MODELLING COASTAL PROCESSES AND HAZARDS TO ASSESS SEA LEVEL RISE IMPACTS FOR INTEGRATION INTO A PLANNING SCHEME

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Abstract

This paper details the range of coastal processes and hazards considered in estimating coastal risk for Clarence City, Tasmania. The work follows on from a first pass assessment undertaken for the entire state of Tasmania by Chris Sharples. The processes considered in this paper include tides and storm surge, extreme open ocean waves, swell wave penetration and local wind waves. Hazards quantified include erosion, recession, estuary entrance stability, wind blown sand, inundation and sea level rise. Most of these processes and hazards already exist, and are expected to become more severe with sea level rise. Estimation techniques, modelling and uncertainties in quantifying each of these processes and hazards are presented. The modelling of physical processes was integrated with separate socio-economic studies. The intended outcome is a better incorporation of both present day and future coastal hazards into Council's planning scheme and to provide a template for assessment in other local government areas.

Key Words: Sea level rise, coastal hazards, coastal processes, coastal setbacks, climate change, coastal modelling, Clarence, Hobart, Tasmania

Introduction

The City of Clarence is located to the east of Hobart (Figure 1). The purpose of this study is to identify localities and infrastructure within Clarence City which may be vulnerable to coastal hazards, both at present and due to sea level rise and climate change into the future. Coastal hazards have been assessed for the present day, 2050 and 2100. The study also investigates adaptive management options in response to present and future coastal hazards.

Coastal Processes and Hazards

There is some overlap as to what may be defined as a coastal process versus a coastal hazard. In this paper, coastal hazards are defined as the consequences of coastal processes which affect the built environment or the safety of people. The following coastal processes are applicable to the study area were considered:

- Astronomical tides (predicted tides).
- Tidal anomalies, through:
    - Barometric setup.
    - Wind setup.

    - Coastally trapped waves.
- Ocean swell waves.
- Local wind waves.
- Wave setup.
- Wave runup and overtopping.
- Longshore sand transport (littoral drift).
- Onshore-offshore sand transport (beach erosion and recovery).

The following coastal hazards may impact the study area:

- Beach erosion.
- Shoreline recession (long term change due to waves or sediment budget).
- Unstable creek or lake entrances.
- Wind blown sand.
- Coastal inundation.
- Slope, cliff or bluff instability (not assessed – see below).
- Stormwater erosion.
- Climate change, including sea level, changes to waves, wind and rainfall.
- Tsunami (not considered in detail).
- Seawater ingress into groundwater table displacing fresh water.
- Potential acid sulfate soils (not assessed in this study).

Considerable discussion was provided in Sharples (2006) on slope instability, including citing previous landslide risk studies undertaken. A separate detailed geotechnical assessment could be undertaken as resources become available, but was not part of this study. Tsunami hazard is being assessed by the SES, BOM and Geoscience Australia.

Climate Change Variables

NCCOE (2004) listed six key climate change environmental variables applicable to coastal engineering, namely:

1. Mean Sea Level
2. Ocean Currents and Temperature
3. Wind Climate
4. Wave Climate
5. Rainfall/Runoff
6. Air Temperature.

A growing body of research has found that ocean acidity (pH) may be changing, and this could be considered an additional key variable.

Quantitative projections and scenarios for most of these variables are less robust and more speculative than for sea level rise. This paper is limited to the key climate change variable of mean sea level, and considers it in combination with the present day extremes for wave climate. NCCOE (2004) also listed 13 secondary or process climate change variables applicable to coastal engineering, namely:

1. Local Sea Level
2. Local Currents
3. Local Winds
4. Local Waves
5. Effects on Structures
6. Groundwater
7. Coastal Flooding
8. Beach Response
9. Foreshore Stability
10. Sediment Transport
11. Hydraulics of Estuaries
12. Quality of Coastal Waters
13. Ecology.

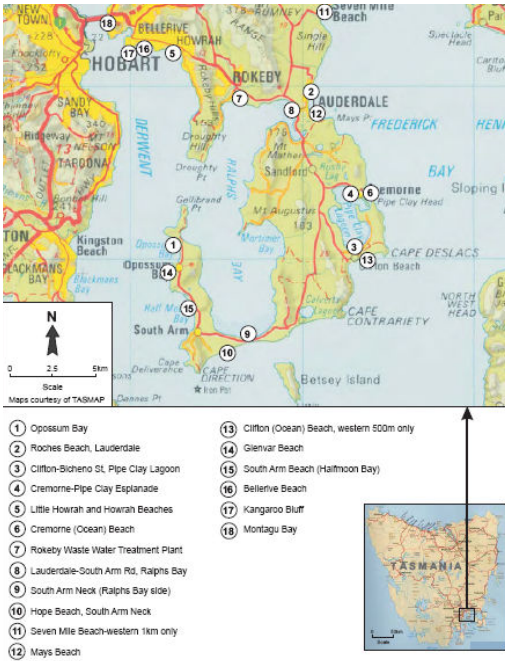


Figure 1: Location

Design Event

It is stressed that the design event is different to the planning timeframe. There are persuasive arguments and related design standards which support a design event of greater than 100 years average recurrence interval (ARI) for a 100 year planning period (eg AS 4997-2005; Delta Committee, 1962) . These suggest an appropriate range of 1,000 to 10,000 year ARI. However, for private housing a design ARI of 100 years is generally used and is consistent with flood policy in Tasmania. It is noted that over a 100 year planning timeframe, a 100 year ARI event has a 63% chance of being exceeded.

Despite this caution, for consistency with current flood policy and common practice, a 100 year ARI design event has been used as the basis for hazard assessment in this study.

Extreme Water Levels

An extensive analysis of the Hobart tide gauge data was undertaken by Hunter (2007). Hunter's analysis found that while the gauge spanned 43 years of data (1/1/1960 to 31/12/2004 at the time of analysis), only 31.8 years of data were useable. Hunter's analysis covered measured water levels (astronomical tide plus tidal anomaly) and did not separate out the tidal anomaly.

Ocean Swell Waves

Ocean swell wave data was considered from three sources, namely:

- A non-directional wave buoy has been operated off Cape Sorrell western Tasmania by the Bureau of Meteorology since 1998, and by CSIRO from 1985 to 1992.
- A non-directional wave buoy has operated off Eden NSW since 8 February 1978 (Lord and Kulmar, 2000; Kulmar et al, 2005) and has a 81% data capture rate.
- The ERA-40 and C-ERA datasets of hindcast global wave heights from global weather models for 45 years (Caires and Sterl, 2005; Hemer et al, 2007).

The largest waves for the Cape Sorell buoy have a south-west to north-west direction. Such waves would lose substantial height in reaching the Clarence coast through refraction and diffraction (see below). The largest waves for the Eden buoy have a south to south-east direction. Such waves would not undergo substantial refraction to reach the most exposed beaches on the Clarence coast (see below), but as shown below, the south to south-east waves are smaller offshore.

A summary of wave data and statistics is shown in Table 1.

Table 1: Summary of extreme offshore waves

ARI (years)	**Eden NSW**	**Cape Sorell**
Record length	25 years	15 years
Maximum reliable ARI (4 times length)	100 years	60 years
	Hs (m)	Hs (m)
1	5.3	9.0
5	5.8	10.5
10	6.4	11.0
20	7.4	11.5
50	8.1	12.3
100	8.5	*13.0*

Wave Transformation Modelling

Offshore swell waves reaching the Clarence coast may be modified by the processes of refraction, diffraction, bed friction and breaking. The model SWAN (Simulating WAves Nearshore) was used to quantify the change in wave conditions from a deepwater boundary beyond Storm Bay to the nearshore zone of the Clarence coast. An example of SWAN modelling of ocean swell is shown in Figure 2.

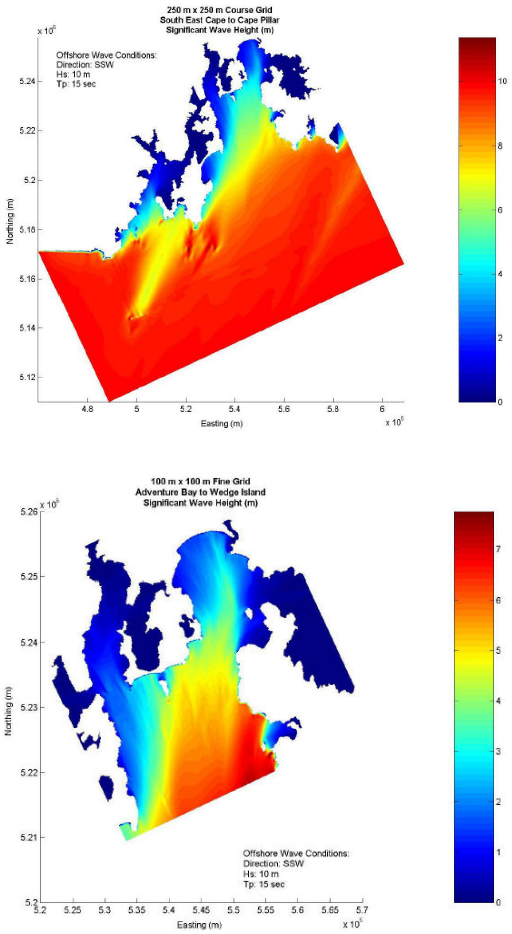


Figure 2: SWAN modelling of ocean swell penetration (250 m grid top, 100 m grid bottom)

Local Wind Waves

Wind wave heights were estimated using the principles of SPM (1984), the US Army Coastal Engineering Manual (CEM: EM 1110-2-1100, 2002) and the software ACES version 4.0.3.1).

Wind Setup

During times of high wind, surface water is transported downwind through surface drag. In an enclosed bay, this water may “pile up” at the downwind end of the bay. Some of this piled up water may return as bed flow, however, if the bay is shallow, the shear between the bed return flow and the surface water may restrict return flow, resulting in noticeable wind setup.

The process occurs at different scales. The regional scale process is included in measurements on the Hobart tide gauge. Local wind setup in Clarence in excess of the regional scale process would be restricted to shallow bays such as Pipe Clay Lagoon and Ralphs Bay. The software CRESS (Version 4.0.2) and equations from Dean and Dalrymple (1991, p 160) was used to model wind setup.

Long term change to the bays, such as progressive infilling or deepening would alter the wind setup values calculated in this report. Ongoing monitoring is the only method of observing such change.

Wave Setup, Wave Runup and Inundation

Wave setup is defined as the quasi-steady increase in water level inside a surf zone due to the conversion of part of the waves’ kinetic energy into potential energy. Numerical models such as Dally, Dean and Dalrymple (1984) are available to calculate wave setup. For an initial engineering approximation on a sandy beach (but not a reflective rocky shore or seawall), wave setup at the shore is typically 15% of the significant wave height at the outer limit of the surf zone (breaker height).

Wave runup is generally calculated on a two-dimensional cross sectional basis, which can change over short distances where structures (eg road embankments) are present. Calibration or verification of runup calculations on beaches is best undertaken with either field measurements, a physical model, or surveys of debris lines (Higgs and Nittim, 1988) following major storm events. Prediction of wave runup on structures is best undertaken with a physical model. For wave runup on beaches, the R2% value is the most commonly used, which is the runup exceeded by 2% of waves. That is, two waves out of 100 will exceed the runup limit quoted. Wave runup was calculated by the method of Mase (1989).

There are several cases of wave runup which need consideration in detailed studies for each precinct:

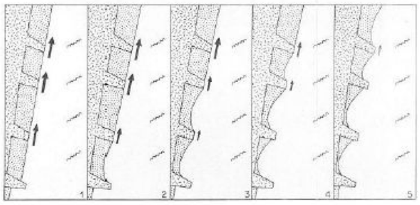
- The wave setup level is the most representative inundation level for areas located away from the foreshore – generally those properties which are not in the front row facing the water.
- The wave runup level is a predictor of dune overtopping and wave impacts on beachfront structures.
- If the dune crest is maintained above the wave runup level, is continuous and contains sufficient sand buffer, the seaward water level (wave setup level) may not extend to the landward side of the dunes.
- In some circumstances, dune overwash or erosion may cause breaching, which may result in additional inundation of backshore areas, however, calculating the magnitude of this would require complex numerical modelling

Erosion Modelling

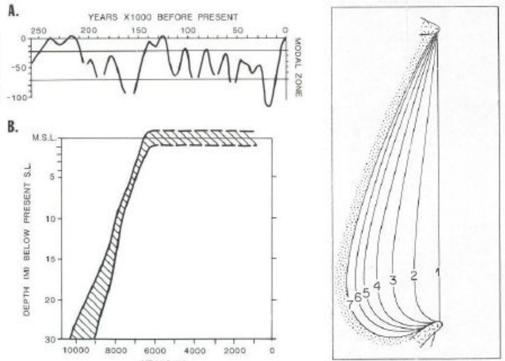
Erosion modelling was undertaken using the model SBEACH. No post storm beach surveys were available for model calibration or verification. In lieu of this, comparison was made with statistics presented for NSW by Gordon (1987) and Adelaide by Deans et al (1994). The SBEACH design storms followed the methodology of Carley and Cox (2003).

Underlying Recession

There is evidence of ongoing underlying recession at some Clarence beaches. Beaches such as Roches and Cremorne show a classic *zeta* curve planform between the hard coastal control points (Chapman et al, 1982; Stephens et al, 1981) which is indicative of northward littoral drift. Figure 3 shows the evolution of *zeta* curve planform beaches, which shows a gradual deepening of the bay over a period of relatively stable sea level.



Evolution of Planform on Littoral Drift Coast (Source: Stephens, Roy and Jones, 1981)



Historical Sea Level (Source: Chapman et al, 1982; Chappell, 1974; Thom and Chappell, 1975)

Evolution of Planform on Littoral Drift Coast (Source: Stephens, Roy and Jones, 1981)

Figure 3: Past global sea level rise and evolution of zeta planform between headlands

The possible causes of recession listed below may occur at all Clarence beaches:

- Imbalances in littoral drift, that is, more sand leaves the coastal compartment than enters it. For example, the sand supply may be slowly depleted or the bed deepening.
- Ongoing evolution (deepening) of the zeta planform (Figure 3), which could still be adjusting to past sea level rise or more recent sea level rise (Hunter et al, 2003; Church and White, 2006).
- Cross shore response to recent sea level rise, such as postulated in the Bruun Rule (see below).
- Changes in the wave climate (height, direction, period) or the relative balance of wind waves and swell. SWAN modelling (Appendix A) indicates that for Roches Beach, nearshore wave direction is not sensitive to offshore direction and period, however, changes in wave

height or wind waves would still alter littoral drift.

- Sediment sinks, which may include Pipe Clay Lagoon, Ralphs Bay, Seven Mile Beach and Pitt Water.
- Sand being supplied in pulses or slugs, which progress northward through the system.
- Changes in seagrass colonies which may trap or liberate sand (Wallace and Cox, 2000; Hart, 1997; EPA, 1999).
- Erosion or sea level rise effects on coastal control points such as Bambra Reef, such that the extent of the salient (locally widened coastal control point in the lee of an offshore reef or island) is reduced.

Recession due to Sea level Rise

Recession due to sea level rise can be estimated using the Bruun Rule (Bruun, 1962, 1988) as the rate of sea level rise divided by the average slope of the active beach profile. This rule is based on the concept that the existing beach profile is in equilibrium with the incident wave climate and existing average water level. It is a simple concept, which assumes that the beach system is two-dimensional and that there is no interference with the equilibrium profile by headlands and offshore reefs. The Bruun rule is typically expressed as

$$R = \frac{r\,X}{h + d_c} \qquad (1)$$

where R is horizontal recession (m)

r is sea level rise (m)

X is the horizontal distance between h and dc

h is active dune/berm height (m)

d_c is profile closure depth (m, expressed as a positive number)

For a given sea level rise and profile, the only contentious variable remaining in the Bruun rule is the closure depth (d_c) for which various formulations and methods exist.

There are few subjects within coastal engineering/science which generate as much controversy and literature as the Bruun Rule. Most strident critics (eg Pilkey and Cooper, 2004) concede that there are few alternatives to the Bruun Rule, while most objective analyses (eg Ranasinghe et al, 2007) caution against its inappropriate application. Ranasinghe et al (2007) reviewed the Bruun Rule and its application around Australia. They summarised policies and/or common practice from around Australia as shown in Table 2.

Bruun Rule factors for Clarence beaches were estimated using the methods of Hallermeier (1981, 1983), SBEACH modelling and profile analysis as shown in Table 3.

It can be seen from Table 3 that there is a wide scatter in the Bruun Rule factor. This may reflect differing vulnerability to sea level rise, but mostly reiterates the position of most practising coastal engineers/scientists (eg Ranasinghe et al, 2007) that the Bruun rule is an order of magnitude estimate only. It can be seen that the best estimate for most of the exposed beaches lies within the “rule of thumb” values of 50 to 100, however, some of the reflective beaches in sheltered locations have Bruun Rule factors of less than 20.

Table 2: Application of Bruun Rule in Australia (Ranasinghe et al, 2007)

State	SLR value	Active profile slope or closure depth	Planning horizon
NSW	0.18 m	1V:50H to 1V:100H based on sensitivity analysis and/or site specific assessment	2050
	0.49 m		2100
QLD	0.3 m	-16 m	50 years
SA	0.3 m	Long term profile surveys or seagrass-sediment boundaries	50 years
	1 m		100 years
VIC	0.3 m	Determined from applying SBEACH to a 100 year ARI storm	50 years
WA	0.38 m (mid range IPCC)	1V:100H	2100

Table 3: Bruun Rule considerations

Location	**Bruun factor**				
	Hallermeier do	**Hallermeier ds**	**SBEACH 100 yr ARI**	**Profile evidence**	**Best estimate**
Bellerive	18	18	18		**18**
Little Howrah Beach	37	35	35		**37**
Seven Mile Beach west	119	432	206	85	**85**
Roches Beach, Lauderdale	22	140	115	31	**31**
Mays Beach	28	94	41	31	**31**
Cremorne (Ocean) Beach	48	93	70		**93**
Clifton (Ocean) Beach, west	54	87	63		**87**
Hope Beach, South Arm Neck	28	35	32		**35**
South Arm Beach - Halfmoon Bay	11	15	14		**15**
Glenvar Beach	13	15	15		**15**
Opossum Bay	11	16	16		**16**

Groundwater Impacts

Potential groundwater impacts considered include:

- Seawater intrusion and lateral migration of the fresh-saline interface.
- Seawater flooding and inundation of unconfined aquifers.
- Flooding and saline contamination of bore heads.
- Changing recharge in the aquifer catchment due to variable rainfall and evapotranspiration.
- Increased groundwater extraction and decreased groundwater levels.
- Changing discharge patterns that may impact on surface waters and groundwater dependent ecosystems.
- Subsidence of land surface.

Coastal Setback Allowances

Allowances for setbacks for erosion and recession comprise the following factors:

S1: Allowance for storm erosion

S2: Allowance for long term (underlying) recession

S3: Allowance for beach rotation

S4: Allowance for reduced foundation capacity (to Stable Foundation Zone)

S5: Allowance for future recession (Bruun Rule)

S1 was determined from SBEACH modelling.

S2 was only determined for Roches Beach with a single indicative value used.

S3 is currently unknown without further monitoring.

S4 is very dependent on the individual dune height used. Detailed assessment of this can be undertaken down to the level of individual properties in accordance with Nielsen et al (1992).

S5 was calculated using Bruun Rule factors of either 20, 50 or 100 based on profile analysis rounded up.

For major new development such as a new subdivision, the design setback S should be the sum of S1 to S5 for 2100, with either mid or high sea level rise.

For infill development, such as new houses having similar alignment to neighbouring properties, some relaxation of the design setback may be considered, for example it could consider the sum of S1 to S5 for 2050 with a mid range sea level rise.

Adaptive Management Strategies

IPCC (2001) listed three classes of adaptive management options namely:

- Retreat
- Accommodate
- Protect

Practical management options include:

- Planning controls, which deal with:
    - Building setbacks.
    - Minimum floor levels.
    - Appropriate engineering assessments.
    - Appropriate construction techniques (eg piled buildings, flood resistant materials).
- Planning controls which may also consider a development freeze in some locations.
- Physical works such as seawalls, groynes, dune management or sand nourishment, offshore breakwaters and/or surfing reefs.
- Ongoing monitoring, analysis and review of findings.
- Additional data collection or studies.
- A timeframe for review – currently 10 years for Council planning schemes.

An example of adaptive management strategies is shown in table 4 for a range of sea level rise scenarios.

Table 4: Preliminary example of adaptive management options

	Feasible?	Unit	Quantity	Rate $k	Cost $M	Benefit/cost
Present day						
Houses affected		No	125	500	62.5	
Seawall	✓	m	4300	4.3	18.0	3.5
Sand nourishment	✓	m	4300	600	2.6	24.0
Groynes	✓	No	9	500	4.5	13.9
Sand nourishment plus groynes	✓	Item			7.1	8.8
Dune raising	✓	m	4300	0.3	1.3	
House raising (of new buildings)	✓	No	??	30	12	
Piled footings for house	✓	No	125	50	6.3	10.0
Raise roads	✓	m	4000			
Set minimum floor levels and setback	✓					
Consider development freeze	✓					
Retreat	✓	No	??	1100		
2050 mid SLR						
Seawall	✓	m	4300	5.0	21.0	3.0
Sand nourishment plus groynes	✓	Item			9.7	6.4
House raising (of new buildings)	✓	No	??	30		
Raise roads	✓	m	4000	400	1.6	
Retreat	✓	No	??	1100		
2050 high SLR						
Seawall	✓	m	4300	5.7	25.0	2.5
Sand nourishment plus groynes	✓	Item			14.8	4.2
House raising (of new buildings)	✓	No	??	30		
Raise roads	✓	m	4000	400	1.6	
Retreat	✓	No	??	1100		
2100 mid SLR						
Seawall	✓	m	4300	6.1	26.0	2.4
Sand nourishment plus groynes	✓	Item			17.4	3.6
House raising (of new buildings)	✓	No	??	30		
Raise roads	✓	m	4000	600	2.4	
Retreat	✓	No	??	1100		
2100 high SLR						
Seawall	✓	m	4300	7.9	34.0	1.8
Sand nourishment plus groynes	✓	Item			27.7	2.3
House raising (of new buildings)	✓	No	??	30		
Raise roads	✓	m	4000	600	2.4	
Retreat	✓	No	??	1100		

Conclusion

Climate change is occurring now and is expected to accelerate. Global sea level rise is the climate change variable most relevant to coastal management, and the only one which can presently be quantified with some veracity.

The latest Intergovernmental Panel on Climate Change (IPCC, 2007) Summary Report provides numerous sea level rise scenarios for 2100. Simplified “mid” and “high” range scenarios developed by WRL for engineering application. Similar engineering scenarios were developed in NCCOE (2004). It should be noted that IPCC (2007, page 17) addresses the doomsday scenario involving the total melting of the Greenland ice sheet (suggested timescale is millennia) which it estimates would elevate global sea levels by a further 7 m. Even more extreme postulations exist, including a rise of up to 70 m (GACGC, 2006) if all the world's ice sheets were to melt, however, the timescale is considered to be millennia. The IPCC represents an international consensus position for planning purposes and has been used for this study. The maximum sea level rise scenario examined in this study, over the planning period to 2100, is 0.9 m.

The desired outcome of this study is practical incorporation of sea level rise into a council planning scheme. The estimation of present day hazard provides useful information regardless of future sea level rise.

Acknowledgements

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