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# Prognostic modelling of sea level rise for the Christchurch coastal environment

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A dissertation  
submitted in partial fulfilment  
of the requirements for the Degree of Master of Applied Science  
at  
Lincoln University  
by  
Ashton Eaves

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Lincoln University  
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Abstract of a thesis submitted in partial fulfilment of the  
requirements for the Degree of Master of Applied Science.

Prognostic modelling of sea level rise for the Christchurch coastal environment

by  
Ashton Eaves

Prognostic modelling provides an efficient means to analyse the coastal environment and provide effective knowledge for long term urban planning. This paper outlines how the use of SWAN and Xbeach numerical models within the ESRI ArcGIS interface can simulate geomorphological evolution through hydrodynamic forcing for the Greater Christchurch coastal environment. This research followed the data integration techniques of Silva and Taborda (2012) and utilises their beach morphological modelling tool (BeachMM tool). The statutory requirements outlined in the New Zealand Coastal Policy Statement 2010 were examined to determine whether these requirements are currently being complied with when applying the recent sea level rise predictions by the Intergovernmental Panel on Climate Change (2013), and it would appear that it does not meet those requirements. This is because coastal hazard risk has not been thoroughly quantified by the installation of the Canterbury Earthquake Recovery Authority (CERA) residential red zone. However, the Christchurch City Council's (CCC) flood management area does provide an extent to which managed coastal retreat is a real option. This research assessed the effectiveness of the prognostic models, forecasted a coastline for 100 years from now, and simulated the physical effects of extreme events such as storm surge given these future predictions. The results of this research suggest that progradation will continue to occur along the Christchurch foreshore due to the net sediment flux retaining an onshore direction and the current hydrodynamic activity not being strong enough to move sediment offshore. However, inundation during periods of storm surge poses a risk to human habitation on low lying areas around the Avon-Heathcote Estuary and the Brooklands lagoon similar to the CCC's flood management area. There are complex interactions at the Waimakariri River mouth with very high rates of accretion and erosion within a small spatial scale due to the river discharge. There is domination of the marine environment over the river system determined by the lack of generation of a distinct river delta, and river channel has not formed within the intertidal zone clearly. The Avon-Heathcote ebb tidal delta aggrades on the inner fan and erodes on the outer fan due to wave domination. The BeachMM tool facilitates the role of spatial and temporal analysis effectively and the efficiency of that performance is determined by the computational operating system.

**Keywords:** Coastal modelling, sea level rise, ArcGIS, BeachMM tool, SWAN, XBeach.

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I would like to thank my supervisor Crile Doscher at Lincoln University for strategic guidance; Ana Nobre Silva at the Science Faculty of Lisbon University for BeachMM tool problem solving; Justin Cope at ECan for the wave buoy dataset; Mark Hadfield at NIWA for bathymetry data; Bruce Gabites at ECan for spit migration maps; Deirdre Hart from the University of Canterbury for ocean current information; Blair Campbell for editing; the New Zealand Coastal Society for conference proceedings and Melissa Benson-Chan for listening to my frustrations over computer modelling.

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# Chapter 1

## Introduction

The effective management of the coastal environment requires robust scientific analysis and detailed planning. To understand the future consequence of sea level rise on coastal environments, the use of predictive models provides the ideal platform for anticipating the impacts. Predictive models create the opportunity to simulate and understand the physical processes affecting the coastal environment and give decision makers valuable quantitative information about a range of coastal conditions (Silva and Taborda, 2012) . Geographic Information Systems (GIS) provide spatial analysis and data integration techniques for accurate mapping and analysis of coastal features (Allen, Oertel & Gares, 2012). When GIS is used in combination with statutory guidance and legislative tools of the New Zealand Coastal Policy Statement 2010 (NZCPS 2010) it enables regional and territorial authorities to provide prudent, efficient and effective outcomes for coastal management.

The Intergovernmental Panel on Climate Change (IPCC) has proposed that the rate of global sea level rise that has occurred since the mid-19th century was larger than the mean rate of the previous two millennia (IPCC, 2013). During the period from 1901-2010 the global mean sea level has risen by 0.19 m (IPCC, 2013), or an estimated mean global rate of 1.7–1.8 mm a<sup>-1</sup> during the last century (Gehrels, Hayward, Newnham, & Southall, 2008). Over the past 7000 years the sea level around New Zealand has remained relatively stable until recently where a rapid rise has occurred evident from saltmarsh cores from southern New Zealand (Gehrels et al. 2008).

The fundamental aim of this research project was whether the current residential zoning of Greater Christchurch meets the obligations outlined in the NZCPS 2010 for future sea level rise. Other research questions to be answered were:

- What is the effectiveness of the predictive computer models SWAN and XBeach for hazard assessment of the Greater Christchurch coastal zone?
- What will the extent of the Greater Christchurch shoreline be in 100 years?
- What will be the effects of storm surge given this futuristic scenario?
- How will the flow discharge of the Waimakariri River effect the coastal environment?

### 1.1 Study area

The Greater Christchurch coastal environment and surrounding coastal marine area in the southern extent of Pegasus Bay was modelled. The terrestrial area covers from Kairiki to the north, to

Scarborough Head to the south. The two coastal water bodies of the Avon-Heathcote (Ihutai) Estuary and Brooklands lagoon were included and their associated rivers of the Avon, Heathcote and Waimakariri. The area modelled extends approximately 4 km inland, 8 km offshore and 30 km along the coast. It is primarily based on the extent of the Light Detection and Ranging (LiDAR) dataset and the computing capacity. Figure 1.1 shows the area of coastline modelled.

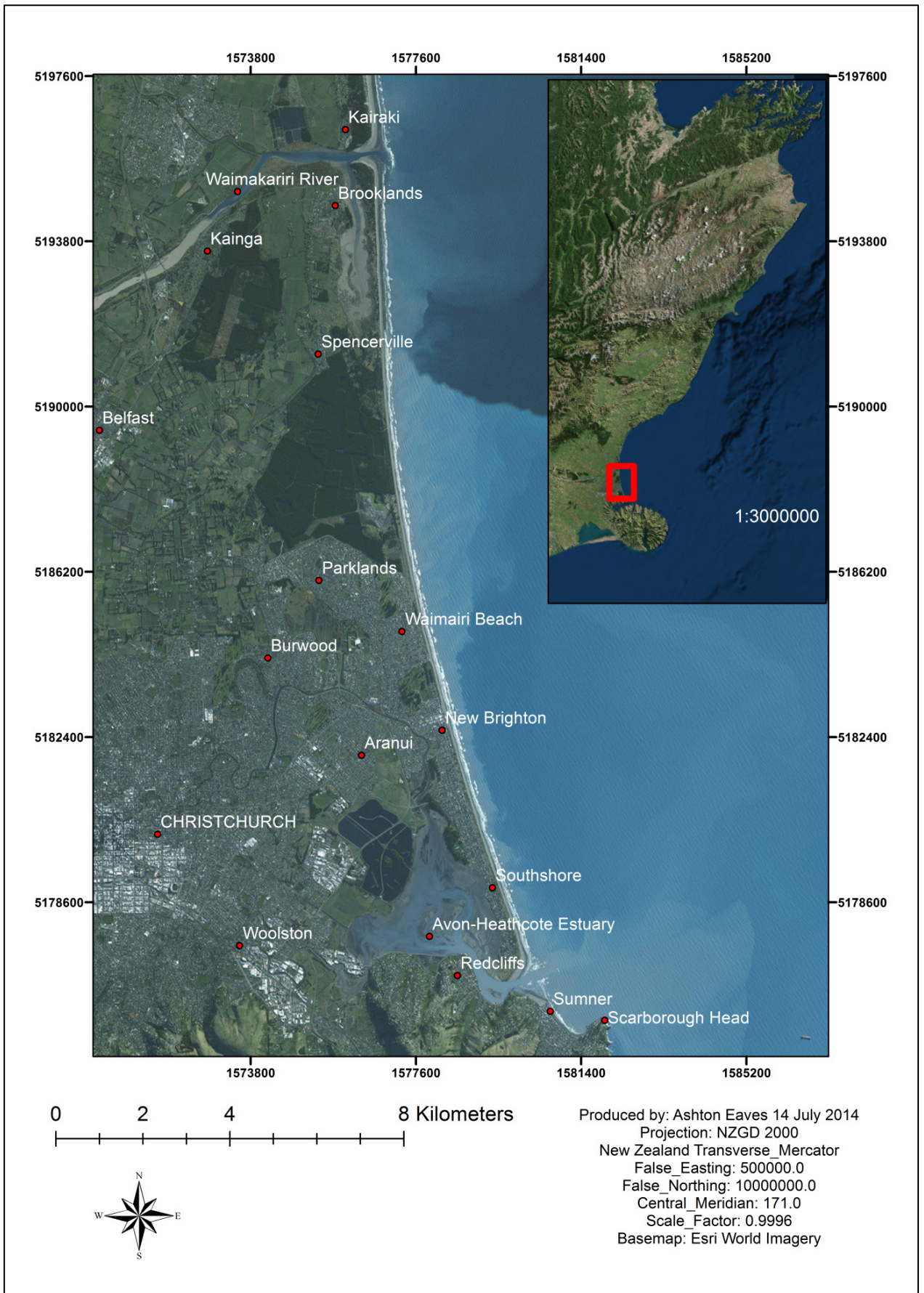


Figure 1.1 The numerical modelling extent of eastern Christchurch.

## Chapter 2

# The geographical setting

Pegasus Bay has been in a progradational state since the last Holocene high stand some 8000 years ago (Schulmeister & Kirk, 1997). Relic shorelines are observable as a series of ridges and swales along the backshore of Pegasus Bay in areas where there has been minimal anthropogenic development. These patterns are treated as a record of horizontal shoreline progradation as well as of vertical sea-level rise (Allen et al. 2012). The New Brighton sand spit confines the Avon-Heathcote lagoon Estuary, which is nourished primarily by sediments debouched by the Waimakariri River that migrate under hydrodynamic forcing. The sediment budget for the coastal environment is partially controlled by patterns of sediment transport which are governed by wave climate and sea level rise (Allen et al. 2012).

The main factors causing significant morphological change within the coastal environment are: long duration swell events, coupled with onshore winds; sediment supply, storm surges and the elapsed time between storm events (Backstrom, Jackson and Cooper, 2009), tidal range, tectonic forcing and geology. Morphological variations of the beach face, foreshore and seabed are strongly connected to the marine forcing mechanisms, particularly the wave action as the foremost factor contributing to coastal morphodynamics (Silva & Taborda, 2012). The morphologic change is not entirely related to oceanographic forcing, as extensive nearshore and shoreface accretion and erosion occurs under calm conditions, or modal high-energy conditions (Backstrom et al. 2009).

Sea level rise in southern New Zealand is higher than the global average, which can be attributed to regional thermal expansion related to the concurrent rise in global temperatures (Gehrels et al. 2008). The global mean sea level rise is anticipated to continue during the 21st century, the rate of which will very likely exceed that observed during 1971–2010 due to increased warming of the ocean and increased loss of ice mass from glaciers sheets (IPCC 2013).

### 2.1 Geomorphology

The continental shelf of Pegasus Bay extends out approximately 60 km to a depth of about 130m where it then descends into the Pegasus Canyon to a depth of over 500 m. The depth of this shelf corresponds roughly to the sea level during the last glacial maximum 20,000 years ago and has a gradient of less than 1° (Hart, Marsden and Francis, 2008) . Beach and dune ridges with intervening swamps illustrate a progradational state; the Christchurch shoreline had a previous position near the suburb of Riccarton, west of the CBD, now its current position is 11 km seaward towards the mouth of the Avon and Heathcote Rivers (Hart et al. 2008) . The New Brighton Spit is a geologically recent

addition to Pegasus Bay, having formed during the past thousand years; it extends south to enclose the estuary (Hart et al. 2008). Figure 2.1.1 shows the transgression and progradation of the Christchurch shoreline. More recent migrations of the distal end of the New Brighton Spit from 1940 to 2013 are shown in figures 2.1.2 and 2.1.3. The progradation of Pegasus Bay is due to the inability of the marine environment to remove wave-eroded sediment from the floor of the bay, leading to gradual nearshore aggradation which is then transported landward to form a new berm (Schulmeister & Kirk, 1997) . However, this wave dominated environment is strong enough to disperse river derived sediment from the Waimakariri, Ashley and Waipara rivers across the nearshore of Pegasus Bay (Schulmeister & Kirk, 1997).

Patterns of backshore ridge and swale sets in parallel orientation are treated as a record of horizontal shoreline progradation as well as vertical sea-level rise (Allen et al. 2012). Under a prograding regime, younger shorelines occur seaward of older shorelines, following the geologic law of superposition, where new beds overlie older beds, creating this gradual horizontal pattern (Allen et al. 2012). The aggradation is dependent on sediment supply and deposition on the foreshore, followed by the building of the dune system by aeolian transport.

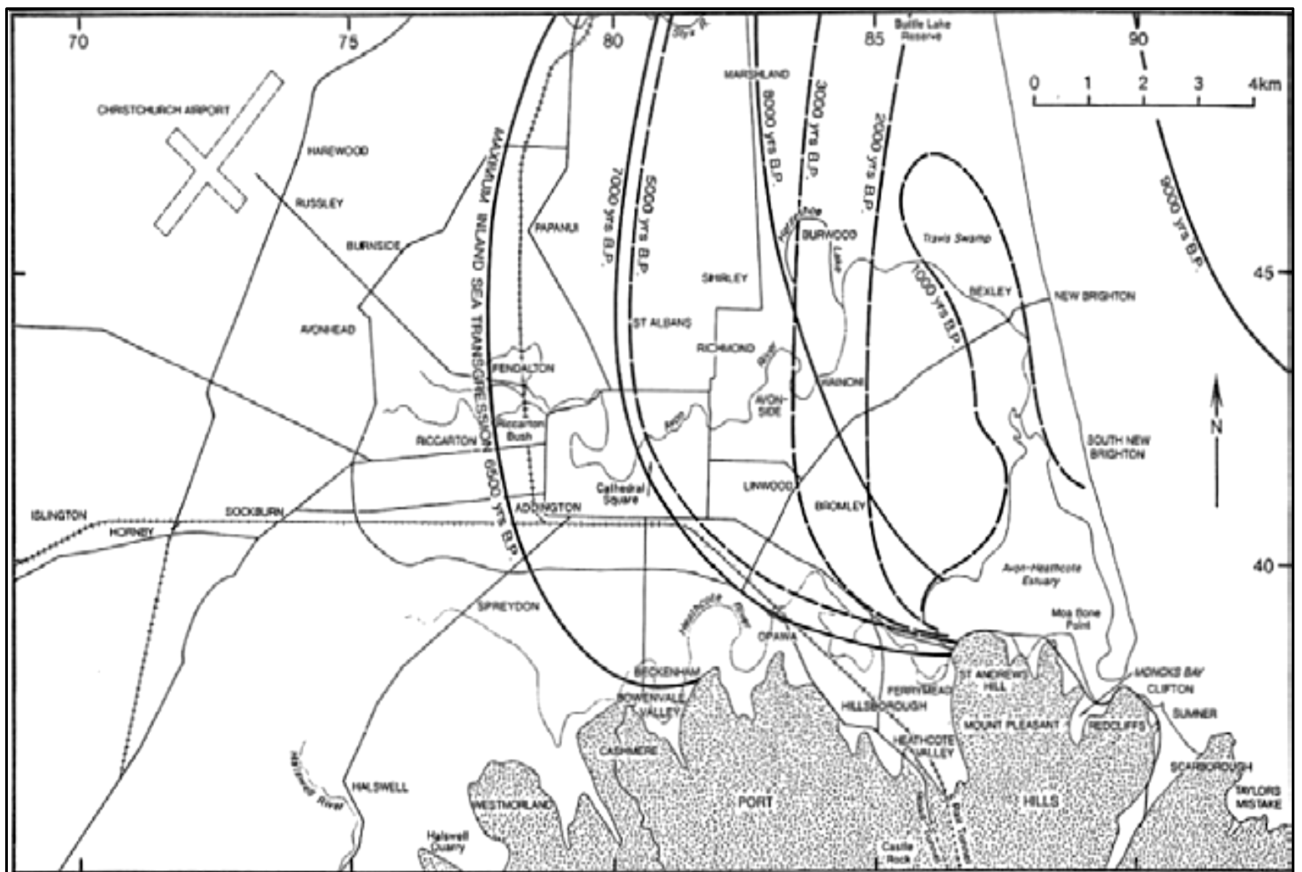
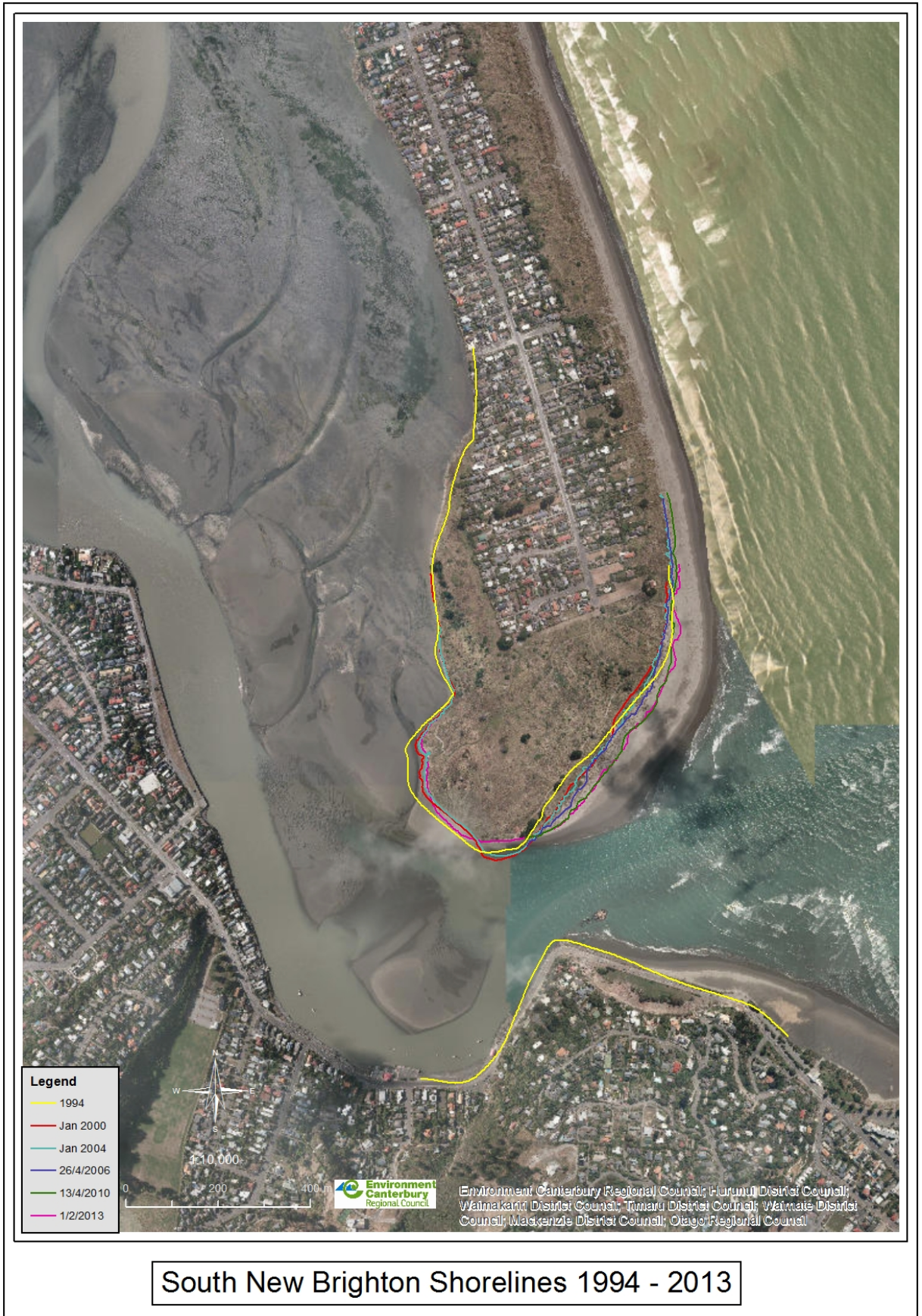


Figure 2.1.1 The Holocene transgression and progradation of the Christchurch shoreline (Brown & Weeber, 1992).



**Figure 2.1.2 The migration of the distal end of the New Brighton Spit between 1940 and 1994. Map courtesy of Bruce Gabites at Environment Canterbury (ECan).**



**Figure 2.1.3 The migration of the distal end of the New Brighton Spit between 1994 and 2013. Map courtesy of Bruce Gabites at ECan.**



## 2.2 Hydrology

Pegasus Bay is sheltered from the predominant hydrodynamic forcing provided by the Southland Current from the south-west. This leads to nourishment of the bay via an eddy in the current; where sediment is dragged north from the Canterbury Bight and settles under calmer conditions (Brown, 1976; Hart et al. 2008; Schulmeister & Kirk; 1997). The Southland Current drives sediment south along the shore in the southern extent and north in the northern extent of Pegasus Bay (Hart et al. 2008). The Southland Current also creates an offshore banner bank at the north-eastern tip of Banks Peninsula (Hart et al. 2008). Within Pegasus Bay, long-shore sediment transport, or net sediment transport, occurs in both north and south directions due to the absence of a dominant drift direction which is dependent on the planform equilibrium of the bay (Brown, 1976). Thus, sediment transport is determined by incident wave angle and ocean current. The ocean currents for the region are outlined by figure 2.2.1.

The tidal front approaches from the south-west of New Zealand, travelling up the east coast and arriving in Canterbury under a semidiurnal regime with a micro-tidal range of approximately 2m (Hart et al. 2008; Stephenson & Schulmeister, 1999). The dominant wave directions in Pegasus Bay are from the east and south-east, with southerly waves refracting around Banks Peninsula which rarely exceed a wave height of 2.5 m (Schulmeister & Kirk, 1997) . North-easterly swells occur during summer months from sub-tropical lows tracking south into Pegasus Bay (Brown, 1976; Schulmeister & Kirk, 1997).

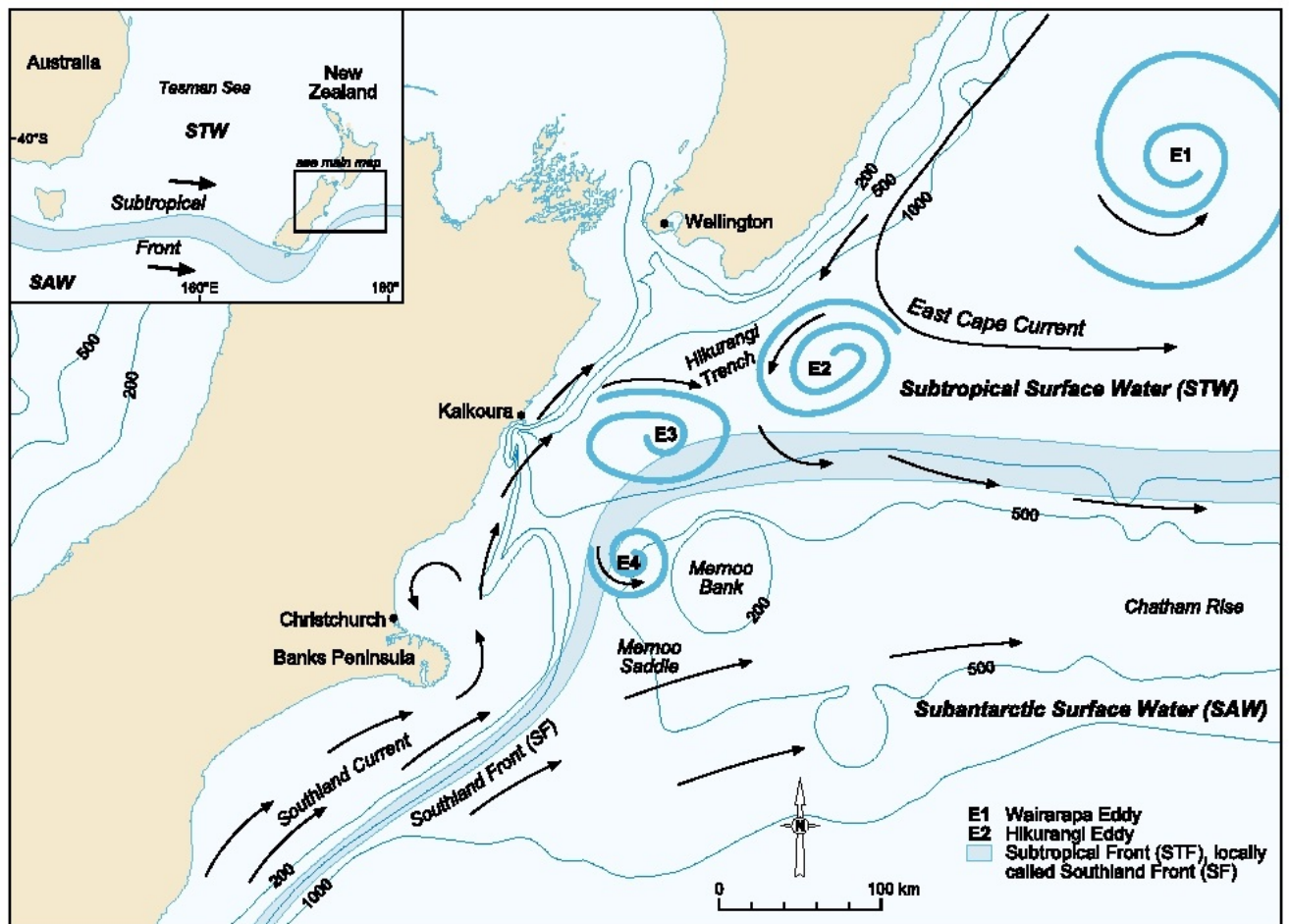


Figure 2.2.1 East coast ocean current systems of central New Zealand. Reproduced with permission from Hart et al. (2008).

### 2.3 Sea level rise

The constituent drivers to a change in sea level are: isostatic changes in the earth's crust through plate tectonics or post-glacial rebound; eustatic changes through thermal expansion or contraction of the oceans via changes in density, salinity or a redistribution of freshwater storage; departures from the global mean ocean circulation resulting in regional storm surge; changes to the significant wave height; and non-uniform atmospheric oscillations from temperature and salinity changes (Nicholls & Lowe, 2004). Non-uniform atmospheric oscillations are also known as the climate related mean sea level anomaly (MSLA), which includes the Interdecadal Pacific Oscillation (IPO) and the El Niño Southern Oscillation (ENSO) (Stephens, Bell, Ramsay & Goodhue, 2013). Stephens et al., (2013) quantified the sea level components as: long-term sea level rise, MSLA, tide, storm surge, and wave setup and run up. A range of ocean processes have been affected by both the long term progressive changes and the decadal variations in the climate, including global sea level rise and the enhanced intensities of storms which generate more extreme waves and elevate storm surges (Komar, Allen, Ruggerio, & Harris, 2013). Figure 2.3.1 illustrates the effects of storm surge on a residence of Southshore during a 1977 storm. Figure 2.3.2 shows photos taken by the author of high water levels

and inundation at Southshore during an extreme storm in Christchurch on the 5th of March 2013, where 112 mm of precipitation was recorded over 4 days (Middlemiss, 2014).

Sea levels in New Zealand have remained relatively stable throughout the late Holocene, although a recent rapid rise has occurred given evidence from salt-marsh cores in southern New Zealand (Gehrels et al. 2008). Hannah (2004) estimated a rate of sea-level rise of  $2.8 \pm 0.5 \text{ mm yr}^{-1}$  for 20th century New Zealand which was a considerably higher rate than that for preceding centuries. This was comparable with the nearest reliable tide-gauge at Lyttelton, 4 km south of the study site, where a rise of  $2.1 \pm 0.1 \text{ mm a}^{-1}$  between 1924 and 2001 was recorded (Gehrels et al. 2008; Hannah, 2004). This rate is higher than the global average of  $1.7 - 1.8 \text{ mm a}^{-1}$ , which can be attributed to regional thermal expansion (Gehrels et al. 2008). Ocean warming will be greater at depth in the Southern Ocean, with best estimates of ocean warming at a depth of about 1000 m by  $0.3^\circ\text{C}$  to  $0.6^\circ\text{C}$  by the end of the 21st century (IPCC, 2013). The IPCC (2013) has estimated that the mean rate of global averaged sea level rise was approximately  $1.7 \text{ mm a}^{-1}$  for the period 1901 and 2010,  $2.0 \text{ mm a}^{-1}$  between 1971 and 2010 and  $3.2 \text{ mm a}^{-1}$  between 1993 and 2010, with glacier mass loss and ocean thermal expansion accounting for 75% of this change since the early 1970's.

Sea-level rise observations also contain inherent error and uncertainties that need to be reported as well as any other diagnostic indicators (Allen et al. 2012). The apparently rapid rise in swale heights over the youngest sets may correspond to the acceleration of sea-level in the past century, or it may also reflect extensive anthropogenic modifications (Allen et al. 2012). Inertia of the global climate system and the successful implementation of mitigation strategies will also dramatically affect any long range forecast (Reisinger, 2009). The 21st century emissions could determine the long-term consequences of climate change and sea level rise for many centuries to come (Reisinger, 2009). This is because greenhouse gas concentrations would continue to increase for a long time after emissions began to fall as rising temperatures would continue for at least another century, and in turn, sea level would continue to rise for many more centuries to come (Reisinger, 2009).



**Figure 2.3.1 Erosion at Torea Lane in 1977. Photo taken from Southshore Residence Association History Group (2006).**



**Figure 2.3.2 Personal observations of high water levels and inundation at Southshore on the 5th of March 2014.**

## **2.4 Earthquake effects**

The Christchurch coastal environment has undergone recent major changes due to tectonic activity. The main cause of seismic changes to the study area were a magnitude 7.1 earthquake centred under Darfield 40km west of Christchurch which occurred on the 4th of September 2010, followed by a significant aftershock of magnitude 6.3 centred under Lyttelton on the 22nd of February 2011, and a 5.8 magnitude earthquake was recorded off the coast of New Brighton on the 23rd of December 2011 (GNS, 2012). Many subsequent aftershocks have also occurred. Many effects of this earthquake series have been observed on the Avon-Heathcote Estuary which suffered extensive liquefaction,

~20-40% of its surface area, and a general tilting of the estuary that has seen subsidence to the northern extent and uplift at its southern extent of approximately 1 m and a reduction in tidal area (Measures et al. 2011).

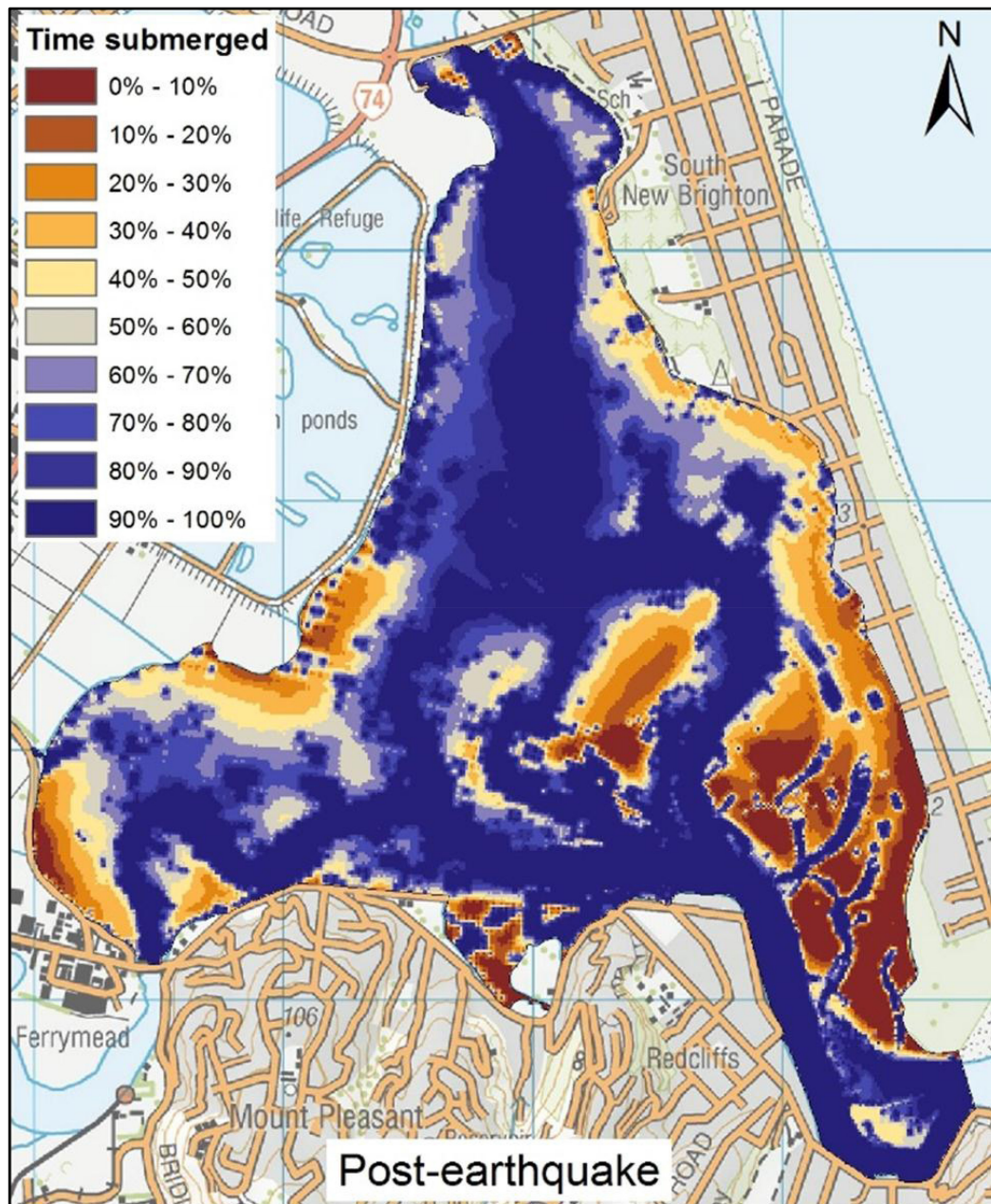
Earthquakes affect both the morphology and evolution of coastlines by introducing abrupt elevation changes of uplift, or subsidence, slumping or tsunami inundation (Cundy et al. 2000). The Napier earthquake of 1931, with a magnitude of 7.8, altered the coastal morphology of the region considerably due to fault movement occurring only 30 km north-west of Napier City, which itself straddles the coast (Komar, 2010). The along-coast land elevation changes at its greatest extent saw uplift of 2 m at Tongioio, 1.8 m in Napier, and 1 m subsidence at Haumoana, Te Awanga and Clifton. Interestingly the earthquake caused abrupt uplift of the Ahuriri lagoon, reducing its area by approximately 12.8 km<sup>2</sup>, which has since become the site of the Napier Airport (Komar, 2010). Similarly, the Gulf of Atalanti, Greece endured significant coastal change during an earthquake series in 1894 which was dominated by a 6.2 magnitude event followed by a 6.9 magnitude event (Cundy et al. 2000). This earthquake series led to extensive coastal slumping, surface faulting, tsunami inundation and coastal subsidence by as much as 1 m (Cundy et al. 2000). Coastal subsidence was caused by the processes of localised slumping, liquefaction and tectonic down warping (Cundy et al. 2000). This earthquake was similar in magnitude, coastal proximity and effects to that of the Canterbury earthquake series, although tsunami inundation did not occur in Canterbury.

## Chapter 3

### Previous coastal modelling of the study area

#### 3.1 The Delft3D model

The Delft3D hydrodynamic model was employed by Measures et al. (2011) to discover tectonic changes to the bathymetry of the Avon-Heathcote Estuary, the tidal reaches of the Avon and Heathcote Rivers and McCormacks Bay. The model was calibrated to observed water levels and then compared pre and post-earthquake extents of the Avon Heathcote Estuary to discover that the greatest changes have occurred during mid-tide in the south western area (Measures et al. 2011). Large parts of the estuary are now dry at mid tide, increasing the total area of exposed bed at mid tide to approximately 50 hectares which represents an increase of 18% of the area exposed at mid tide. This is illustrated by figure 3.1. The northern extent where the Avon discharges has subsided by 0.2 - 0.5 m. The southern extent, including the estuary mouth and the Heathcote River, has risen by 0.3 - 0.5 m. The overall pattern suggests south-north downward tilting which has led to 38% reduction in the area at the mouth of the estuary, and an 18% reduction in the mouth width (Measures et al. 2011).



**Figure 3.1** Post earthquake Avon-Heathcote Estuary with percentage of bed submersion (Measures et al. 2011).

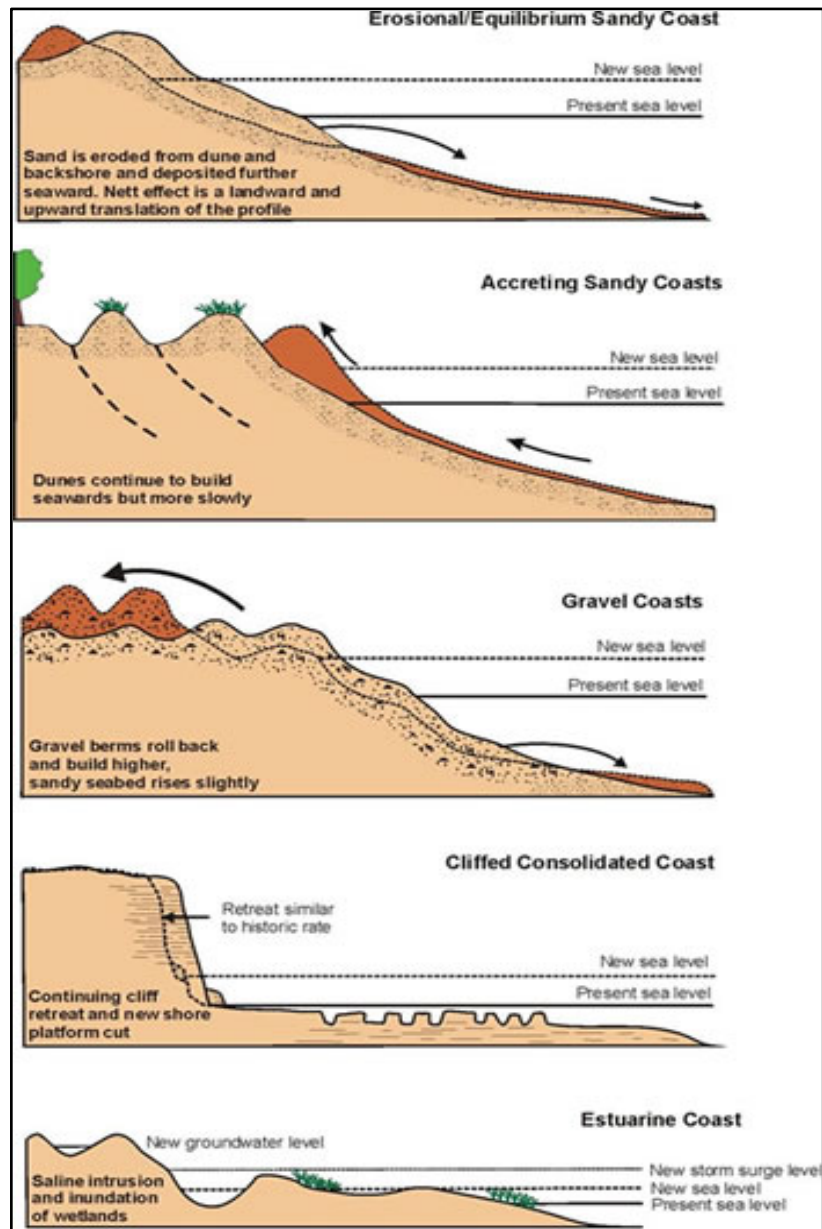
### 3.2 The passive inundation approach and the Bruun Rule

Tonkin and Taylor Ltd (2013) have produced a report into projecting a sea level rise of 1.0 m by 2050, in line with Ministry for the Environment guidelines of 2008. Their findings conclude that storm inundation, greater frequency of extreme tidal levels and the progressive retreat of the shoreline in low lying areas will be the main impacts (Tonkin and Taylor Ltd, 2013). They utilised the passive inundation, or ‘bathtub’ approach, and the Bruun rule. Passive inundation is calculated by mapping where a certain sea level rise will intersect the terrestrial contour height, or the line where the MHWs in 2115 will intersect the existing cross-shore profile (EShorage, 2010). The second model used to predict the extent of sea level rise employed by Tonkin and Taylor Ltd (2013) and the



Ministry for the Environment (2008) is the Bruun Rule (1962). This model was deemed suitable by the Environment Court (*Skinner v Tauranga District Council A163/02*) as a precautionary approach to coastal hazard planning for an open coast beach. It is illustrated in the 'Erosional /equilibrium sandy coast' plate in figure 3.2. However, this simple two-dimensional model assumes: a closure depth of offshore sediment exchange, no onshore or offshore gains or losses, no long term seasonal anomaly, instantaneous response to sea level change, and no account of sediment characteristics (Tonkin and Taylor Ltd, 2013).

The Tonkin and Taylor Ltd (2013) report illustrates specific changes to the coastal system due to the tectonic activity in Canterbury. These include: Subsidence of the shoreline along Northern New Brighton and uplift along Southshore, which may reduce the southerly long-shore drift and decrease the tidal prism of the Avon-Heathcote Estuary (Measures et al., 2011). This reduces tidal velocities resulting in a landward movement of the ebb tidal delta with the excess sediment blocking the inlet, reducing its size, or migrating to nearby beaches (Measures et al., 2011). Land subsidence adjacent to the lower reaches of the Avon River and the northern extent of the Estuary has increased the risk of flooding (Tonkin and Taylor Ltd, 2013). Appendices C and D provide the mapped inundation extents from the Tonkin and Taylor Ltd (2013) report.



**Figure 3.2** The general response of coastal geomorphology to sea level rise, adapted by the Ministry for the Environment (2008). The Bruun rule is outlined by the sandy coast scenarios.

The results of the Tonkin and Taylor Ltd 2013 report for a 1.0 m sea level rise over the next 100 years are shown in table 3.1, with an upper and lower range of 0.5 m and 1.5 m. Uncertainty around sediment supply from the Waimakariri River has led to the assumption that the hydrodynamic system is in dynamic equilibrium and that in future there will be no long term trend of progradation (Tonkin and Taylor Ltd, 2013). The risk of inundation along the New Brighton dune system is not expected to have any effect as the elevations are above storm surge levels (Tonkin and Taylor Ltd, 2013). Along the Sumner and Clifton revetments a general lowering of the beach profile will occur due to scouring at the base with inundation likely due to low points in the road and structure in the future, with Clifton beach facing coastal squeeze (Tonkin and Taylor Ltd, 2013). The inundation of the lower Avon and Heathcote rivers reported by Tonkin and Taylor (2013) are given in table 3.2, which

utilises an inundation level of 3.3 m above Lyttelton Vertical Datum 1937 (LVD37) and the passive inundation method. This inundation level was based on a MHWS 1.15 m above LVD37 mean sea level that is exceeded 10% of the time and a sea level rise of 1.0 m, giving a passive inundation level of 2.15 m, and thus the MHWS level in 2115 would be the 2.2 m contour (Tonkin and Taylor Ltd, 2013).

**Table 3.1 Summary of estimated shoreline retreat due to sea level rise (Tonkin and Taylor Ltd, 2013).**

Site	ECan Profile	Dune height (m)	Slope	Sea level rise (m)	Shoreline Retreat (m)	Shoreline Retreat range (m)
Spencer Park	C1755	5.0	0.01	1.0	70	30-100
Bottle Lake	C1400	9.0	0.01	1.0	70	30-100
Effingham Street, North New Brighton	C1065	5.1	0.01	1.0	70	30-100
Rawhiti Road, New Brighton	C0952	8.3	0.01	1.0	60	30-80
Rodney Street, New Brighton	C0815	8.6	0.01	1.0	60	30-80
Jellico Street, South New Brighton	C0600	8.7	0.01	1.0	60	30-80
Heron Street, Southshore	C0471	6.9	0.01	1.0	60	30-90

Site	Dune height (m)	Nearshore slope	Sea level rise (m)	Shoreline retreat (m)	Shoreline retreat range (m)
Scarborough	3.9	0.016	1.0	60	30-90
Taylor's Mistake	4.6	0.025	1.0	40	20-60

**Table 3.2 Summary of inundation impacts for the Lower Avon and Heathcote Rivers (Tonkin and Taylor Ltd, 2013).**

	Avon River	Heathcote River
Area of land inundated by 3.3 m level (1% AEP event) <sub>1</sub>	1,226 ha	1,171 ha
Suburbs affected by a 1% AEP event inundation level	Travis Wetland Avondale Wainoni Dallington Horseshoe Lake Bexley	Ferrymead Woolston Linwood Hillsborough

## Chapter 4

### Urban planning and statutory requirements

The effects of a rising sea level require the implementation of effective coastal planning and forecasting of which areas are likely to be directly affected. This hypothesised increasing trend also means the definition of realistic, rather than nominal, planning timeframes becomes abundantly more important than it has previously been (NIWA MWH GNS and BRANZ, 2012). The NZCPS 2010 has a number of directives that require action by regional and territorial authorities in order to address expected coastal changes. These objectives and policies initiated by the New Zealand Government (2010) are:

- *Objective 5: To ensure that coastal hazard risks taking account of climate change, are managed by: locating new development away from areas prone to risks; considering responses, including managed retreat, for existing development in this situation; and protecting or restoring natural defences to coastal hazards (NZCPS 2010, p. 10).*
- *Policy 6: (1) (i) set back development from the coastal marine area and other water bodies, where practicable and reasonable, to protect the natural character, open space, public access and amenity values of the coastal environment (NZCPS 2010, p. 13).*
- *Policy 24: Identification of coastal hazards (1) Identify areas in the coastal environment that are potentially affected by coastal hazards, giving priority to the identification of areas at high risk of being affected. Hazard risks, over at least 100 years, are to be assessed having regard to: (a) physical drivers and processes that cause coastal change including sea level rise; (b) short-term and long-term natural dynamic fluctuations of erosion and accretion; (c) geomorphological character; (d) the potential for inundation of the coastal environment, taking into account potential sources, inundation pathways and overland extent; (e) cumulative effects of sea level rise, storm surge and wave height under storm conditions; (f) influences that humans have had or are having on the coast; (g) the extent and permanence of built development; and (h) the effects of climate change on: (i) matters (a) to (g) above; (ii) storm frequency, intensity and surges; and (iii) coastal sediment dynamics; taking into account national guidance and the best available information on the likely effects of climate change on the region or district (NZCPS 2010, p. 23).*

Planning and engineering design has historically focussed on extremes in climate variability due to the slow rate of sea level rise and therefore parameters were considered to be stationary (Ministry for the Environment, 2008). Now, planning timeframes have had to adapt to the increasing sea level using practical high tide levels such as MHWS tide being exceeded 10% of the time, and estimates of extreme high storm tides (Ministry for the Environment, 2008). However, global climate change has been increasingly well documented, regional impacts and changes can be less well quantified and differ between regions leading to subjective interpretations of the future risk (Reisinger, 2009). Key vulnerabilities from potential changes can be identified as: the magnitude of the impact on people, the environment, or cost; its timing; its persistence or reversibility; the potential for adaptation; who is most affected; the probability of occurrence; and the intrinsic importance of the impact (Reisinger, 2009). Due to the lag in system response, taking action now to create a fall in atmospheric temperature now would not see a change in sea levels for centuries to come (Reisinger, 2009). The Ministry for the Environment (2008) has classified a range of coastal landforms and their sensitivity to climate change by assessing the interrelationships between geomorphology, sediment and human influences. These are visible in table 4.1.

Local government and Crown entities have created zones of increased hazard risk in the post-seismic Christchurch coastal environment. The CERA was established by the central government to facilitate the recovery of greater Christchurch after the tumultuous earthquake events. Their direction saw the implementation of the residential red zone where residents were financially compensated for their voluntary relocation from areas of high risk from coastal or fluvial hydrological inundation. This residential red zone comprised flanks of the Avon River and the Avon – Heathcote Estuary within the study area (Canterbury Earthquake Recovery Authority, 2014). Similarly, the CCC has created a non-statutory flood management area (FMA) of land that is at risk of longer term hydrological inundation. The FMA for the study area is visible in appendix E.

**Table 4.1 Coastal landform sensitivity to climate change (Ministry for the Environment, 2008).**

Landform type	Sea-level rise	Storm surge	Precipitation	Wave height	Wave direction
Simple cliff	High	Moderate	Moderate	High	Low
Simple landslide	High	Low	High	High	Low
Composite cliff	Moderate	Low	Moderate	High	Low
Complex cliff	Moderate	Low	High	High	Low
Relict cliff	High	Low	High	High	Low
Embryonic dunes	High	High	Low	High	Low
Foredunes	High	High	Moderate	High	Low
Climbing dunes	Moderate	Moderate	Moderate	Moderate	Low
Relict dunes	Low	Low	Moderate	Low	Low
Parabolic dunes	Moderate	High	Low	High	Low
Transgressive dunes	Moderate	Moderate	Low	Moderate	Low
River delta	High	High	Moderate	High	Moderate
Tide dominate delta	High	High	Low	High	Moderate
Wave dominated delta	High	High	Low	High	Low
Shore platform	High	Moderate	Low	High	Low
Sandflats	High	High	Low	High	Low
Mudflats	High	High	Low	High	Moderate
Pioneer saltmarsh	High	High	Moderate	High	Low
Saltmarsh	High	High	Moderate	High	Low
Sand beach	Moderate	Moderate	Low	Moderate	High
Gravel beach	Moderate	Moderate	Low	High	Moderate
Mixed beach	Moderate	Moderate	Low	High	Moderate
Composite beach	Moderate	Moderate	Low	High	Moderate
Boulder beach	Low	Low	Low	Moderate	Low
Barrier island	High	High	Low	High	High
Barrier beach	High	High	Low	High	High
Spit	High	High	Low	High	High
Cuspate foreland	Low	Low	Low	High	Low

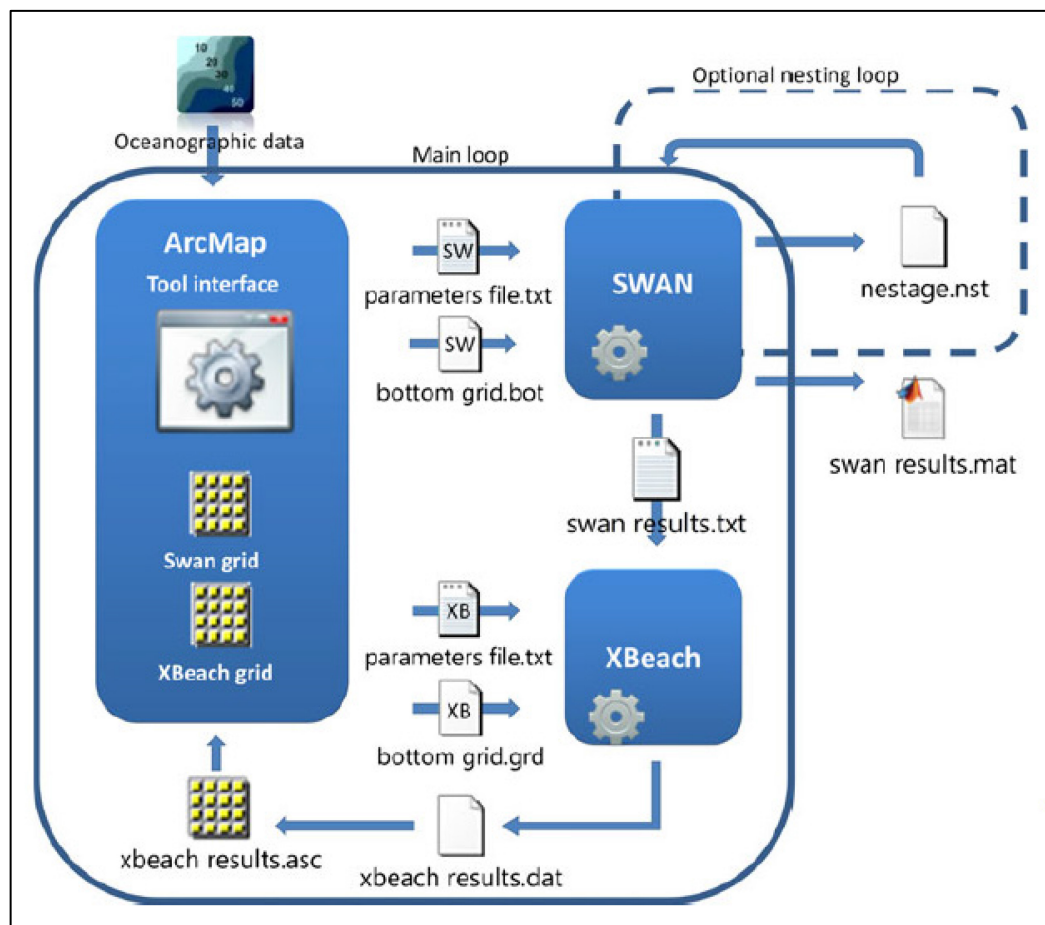
## **Chapter 5**

### **Methods and materials**

To achieve the research questions the numerical models of SWAN and XBeach were incorporated into the ArcGIS platform via the BeachMM tool to calculate coastal evolution and inundation. The methods used follow those created by Silva and Taborda (2012) and were adapted for the Christchurch coastal environment over a longer time period. Silva and Taborda (2012) developed the Beach Morpho-Modelling Tool Version 1.1 (BeachMM tool), a python interface to link the numerical models and the GIS environment. The models were run utilising local parameters for the present scenario to validate the model output, and again for an estimated sea level projection of 100 years from now given NZCPS 2010 directives and IPCC 2013 predictions. Two of the IPCC projections were used to promote their minimum and maximum predictions. Mean conditions and conditions under storm surge events were simulated to account for the effects of sea level rise and anomaly storm scenarios. The study area was divided into two grid extents, one focussing on the Avon-Heathcote Estuary, and the other focussed on the Waimakariri River mouth. The Waimakariri River extent was only run under the maximum IPCC (2013) projection.

Predictive computer modelling for this set up derives assumptions from general theory, through the numerical hydrological equations used in SWAN and XBeach, to create idealised representations from specific data input that is to be interpreted in ArcGIS via the BeachMM tool (Silva and Taborda, 2012). The third-generation SWAN wave model provides realistic estimates of wave parameters in coastal areas utilising wind, bottom and current conditions (Booij, 2012). SWAN solves the spectral action balance equation by taking into account spatial wave propagation, generation, refraction, shoaling, dissipation, long-shore drift and non-linear wave-wave interactions, as it models the propagation from deep water oceanic waves to the surf zone (Silva & Taborda, 2012). Nesting is commonly employed in SWAN to increase the computational efficiency through modelling waves over a larger region to then apply the results of this to a smaller region (Silva & Taborda, 2012). The idea of nesting is to first compute the wave environment over a coarse grid for a larger region and then on a finer grid, where the computation on the fine grid uses boundary conditions that are generated by the computation on the coarse grid (Booij, 2012). This produces a more representative environment to set the boundary conditions for the study area. The hydrological wave model SWAN represents the most advanced form for modelling the propagation of nearshore waves (Silva & Taborda, 2012). XBeach is a recent and open source model for nearshore processes, which allows for the computation of natural coastal response to temporally varying storm conditions that include dune erosion, over-washes and breaching (Roelvink, Reniers, Van Dongeren, De Vries, Lescinski &

McCall, 2010) . It has been successfully field tested and validated for a number of sites throughout Europe under a wide range of environmental conditions (Silva & Taborda, 2012). The BeachMM tool is a relatively new geoprocessing tool that integrates these two numerical models into the ArcGIS platform using Python script language, streamlining the process and utilising Python’s object-orientated and cross-platform capacity for modelling beach morphodynamics (Silva & Taborda, 2012). The application of this tool simplifies dataflow, permits tight coupling, minimises human error, and allows for enhanced visualisation of results (Silva & Taborda, 2012). The integration of these tools for coastal modelling provide for a seamless integration of geospatial data, automates the model chain, and enables extensive visualisation and analysis of the model results (Silva & Taborda, 2012). The schematic approach outlined in figure 5.1 illustrates how the BeachMM tool integrates into the ArcGIS platform. It shows the process by which the BeachMM tool calls SWAN and XBeach numerical models within the ArcGIS platform and the dataset flow required to operate the model.



**Figure 5.1 Schematic diagram of the process employed by the BeachMM tool (Silva & Taborda, 2013).**

LiDAR data was used to create a digital elevation model (DEM) of the Christchurch coastal environment, a technique previously used by White & Wang (2003) to analyse morphologic change. LiDAR improves accuracy, extent of mapping, and spatial analysis through overcoming vegetation canopy masking (Allen et al. 2012). A bathymetric bottom grid was fused to the LiDAR dataset to



provide a seamless transition of offshore, nearshore and terrestrial surfaces within the DEM. A coarse input grid was then used to generate the boundary conditions for the finer computational grid, utilising nesting capabilities. The BeachMM tool performed four main tasks: 1) conversion between GRID and ASCII raster formats; 2) automation of input parameters; 3) output results into an ArcGIS compatible format; and 4) calling the external models to operate in ArcGIS (Silva and Taborda, 2013). The IPCC sea level rise predictions are driven by greenhouse gas concentration trajectories, or Representative Concentration Pathways (RCPs), that are determined by estimates of future emissions. To give an overall view, the minimum and maximum RCP values were modelled. Thus, *“the global mean sea level rise for 2081–2100 relative to 1986–2005 will likely be in the ranges of 0.26 to 0.55 m for RCP2.6, and for RCP8.5, the rise by the year 2100 is 0.52 to 0.98 m, with a rate during 2081–2100 of 8 to 16 mm a<sup>-1</sup>. These ranges are derived from CMIP5 climate projections in combination with process-based models and literature assessment of glacier and ice sheet contributions”* (IPCC, 2013). Therefore a lower value of 0.26 m and an upper value of 0.98 m were used. SWAN and XBeach were executed with mean and significant storm data from the Canterbury offshore wave buoy.

## 5.1 Raster grids

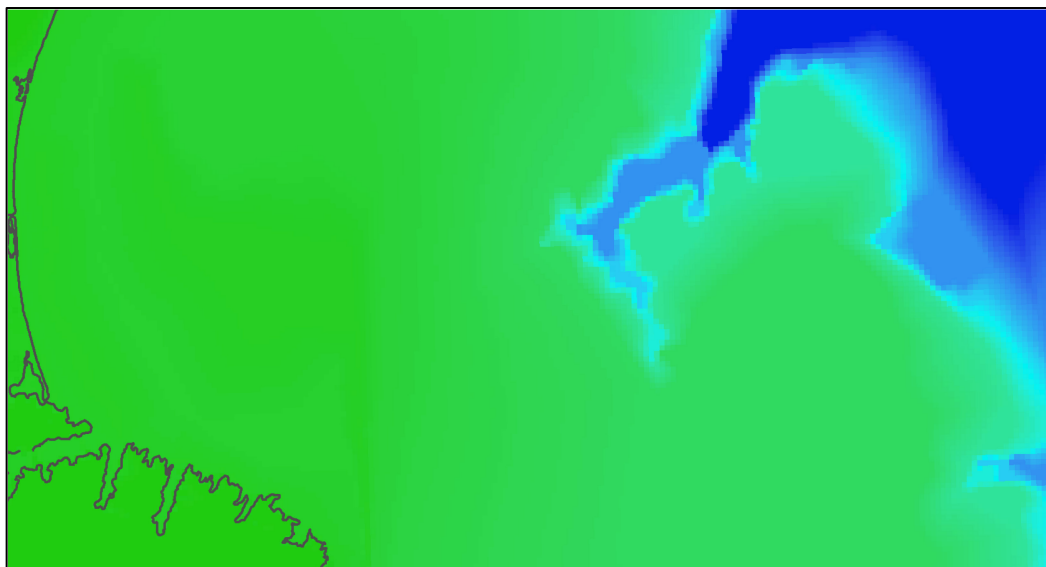
The development of a seamless topobathy follows a similar technique used by Allen et al. (2012) where the integration of topographic and bathymetric data derived a triangular irregular network (TIN) and in turn a rasterized DEM. Generation of bathymetric bottom grids on which to run SWAN and XBeach were developed by merging the following files:

- Terrestrial LiDAR data was obtained from Lincoln University. This airborne laser scanning survey was conducted over Christchurch City and Lyttelton from 20th - 30th May 2011, and was designed to support the February 2011 earthquake recovery effort (AAM Pty Ltd, 2011). It captured a vector terrain model with an average point separation of 0.5m with ground support provided by GeoSystems NZ by way of GNSS base stations to assess the accuracy (AAM Pty Ltd, 2011).
- Bathymetric vector contours and hydro sounding points were obtained from the Land Information New Zealand (LINZ) data service (LINZ, 2013a).
- New Zealand geographic contours were also obtained from the LINZ data service (LINZ, 2013a) for terrestrial values outside the LiDAR dataset required by the grid.

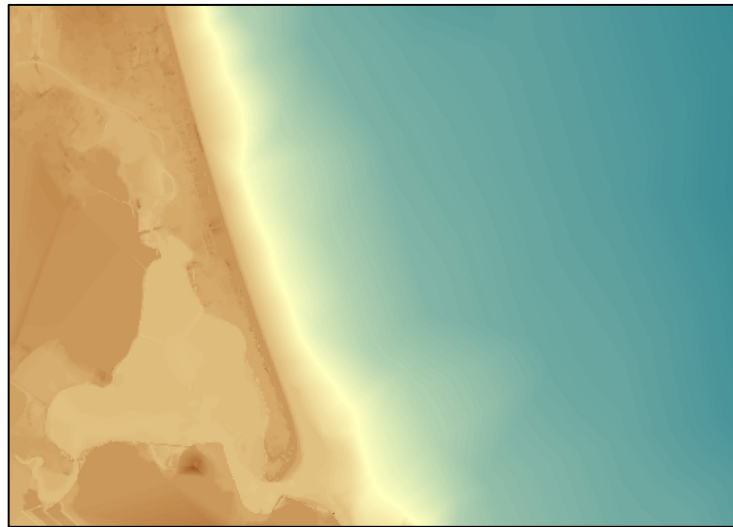
This pre-processing of the datasets was required in order to run the BeachMM tool because the DEM needed to be in a recognisable format in order for the numerical computations to be performed. This required the conversion of polylines into a TIN, then into a DEM with a grid of 25 m. This grid was then clipped, or masked to produce an area at a resolution over which XBeach would operate and

then reformatted into ESRI GRID. Distortion created over terrestrial values created by the TIN outside the area of the LiDAR area were ignored but necessary as this space needed to be occupied in order for the XBeach model to run. The same process was used to create the larger input grid extent used by SWAN for hydrodynamic forcing. This extent was 110 km by 70 km and encompasses part of Banks Peninsula and the Pegasus Canyon. The study area comprised two computational grids, one centred on East Christchurch and encompassing the Avon-Heathcote Estuary, where the other focussed on the Waimakariri coastal environment.

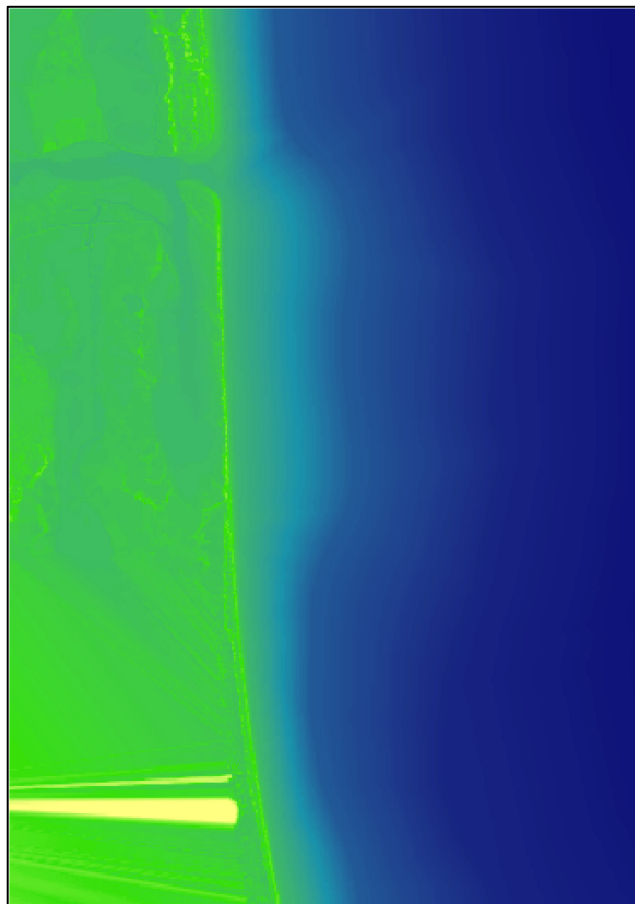
The BeachMM tool instructs SWAN to propagate the hydrodynamic forcing over the input grid and produce results for the computational grid which XBeach then employs to manipulate the nearshore to discover any sedimentation, erosion, bottom change, or water level change. The terrestrial areas of the grids were restricted to 4 m above LVD37 mean sea level (MSL) as XBeach fails to recognise terrestrial values and struggles to compute. Similarly, XBeach requires that all grids are rotated so the offshore boundary is aligned to the east in order for the program to propagate from deep to shallow water, or left to right in ASCII format. Rotation occurred around a pivot point of 1574004.11, 5146388.554. LVD37 was used for the LiDAR dataset and therefore corresponds to all z values. The projection coordinate system can affect the rectangular shape of the grid and therefore must be perfectly square and clipped to generate a grid without “Nodata” missing values, otherwise XBeach fails to launch. Similarly, all numbers in ArcGIS should be formatted without commas or special characters. New Zealand Transverse Mercator was used for all files. The computers’ virtual memory can also be an issue as the run-time implodes for large grids or fine resolution grids. This leads to computing capacity determining the size and resolution of the grids for the scenarios. The raster grids used for input and computation are illustrated in figures 5.1.1, 5.1.2 and 5.1.3.



**Figure 5.1.1 BeachMM tool input grid: grid size = 222 by 140; cell size = 500 m by 500 m; origin = x = 1574004.11, y = 5146388.554.**



**Figure 5.1.2 BeachMM tool Avon-Heathcote computational grid: grid size = 274 by 215; cell size = 25 m by 25 m; origin = x = 1575310, y = 5175832.801.**



**Figure 5.1.3 BeachMM tool Waimakariri computational grid: grid size = 324 by 458; cell size = 25 m by 25 m; origin = x = 1573951.73, y = 5186365.142.**

## 5.2 Hydrological and climatic parameters

The SWAN hydrological input parameters were calculated from the LINZ sea level dataset (LINZ, 2013b), the Canterbury wave buoy dataset provided by ECan, and the climatic conditions were taken from NIWA's (2013) Cliflo server. The wave buoy dataset starts in February 1999 and ends in July 2013 with measurements taken approximately every half hour. It is moored 17 km east of Le Bons Bay, Banks Peninsula with a Latitude of 43° 45' South and a Longitude of 173° 20' East in approximately 76 m of depth ensuring no interference by the seabed or terrestrial landmass with the measurements (Environment Canterbury, 2014). The Cliflo dataset was taken from the weather station at New Brighton Pier as 3-hourly measurements from the 27th of August 2009 to the 1st of January 2013.

There were two types of parameter settings used in the simulations with differing water levels over different time periods; one utilised mean hydrological and atmospheric conditions, and the other utilised the hydrological and atmospheric conditions during a storm. The parameters are: significant wave height (H sig); wave period (T); the direction from which waves propagate (Sea  $\theta$ ); the velocity of the wind (Wind v); and wind direction (Wind  $\theta$ ). For the mean forcing, the mean statistics from the various datasets were used for the parameters, except for wind direction where the mode was used. For storm forcing conditions the peak values were obtained for the different parameters during a recent storm on the 28th of June 2012, which ran over two days, and applied to the simulation. This storm is considered an extreme event as H sig falls within the top 1 % of all significant wave heights (Komar et al., 2013) and was chosen based on the availability of data for all parameters. Table 5.2.1 outlines the various parameter settings used in the simulations. Water levels have been calculated according to table 5.2.2 from data acquired from LINZ (2013b) on the Lyttelton tidal regime, IPCC predictions, and storm surge calculations, with MHWS referring to the mean high water spring tide. Table 5.2.3 outlines the tidal regime data from LINZ (2013b). Storm surge was calculated by subtracting the predicted tide level provided by LINZ (2013a) from the observed tide level recorded by the offshore wave buoy at the time of the storm. Storm surge was calculated at 0.77 m and is shown in table 5.2.2. Appendix A illustrates a SWAN input file used. The Waimakariri coastal environment simulation was operated utilising only the upper limit of the IPCC (2013) predictions of 0.98 m.

**Table 5.2.1 Parameters used in the simulations.**

Simulation	Water level (m)	H sig (m)	T (s)	Sea $\theta$ ( $^{\circ}$ , mode)	Wind v ( $\text{m s}^{-1}$ )	Wind $\theta$ ( $^{\circ}$ , mode)
Mean	0	1.95	8.8	194.2	5.11	75
Storm	1.96	7.49	13.3	140	9.2	230

**Table 5.2.2 Water level calculations given different scenarios.**

	Present mean (m)	Present storm (m)	100 year SLR min (0.27 m)	100 year SLR max (0.98 m)
<b>MHWS</b>	0	1.19	1.19	1.19
<b>Storm surge</b>	0	0.77	0.77	0.77
<b>SLR</b>	0	0	0.27	0.98
<b>TOTAL</b>	0	1.96	2.23	2.94

**Table 5.2.3 Tide data for Lyttelton (LINZ, 2013b).**

Standard Port	MHWS (m)	MHWN	MLWN	MLWS	Spring	Neap	MSL	HAT	LAT
					Range	Range			
Lyttelton	2.57	2.06	0.68	0.22	2.35	1.38	1.38	2.69	0.1

River discharge was incorporated into the XBeach model by way of location and time series text files that are then called into the computational domain. These files included the location, width, and flow rate of water for the Avon, Heathcote and Waimakariri rivers. The rate for the Avon River was set at  $2 \text{ m}^3 \text{ s}^{-1}$  and for the Heathcote River at  $1 \text{ m}^3 \text{ s}^{-1}$  taken from Measures (2011). An average flow rate of  $138.9 \text{ m}^3 \text{ s}^{-1}$  was used for the Waimakariri River which was recorded at State Highway 1 and obtained from ECan (2014).

### 5.3 Simulation time interval and alternative XBeach settings

Due to the long time scale of 100 years undertaken by this research, the morphological factor (morfac) available in XBeach was utilised. A morfac of 6 corresponded to 10 minutes of hydrodynamic forcing becoming 1 hour of forcing (Roelvink et al., 2010). This acceleration technique, or multiplier, sped up computation considerably, although was unreliable above 400 or near its maximum of 1000 for these simulations. The mean simulations were run at a morfac of 200, and storm simulations at a morfac of 6. Short simulations were also an issue under mean conditions as the XBeach model required a long period of time to propagate a result.

To recreate a real-world scenario, SWAN and XBeach were then run for a 10 year period, followed by a 2 day storm and repeated with increasing water levels until 100 years had passed. The division of the time period was also necessary as the XBeach program would implode with such large timeframes given the computing capacity. Therefore the 10 year simulation with a morfac of 200 was run for 1,576,800 s and the 2 day simulation with a morfac of 6 was run for 28,800 s.

Within the XBeach parameters file, some of the default settings were altered to better reflect the environmental situation. These included: The flow input latitude was changed to 43 (Lat=43) to better represent mid-latitude forcing; unfortunately negative values were not accepted. One time-varying water level signal was added (Tideloc=1). The equilibrium sediment concentration

computation option was set to ‘wave averaged’ (Turb=1). Longwave stirring was turned on (LWS=1). Shortwave stirring was stirred on (SWS=1). Appendix B illustrates the XBeach parameter file.

## 5.4 Simulations

Two grouped simulations were conducted to predict the future outcome for the Christchurch coastal environment consisting of twenty cumulative simulations with increasing water levels and intermittent storms, these were:

1. Future maximum scenario; computed with the IPCC 100 year sea level rise maximum prediction of 0.98 m, as illustrated in table 5.4.1.

**Table 5.4.1 Simulations for the future maximum scenario.**

Run	Forcing type	Water level (m)	H sig (m)	T (s)	Sea $\theta$ ( $^{\circ}$ , mode)	Wind v ( $m s^{-1}$ )	Wind $\theta$ ( $^{\circ}$ , mode)	Time interval	Morfac
1	Mean	0	1.95	8.8	194.2	5.11	75	10 years	200
2	Storm	1.96	7.49	13.3	140	9.2	230	2 days	6
3	Mean	0.11	1.95	8.8	194.2	5.11	75	10 years	200
4	Storm	2.07	7.49	13.3	140	9.2	230	2 days	6
5	Mean	0.23	1.95	8.8	194.2	5.11	75	10 years	200
6	Storm	2.19	7.49	13.3	140	9.2	230	2 days	6
7	Mean	0.34	1.95	8.8	194.2	5.11	75	10 years	200
8	Storm	2.30	7.49	13.3	140	9.2	230	2 days	6
9	Mean	0.46	1.95	8.8	194.2	5.11	75	10 years	200
10	Storm	2.42	7.49	13.3	140	9.2	230	2 days	6
11	Mean	0.56	1.95	8.8	194.2	5.11	75	10 years	200
12	Storm	2.52	7.49	13.3	140	9.2	230	2 days	6
13	Mean	0.67	1.95	8.8	194.2	5.11	75	10 years	200
14	Storm	2.63	7.49	13.3	140	9.2	230	2 days	6
15	Mean	0.79	1.95	8.8	194.2	5.11	75	10 years	200
16	Storm	2.75	7.49	13.3	140	9.2	230	2 days	6
17	Mean	0.90	1.95	8.8	194.2	5.11	75	10 years	200
18	Storm	2.86	7.49	13.3	140	9.2	230	2 days	6
19	Mean	0.98	1.95	8.8	194.2	5.11	75	10 years	200
20	Storm	2.94	7.49	13.3	140	9.2	230	2 days	6

2. Future minimum scenario; computed with The IPCC 100 year sea level rise minimum prediction of 0.27 m, as illustrated in table 5.4.2.

**Table 5.4.2 Simulations for the future minimum scenario.**

Run	Forcing type	Water level	H sig (m)	T (s)	Sea $\theta$ ( $^{\circ}$ , mode)	Wind v ( $m s^{-1}$ )	Wind $\theta$ ( $^{\circ}$ , mode)	Time interval	Morfac
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		(m)							
1	Mean	0	1.95	8.8	194.2	5.11	75	10 years	200
2	Storm	1.96	7.49	13.3	140	9.2	230	2 days	6
3	Mean	0.03	1.95	8.8	194.2	5.11	75	10 years	200
4	Storm	1.99	7.49	13.3	140	9.2	230	2 days	6
5	Mean	0.06	1.95	8.8	194.2	5.11	75	10 years	200
6	Storm	2.02	7.49	13.3	140	9.2	230	2 days	6
7	Mean	0.09	1.95	8.8	194.2	5.11	75	10 years	200
8	Storm	2.05	7.49	13.3	140	9.2	230	2 days	6
9	Mean	0.12	1.95	8.8	194.2	5.11	75	10 years	200
10	Storm	2.08	7.49	13.3	140	9.2	230	2 days	6
11	Mean	0.15	1.95	8.8	194.2	5.11	75	10 years	200
12	Storm	2.11	7.49	13.3	140	9.2	230	2 days	6
13	Mean	0.18	1.95	8.8	194.2	5.11	75	10 years	200
14	Storm	2.14	7.49	13.3	140	9.2	230	2 days	6
15	Mean	0.21	1.95	8.8	194.2	5.11	75	10 years	200
16	Storm	2.17	7.49	13.3	140	9.2	230	2 days	6
17	Mean	0.24	1.95	8.8	194.2	5.11	75	10 years	200
18	Storm	2.20	7.49	13.3	140	9.2	230	2 days	6
19	Mean	0.27	1.95	8.8	194.2	5.11	75	10 years	200
20	Storm	2.23	7.49	13.3	140	9.2	230	2 days	6

The variables that were measured by the BeachMM tool for this study were net sedimentation or erosion (sedero), bed level and water level. Each new bed level created was incorporated into the next simulation, thereby incrementally adjusting the bathymetry. The sedero output required post-processing analysis to create a fuzzy overlay in ArcGIS which summed all of the outputs created to produce the net sedimentation or erosion. The results of the final simulation were used as output for the bed level and water level due to the incremental increase. Resulting grids were then rotated back to the original space. The ArcGIS conversion tools used to generate the grid and the post processing analysis are visible in figure 5.4.1.

The current enforced CERA (2014) red zone was also digitised to illustrate current planning changes after the Canterbury earthquakes of 2010 and 2011. The current residential red zones enforced by CERA have now mostly been abandoned due to a high potential risk of flooding.

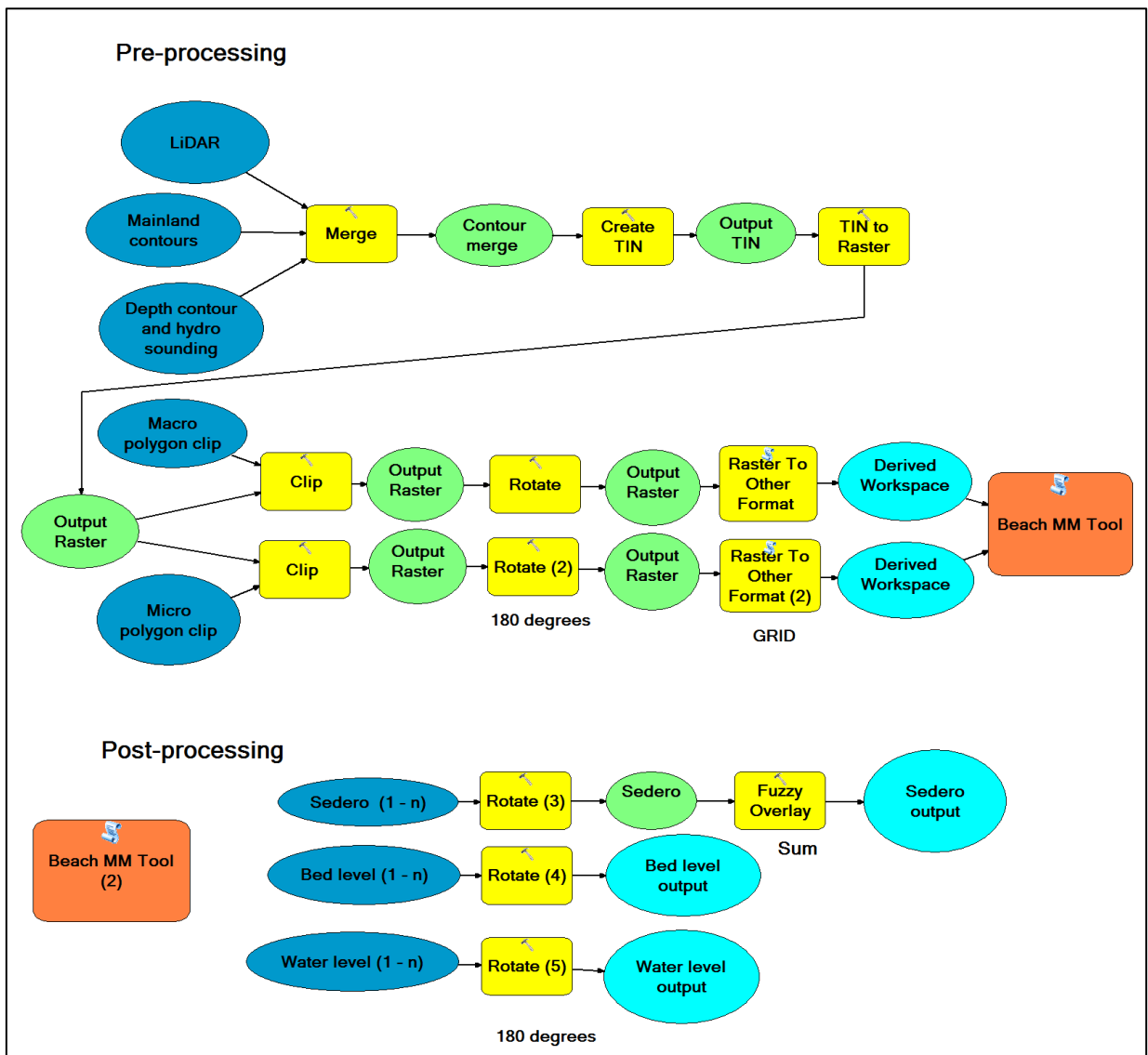


Figure 5.4.1 A flow diagram showing the pre and post processing tools used for analysis.

## 5.5 Calibration, assumptions and related limitations of the models

The model was calibrated through remote desktop application and observation as time constraints did not allow for direct field measurements. The SWAN graphic user interface (GUI) was utilised to test the hydrodynamic forcing, bathymetric grid and changing water level. This GUI allows for simplified visualisations of the resultant hydrodynamic forcing. Wave height, wave period, wind direction and wind velocity used to run the simulations were then compared with those forecasted by Meteo365 (2013) and observed from the foreshore and the surf zone. Appendix F shows calibration of the hydrodynamic forcing for recent observed conditions using the SWAN GUI.

The modelled scenarios operate over a closed system to sediment flux and river sediment discharge was not programmed into the models as little data is available for the associated rivers. Mean measurements were used for climate and hydrodynamic parameters to reduce the processing times for such a long study period.



The limitations of the SWAN and XBeach models that are relevant to their use in these simulations are to follow.

Limitations of the SWAN model:

- SWAN does not compute wave-induced currents (Booij, 2012).
- Unexpected interpolation patterns on the computational grid may arise from the differing resolution of the input grid (Booij, 2012).
- SWAN can have convergence problems due to the iteration process (Booij, 2012).
- Unintentional coding bugs may be present (Booij, 2012).

Limitations of the XBeach model:

- XBeach does not perform well in very shallow water (Roelvink et al., 2010).
- The alongshore gradient of wave energy is zero in the stationary case (Roelvink et al., 2010).
- The computational x-axis must be orientated toward the coast and rectilinear (Roelvink et al., 2010).
- Under sheet flow conditions, greater velocities lead to greater sediment transport rates, but not to greater equilibrium sediment concentrations (Roelvink et al., 2010).
- The sediment flux cannot be included at the river discharge boundary.

## Chapter 6

### Results

#### 6.1 SWAN wave propagation model

The results for the significant wave height of the SWAN run are shown in figure 6.1 for a) mean conditions, and b) storm conditions. The mean wave height under normal conditions approaching the shore of Pegasus Bay is 0.2 – 0.4 m, and 1 – 3 m under storm conditions. The mean period of waves approaching the shore of Pegasus Bay is 8 – 8.5 m s<sup>-1</sup> under normal conditions, and 11 – 12 m s<sup>-1</sup> under storm conditions. The direction under normal conditions is 194°, and under storm conditions is 140°.

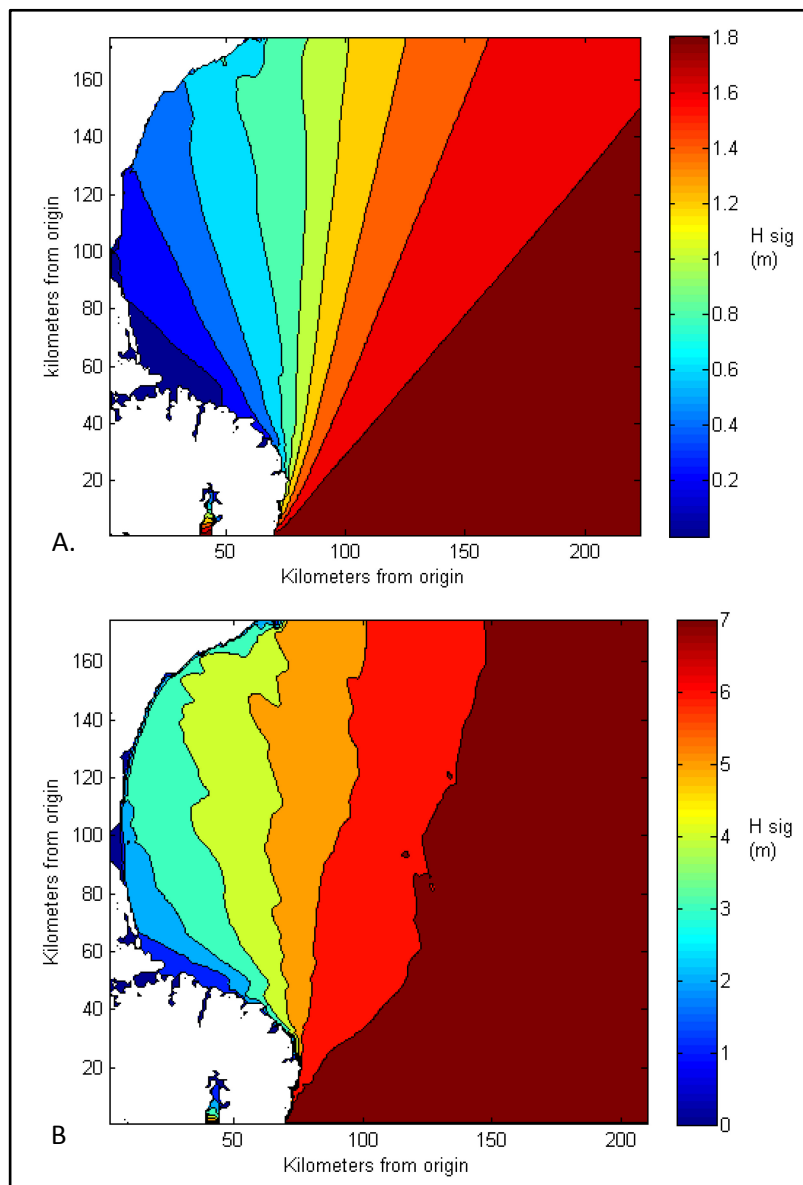


Figure 6.1 SWAN propagation of the significant wave height ( $H_{sig}$ ) for a) the present mean simulation, and b) the present storm simulation.

## 6.2 BeachMM tool

### 6.2.1 Sedimentation and Erosion

The net result of all simulations for sedimentation and erosion (sedero) over the 100 year period for both the minimum and maximum scenarios illustrates a slight progradation of the foreshore with the majority of the sediment being received from the nearshore, although the minimum scenario is a magnitude smaller. The most dynamic areas are the Avon-Heathcote Estuary ebb tidal delta, the Waimakariri River mouth and the Scarborough Heads; with rates of deposition being relatively high on the western aspects and higher erosional rates on the eastern aspects of these features.

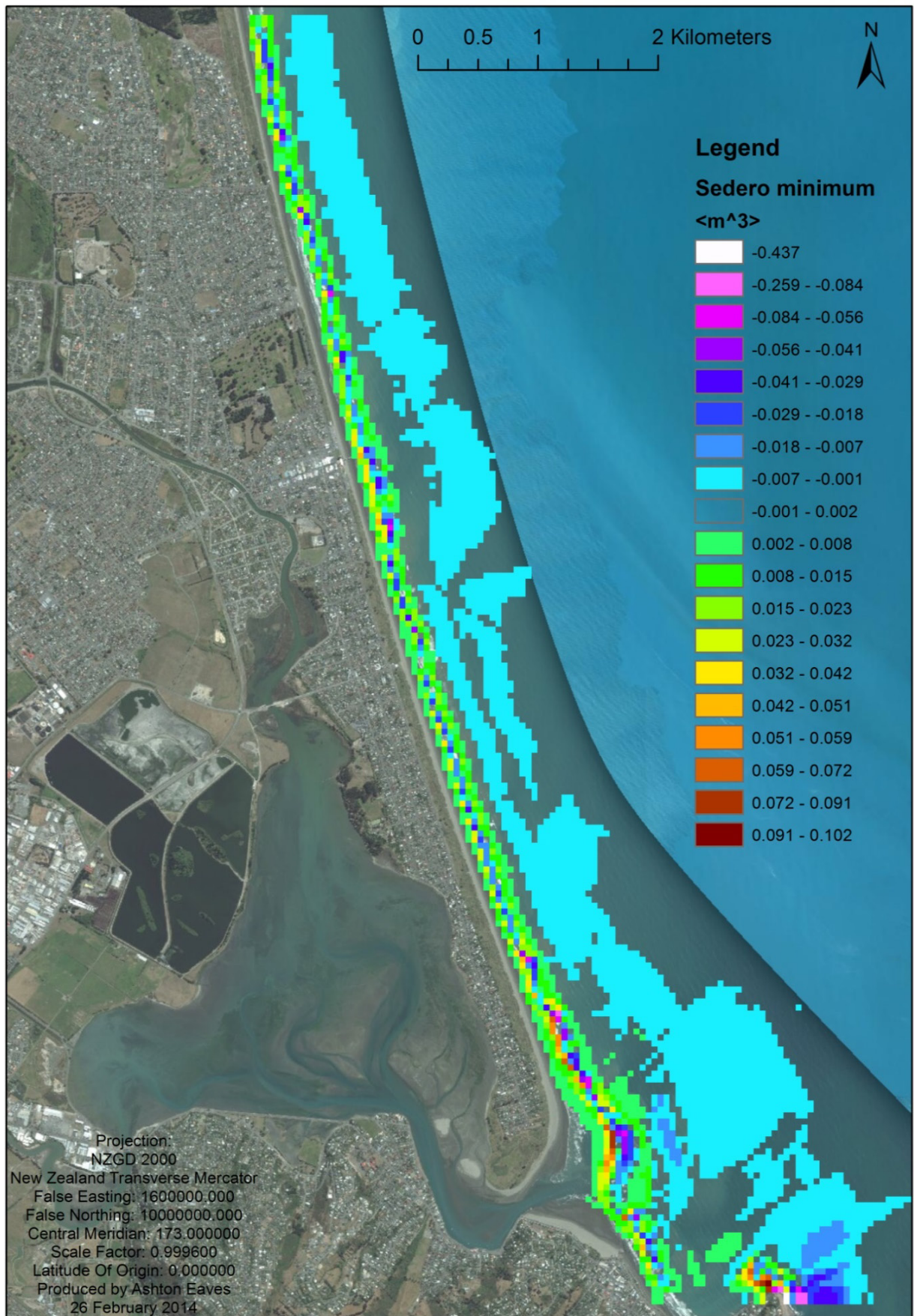
The sedimentation rate for the minimum scenario for the majority of the foreshore is  $0.00002 \text{ m}^3 \text{ a}^{-1}$  to  $0.00023 \text{ m}^3 \text{ a}^{-1}$ , with pockets of erosion present throughout of  $0.00031 \text{ m}^3 \text{ a}^{-1}$  to  $0.00153 \text{ m}^3 \text{ a}^{-1}$ . Sedimentation rates are higher on the western aspect of the Avon-Heathcote Estuary ebb tidal delta and at Scarborough Head ranging from  $0.00023 \text{ m}^3 \text{ a}^{-1}$  to  $0.00102 \text{ m}^3 \text{ a}^{-1}$ . On the eastern aspects, erosion rates are higher ranging from  $0.00018 \text{ m}^3 \text{ a}^{-1}$  to  $0.00437 \text{ m}^3 \text{ a}^{-1}$ . The nearshore appears to erode at a minimal rate of  $0.00001 \text{ m}^3 \text{ a}^{-1}$  to  $0.00007 \text{ m}^3 \text{ a}^{-1}$  at approximately 1 km out. These results can be seen in figure 6.2.1.1. The mean statistic for the sedero results is negligible at  $-0.0001 \text{ m}^3$ , with a standard deviation of 0.004 for the period.

The sedimentation rate under the Avon-Heathcote Estuary simulations for the maximum scenario for the majority of the foreshore is  $0.00017 \text{ m}^3 \text{ a}^{-1}$  to  $0.0009 \text{ m}^3 \text{ a}^{-1}$ , with pockets of erosion present throughout of  $0.00018 \text{ m}^3 \text{ a}^{-1}$  to  $0.00041 \text{ m}^3 \text{ a}^{-1}$ . Sedimentation rates are higher on the eastern aspect of the Avon-Heathcote Estuary ebb tidal delta and at Scarborough Head, ranging from  $0.00017 \text{ m}^3 \text{ a}^{-1}$  to  $0.00162 \text{ m}^3 \text{ a}^{-1}$ . On the eastern aspects, erosion rates are higher, ranging from  $0.00055 \text{ m}^3 \text{ a}^{-1}$  to  $0.00614 \text{ m}^3 \text{ a}^{-1}$ . The nearshore appears to erode at a minimal rate of  $0.00007 \text{ m}^3 \text{ a}^{-1}$  to  $0.00031 \text{ m}^3 \text{ a}^{-1}$  at approximately 1 km out. These results can be seen in figure 6.2.1.2. The mean statistic for the sedero results is negligible at  $-0.0001 \text{ m}^3$ , with a standard deviation of 0.006 for the period.

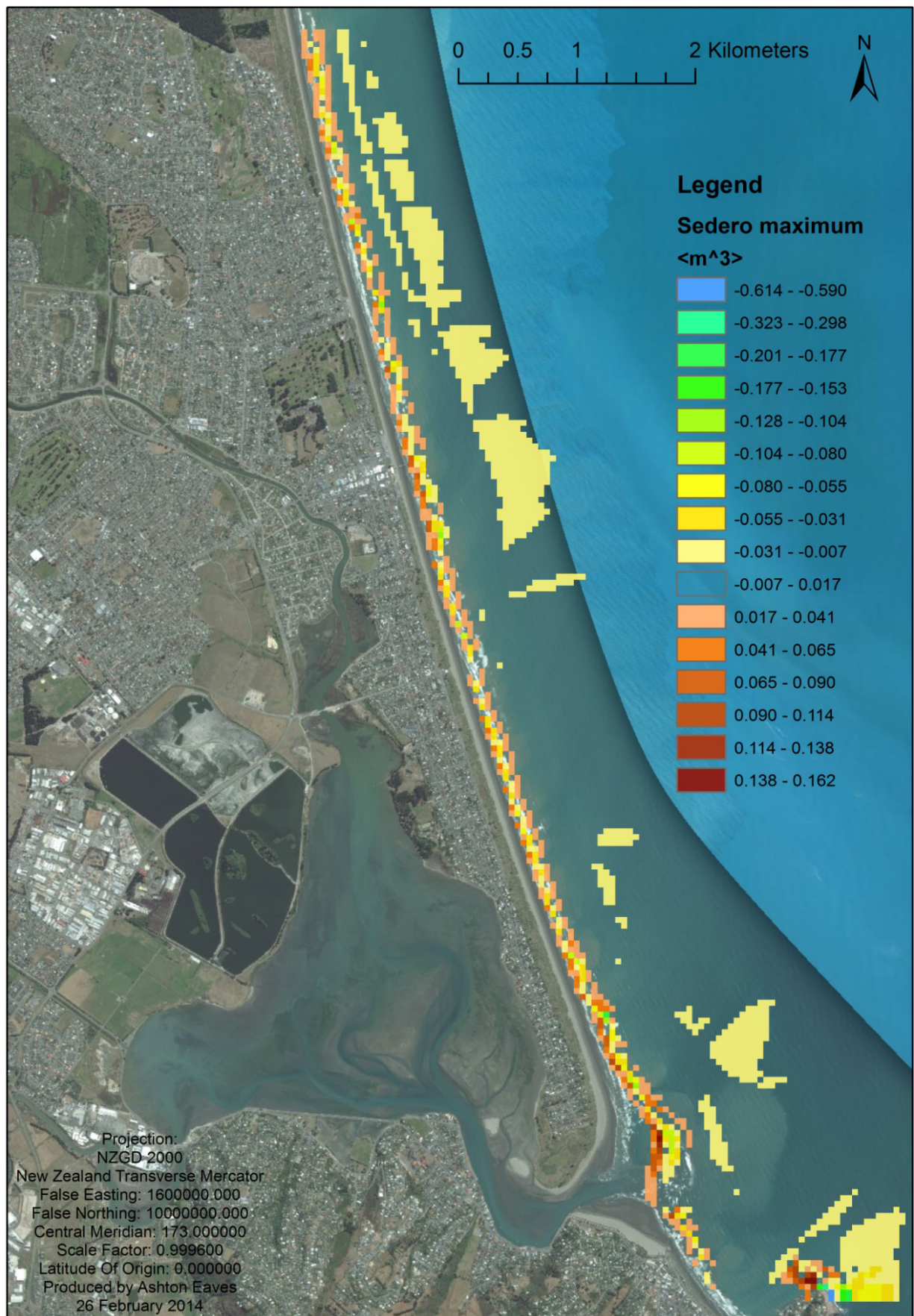
The sedimentation rate for the Waimakariri coastal environment also illustrates that the coast will prograde at the expense of the nearshore. The nearshore illustrates a net sediment flux of  $-0.00032 \text{ m}^3 \text{ a}^{-1}$  to  $-0.00222 \text{ m}^3 \text{ a}^{-1}$ , whereas the beach face has undergone a deposition of  $0.00031 \text{ m}^3 \text{ a}^{-1}$  to  $0.00285 \text{ m}^3 \text{ a}^{-1}$ , which is illustrated in figure 6.2.1.3. The mean statistic for the sedero results is negligible at  $-0.0004 \text{ m}^3$ , with a standard deviation of 0.024 for the period.

The future foreshore of East Christchurch will prograde over the 100 year period by 0.008 m to 0.041 m. Conversely the nearshore seabed will erode by 0.004 m to 0.031 m over this closed system. Similarly, the Waimakariri coastal zone foreshore will be slightly higher over the 100 year period by 0.095 m to 0.158 m where the nearshore will be slightly lower by 0.095 m to 0.032 m. The Avon-

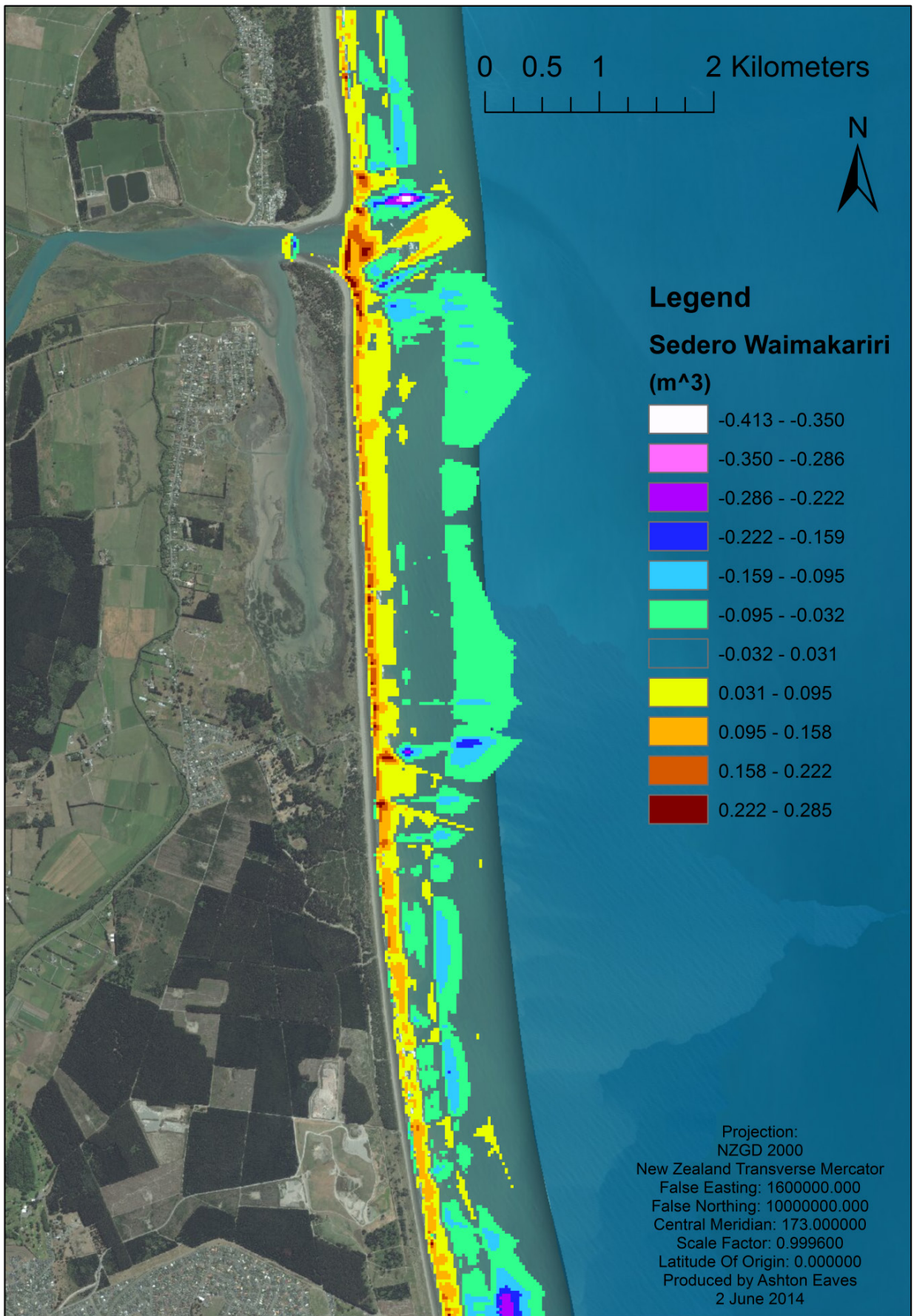
Heathcote ebb tidal delta appears to aggrade on the inner fan and erode on the outer fan due to wave domination across its surface. At Scarborough Head erosion will occur to areas of high wave climate exposure on the eastern flank and accumulate in the nearby north facing flank. There are complex interactions at the Waimakariri River mouth with very high rates of accretion and erosion within a small spatial scale due to fluvial discharge. There is domination of the marine environment over the river system determined by the lack of generation of a distinct delta, and a river channel has not clearly formed within the intertidal zone. An alluvial deposit is created in the nearshore that has not fully developed into a delta as marine hydrodynamic forcing is preventing this occurrence. A deep pool has scoured out on the northern flank of the delta to allow the river to discharge. A smaller pool can be seen on the southern flank.



**Figure 6.2.1.1** Minimum predicted net sedimentation and erosion for East Christchurch over 100 years. Complex changes in sediment occur at the Avon-Heathcote ebb tidal delta and Scarborough Head.



**Figure 6.2.1.2 Maximum predicted net sedimentation and erosion for East Christchurch over 100 years. Complex changes in sediment occur at the Avon-Heathcote ebb tidal delta and Scarborough Head.**



**Figure 6.2.1.3** Maximum predicted net sedimentation and erosion for the Waimakariri coastal zone over 100 years. Complex changes in sediment occur at the river mouth with sediment plumes in the nearshore eroded and deposited on the beach face.

## **6.2.2 Future water level**

The future minimum and maximum water levels under storm conditions will lead to inundation of coastal areas of Greater Christchurch. The areas affected will primarily be around the fringes of the Avon-Heathcote Estuary, Brooklands and Kairiki due to their low topography. Summer, the lower reaches of the Avon and Heathcote rivers, and farmland adjacent to the Brooklands lagoon will also be inundated to varying extents.

The level of inundation for both the minimum of 2.23 m above MSL and maximum of 2.94 m above MSL are visible in figure 6.2.2.1. The future minimum and maximum mean water levels or MSL are visible in figure 6.2.2.2. This extent is very similar to the present extent of 2013. The extent of flooding for the Waimakariri coastal environment under the maximum scenario is visible in figure 6.2.2.3. The dune system within the study area appears to have enough elevation to prevent inundation occurring from an easterly direction and remains free of flooding. However, inundation occurs via the confluence of water bodies.



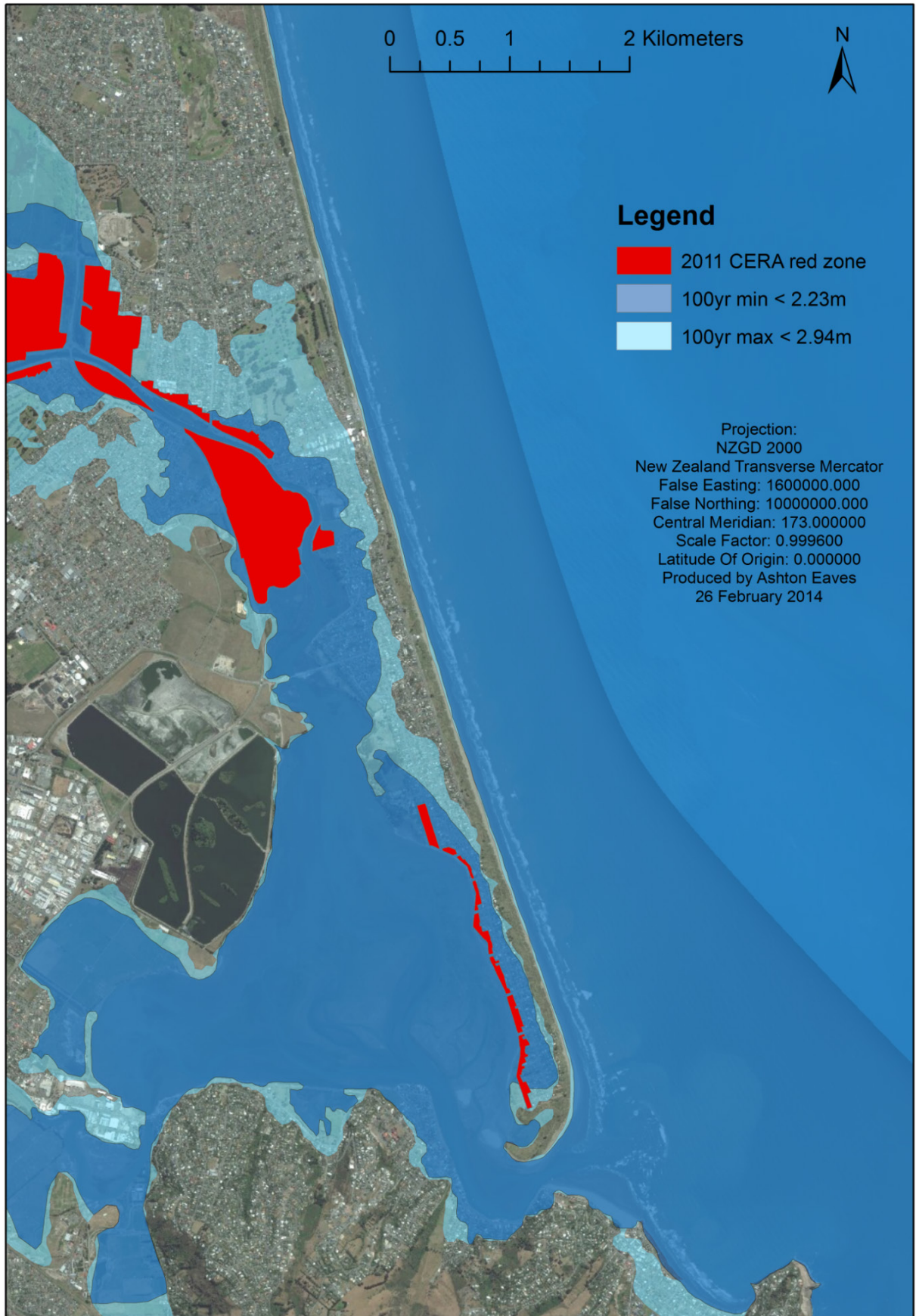
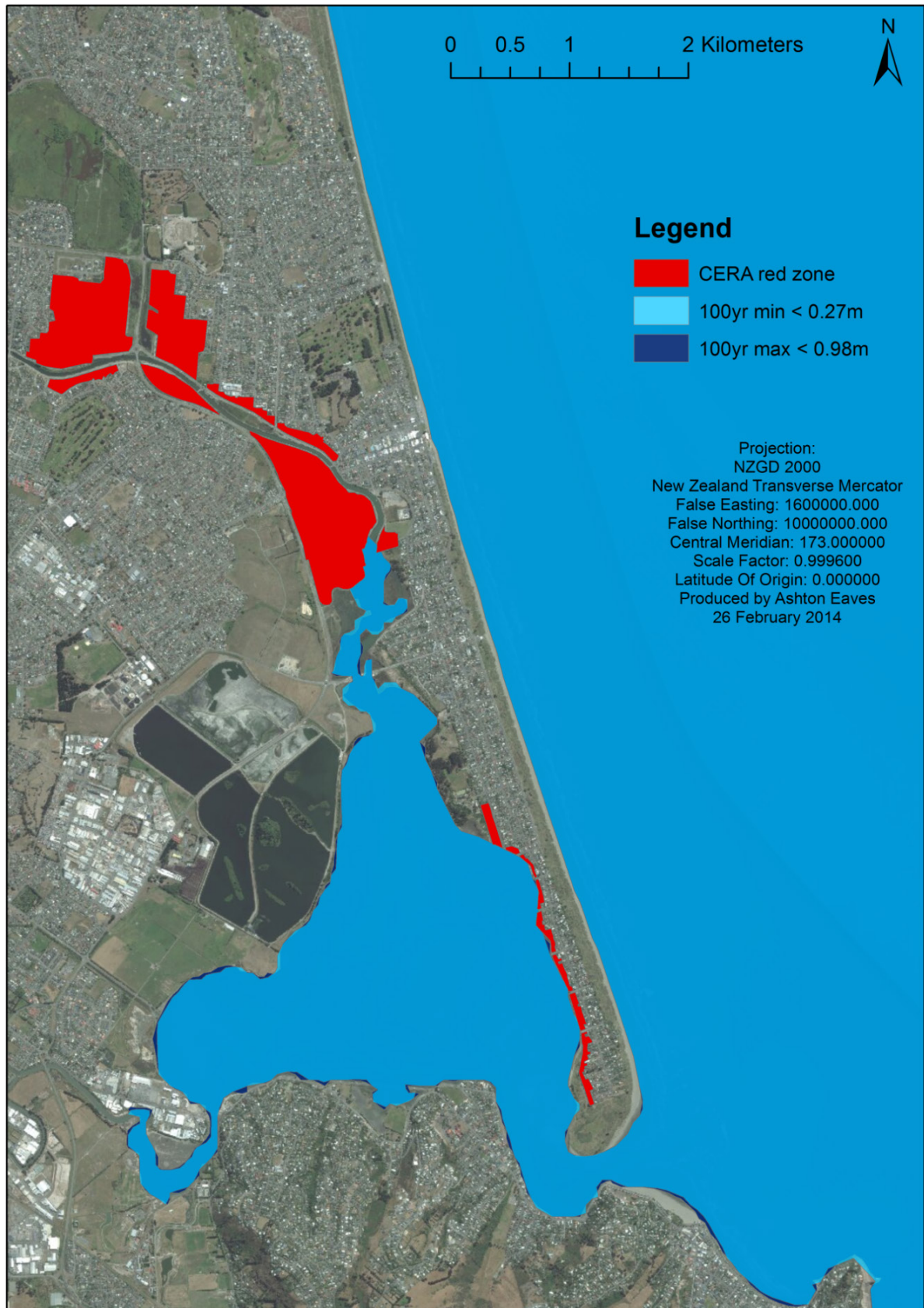
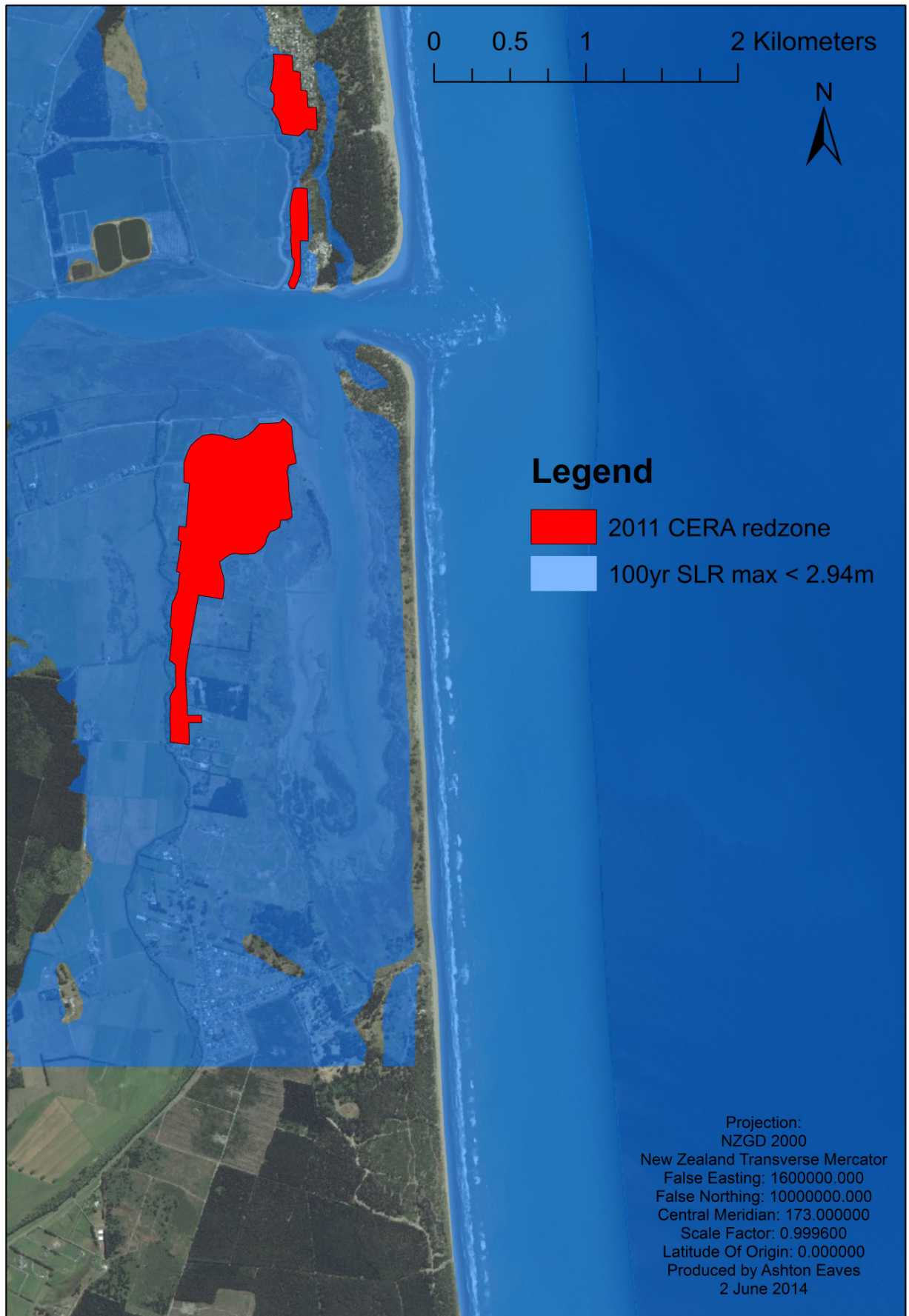


Figure 6.2.2.1 Inundation scenarios modelled under storm conditions for East Christchurch given a sea level rise for 100 years of 0.23 m (min) and 0.98 m (max), a storm surge of 0.77 m, during a MHWS of 1.19 m. Inundation propagates inland beyond the study area.



**Figure 6.2.2.2** Inundation scenarios modelled under mean conditions for East Christchurch given a sea level rise for 100 years of 0.23 m (min) 0.98 m (max). Inundation is minimal under mean conditions.



**Figure 6.2.2.3** Inundation scenario for the Waimakariri coastal environment under storm conditions given a sea level rise for 100 years of 0.98 m (max), a storm surge of 0.77 m, during a MHS of 1.19 m. Inundation propagates inland beyond the study area.

## Chapter 7

### Discussion

The fundamental aim of this research project was whether the current CERA zoning for Greater Christchurch meets the obligations outlined in the NZCPS 2010 for future sea level rise, and it would appear that it does not meet those requirements. This is because coastal hazard risk has not been comprehensively quantified by the installation of the CERA residential red zone. However, the CCC's flood management area does provide an extent to which managed retreat is a real option. Development can still be undertaken on areas that are at risk from moderate predicted levels of inundation. The present MHWS level will frequently be exceeded in the future, particularly in areas with a low tidal range like those occurring through the central parts of the east coast, leading to storm inundation having greater influence and enhanced coastal erosion (Ministry for the Environment, 2008). The expected changes to atmospheric conditions, storms and cyclones will also lead to coastal erosion and inundation through changes to the wave climate and beach sediment movement (Ministry for the Environment, 2008). Local government is required to effectively identify, account, avoid and mitigate any coastal hazards, vulnerabilities, or consequences over at least a 100 year period to preserve coastal environments from inappropriate development while enhancing public access (New Zealand Government, 1991). Simulating coastal change at timescales relevant to planning and development requires new types of modelling approaches over large temporal and spatial scales, these should incorporate high quality datasets to enable the refinement, calibration and validation of such models (Ministry for the Environment, 2008).

#### **7.1 The effectiveness of the predictive computer models for the hazard assessment of the Christchurch coastal zone**

The BeachMM tool and the numerical models of SWAN and XBeach were effective in modelling shoreline evolution. After formatting, the tool provided easy integration into a GIS platform of complex dynamic parameters. It simplified the dataflow effort, reduced human error and provided dynamic visualisation of the modelling results (Silva & Taborda, 2012), allowing a system to be constructed, investigated, reconfigured and tested with comparative ease (Duncan, 2008). Simulations in predictive models provide decision makers with valuable quantitative information about the state of the coast (Silva & Taborda, 2013). The BeachMM tool through its user friendly interface allows beginner programmers the ability to experiment with coastal dynamics without the requirement of expertise in IT. Such spatial analysis and data integration techniques in GIS provide accurate mapping and analysis of dynamic coastal environments that are governed by wave climate and sea level rise (Allen et al. 2012).

The XBeach model performed well under open coast conditions although not so well under estuarine conditions. This is because the water level is expectedly shallow in this intertidal zone and propagation of hydrodynamic forcing is near impossible. The time interval was also an issue as the morphological updating required a certain timeframe to evolve and inhibited some application of the morphological acceleration. XBeach did perform the tasks of dune and nearshore erosion, berm and foreshore sedimentation, sea bed updating, over washes and breaches well to simulate a natural coastal response to a range of timeframes and conditions.

With any abstraction of the environment into a computerized simulation, limitations exist as common constraints arise from the scale of observation, computational limitations, uncertainty, and error propagation in GIS and its applications (Allen et al. 2012). These limitations were: the effects of interdecadal climatic oscillations such as ENSO on regional sea levels; the accuracy of models to incorporate detailed sediment flux analysis from rivers or at the grid boundary; and the amount of computing capacity. The beach MM tool needs to be programmed with a greater range of atmospheric and sea state conditions by calling a file with a diverse range of conditions over at least a decadal time period. This would help to overcome anomalies such as ENSO and southern oscillation projections that need to be included in any future study. Inclusion of the Waimakariri River sediment discharge was not applicable as this sediment has not been readily quantified and XBeach does not have the ability to input sediment at the boundary without development of the program. This research was also limited by computing capacity. Grid resolution, size and morphological updating over time were completely dependent on the computers' virtual memory, which led to reduced grids at a lower resolution than first tested.

Overall the integration of the SWAN and XBeach model into a GIS platform through the BeachMM tool in ArcGIS proved to be very useful and powerful. SWAN provided a very stable environment on which to gather the hydrodynamic forcing dataset as it has been in creation for many years and therefore is well refined. Conversely, XBeach is a recently developed program with very little support for those choosing to operate it over a GIS platform as it has been designed to operate primarily through Matlab. As stated by Silva and Taborda (2012) the BeachMM tool does provide: seamless integration of geospatial data into existing numerical models, model chain automation, powerful visualising and analysis tools for the exploitation of model results. Furthermore, any prognostic modelling should be correlated with successive observations and monitoring to discover the model's accuracy.

## **7.2 The extent of the Christchurch shoreline in 100 years**

The extent of the Christchurch shoreline in 100 years will be similar to that exhibited by the inundation scenarios visible in figure 6.2.1.1 and figure 6.2.1.3. The Greater Christchurch sandy

coastline will continue to prograde given sediment supply from the Waimakariri River continues. The results of this research provide a minimal amount of progradation that is likely to occur over the period as a closed system to sediment supply was modelled. Changes in the west-east gradient in rainfall will see it wetter in the west and drier in the east with an increase in rainfall intensity during severe storms (Ministry for the Environment, 2008). The catchment of the Waimakariri River extends to the main divide and receives westerly rainfall which should facilitate enhanced flow and sediment supply to the coast. As Pegasus Bay is marine dominated, where sediment can be dispersed but not removed from the nearshore, what is not lost to deep water during storms will incrementally nourish terrestrial dunes during modal conditions (Schulmeister & Kirk, 1997). This was indicated by the model in the absence of the Waimakariri River sediment flux as slight progradation occurred at the expense of the nearshore. Assuming replacement of this sediment by the Waimakariri sediment flux, progradation will continue to occur.

The accumulation of sediment on the inner fan of the ebb tidal delta of the Avon-Heathcote Estuary may significantly reduce channel width and depth. The reduced tidal flow may lead to the New Brighton spit making landfall on the peninsula with intermittent openings to the sea in times of flood. This has occurred on Lake Ellesmere to the south of Banks Peninsula. The New Brighton Spit has made landfall on the peninsula before to form a barrier lagoon system (Hart et al., 2008; Schulmeister & Kirk, 1997). For planning purposes spits are not landforms but mobile coastal features that are characterised by large shoreline migrations over relatively short time periods (Hart et al., 2008). Although, sea level rise could scour and deepen estuarine channels if these changes exceed sediment build up, or where sedimentation fills estuaries from enhanced rainfall events, then the estuary may cease to exist (Ministry for the Environment, 2008). Therefore close monitoring of the sedimentation of the Avon-Heathcote Estuary will help determine spatial patterns of inundation.

Estimates of Greater Christchurch coastal dune recession with sea level rise relies on an overly simplified coastal environment. The two-dimensional Bruun Rule is obsolete in predicting the contemporary geomorphology of foredunes in response to sea level rise (Hilton, 2013). This is because the Bruun Rule assumes unconsolidated sediment, no sediment inputs, and no net alongshore flux (Hilton, 2013). The introduced Marram grass species has forced accretion on many South Island beaches due to its efficiency at sand entrapment, this has the potential of further foredune accretion with increasing mean wind speeds (Hilton, 2013).

### **7.3 The effects of future storm surge**

The current CERA red zone is ineffective at dealing with a 100 year flooding hazard given sea level rise. This is because the extent of the area of inundation will be larger than that already designated. Coastal processes will maintain an adequate buffer against storm surge along the dune system,

although storm surge with a MHWS tide will not be prevented from inundation of the low lying areas adjacent to the Avon-Heathcote Estuary and the Brooklands Lagoon. The lower reaches of the Avon and Heathcote Rivers are also tidal making parts of these catchments vulnerable to sea level rise, although the Christchurch earthquake of 22 February 2011 lifted the tidal portion of the Heathcote catchment by about 0.4 m and lowered the rest by 0.1-0.3 m (Tonkin and Taylor Ltd, 2013). This report describes the minimum inundation hazard zone as the 100 year maximum of 2.94 m above mean sea level outlined in figures 6.2.2.1 and 6.2.2.3, or the setback limit for development. The flood management areas assigned by the Christchurch City Council that are visible in appendix E, provide an acceptable extent by which to inhibit development and are similar to the modelled extent for the future maximum inundation during storm conditions. However, given the risk associated with future inundation, parts of these flood management areas should also be zoned red.

The maximum inundation scenario is not as great as that modelled by Tonkin and Taylor Ltd (2013) (appendices C and D) as the modelling extent was smaller and coastal processes were taken into account which limited dune overtopping and coastal erosion. Tonkin and Taylor Ltd (2013) employed the passive inundation approach which will tend to overestimate inundation (Ministry for the Environment, 2008). However, their report was more accurate in dealing with sections of the coastal environment that were backed by revetments as the coarse 25 m resolution employed by this study could not differentiate hard and soft structures without a higher resolution grid and further model programming. Tonkin and Taylor (2013) did employ a similar sea level rise that was 1.0 m by 2115. They also allowed a free board of 0.4 m to allow for localised wave effects and other uncertainties (Tonkin and Taylor Ltd, 2013).

The effects of storm surge given the futuristic Waimakariri coast scenario will see extensive flooding of Brooklands, Kairiki and the surrounding low lying area which is predominantly agricultural. Coastal lagoon topography is generally low, otherwise they would cease to exist and rivers would drain freely into the ocean. The amount of flooding modelled is a modest estimation as during a period of storm surge, precipitation is likely which would elevate the river discharge and increase the water level in the lagoon at high tide. This parameter was not included into the modelling exercise, but is worth investigating. The red zone installed by CERA (2014) at Brooklands was appropriate as this area is highly susceptible to flooding, although it needs to be extended landward. Much of the rest of this area is under agricultural landuse and therefore is at less risk than developed residential land. An expansion of the Kairiki red zone is advised.

Finally, with the advent of accurate predictive computer modelling and the general acceptance of climate change, the use of historical annual exceedance probabilities and return periods becomes increasingly redundant. The use of these static measures prescribed from recent human history for

the classification of episodic hazard events becomes very difficult with climate change, which may be exponential, parabolic or quasi-linear. The integration of GIS, satellite imagery, sensor technology and numerical modelling provides for a more objective scientific expression.

### **7.3.1 Coastal geomorphology and fluvial processes**

The results of the BeachMM tool show that the marine environment dominates over the fluvial processes. A prominent delta failed to form in the intertidal or subtidal zone where the flow exits the Waimakariri River and the Avon-Heathcote delta is formed by the ebb tide. However, poorly-formed sediment was deposited, with incised alluvial or tidal scouring in these zones. The modelling shows that any sediment accumulating in the nearshore as a result of fluvial processes will be forced landward to the foreshore, which is then transported by aeolian mechanisms into the dune system.

The original Waimakariri DEM showed two fan deposits south of the river mouth that were eroded by hydrodynamic forcing and deposited to the foreshore by the model. It is speculated that these deposits may be the result of Waimakariri flooding events of the recent past. During peak flood events the Waimakariri River can debouch  $800 \text{ m}^3 \text{ s}^{-1}$  (Canterbury Regional Council, 2014). This could explain the presence of these disjointed sediment deposits in the subtidal zone. Breach events of coastal barriers at river mouths inject coarse slugs of sediment into the coastal environment which nourish down-drift beaches (Hart & Bryan, 2008). Further analysis and quantification of sediment load and bed load debouching into Pegasus Bay from the Waimakariri River is required. The mouth of the Waimakariri River does not meander up and down the coast, unlike the Rakia, Rangitata, Ashburton and Waitaki (Hart & Bryan, 2008), and the Hurunui and the Ashley rivers. Reasons for this could include: anthropogenic constraints of the channel; gravel extraction in the catchment near the coast; or the long shore drift at the Waimakariri River mouth being in a state of dynamic equilibrium. Given the storm surge scenario modelled in this report, the dune system adjacent to the Brooklands Lagoon could easily be compromised during this event creating a new location for the river mouth. The Waimakariri coastal environment in 100 years will see a continuation of a slow progradation under sea level rise and assuming river flows do not decrease due water abstraction in the catchment. The domination of the marine environment will force sediment north and south of the river mouth (Schulmeister & Kirk, 1997). There is the possibility that a subtidal delta may form temporarily, to then be removed by hydrodynamic forcing over time.

Due to the low flows associated with the Avon and Heathcote rivers, the ebb-tidal delta is primarily formed by tidal flow and supplemented by river discharge. Marine hydrodynamic forcing may lead to the intermittent closure of the estuary due to continuous sediment supply not being removed by fluvial mechanisms. Marine hydrodynamic forcing is slightly lower than that associated with the Waimakariri coastal zone to the north due to Banks Peninsula providing shelter from prevailing



marine and climatic conditions. This favours the ebb-tidal delta formation and sands spit deposition. Again, water abstraction in the catchment of the Avon and Heathcote rivers will also determine the outcome for the estuary and ebb-tidal delta.

### **7.3.2 The BeachMM tool**

The BeachMM tool provides insight through prognostic modelling into coastal morphodynamics at varying timescales. It allows for the desktop use of a model which is usually only appropriate for super computers with abundant RAM and processing power. There are also endless options for further development through its python script language for time series animations of storms, enhanced climate and river data integration, and assessing the outcomes of Tsunamis.

The ability for the BeachMM tool to operate over both temporal and spatial scales allows users a type of GIS analysis frequently constrained to low resolution numerical models. Combining numerical models into the GIS platform allows for easily accessible high resolution spatial data to be analysed over time with different parameters. Combining the universally accepted and tested hydrodynamic SWAN model and the empirically tested geomorphological XBeach model provides the user with confidence in the results. As the BeachMM tool can run on desktop or laptop computers, this provides access of its application to a vast numbers of users. Thus providing greater accessibility than if it was to be operated via powerful super computers which are usually required for prognostic modelling.

There are endless possibilities to the advancement of the BeachMM tool due to its versatile python script. The ability to output results at incrementally varying time intervals throughout the simulation makes it possible to produce animations of hydrodynamic forcing or coastal evolution. This could also be extended to the effects of Tsunamis on the shore, although the hydrodynamics are slightly different for tsunamis and therefore may require modification of the model. The validity of the model would be enhanced through improved climate and river datasets. This is possible by calling detailed datasets into the SWAN or XBeach parameter file with diverse atmospheric conditions or discharge rates over time. Conversely, an atmospheric numerical model could be directed by the BeachMM tool to couple with SWAN or XBeach.

### **7.3.3 Limitations**

With any abstraction of reality there are limitations, some of which have been highlighted already. The main limitations of this research are: climatic and hydrodynamic conditions were only applied utilising mean and mode statistics. A river flow time series that included peaks and troughs would better represent reality. Due to a fundamental lack of empirical knowledge over the coastal and fluvial sediment flux, the sediment input at the boundary was ignored. GIS can cause virtual memory

problems created through high resolution grids or large grid extents. This is exacerbated by numerical modelling and therefore a compromise must be made between extent and detail.

## Chapter 8

### Conclusion

Prognostic modelling provides an efficient means to analyse the coastal environment and provide effective knowledge for long term urban planning. The BeachMM tool which utilises the numerical models of SWAN and XBeach proved to be very effective at predicting geomorphological evolution through hydrodynamic forcing for the Greater Christchurch coastal environment. The statutory requirements outlined in the NZCPS 2010 were assessed to determine whether these guidelines are currently being complied with when applying the recent sea level rise predictions by the IPCC (2013) and it would appear that it does not meet those requirements. This is because coastal hazard risk has not been comprehensively quantified by the installation of the CERA residential red zone as the results of this research predicted a water level under storm conditions to be further landward. The BeachMM tool predicted water level aligned more accurately with the Christchurch City Council's flood management area, an extent to which managed retreat is a real option. Thus, inundation during periods of storm surge poses a risk to human habitation on low lying areas around the Avon-Heathcote Estuary and Brooklands Lagoon. The results of this research discovered that progradation will continue to occur along the Greater Christchurch foreshore due to the net sediment flux retaining an onshore direction and the current marine hydrodynamic activity not being strong enough to move sediment offshore. The BeachMM tool facilitates the role of spatial and temporal analysis effectively and the efficiency of that performance is determined by the computational operating system. Development of this GIS application has endless possibilities for dynamic prognostic modelling.

## Appendix A

### SWAN input file for the future maximum

```
$*****HEADING*****
$
PROJ 'BMM Tool' ''
$ Field case: SWAN Propagation
$ Time of simulation: MONTH DD, YYYY
$
$*****MODEL INPUT*****
SET LEVEL 2.99
SET NAUTICAL
CGRID 1463254.1102 5076643.925 0 110500.0 69500.0 221 139
CIRCLE 36 0.04 1.0 31
$ NOTE: use exception value (-99 in this case) here to get good load balancing!
INPGRID BOTTOM 1463254.1102 5076643.925 0 221 139 500.0 500.0
EXC -9999
READINP BOTTOM -1 'macrogrid1_Rotate1.bot' 1 0 FREE
$
$*****BOU.CONDITIONS*****
$
BOUN SHAPespec JONswap PEAK DSPR POWer
BOUN SIDE W CCW CONSTANT PAR 7.49 13.3 230
BOUN SIDE N CCW CONSTANT PAR 7.49 13.3 230
BOUN SIDE S CCW CONSTANT PAR 7.49 13.3 230
BOUN SIDE E CCW CONSTANT PAR 7.49 13.3 230
$spctra
$
$*****PHYSICS*****
$WIND 320. 9.2
$GEN3 JANSSEN
$TRIAD
OFF QUAD
$BREAKING
FRICTION MADSEN 0.05
$
$*****NUMERICAL REQUESTS *****
$NUMERIC ACCUR .10 .10 .10 90. 00 STAT 20
$
$*****OUTPUT REQUESTS *****
$mat
$spec
$nest
$ set itest=1 in order to get detailed information
$TEST 1,0
COMPUTE
STOP
```

## Appendix B

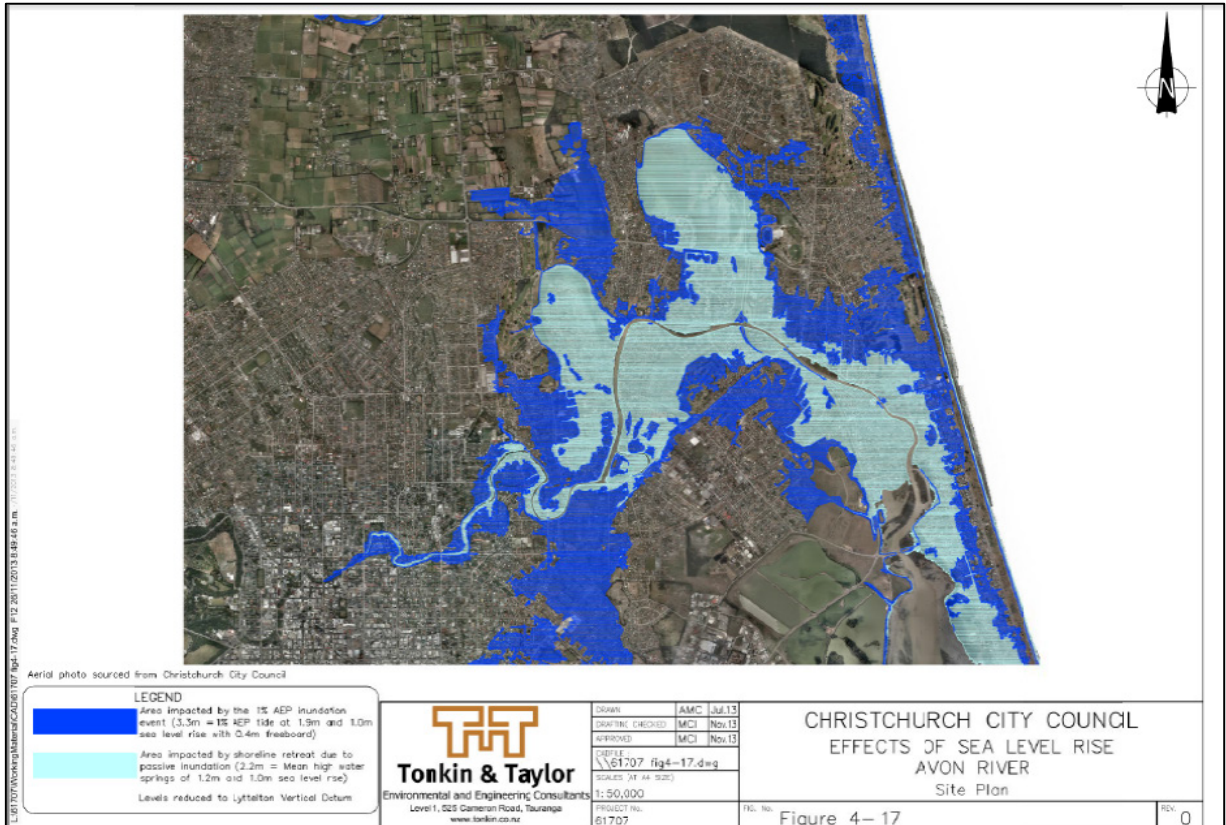
### XBeach input file for the future maximum

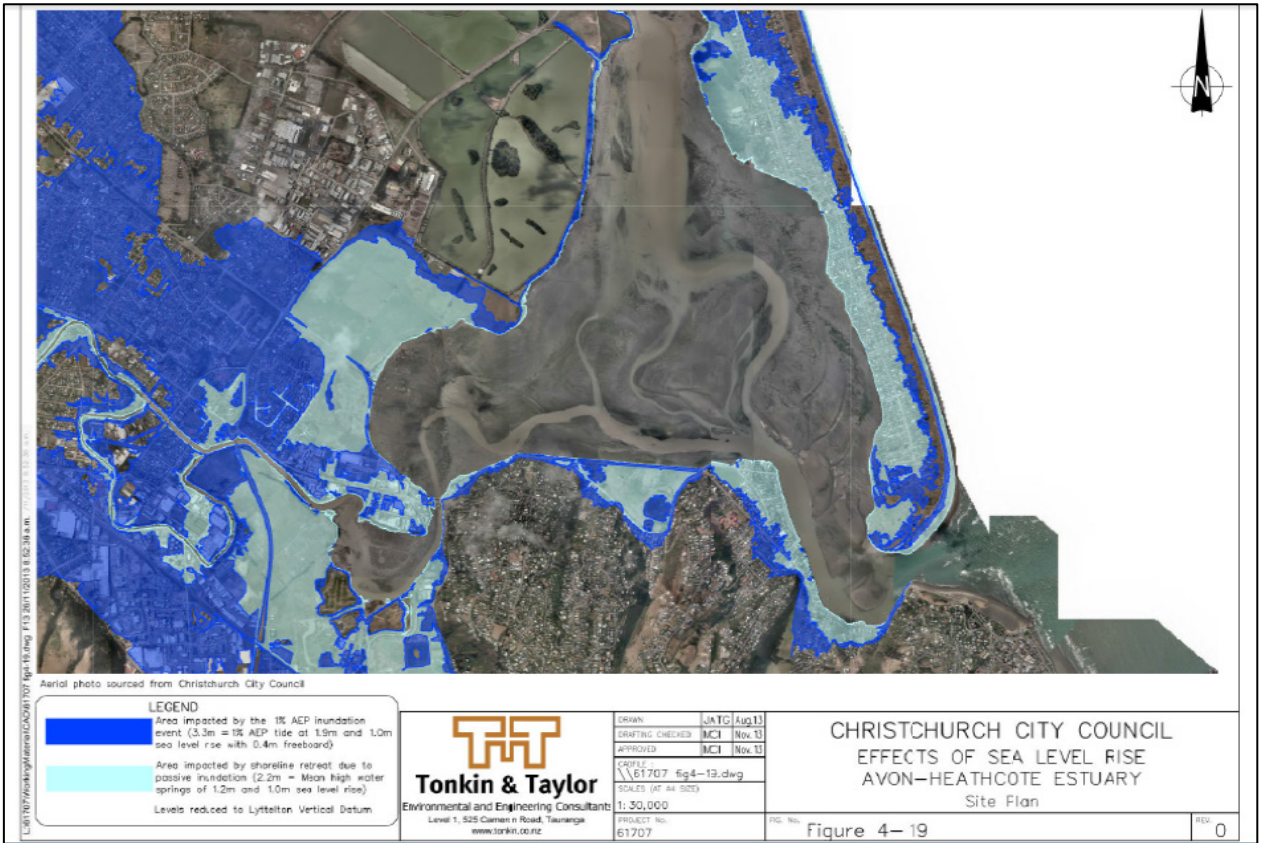
<u>Gridinput</u> nx=273 ny=214 dx=50.0 dy=50.0 xori=1559023.22 yori=5106219.3074 alfa=0.00 depfile=zb_t10.grd posdwn=-1 vardx=0	<u>Boundaryconditionoptions</u> Wave generating boundary options taper instat = 5 ARC order = 2 bcfile = swan_res.txt rt = 7200 dtbc = 1	<u>WaveInput</u> dir0 Hrms wavint m=100 Tm01 thetamin=-90 thetamax=90 dtheta=10. thetanaut=0 taper=100 nspr=0 wci=0 scheme=1
<u>Wavedissipationmodel</u> break=3 gamma=0.6 alpha=1 n=5	<u>Rollermodel</u> roller=1 beta=0.15	<u>Flowinput</u> cf=0.003 C=20 nuh=0.5 nuhfac=0 nuhv=1 lat=43 wearth 0.0417
<u>Flowboundaryconditions</u> front=1 ARC=1 order=2 back=2 epsi=0 left=0 right=0 carspan=0 fcutoff=0 sprdthr=0.08	<u>Time-varyingtide/surge</u> tideloc=0 zs01=2.99 paulrevere=0	<u>Wind</u> rhoa=1.25 Cd=0.002 windv=9.2 windth=50
<u>Limiters</u> hmin=0.01 eps=0.01 umin=0.1 Hwci 0.01	<u>Hydrodynamicssimulation</u> tstart=120 tint=14400 tstop=28800 CFL=0.5	<u>Sedimenttransport</u> form=1 disco 1 z0=0.006 facsl=0 hswitch=0.1 rhos=2650 struct=0 ngd=1 nd=3

		dzg=0.1 D50=0.0002 D90=0.0003 D502=0 D902=0 D503=0 D903=0 lws=1 sws=1 sedcal1=1 sedcal2=1 sedcal3=1 tsfac=0.1 thet anum=1 turb=1 smax=-1
<u>Morphological updating</u> morfac=6 morstart=1 por=0.4 wetslp=0.3 dryslp=1 hswitch=0.1	<u>Discharge boundaries</u> disch_loc_file= discharge_locations.txt disch_timeseries_file= discharge_timeseries.txt	<u>Output data options</u> nglobalvar=3 zb sedero H Zs Thetamean dzbdtd

# Appendix C

## Effects of sea level rise for the Avon-Heathcote Estuary reported by Tonkin and Taylor (2013)

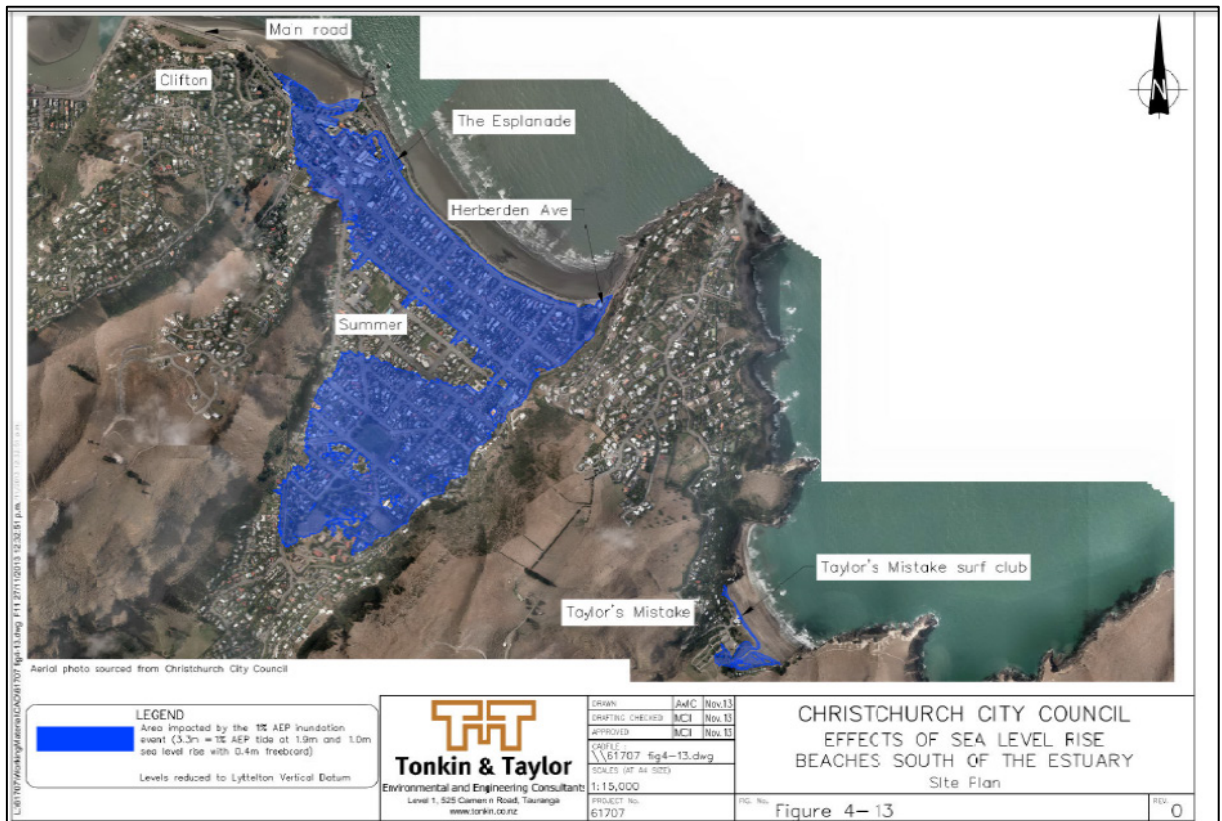






## Appendix D

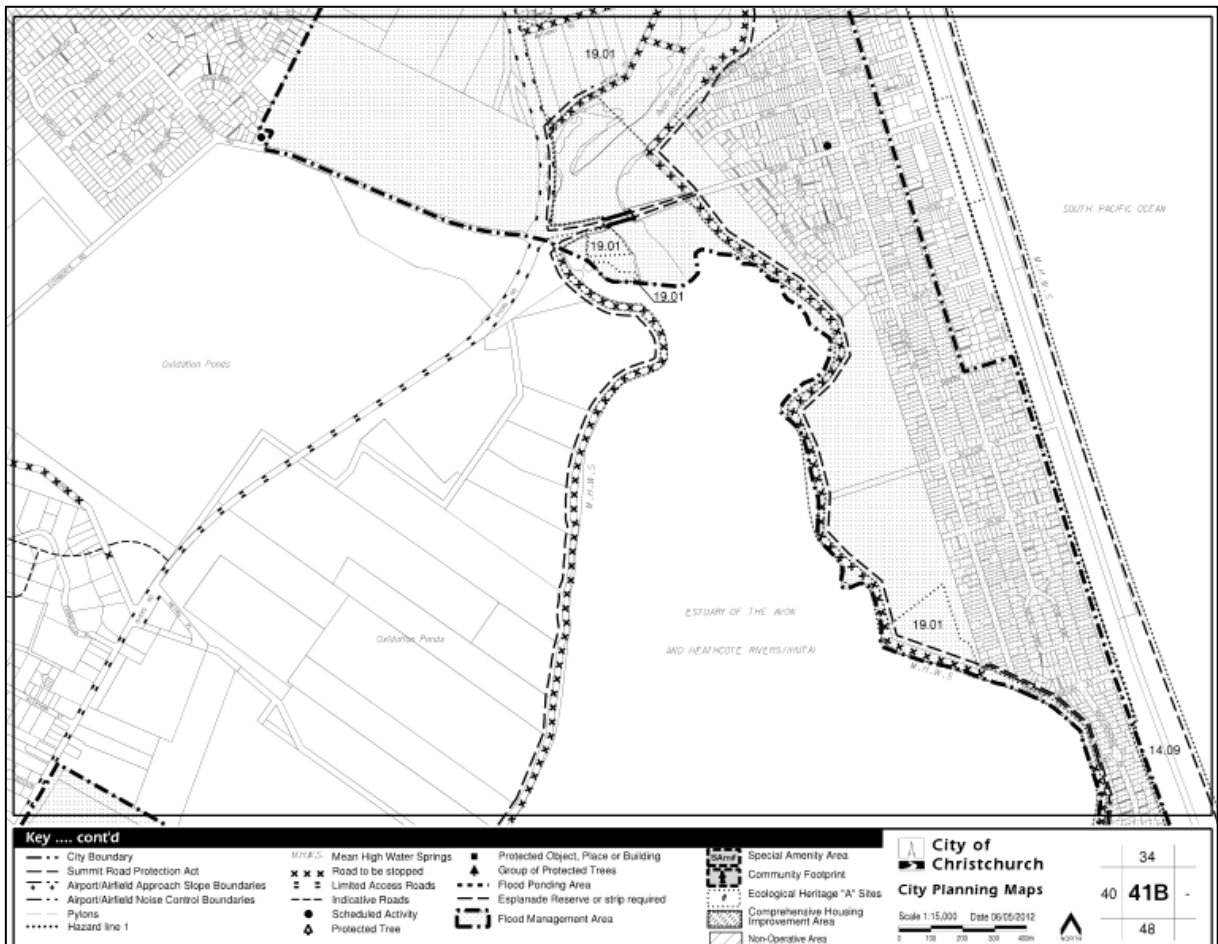
# Effects of sea level rise for the Sumner area reported by Tonkin and Taylor (2013)



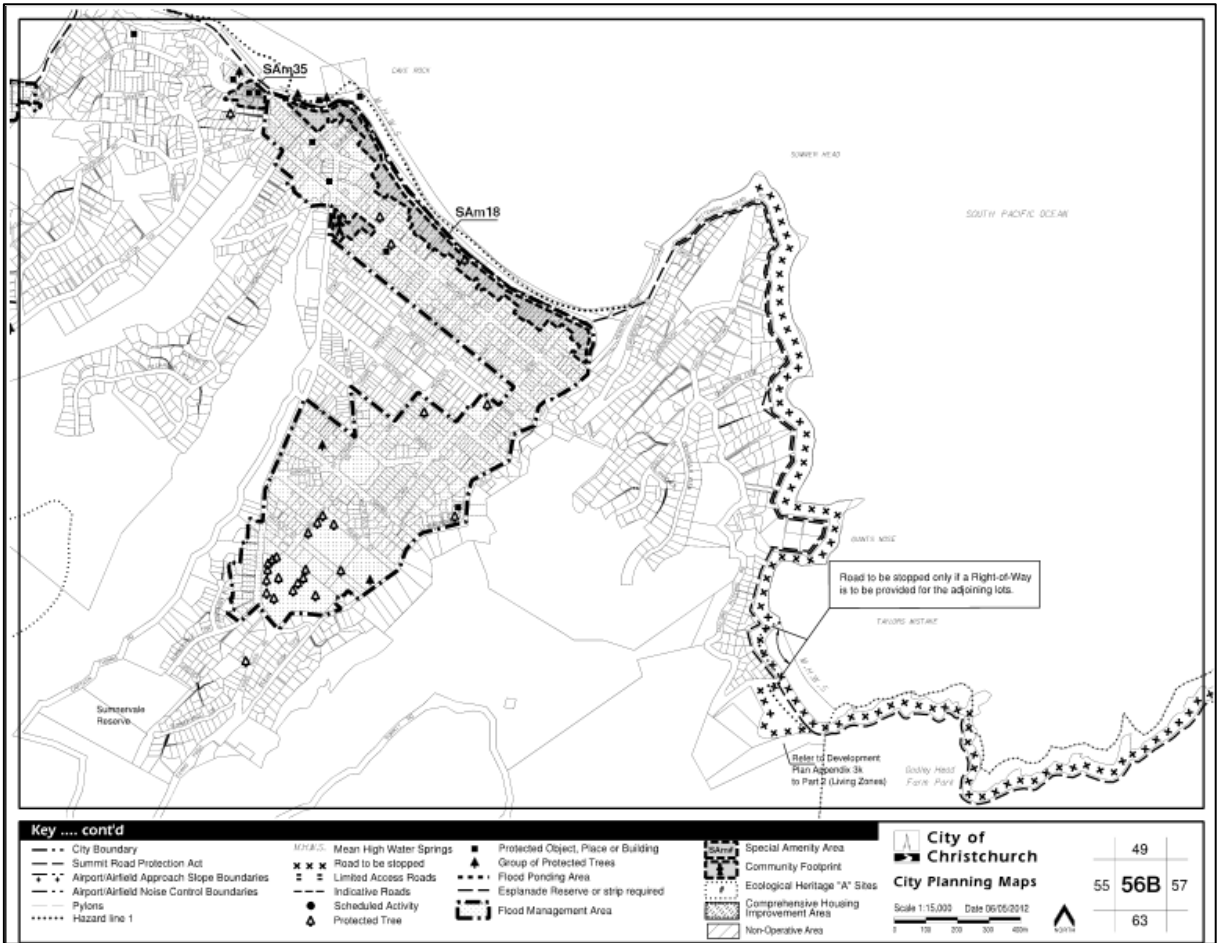
# Appendix E

## Christchurch City Council Flood management areas 2012

(Christchurch City Council, 2012)

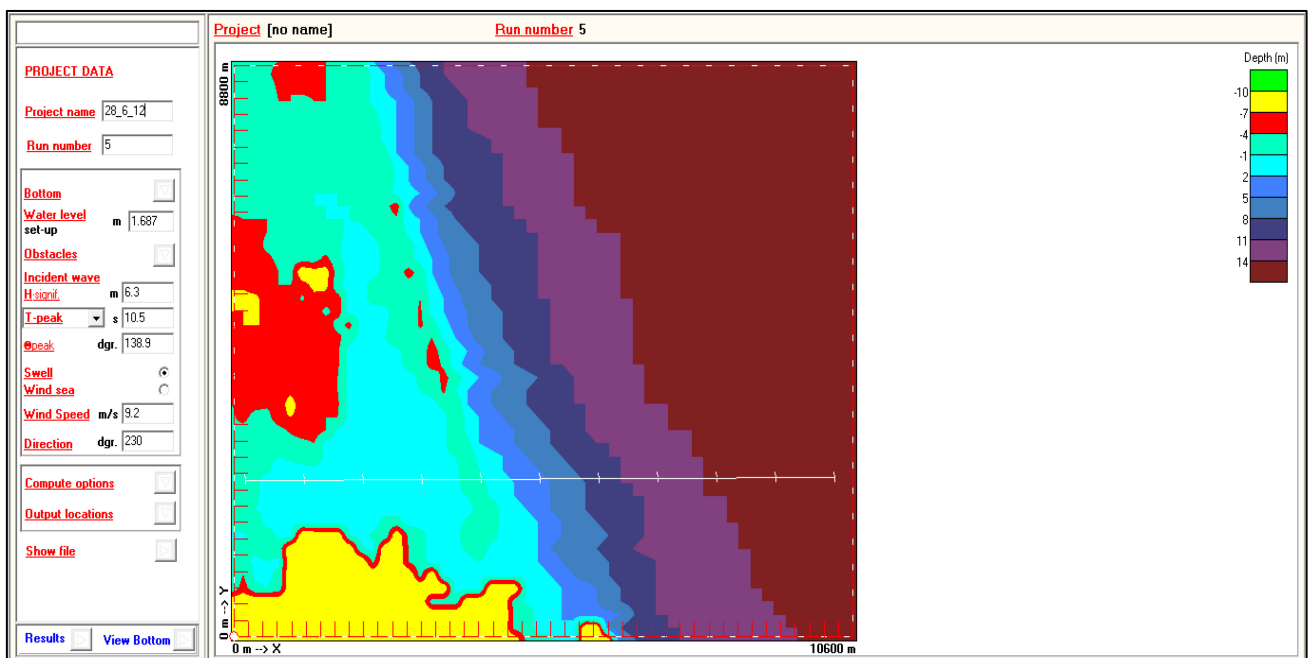
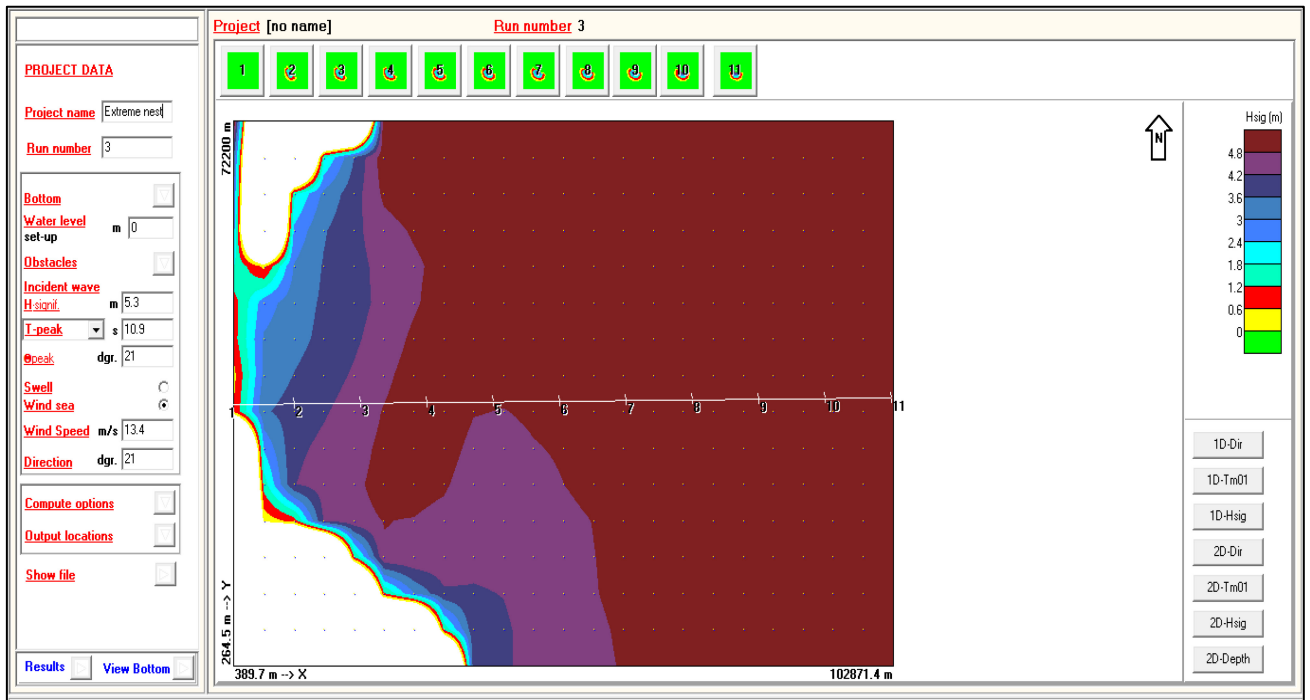


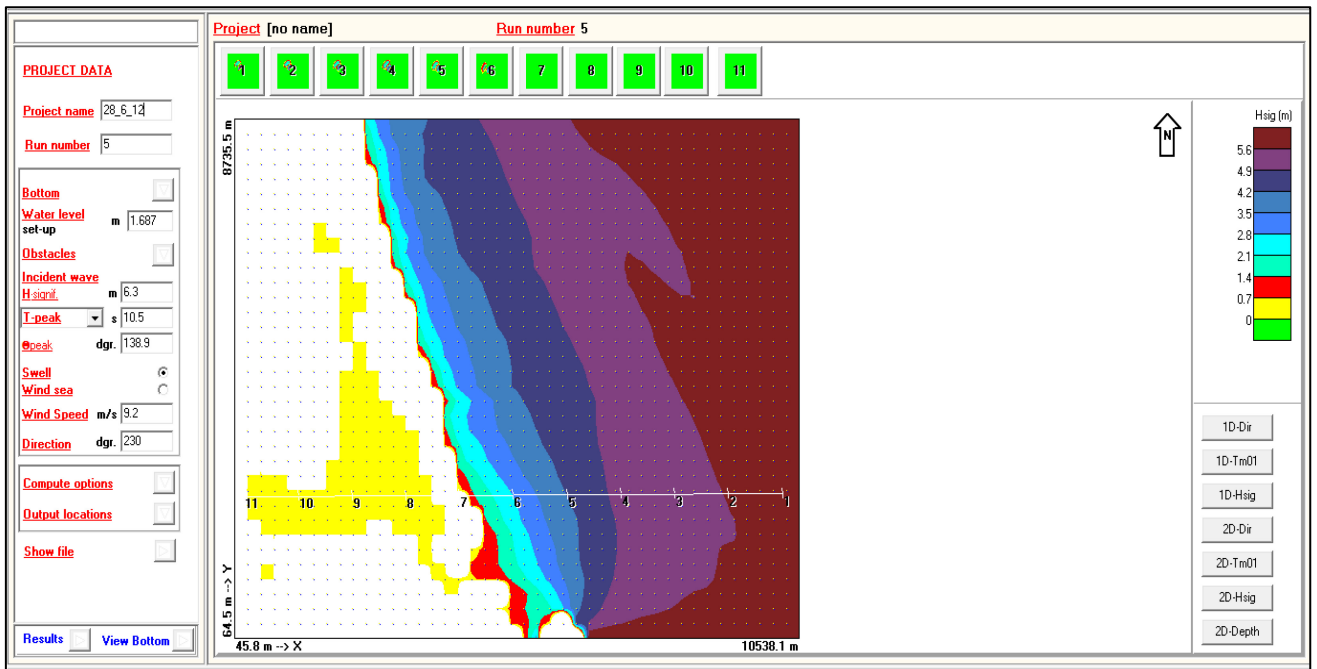




## Appendix F

### Calibration results from the SWAN GUI of hydrodynamic forcing for observed conditions.





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