a range in combined ARI storms, e.g. 1 in 10, 1 in 10, 1 in 10 years, a 1 in 35, 1 in 35, 1 in 35 years, or 1 in 100, 1 in 10, 1 in 10 years. What may be considered a 1 in 100 year ARI East Coast Cyclone storm during the 20th century was likely a 1 in ~35 year storm during the 18th century (Goodwin et al, in press). While these cycles have not been assessed during this study, implications may be that during particular stages of climate cycles, the ARI or AEP of an event of particular magnitude is decreased or that once an event has occurred, the probability of experiencing another large event is temporarily increased. There is also an increased risk that extreme storms will occur within a narrow time window, e.g. one month, such as June, 2007 on the east coast of Australia, or January, 2010 in north Queensland.

Storm clustering has a significant impact on both the interpretation of the ARI of storm waves, but more importantly on the cumulative impact upon beaches, dunes and estuarine inlets. The relationship between the ARI of storm characteristics to the ARI of physical storm impacts is likely to be statistically heterogeneous between individual and clustered storm events. The ARI magnitude of the first storm in a sequence of storms preconditions the sediment storage on the beach and shoreface for the impact of the subsequent storms. Since extreme storm sequences can occur within short time-scales of a few weeks to a month, then beach and upper shoreface recovery to initial storm erosion is minimal. Hence, a 1 in 10 year ARI storm may produce beach erosion of a substantially greater return interval if preceded by an equivalent or more extreme storm. Storm clusters that occur over a longer time-scale such as a season may have a less extreme physical impact since there is time for the shoreface to reach an equilibrium with the persistent storm wave energy.

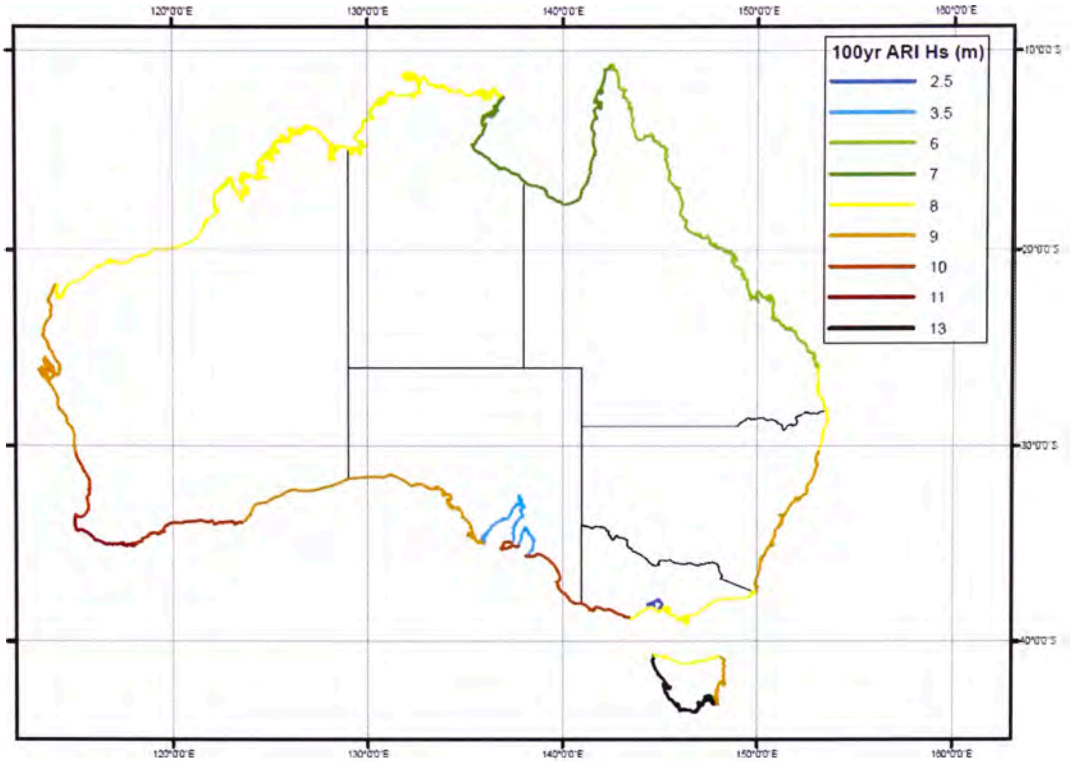


Figure 3-10 100 year ARI Significant Wave Height

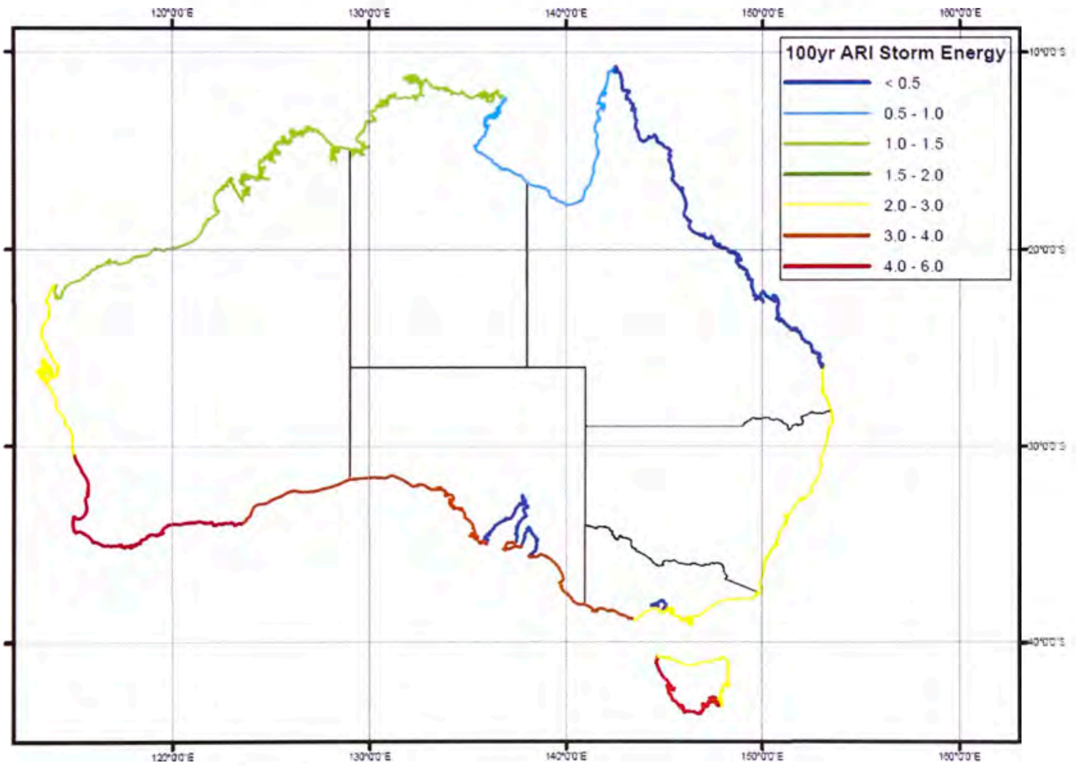


Figure 3-11 100 year ARI Storm Energy (MJ/m2)

3.3.4 Medium to Long Term Changes

The effects of long-term climate change on storm frequency, intensity and spatial distribution are less well understood than temperature and sea level, although there is suggestion that general warming of the Eastern Pacific over the last two decades has led to a higher occurrence of El Niño events (NCCOE, 2004). DCC (2009) suggests that extreme wind speeds associated with tropical cycles and mid-latitude lows may increase along with greater variations in air pressure leading to increased storm surge and wave height. However, other studies (e.g. Hemer at al., 2010) have also predicted less large southerly wave events and a slightly reduced overall mean significant wave height climate under a warmer climate scenario.

Some assessments have been undertaken on available medium-term wave height data. Young et al. (2011) used satellite altimeter measurements from 1985 to 2008 to investigate global changes in oceanic wind speed and wave height. He found some evidence of increase in global monthly mean wave heights (8% of trends in mean monthly wave height statistically significant) and more pronounced upward trends in the 90 and 99th percentile monthly wave heights (12% and 47% statistically significant respectively). However, Shand et al. (2011) argues that agreement with buoy data is questionable. Shand et al. (2011) found that while both Australian east and west coast buoys exhibit upward trends in monthly mean wave height (up to 2 mm/year and 7 mm/year respectively), none exhibited statistical significance and the Australian south coast buoys exhibit non-statistically significant downward trends of -1 to -5 mm/year. Similar non-statistically-significant trends were observed for the 90th and 99th percentile monthly wave height. No statistically significant temporal trends in storm magnitude were found, although one east coast buoy showed a small statistically significant increase in storm frequency.

3.4 Water Levels

3.4.1 Astronomical Tide

Tide is the periodic rising and falling of the level of the sea surface caused by the gravitational interaction of the sun and moon on the earth's waters and harmonics of such interactions. These various influences induce individual water level motions known as constituent tides. Tidal cycles and range at any particular location are the result of a number of constituent tides comprising an individual period, amplitude and phase superimposed on one another. Individual constituent periods range from a few minutes to 18.6 years and amplitudes from a few millimetres to metres.

Tides behave as long period waves and while they typically exhibit low amplitude in deep water, amplitudes increase in shallow coastal waters due to shoaling. Figure 3–12 shows indicative tidal ranges around Australia with significantly larger tides observed in northern parts of Australia, where continental shelves are wide and relatively shallow compared with the south. Specific bathymetry and embayment configurations may further increase tidal elevations with astronomical tides reaching 9 m in Queensland's McEwen Islet and over 12 m at Derby in north-west Western Australia. Other parts of Australia's open coast have astronomical tides of only 1.0 to 1.3 m, e.g. Warrnambool Victoria and Geraldton WA.

As tides are driven by quasi-constant astronomical process, tides are deterministic and may be predicted for a particular location and time. Dominant tidal cycles around Australia range from semi-diurnal, with two near equivalent tidal cycles occurring per day to mixed, with two tide cycles of differing amplitude occurring during the day and diurnal with a single tide occurring per day. Other dominant tidal cycles occur at fortnightly and monthly intervals influenced by sun-moon phasing (spring - neap tides) and the moons distance from earth (perigean - apogean tides). The phasing of these various constituents can lead to abnormally high tides at periods of between 18 months and 18.6 years. The highest astronomical tide (HAT) refers to the highest calculated tide in 18.6 years under normal weather conditions.

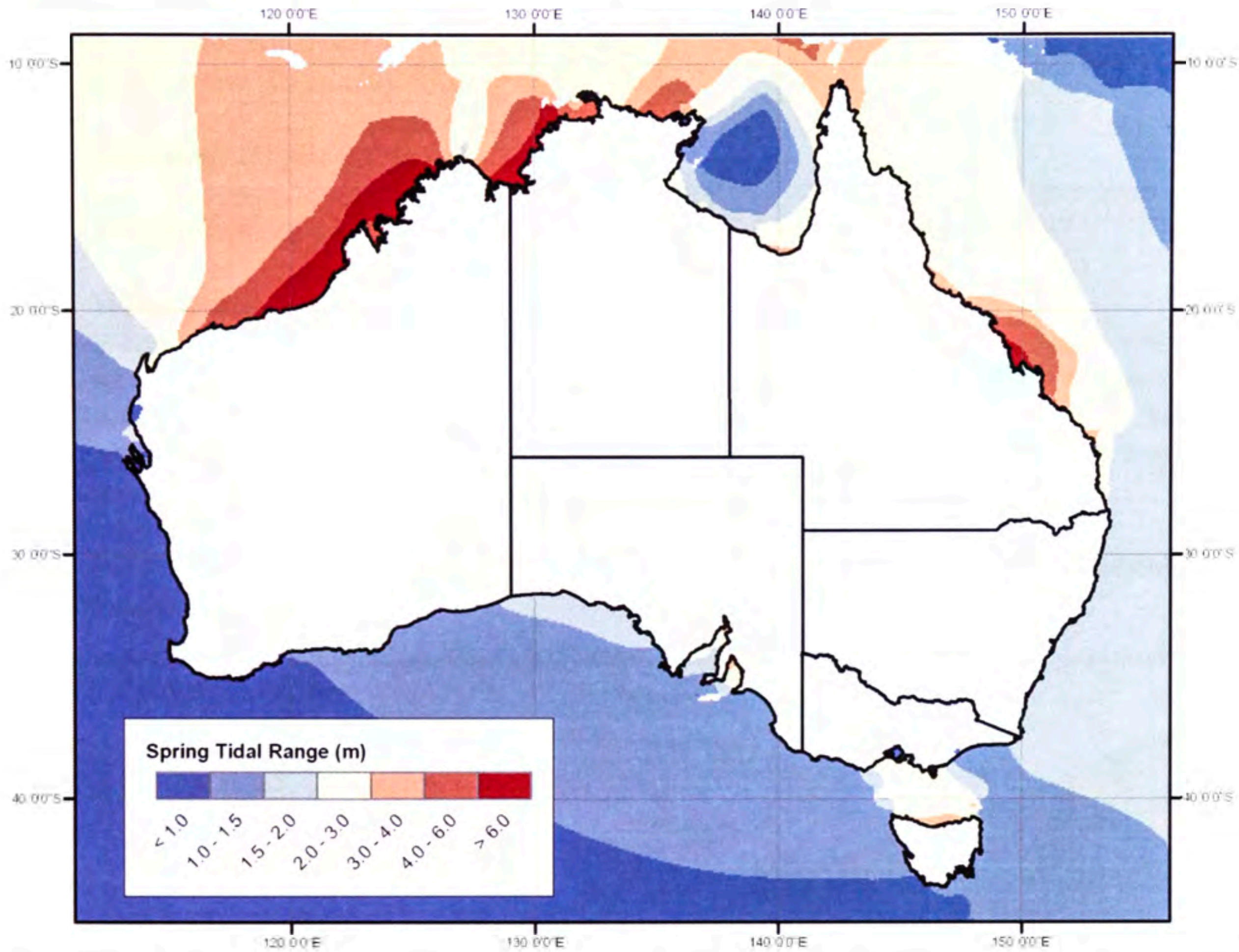


Figure 3–12 Australian Spring Tidal Range [2 x (M2 + S2 + O1 + K1)] (source: BoM, 2010)

3.4.2 Tidal Anomaly

Water level elevation influences coastal erosion as it affects the amount of wave energy able to reach, and act upon, the backshore region. Coastal water levels are affected by both deterministic processes such as astronomical tide (forced by the sun, moon and planets) and stochastic processes associated with oceanic, meteorological and geological phenomenon. The difference between observed water level and water level predicted due solely to astronomical processes is termed a tidal residual. Key components contributing to tidal anomaly include:

- ***The Inverse Barometer Effect***
  A uniform rise in mean sea level for reduction in air pressure below the mean air pressure at sea level. Given roughly as an increase in sea level by 1 cm for every 1 hPa drop in atmospheric pressure, moving systems may generate larger surge dependent on speed, bearing and depth (Nielsen, 2009).

- ***Wind Setup***
  Increase in water level due to shear stress exerted by onshore (or alongshore in a more complex situation) wind on the water surface. The combination of wind setup and the inverse barometer effect is frequently referred to as storm surge.

- ***Ekman Transport***
  A wind-driven current resulting, which is deflected (to the left in the southern hemisphere) due to the rotation of the earth.

- ***Coastally Trapped Waves***
  Low frequency oscillations (propagating anticlockwise in Australia) generated by the displacement of water on a continental shelf by a moving weather system.

- ***Wave Setup and Run-up Processes***
  Wave set-up is a super-elevation of the mean water surface over normal 'still' water level due to wave action alone. Wave runup is the height above the still water level reached by wave swash before gravity exceeds the wave's momentum and is therefore superimposed on any wave setup present. In setting inundation levels, it is common to adopt the highest 2% runup level.

Figure 3-13 diagrammatically represents some of the different components contributing to elevated coastal water levels.

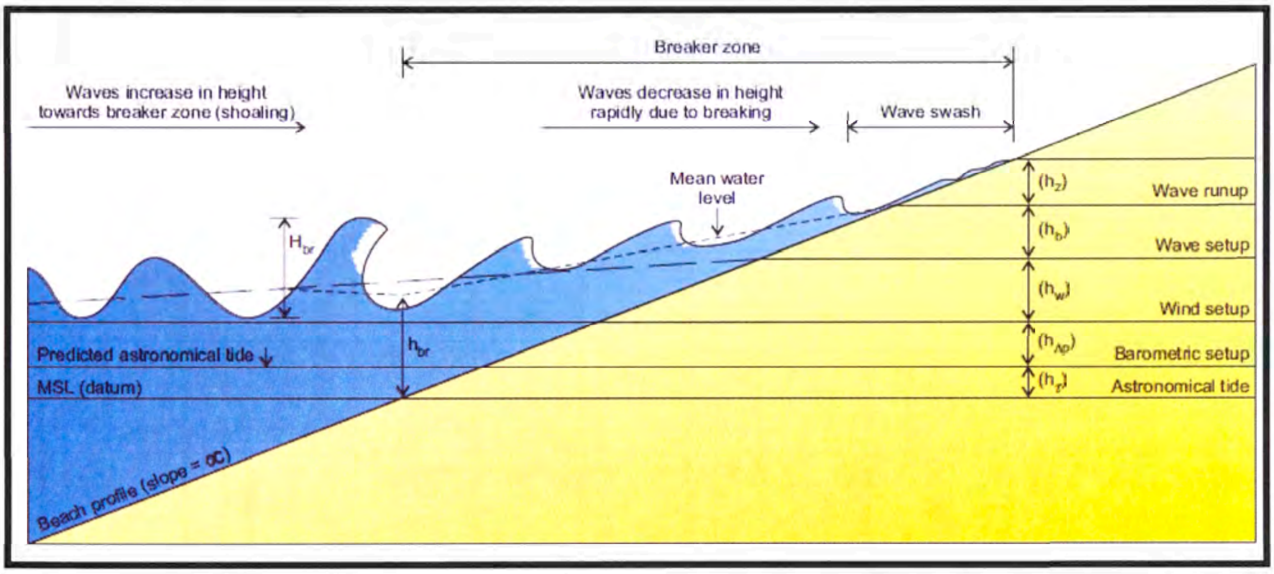


Figure 3-13 Components Elevated Water Levels

Many studies have been undertaken to define storm surge and storm tide (combined astronomical tide and surge but generally excluding wave setup) levels around Australia. These include both site-specific and Australian-wide investigations. A summary of studies (non-exhaustive) is presented in Table 3.5. It should be noted that storm surge can be very site-specific with local topography and bathymetry significantly affecting levels. This list provided within Table 3.5 is therefore unlikely to be a complete representation of maximum levels at all location around the country.

Table 3.5 Summary of Australian Extreme Water Level Analyses (non-exhaustive)

Location	Study	Data source	Finding
Australia-wide	Silvester and Mitchell (1977)	Wind hindcast	Uses shelf profiles and extreme wind fields to calculate average and extreme storm surge for 35 regions around Australia. Derived extreme values range from 0.3 – 0.6 m in southern Australia (<~30° Lat), although the Spencer Gulf and Gulf St Vincent could reach 2.5 m. Extreme surge increased in the north, up to 4.3 m in parts of north-west, 5 m in the Gulf of Carpentaria and 5.5 m in parts of Queensland.
	Stark (1978)		Discusses methodology for simulation and probabilistic assessment of tide and cyclonic storm surges. Specific values not given.
	Leigh and Chen (2006)	Multiple previous studies	Previous studies assessed and a mixture of storm surge and storm tide values presented. These include: Queensland: Cites Hardy (2004) levels for multiple locations New South Wales: Typical storm surge (SS) 0.3 to 0.6m, 100 year ARI 0.5 to 0.6 m (Hanslow, 2006) Western Australia: Karratha 100 year ARI SS 4.9 to 6.2 m AHD (BoM, 1996); Perth SS 0.9m during May 1994 event Northern Territory: Darwin 100 year ARI storm tide 4.9 m AHD (SKM 1999) Victoria: SE Vic 100 year SS 0.55 to 0.75 m (McInnes et al. 2005); Port Phillip Bay 100 year ARI Storm Tide 1.3m AHD (Crapper and Wood, 1991)
Western Australia	Stark and McMonagle (1982)	Analytically Hindcast	Synthetic cyclone record simulated and combined with predicted astronomical tide. 100 year ARI storm tide level for Karratha found to be 6.2 m AHD.
	Harper *et al.* (1993)	North Rankin 'A' platform north of Dampier	Analysis of local buoy and wind data and numerical simulation of Tropical Cyclone Orson, a category 5 cyclone which crossed land west of Karratha April 23, 1989. Maximum observed Hs was 8.8 m, although buoy records ceased before the storm peak. Numerical hindcast showed Hs = 11 m, with Tp = 16 s. Peak wave heights relatively short with Hs > 3 m for less than 1.5 days.
	Pattiaratchi and Eliot (2005)	Water Level Gauges	Describe major processes influencing water level in SW Australia: Astronomical Tide: 0.8 m, Storm Surge: 0.8 m, Seasonal (Leeuwin Current): 0.3 m; Inter-annual (ENSO) = 0.3 m.
	Eliot and Pattiaratchi (2010)	Water Level Gauges at Geraldton, Fremantle, Albany (all 1988 to 1998)	Surges resulting from various cyclonic forcing systems analysed with maximum surge of 0.64 m found Geraldton, 0.62 m at Fremantle and 0.63 m at Albany.
	Anonymous	Varied	A number of confidential studies undertaken for private industry by a range of organisations.
Victoria	McInnes *et al.* (2009a; 2009b)	Analysis of Select Water Level Gauge and Numerical Simulation	Extreme storm surge and storm tide levels for 13 locations across open-coast Victoria and 12 locations within Port Phillip Bay. On the open coast, 100 year ARI storm surge found to range from 0.55 m at Portland to 0.93 m at Seaspray and 100 year storm tide from 1.01 m to 1.98 m. Within Port Phillip Bay 100 year ARI storm surge ranged from 0.76 to 0.94 m and storm tide levels from 1.0 to 1.41 m.

Tasmania	McInnes *et al.* (2007)	Numerical Modelling	Model outputs around Tasmania show 100 year ARI storm surge heights of 0.4 to 0.6 m along the north coast, 0.6 to 0.8 m along the east and west coasts and up to 0.9 m around the south coast.
	Carley *et al.* (2008)	Hobart Tide Gauge	Extrapolated data analysed by Hunter (2007) to obtain extreme water levels of 0.97, 1.37 and 1.44 m AHD for 1, 50 and 100 year ARI events respectively.
New South Wales	MHL (1992)	Gauges at Crowdy Head, Tomaree, Fort Denison, Creswell & Batemans Bay	20, 50, 100 year ARI storm tide levels estimated at each location. Generally found to increase from south to north with 20 year ARI = 1.33 to 1.41 m AHD, 50 year ARI = 1.38 to 1.46 m AHD, 100 year ARI = 1.41 to 1.49 m AHD.
	Wyllie *et al.* (1993)	Fort Denison Tide Gauge	Estimated 0.6 m anomaly at 76 year ARI, 0.5 m anomaly at 2 year ARI.
	Watson and Lord (2008)	Fort Denison Tide Gauge	1 year ARI = 1.235 m AHD; 10 year ARI = 1.345 m AHD; 100 year ARI = 1.435 m AHD.
	Modra (2011)	26 Water Level Gauges along NSW.	Gauges analysed to determine tidal planes along NSW and causes and magnitudes of tidal residual and storm tide. 1 year ARI residual found to vary from around 0.36 m at Bermagui to 0.5 m at Yamba. Anomalies within entrances subject to river flooding may be larger. 100 year ARI storm tide levels found to range from 1.3 m AHD at Bermagui to 1.55 m AHD at Tweed Heads.
Queensland	Patterson (1986)	Statistical Hindcast based on cyclone records	Storm tide statistics presented for a number of mainland Queensland regions. 100 year ARI storm tide levels range from 1.3 m AHD at the Gold Coast to 4.1 m at Mackay before reducing to 1.67 m of approximately HAT at Cooktown. Studies largely superseded by Hardy et al. (2004) and others.
	Harper and Robinson (1997)		Review previous large surge events and estimate storm tide levels along the Queensland coast for 50, 100, 500 and 1,000 year ARI events. 100 year ARI levels range from 0.2 m above HAT at the Gold Coast to 0.9 m above HAT at Townsville.
	Hardy *et al.* (2004)	Numerically synthesised storm events	Storm tide levels assessed for 50 locations inside the Great Barrier Reef as part of the *Queensland climate change and community vulnerability to tropical cyclones: Ocean hazards assessment.* 100 year ARI storm tide values (exclusive of future SLR) range from 1.22 m at the Gold Coast to 4.77 m at Clairview, to 1.82 m at the Lockhart River.
	EPA (2006) Mackay Coast Study	Storm Tides from Harper (1998)	For the Mackay Region, present 50 and 100 year ARI storm tide = 3.8 m and 4.1 m, respectively.
	Harper *et al.* (2011)	Numerical Assessment	Storm tide levels derived numerically for islands within the Torres Strait. 100 year ARI values range from 1.9 to 2.7 m above MSL.
	Anonymous	Varied	A number of confidential studies undertaken for private industry by a range of organisations.
Northern Territory	SEA (2006)	Darwin Harbour Tide Gauge and Numerical Assessment	Numerical assessment undertaken to define extreme storm tide levels. Modelling calibrated using gauge values observed during cyclonic events. Derived storm tide values around Darwin reached 3.9 m AHD for a 2 year ARI event, 4.0 m AHD for a 10 year ARI event and 4.9 m for a 100 year ARI event.
	Harper (2010)	Darwin Harbour Tide Gauge and Numerical Hindcast	Gauge analysis and numerical hindcast of Tropical Cyclone Tracey, a small but intense tropical cyclone that made landfall at Darwin on 24 December, 1974. Maximum storm surge at Darwin tide gauge reached 1.55 m, although the event occurred during neap tides to give a maximum storm tide level of only 2.8 m MSL.

3.4.3 ACE-CRC Sea Level Calculator

The Bureau of Meteorology National Tidal Centre (NTC) maintains a network of water level gauges around Australia (Figure 3-14). These gauges record water level hourly and, after undertaking harmonic analysis to determine astronomical components, separate tidal residual from the record. The resultant values may be assessed and probabilistic estimates of water level derived. ACE-CRC has undertaken such an assessment and have developed Sea Level Calculator Tool to provide the probability of exceedance of a certain water level elevation over a given time period (Hunter, 2009).

Water levels for a range of annual exceedance probabilities as determined by ACE-CRC are presented in Table 3.6. The online sea-level calculator also includes a provision for long-term sea level rise, discussed further within the following section.

Figure 3-14 Australian Tide Gauges analysed by ACE-CRC

Peak storm tide water levels have been derived around the Australian coastline based on studies presented within Table 3.5 and values provided within the ACE-CRC Sea-Level Calculator values (Table 3.6). Peak storm tide levels are presented within Figure 3-15 for a 100 year ARI event.

Table 3.6 Water Level (m AHD) for Various AEP used within the ACE-CRC Sea Level Calculator Tool

Location	AEP (ARI, year)			
	0.10 (10)	0.05 (20)	0.02 (50)	0.01 (100)
Albany	1.00	1.02	1.03	1.04
Brisbane	1.61	1.63	1.65	1.66
Bundaberg	2.04	2.10	2.17	2.22
Broome	5.21	5.25	5.28	5.30
Burnie	1.86	1.88	1.90	1.91
Bunbury	1.25	1.36	1.50	1.61
Cairns	1.90	1.94	1.99	2.02
Carnarvon	1.44	1.57	1.76	1.92
Darwin	3.93	3.97	4.02	4.05
Esperance	1.17	1.19	1.21	1.23
Fort Denison	1.35	1.39	1.43	1.46
Fremantle	1.07	1.13	1.19	1.23
Geelong	1.00	1.03	1.07	1.09
Geraldton	1.02	1.07	1.13	1.18
Georgetown	1.92	1.95	1.98	2.00
Hobart	1.16	1.22	1.29	1.34
Point Lonsdale	1.24	1.27	1.31	1.34
Mackay	3.72	3.81	3.91	3.99
Newcastle	1.23	1.27	1.31	1.34
Port Adelaide-outer	2.20	2.27	2.34	2.38
Port Adelaide-inner	2.35	2.43	2.54	2.61
Port Hedland	3.70	3.78	3.90	3.98
Port Lincoln	1.65	1.72	1.81	1.88
Port Pirie	2.56	2.64	2.73	2.79
Townsville	2.36	2.43	2.51	2.57
Thevenard	1.90	1.95	2.00	2.03
Victor Harbour	1.50	1.55	1.61	1.64
Williamstown	1.01	1.03	1.06	1.07
Wyndham	4.05	4.12	4.23	4.32

3.4.4 Long-Term Change

Long term changes, which may affect coastal inundation, include changes in average sea level or in the frequency, intensity and spatial distribution of storm systems over timescales of decades to centuries. A substantial body of literature exists on projected changes in sea level over the coming 50 to 100 years but the effects of long-term climate change on storm frequency, intensity and spatial distribution is less well understood.

The latest IPCC Summary for Policymakers Report (IPCC SPM, 2007a) and Working Group 1 Report (IPCC, 2007b) provide numerous sea level rise scenarios for 2090 to 2100 ranging from

0.18 m to 0.59 m (excluding ice melt), which are normally presented as 0.28 m to 0.79 m including suggested allowances for ice melt. Based on these scenarios, a range of planning levels has been produced by a range of state and national bodies and organisations (see Table 2.3 in Section 2). These values, based on IPCC (2001 and 2007) recommendations, range between 0.30 for 2050 to 1.0 m to 2100. Further, the Department of Climate Change have evaluated literature published more recently than the IPCC (2007) report and give a "plausible range of sea level rise values" between 0.50 and 1.1 m to 2100.

Values adopted by ACE-CRC in their Sea Level Calculator Tool for low, moderate and high sea level rise scenarios are presented in Table 3.7. These same SLR scenarios have been adopted for the present study.

Table 3.7 Sea-level Rise Scenarios Adopted within the ACE-CRC Sea Level Calculator Tool (source: Hunter, 2009)

Scenario	Impact	Increase at 2050[1] (m)		Increase at 2100[1] (m)	
		5% Minima	95% Maxima	5% Minima	95% Maxima
B1	Low	0.105	0.227	0.198	0.496
A1B	Moderate	0.102	0.266	0.208	0.649
A1FI	High	0.096	0.278	0.266	0.819

1 Compared to 1990 levels.

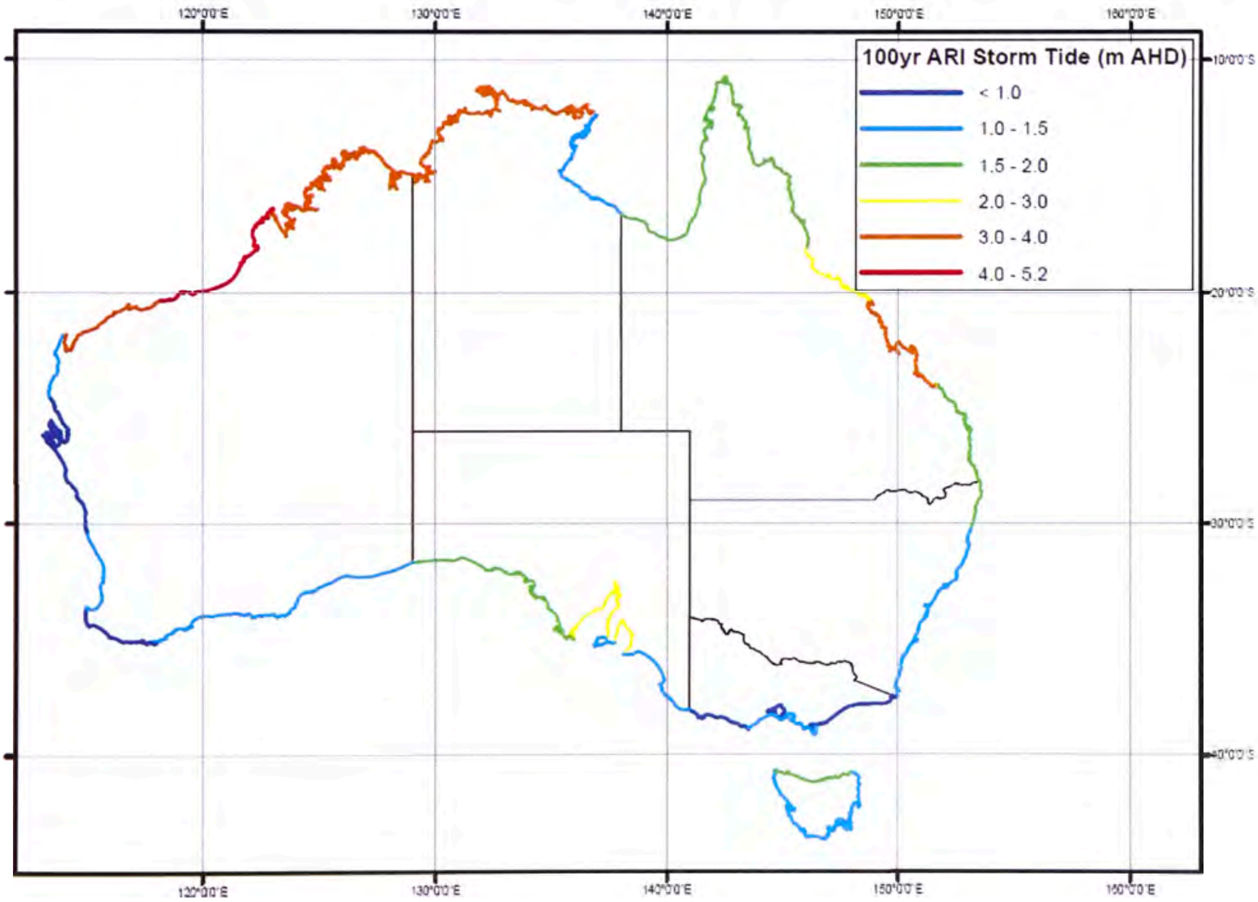


Figure 3-15 100 year ARI Storm Tide Level

3.5 Synthetic Design Storm Events

A synthetic design storm for defined ARI provides time series information of wave height and period for the calculation of beach erosion and coastal inundation (Carley and Cox, 2003).

To estimate synthetic design storm events, the following process is recommended (Shand et al., 2011) and illustrated within Figure 3-16:

1. Identify the envelope of H_s exceedance for specific durations (Figure 3-16, Upper Panel). This provides an upper limit of wave height as a function of duration.
2. Find the total cumulative storm energy for the specific ARI event.
3. Define a synthetic height distribution so that the height-duration envelope is not exceeded and the cumulative energy is equal to that specified for the particular event (Figure 3-16, Second Panel). The height distribution of a synthetic design storm is not necessarily unique and storms may be shorter and more intense (i.e. Event Type 1) or longer and less intense (i.e. Event Type 2);
4. Convert the synthetic height distribution into a time series of wave height incorporating any mean asymmetry in storm shape (Figure 3-16, Third Panel).
5. Define a synthetic wave period for the storm event. Examination of the time series for the largest five events at each buoy suggest that within a singular storm event, peak period also increases with wave height, reaching a maximum at around the time of peak wave height. (Figure 3-16, Lower Panel)
6. Estimate confidence intervals for the time series based on extreme H_s, E_{cum} and T_p confidence intervals.

Summaries of 100 year ARI design storms for eight Australian wave buoys as analysed by Shand et al., (2011) are provided within Figure 3-17. These design storms relate to the Type 1 (more intense) storm configuration.

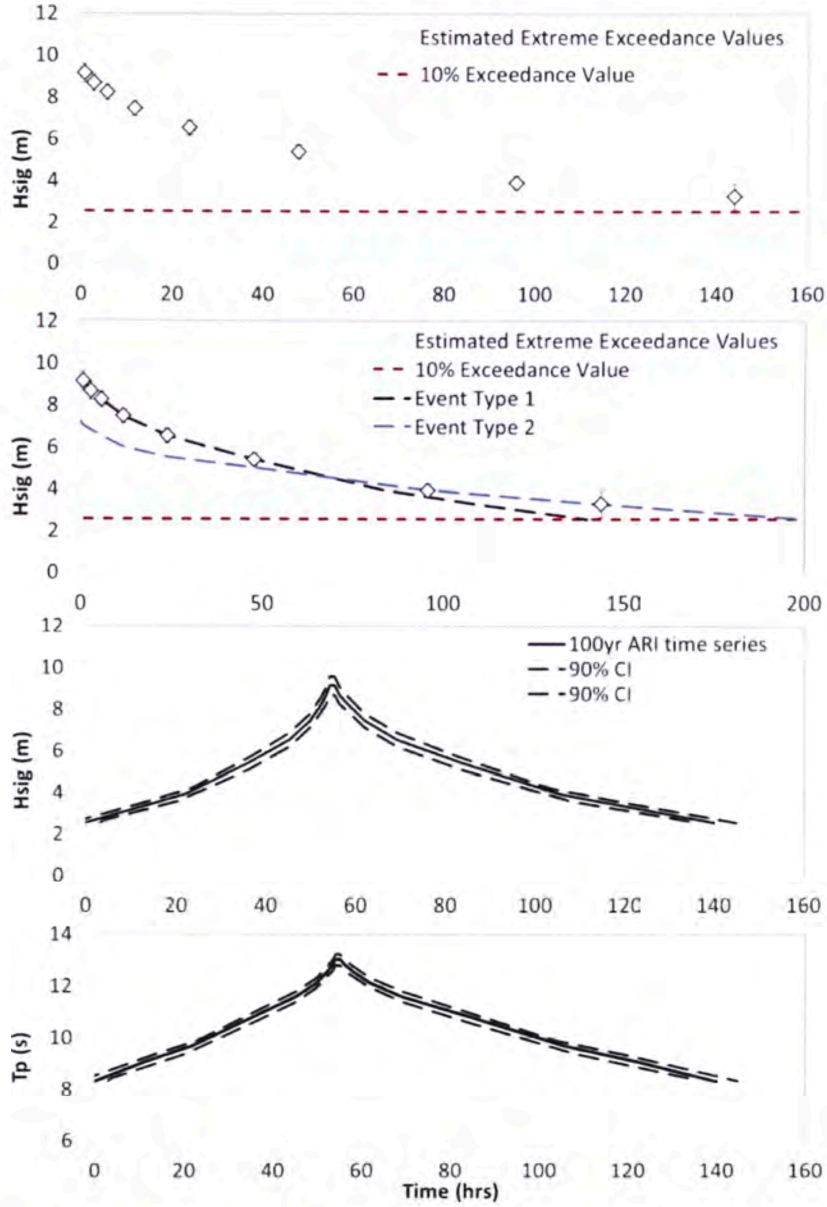


Figure 3–16 Example of the construction of a Synthetic Design Storm for a 100 year ARI event at Botany Bay, NSW

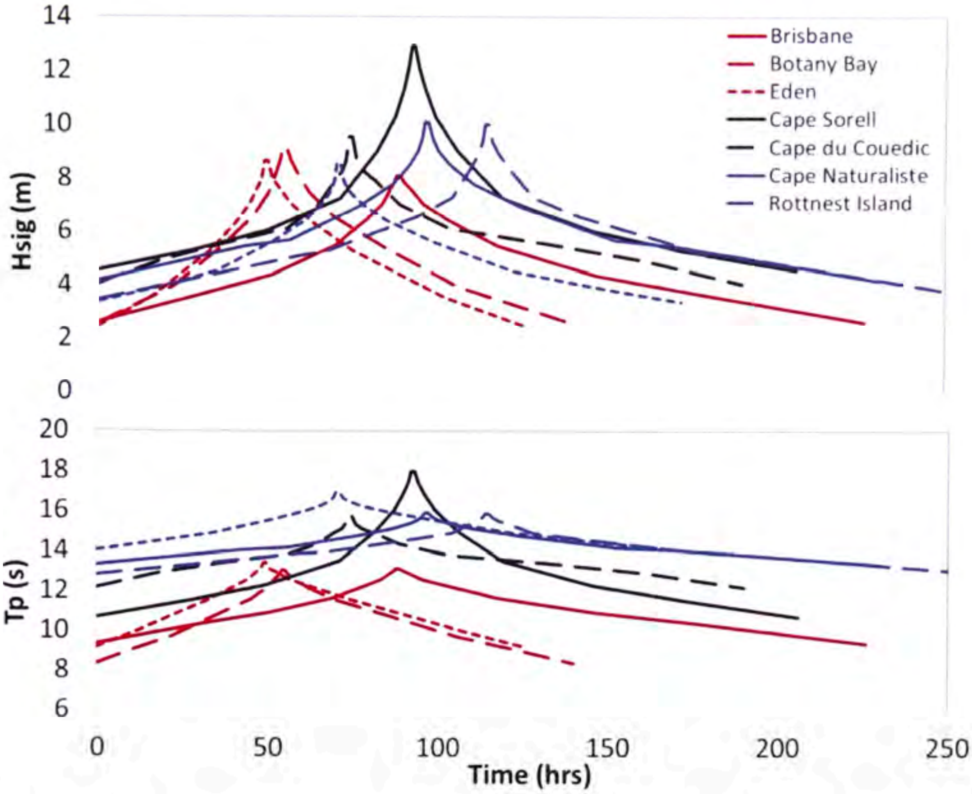


Figure 3–17 Examples of 100 year ARI Synthetic Design Storm Events for each Assessed Buoy

The design storms presented by Shand et al. (2011) do not include any buoys from tropical cyclone (TC) dominated regions. Buoy records and numerical simulations of notable events (i.e. Harper et al., 1993, 2011; DERM, 2010, 2011) show the elevated wave heights and water levels to be relatively short-lived compared to longer duration events on the southern coasts.

For example, Harper et al., (1993) analysed data from and numerically simulated TC Orson, a notably severe Category 5 cyclone that occurred in April 1989 in Western Australia. The cyclone moved west from Ashmore Reef before descending south towards the Dampier coastline where a wave buoy at the 'North Rankin A' site, approximately 130 km offshore of Dampier, recorded significant wave heights of 8.8 m before instrument failure. Waves of up to 20 m are believed to have impacted the gas production platform, which gives an estimated peak significant wave height of over 11 m; in agreement with subsequent modelling by Harper et al., the modelling also estimated a peak wave period of 16 s. This relatively long period compared to typical cyclonic waves is likely a function of the 'fetch enhancement' as the system descended south for around 900 km towards the coast, with the wind field continually developing the sea state (see Callaghan et al., 2006). However, the duration of the event (Hs > 2 m) was 2 days with a total cumulative energy of only 0.9 MJ/m^2 (Eqn. 3-1) compared to 2.8 MJ/m^2 for the 100 year ARI event at Jurien Bay. It should be noted that the cyclone continued towards shore after passing North Rankin A and that both the height and duration of large waves nearer the shore may be greater.

The limited-duration of extreme events is more pronounced within the Great Barrier Reef in Queensland where the offshore reef significantly restricts the fetch over which extreme wave height may develop. Tropical Cyclone Ului impacted northern Queensland in March 2003. The wave buoy at Mackay reached a maximum significant wave height of around 5.5 m (DERM, 2010) or around a 100 year ARI (Patterson, 1986), however, the wave height only exceeded 3 m for 24 hours with a peak period of 11 s. The total cumulative energy for this event was approximately 0.3 MJ/m^2, or approximately an order of magnitude less than the 100 year ARI storm at Brisbane.

Similarly, TC Yasi crossed the Queensland coast near Mission Beach in February 2011 as a category 5 cyclone. A minimum central pressure of 929 hPa was measured and maximum sustained wind speed was estimated at 205 km/h (DERM, 2011). Maximum measured Hs at Townsville exceeded 5 m, although approximately 9 hours of data during the passage of the storm is missing. This gap has been attributed to wave breaking (DERM, 2011). Significant wave height exceeded 2 m for less than 36 hours, with a total cumulative energy of between approximately 0.25 and 0.35 MJ/m^2 depending on the assumption made for wave height during the period of missing data.

The significant wave heights reached during TC Ului and TC Yasi in Queensland were approximately 100 year ARI events based on existing studies (Table 3.3). If an assumption is made that the cumulative storm energy was close to 100 year ARI also, synthetic design storms can be produced and scaled to the appropriate return period. Tropical cyclone Orson on the West Australian coast was noted by Harper (1993) as the most severe recorded in Australia and a worthy 'design storm'. Due to this region very flat offshore bathymetry, the peak water level is generally the dominating factor in influencing the amount of energy able to reach the backshore and induce storm erosion. TC Orson may therefore be adopted as the synthetic design storm for north-west Western Australia.

Water level has been incorporated into the synthetic design storm by assuming complete dependence between extreme wave height and water level. This implies that a 100 year ARI water level occurs simultaneously with a 100 year ARI wave event. This assumption, while conservative, is considered appropriate for this broad level of study. A rigorous analysis of the relative timing of wave heights and storm surge/water level would exceed the resources of this entire study.

The coastline was split into 30 regions based on state boundaries and extreme wave and water level characteristics (Figure 3-18). For each design event, synthetic design storm time series have been derived for these combinations based on the methods and findings of Carley and Cox (2003) and Shand et al. (2011) discussed in Section 3.3. Synthetic design storms for a 100 year ARI event are presented for each region within Appendix B.

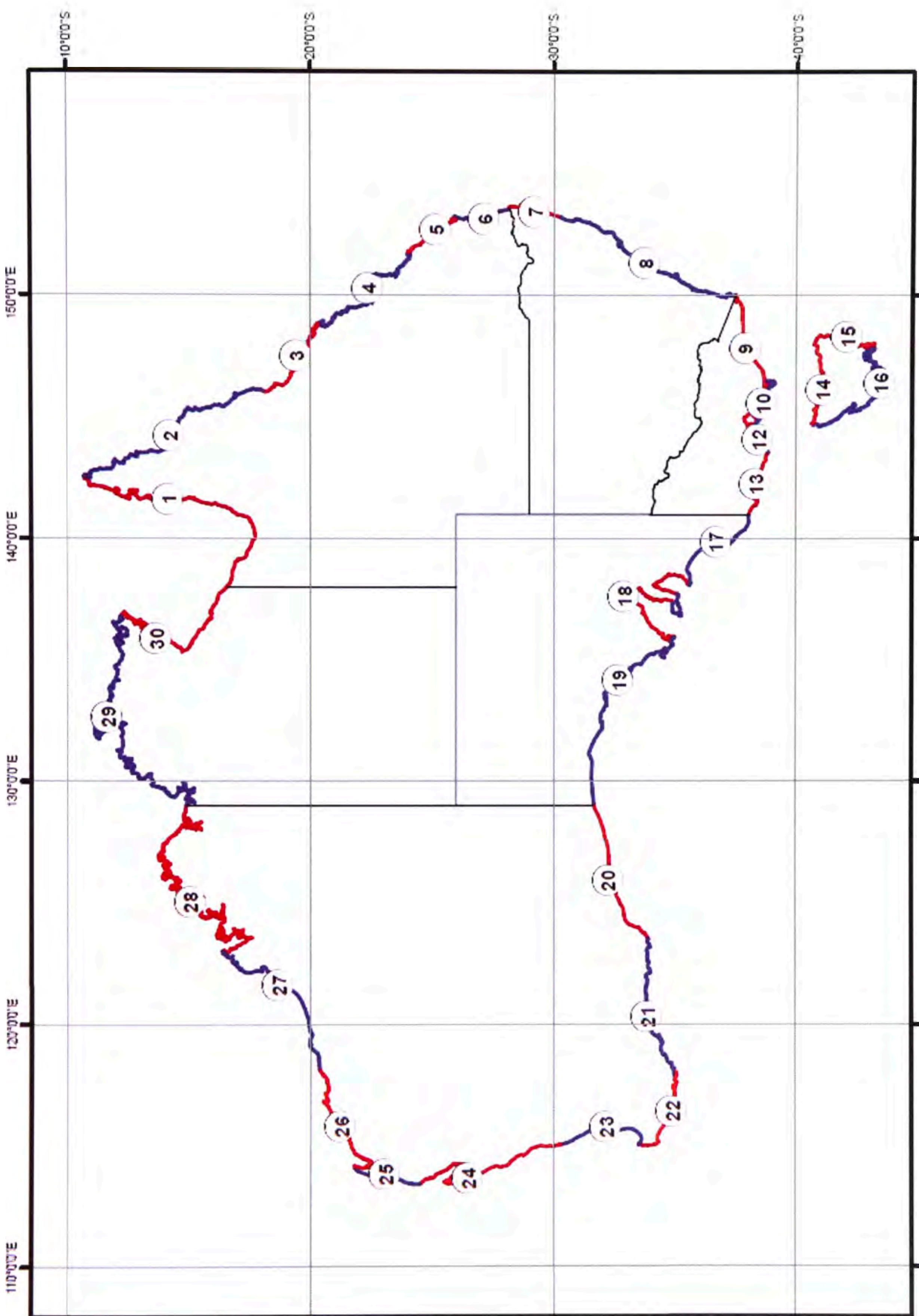


Figure 3–18 Australian Coastal Sections

4. Beach Response Modelling

4.1 Introduction

The beach system dynamically responds to the hydrodynamic forcings it is subject to, primarily waves and water level fluctuations. Several methods are available to predict the beach fluctuations in response to erosive phenomena during storm events, these can be divided into two broad categories:

- Deterministic process models which, based on the specified succession of wave and water level conditions, calculate the sediment redistribution within the beach system; Models range from simple geometric (e.g. Bruun, 1983, Vellinga, 1986) to complex numerical modes such as XBEACH; and
- Statistical models founded on the extrapolation of trends and cycles from past observations. Long datasets of historical measurements are essential to undertake a probabilistic type approach.

For this study a deterministic process model approach was used. Deterministic process models describe changes in the initial input bathymetry based on the cumulative effect of a series of input hydrodynamic conditions (waves and water levels). Section 3.2 of this report described the beach profile and bathymetric data that was collected and analysed at several locations along the Australian coastline. This data constituted the initial input bathymetry for the deterministic model. Section 3.5 reported on the derivation of synthetic design storms comprising time series of wave heights, peak wave periods and water levels, which constituted the input hydrodynamic conditions for the deterministic erosion model.

Wave transformation equations are implemented in these models to account for the propagation of waves from the boundary, generally deep water, to shallow water including the processes of wave breaking and dissipation, wave setup and wave-induced currents. A combination of sediment continuity equation and sediment transport rates are then determined from the hydrodynamic calculations in particular from the moments of the wave orbital velocities at seabed.

Callaghan et al. (2009) presented a comparison between a deterministic and probabilistic (Joint Probabilistic Method, JPM) approach applied at Narrabeen Beach in New South Wales and found that both approaches provide similar underestimation of erosion events for ARI events up to 3 years. The Joint Probability Method was found to provide better agreement with observation for events of less than 10 year ARI, and the deterministic method provided better agreement for events between 20 and 30 years.

4.2 Model Background

A number of beach erosion models have been developed to predict beach response to storm impact. These include the Kriebel and Dean (1993) model, the Larson and Kraus model (1993), the Bailard model (1991), the Danish Hydraulic Institute model (DHI, 1991) and the XBeach model (Roelvink et al., 2009). Some of these models have been implemented in the well-known commercial packages for beach response modelling such as UNIBEST by Delft Hydraulics, SBEACH by USACE or LITCROSS by DHI.

For the purpose of this study, two models were selected to undertake the numerical simulation of erosive process at Australian beaches, the XBeach model based on the Roelvink et al. (2009) and the SBEACH model based on Larson and Kraus (1993).

The SBEACH model has been used academically and within industry for evaluating beach response for many years and has been successfully calibrated and verified for a number of Australian Beaches (Carley, 2001). The XBEACH model was developed in 2009 to assess dune erosion in response to extreme storm conditions where the coast presents complex and significant alongshore variability due to natural features such as rip channels and shoals or man-made structures such as revetments, artificial inlets and seawalls. The XBeach model is still under development and indeed the dune erosion component of the model is empirically rather than process-based.

Both models require as input:

- Beach and dune profile and nearshore bathymetry;
- Offshore wave parameters;
- Water levels; and
- Sediment properties.

In this study both models were used in one-dimensional (cross-shore) profile mode i.e. assuming uniformity of the coast in the alongshore direction.

4.2.1 XBeach

XBeach is a two-dimensional process-based numerical model designed to model extreme beach erosion caused by extreme storm, hurricane or cyclone events. While previous erosion modelling tools assumed alongshore uniformity, XBeach allows the modelling of alongshore variation such as variation in dune heights and the presence of shoals, rip channels, barrier islands, artificial inlets, revetments and seawalls.

XBeach hydrodynamic and sediment transport equations are extensively described in Roelvink et al. (2009) and in the XBeach Model Description and Manual (2010). In particular, the model resolves swash dynamics using a detailed formulation of wave grouping and associated infragravity waves.

XBeach is available in open source and is therefore in constant progress and evolution. It is currently implemented within numerous research programs, however, its use for practical coastal engineering is limited. The XBeach version used in this study dates 22/09/2011.

4.2.2 SBEACH

SBEACH is a one-dimensional (cross-shore) sediment transport numerical model developed by the United States Army Corps of Engineers, Coastal Engineering Research Center (USACE - CERC). Details of the model scientific basis and field verifications have been extensively published through CERC technical reports (Larson and Kraus, 1989; Kraus and Byrnes, 1990) and scientific journal papers (Schoonees and Theron, 1995).

SBEACH has been developed and extensively verified with field and laboratory data collected during major American field experiments (Duck and Super Duck experiments). In Australia, SBEACH was successfully calibrated and verified for a number of beaches (Carley, 2001, Carley and Cox, 2003). SBEACH is endorsed in many state policies for the numerical modelling of beach erosion.

4.3 Modelling of Selected Events and Sites with Good Data

Most of the deterministic models were developed in conjunction with comparisons against laboratory experiments i.e. two-dimensional physical model testing in wave flumes and/or three-dimensional physical model testing in wave basins. During their development phase, in addition to wave flume tests, both XBeach and SBEACH were validated for specific sites using different field data sets including the ones from the US based field research facility at Duck, North Carolina (Larson et al., 1989, Roelvink et al., 2009). Carley (2001) successfully modelled erosion during storm events using SBEACH at several Australian beaches. Splinter et al. (2011) used XBeach to predict an East Coast Low storm impact at the Gold Coast (Australia).

Field data sets incorporating pre- and post-storm bathymetry are required in order to validate the models. These data sets are often scarce and limited to selected key locations where beach surveys have been undertaken regularly and in concomitance with significant storm events. Models need to be validated and verified with different data for application to specific site. For this project, WRL consulted and obtained topographic and bathymetric data from a number of sources including the:

- Department of Transport WA;
- Department of Environment and Resource Management QLD;
- Coastal Observation Program (COPE) QLD;
- Department of Environment and Natural Resources SA;
- Tasmanian Shoreline Monitoring and Archiving (TASMARC) project, TAS;
- Office of Environment and Heritage NSW;
- Andy Short (personal communication);
- WRL of University of New South Wales;
- Northern Territory Government; and
- Department of Sustainability and Environment VIC.

Beach and shoreface profiles data were obtained for several locations, however, quality datasets suitable for model validation, including pre- and post-storm profiles, were limited to the locations and storm events described below.

4.3.1 May 2009 Storm at Gold Coast, QLD

Between the 20 and 25 May 2009 south-eastern Queensland and north-eastern New South Wales were impacted by an intense storm event (East Coast Low) resulting in significant erosion on several beaches. The Gold Coast waverider buoy recorded significant wave heights up to 6.1 m and peak wave period of 14 s. The Southport tide gauge recorded a highest water level of 1.2 m AHD. Figure 4–1 shows recorded significant wave height, spectral wave period and water levels (including tide and storm surge).

Pre-storm surveys were completed between October and December 2008 while a post-storm survey was undertaken within a week from the storm impact in June 2009.

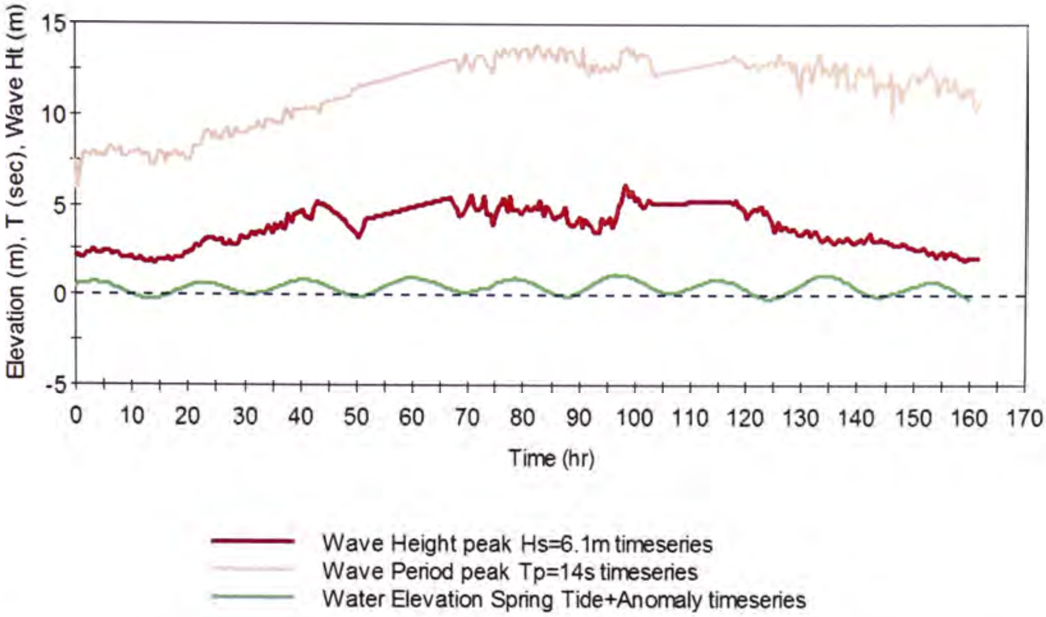


Figure 4-1 Recorded Significant Wave Height, Peak Spectral Wave Period and Water Level During the May 2009 Storm (source: QLD Department of Environment and Resource Management)

4.3.2 August 1986 Storm at Narrabeen, NSW

Between 5 and 10 August 1986, central and southern New South Wales was impacted by a storm that resulted in significant damage to infrastructures along the beach. Significant wave heights peaked at 7.0 m with a peak wave period of 13 s; the maximum water level at the Sydney tide gauge was 1.2 m AHD. Pre and post-storm profile at Narrabeen were surveyed by Short (PWD, 1987). Figure 4-2 shows plots of significant wave height and peak spectral wave period as recorded by the Sydney waverider buoy and water levels (including tide and storm surge) at the Sydney tide gauge.

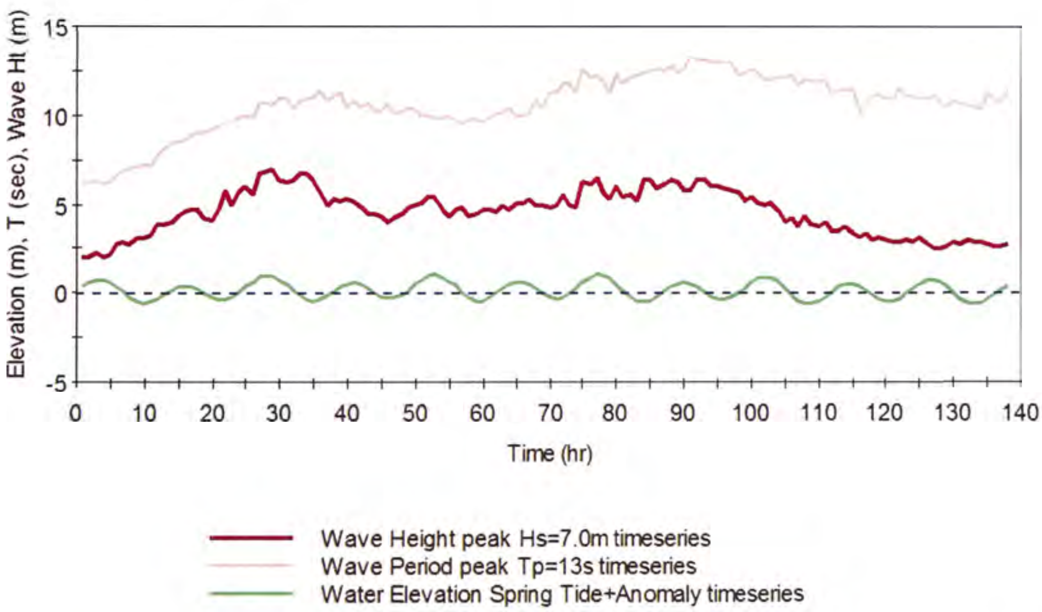


Figure 4-2 Recorded Significant Wave Height, Peak Spectral Wave Period and Water Level During the August 1986 Storm (source: Manly Hydraulics Laboratory)

4.3.3 July 2011 Storm at Narrabeen, NSW

Between 19 and 26 July 2011, a storm impacted the Sydney region with a peak wave significant height of 6.3 m, 12 s peak wave period and a peak water level at the Sydney tide gauge of 0.70 m AHD. Figure 4-3 presents the recorded wave and water level (including tide and storm surge) time series. Beach profiles at Narrabeen beach were surveyed using GPS-RTK technology prior the storm and shortly after the event by WRL.

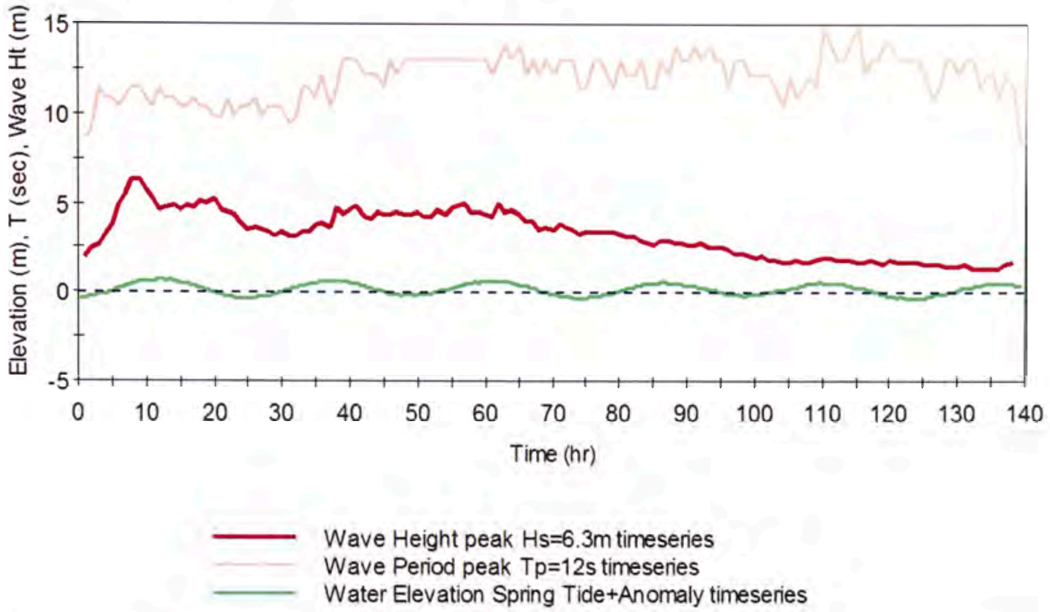


Figure 4-3 Recorded Significant Wave Height, Peak Spectral Wave Period and Water Level During the July 2011 Storm (source: Manly Hydraulics Laboratory)

4.3.4 Model to Prototype Data Comparison

XBeach and SBEACH were used to predict erosion volumes for the 2009 storm at Narrowneck on the Gold Coast and the 1986 and July 2011 storms at Narrabeen (Malcolm Street). Models were run in calibrated mode. Calibrated model parameters are shown in Appendix D. Calibration was based on:

- Minimising the difference between model predictions and measured erosion volumes above 0 m AHD; and
- Using the same set of model parameters for different sites and storm events.

The modelling utilised the hourly time series data from waverider buoys and tide gauges. Modelling results in terms of erosion volumes above 0 m AHD are depicted in Table 4.1. Good model-data agreement was achieved at Narrowneck (Gold Coast) for XBeach while SBEACH under-predicted erosion volumes at this site. However, at Narrabeen, XBeach over-predicted the observed erosion for both 1986 and 2011 storms while SBEACH model results were in reasonable agreement with the observations.

Table 4.1 Summary of Model Validation Results

Location	ARI	Storm Characteristics				Erosion Volume above 0 m AHD		
	(years)	Max H_s (m)	T_p (s)	Duration (h)	Max WL (m AHD)	Measured (m^3/m)	XBeach (m^3/m)	SBEACH (m^3/m)
Gold Coast 2009	~5	6.1	12.0	161	1.2	66	79	39
Narrabeen 1986	5-8	7.0	10.6	137	1.1	65	83	75
Narrabeen 2011	~1	6.3	12.0	138	0.7	12	31	15

Figures 4.4 and 4.5 show plots of pre and post-storm beach profiles for the Gold Coast (Narrowneck) and Narrabeen (Malcolm Street) respectively. At Narrowneck, XBeach predictions for shoreline change and dune erosion compared well with the observations, while SBEACH under-predicted overall shoreline erosion. However, SBEACH predictions for shoreline change in the upper part of the dune were reasonable.

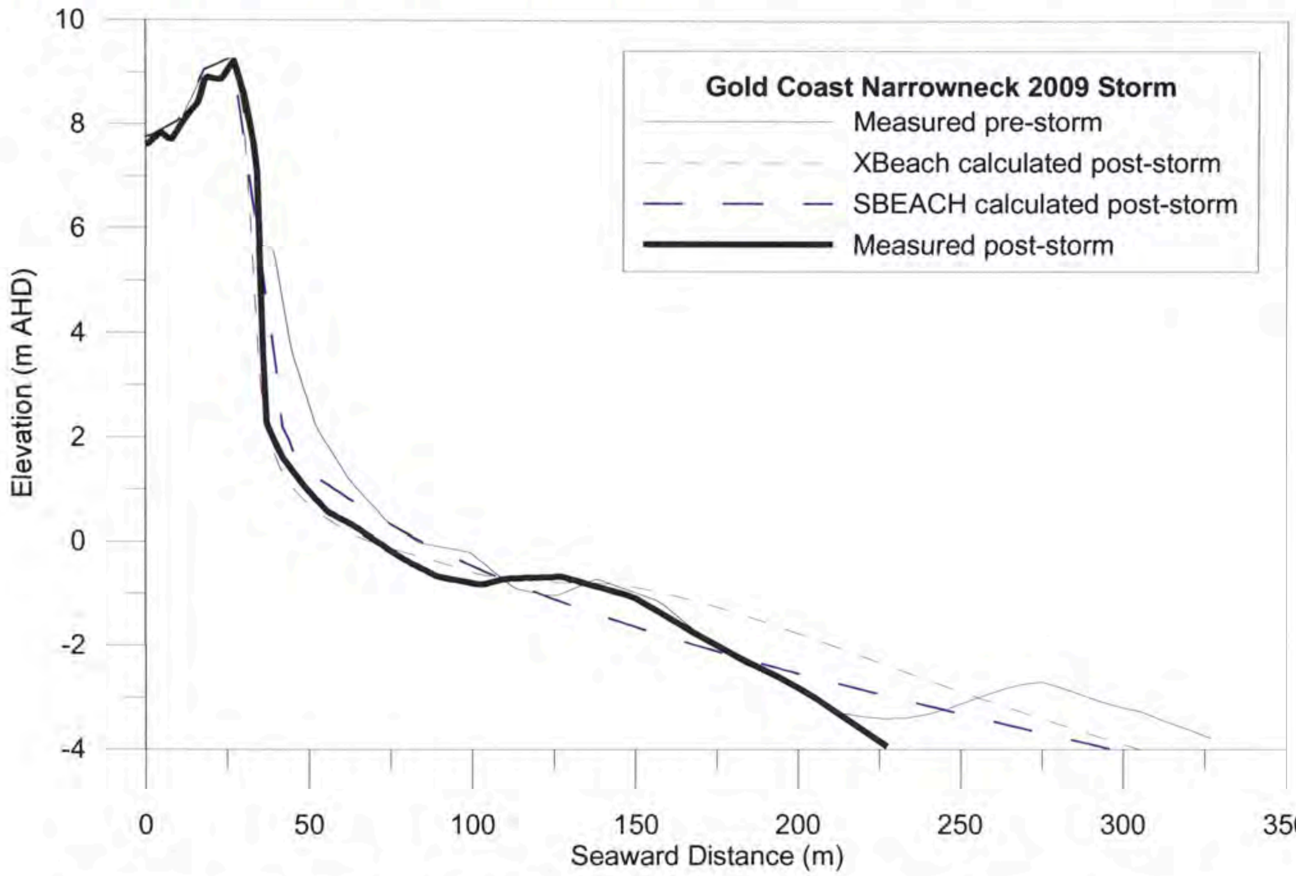
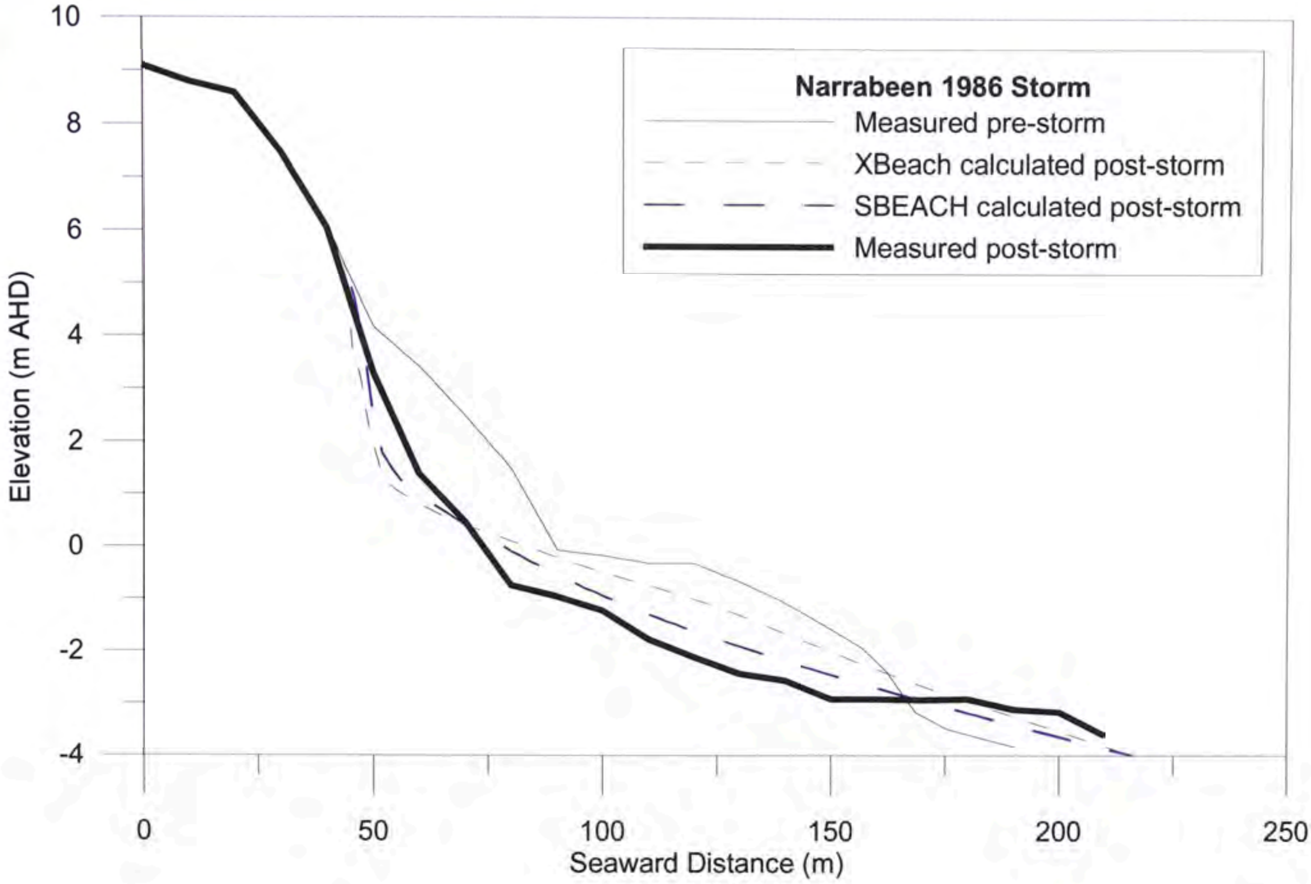


Figure 4–4 XBeach and SBEACH Predictions for the 2009 Gold Coast Storm at Narrowneck

Overall, the range of model predictions was found to be acceptable compared with the observations. Errors in offshore bathymetry, longshore gradients and wave focusing, which are not accounted for in the 1D models, were considered potential sources of error.

The offshore depth beyond which profile variations are insignificant is known as the closure depths. Closure depths as estimated by the numerical models are presented in Table 4.2. Paucity of data does not allow any validation for the Narrabeen storms, however, for the Gold Coast storm, both models predicted depths in broad agreement with the measured data. The closure depth has significance for the estimation of shoreline recession due to sea level rise as described in Section 5.



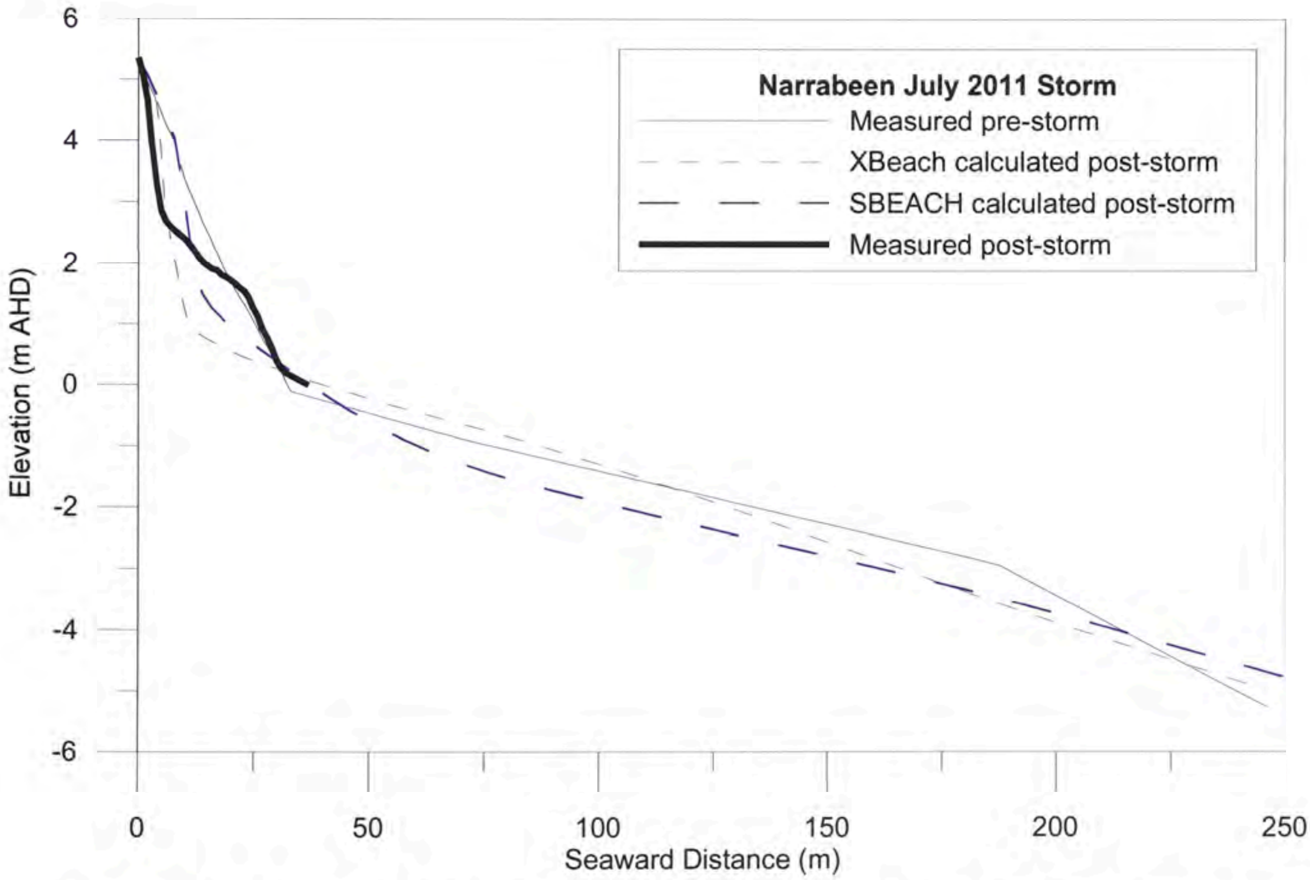


Figure 4–5 XBeach and SBEACH Predictions for the 1986 and 2011 Narrabeen Storms

Table 4.2 Summary of Calculated Closure Depths

Location/Storm	Measured (m AHD)	XBeach (m AHD)	SBEACH (m AHD)
Gold Coast 2009	-13	-11	-11
Narrabeen 1986	-16	-8	-8
Narrabeen 2011	n/a	-12	-12

4.3.5 Discussion

In XBeach, detailed physics of wave transformation and sediment transport are specified through a large number (>100) of free parameters. Splinter et al. (2012) showed that (i) the predicted erosion volumes were very sensitive to changes in model free parameters, (ii) using default parameter values, the model significantly over-estimated upper beach erosion and (iii) suggested the need of site specific calibration. Carley (2001) obtained good model-data agreement at different sites in Australia with minimal calibration using the more simplified physics-based model SBEACH (<20 model parameters).

Undertaking specific model calibration for each study site was both infeasible and beyond the present scope of works. The purpose of the project being to apply XBeach as a generic erosion model to in excess of 100 locations along the Australian coastline. Therefore, the XBeach model parameters were optimised using the two sites (Narrowneck in QLD and Narrabeen in NSW) for which datasets incorporating pre- and post-storm profiles were made available for this project. The same set of model parameters (with the exception of grain size, which was site specific) was then applied at all of the beach locations investigated.

The initial modelling process undertaken at the two study sites (Narrowneck and Narrabeen) prompted the following conclusions:

- XBeach is expected to produce conservative results without specific site calibration;
- Due to the scarcity of validation field data sets, XBeach model predictions at different locations along the Australian coast cannot be validated at present; and
- SBEACH should be run in parallel to XBeach at selected sites in order to compare its predictions with XBeach predictions.

4.4 Model Setup

4.4.1 Beach Profiles Available for this Study

In Section 3.2, the Australian beach type classification after Short (2006) was introduced as well as the beach profile data made available for this study by state government departments and research institutions at several locations along the Australian coastline. Each beach profile was assigned a beach type (Table 3.1) taking in consideration upper shoreface and beach slope as well as general knowledge of the geomorphology and hydrodynamic conditions of each specific site. Plots of beach profiles are presented in Appendix A.

Approximately 50 beach profiles at 30 different locations along the coastline were collected providing a reasonable coverage of the most populated and developed coastal areas. However, for extensive stretches along the coasts of SA, WA, NT, and northern QLD, no beach profile data was made available. The scope of works involved the modelling of beach erosion at in excess of 100 sites to uniformly cover the range of occurrence along the Australian coastline of different beach types; the purpose being the assessment of storm erosion vulnerability on a regional level and the provision of range of storm erosion volumes along the Australian coastline.

At locations where beach profiles were unavailable, "proxy" profiles were selected from other locations where profiles were available. As explained previously, selection was based on consideration of several criteria such as upper shoreface slope, sediment size, tidal range and wave conditions. Although no substitute for the real profiles, it was believed that the representative ("proxy") profiles would provide useful estimates of beach erosion vulnerability to the local wave and water level storm design conditions in the absence of viable alternatives.

4.4.2 Design Storm Events

In Section 3.5, the derivation of synthetic design storms (SDS) consisting of time series of waves and water levels (including tide and storm surge) was described. The Australian coastline was discretised into 30 regions (hydraulic zones) based on state boundaries and extreme wave and water level characteristics (see Figure 3-18). For each hydraulic zone, synthetic design storms were produced for the 1 in 1, 1 in 10, 1 in 100 and 2×100 year ARI design events. Each hydraulic zone was then allocated the beach types most relevant and common within the zone. A total of 90 SDS were generated corresponding to design events for each of the three average recurrence intervals considered and each of the 30 hydraulic zones. Adopted SDS are presented in Appendix B.

Table 4.3 shows the regional segmentation based on hydraulic conditions (i.e. design wave and water level conditions), the regional coast type, the beach profile data available for each region and the prevalent beach types within the zone. As explained in Section 4.4.1, for the locations where beach profiles were unavailable, "proxy" profiles were selected from other locations where profiles were available and assigned to each beach type present in the area. The representative beach profiles were allocated taking into consideration the general beach and shoreface slope, the presence of geomorphic features typical to the beach type (sand bars, low tide terraces, rock shelves, etc.) and the dominant hydrodynamics conditions characterising the area.

Hard substrate and rocks within the beach and fine cohesive sediment were not implemented in the model; Types 14 and 15 (Short, 2006) were therefore not considered.

Table 4.3 Hydraulic Zones and Beach Type Segmentation

Zone	State	Regional Coast	Regional Coast Type	Beach Type	Beach Profiles Made Available for this Study	Proxy Beach Profile
1	QLD	Weipa–Cape York Coast	Tide Dominated	4	*None*	*Byron
				9	*None*	*Cairns (MU 8)
2	QLD	Cairns Coast	Tide Modified	8	Cairns (MU 11/12)	-
				9	Cairns (MU 8)	-
3	QLD	Townsville Coast	Tide Dominated	10	*None*	*Mackay (MAC 155)
				12	*None*	*Mackay (MAC 104)
4	QLD	Mackay Coast	Tide Dominated	10	Mackay (MAC 155)	-
				12	Mackay (MAC 104)	-
5	QLD	Gladstone Coast	Tide Dominated (excludes Agnes Water)	10	Hervey Bay 104	-
				12	Hervey Bay 108	-
6	QLD	Fraser-Gold Coast	Wave Dominated	2	Narrowneck	-
				3	Kirra	-
				4	*None*	*Byron
7	NSW	Coffs Harbour-Tweed Coast	Wave Dominated	2	*None*	*Narrowneck
				3	*None*	*Kirra
				4	Byron/Kingscliff	-
8	NSW	Coffs Harbour-Cape Howe Coast	Wave Dominated	2	*None*	*Narrowneck
				3	Narrabeen St	-
				4	Wamberal Profile 2	-
				5	Wamberal Profile 5	-
				6	Stockton	-
9	VIC	East Gippsland Coast	Wave Dominated	2	Seaspray	-
				3	*None*	*Narrabeen St
10	VIC	South Gippsland-Mornington Pen Coast	Wave Dominated	2	Gunnamatta	-
				3	*None*	*Narrabeen St
11	VIC	Port Phillip Bay Coast	Tide Modified/Dominated	6	St Kilda	-
12	VIC	Lonsdale to Lorne Coast	Wave Dominated	2	*None*	*Gunnamatta
				4	*None*	*Kingscliff
				9	Lorne	-
13	VIC	Port Campbell-Portland Coast	Wave Dominated	1	Discovery 3	-
				3	Discovery 1	-
				4	Port Fairy	-
14	TAS	North Tasmania Coast	Tide Modified/Wave Dominated	5	Adams Beach	-
				9	*None*	*Cairns (MU 8)
15	TAS	East Tasmania Coast	Wave Dominated	3	*None*	*Narrabeen St
				4	*None*	*Wamberal Profile 2
				5	*None*	*Wamberal Profile 5
				6	*None*	*Stockton
15A	TAS	Storm Bay	Tide Dominated/ Wave Dominated	4	*None*	*Port Fairy
				7	Roches Beach	-
16	TAS	West–South Tasmania Coast	Wave Dominated	1	*None*	*Discovery 3
				2	*None*	*Discovery 2
17	SA	Kingston-Goolwa Coast	Wave Dominated	1	*None*	*Discovery 3
				2	Goolwa Beach	-
18	SA	Gulf St Vincent-Spencer	Tide Modified	7	Semaphore Park	-

Zone	State	Regional Coast	Regional Coast Type	Beach Type	Beach Profiles Made Available for this Study	Proxy Beach Profile
19	SA	Port Lincoln–Eucla Coast	Wave Dominated	1	*None*	*Discovery 3
				3	*None*	*Narrabeen St
20	WA	Eucla–Cape Pasley Coast	Wave Dominated	2	*None*	*Gunnamatta
				3	*None*	*Narrabeen St
21	WA	Esperance Coast	Wave Dominated	1	*None*	*Discovery 3
				3	*None*	*Narrabeen St
				4	Esperance	-
22	WA	Albany–Cape Naturaliste Coast	Wave Dominated	1	*None*	*Discovery 3
				3	*None*	*Narrabeen St
23	WA	Cape Naturaliste to Geraldton	Wave Dominated	4a	North Fremantle	-
				4b	Mandurah	-
				5a	Brighton beach	-
				5b	Port Denison	-
24	WA	Geraldton-Carnarvon Coast	Wave Dominated	2	*None*	*Gunnamatta
				3	*None*	*Narrabeen St
25	WA	Cape Cuvier to NW Cape	Wave Dominated	3	*None*	*Narrabeen St
26	WA	Exmouth to Dampier Coast	Tide Dominated/Wave Dominated	2	Port Samson	-
				13	*None*	*Mackay (MAC104)
27	WA	Port Headland to Broome	Tide Modified/Dominated	12	*None*	*Mackay (MAC104)
28	WA	Kimberley Coast	Tide Modified/Dominated	13	*None*	*Mindil 3
29	NT	Darwin-Arnhem Land Coast	Tide Modified/Tide Dominated	7	Vesteys	-
				10	Casuarina 13	-
				12	Mindil 3	-
30	NT	East Arnhem Land-Weipa Coast	Tide Dominated/Wave Dominated	4	*None*	*Byron
				7	*None*	*Vesteys
				12	*None*	*Mindil 3/MAC 104

Notes:
*Profile data for this beach type was unavailable in this zone so a proxy beach profile was selected from the locations where profiles were available.

4.4.3 Scenarios

For each hydraulic zone, the XBeach model was run in 1D profile (cross-shore) mode with the following inputs:

- Synthetic design storms specific to each zone;
- Local representative sediment grain size; and
- Beach profiles representative of beach types most relevant within the zone.

The design events considered in the modelling were the 1 in 1, 1 in 10 and 1 in 100 year ARI events. Two consecutive 100 year storm events were also modelled to evaluate consecutive storm impacts on the beach as described in Section 3.3. While it may appear to be excessive, the 2×100 year ARI values account for clustering of extreme storms. The 2x100 year ARI storms scenario approximates the 100 year ARI erosion volume statistics for NSW published by Gordon (1987) and the volume change observed at Bengello Beach, South Broulee (Moruya, NSW) observed by Thom and Hall (1991) during the erosive period in the early 1970s. As discussed in Section 2, the only states with explicit policies regarding erosion calculation are

WA and QLD. WA specifies three design storms to account for storm clustering. QLD specifies a single design storm, but adds a factor of safety of 40% to this value.

The beach profile data collected at several locations along the Australian coastline was used as initial input bathymetry for the modelling. Figure 4-6 presents a conceptual diagram depicting an example of the model run process. In Hydraulic Zone 2 for example, the most common and relevant beach types are Types 8 and 9. Therefore, the XBeach model was run with the representative beach profile for Type 8 (and in this specific zone also for Type 9) and the synthetic design storms (1, 10, 100 and two consecutive 100 year ARI events) specific to Zone 2.

As shown in Table 4.3, the hydraulic zones present variable diversity and heterogeneity in terms of beach type as this depends on the general geomorphology of the coastline and the prevalent hydrodynamic conditions specific to each geographical region.

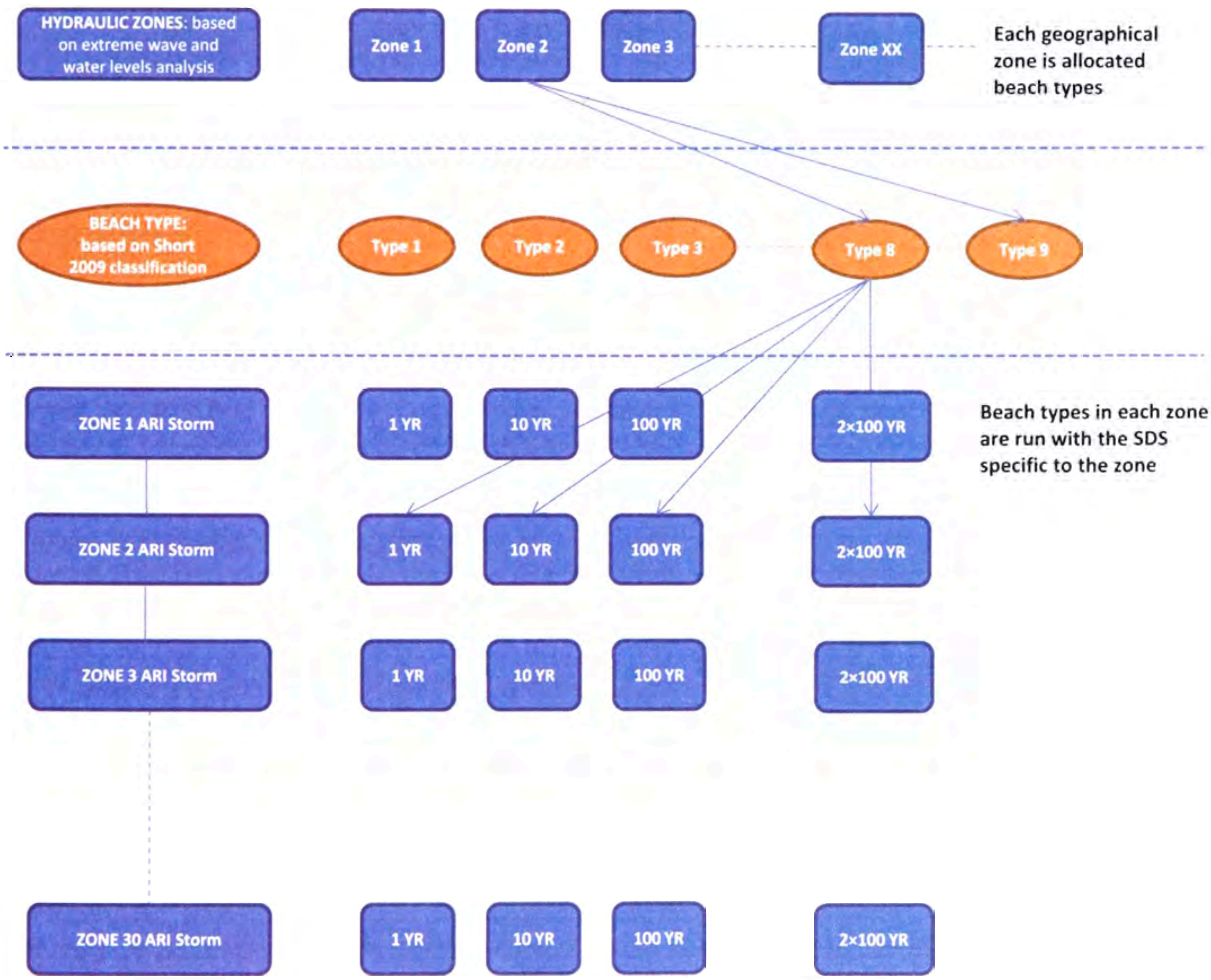


Figure 4–6 Schematic Diagram of XBeach Model Runs

4.5 XBeach Raw Model Output

Beach erosion model results were presented in terms of erosion volume or "storm demand". Erosion volume or storm demand relates to the process of erosion of the beach by a single extreme storm event or from several storm events in close succession (DECCW, 2010). The amount of sand (above 0 m AHD) transported offshore by wave action is referred to as storm demand and expressed as a volume of sand per metre length of beach (m^3/m). Erosion volumes can be used to estimate immediate setback distances (see Section 6).

Table 4.4 presents raw XBeach erosion volume output (V_{SD} - storm demand volumes) for each representative beach type for the 1 in 1, 10 and 100 year ARI design events as well as for two consecutive 100 year ARI events. As stated in the table, **these values are recommended for initial rapid assessment only.** If other factors (sand grain size and input waves and water levels) are equivalent, a Type 1 (Dissipative Beach) should have less erosion for the same storm event compared to a Type 2 (Longshore Bar and Trough) or Type 3 (Rhythmic Bar and Beach). This trend is not always evident in the model outputs in Table 4.4, and is likely to be due to:

1. The use of "proxy" rather than real profiles for many locations – labelled P and R respectively in Table 4.4.
2. Limited sand grain size data.
3. The lack of site specific model calibration.

SBEACH storm demand predictions for the 1 in 100 year ARI event and 2×100 year ARI (when available) are also presented for selected locations. It is important to note that the comparison between the two model results does not constitute a validation or contradiction of either results. Validation should be compared to measured pre- and post-storm sand volumes at each specific site. The paucity of datasets incorporating pre- and post-storm survey data does not allow any validation of the model predictions, however, the comparison between the two model outputs provide some indication of the uncertainty related to these predictions. Pre- and post-storm profiles for the 1 in 100 year ARI event are shown in Appendix C for selected locations.

Model erosion volumes ranged from less than 1 to over 300 m^3/m depending on the combination of wave and water level conditions and beach profile parameters such as shoreface slope, sediment size and dune height. Typically, beaches characterised by steeper shoreface gradients and finer sediments were associated with higher erosion volumes. Flatter shoreface slopes insured higher dissipation of wave energy and consequently less erosion. The presence in the initial beach profile of morphological features such as single or multiple sandbars, low tide terraces, deep troughs, etc., also affected wave attenuation/dissipation and therefore erosion processes.

It is important to note that for tide dominated beaches (Types 10 to 15), tidal energy has a greater impact on beach morphology than wave energy and site specific investigation needs to be considered. At these sites typically characterised by extremely flat shoreface gradients, the XBeach model was not able to produce reliable results due to convergence problems associated with very shallow water. Similarly, the SBEACH model was not able to model erosion processes at such sites. The extremely dissipative nature of these profiles means that storm erosion is low and the outputs of the models may not be unrealistic.

Processes of wave dissipation over fringing reefs were not considered in the modelling. Therefore, the erosion volumes reported are conservative estimates at locations where offshore fringing reefs are present. Only unconsolidated sandy beaches were considered and the presence of rock/hard substrates was not modelled.

Within the XBeach and SBEACH models, numerical modelling was undertaken in profile mode, therefore only cross-shore sediment transport processes were considered. Alongshore variability and processes such as longshore currents were not considered. However, dune and beach erosion during extreme storm events is mainly a cross-shore process and the model output provides realistic estimates of storm impact on beaches. The effect of seawalls in limiting the erosion was not considered in the modelling.

Model predictions are only appropriate for the assessment of relative beach vulnerability to storm erosion and general regional variability of storm impacts. **Detailed site-specific studies by qualified practitioners using the most recently available data should always be undertaken for local-scale planning and coastal hazard assessment.**

Table 4.4 XBeach Model Output Storm Demand (in m^3/m) Above 0 m AHD

*** (This information does not replace a detailed, site specific coastal engineering assessment and is to be used for rapid assessment only.)**

Zone	Regional Coast(5)	Beach Type R=Real P=Proxy		XBeach Volume of Storm Demand V_{SD} (m^3/m)				SBEACH V_{SD} (m^3/m)	
				ARI (years)				ARI (years)	
				1	10	100	2×100	100	2×100
1	Weipa–Cape York Coast	4	P	7	17	33	56	n/a	n/a
		9	P	15	26	52	69	72	n/a
2	Cairns Coast	8	R	3	5	7	11	34	49
		9	R	8	12	17	23	54	76
3	Townsville Coast	10	P	1	1	2	3	13	n/a
		12	P	n/a	n/a	n/a	n/a	n/a	n/a
4	Mackay Coast	10	R	0	1	1	3	16	26
		12	R	n/a	n/a	n/a	n/a	<1	<1
5	Gladstone Coast (excl Agnes Water)	10	R	n/a	n/a	n/a	n/a	<1	<1
		12	R	n/a	n/a	n/a	n/a	<1	<1
6(1)	Fraser-Gold Coast	2	R	67	88	151	215	70	132
		3	R	27	45	59	72	33	68
		4	P	42	68	104	161	n/a	n/a
7(1)(2)	Coffs Harbour-Tweed Coast	2	P	67	88	151	215	70	132
		3	P	27	45	59	72	33	68
		4a	R	42	68	104	161	n/a	n/a
		4b	R	37	59	102	160	n/a	n/a
8	Coffs Harbour-Cape Howe Coast	2	P	73	88	109	173	n/a	n/a
		3	R	46	63	84	135	79	n/a
		4	R	22	34	50	84	43	n/a
		5	R	36	49	56	67	71	n/a
		6	R	50	66	89	140	88	n/a

Zone	Regional Coast[5]	Beach Type R=Real P=Proxy		XBeach Volume of Storm Demand V_{SD} (m^3/m)				SBEACH V_{SD} (m^3/m)	
				ARI (years)				ARI (years)	
				1	10	100	2×100	100	2×100
9	East Gippsland Coast	2	R	46	60	70	98	n/a	n/a
		3	P	58	80	110	171	n/a	n/a
10	South Gippsland–Mornington Pen Coast	2	R	41	60	70	93	n/a	n/a
		3	P	72	95	138	211	n/a	n/a
11	Port Phillip Bay Coast	6	R	1	1	1	2	4	7
12	Lonsdale to Lorne Coast	2	P	37	55	85	140	n/a	n/a
		4	P	51	71	101	154	n/a	n/a
		9	P	45	61	81	144	n/a	n/a
13	Port Campbell-Portland Coast	1	R	45	54	80	119	n/a	n/a
		3	R	61	72	97	139	n/a	n/a
		4	R	n/a	n/a	n/a	n/a	25	53
14	North Tasmania Coast	5	R	20	25	25	25	20	25
		9	P	77	84	91	110	n/a	n/a
15	East Tasmania Coast	3	P	44	62	83	134	n/a	n/a
		4	P	26	43	62	102	n/a	n/a
		5	P	43	59	65	75	n/a	n/a
		6	P	43	57	79	125	n/a	n/a
15A	Storm Bay	4	P	21	34	44	71	n/a	n/a
		7	R	43	46	65	92	n/a	n/a
16	West–South Tasmania Coast	1	P	79	101	120	193	n/a	n/a
		2	P	91	122	144	245	n/a	n/a
17	Kingston-Goolwa Coast	1	P	74	108	132	197	n/a	n/a
		2	R	57	95	114	176	n/a	n/a
18	Gulf St Vincent-Spencer Gulf Coast	7	R	1	2	2	5	16	26
19	Port Lincoln–Eucla Coast	1	P	51	62	82	130	n/a	n/a
		3	P	105	145	188	289	n/a	n/a
20	Eucla–Cape Pasley Coast	2	P	59	82	109	179	n/a	n/a
		3	P	84	118	152	237	n/a	n/a
21[3]	Esperance Coast	1	P	69	96	116	172	n/a	n/a
		3	P	90	147	197	302	140	250
		4	R	226	343	434	603	200	296
22	Albany–Cape Naturaliste Coast	1	P	76	96	111	171	n/a	n/a
		3	P	111	154	193	305	n/a	n/a
23[3] [4]	Cape Naturaliste-Geraldton	4a	R	45	84	133	206	n/a	n/a
		4b	R	50	74	108	155	60	91
		5a	R	78	129	185	274	n/a	n/a
		5b	R	111	168	234	322	90	146
24	Geraldton-Carnarvon Coast	2	P	56	75	100	163	n/a	n/a
		3	P	86	108	144	225	n/a	n/a
25	Cape Cuvier to North West Cape Coast	3	P	94	119	173	266	n/a	n/a

Zone	Regional Coast(5)	Beach Type R=Real P=Proxy		XBeach Volume of Storm Demand V_{SD} (m^3/m) ARI (years)				SBEACH V_{SD} (m^3/m) ARI (years)	
				1	10	100	2×100	100	2×100
26	Exmouth to Dampier Coast	2	R	16	31	39	50	n/a	n/a
		13	P	n/a	n/a	n/a	n/a	44	66
27	Port Headland to Broome Coast	12	P	n/a	n/a	n/a	n/a	53	75
28	Kimberley Coast	13	P	n/a	n/a	n/a	n/a	36	50
29	Darwin-Arnhem Land Coast	7	R	27	62	73	89	n/a	n/a
		10	R	n/a	n/a	n/a	n/a	14	27
		12	R	n/a	n/a	n/a	n/a	40	67
30	East Arnhem Land-Weipa Coast	4	P	7	16	33	53	n/a	n/a
		7	P	10	23	33	48	n/a	n/a
		12	P	4	10	16	25	n/a	n/a

Notes:

(1) For Zones 6 and 7, identical synthetic design storms were used.

(2) Zone 7 model predictions for Types 4a and 4b were calculated using the Kingscliff and Byron Bay representative profile respectively.

(3) Wave dissipation processes over reef and the presence of hard rock substrates on the beach are not considered; estimate or erosion volumes will be conservative at sites where such features are present.

(4) In Zone 23, model predictions for Types 4a and 4b were calculated using Mandurah and North Fremantle profiles. Types 5a and 5b were calculated using Brighton Beach and Port Denison profiles.

(5) For tide dominated beaches (Types 10 to 15) wave processes are less relevant to beach erosion than tide processes; at these sites, model predictions were not considered reliable and storm erosion modelling not applicable (n/a).

4.6 Suggested Design Values for Storm Demand

Based on the modelling results, familiarity with previous coastal engineering studies and engineering judgement, suggested values of storm demand for each coastal region are presented in Table 4.4. Due to the limited availability of accurate data for different beach types and regions, the suggested erosion values are not presented down to the level of detail of different beach types. Site specific data and model calibration would be needed to confidently differentiate design values for different beach types.

It should be noted that erosion values higher than those shown in Table 4.5 cannot be excluded. Some locations with apparent high erosion may also be subject to ongoing underlying recession (S2 component in Sections 1, 2 and 5). If this component is not properly considered, it may be erroneously include into the S1 storm erosion component.

Table 4.5 Suggested Design Erosion Volumes based on XBeach, SBEACH and Engineering Judgement

Zone	Regional Coast	Suggested design V_{SD} (m^3/m above AHD) based on 2 x 100 year ARI storms
1	Weipa–Cape York Coast	**80**
2	Cairns Coast	**80**
3	Townsville Coast	**80**
4	Mackay Coast	**80**
5	Gladstone Coast (excl Agnes Water)	**50**
6	Fraser-Gold Coast	**200**
7(	Coffs Harbour-Tweed Coast	**200**
8	Coffs Harbour-Cape Howe Coast	**200**
9	East Gippsland Coast	**200**
10	South Gippsland–Mornington Pen Coast	**200**
11	Port Phillip Bay Coast	**20**
12	Lonsdale to Lorne Coast	**150**
13	Port Campbell-Portland Coast	**200**
14	North Tasmania Coast	**100**
15	East Tasmania Coast	**150**
15A	Storm Bay	**100**
16	West–South Tasmania Coast	**250**
17	Kingston-Goolwa Coast	**200**
18	Gulf St Vincent-Spencer Gulf Coast	**50**
19	Port Lincoln–Eucla Coast	**250**
20	Eucla–Cape Pasley Coast	**250**
21	Esperance Coast	**250**
22	Albany–Cape Naturaliste Coast	**250**
23	Cape Naturaliste-Geraldton	**150**
24	Geraldton-Carnarvon Coast	**150**
25	Cape Cuvier to North West Cape Coast	**150**
26	Exmouth to Dampier Coast	**80**
27	Port Headland to Broome Coast	**80**
28	Kimberley Coast	**80**
29	Darwin-Arnhem Land Coast	**80**
30	East Arnhem Land-Weipa Coast	**80**

5. Coastal Response to Sea Level Rise

5.1 Background

The response of coastlines to future sea level rise is of concern to coastal managers, planners, engineers and the general public. This concern is based on the well-accepted theory that an elevation in sea level will result in recession of the coastline (Bruun, 1962 and 1983; Cowell et al., 1992; Komar et al., 1997) and the resultant threat to billions of dollars' worth of coastal developments and infrastructure (Ranasinghe et al., 2011).

A number of methods for estimating coastal response to changes in sea level have been developed over the past 50 years. These methods include approaches based on basic geometric principles to more complex process-based assessment. While some methods are used more widely than others, none have been proved categorically correct and adopted universally; much controversy remains.

This section briefly describes a number of shoreline response models in use in Australia before describing the adopted model, the methodology employed and the model results. Readers are referred to SCOR (1991) and Ranasinghe et al. (2007) for more complete reviews of available methods.

The Bruun Rule

The most widely known model for beach response is that of Bruun (1962). The Bruun model (as separately defined from the *Bruun Rule*) assumes that as sea level is raised, the equilibrium profile is moved upward and landward conserving mass and original shape (Figure 5.1). This occurs by the following assumptions (SCOR, 1991):

1. The upper beach is eroded due to the landward translation of the profile;
2. The material eroded from the upper beach is transported immediately offshore and deposited, such that the volume eroded is equal to the volume deposited; and
3. The rise in the nearshore profile as a result of this deposition is equal to the rise in sea level.

The horizontal extent of landward retreat (R) in the profile is expressed by the relatively simple relationship shown in Eqn. 5-1:

$$R = \frac{L_*}{B + h_*} S \qquad (5\text{-}1)$$

Where h_* defines the maximum depth of sediment exchange, L_* is the horizontal distance from the shoreline to the offshore position of h_*, B is the height of the berm/dune crest within the eroded backshore and S is the sea level rise. As the distance over elevation term within Eqn. 5-1 is essentially a cross-shore slope ($1/\tan\theta$), SCOR (1991) rearrange this to the form shown in Eqn. 5-2:

$$R = \frac{1}{\tan\theta} S \qquad (5\text{-}2)$$

This revised form of the equation implies that the rule is simply a translation of the nearshore profile up a regional slope. Given a typical cross-shore slope (tanθ) of 0.01 to 0.02 for many coastal sites, the resultant recession would be of the order of 50S to 100S (SCOR, 1991).

This relationship was termed the Bruun Rule by Schwartz (1967) and has remained the principal method for establishing 'rule of thumb' shoreline response to sea level rise (DCC, 2009). As the rule is governed by simple, two-dimensional conservation of mass principles, it is limited in its application in a number of aspects:

1. The rule assumes that there is an offshore limit of sediment exchange or a 'closure depth', beyond which the seabed does not rise with sea level.
2. The rule assumes no offshore or onshore losses.
3. The rule assumes instantaneous profile response following sea level change.
4. The rule assumes an equilibrium beach profile where the beach may fluctuate under seasonal and storm-influences but returns to a statistically average profile (i.e. the profile is not undergoing long-term steepening or flattening). This being stated, the precise configuration of the profile is irrelevant provided it is maintained as the water level changes (SCOR, 1991).
5. The rule does not accommodate variations in sediment properties across the profile or profile control by hard structures such as substrate geology or adjacent headlands or engineered structures.

To overcome a number of these limitations, Hands (1980, 1983) proposed a modified Bruun Rule shown in Eqn. 5-3 to account for losses of fines from the littoral zone using an 'overfill ratio' ($F_A > 1$) and net longshore movement of sediment (ΣQ_S) into or out of a control shoreline length (Y) in the time period of consideration.

$$R = \frac{L_* F_A}{B + h_*} S + \frac{\Sigma Q_S}{Y(B + h_*)} \qquad (5\text{-}3)$$

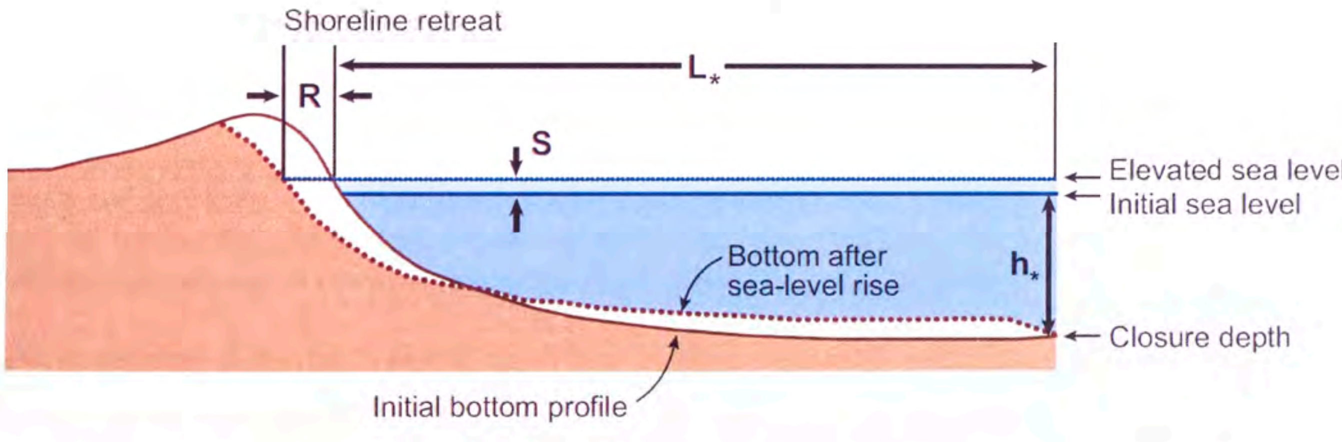


Figure 5–1 Schematic diagram showing the Bruun Rule principle (after Cooper and Pilkey, 2004)

Numerous researchers have tested the Bruun Rule against a variety of field and laboratory data (Schwartz, 1965 and 1967; Dubois, 1975; Hands, 1979, 1980 and 1983; Rosen, 1978; Everts, 1985; Pilkey and Davis, 1987; Dean, 1990, Zhang et al., 2004 and others). Using field data to assess long-term responses is complicated by overlying short-term fluctuations, underlying sediment budget imbalances and three-dimensional effects. Similarly, using laboratory data is limited by scale errors and testing duration.

Some of the better known comparisons include studies by Hands (1979, 1980 and 1983) in Lake Michigan where twenty five beach profiles over 50 km were monitored over 8 years where lake levels rose and fell by up to 0.39 m. Results showed overall recession, followed by progradation as lake levels rose and fell and overall mass balance between offshore deposition and erosion. Observations showed less profile response than predicted by the Bruun Rule (with closure depth defined according to the seaward extent of the envelope of profile change) which was attributed to a lag in profile response time. While the eventual drop in lake level brought the observed profile position back into agreement with the Bruun Rule prediction, SCOR (1991) argue that with a continual increase in sea level, the disagreement between modelled and observed recession would have persisted and increasingly diverged. Region-wide field studies have found mixed agreement between the Bruun Rule predictions and observations with Rosen (1978) finding significant scatter in site-specific results, but Everts (1985) finding very close agreement when sediment budgets are accounted for. Similarly, in a large-scale study along the US east coast, Zhang et al. (2004) found good agreement between Bruun Rule predictions and observations when sites exhibiting net long-shore gradients in sediment transport were excluded.

Full reviews of these comparisons are provided within SCOR (1991) and Ranasinghe et al. (2007) but, in general, while the overall principles of the Bruun model have been verified (i.e. an increase in sea level results in an upward and landward shift in the profile), the quantitative accuracy of the Bruun Rule has not been convincingly verified. Predictions for specific sites have varied from measured rates by factors of 2 to 5 (both over- and under-prediction), although predictions are substantially improved by inclusion of a full sediment budget (SCOR, 1991).

Major uncertainties that remain in using the Bruun Rule include the definition of a closure depth (h_*) or cross-shore slope ($1/\tan\theta$) and major limitations include the lack of any lag time between sea level change and profile response. While many practitioners have questioned the actual existence of a closure depth (i.e. Pilkey et al., 1994), the rule is not necessarily reliant on its physical existence. While long-term sediment exchange may occur to very deep water depths, i.e. the 'pinch-out' point (Hands, 1980), this 'ultimate' profile adjustment extent is only valid if either the profile response is instantaneous or if sea level changes and then stabilises with the profile 'catching up'. As sea level rise is expected to be ongoing (IPCC, 2007) and a lag in profile response is apparent (Hands, 1983), the outer limit of profile adjustment is likely to be 'left behind' as sea levels rise. The closure depth can therefore be more realistically defined as the point at which the profile adjustment can 'keep up' with sea-level change and becomes a calibration parameter in lieu of an adequate depth-dependent lag parameter.

Various definitions of closure depth have been presented in the literature including an ultimate definition of closure of 3.5 x H_{sb} (Bruun, 1988) where H_{sb} is related to an extreme significant wave height (50 or 100 year ARI) or 2 x H_{sb} (USACE, 2006) where H_{sb} is the significant wave height with ARI approximating the design life of interest (i.e. 20 year ARI for a 20 year planning period). However, as discussed above these 'ultimate limit' closure depths are likely to over-predict recession during on-going sea level rise.

The method of Hallermeier (1978, 1981 and 1983) is one of the most widely accepted for defining closure depths, as it is based on site specific physical characteristics and processes. Hallermeier (1983) defined three profile zones, namely the *littoral zone*, *buffer zone* and *offshore zone,* and surmised that the actual closure depth falls somewhere between the seaward limit of the littoral zone (or inner depth d_{inner}) and the offshore zone (d_{outer}). Hallermeier suggests that the inner closure depth, d_{inner}, is a function of sediment characteristics and local wave climate but, for a sandy beach, can be approximated (Nicholls, 1998) as shown in Eqn. 5-4:

$$d_{inner} = 2.28H_{s,t} - 68.5(H_{s,t}^2 / gT_s^2) \cong 2 \times H_{s,t} \qquad (5\text{-}4)$$

Where d_{inner} is the closure depth below *mean low water springs,* $H_{s,t}$ is the non-breaking significant wave height exceeded for 12 hours in a defined time period, nominally one year, and T_s is the associated significant wave period. The outer closure depth can then be approximated as $d_{outer} \approx 1.5 \times d_{inner}$. Hallermeier notes that uncertainties remain in this definition of closure, especially when d_{outer} exceeds 20 m, which is usually cited as an ultimate limit to significant wave-induced sand transport (Dietz and Fairbridge, 1968).

Birkemeier (1985), utilizing numerous beach profile datasets, modified Hallermeier's relationship to better fit his field data as shown in Eqn. 5-4b:

$$d_b = 1.75H_{s,t} - 57.9(H_{s,t}^2 / gT_s^2) \cong 1.57 \times H_{s,t} \qquad (5\text{-}4b)$$

Other definitions of closure depth include changes in seabed geometry or seaward limit of *significant* profile change. Nicholls et al. (1988) defines this seaward limit of *significant* change according to a 6 cm change criterion. Using field data from a range of sites in the United States and Europe, he found the d_{outer} criterion of Hallermeier (1983) to provide a robust outer limit for this profile change criterion, although the mean limit was 69% of d_{inner}, indicating that d_{inner} may still over-predict retreat due to sea level rise.

Overall, while the general principles of the Bruun model have been verified (i.e. an increase in sea level results in an upward and landward shift in the profile), the quantitative accuracy of the Bruun Rule has not been convincingly verified with predictions for specific sites found to vary from measured rates by factors of 2 to 5 (SCOR, 1991). While many of the arguments against the Bruun Rule include factors obviously (and stated to be) outside the scope of the original rule (Eqn. 5-1) such as net longshore or cross-shore sediment transport, these factors may be included in a modified Bruun Rule (Eqn. 5-3) or incorporated separately. Acknowledging these limitations, and with tests of sensitivity using a range of closure depth definitions, the Bruun Rule remains a useful tool for first-order assessment.

Shoreface Translation Model

Cowell et al. (1992, 1995) acknowledge that while complete behaviour of coastal morphology at all scales is represented by the sediment continuity equation including all geometric and sediment transport terms, considerable uncertainty surrounds many of the terms. They suggest that this uncertainty may be bypassed by focusing only on the morphological behaviour of the profile kinematics constrained through a sediment mass balance. This is similar to the underlying principle of the Bruun Rule (Bruun, 1962), although the Bruun Rule (Eqn. 5-1) relies on a closed sediment budget and a profile in equilibrium.

The Shoreface Translation Model (termed STM for brevity) has been derived by Cowell et al. (1992, 1995) to accommodate the upward and landward translation of a profile under sea level rise but allowing for differing substrates (Figure 5–2) and changes in sediment budgets and profile morphology through time. The main modes of the STM are a transgressive barrier mode where the profile migrates landward by overwash (Figure 5–2A) and an encroachment mode similar to the original Bruun model (Figure 5-2C), although a continuum of possibilities exist between the two states. While the model is time-dependent, it is driven by changes in sea-level, external gains or losses in the sediment budget and changes in the geometry of the active sand body rather than any hydrodynamic forcing.

The ability of the STM to simulate large scale coastal behaviour was tested using reconstructions of barrier deposits in the Tuncurry embayment (NSW) which occurred during the post-glacial marine transgression where sea level rise reached rates of 15 to 20 mm/year. The model could be calibrated to replicate long-term changes but was found to be very sensitive to small changes in the net littoral sediment budget with this parameter dominating even under rapid sea level rise.

The STM represents a pragmatic modelling approach based on simple geometric transformation and sediment budget principles. The model is highly user controlled and the accuracy of any results is dependent on the user's understanding of the physical processes affecting a particular site. With sufficient information, this model represents an improved method of evaluating shoreline response; with minimal information, the model reduces to a Bruun-type rule.

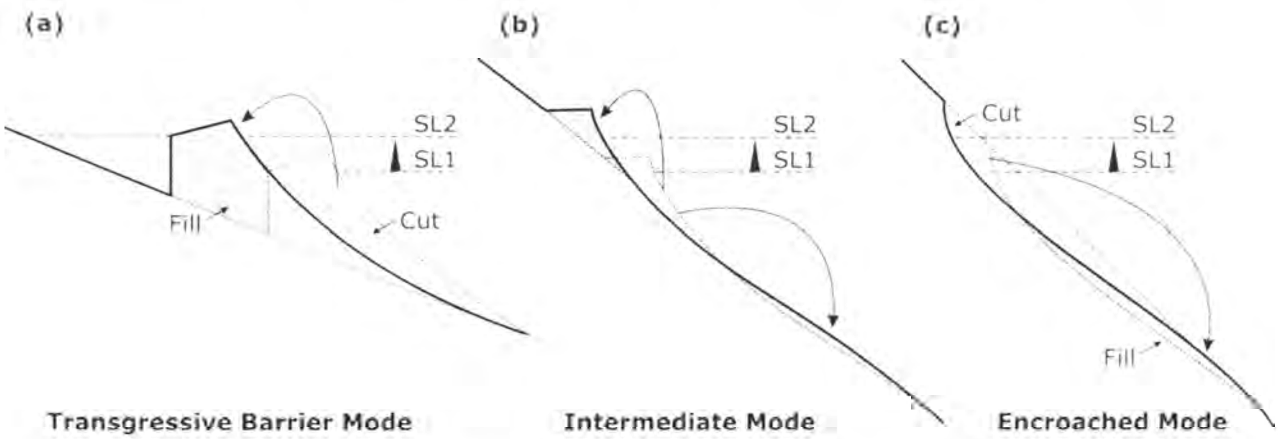


Figure 5-2 Examples of Shoreface Translation Model Modes in Response to Sea Level Rise (after Cowell et al., 1995)

Komar Geometric Model

The Komar Geometric Model of Foredune Erosion (1997) was developed primarily as an alternative to process-based models (i.e. SBEACH) in determining storm erosion during periods of elevated water level on the United States west coast. However, the model is often also quoted with respect to assessing longer-term shoreline response to sea level rise. The general rule is similar to the Bruun Rule in that it is a two-dimensional, geometric translation model, which conserves mass as shown in Eqn. 5-5.

$$DE_{\max} = \frac{(WL - H_J) + \Delta BL}{\tan\theta} \tag{5-5}$$

Where $WL-H_J$ is the elevation of water level (WL) above the dune toe level (H_J), ΔBL is the potential lowering of the profile due to storm erosion and tanθ is the slope of the beach face (Figure 5.3). This equation essentially reduces to the Bruun Rule except the beach face slope is adopted rather than the slope to profile closure. In this respect, while the model produced results in good agreement with storm erosion potential (Komar, 1997), the model would appear unsuitable for assessing long-term profile response where accretion of the entire nearshore profile is likely.

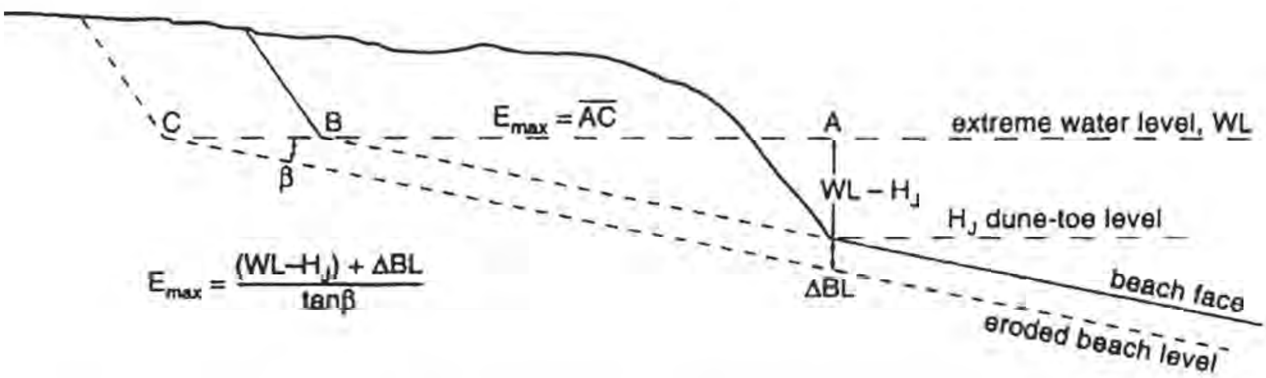


Figure 5–3 Geometric model used to evaluate the maximum potential erosion during an erosion event

RD-A Model

Davidson-Arnott (2005) refutes the Bruun model principle that as sea level rises, sediment is eroded from the upper beach and deposited offshore raising the bed level. This argument is based on the premise that while the Bruun model includes the beach-nearshore interaction, it omits the beach-dune interaction and conservation of the dune sediment budget. Instead Davidson-Arnott proposes that as sea level rises, the equilibrium profile is translated upward and landward. There is a net onshore migration of sediment and sediment eroded from the shoreface is transferred landward maintaining the overall dune sediment budget.

While the proposed model (termed the RD-A model) is conceptual only and has not been quantitatively compared with field or laboratory measurements, it is very similar in form to the transgressive barrier mode of the Shoreface Translation Model (Cowell, 1992).

EShorance

The applicability of the Bruun Rule within an estuarine environment is questionable given the differing sediment properties and processes affecting the generally steeper upper beach and flatter offshore profile. For a very flat and wide nearshore profile with low backshore elevation typical of many estuarine shorelines, the Bruun Rule would predict very large potential recession.

The model eShorance (Stevens and Giles, 2010) was developed as an alternative model to assess landward recession in estuarine environments. This model is based on the assumption that sediment lost from the upper beach or topographic profile does not settle on the nearshore or bathymetric profile and that the profile is simply translated upward and landward to reach a new equilibrium (Figure 5–4). While the model proposes that there are components to account for shoreline movement from inundation (Eqn. 5-6) and from recession (Eqn. 5-7), once rearranged the profile is simply translated by a Bruun principle using the nearshore profile slope (Eqn. 5-8).

$$R_{Inundation} = (s/m_t) \qquad (5\text{-}6)$$

$$R_{Recession} = (s/m_b - s/m_t) \quad (5\text{-}7)$$

Where $R_{Inundation}$ is the shoreline retreat due to inundation, $R_{Recession}$ is the shoreline retreat due to additional recession and $R_{Combined}$ is the combined shoreline retreat, s is the sea level rise, m_b and m_t are the bathymetric and topographic slopes defined according to rise/run.

$$R_{Combined} = (s/m_b) \quad (5\text{-}8)$$

Stevens and Giles (2010) find total recession of 20 m for an example case and suggest that this is less than 50 to 100 m which would be found using rule-of-thumb Bruun factors (R = 50S to 100S) adopted for open coast studies. However, given their example offshore profile is relatively steep at m = 0.05 the total retreat predicted by the Bruun Rule would be 20 m (or less if the steeper upper profile is also taken into account as is usual). For very flat offshore profiles, both the Bruun Rule and eShoreance would predict large recession distances.

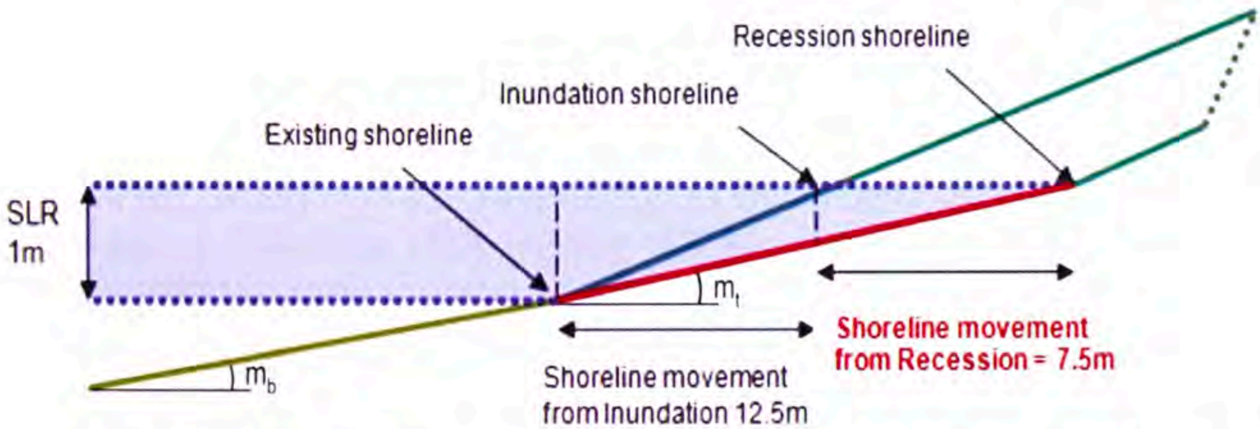


Figure 5–4 Estuarine shoreline response to sea level rise predicted by the eShorance model

Process Based Models

While geometric translation models are concerned only with ultimate morphological response, process-based models include time-dependent forcing and profile response. As discussed within Section 4, process-based models have been used extensively to simulate shoreline change during storm events, i.e. the Convolution Method developed by Kriebel and Dean (1985 and 1993), SBEACH (Larson and Kraus, 1989), and more recently XBeach (Roelvink et al., 2009). While process-based models have the capacity to more accurately simulate changes over time, they require significantly more location-specific information including initial morphology, forcing conditions and sediment characteristics. Even with this information, most process models require site-specific calibration of various coefficients to accurately predict short-term change. Any errors in the assumed coefficients are magnified when the models are used to predict long-term change.

Process-based models are beginning to be used to simulate the long-term effects of sea level rise. Crude approximations of this include simulating a single storm event with sea level elevated to represent some future condition (Irish et al., 2010). However, as profile response is known to significantly lag sea level changes (Hands, 1980 and 1983), such short-term modelling will likely under-predict the ultimate profile response. Other methods include simulating multiple storm events while raising the sea level incrementally between each. However, since this method does not usually incorporate any accretionary component, the profile remains in a permanently eroded state and is physically unrealistic.

Ranasinghe et al. (2011) present a probabilistic semi-process based model (the Probabilistic coastline recession model, PCR model). This model couples simplified erosion and accretion models with temporal forcing conditions (time series of storm waves and water levels) and long-term sea level rise to provide probabilistic estimates of shoreline position at a future date.

Storm time series are derived using a joint probability method (Callaghan et al., 2008). For computational efficiency, a dune erosion model (Larson et al., 2004) is used rather than more complete profile response models (although the authors note that such models could be incorporated). The Larson et al. (2004) model computes the volume of sand eroded from a dune face as a function of wave impact force (approximated by the run-up elevation and wave period) and an empirical coefficient. The resulting changes in the dune toe position are deemed a proxy for shoreline response. The model coefficient has been calibrated by Ranasinghe et al. (2011) using 30 years of field measurements at Narrabeen Beach, NSW and while the resultant value was found to be within the recommendations of Larson et al. (2004), it is noted that the recommended values range over three orders of magnitude, emphasising the model's large dependence on calibration. A linear rate of accretion (dune recovery rate) between storm events is determined using an iterative process where the model is able to maintain an average dune toe position at 2 m above MSL during a 110 year simulation period excluding any sea level change.

The result of the PCR model applied to Narrabeen Beach is a probabilistic estimate of coastal recession relative to the initial position (Figure 5-5). The PCR results are compared to values predicted using the Bruun Rule and three depths of closure (DoC) including the Hallermeier inner (d_{inner}) and outer (d_{outer}) depths and the depth of closure presented by Nicholls et al. (1996) (d_c). Results show the Bruun factor at 2100 (R/S_{2100}) using the inner Hallermeier depth to be predicted at 34, approximately equivalent to the 8% exceedance probability level predicted by the PCR model, and values for the other two DoCs (R/S_{2100} = 68 and 55 respectively) to exceed the 1% PCR level. These results indicate that for this site, shoreline recession estimated by the Bruun Rule remains conservative.

Overall, while this method presents a powerful framework for assessing long-term shoreline response, the simplified erosion and accretion models are highly reliant on calibrated coefficients. Without adequate site-specific data or universally applicable values, significant uncertainties remain in applying the model in other locations. Given that the actual probabilistic exceedance level selected by engineers, planners and managers in determining zones and hazard lines is likely to be relatively low, i.e. of the order of 1% to 10%, the Bruun Rule estimates determined within the study appear in good agreement. Finally, similar to the Bruun Rule, the method is two-dimensional and any net cross-shore or longshore sediment flux would need to be allowed for either within the model framework or externally.

Shoreline Response Model

Huxley (2011) describes a shoreline response model capable of simulating both short- and long-term changes in both the cross shore and longshore directions. The cross shore model is based on a Miller and Dean (2004) beach response model which has been modified to extend seaward of the depth of closure. This model calculates the equilibrium or maximum response profile to a change in wave and/or water level conditions then incorporates an exponentially lagged response to simulate more 'natural' response. Beach accretion is incorporated at a uniform rate. The model was calibrated against observed short-term beach response during storms on the Gold Coast in 1967 and 1988 with good agreement achieved. Response to long-term change is assessed using constant wave forcing and by annually increasing the water level. The long-term horizontal recession was compared to that predicted by the Bruun Rule using a specified closure depth of 15 m with agreement to within 3 m or around 7%. However, the sensitivity of the Bruun Rule to selection of closure depth and the effect of this on 'verification' is not discussed.

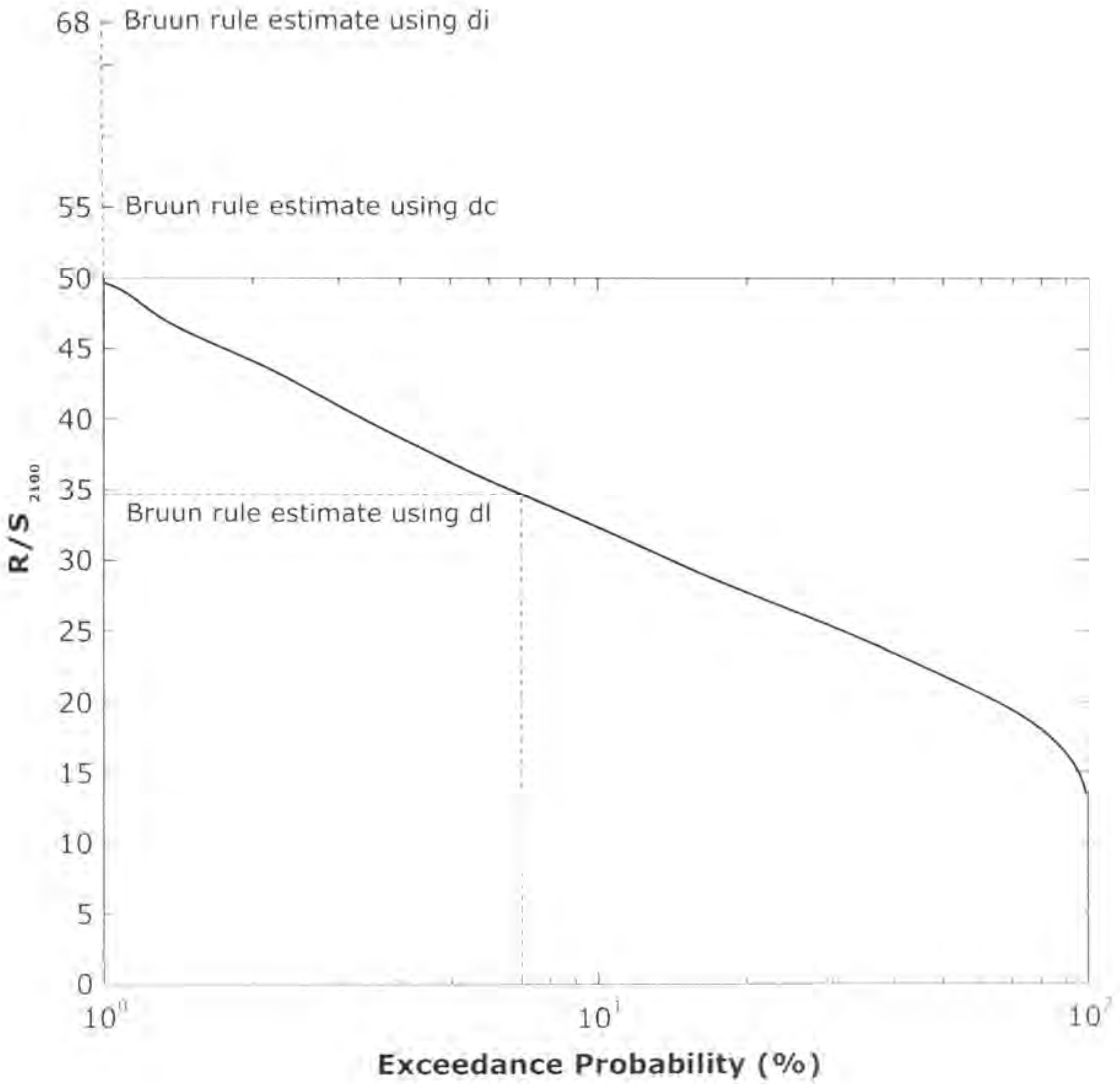


Figure 5–5 Model-predicted probabilistic estimate of coastal recession at Narrabeen Beach at 2100 compared to 1990 with Bruun Rule estimates (adapted from Ranasinghe et al., 2011)

5.2 Adopted Recession Model

Selection of a suitable model for assessing shoreline recession at a particular site is dependent on the understanding of physical processes occurring at that site. Increasing the complexity of a model without adequate understanding of the processes does not improve the accuracy of predictions but can amplify the uncertainty (Cowell et al., 1995). Such understanding of processes requires either generically applicable and robust descriptions of processes (i.e. gravity = 9.81 m/s), or site-specific data for calibration and verification.

Most studies have shown that incorporation of sediment budgets are critical in the long-term prediction of shoreline change and have been found to overwhelm sea level induced changes at sites along the Australian east coast (Cowell et al., 1995). In the absence of such data, time-dependent geometric methods such as the Shoreface Translation Model (Cowell, 1992) reduce back to a basic Bruun Rule-type model. Additionally, without either detailed site-specific profile data to derive erosion and accretion variables or generically applicable and robust values, process methods such as that proposed by Ranasinghe et al. (2011) are impractical and may not offer any improvement in accuracy over basic geometric translation models.

DCC (2009) suggests that in the absence of site-specific information, the Bruun Rule may be used to provide a generalised indication of the amount of recession accompanying sea-level rise. Given the broad-scale scope of the present assessment, the Bruun Rule with judicious selection of closure depth is deemed the most appropriate method and has been adopted within this study. The effects of imbalanced sediment budgets are allowed for separately via a user-controlled variable enabling long-term shoreline retreat or accretion to be incorporated (refer Section 6).

5.3 Closure Depth for Australian Sites

Different methodologies for estimating closure depth were described and reviewed in detail in Section 5.1. In this report, the method for determining closure depth has been based on a combination of Hallermeier (1978, 1981 and 1983) and Birkemeier (1985) inner and outer closure depths and the offshore limit of storm profile response as determined by the beach response modelling described in Section 4. Table 5.1 presents (i) closure depths calculated for each coastal hydraulic zone using Birkemeier (1985), and (ii) inner and outer depths inferred using Hallermeier (1978, 1981 and 1983).

Table 5.2 presents for each beach location assessed, the offshore limit of profile variation in response to the 1 in 100 year ARI storm as determined from XBeach numerical modelling.

Table 5.1 Closure Depths (Hallermeier, 1978, 1987 and 1983 and Birkemeier, 1985)

Zone	State	From	To	Birkemeier	Hallermeier	
				d_b (m)	d_{inner} (m)	d_{outer} (m)
1	QLD	West Qld Border	Cape York	6	8	12
2	QLD	Cape York	Innisfail	5	7	11
3	QLD	Innisfail	Airlie Beach	5	7	11
4	QLD	Airlie Beach	Gladstone	5	7	11
5	QLD	Gladstone	Harvey Bay	5	7	11
6	QLD	Harvey Bay	South Qld Border	8	10	15
7	NSW	North NSW Border	Coffs Harbour	8	10	15
8	NSW	Coffs Harbour	South NSW Border	9	12	18
9	VIC	East VIC Border	Wilsons Promontory	8	10	15
10	VIC	Wilsons Promontory	Port Phillip Bay	8	10	15
11	VIC	Port Phillip Bay	Port Phillip Bay	3	4	6
12	VIC	Port Phillip Bay	Cape Otway	8	10	15
13	VIC	Cape Otway	West VIC Border	11	14	21
14	TAS	NW Tasmania	NE Tasmania	8	10	15
15	TAS	NE Tasmania	SE Tasmania	9	12	18
16	TAS	NW Tasmania	SE Tasmania	13	17	26
17	SA	East SA Border	York Peninsula	11	14	21
18	SA	Gulf St Vincent	Spencer Gulf	3	4	6
19	SA	Port Lincoln	West SA Border	9	12	18
20	WA	East WA Border	Cape Arid	9	12	18
21	WA	Cape Arid	Albany	11	14	21
22	WA	Albany	Cape Naturaliste	12	15	23
23	WA	Cape Naturaliste	Jurien Bay	11	14	21
24	WA	Jurien Bay	Carnarvon	9	12	18
25	WA	Carnarvon	Exmouth	9	12	18
26	WA	Exmouth	Port Hedland	8	10	15
27	WA	Port Hedland	Dampier Peninsula	8	10	15
28	WA	Dampier Peninsula	East WA Border	8	10	15
29	NT	West NT Border	Melville Bay	8	10	15
30	NT	Melville Bay	East NT Border	6	8	12

Note: depths should be considered from Mean Low Water Springs.

Table 5.2 Offshore Limit of Storm Profile Response for 100 year ARI event from Xbeach modelling

Zone	Regional Coast(5)	Beach Type	Offshore Limit (m AHD)
1	Weipa–Cape York Coast	4	-4
		9	-4
2	Cairns Coast	8	-4
		9	-4
3	Townsville Coast	10	-2
		12	n/a
4	Mackay Coast	10	-3
		12	n/a
5	Gladstone Coast	10	n/a
		12	n/a
6(1)	Fraser-Gold Coast	2	-13
		3	-12
		4	-12
7(1)(2)	Coffs Harbour-Tweed Coast	2	-13
		3	-12
		4a	-12
		4b	-12
8	Coffs Harbour-Cape Howe Coast	2	-12
		3	-18
		4	-10
		5	-11
		6	-8
9	East Gippsland Coast	2	-7
		3	-15
10	South Gippsland–Mornington Pen Coast	2	-12
		3	-15
11	Port Phillip Bay Coast	6	-2
12	Lonsdale to Lorne Coast	2	-13
		4	-7
		9	-6
13	Port Campbell-Portland Coast	1	-17
		3	-16
		4	-15
14	North Tasmania Coast	5	-3
		9	-8
15	East Tasmania Coast	3	-18
		4	-10
		5	-12
		6	-8

Zone	Regional Coast(5)	Beach Type	Offshore Limit (m AHD)
15A	Storm Bay	4	-2
		7	-5
16	West–South Tasmania Coast	1	-4
		2	-19
17	Kingston-Goolwa Coast	1	-4
		2	-4
18	Gulf St Vincent-Spencer Gulf Coast	7	-5
19	Port Lincoln–Eucla Coast	1	-4
		3	-19
20	Eucla–Cape Pasley Coast	2	-13
		3	-19
21(3)	Esperance Coast	1	-4
		3	-19
		4	-11
22	Albany–Cape Naturaliste Coast	1	-4
		3	-19
23(3) (4)	Cape Naturaliste-Geraldton	4a	-12
		4b	-7
		5a	-14
		5b	-13
24	Geraldton-Carnarvon Coast	2	-13
		3	-19
25	Cape Cuvier to North West Cape Coast	3	-19
26	Exmouth to Dampier Coast	2	-9
		13	n/a
27	Port Headland to Broome Coast	12	n/a
28	Kimberley Coast	13	n/a
29	Darwin-Arnhem Land Coast	7	-13
		10	n/a
		12	n/a
30	East Arnhem Land-Weipa Coast	4	-4
		7	-2
		12	n/a

Notes on Table 5.2:

(1) For Zones 6 and 7, identical synthetic design storms were used.

(2) Zone 7 model predictions for Types 4a and 4b were calculated using the Kingscliff and Byron Bay representative profile respectively.

(3) Wave dissipation processes over reef and the presence of hard rock substrates on the beach are not considered; estimate or erosion volumes will be conservative at sites where such features are present.

(4) In Zone 23, model predictions for Types 4a and 4b were calculated using Mandurah and North Fremantle profiles. Types 5a and 5b were calculated using Brighton Beach and Port Denison profiles.
(5) For tide dominated beaches (Types 10 to 15) wave processes are less relevant to beach erosion than tide processes; at these sites, model predictions were not considered reliable and storm erosion modelling not applicable (n/a).

5.4 SLR Scenarios

As discussed within Section 3.4.4, ACE-CRC has selected three sea level rise scenarios within their Sea Level Calculator. These include the B1 (low), A1B (moderate) and A1F1 (high) scenarios. The adopted 5% and 95% sea level increases at 2050 and 2100 are reproduced in Table 5.3. Overall, 95% increase scenarios range from 0.23 to 0.28 m at 2050 and 0.50 to 0.81 m at 2100.

Table 5.3 Sea-level Rise Scenarios Adopted within the ACE-CRC Sea Level Calculator Tool (source: Hunter, 2009)

Scenario	Impact	Increase at 2050[1] (m)		Increase at 2100[1] (m)	
		5% Minima	95% Maxima	5% Minima	95% Maxima
B1	Low	0.105	0.227	0.198	0.496
A1B	Moderate	0.102	0.266	0.208	0.649
A1FI	High	0.096	0.278	0.266	0.819

1 Compared to 1990 levels.

5.5 Active Slope or Bruun Factor for Australian Sites

Active slope or "Bruun factors" were calculated as:

$$B_f = \frac{L_c}{B + d_c} \qquad (5\text{-}9)$$

Where:

- d_c is the closure depth or maximum depth of sediment exchange;
- L_c is the horizontal distance from the shoreline to the offshore position of d_c; and
- B the height of the berm/dune crest within the eroded backshore.

Depths of closure and offshore positions were derived for each profile considering (i) the XBeach model outputs with regards to the offshore limit of profile response to the 100 year ARI storm erosion, and (ii) closure depths calculated using the Hallermeier and Birkemeier methods as described above.

Table 5.4 presents Bruun factors (active slopes) for each beach type considered, however, these should be treated with extreme caution because in many cases "proxy" rather than real profiles were used. For generic setbacks, a column of suggested Bruun factors is also shown in Table 5.4, based on the initial indicated value, knowledge of more detailed studies, state policy and practice, and engineering judgement. A full summary of depths of closure, offshore positions and Bruun factors derived by all methods for each profile is presented in Appendix E.

It is important to note that on low energy coasts and tide dominated beaches (Types 10 to 15), the Bruun Rule is not strictly applicable and Bruun factors calculated using depths of closure derived from model outputs would result in high factors (>100). These beaches are typically characterised by a wide, flat intertidal zone and a steeper beachface. For these beaches, Bruun factors are derived considering the active slope of the upper beach and dune area as recommended in DERM (2012b).

Table 5.4 Bruun Factors Estimated from XBeach Model Outputs

*** (This information does not replace a detailed, site specific coastal engineering assessment and is to be used for rapid assessment only.)**

State	Zone	Regional Coast	Beach Type From Table 4.3	R=Real P=Proxy	Indicated Active Slope or Bruun Factor	(1)(3)Suggested Bruun Factor
QLD	1	Weipa–Cape York Coast	4	P	20	100
			9	P	20	
	2	Cairns Coast	8	R	15	100
			9	R	15	
	3	Townsville Coast	10	P	n/a	100
			12	P	n/a	
	4	Mackay Coast	10	R	n/a	100
			12	R	n/a	
	5	Gladstone Coast (excl. Agnes Water)	10	R	n/a	100
			12	R	n/a	
	6	Fraser-Gold Coast	2	R	30	50
			3	R	60	
			4	P	45	
NSW	7	Coffs Harbour-Tweed Coast	2	P	30	50
			3	P	60	
			4a	R	45	
			4b	R	40	
	8	Coffs Harbour-Cape Howe Coast	2	P	30	50
			3	R	50	
			4	R	40	
			5	R	35	
			6	R	30	
VIC	9	East Gippsland Coast	2	R	35	50
			3	P	30	
	10	South Gippsland–Mornington Pen Coast	2	R	25	50
			3	P	30	
	11	Port Phillip Bay Coast	6	R	60	100
	12	Lonsdale to Lorne Coast	2	P	30	50
			4	P	40	
			9	R	20	
	13	Port Campbell-Portland Coast	1	R	20	50
			3	R	40	
			4	R	50	

State	Zone	Regional Coast	Beach Type R=Real P=Proxy		Indicated Active Slope or Bruun Factor	(1)(3)Suggested Bruun Factor
TAS	14	North Tasmania Coast	5	R	50	50
			9	P	20	
	15	East Tasmania Coast	3	P	30	50
			4-5	P	40	
			6	P	40	
	15A	Storm Bay	4	P	20	50
			7	R	40	
	16	West–South Tasmania Coast	1	P	20	50
			2	P	40	
SA	17	Kingston-Goolwa Coast	1	P	20	50
			2	R	40	
	18	Gulf St Vincent-Spencer Gulf Coast	7	R	80	100
	19	Port Lincoln–Eucla Coast	1	P	20	50
			3	P	30	
WA(2)	20	Eucla–Cape Pasley Coast	2	P	30	100
			3	P	40	
	21	Esperance Coast	1	P	20	
			3	P	30	
			4	R	60	
	22	Albany–Cape Naturaliste Coast	1	P	20	
			3	P	40	
	23	Cape Naturaliste-Geraldton	4	R	60	
			5	R	70	
	24	Geraldton-Carnarvon Coast	2	P	30	
			3	P	40	
	25	Cape Cuvier to North West Cape Coast	3	P	40	
	26	Exmouth to Dampier Coast	2	R	100	
			13	P	n/a	
	27	Port Headland to Broome Coast	12	P	n/a	
	28	Kimberley Coast	13	P	n/a	
NT	29	Darwin-Arnhem Land Coast	7	R	80	100
			10	R	45	
			12	R	50	
	30	East Arnhem Land-Weipa Coast	4	P	30	100
			7	P	20	
			12	P	20	

Notes:

(1) Values are conservative.

(2) WA State policy requires the use of a Bruun factor of 100.

(3) For beaches characterised by low wide shoreface gradients within low wave climate regions, Bruun factors are not strictly applicable (n/a) and site specific studies are necessary.

5.6 Suggested Bruun Factors for Coastal Setbacks

Without site specific analyses, which should extend to consideration of sediment boundaries, WRL recommends that the following Bruun factors (shown in Table 5.4) be used for generic assessment of setbacks:

- For a conservative assessment, a Bruun factor of 100 is recommended.
- For WA, a Bruun factor of 100 is required under state policy.
- For the open coasts of QLD (south of Fraser Island), NSW, VIC, TAS and SA, the Bruun factor may be reduced to 50 as an initial "best estimate".
- For the other coasts of Australia, a Bruun factor of 100 should be used for generic assessment.

6. Generic Setback Distances

6.1 Setback Components

6.1.1 List of Setback Components

As described in Table 2.3 of Section 2, five key components for coastal setback are typically defined and incorporated into the hazard line, namely:

- S1: Allowance for short term storm erosion (storm demand);
- S2: Allowance for ongoing underlying recession;
- S3: Allowance for recession due to future sea level rise;
- S4: Allowance for beach rotation; and
- S5: Allowance for dune stability (Zone of Reduced Foundation Capacity - ZRFC as defined by Nielsen et al. 1992).

Figure 6-1 diagrammatically presents the position of immediate and future coastal hazard lines. The landward limit of the coastal hazard zone corresponds to the estimated position of the backshore erosion scarp for the particular planning period. The immediate hazard line position is obtained by considering the erosion hazard due to storm demand and allowing for slope instability. The future hazard line (for future planning horizons) is estimated by adding the underlying shoreline recession and sea level rise induced shoreline recession.

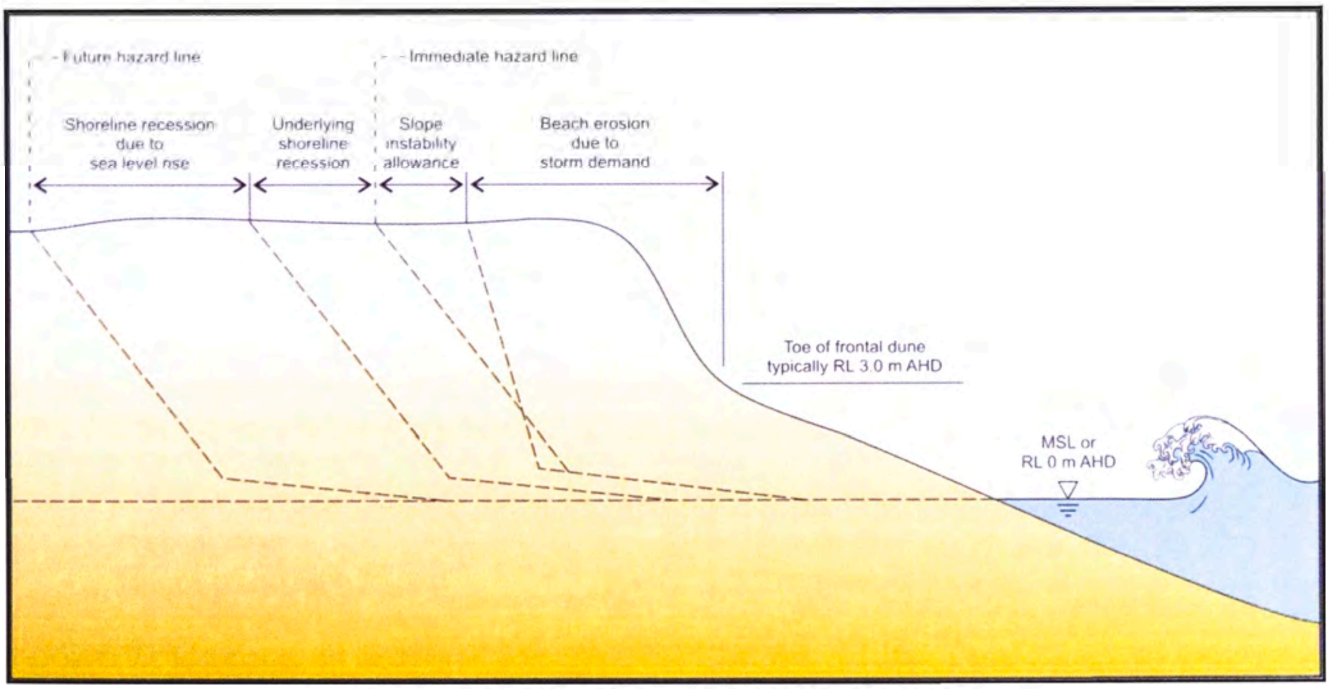


Figure 6-1 Estimation of Coastal Hazard Lines

6.1.2 Brief Description of Setback Components

S1: *Allowance for short term storm erosion*, is for erosion due to an oceanic storm or series of storms. It is generally expressed in m^3/m above Australian Height Datum (AHD).

S2: *Allowance for ongoing underlying recession*, is a long term trend in the beach planform, which may be receding or accreting. High values of this component over long durations (decades to a centuries) can exceed all other setback components. Detailed site specific studies are needed to estimate this component. It is generally estimated from photogrammetric survey data extending over approximately 50 years and expressed in terms of m/year. It is zero for many beaches, however, examples where it is not zero include:

- Blacks Beach, Mackay QLD: up to 1.8 m/year (QLD EPA, 2005);
- Woody Head NSW: 0.9 to 3 m/year, with 2 m/year adopted for planning (Moratti and Lord, 2000);
- Cullendulla Beach, Batemans Bay NSW: up to 0.8 m/year (Coghlan et al., 2012);
- Somers VIC: up to 2.5 m/year (Bird, 1993), up to 1.5 m/year (Kotvojs and Byrne, 1995);
- Dutton Way, Portland VIC: 1.0 to 4.2 m/year (AECOM, 2010);
- Roches Beach, Hobart TAS: up to 0.2 m/year (Sharples, 2007, Shand et al, 2011);
- Tingira Place, Semaphore Park SA: 1.4 m/year (Fotheringham, 1989); and
- Norman Road, Busselton area, WA: up to 8 m/year downdrift of a groyne (Shore Coastal, 2010).

S3: *Allowance for recession due to future sea level rise*, is a projection of future shoreline recession due to a rise in mean sea level. It is usually calculated with the Bruun Rule (Bruun, 1962 and 1988). On open coasts, the Bruun factor "rule of thumb" is typically in the range of 50 to 100. That is, coastal recession will be 50 to 100 times the sea level rise. Specific calculations taking account of the measured profile, wave climate and sand characteristics are preferred. There is considerable controversy regarding the Bruun Rule, however, there are few alternatives, which can provide an immediate answer. Obviously, long term monitoring is preferable, but is not feasible if an answer is required in the short term.

S4: *Allowance for beach rotation*, involves either a cyclic or one way change in the alignment of a beach's planform due to changes in the wave direction over medium (weeks to months) to long (decades) term time scales.

S5: *Allowance for dune stability*, encompasses an additional setback component relating to the geotechnical stability of dunes as described in Nielsen *et al.* (1992). This method delineates a *Stable Foundation Zone* and a *Zone of Reduced Foundation Capacity.* In this method, buildings constructed seaward of the *Stable Foundation Zone* (SFZ) need to be constructed on piles due to the reduced bearing capacity in the *Zone of Reduced Foundation Capacity* (ZRFC).

The total design setback (S) for present and future planning horizons typically comprises:

- Present day: S = S1 + S5; and
- Future planning horizon: S = S1 + S2 + S3 + S4 + S5.

For specific locations, an additional allowance incorporating a factor of safety can be included to the total setback.

6.2 Generic Setback Distances

Allowances for (i) short term storm erosion (S1), (ii) recession due to SLR (S3) and (iii) dune stability (S5) are summarised for each beach type and location in Table 6.1. Allowances for ongoing underlying recession due to sediment imbalance (S2) and for rotation/medium term fluctuations (S4) were not considered in this study as these need to be considered specifically at each site of interest.

Setback distances are provided for a range of average ground levels (GL) at the back of the beach. Allowances for recession due to SLR (S3) are calculated for sea level rise projections of 0.4 m and 0.9 m and are based on the application of the Bruun Rule. The suggested values for storm demand (V_{SD}) and Bruun factors (BF) were presented in Tables 4.5 and 5.4, respectively. S1 was obtained as the ratio of suggested storm demand and average ground level at the back of the beach. S5 was calculated applying the methodology by Nielsen et al. (1992).

Table 6.1 Summary of Generic Coastal Setback Components (Excluding S2 and S4)

State	Zone	Regional Coast	Beach Type	[1]Suggested V_{SD} (m^3/m)	S1 (m)			[1]Suggested BF (-)	S3 (m)		S5 (m)		
					GL (m AHD)	GL (m AHD)	GL (m AHD)		SLR (m)		GL (m AHD)	GL (m AHD)	GL (m AHD)
					4.0	***6.0***	***10.0***		***0.4***	***0.9***	***4.0***	***6.0***	***10.0***
[2]QLD	1	Weipa–Cape York Coast	4	80	20	13	8	100	40	90	11	13	19
			9	80	20	13	8	100	40	90	11	13	19
	2	Cairns Coast	8	80	20	13	8	100	40	90	11	13	19
			9	80	20	13	8	100	40	90	11	13	19
	3	Townsville Coast	10	80	20	13	8	100	40	90	11	13	19
			12	80	20	13	8	100	40	90	11	13	19
	4	Mackay Coast	10	80	20	13	8	100	40	90	11	13	19
			12	80	20	13	8	100	40	90	11	13	19
	5	Gladstone Coast	10	50	13	8	5	100	40	90	11	13	19
			12	50	13	8	5	100	40	90	11	13	19
	6	Fraser-Gold Coast	2	200	50	33	20	50	20	45	11	13	19
			3	200	50	33	20	50	20	45	11	13	19
			4	200	50	33	20	50	20	45	11	13	19

State	Zone	Regional Coast	Beach Type	[1]Suggested V_{SD} (m^3/m)	S1 (m) GL (m AHD)	S1 (m) GL (m AHD)	S1 (m) GL (m AHD)	[1]Suggested BF (-)	S3 (m) SLR (m)	S3 (m) SLR (m)	S5 (m) GL (m AHD)	S5 (m) GL (m AHD)	S5 (m) GL (m AHD)
					4.0	***6.0***	***10.0***		***0.4***	***0.9***	***4.0***	***6.0***	***10.0***
NSW	7	Coffs Harbour-Tweed Coast	2	200	50	33	20	50	20	45	11	13	19
			3	200	50	33	20	50	20	45	11	13	19
			4	200	50	33	20	50	20	45	11	13	19
	8	Coffs Harbour-Cape Howe Coast	2	200	50	33	20	50	20	45	11	13	19
			3	200	50	33	20	50	20	45	11	13	19
			4	200	50	33	20	50	20	45	11	13	19
			5	200	50	33	20	50	20	45	11	13	19
			6	200	50	33	20	50	20	45	11	13	19
VIC	9	East Gippsland Coast	2	200	50	33	20	50	20	45	11	13	19
			3	200	50	33	20	50	20	45	11	13	19
	10	South Gippsland–Mornington Pen Coast	2	200	50	33	20	50	20	45	11	13	19
			3	200	50	33	20	50	20	45	11	13	19
	11	Port Phillip Bay Coast	6	20	5	3	2	100	40	90	11	13	19
	12	Lonsdale to Lorne Coast	2	150	38	25	15	50	20	45	11	13	19
			4	150	38	25	15	50	20	45	11	13	19
			9	150	38	25	15	50	20	45	11	13	19
	13	Port Campbell-Portland Coast	1	200	50	33	20	50	20	45	11	13	19
			3	200	50	33	20	50	20	45	11	13	19
			4	200	50	33	20	50	20	45	11	13	19

State	Zone	Regional Coast	Beach Type	(1)Suggested V_{SD} (m^3/m)	S1 (m) GL (m AHD) 4.0	S1 (m) GL (m AHD) 6.0	S1 (m) GL (m AHD) 10.0	(1)Suggested BF (-)	S3 (m) SLR (m) 0.4	S3 (m) SLR (m) 0.9	S5 (m) GL (m AHD) 4.0	S5 (m) GL (m AHD) 6.0	S5 (m) GL (m AHD) 10.0
TAS	14	North Tasmania Coast	5	100	25	17	10	50	20	45	11	13	19
			9	100	25	17	10	50	20	45	11	13	19
	15	East Tasmania Coast	3	150	38	25	15	50	20	45	11	13	19
			4	150	38	25	15	50	20	45	11	13	19
			5	150	38	25	15	50	20	45	11	13	19
			6	150	38	25	15	50	20	45	11	13	19
	15 A	Storm Bay	4	100	25	17	10	50	20	45	11	13	19
			7	100	25	17	10	50	20	45	11	13	19
	16	West-South Tasmania Coast	1	250	63	42	25	50	20	45	11	13	19
			2	250	63	42	25	50	20	45	11	13	19
SA	17	Kingston-Goolwa Coast	1	200	50	33	20	50	20	45	11	13	19
			2	200	50	33	20	50	20	45	11	13	19
	18	Gulf St Vincent-Spencer Gulf Coast	7	50	13	8	5	100	40	90	11	13	19
	19	Port Lincoln-Eucla Coast	1	250	63	42	25	50	20	45	11	13	19
			3	250	63	42	25	50	20	45	11	13	19

State	Zone	Regional Coast	Beach Type	(1)Suggested V_{SD} (m^3/m)	S1 (m)			(1)Suggested BF (-)	S3 (m)		S5 (m)		
					GL (m AHD)	GL (m AHD)	GL (m AHD)		SLR (m)		GL (m AHD)	GL (m AHD)	GL (m AHD)
					4.0	***6.0***	***10.0***		***0.4***	***0.9***	***4.0***	***6.0***	***10.0***
(3)WA	20	Eucla–Cape Pasley Coast	2	250	63	42	25	100	40	90	11	13	19
			3	250	63	42	25	100	40	90	11	13	19
	21	Esperance Coast	1	250	63	42	25	100	40	90	11	13	19
			3	250	63	42	25	100	40	90	11	13	19
			4	250	63	42	25	100	40	90	11	13	19
	22	Albany–Cape Naturaliste Coast	1	250	63	42	25	100	40	90	11	13	19
			3	250	63	42	25	100	40	90	11	13	19
	23	Cape Naturaliste-Geraldton	4	150	38	25	15	100	40	90	11	13	19
			5	150	38	25	15	100	40	90	11	13	19
	24	Geraldton-Carnarvon Coast	2	150	38	25	15	100	40	90	11	13	19
			3	150	38	25	15	100	40	90	11	13	19
	25	Cape Cuvier to North West Cape Coast	3	150	38	25	15	100	40	90	11	13	19
	26	Exmouth to Dampier Coast	2	80	20	13	8	100	40	90	11	13	19
			13	80	20	13	8	100	40	90	11	13	19
	27	Port Headland to Broome Coast	12	80	20	13	8	100	40	90	11	13	19
	28	Kimberley Coast	13	80	20	13	8	100	40	90	11	13	19

State	Zone	Regional Coast	Beach Type	[1]Suggested V_{SD} (m^3/m)	S1 (m)			[1]Suggested BF (-)	S3 (m)		S5 (m)		
					GL (m AHD)	GL (m AHD)	GL (m AHD)		SLR (m)		GL (m AHD)	GL (m AHD)	GL (m AHD)
					4.0	***6.0***	***10.0***		***0.4***	***0.9***	***4.0***	***6.0***	***10.0***
NT	29	Darwin-Arnhem Land Coast	7	80	20	13	8	100	40	90	11	13	19
			10	80	20	13	8	100	40	90	11	13	19
			12	80	20	13	8	100	40	90	11	13	19
	30	East Arnhem Land-Weipa Coast	4	80	20	13	8	100	40	90	11	13	19
			7	80	20	13	8	100	40	90	11	13	19
			12	80	20	13	8	100	40	90	11	13	19

Notes:

(1) Values to be used for initial rapid assessment only.

(2) Based on QLD State Policy (see Section 2) S1+S5 ≥ 40 m.

If site specific modelling is not undertaken, based on WA State Policy (see Section 2), S1 = 40 m and BF = 100

7. Summary

While terminology and the requirement for consideration (or not) varies between jurisdictions, the components for coastal setbacks on sandy shorelines can be defined as:

- S1: Allowance for short term storm erosion (storm demand);
- S2: Allowance for ongoing underlying recession;
- S3: Allowance for recession due to future sea level rise;
- S4: Allowance for beach rotation;
- S5: Allowance for dune stability (Zone of Reduced Foundation Capacity - ZRFC as defined by Nielsen et al. 1992); and
- FS: A factor of safety, which may apply to none, one, more than one, or all of the above components.

This report assessed the components S1, S3 and S5 at a regional level for 30 hydraulic zones around the coast of Australia, presented a range of values for the S2 component, and described the current limited state of knowledge for the S4 component. The following tasks were undertaken:

- Review of policy and practice in Australian jurisdictions;
- Development of synthetic design storms (waves and water levels) for 30 hydraulic zones around the coast of Australia;
- Acquisition of beach profile data;
- Review of methods for estimating recession due to sea level rise (S3 component);
- Setup and run the Xbeach and SBEACH numerical models, in combination with the Bruun Rule, to assist with developing values for S1 and S3 for a range of profiles in 30 hydraulic zones around the coast of Australia; and
- Incorporating the above tasks with engineering judgement and state policies to derive generic values of the components S1, S3 and S5 at a regional level for the 30 hydraulic zones.

The usefulness of the numerical models was constrained by the limited availability of beach profile and sand grain size data. Apart from a small number of sites, before and after profiles for storm events, which would be needed for calibration and verification of the numerical models, were unavailable. The numerical models were applied in an uncalibrated state, but their outputs were interpreted with regard to known detailed studies, state policies and judgement.

Suggested generic regional coastal setbacks were presented in Section 6. They are useful for first pass vulnerability assessments, but detailed site specific studies should be undertaken before any decision is made regarding the development of a site or area.

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Appendix A Beach Profiles

Table A.1 summarises the available beach profiles with median sediment size D_{50}. Data was made available by a number of sources which are acknowledged and listed below:

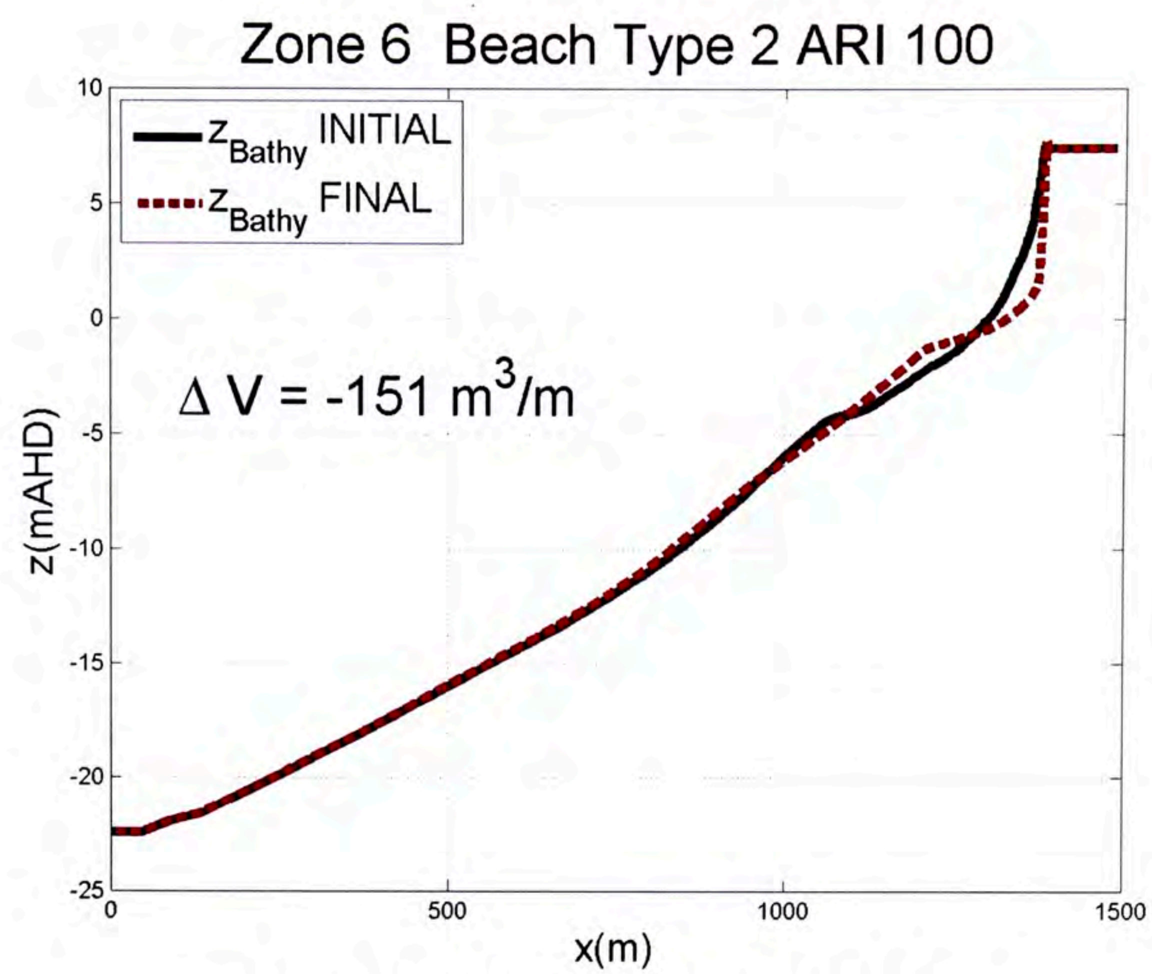
- Department of Transport WA;
- Department of Environment and Resource Management QLD;
- Coastal Observation Program (COPE) QLD;
- Department of Environment and Natural Resources SA;
- Tasmanian Shoreline Monitoring and Archiving (TASMARC) project, TAS;
- Office of Environment and Heritage NSW;
- Andy Short (personal communication);
- WRL of University of New South Wales;
- Northern Territory Government; and
- Department of Sustainability and Environment VIC.

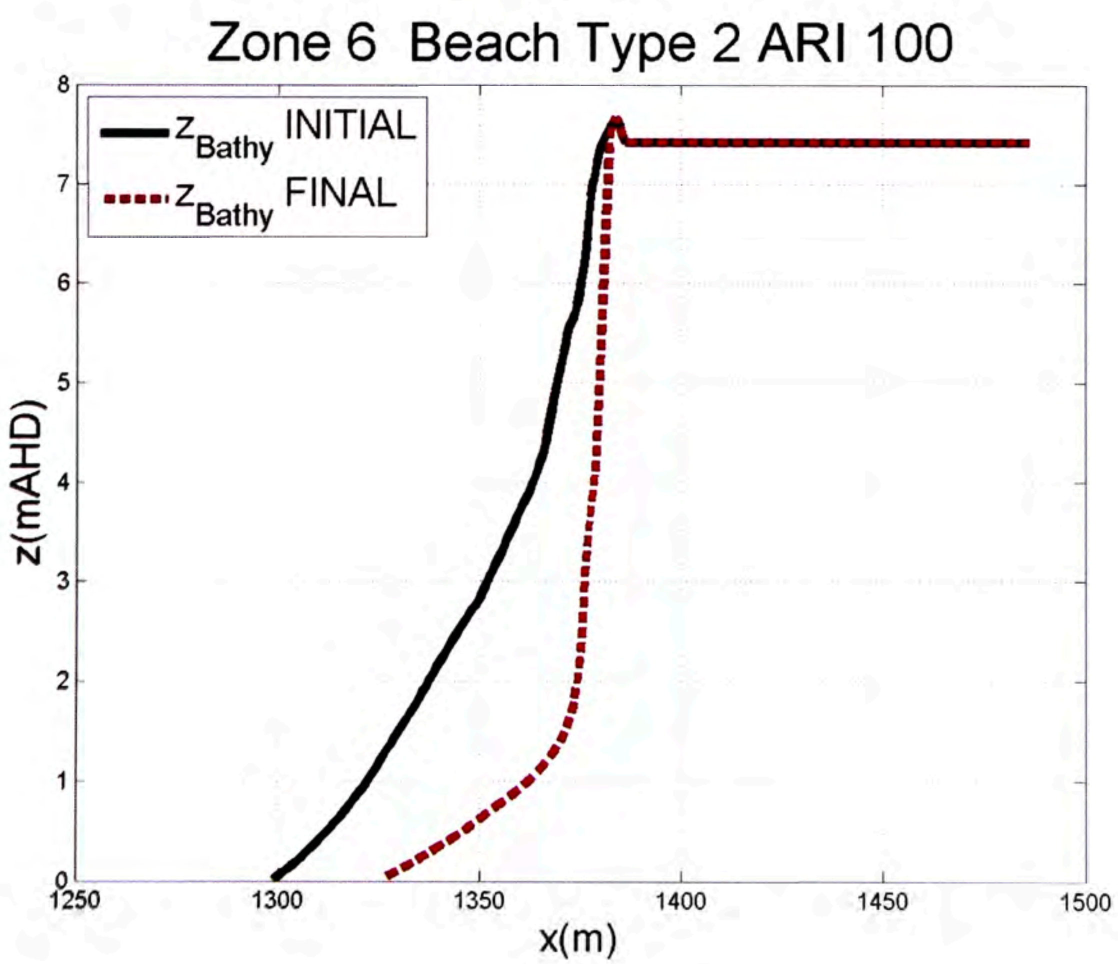
Table A.1: Available Beach Profiles

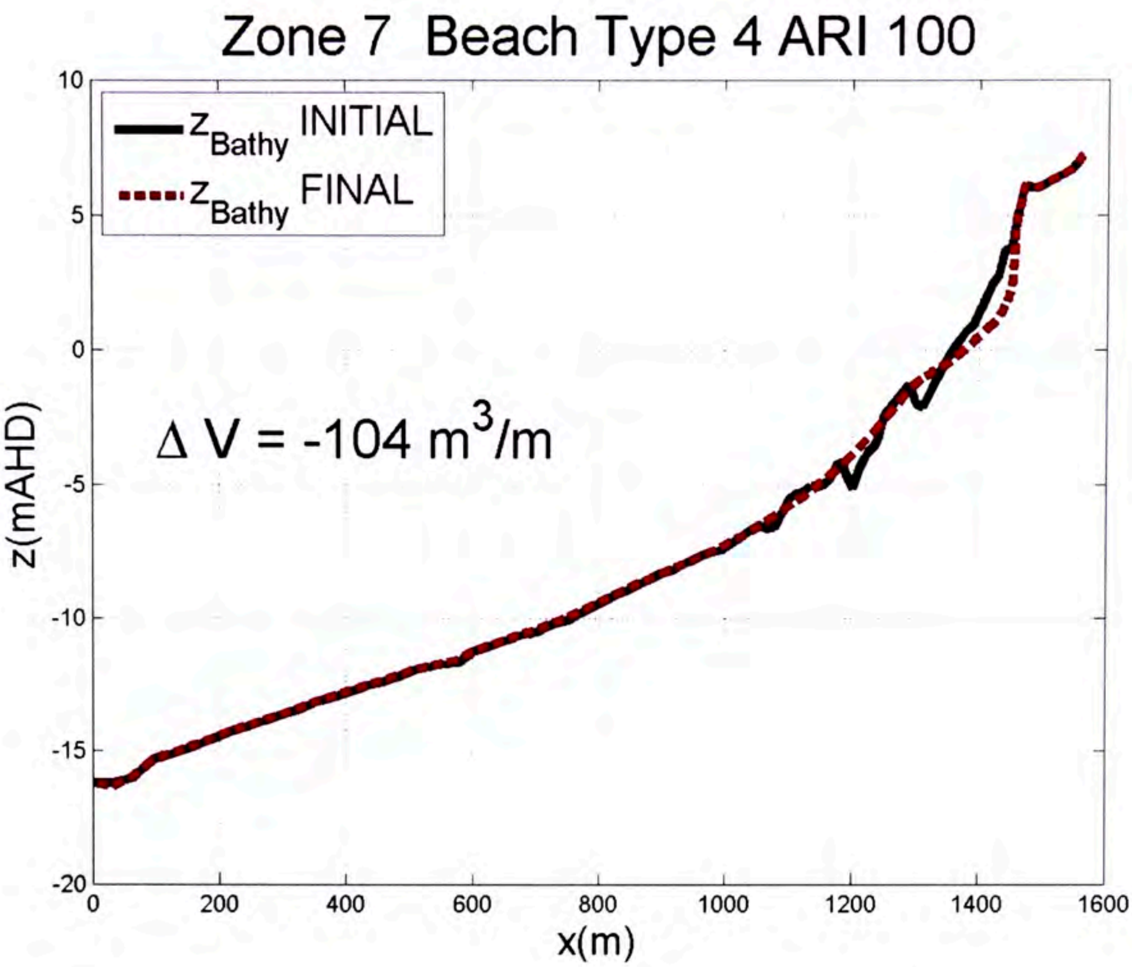
State	Site	D_{50} (mm)
NSW	Narrabeen	0.35
NSW	Wamberal #2 -Terrigal	0.30
NSW	Wamberal #5 -Terrigal	0.30
NSW	Kingscliff, NSW	0.25
NSW	Byron Bay, NSW	0.21
NSW	Stockton, NSW	0.30
NT	Darwin Mindil	0.13
NT	Darwin Casuarina	unrepor.
NT	Darwin Vesteys	0.18
QLD	Gold Coast, Narrowneck	0.22
QLD	Kirra	0.22
QLD	Hervey Bay #104	0.12
QLD	Cairns MU8	0.10
QLD	Cairns MU11	0.10
QLD	Mackay (MAC 155)	0.70
QLD	Mackay (MAC 104)	0.70
SA	Adelaide, Gulf (Semaphore)	0.25
SA	Goolwa	0.15
SA	Wilkinson Avenue, Adelaide	0.25
SA	Beach Road, Goolwa	0.15
TAS	Adam's Beach - Bridport	0.18
TAS	Roches Beach, Tasmania	0.25
VIC	Discovery Bay	0.27
VIC	Port Fairy	0.13
VIC	Lorne	0.21
VIC	Port Phillip Bay (St Kilda)	0.50
VIC	Gunnamatta Beach	0.25
VIC	90 miles beach, Seaspray	0.30
WA	Esperance	0.13
WA	Brighton Beach	0.35
WA	Mandurah, WA	0.25
WA	North Fremantle	0.50
WA	Point Samson	0.13
WA	Port Denision	0.13

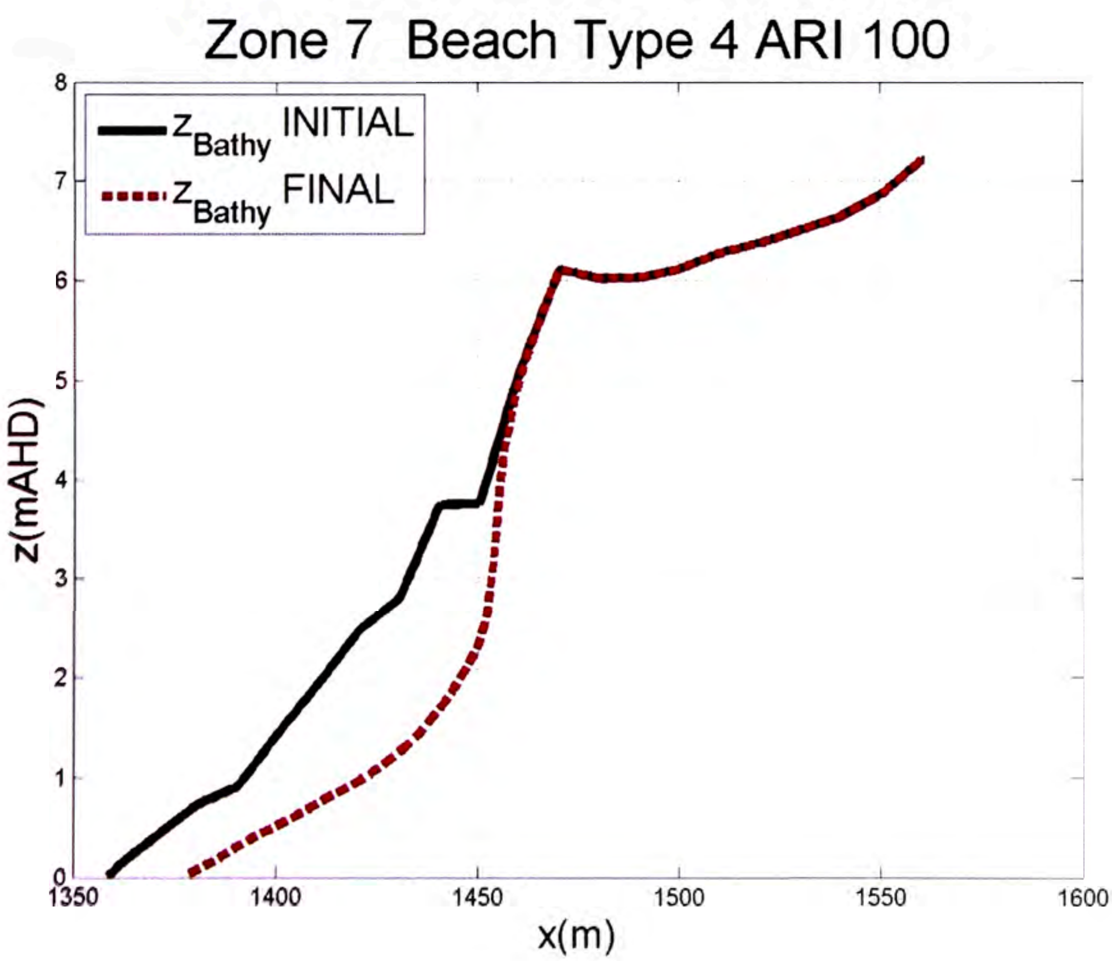
Note: Sediment data sourced from the Surf Life Saving Australia database

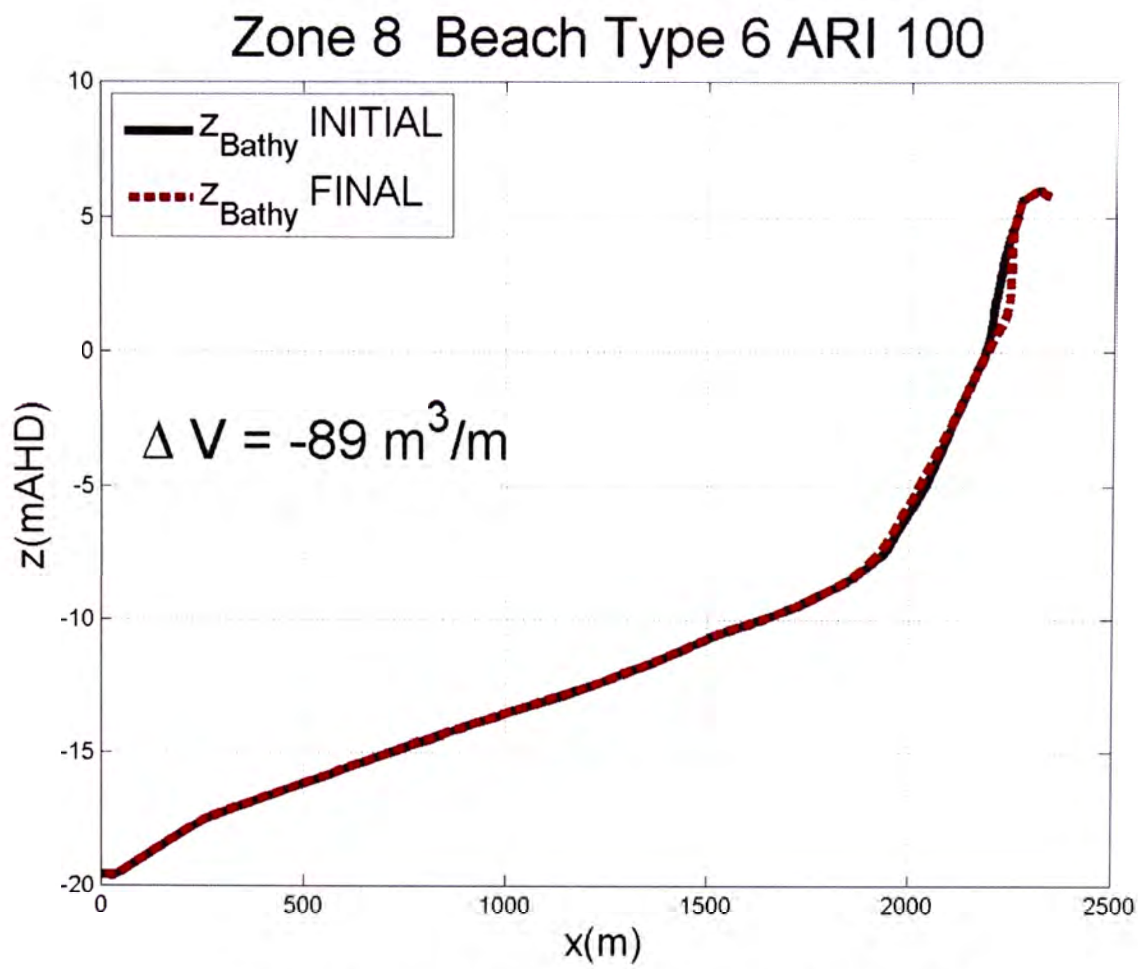
The following figures present example plots of pre and post storm profiles for the 1 in 100 year ARI design event as predicted by XBeach numerical.

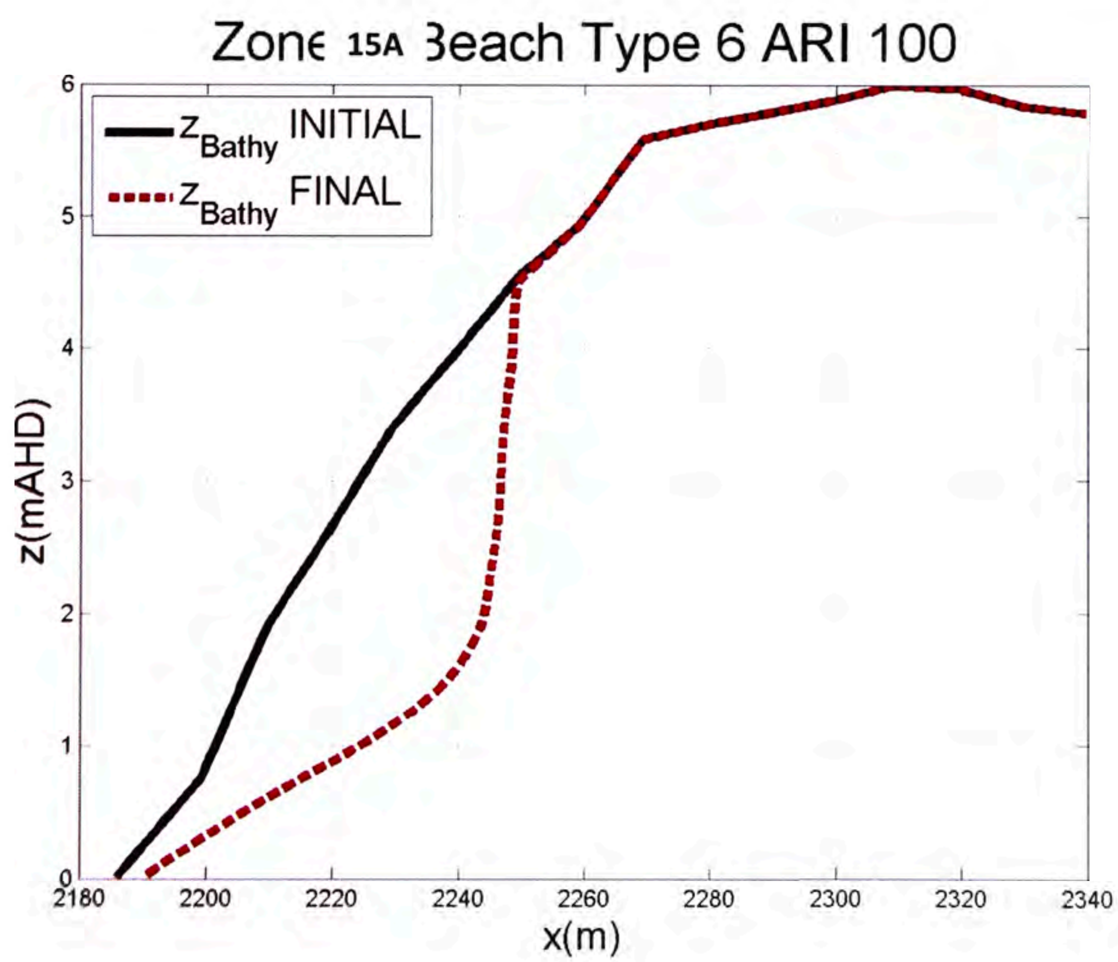

Zone 6 Beach Type 2 ARI 100
z_{Bathy} INITIAL
z_{Bathy} FINAL
ΔV = -151 m^3/m
z(mAHD)
x(m)
10
5
0
-5
-10
-15
-20
-25
0
500
1000
1500


Zone 6 Beach Type 2 ARI 100
z_{Bathy} INITIAL
z_{Bathy} FINAL
z(mAHD)
x(m)
8
7
6
5
4
3
2
1
0
1250
1300
1350
1400
1450
1500


Zone 7 Beach Type 4 ARI 100
z_{Bathy} INITIAL
z_{Bathy} FINAL
$\Delta V = -104\ m^3/m$
z(mAHD)
x(m)
10
5
0
-5
-10
-15
-20
0
200
400
600
800
1000
1200
1400
1600


Zone 7 Beach Type 4 ARI 100
z_{Bathy} INITIAL
z_{Bathy} FINAL
z(mAHD)
x(m)
8
7
6
5
4
3
2
1
0
1350
1400
1450
1500
1550
1600


Zone 8 Beach Type 6 ARI 100
z_Bathy INITIAL
z_Bathy FINAL
Δ V = -89 m³/m
z(mAHD)
x(m)
10
5
0
-5
-10
-15
-20
0
500
1000
1500
2000
2500


Zone 15A Beach Type 6 ARI 100
z_Bathy INITIAL
z_Bathy FINAL
z(mAHD)
x(m)
6
5
4
3
2
1
0
2180
2200
2220
2240
2260
2280
2300
2320
2340

Appendix B Adopted Synthetic Storms

For each coastal hydraulic zone, Table B.1 presents peak significant wave height H_s, peak spectral wave period T_p and duration of the adopted 1 in 1, 10 and 100 year ARI synthetic design storms. Table B.2 summarises adopted extreme water levels incorporating astronomical tide, barometric setup and wind setup.

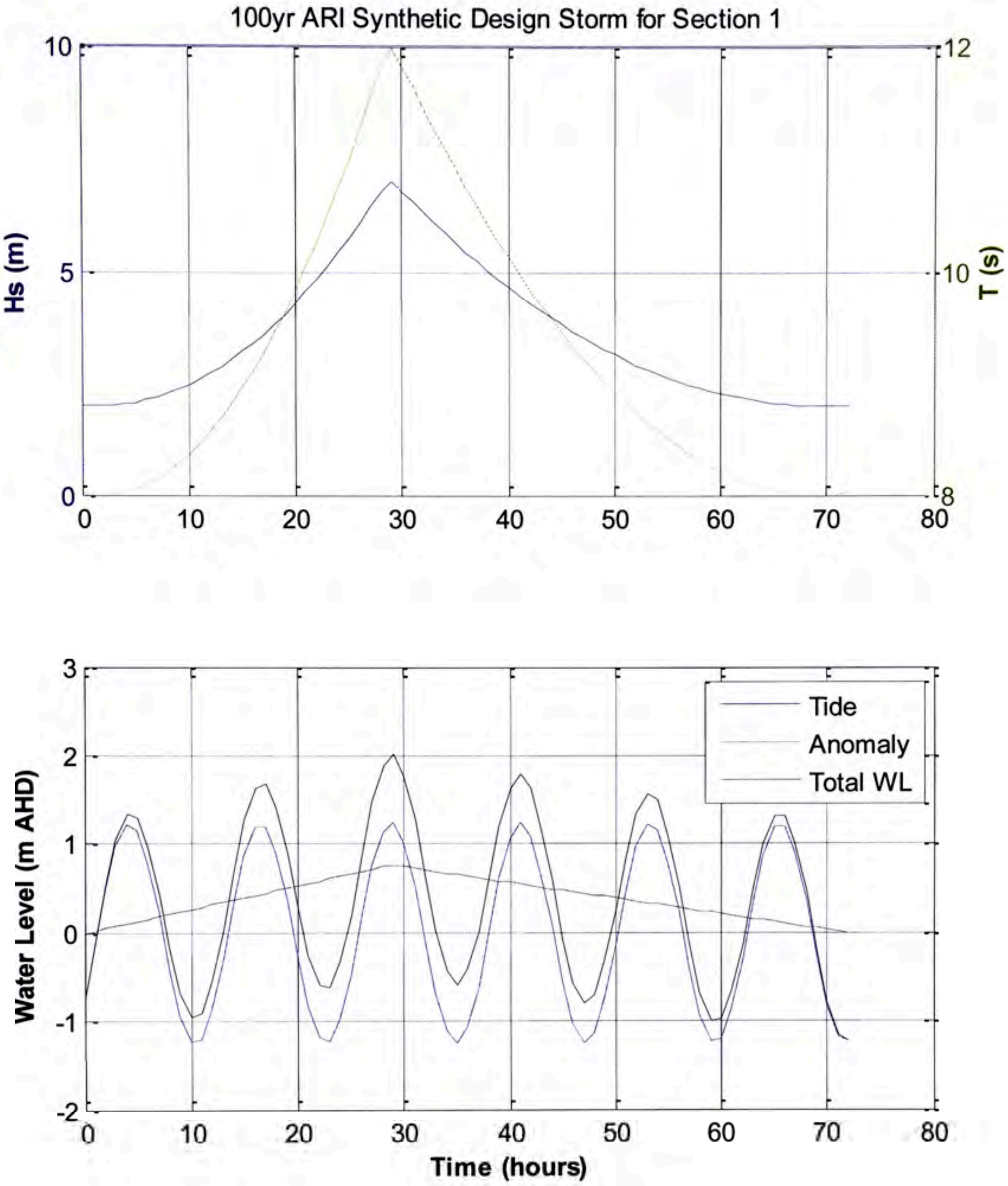
Table B.1: Wave Condition Characteristics of Adopted Synthetic Storms

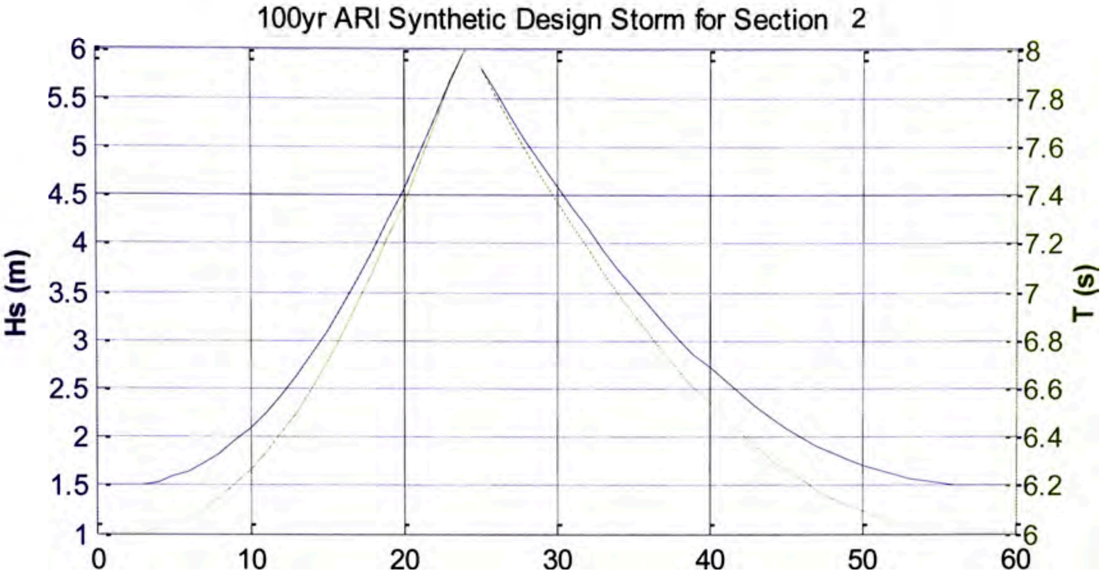
		100 year ARI			10 year ARI			1 year ARI		
Zone	**State**	*Hs (m)*	*Tp (s)*	*Duration (hrs)*	*Hs (m)*	*Tp (s)*	*Duration (hrs)*	*Hs (m)*	*Tp (s)*	*Duration (hrs)*
1	QLD	7	12	72	5.5	10	60	4	8	48
2	QLD	6	8	60	4.5	7	48	3.5	6	36
3	QLD	6	8	60	4.5	7	48	3.5	6	36
4	QLD	6	8	60	4.5	7	48	3.5	6	36
5	QLD	6	8	60	4.5	7	48	3.5	6	36
6	QLD	8	13	216	6.5	12	180	5	11	110
7	NSW	8	13	216	6.5	12	180	5	11	110
8	NSW	9	13	144	7.5	12	120	6	11	90
9	VIC	8	16	160	6.5	15	130	5	14	100
10	VIC	8	16	160	6.5	15	130	5	14	100
11	VIC	2.5	6	48	2.3	6	36	2.1	6	24
12	VIC	8	16	160	6.5	15	130	5	14	100
13	VIC	10	16	190	8.5	15	150	7	14	100
14	TAS	8	16	160	6.5	15	130	5	14	100
15	TAS	9	13	144	7.5	12	120	6	11	90
16	TAS	13	18	200	11	16	160	8.5	15	110
17	SA	10	16	190	8.5	15	150	7	14	100
18	SA	3.5	8	60	3	8	48	2	7	36
19	SA	9	16	180	8	15	150	6	14	90
20	WA	9	16	180	8	15	150	6	14	90
21	WA	10	16	250	9	15	170	7	15	120
22	WA	11	16	230	10	15	170	7.5	15	120
23	WA	10	16	250	9	15	170	7	15	120
24	WA	9	16	170	8	16	140	6	16	100
25	WA	9	16	170	8	16	140	6	16	100
26	WA	8	14	84	6.5	12	72	5	10	48
27	WA	8	14	84	6.5	12	72	5	10	48
28	WA	8	14	84	6.5	12	72	5	10	48
29	NT	8	14	84	6.5	12	72	5	10	48
30	NT	7	12	72	5.5	10	60	4	8	48

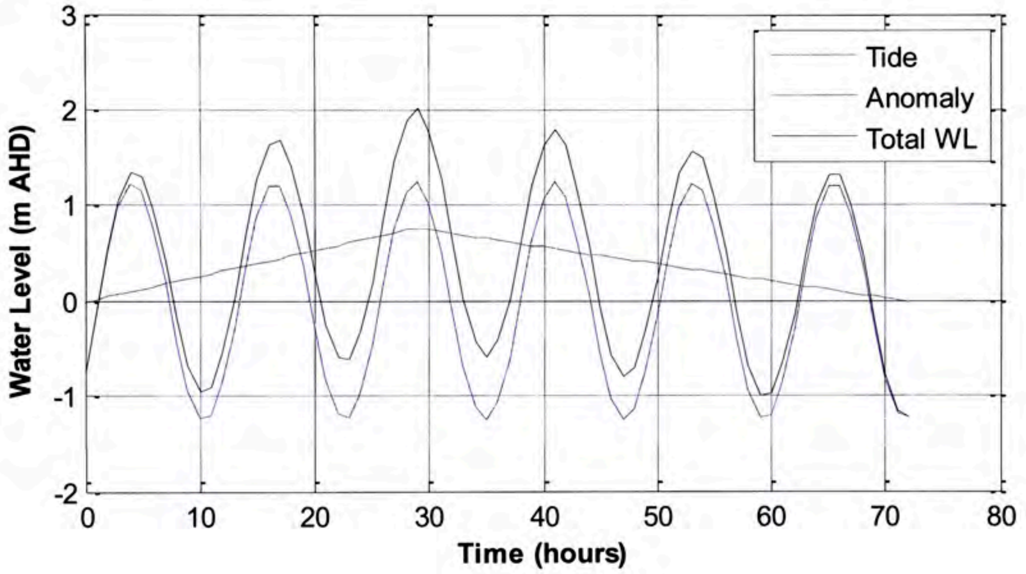
Table B.2: Extreme Water Levels of Adopted Synthetic Storms (including astronomical tide, barometric setup and wind setup)

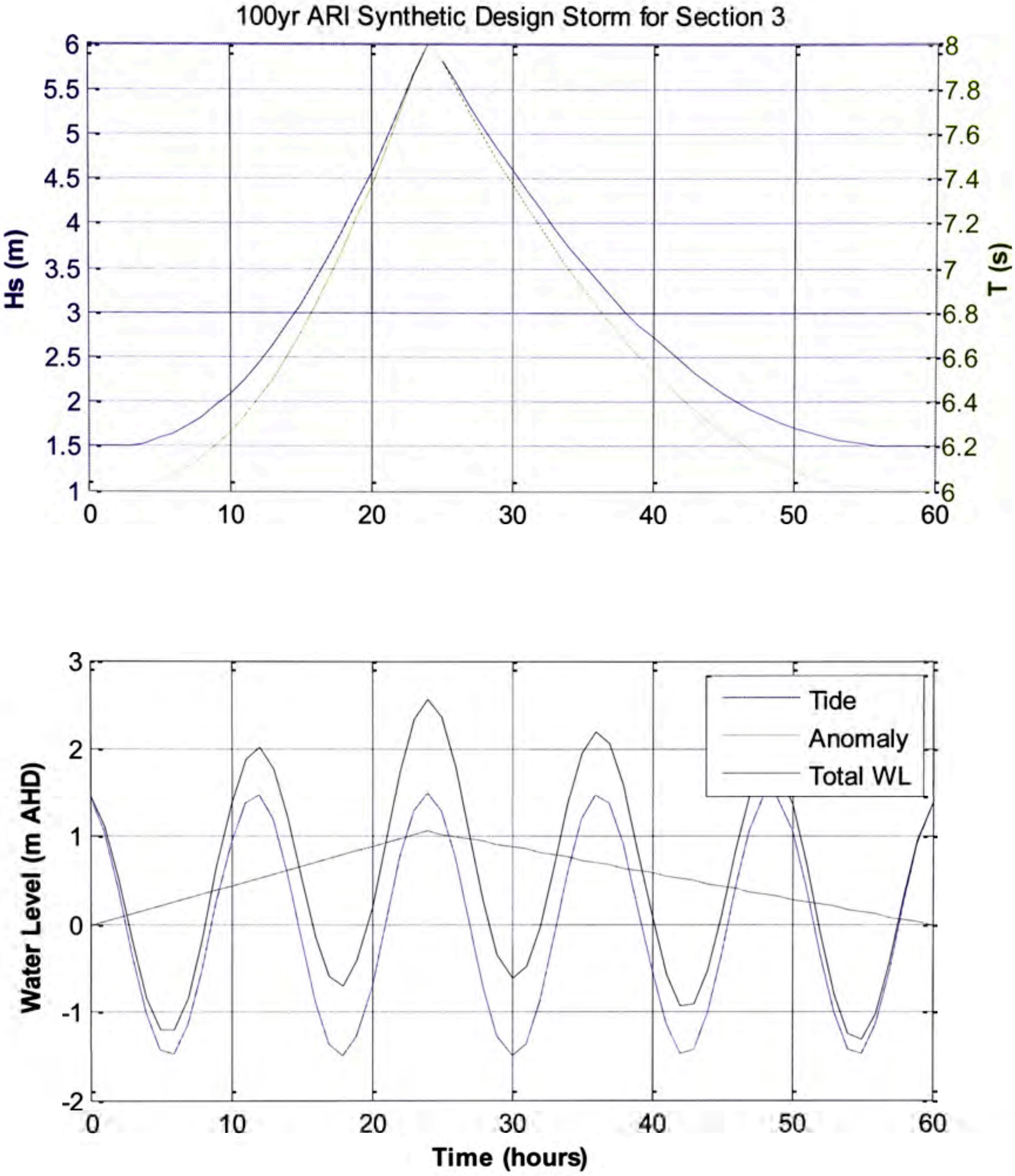
Zone	Peak Water Levels		
	1 year ARI	*10 year ARI*	*100 year ARI*
1	1.85	1.90	2.02
2	1.85	1.90	2.02
3	2.29	2.36	2.57
4	3.63	3.72	3.99
5	1.98	2.04	2.22
6	1.59	1.61	1.66
7	1.59	1.61	1.66
8	1.31	1.35	1.46
9	0.94	1.10	1.21
10	1.45	1.54	1.96
11	0.96	1.00	1.09
12	1.19	1.32	1.69
13	0.90	1.10	1.34
14	1.87	1.92	2.00
15	1.10	1.16	1.34
16	1.10	1.16	1.34
17	1.43	1.50	1.64
18	2.13	2.20	2.38
19	1.84	1.90	2.03
20	1.13	1.17	1.23
21	1.13	1.17	1.23
22	0.97	1.00	1.04
23	1.14	1.25	1.61
24	0.96	1.02	1.18
25	1.31	1.44	1.92
26	3.60	3.70	3.98
27	5.15	5.21	5.30
28	3.99	4.05	4.32
29	3.90	4.00	4.90
30	1.40	1.43	1.55

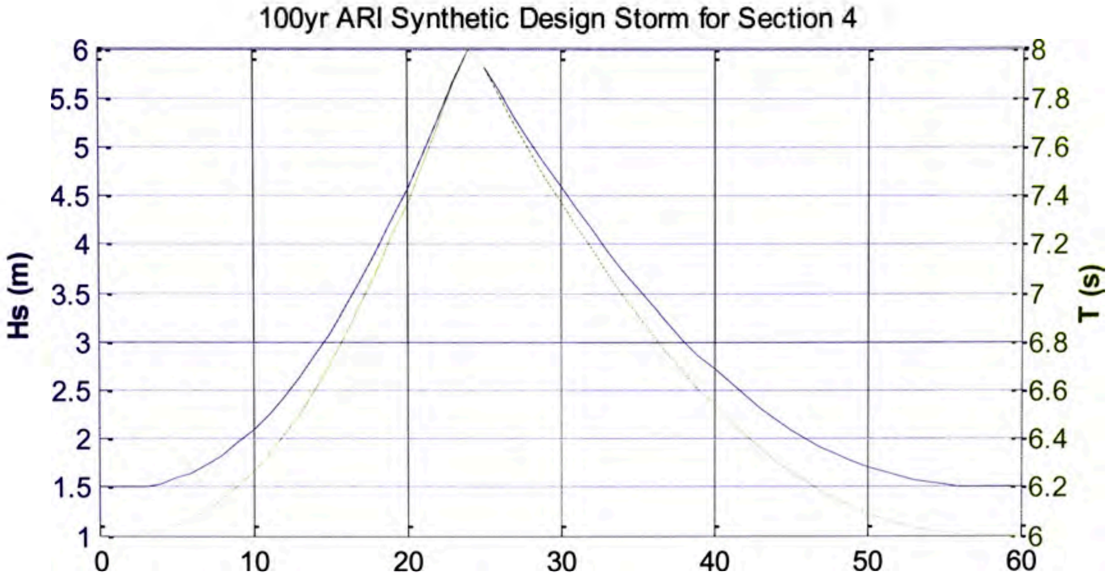
Plots of significant wave height Hs, spectral wave period Tp and extreme water levels for the adopted 1 in 100 year ARI design storms are shown for each coastal section in the following figures.

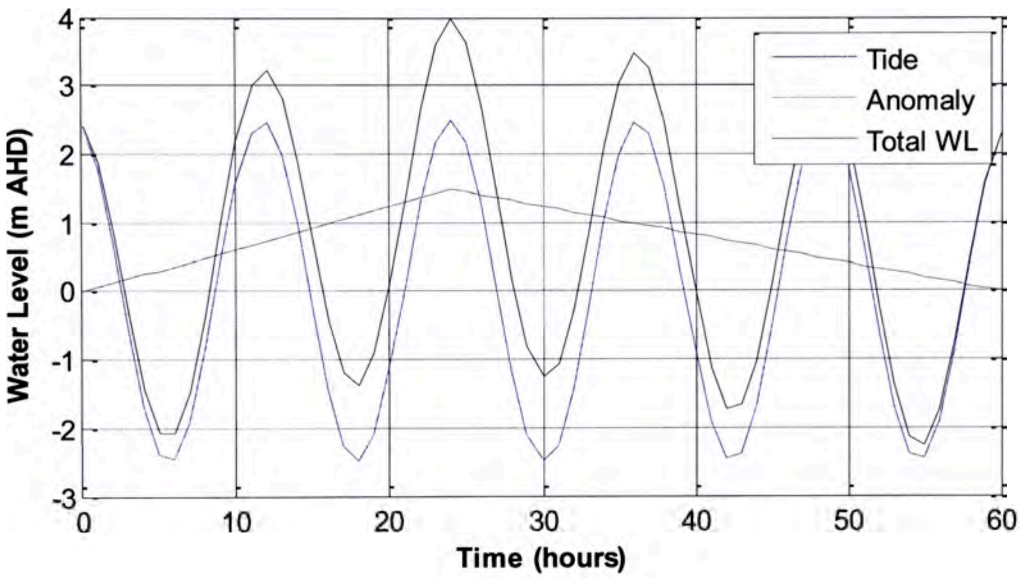

100yr ARI Synthetic Design Storm for Section 1
Hs (m)
T (s)
Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)

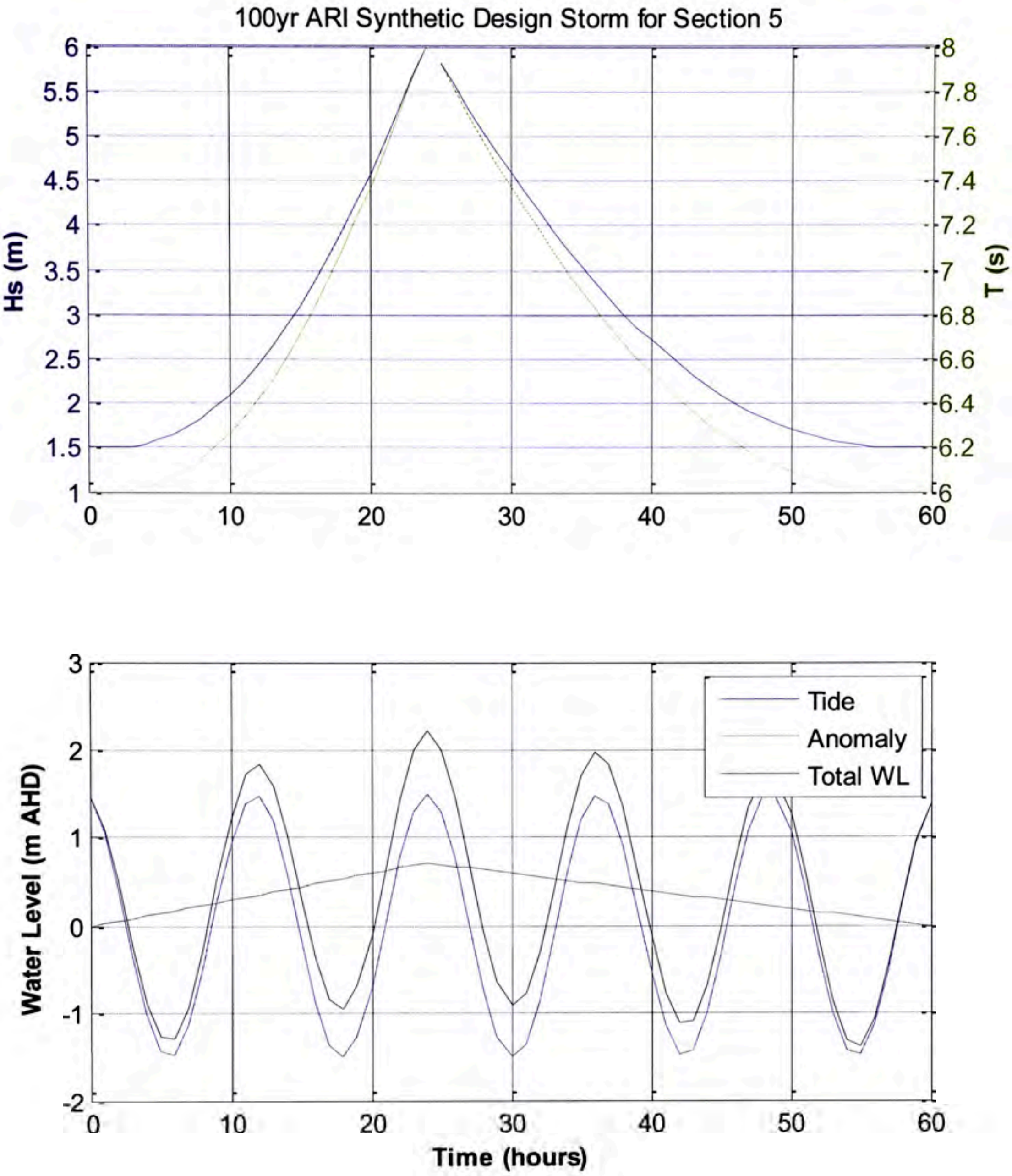

100yr ARI Synthetic Design Storm for Section 2
Hs (m)
T (s)
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
8
7.8
7.6
7.4
7.2
7
6.8
6.6
6.4
6.2
6
0
10
20
30
40
50
60

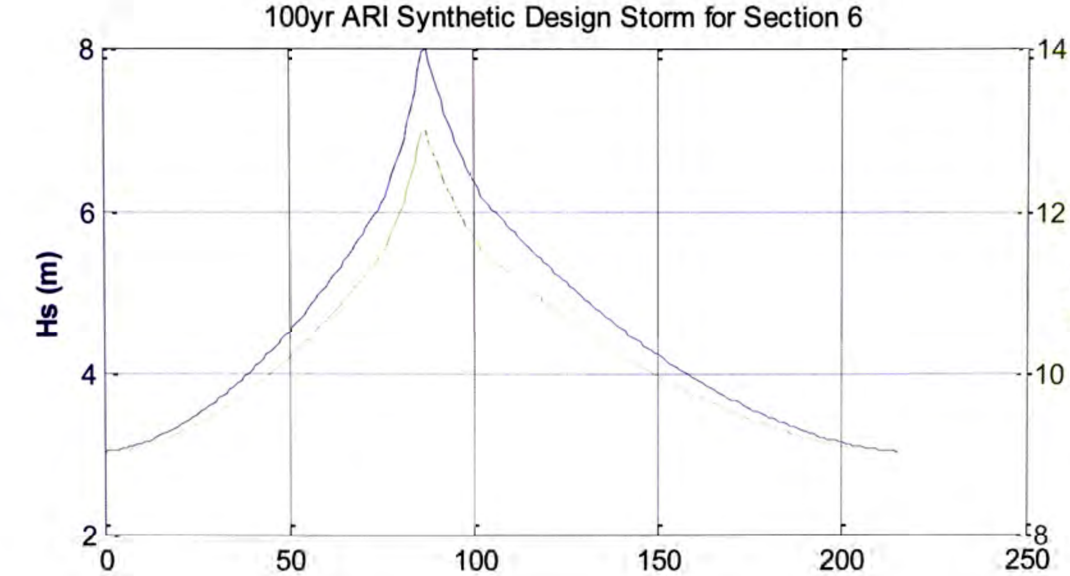

Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)
3
2
1
0
-1
-2
0
10
20
30
40
50
60
70
80

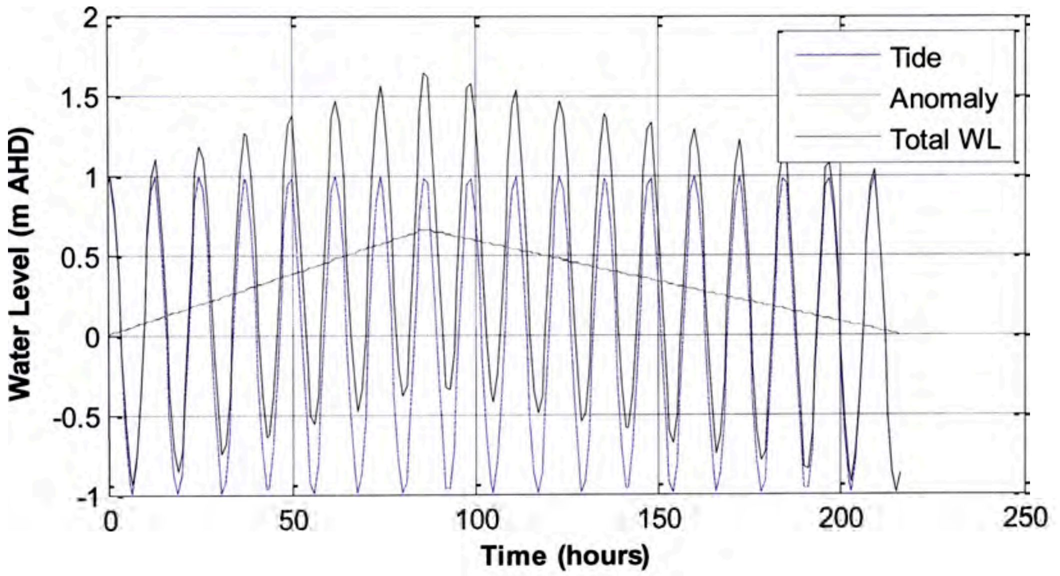

100yr ARI Synthetic Design Storm for Section 3
Hs (m)
T (s)
Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)

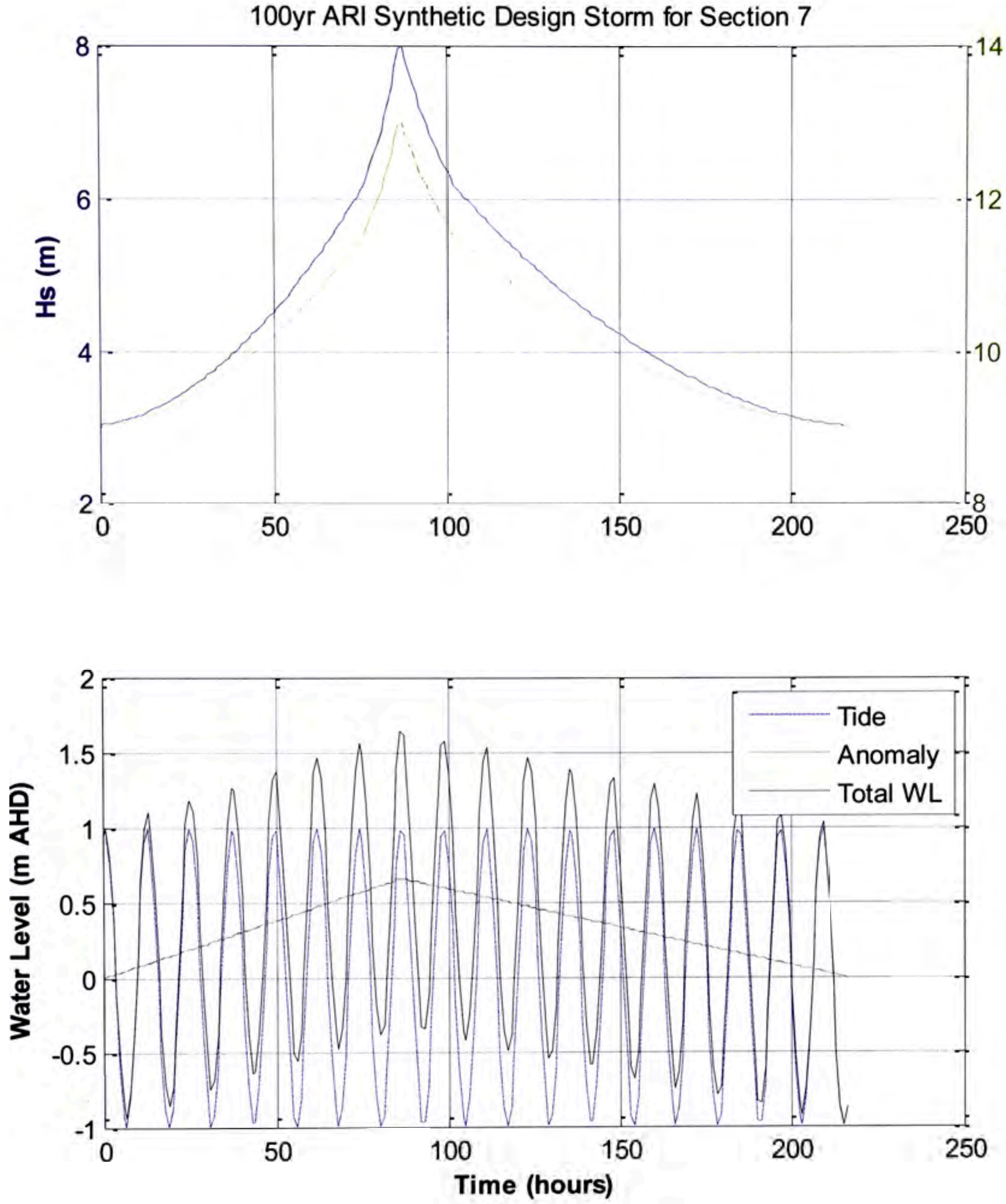

100yr ARI Synthetic Design Storm for Section 4
Hs (m)
T (s)
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
8
7.8
7.6
7.4
7.2
7
6.8
6.6
6.4
6.2
6
0
10
20
30
40
50
60

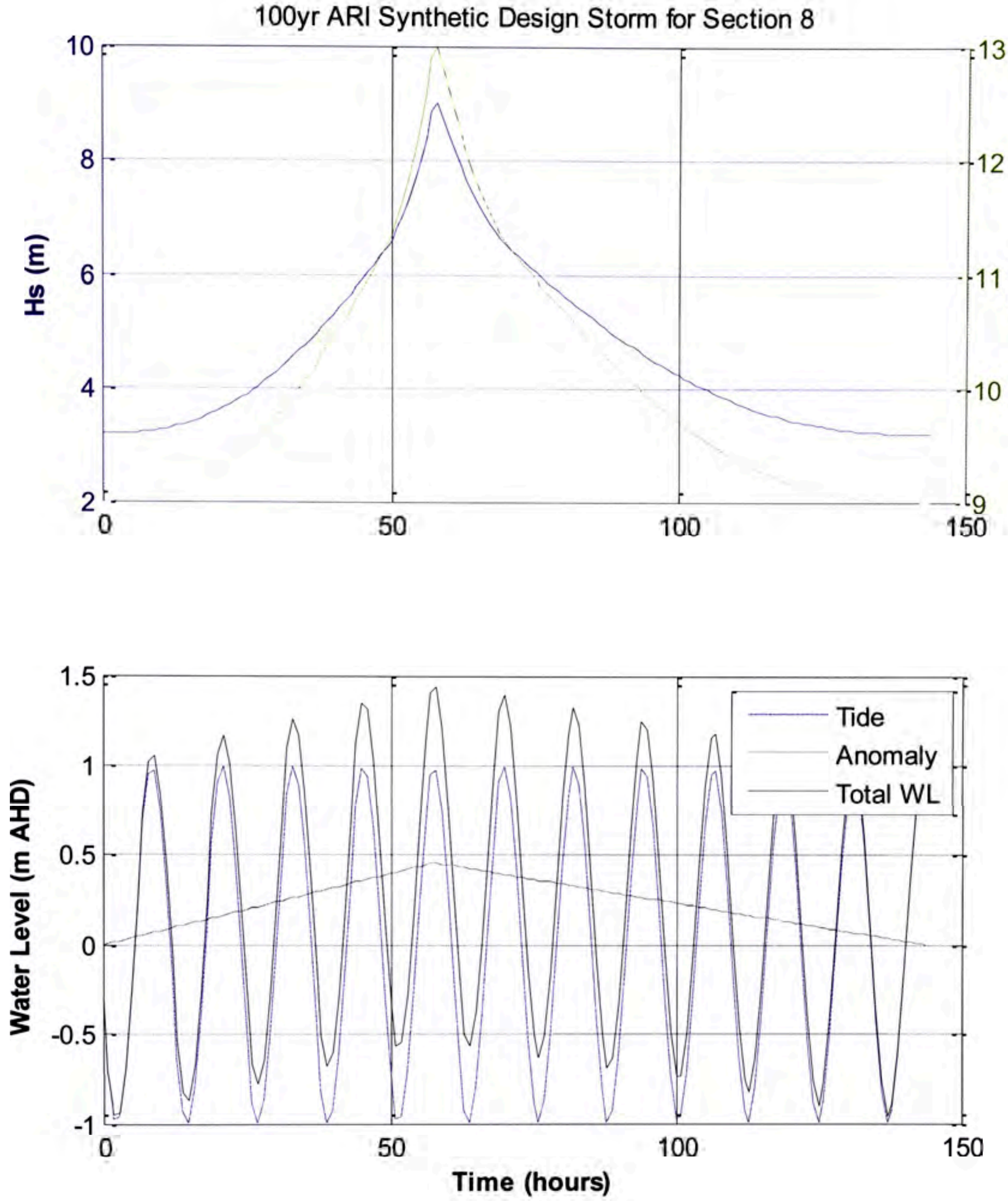

Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)
4
3
2
1
0
-1
-2
-3
0
10
20
30
40
50
60

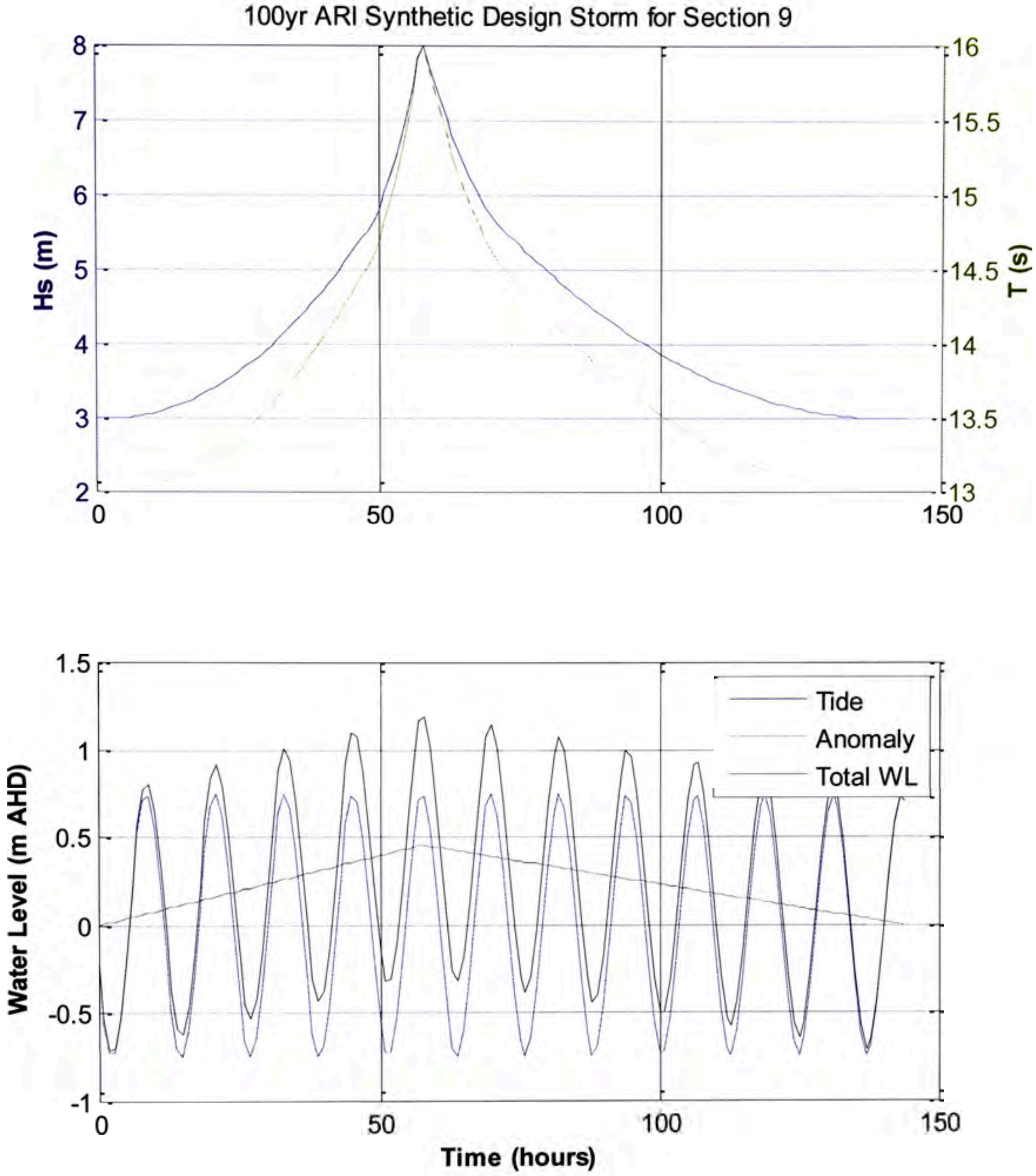

100yr ARI Synthetic Design Storm for Section 5
Hs (m)
T (s)
Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)

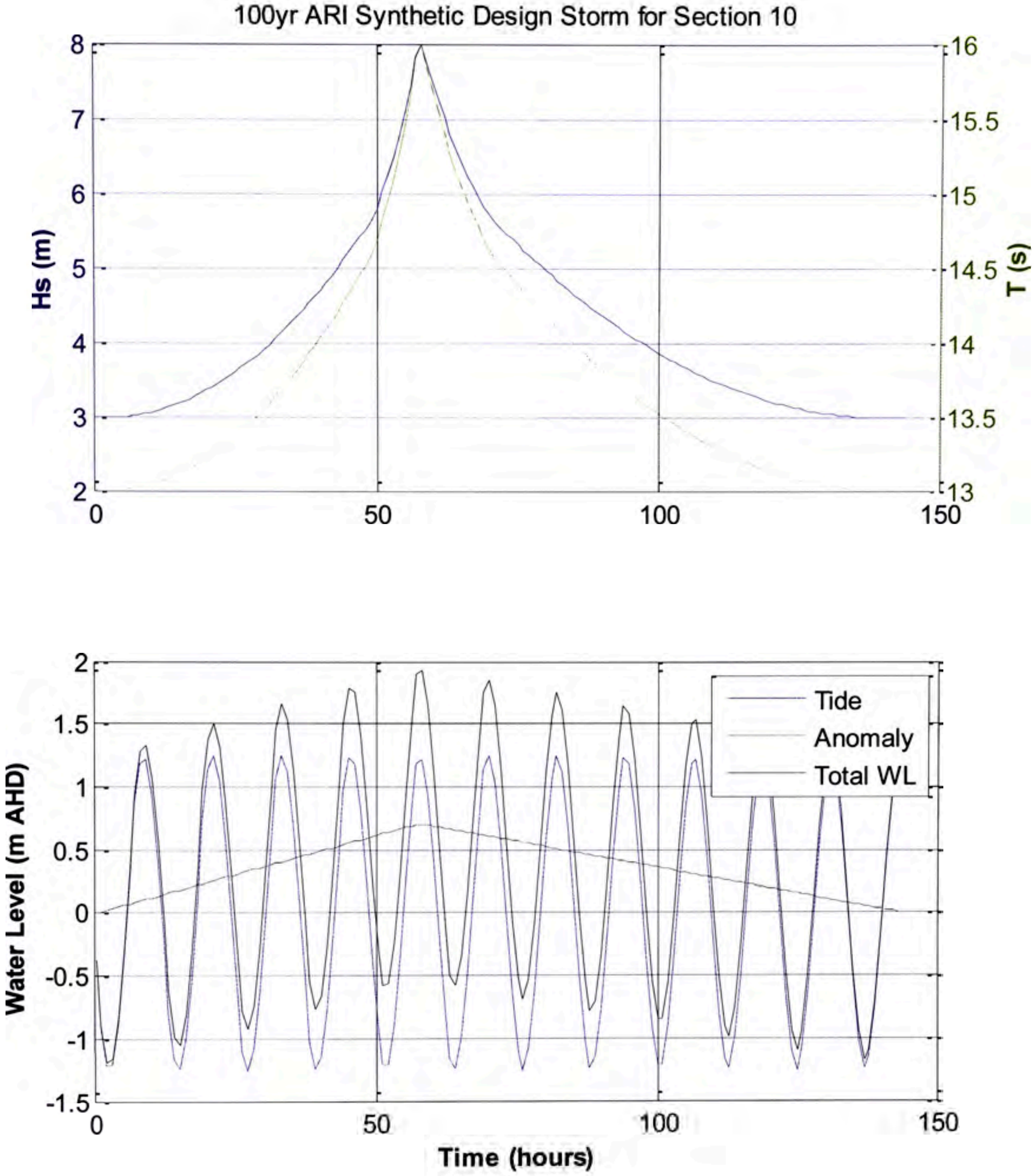

100yr ARI Synthetic Design Storm for Section 6
Hs (m)
T (s)
8
6
4
2
14
12
10
8
0
50
100
150
200
250

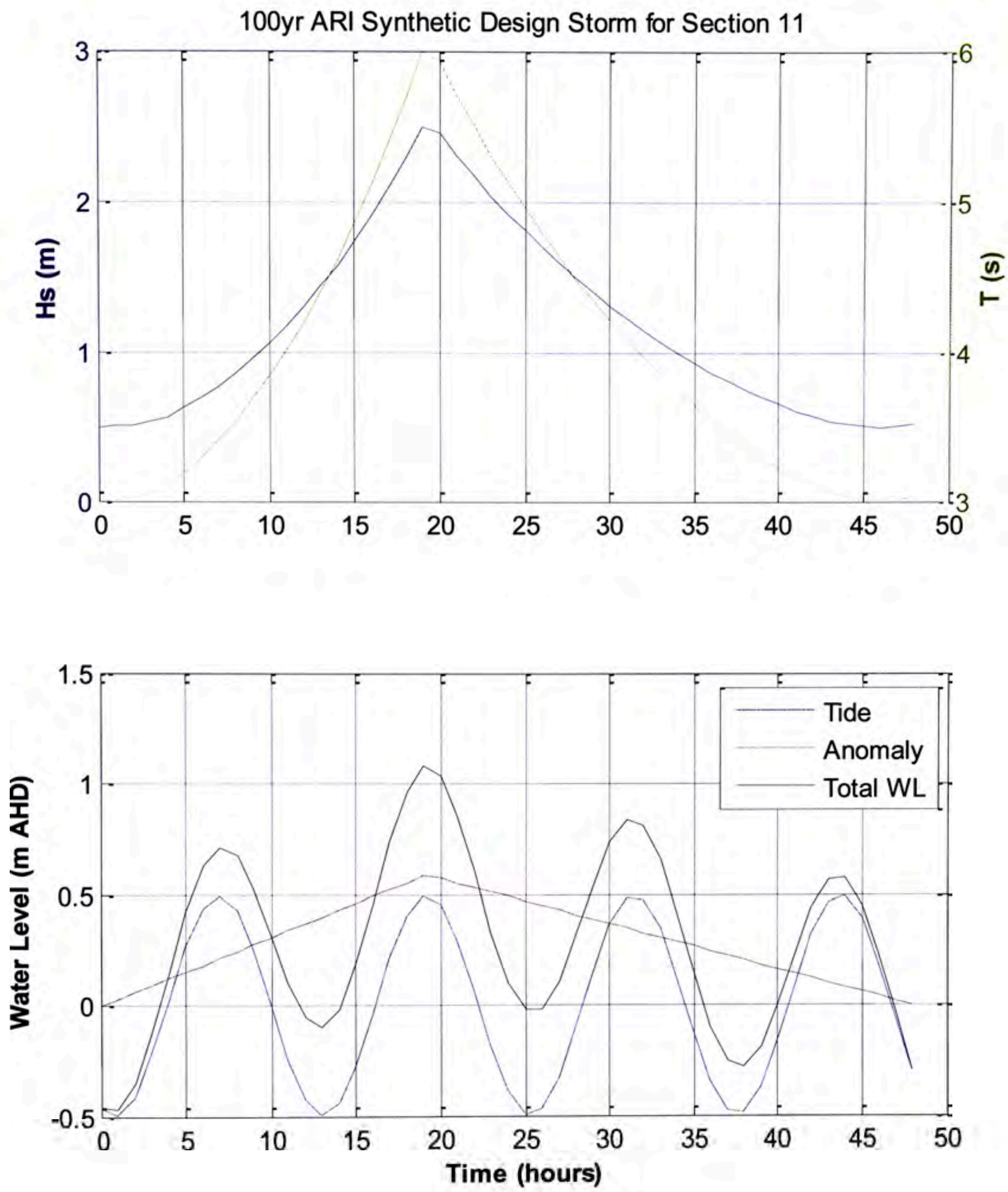

Tide
Anomaly
Total WL
Water Level (m AHD)
2
1.5
1
0.5
0
-0.5
-1
0
50
100
150
200
250
Time (hours)


100yr ARI Synthetic Design Storm for Section 7
Hs (m)
T (s)
Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)

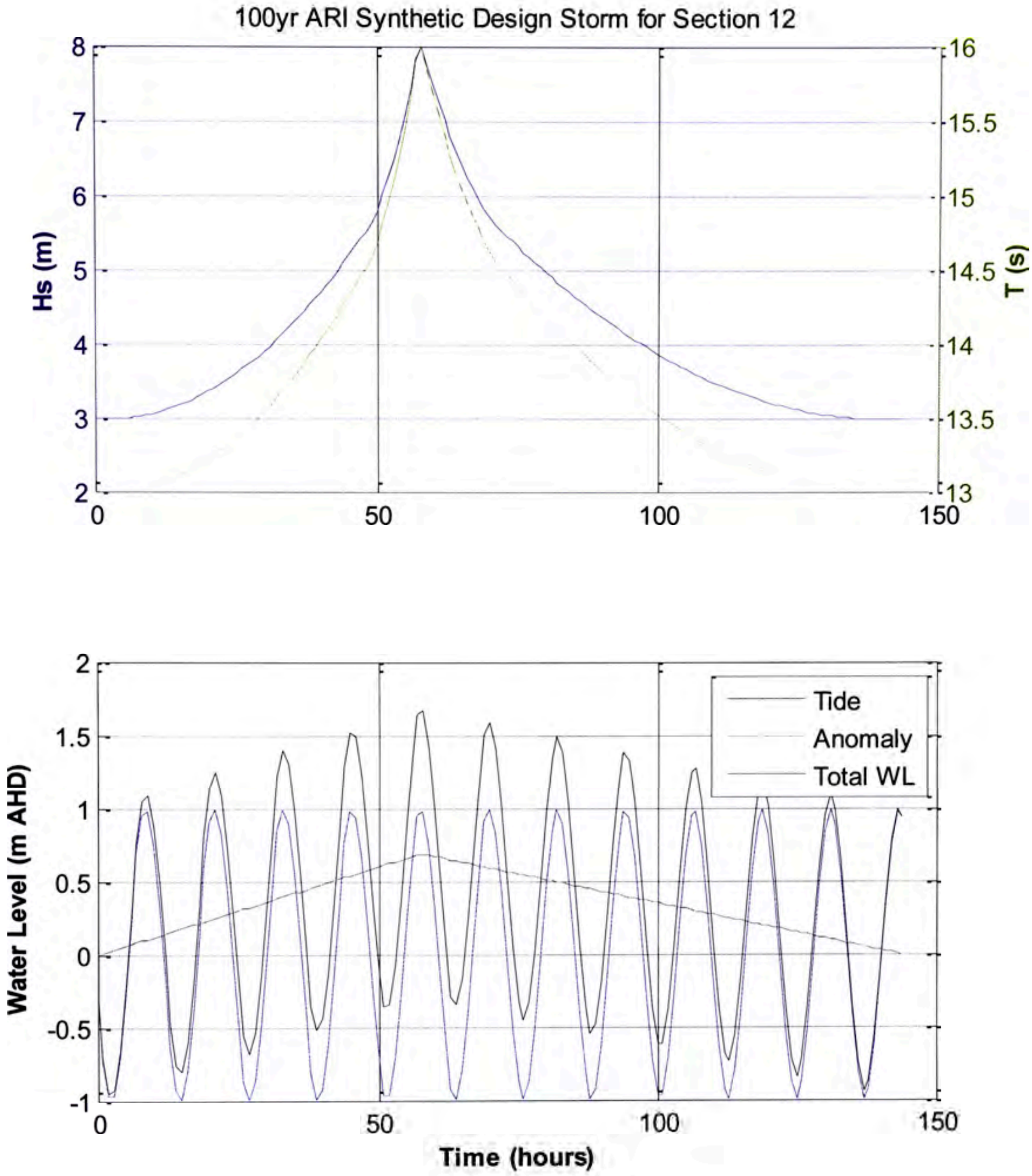

100yr ARI Synthetic Design Storm for Section 8
Hs (m)
T (s)
Water Level (m AHD)
Tide
Anomaly
Total WL
Time (hours)

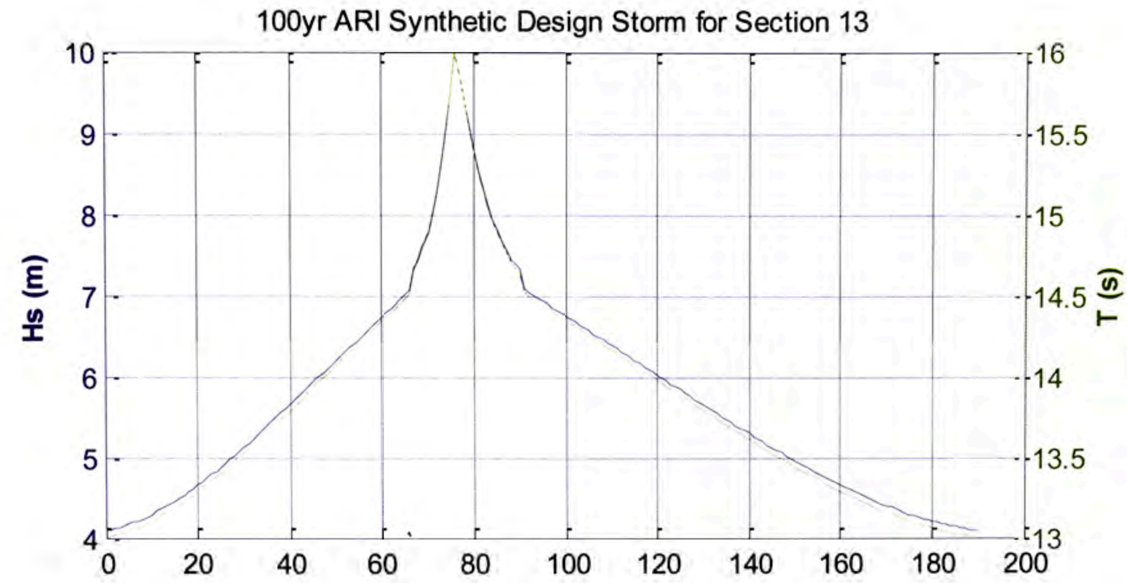

100yr ARI Synthetic Design Storm for Section 9
Hs (m)
T (s)
Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)

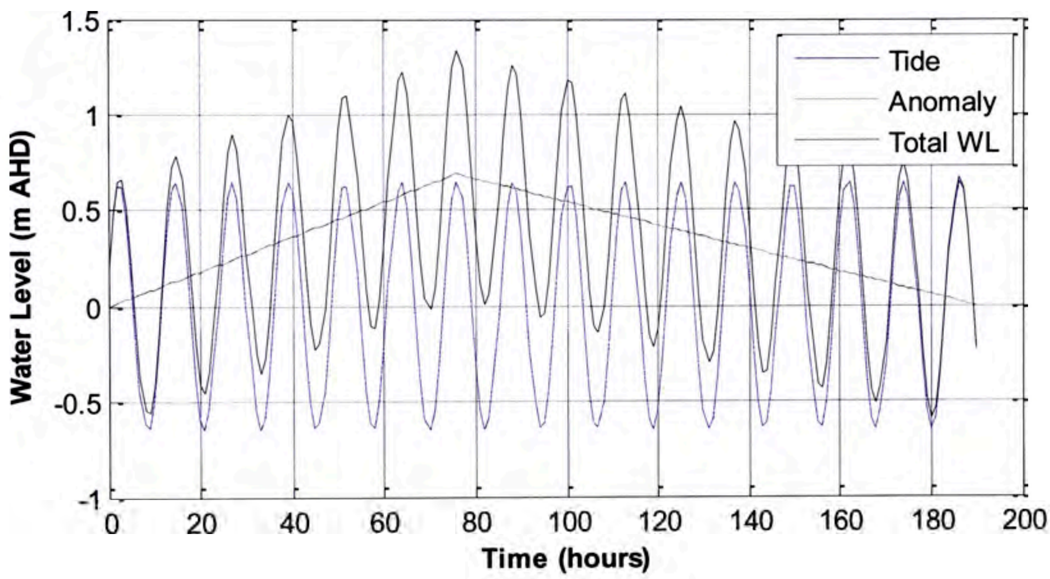

100yr ARI Synthetic Design Storm for Section 10
Hs (m)
T (s)
Water Level (m AHD)
Time (hours)
Tide
Anomaly
Total WL

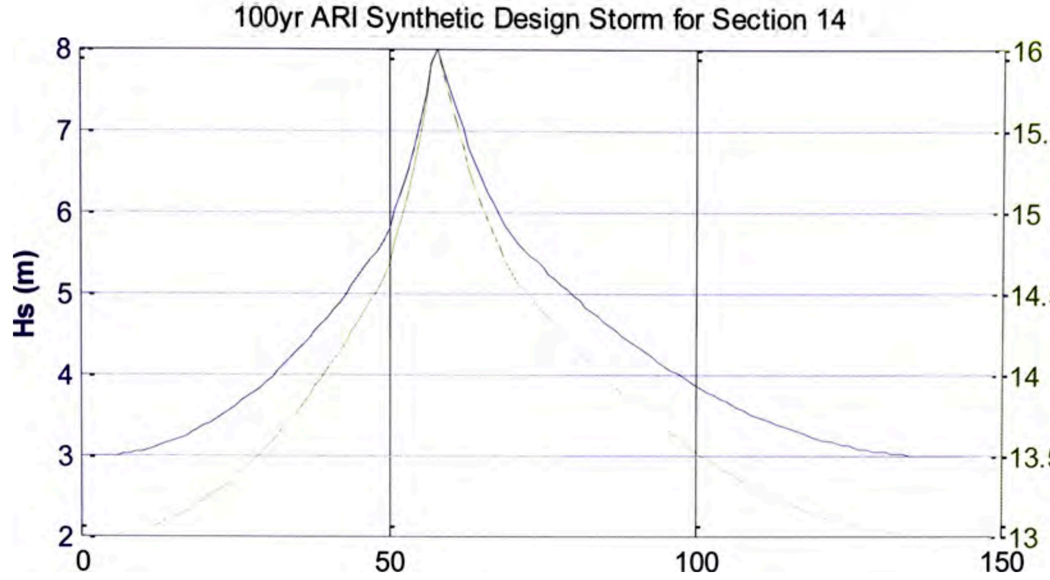


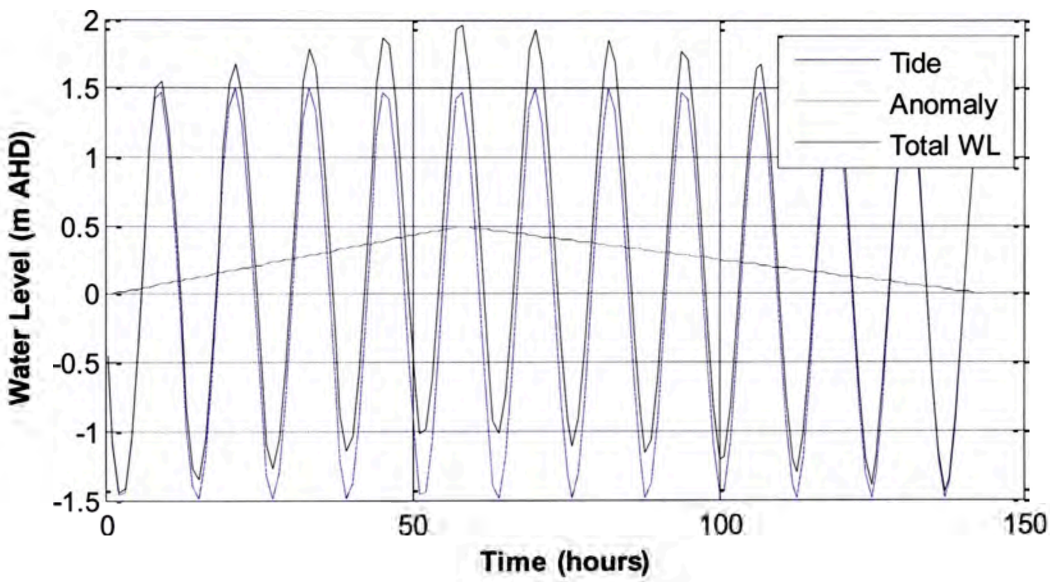
100yr ARI Synthetic Design Storm for Section 11
Hs (m)
T (s)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
5
10
15
20
25
30
35
40
45
50
Tide
Anomaly
Total WL
Water Level (m AHD)
-0.5
Time (hours)

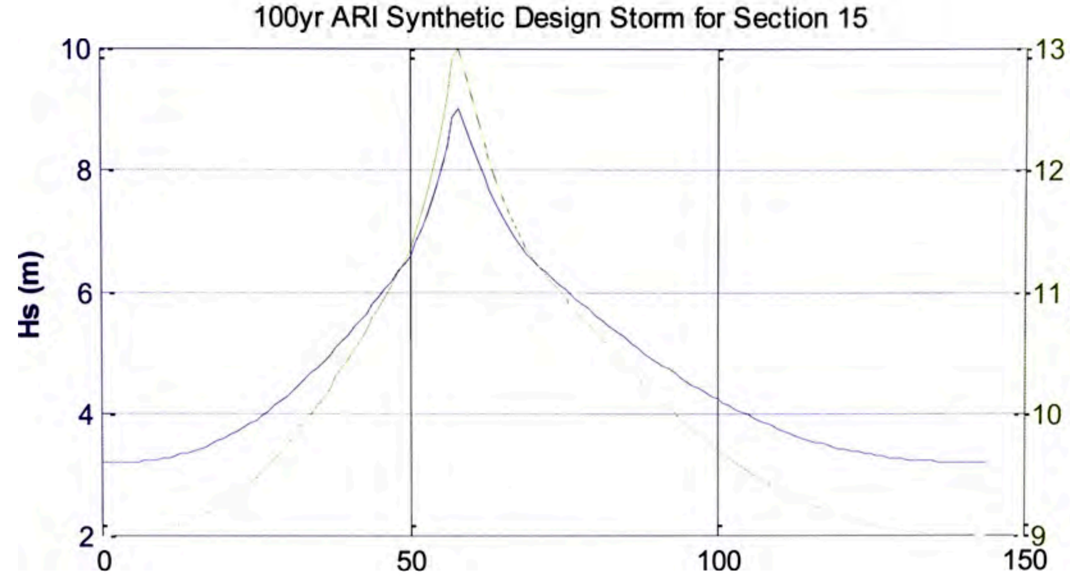

100yr ARI Synthetic Design Storm for Section 12
Hs (m)
T (s)
Water Level (m AHD)
Time (hours)
Tide
Anomaly
Total WL

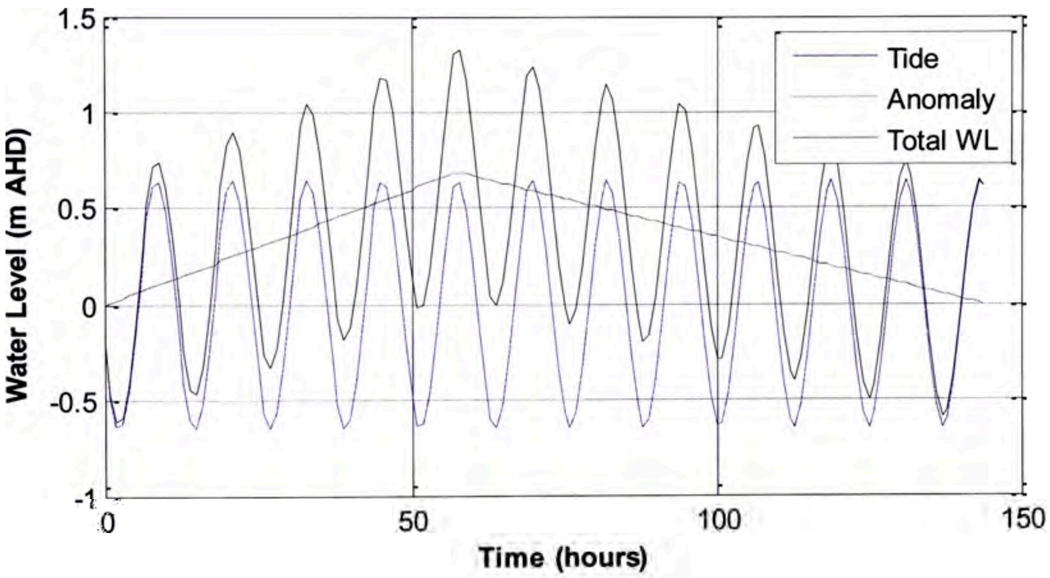

100yr ARI Synthetic Design Storm for Section 13
Hs (m)
T (s)
10
9
8
7
6
5
4
16
15.5
15
14.5
14
13.5
13
0
20
40
60
80
100
120
140
160
180
200

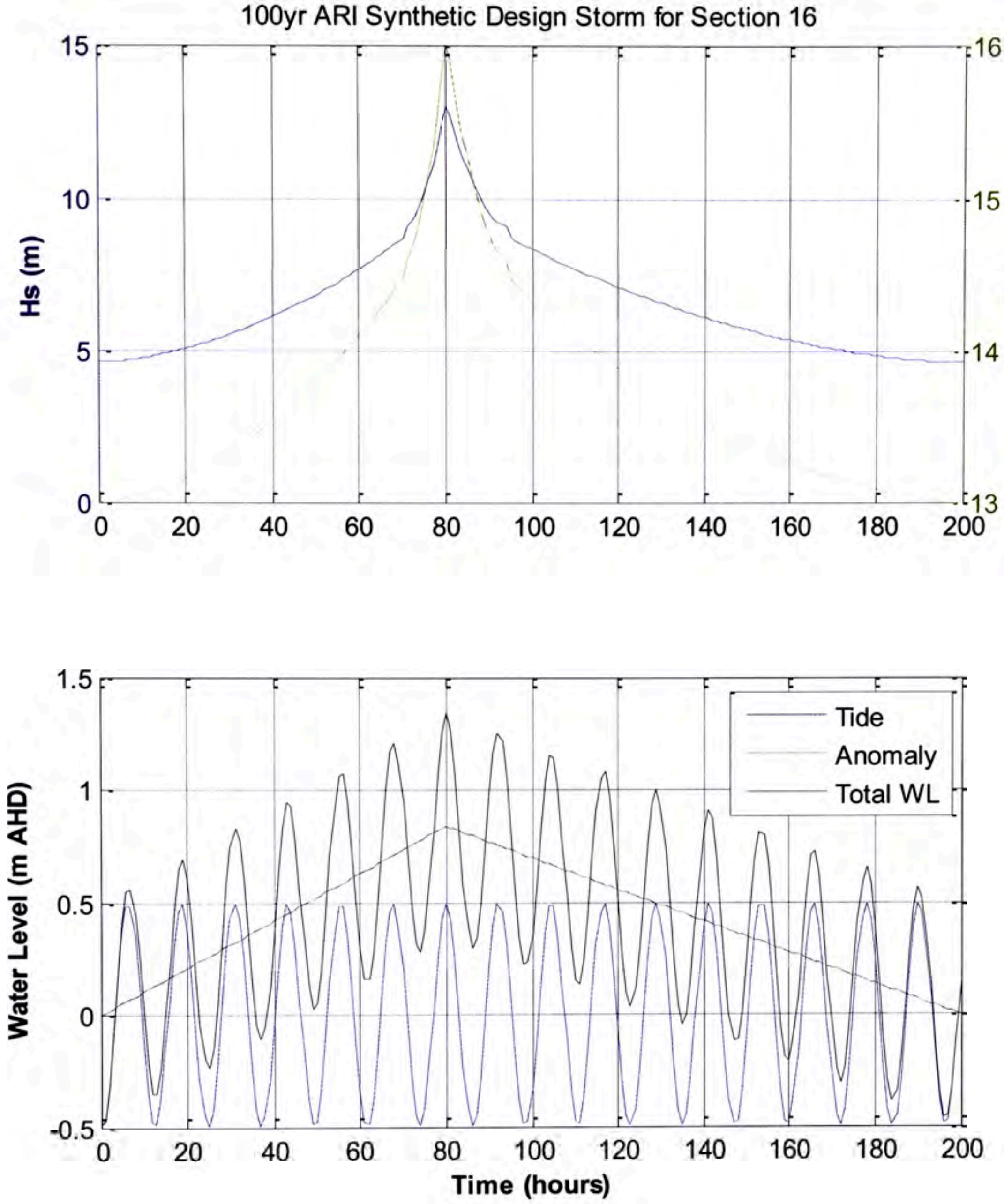

Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)
1.5
1
0.5
0
-0.5
-1
0
20
40
60
80
100
120
140
160
180
200

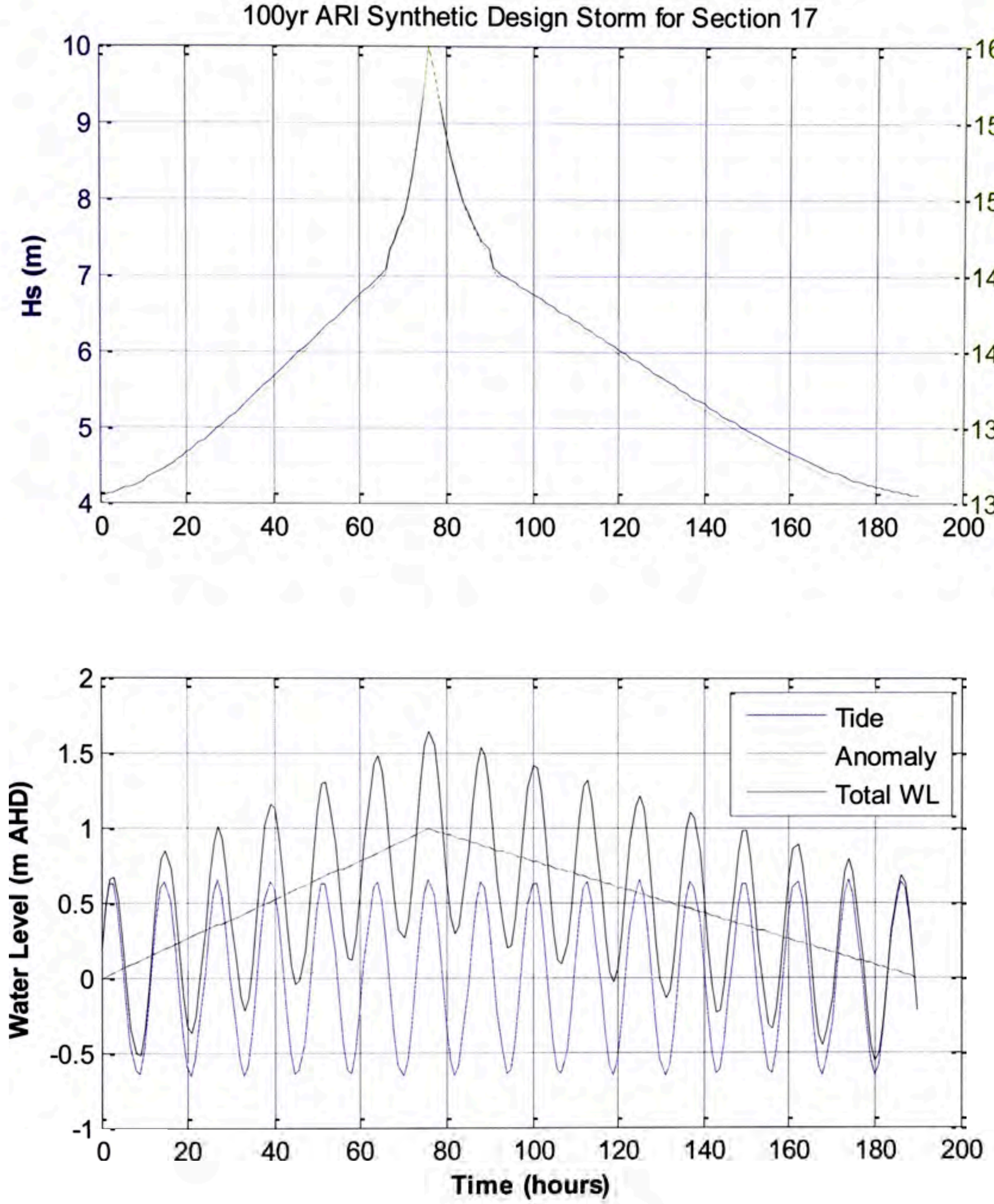

100yr ARI Synthetic Design Storm for Section 14
Hs (m)
T (s)
8
7
6
5
4
3
2
16
15.5
15
14.5
14
13.5
13
0
50
100
150


Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
50
100
150

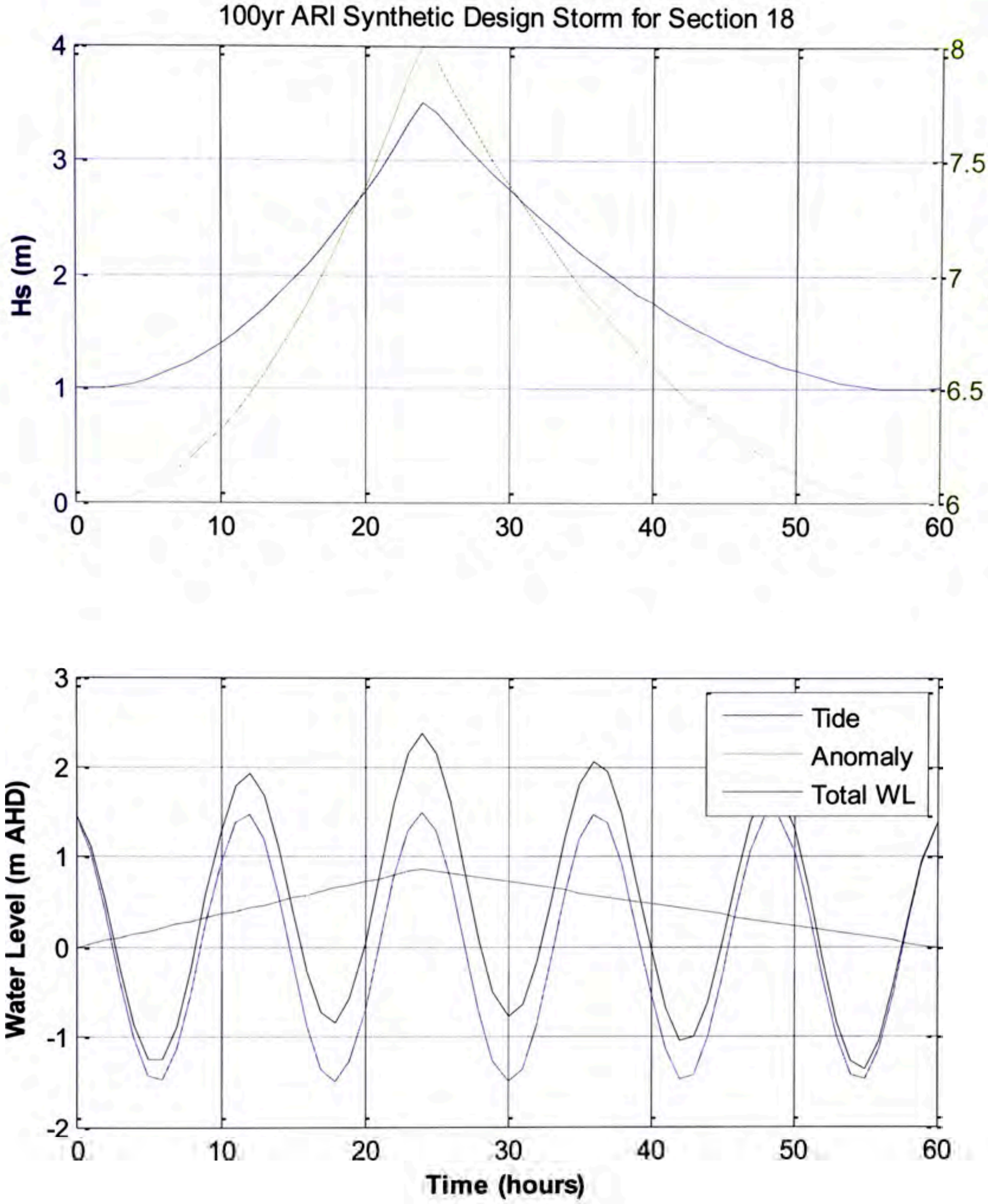

100yr ARI Synthetic Design Storm for Section 15
Hs (m)
T (s)
10
8
6
4
2
13
12
11
10
9
0
50
100
150

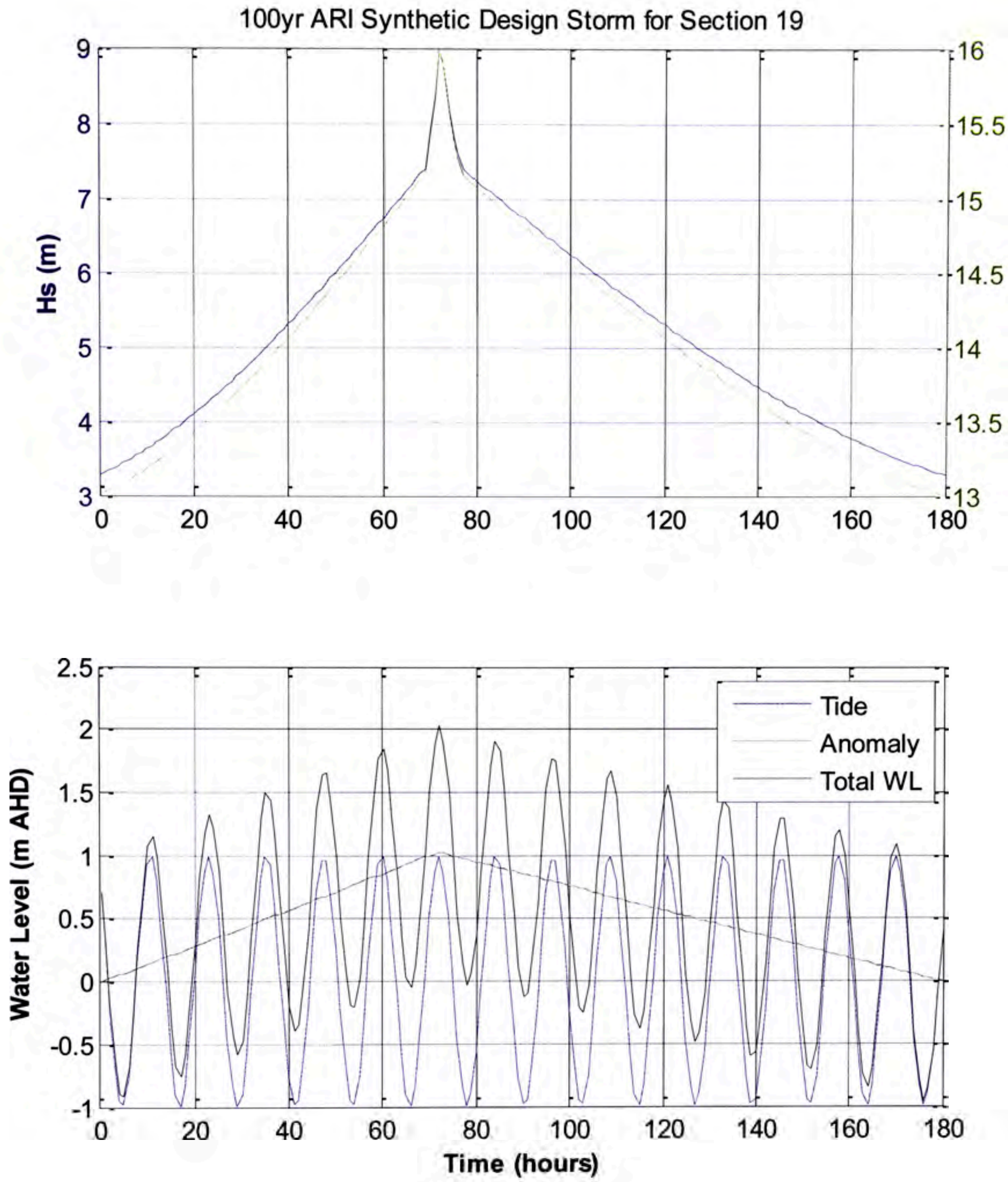

Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)
1.5
1
0.5
0
-0.5
-1
0
50
100
150

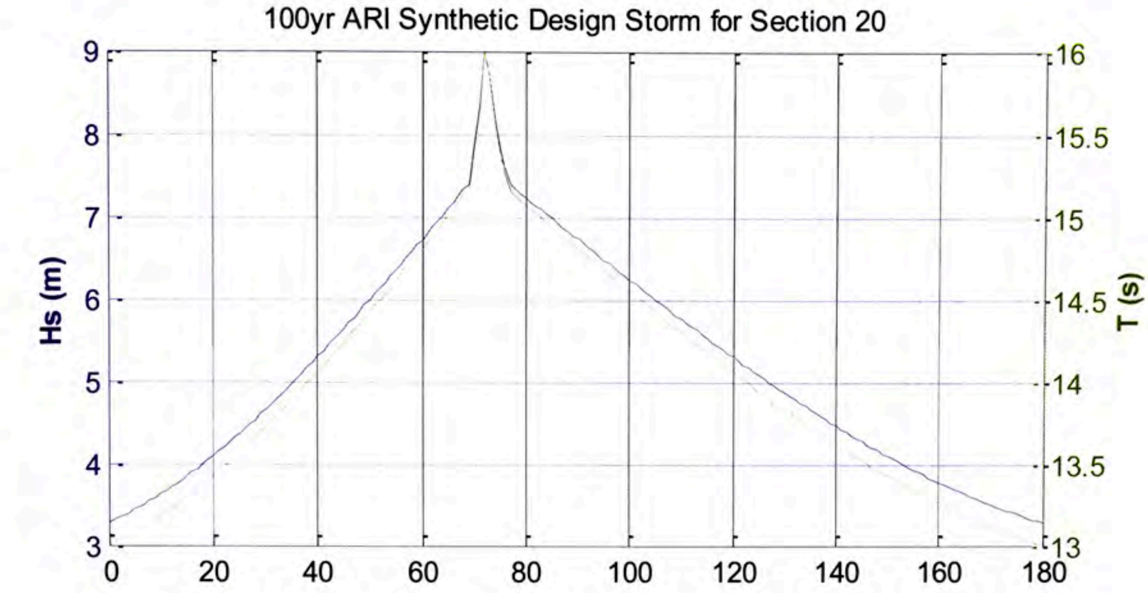

100yr ARI Synthetic Design Storm for Section 16
Hs (m)
T (s)
Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)

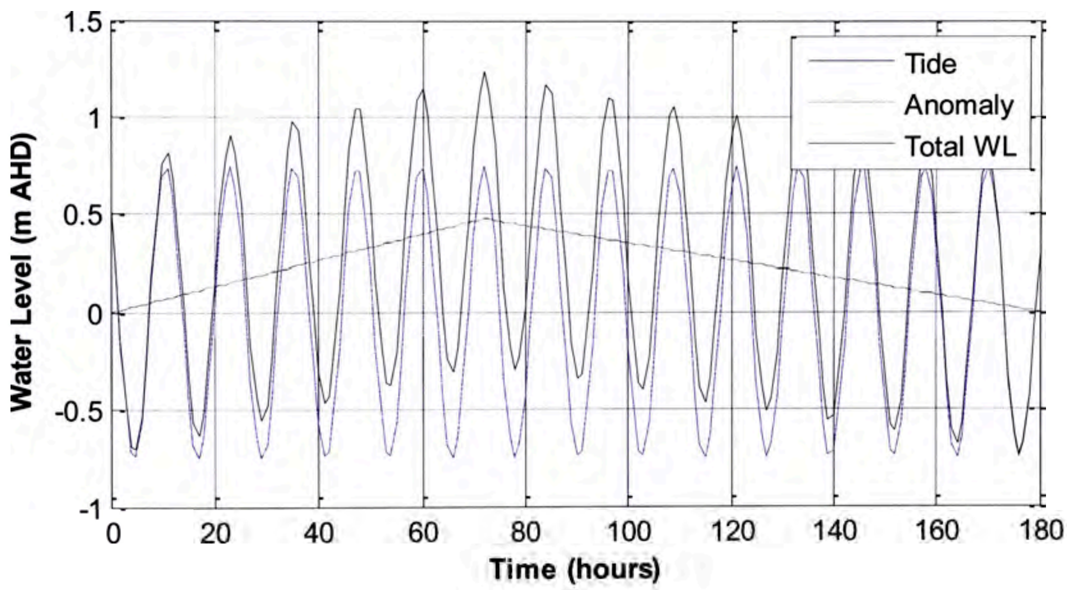


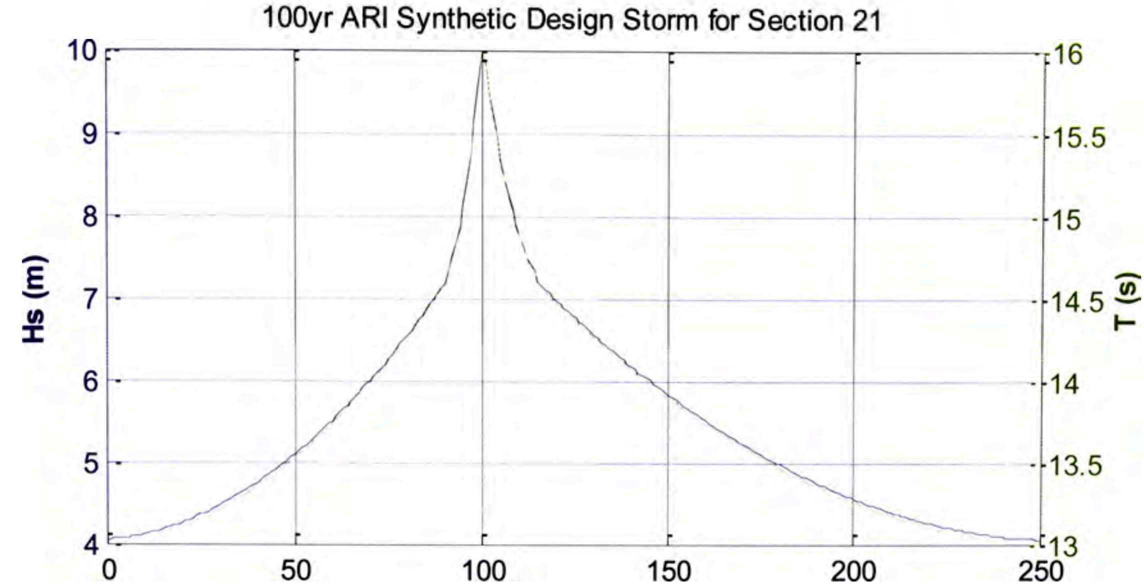
100yr ARI Synthetic Design Storm for Section 17
Hs (m)
T (s)
10
9
8
7
6
5
4
16
15.5
15
14.5
14
13.5
13
0
20
40
60
80
100
120
140
160
180
200
Water Level (m AHD)
2
1.5
1
0.5
0
-0.5
-1
Tide
Anomaly
Total WL
Time (hours)

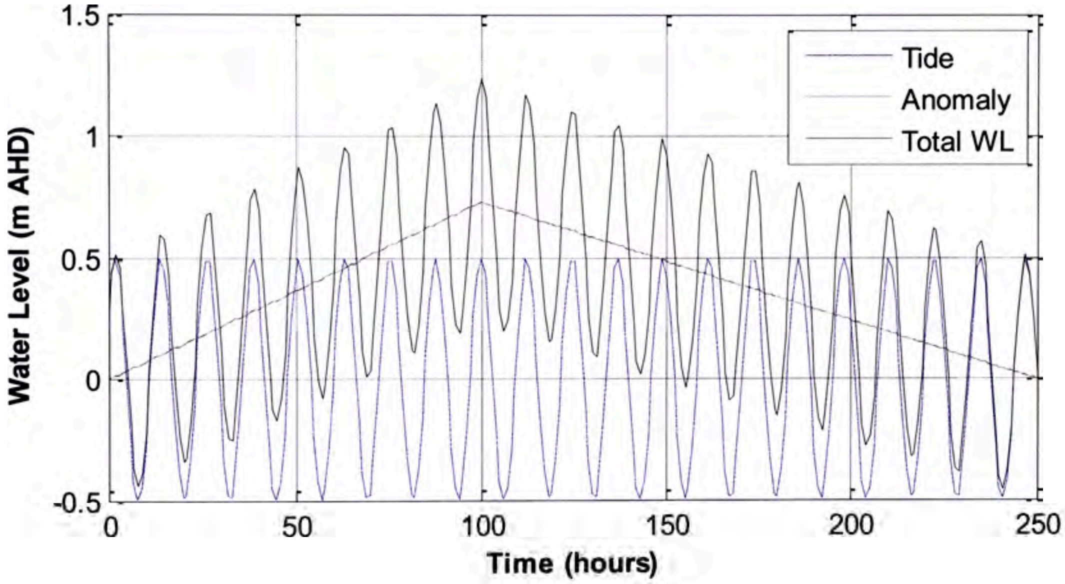

100yr ARI Synthetic Design Storm for Section 18
Hs (m)
T (s)
Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)

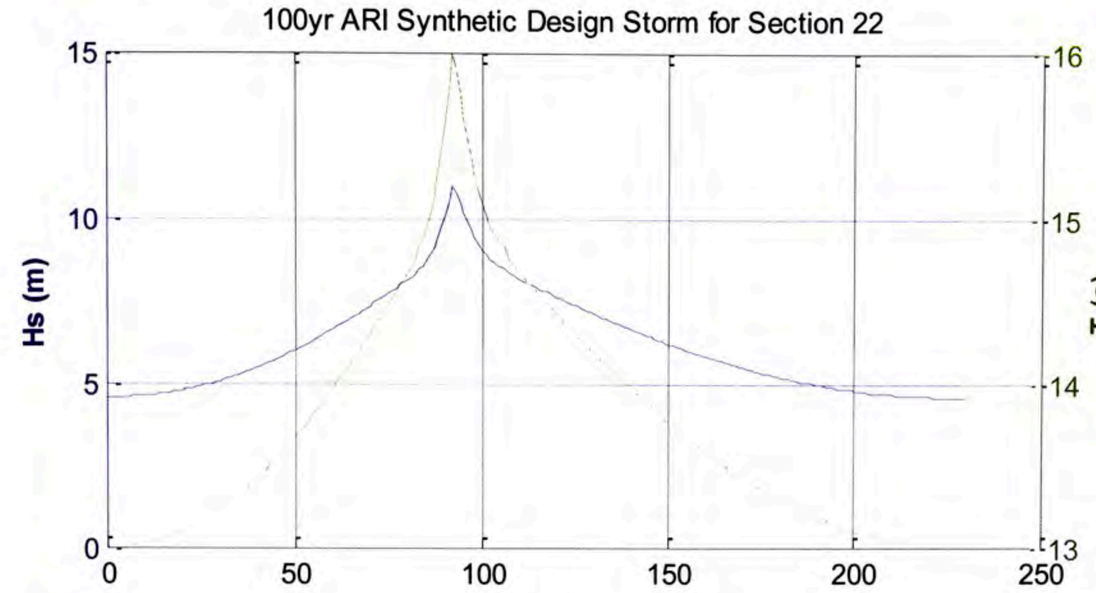

100yr ARI Synthetic Design Storm for Section 19
Hs (m)
T (s)
Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)

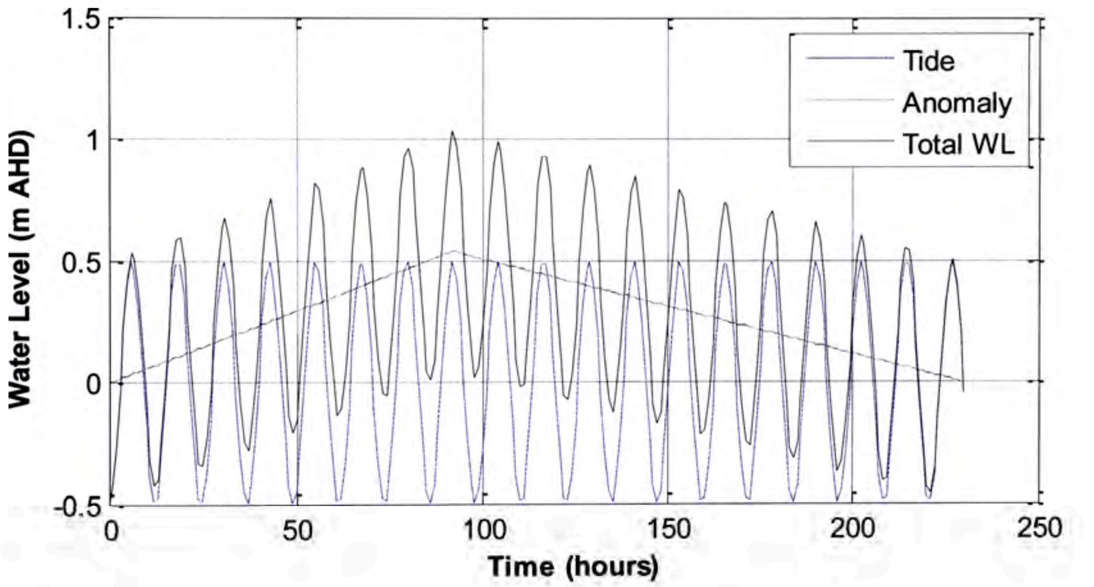

100yr ARI Synthetic Design Storm for Section 20
Hs (m)
T (s)
9
8
7
6
5
4
3
16
15.5
15
14.5
14
13.5
13
0
20
40
60
80
100
120
140
160
180

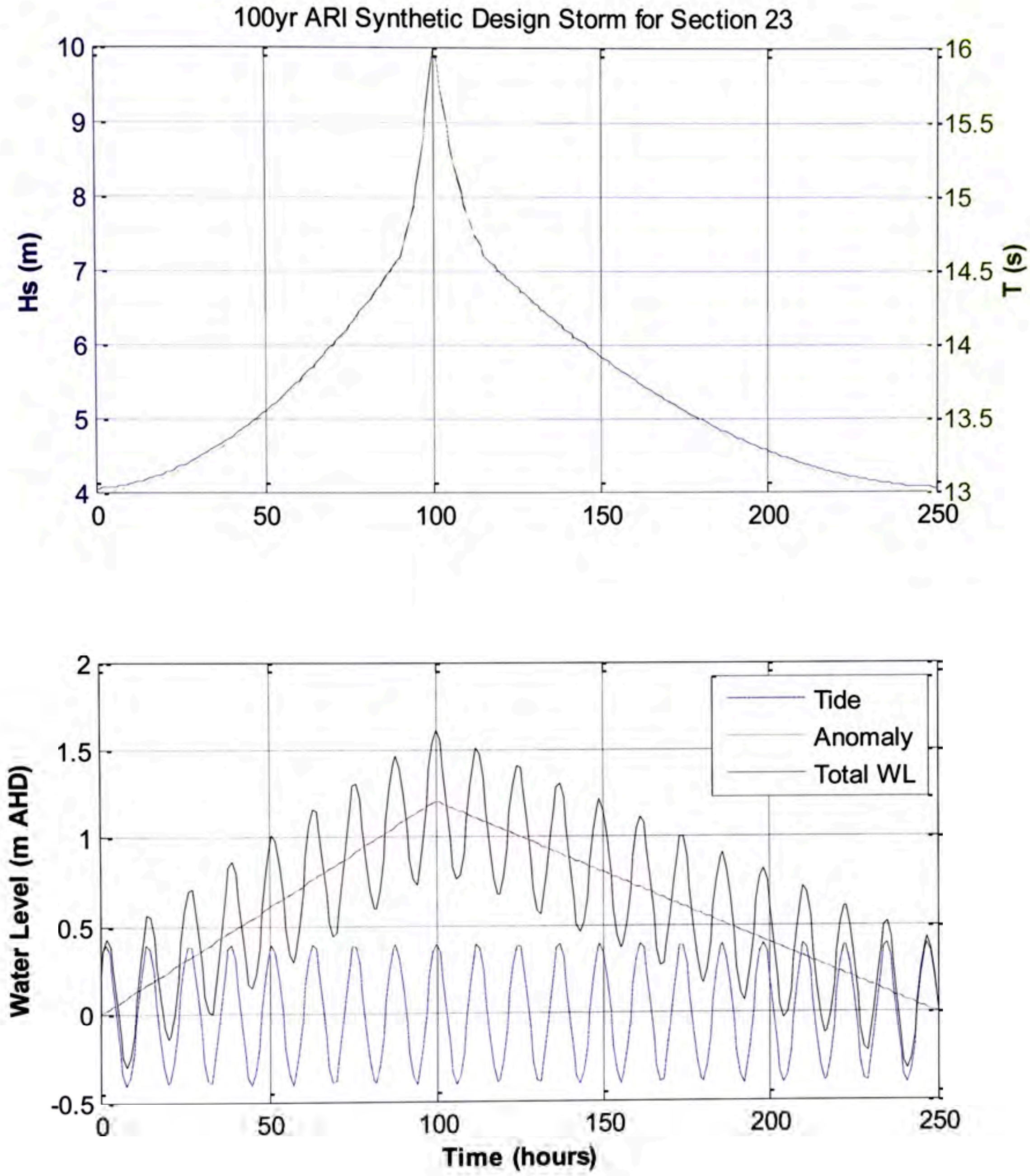

Tide
Anomaly
Total WL
Water Level (m AHD)
1.5
1
0.5
0
-0.5
-1
0
20
40
60
80
100
120
140
160
180
Time (hours)

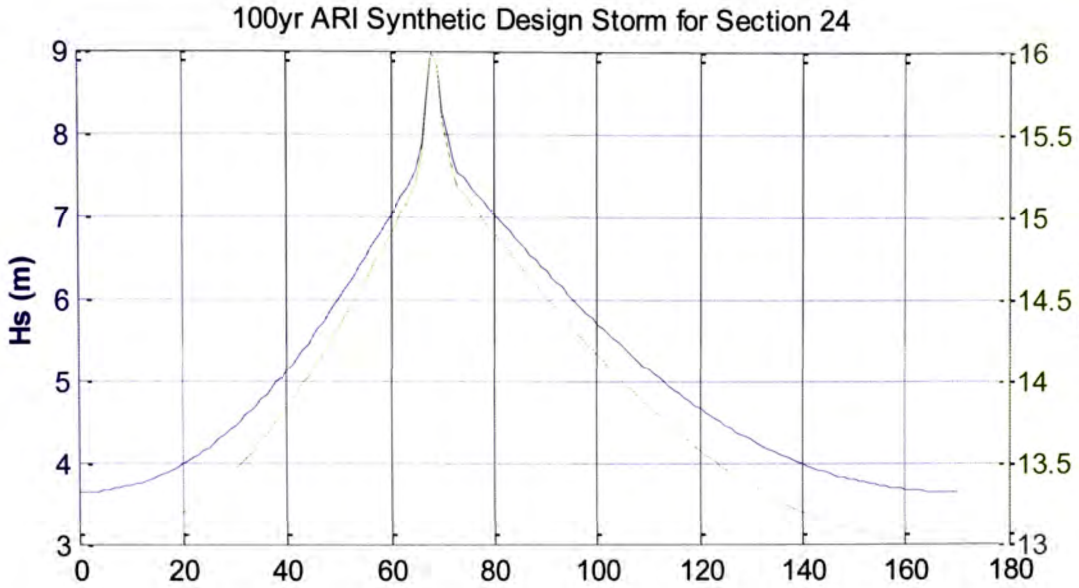

100yr ARI Synthetic Design Storm for Section 21
Hs (m)
T (s)
10
9
8
7
6
5
4
16
15.5
15
14.5
14
13.5
13
0
50
100
150
200
250

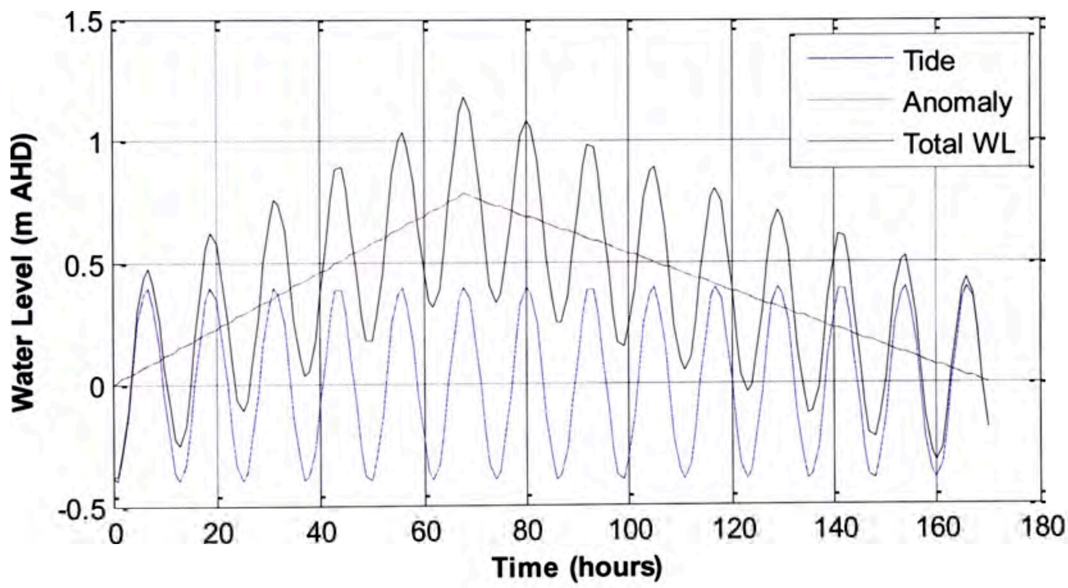

Tide
Anomaly
Total WL
Water Level (m AHD)
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
Time (hours)

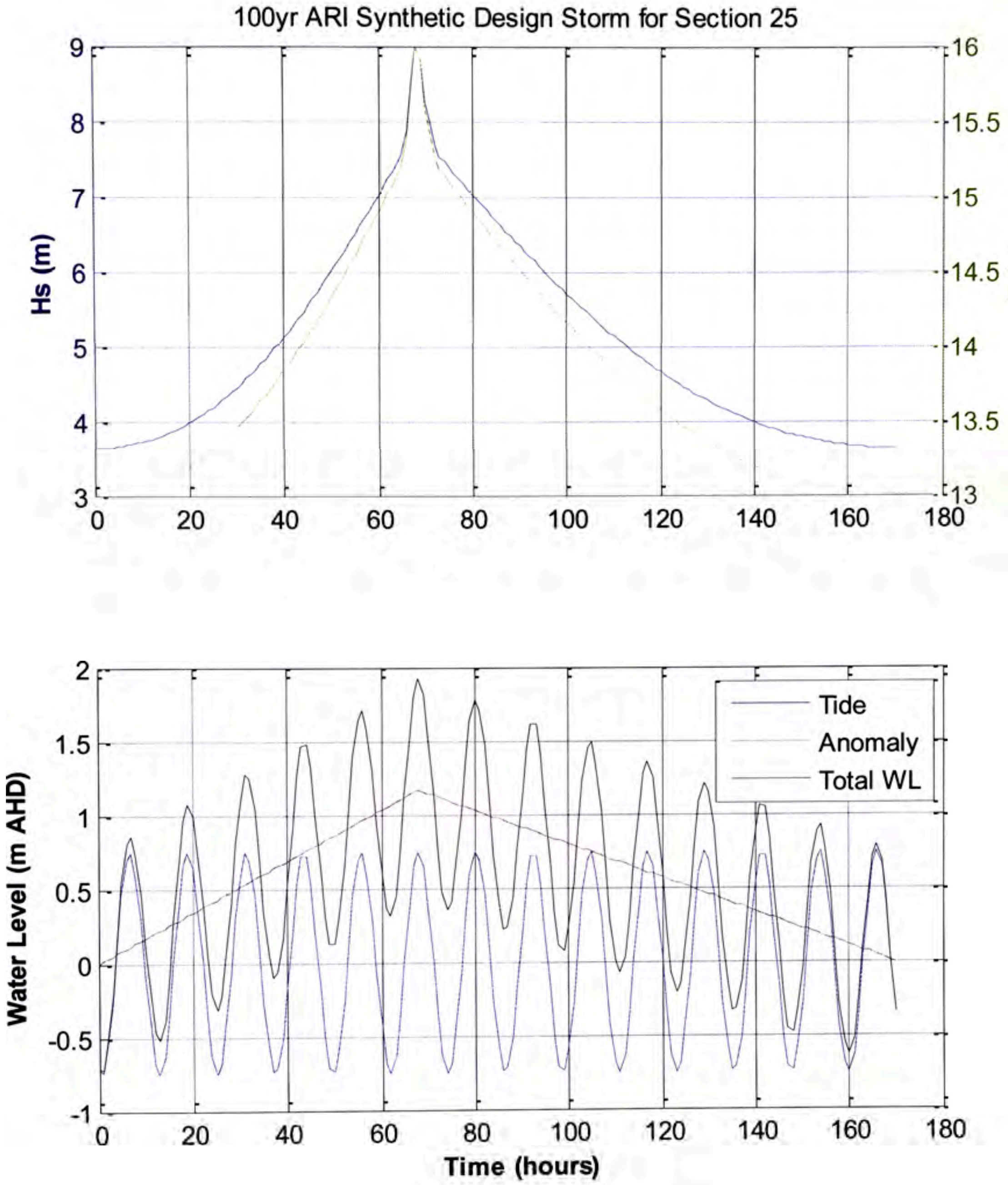

100yr ARI Synthetic Design Storm for Section 22
Hs (m)
T (s)
15
10
5
0
16
15
14
13
0
50
100
150
200
250

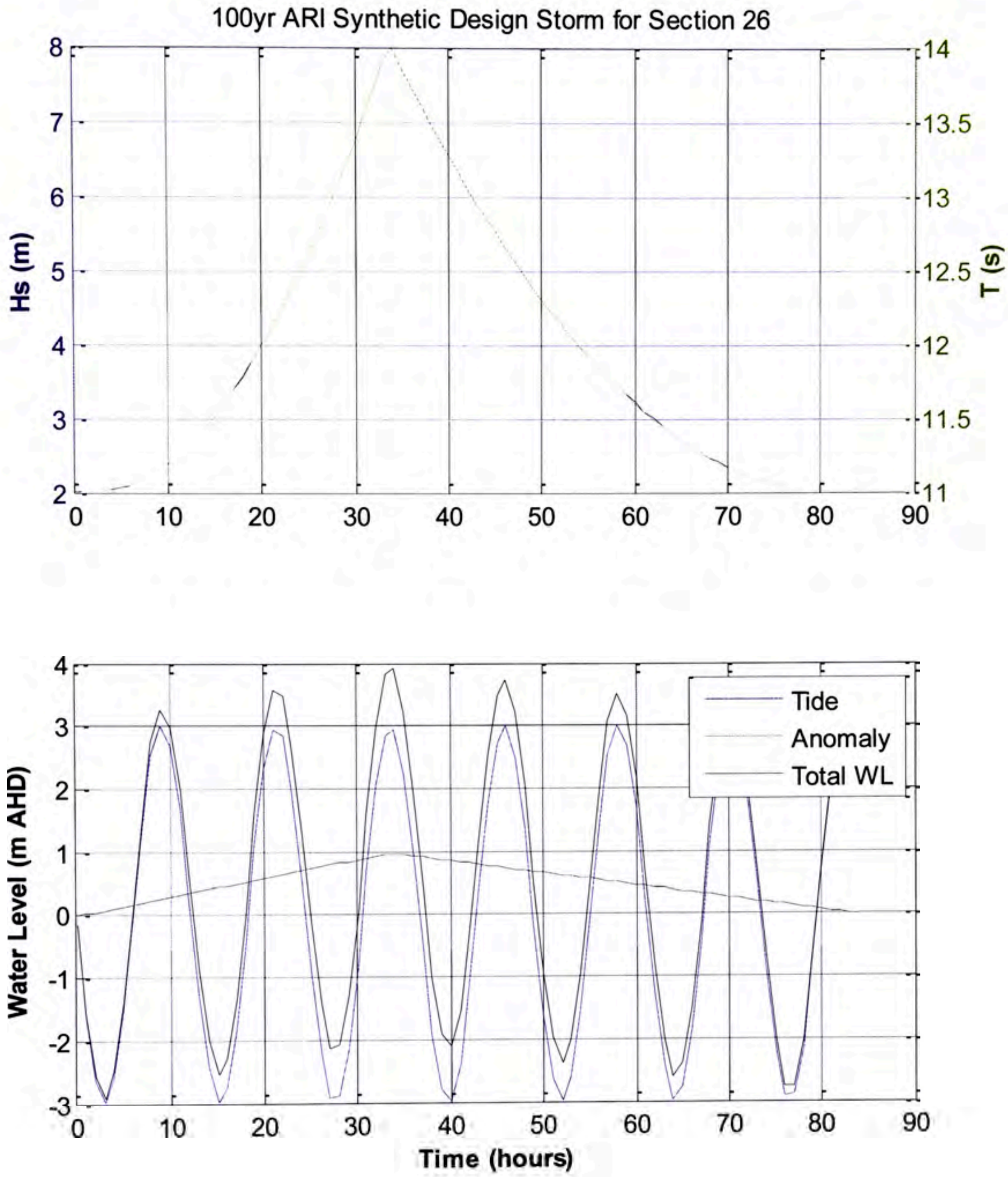

Tide
Anomaly
Total WL
Water Level (m AHD)
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
Time (hours)

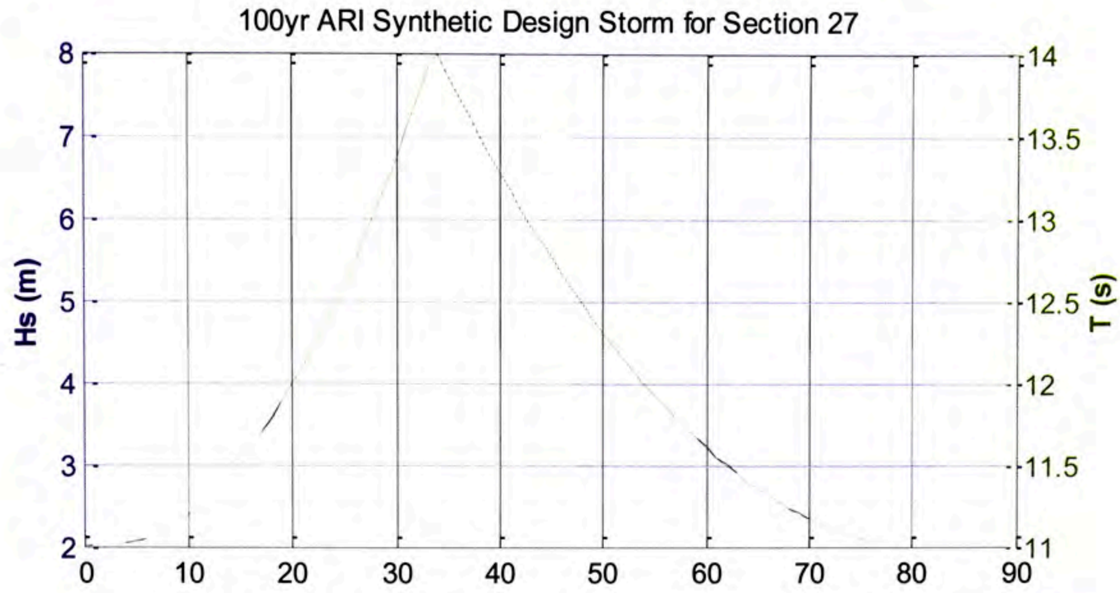

100yr ARI Synthetic Design Storm for Section 23
Hs (m)
T (s)
Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)

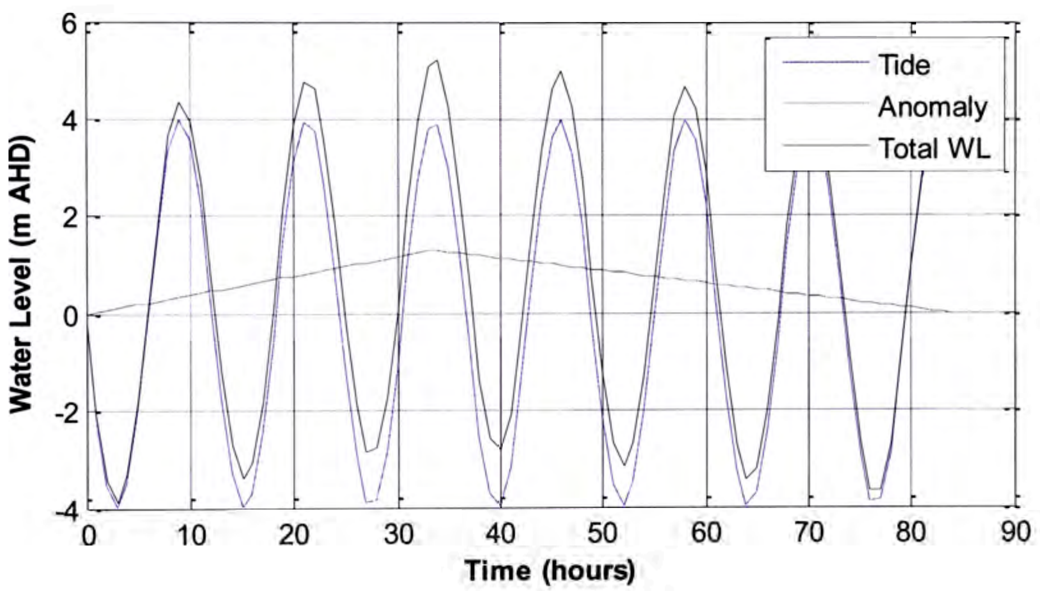

100yr ARI Synthetic Design Storm for Section 24
Hs (m)
T (s)
9
8
7
6
5
4
3
16
15.5
15
14.5
14
13.5
13
0
20
40
60
80
100
120
140
160
180

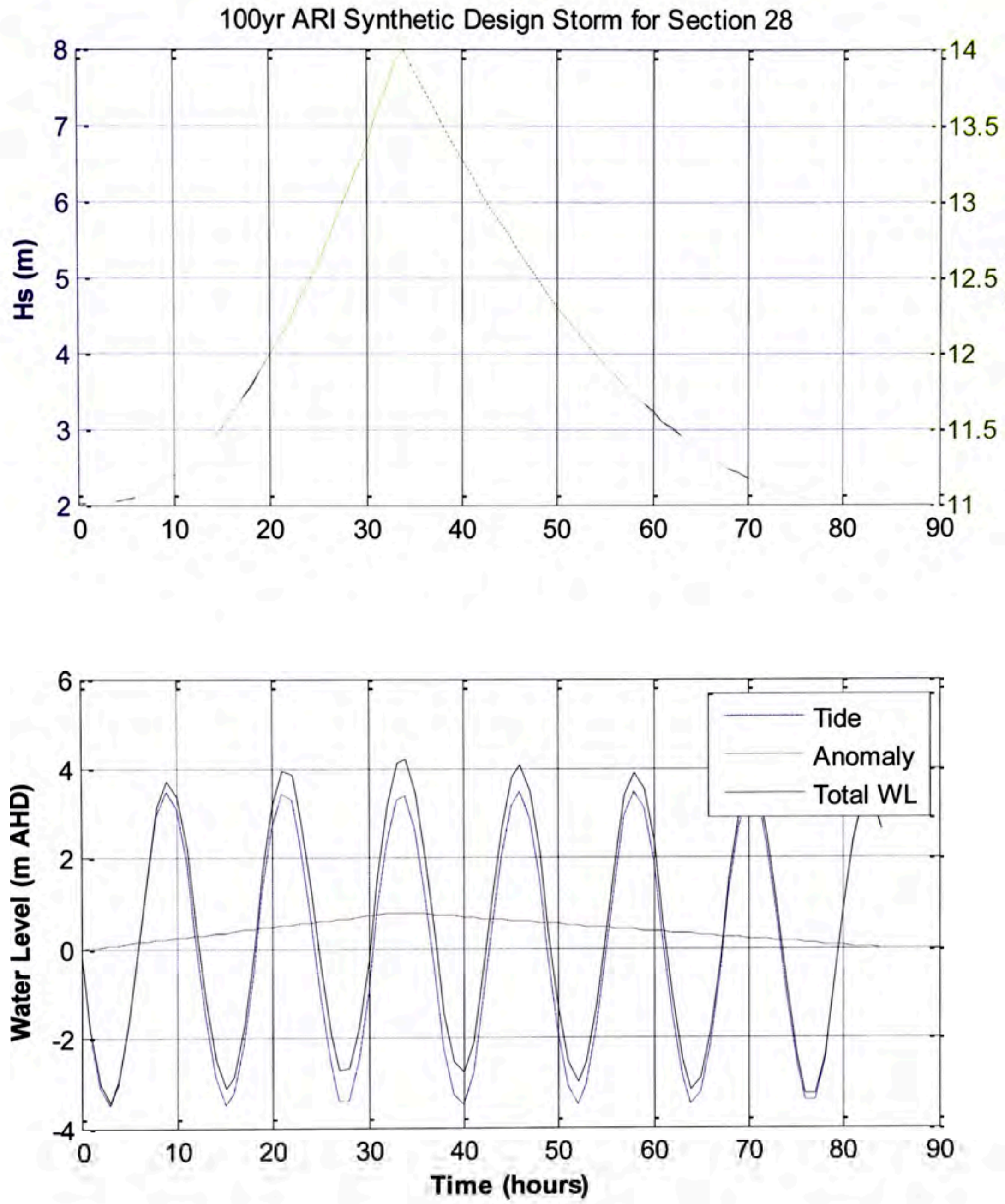

Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)
1.5
1
0.5
0
-0.5
0
20
40
60
80
100
120
140
160
180

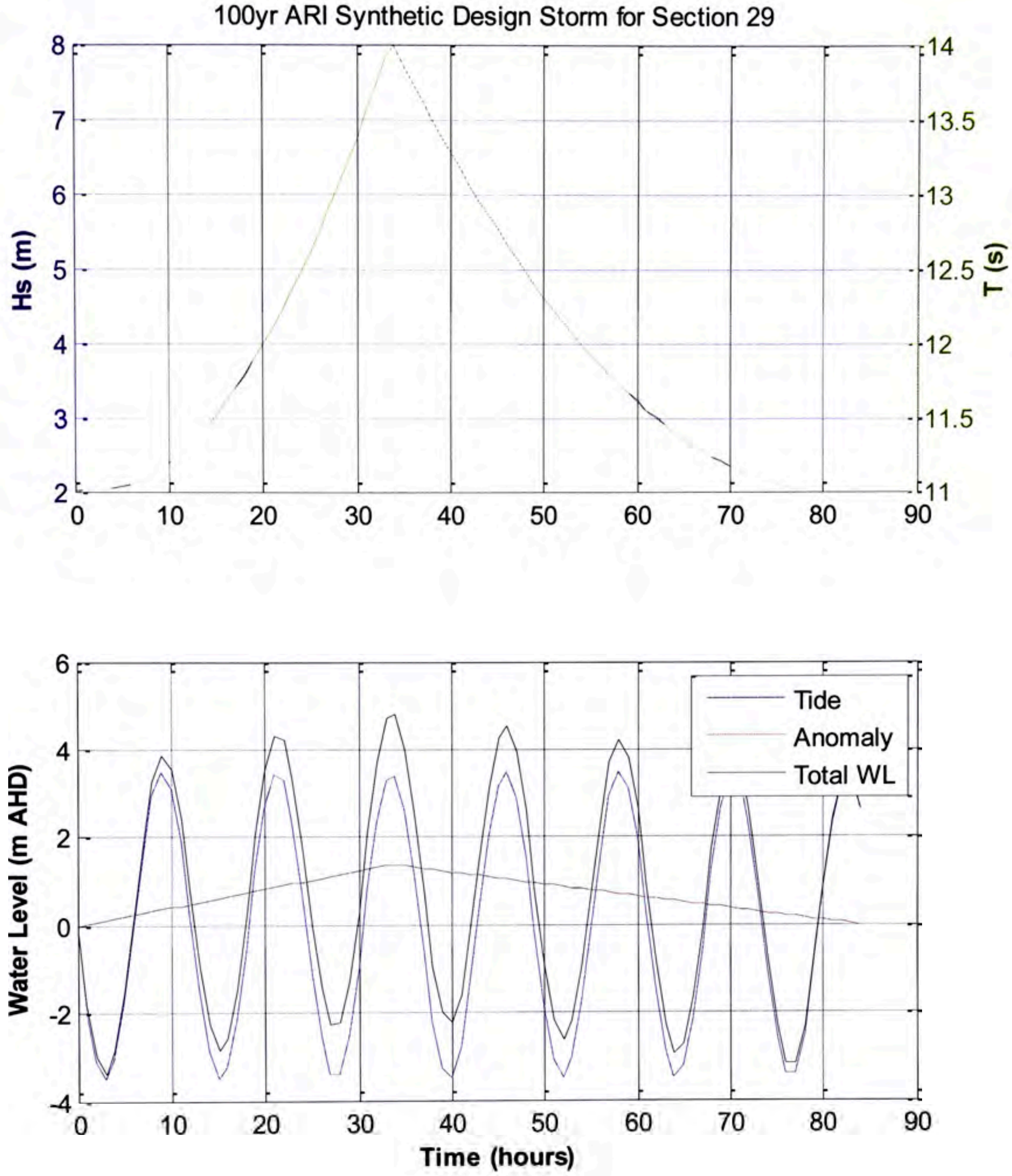

100yr ARI Synthetic Design Storm for Section 25
Hs (m)
T (s)
Tide
Anomaly
Total WL
Water Level (m AHD)
Time (hours)


100yr ARI Synthetic Design Storm for Section 26
Hs (m)
T (s)
Water Level (m AHD)
Time (hours)
Tide
Anomaly
Total WL

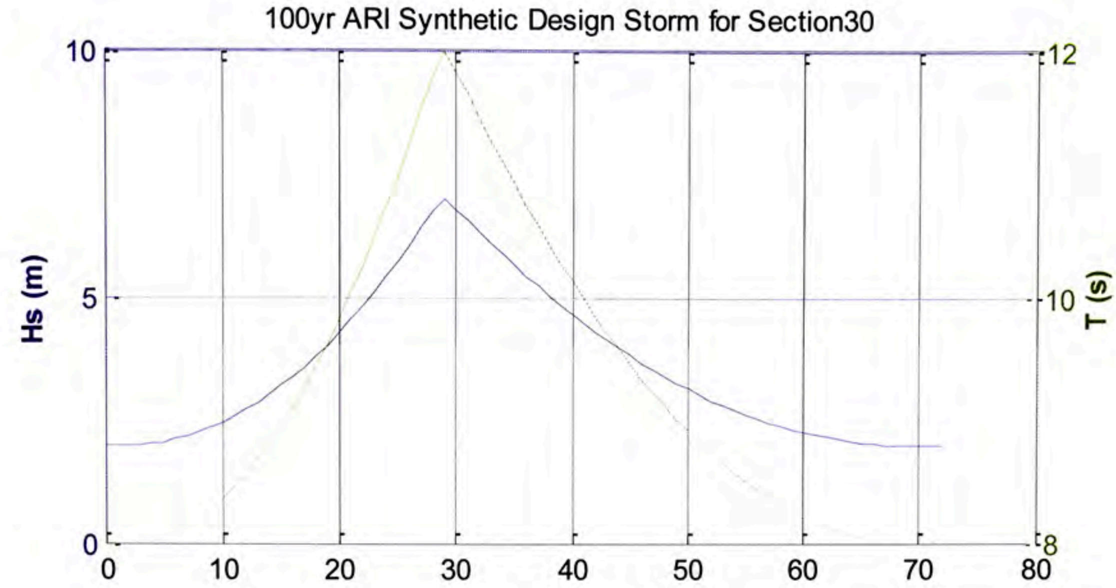

100yr ARI Synthetic Design Storm for Section 27
Hs (m)
T (s)
8
7
6
5
4
3
2
14
13.5
13
12.5
12
11.5
11
0
10
20
30
40
50
60
70
80
90

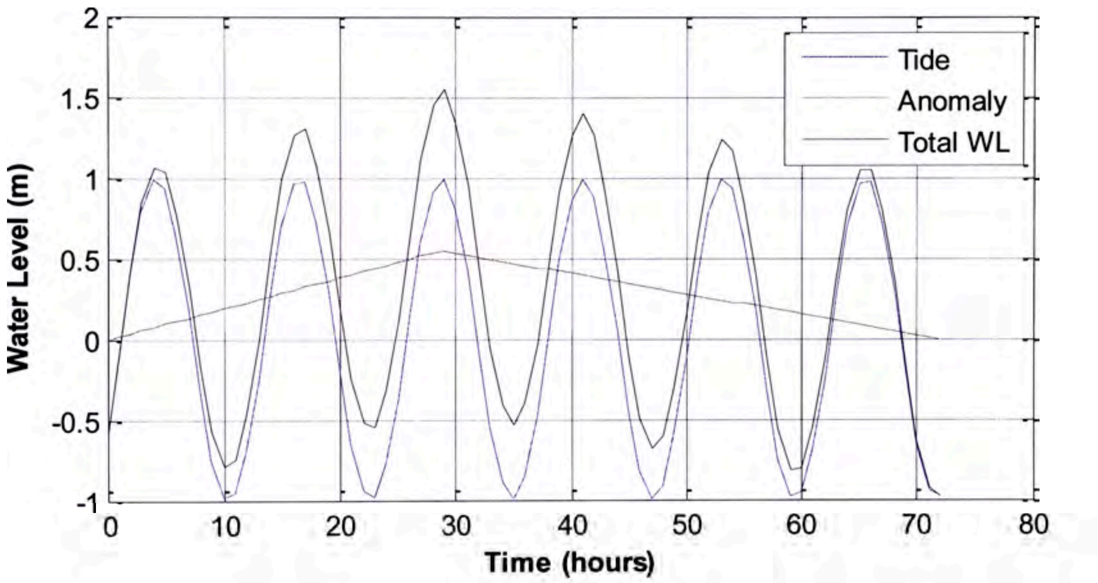

Water Level (m AHD)
Time (hours)
Tide
Anomaly
Total WL
6
4
2
0
-2
-4
0
10
20
30
40
50
60
70
80
90


100yr ARI Synthetic Design Storm for Section 28
Hs (m)
T (s)
Water Level (m AHD)
Time (hours)
Tide
Anomaly
Total WL



100yr ARI Synthetic Design Storm for Section 29
Hs (m)
T (s)
8
7
6
5
4
3
2
14
13.5
13
12.5
12
11.5
11
0
10
20
30
40
50
60
70
80
90
Water Level (m AHD)
Time (hours)
Tide
Anomaly
Total WL
6
4
2
0
-2
-4

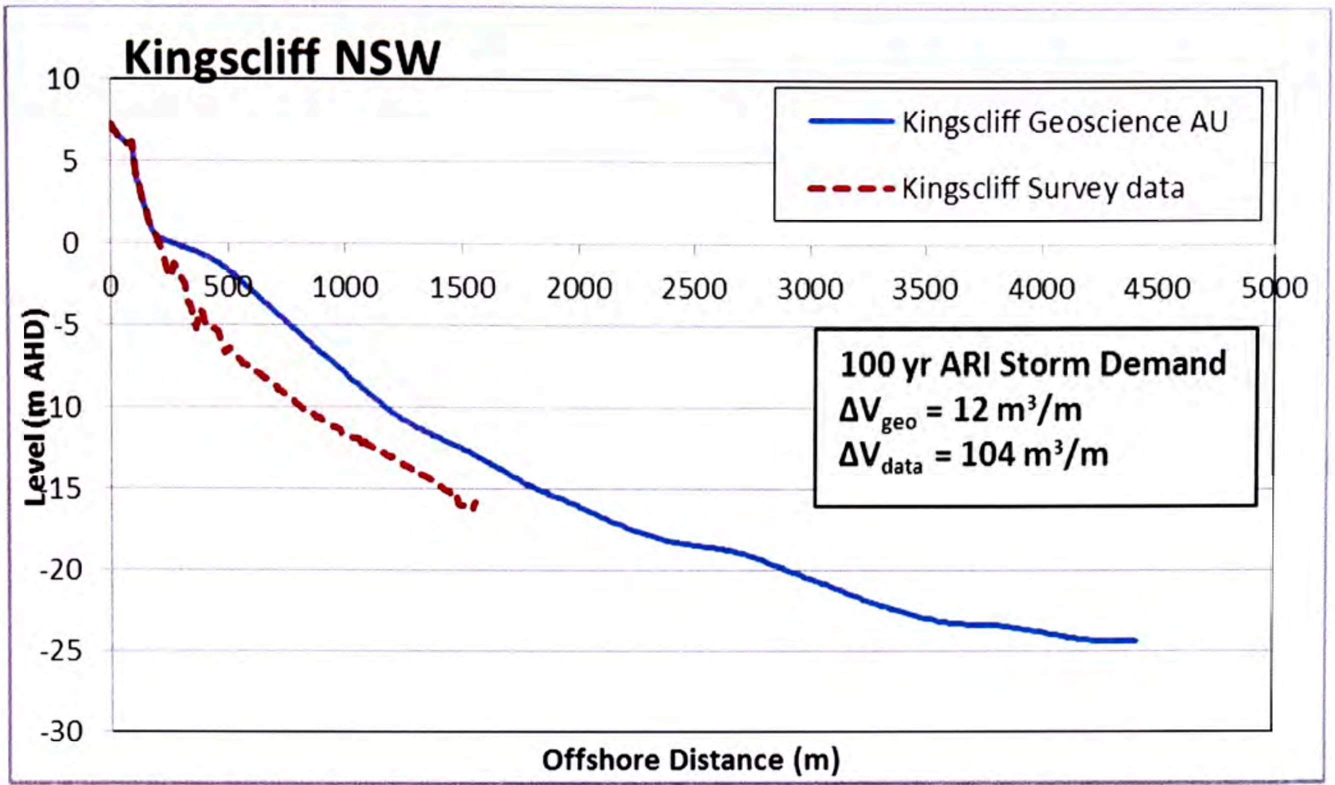

100yr ARI Synthetic Design Storm for Section30
Hs (m)
T (s)
0
5
10
8
10
12
0
10
20
30
40
50
60
70
80

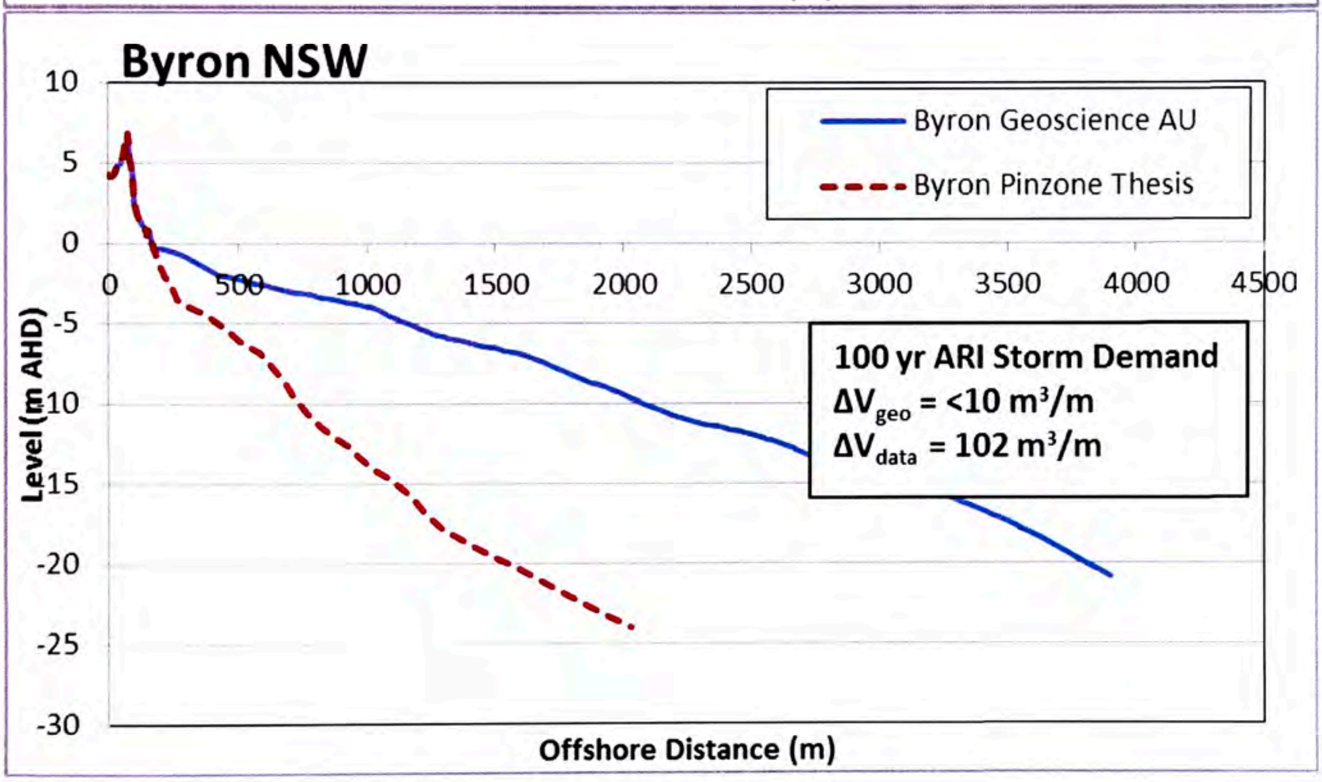

Tide
Anomaly
Total WL
Water Level (m)
Time (hours)
-1
-0.5
0
0.5
1
1.5
2
0
10
20
30
40
50
60
70
80

Appendix C Generic Design Setback Distances

Profile data provided by a number of governmental organisations mostly related to the sub-aerial beach, with detailed surveys of the surfzone and nearshore bathymetry available only at few locations. Where necessary, data was initially complemented with nearshore bathymetry derived from the analysis of bathymetric charts (Australian Bathymetry and Topography Grid, GeoScience Australia). However, the accuracy of the Geoscience bathymetric data proved inadequate for the purposes of this study. Consequently, higher quality survey data was collected from several sources and additional modelling was undertaken with the correct bathymetric data.

The figures below show plots of beach profiles at several locations. The sub-aerial profile data was derived from photogrammetric and/or survey data. The plots present nearshore bathymetric data as extrapolated from the (i)Geoscience data and from (ii)survey data. For the cases analysed, surfzone profiles derived from the Geoscience data are consistently characterised by flatter and shallower gradients which induce significant wave energy dissipation through breaking on the shallower depths. As a consequence, the initial modelling significantly under-predicted storm erosion where the Geoscience data was utilised. This may be due to interpolation between depth contours, which straightens out the concave profile of the nearshore surfzone. Differences may also occur due to changes in vertical datum and horizontal grid.


Kingscliff NSW
Kingscliff Geoscience AU
Kingscliff Survey data
100 yr ARI Storm Demand
ΔVgeo = 12 m³/m
ΔVdata = 104 m³/m
Level (m AHD)
Offshore Distance (m)
10
5
0
-5
-10
-15
-20
-25
-30
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


Byron NSW
Byron Geoscience AU
Byron Pinzone Thesis
100 yr ARI Storm Demand
ΔVgeo = <10 m³/m
ΔVdata = 102 m³/m
Level (m AHD)
Offshore Distance (m)
10
5
0
-5
-10
-15
-20
-25
-30
0
500
1000
1500
2000
2500
3000
3500
4000
4500

Appendix D Model Parameters

D1: XBeach Calibrated Model Parameters

The calibrated set of XBeach model parameters is listed below.

Physical processes:

swave	= 1
lwave	= 1
flow	= 1
sedtrans	= 1
morphology	= 1
avalanching	= 1
nonh	= 0
gwflow	= 0
q3d	= 0

Physical constants:

rho	= 1025.0000
g	= 9.8100
depthscale	= 1.0000

Wave boundary condition parameters:

instat	= jons_table
bcfile	= waves.txt
taper	= 120.0000
nmax	= 0.8000
leftwave	= neumann
rightwave	= neumann

Wave-spectrum boundary condition parameters:

random	= 0
fcutoff	= 0.0000
nspr	= 0
trepfac	= 0.8000
sprdthr	= 0.0800
oldwbc	= 0
newstatbc	= 1
correctHm0	= 1
oldnyq	= 0
Tm01switch	= 0

Flow boundary condition parameters:

front	= abs_1d
left	= wall
right	= wall
back	= wall
ARC	= 1
order	= 2.0000
carspan	= 0
freewave	= 0
epsi	= 0.0000
tidetype	= velocity

Tide boundary conditions:

tideloc	= 1
zs0file	= ***waterlevel.WL***

Discharge boundary conditions:

disch_loc_file	= None specified
disch_timeseries_file	= None specified
ndischarge	= 0
ntdischarge	= 0

Wave breaking parameters:

break	= roelvink1
gamma	= 0.5500
alpha	= 1.0000
n	= 10.0000
gammax	= 2.0000
delta	= 0.0000
fw	= 0.0000
fwcutoff	= 1000.0000
breakerdelay	= 1
shoaldelay	= 0
facsd	= 1.0000

Roller parameters:

roller	= 1
beta	= 0.1000
rfb	= 1

Wave-current interaction parameters:

wci	= 0
hwci	= 0.1000
cats	= 7.0000

Flow parameters:

bedfriction	= chezy
bedfricfile	= None specified
cf	= 0.0050
nuh	= 0.1000
nuhfac	= 1.0000
nuhv	= 1.0000
smag	= 1

Coriolis force parameters:

wearth	= 0.0417
lat	= 0.0000

Wind parameters:

rhoa	= 1.2500
Cd	= 0.0020
windfile	= None specified
windv	= 0.0000
windth	= 270.0000

Bed composition parameters:

ngd	= 1
nd	= 3
por	= 0.4000
D50	*= 0.0003 (these are site specific)*
D90	*= 0.0008 (these are site specific)*
rhos	= 2650.0000
dzg	= 0.1000
dzg1	= 0.1000
dzg2	= 0.1000
dzg3	= 0.1000
sedcal	= 1.0000
ucrcal	= 1.0000

Sediment transport parameters:

form	= vanthiel_vanrijn (no record found, default value use d)
waveform	= vanthiel
sws	= 1
lws	*= 0 (Note that lws = 1 for the Narrowneck run only)*
BRfac	= 1.0000
facsl	= 0.0000
z0	= 0.0060
smax	= -1.0000
tsfac	= 0.1000
facua	= 0.1000
facSk	= 0.1000
facAs	= 0.1000
turb	= bore_averaged
Tbfac	= 1.0000
Tsmin	= 0.2000
lwt	= 0
betad	= 1.0000
sus	= 1
bed	= 1
bulk	= 1

Morphology parameters:

morfac	= 10.0000
morfacopt	= 1
morstart	= 120.0000
morstop	*= 493200.0000 (this is storm specific)*
wetslp	= 0.3000
dryslp	= 1.0000
hswitch	= 0.1000
dzmax	= 0.0500
struct	= 0

Wave numerics parameters:

scheme	= lax_wendroff

Flow numerics parameters:

eps = 0.0500
umin = 0.0000
hmin = 0.2000
secorder = 0
oldhu = 0

Sediment transport numerics parameters:

thetanum = 1.0000
sourcesink = 0
cmax = 0.1000

Bed update numerics parameters:

frac_dz = 0.7000
nd_var = 2
split = 1.0100
merge = 0.0100

D2: SBEACH Calibrated Model Parameters

The calibrated set of SBEACH model parameters is listed in Table D.1.

Table D.1: SBEACH Calibrated Model Parameters

Coefficient / Variable	Value
X grid	Variable
Time Step	Variable
Sediment transport rate coefficient	2.2 x 10^{-6} m^4/N
Overwash transport parameter	0.005
Slope dependent transport rate coefficient	0.002 m^2/s
Transport rate decay coefficient multiplier	0.5
Water temperature	20 degrees Celsius
Seed for random number generator	4567
Random variation in wave height	20%
Landward surfzone depth	0.3 m
Effective median grain size	Variable
Avalanching angle	34 degrees

Appendix E Bruun Factors – All Methods

State	Zone	Regional Coast	Beach Type	Beach Type	B	XBeach, d	Xbeach, h*	Xbeach, L*	Xbeach, Bf	Birkemeier, d	Birkemeier, h*	Birkemeier, L*	Birkemeier, Bf	Hallermeier (inner), d	Hallermeier (inner), h*	Hallermeier (inner), L*	Hallermeier (inner), Bf	Hallermeier (outer), d	Hallermeier (inner), h*	Hallermeier (inner), L*	Hallermeier (inner), Bf	Indicated Active Slope	Suggested Bruun Factor
(-)	(-)	(-)	(-)	R=Real, P=Proxy	(m AHD)	(m AHD)	(m)	(m)	(-)	(m AHD)	(m)	(m)	(-)	(m AHD)	(m)	(m)	(-)	(m AHD)	(m)	(m)	(-)	(-)	(-)
QLD	1	Weipa –Cape York Coast	4	P	6.82	-3.92	10.74	130.74	12.17	-6.67	13.5	493	36.53	-8.43	15.26	586	38.41	-8.07	14.89	571	38.35	20	100
QLD	1	Weipa –Cape York Coast	9	P	4.98	-4	8.98	1087	121	-6.67	11.66	3660	314	-8.43	13.42	4182	311.71	-5.08	10.06	3108	308.92	20	100
QLD	2	Cairns Coast	8	R	3.43	-3.5	6.93	644	92.89	-4.81	8.24	1179	143.1	-6.21	9.65	2725	282.44	-5.64	9.07	2124	234.22	15	100
QLD	2	Cairns Coast	9	R	4.98	-4	8.98	1087	121	-4.81	9.79	2977	304.11	-6.21	11.2	3548	316.84	-5.64	10.62	3275	308.42	15	100
QLD	3	Townsville Coast	10	P	6.47	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	100
QLD	3	Townsville Coast	12	P	5.44	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	100
QLD	4	Mackay Coast	10	R	6.47	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	100
QLD	4	Mackay Coast	12	R	5.44	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	100
QLD	5	Gladstone Coast (excl Agnes Water)	10	R	2.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	100
QLD	5	Gladstone Coast (excl Agnes Water)	12	R	4.07	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	100
QLD	6	Fraser-Gold Coast	2	R	7.68	-13.46	21.14	637.9	30.17	-7.82	15.5	452	29.17	-10.14	17.81	545	30.6	-15.07	22.75	825	36.27	30	50
QLD	6	Fraser-Gold Coast	3	R	4.13	-11.72	15.85	930.7	58.73	-7.82	11.95	738	61.77	-10.14	14.26	882	61.84	-15.07	19.2	1259	65.58	60	50
QLD	6	Fraser-Gold Coast	4	P	7.21	-11.72	18.94	804.56	42.49	-7.82	15.03	556	36.99	-10.14	17.35	664	38.28	-15.41	22.63	1062	46.94	45	50
NSW	7	Coffs Harbour-Tweed Coast	2	P	7.68	-13.46	21.14	637.9	30.17	-7.67	15.35	448	29.19	-9.99	17.66	541	30.63	-39.13	46.81	2767	59.11	30	50
NSW	7	Coffs Harbour-Tweed Coast	3	P	4.13	-11.72	15.85	930.7	58.73	-7.67	11.8	729	61.8	-9.99	14.11	877	62.15	-39.13	43.26	2525	58.37	60	50
NSW	7	Coffs Harbour-Tweed Coast	4	R	7.21	-11.72	18.94	804.56	42.49	-7.67	14.88	550	36.96	-9.99	17.2	660	38.38	-40.04	47.26	3987	84.37	45	50
NSW	8	Coffs Harbour-Cape Howe Coast	2	P	7.68	-12.1	19.78	559.85	28.31	-7.74	15.42	448	29.06	-10.06	17.73	541	30.51	-39.2	46.88	2776	59.21	30	50
NSW	8	Coffs Harbour-Cape Howe Coast	3	R	9.09	-18.17	27.26	637.42	23.39	-7.74	16.83	765	45.45	-10.06	19.15	1044	54.53	-31.18	40.27	3506	87.06	50	50
NSW	8	Coffs Harbour-Cape Howe Coast	4	R	6.26	-9.61	15.87	339.51	21.4	-7.74	14	344	24.58	-10.06	16.31	457	28.02	-27.2	33.45	1500	44.84	40	50
NSW	8	Coffs Harbour-Cape Howe Coast	5	R	2.57	-11.41	13.98	349.28	24.98	-7.74	10.31	283	27.44	-10.06	12.63	357	28.27	-27.2	29.77	2098	70.48	35	50
NSW	8	Coffs Harbour-Cape Howe Coast	6	R	5.99	-8	13.99	288.13	20.6	-7.74	13.74	417	30.36	-10.06	16.05	721	44.92	-37.83	43.82	4162	94.97	30	50
VIC	9	East Gippsland Coast	2	R	4.84	-7.43	12.26	413.8	33.74	-8.26	13.09	526	40.18	-10.66	15.49	712	45.96	-48.55	53.38	12141	227.43	35	50
VIC	9	East Gippsland Coast	3	P	9.09	-15.37	24.46	567.37	23.19	-8.26	17.35	838	48.31	-10.66	19.75	1113	56.37	-44.55	53.64	5076	94.62	30	50
VIC	10	South Gippsland – Mornington Pen Coast	2	R	14.99	-12.35	27.35	608.12	22.24	-8.61	23.6	519	21.99	-11.01	26	665	25.58	-53.26	68.25	2893	42.39	25	50
VIC	10	South Gippsland – Mornington Pen Coast	3	P	9.09	-15.37	24.46	567.37	23.19	-8.61	17.7	872	49.28	-11.01	20.1	1148	57.12	-44.91	54	5111	94.66	30	50
VIC	11	Port Phillip Bay Coast	6	R	4.1	-1.7	5.8	903	155.69	-3.15	7.25	312	43.06	-4.08	8.18	80	9.78	-1.85	5.95	370	62.19	60	100
VIC	12	Lonsdale to Lorne Coast	2	P	14.99	-12.35	27.35	608.12	22.24	-8.73	23.72	526	22.18	-11.13	26.12	553	21.17	-53.37	68.37	2814	41.16	30	50
VIC	12	Lonsdale to Lorne Coast	4	P	7.21	-6.52	13.73	307.33	22.38	-8.73	15.94	601	37.71	-11.13	18.34	717	39.1	-53.37	60.59	5692	93.95	40	50
VIC	12	Lonsdale to Lorne Coast	9	R	13.1	-5.5	18.6	292	15.7	-8.73	21.83	1066	48.84	-11.13	24.23	1543	63.69	-58.13	71.23	4365	61.28	20	50
VIC	13	Port Campbell-Portland Coast	1	R	22.35	-17	39.35	1221	31.03	-11.06	33.41	929	27.8	-14.35	36.7	1091	29.73	-82.37	104.72	4958	47.35	20	50
VIC	13	Port Campbell-Portland Coast	3	R	11.83	-16.46	28.29	1061.21	37.51	-11.06	22.89	908	39.67	-14.35	26.17	1070	40.88	-82.37	94.2	4937	52.41	40	50
VIC	13	Port Campbell-Portland Coast	4	R	11.36	-15	26.36	1316	49.93	-11.06	22.42	856	38.18	-14.35	25.71	1228	47.77	-118.88	130.24	12837	98.57	50	50
TAS	14	North Tasmania Coast	5	R	2.47	-2.58	5.05	284.58	56.31	-8.65	11.12	1260	113.34	-11.05	13.52	1704	126.06	-63.23	65.7	7148	108.8	50	50
TAS	14	North Tasmania Coast	9	P	5	-2	7	74	10.57	-8.65	13.65	4225	309.59	-11.05	16.05	4908	305.84	-48.94	53.94	15047	278.96	20	50
TAS	15	East Tasmania Coast	3	P	9.09	-18.17	27.26	637.42	23.39	-9	18.08	918	50.76	-11.72	20.81	1229	59.06	-44.76	53.85	5099	94.69	30	50
TAS	15	East Tasmania Coast	4	P	6.26	-9.91	16.17	359.34	22.22	-9	15.25	385	25.25	-11.72	17.97	563	31.32	-48.75	55.01	2872	52.21	40	50
TAS	15	East Tasmania Coast	5	P	2.57	-11.7	14.27	372.67	26.12	-9	11.57	323	27.93	-11.72	14.29	385	26.94	-48.75	51.32	5370	104.63	40	50
TAS	15	East Tasmania Coast	6	P	5.99	-8	13.99	288.13	20.6	-9	14.99	551	36.76	-11.72	17.71	987	55.72	-48.75	54.75	5288	96.59	40	50
TAS	15A	Storm Bay	4	P	11.36	-1.92	13.28	52.5	3.95	-9.01	20.38	681	33.42	-11.74	23.1	910	39.39	-73.43	84.79	7790	91.87	20	50
TAS	15A	Storm Bay	7	R	3.5	-5	8.5	300	35.29	-9.01	12.51	3512	280.64	-11.74	15.24	4897	321.36	-53.13	56.63	27095	478.48	40	50
TAS	16	West – South Tasmania Coast	1	P	22.35	-3.94	26.29	267.47	10.17	-13.05	35.4	1033	29.18	-17.02	39.37	1221	31.01	-94.82	117.17	5669	48.38	20	50
TAS	16	West – South Tasmania Coast	2	P	13.64	-18.55	32.19	1168.28	36.29	-13.05	26.7	1009	37.8	-17.02	30.66	1197	39.04	-94.82	108.47	5445	50.2	40	50
SA	17	Kingston- Goolwa Coast	1	P	22.35	-4.07	26.42	275.6	10.43	-11	33.35	924	27.71	-14.28	36.63	1091	29.78	-82.31	104.66	4952	47.32	20	50
SA	17	Kingston- Goolwa Coast	2	R	7.27	-3.6	10.87	369.05	33.95	-11	18.27	1420	77.74	-14.28	21.55	1778	82.51	-111.15	118.42	20233	170.86	40	50
SA	18	Gulf St Vincent-Spencer Gulf Coast	7	R	6.76	-5	11.76	980	83.31	-3.75	10.51	593	56.4	-4.68	11.44	925	80.84	-12.11	18.88	3372	178.65	80	100
SA	19	Port Lincoln – Eucla Coast	1	P	22.35	-4.2	26.55	283.99	10.7	-9.92	32.27	870	26.96	-12.77	35.12	1018	28.99	-79.36	101.71	4786	47.06	20	50
SA	19	Port Lincoln – Eucla Coast	3	P	9.09	-18.58	27.67	674.59	24.38	-9.92	19.01	1021	53.71	-12.77	21.86	1360	62.22	-69.7	78.79	8016	101.74	30	50
WA	20	Eucla – Cape Pasley Coast	2	P	14.99	-12.55	27.54	633.22	22.99	-9.77	24.77	1009	40.74	-12.62	27.62	1336	48.38	-69.55	84.55	8004	94.67	30	100
WA	20	Eucla – Cape Pasley Coast	3	P	9.09	-18.58	27.67	674.59	24.38	-9.75	18.84	2242	118.98	-12.6	21.69	2983	137.52	-88.16	97.25	18239	187.55	40	100
WA	21	Esperance Coast	1	P	22.35	-4.2	26.55	283.99	10.7	-11.21	33.56	934	27.83	-14.53	36.88	1100	29.83	-82.29	104.64	4952	47.33	20	100
WA	21	Esperance Coast	3	P	9.09	-18.58	27.67	674.59	24.38	-11.21	20.3	1171	57.69	-14.53	23.62	1567	66.35	-72.24	81.33	8309	102.17	30	100
WA	21	Esperance Coast	4	R	6.11	-10.57	16.68	849.26	50.91	-11.21	17.32	865	49.94	-14.53	20.64	1253	60.71	-118.8	124.91	12826	102.68	60	100
WA	22	Albany – Cape Naturaliste Coast	1	P	22.35	-4.33	26.68	292.65	10.97	-11.94	34.29	971	28.32	-15.48	37.83	1146	30.29	-85.52	107.87	5136	47.61	20	100

State	Zone	Regional Coast	Beach Type	Beach Type	B	XBeach, d	Xbeach, h*	Xbeach, L*	Xbeach, Bf	Birkemeier, d	Birkemeier, h*	Birkemeier, L*	Birkemeier, Bf	Hallermeier (inner), d	Hallermeier (inner), h*	Hallermeier (inner), L*	Hallermeier (inner), Bf	Hallermeier (outer), d	Hallermeier (inner), h*	Hallermeier (inner), L*	Hallermeier (inner), Bf	Indicated Active Slope	Suggested Bruun Factor
(-)	(-)	(-)	(-)	R=Real, P=Proxy	(m AHD)	(m AHD)	(m)	(m)	(-)	(m AHD)	(m)	(m)	(-)	(m AHD)	(m)	(m)	(-)	(m AHD)	(m)	(m)	(-)	(-)	(-)
WA	22	Albany – Cape Naturaliste Coast	3	P	9.09	-18.88	27.97	712.35	25.47	-11.94	21.03	1251	59.48	-15.48	24.57	1685	68.58	-75.09	84.17	8649	102.75	40	100
WA	23	Cape Naturaliste - Geraldton	4	R	4.86	-6.6	11.46	647.14	56.46	-11.4	16.26	883	54.29	-14.72	19.58	1278	65.26	-105.34	110.2	11328	102.79	60	100
WA	23	Cape Naturaliste - Geraldton	5	R	5.18	-13.05	18.23	1153.19	63.26	-11.4	16.58	523	31.55	-14.72	19.9	2198	110.47	-54.06	59.24	8407	141.92	70	100
WA	24	Geraldton-Carnarvon Coast	2	P	14.99	-12.55	27.54	633.22	22.99	-10.05	25.04	569	22.72	-12.94	27.94	786	28.13	-76.01	91	3754	41.25	30	100
WA	24	Geraldton-Carnarvon Coast	3	P	9.09	-18.58	27.67	674.59	24.38	-10.05	19.14	1032	53.92	-12.94	22.03	1373	62.32	-64	73.09	7348	100.53	40	100
WA	25	Cape Cuvier to North West Cape Coast	3	P	9.09	-18.58	27.67	674.59	24.38	-10.16	19.25	1055	54.79	-13.06	22.15	1398	63.12	-64.12	73.21	7360	100.54	40	100
WA	26	Exmouth to Dampier Coast	2	R	13.25	-8.95	22.2	2489.74	112.14	-7.93	21.18	455	21.49	-10.2	23.45	550	23.46	-39.64	52.89	2810	53.13	100	100
WA	26	Exmouth to Dampier Coast	13	P	5.44	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	100
WA	27	Port Headland to Broome Coast	12	P	5.44	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	100
WA	28	Kimberley Coast	13	P	5.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	100
NT	29	Darwin-Arnhem Land Coast	7	R	6.85	-4.7	11.55	823	71.26	-9.28	16.13	4065	252.06	-11.55	18.4	4599	250.01	-14.32	21.17	5178	244.63	80	100
NT	29	Darwin-Arnhem Land Coast	10	R	6.7	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	100
NT	29	Darwin-Arnhem Land Coast	12	R	5.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	100
NT	30	East Arnhem Land-Weipa Coast	4	P	6.82	-3.92	10.74	130.74	12.17	-5.77	12.59	415	32.96	-7.53	14.35	541	37.69	-14.83	21.65	1018	47.01	30	100
NT	30	East Arnhem Land-Weipa Coast	7	P	6.85	-2.23	9.08	84.33	9.29	-5.77	12.62	1074	85.12	-7.53	14.38	1377	95.77	-12.56	19.41	4811	247.9	20	100
NT	30	East Arnhem Land-Weipa Coast	12	P	5.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	100

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