REPORT

Coastal Hazard Assessment for Christchurch District

Technical Report

Prepared for
Christchurch City Council

Prepared by
Tonkin & Taylor Ltd

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Cover photo: The Christchurch District coastline viewed from the International Space Station in 2014 (Credit: ESA/A.Gerst CC BY-SA 2.0. ID: 2014 945_5391).

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Glossary of terms

Term	Description
AEP	Annual Exceedance Probability
ARI	Average Recurrence Interval
ASCE	Area Susceptible to Coastal Erosion
AWS	Automatic Weather Station
Beach face slope	Beach slope around the extreme still water level (i.e. typically between 1 m and 4 m NZVD2016).
Bruun Rule	A simple mathematical relationship that states: as sea-level rises, the shoreface profile moves up and back while maintaining its original shape
CCC	Christchurch City Council
CD	Chart Datum
Class 1 structures/significantly modified shorelines	Shorelines which have been significantly modified with erosion protection structures
CES	Canterbury Earthquake Sequence (2010-2011)
CI	Confidence interval
Coastal accretion	A long-term trend of shoreline advance and/or gain of beach sediment volume
Coastal erosion	Landward movement of the shoreline which may include both long-term retreat over several years or decades and short-term loss of sediment due to storms
Coastal hazard	Where coastal processes adversely impact on something of value resulting in a hazard
Coastal inundation	Flooding of land by the sea.
DEM	Digital Elevation Model
DS	Dune stability component
ECan	Environment Canterbury
EWS	Electronic Weather Station
H_c	Height of bank or cliff
H_s	Significant wave height
LiDAR	Light Detection and Ranging – a method of remotely deriving land elevation, generally from an aeroplane
LT	Long-term erosion component
LT_H	Historical long-term erosion component
LT_F	Future long-term erosion component
LVD-37	Lyttelton Vertical Datum 1937
m	Sea level rise response factor for cliffs
MfE	Ministry for Environment
MHWS	Mean high water springs – a measure of high tide based on a statistical exceedance of high tides in a month
MHWPS	Mean high water perigean springs. A perigean spring tide is the highest spring tide and occurs three or four times per year when the moon is closest to the earth.

Term	Description
MLWS	Mean low water spring – a measure of low tide based on a statistical exceedance of low tides in a month
MSL	Mean sea level. Sea level averaged over a long (multi-year) period
NZVD2016	New Zealand Vertical Datum 2016
RCP Scenario	Representative Concentration Pathways (RCPs) are four greenhouse gas concentration trajectories adopted by the IPCC for its fifth Assessment Report (AR5) in 2014
RL	Reduced Level
SLR	Sea level rise. Trend of annual mean sea level over timescales of at least three or more decades. Must be tied to one of the following two types: global – overall rise in absolute sea level in the world's oceans; or relative – net rise relative to the local landmass (that may be subsiding or being uplifted)
SL	SLR component
SS	Slope stability allowance
ST	Short-term erosion component
Surfzone slope	Slope below the 1 m NZVD2016 contour offshore to where waves start breaking or to where data is available.
T+T	Tonkin + Taylor (Tonkin & Taylor Ltd)
VLM	Vertical land movements

Executive summary

Christchurch City Council (CCC) has engaged Tonkin & Taylor Ltd. (T+T) to undertake a coastal hazard assessment (CHA) for the entire Christchurch district.

The intended purpose of this assessment is to help inform the CCC Coastal Hazards Adaptation Planning (CHAP) programme. The scope of the assessment has been developed in conjunction with Council's CHAP project team and technical reviewer, who have confirmed that the methodology described in this report is suitable for this intended purpose. For more information about adaptation planning and how the outputs of this coastal hazard assessment will be used, refer to the cover letter "Coastal Hazards Assessment Methodology: Purpose and context" which accompanies this report on the CCC website.

This report (the "Technical Report") provides an in-depth explanation of the environmental data that was used for the hazard assessment, the methodology that was applied and the analysis results. It collates all the technical details together in one place to provide a self-contained record of the work for technical review and future reference. As such, of necessity, this report contains a large amount of information which is highly technical in nature.

A companion report (the "Summary Report") is also available alongside this report on the CCC website and will be the more relevant and engaging report for most people. The Summary Report provides a more straightforward description of how the hazard was identified and analysed, and the key findings for each part of the Christchurch coastline.

1 Introduction

1.1 Background

There are two key factors which have driven the need for the coastal hazard assessment presented in this report:

- In October 2019, Christchurch City Council (CCC) resolved to address earthquake legacy issues along the Avon-Heathcote Estuary edge and to develop a coastal hazards adaptation planning programme of work for all Christchurch District coastal environments.
- Updated information on sediment supply, ground levels, storm events, groundwater and high tide statistics has recently become available. This information has implications for the identification of areas susceptible to coastal hazards.

Therefore, to support sound adaptation planning discussions with coastal communities and ultimately robust and defensible decisions by the Council, T+T have been commissioned to undertake this coastal hazard assessment for the entire Christchurch District.

Since an updated technical assessment is being undertaken, this has provided an opportunity to also incorporate the following:

- More recent topographic data and longer datasets of beach profiles, water level information and wave climates
- Suggestions from the 2016 Peer Review (Kenderdine et al. 2016) of the 2015 Coastal Hazards Assessment that were not able to be included in the previous 2017 assessment
- Additional scenarios and outputs designed for engagement and adaptation
- Wider geographic scope to cover the entire Christchurch District coastline (including the entire Banks Peninsula coastline)
- Ensure consistency of hazard identification with national-level guidance released since the previous assessment such as the 2017 Ministry for the Environment Coastal Hazards and Climate Change Guidance

1.2 Purpose of this coastal hazard assessment

The purpose of this assessment is to provide CCC with specialist technical coastal hazard (inundation, erosion and flood depth) and associated groundwater information, with the primary objective of presenting this information for public use in a format that is easily accessible, comprehensive and unambiguous. The focus of following technical report is to produce the “raw” hazard information. This information can then feed into engagement, risk evaluation and risk mitigation and adaptation planning undertaken by CCC in future.

The following assessment supersedes the previous coastal hazard assessments for the area undertaken by T+T between 2015 and 2018.

The primary intended purpose of the updated coastal hazard and groundwater information is to help inform coastal hazards adaptation planning for Christchurch District. The results of the assessment could also inform a range of other purposes, provided the uncertainties and limitations are understood and appropriately managed. These other uses might include review of the coastal hazards provisions in the Christchurch District Plan, infrastructure planning decisions, consenting applications and Civil Defence Emergency Management. In many cases, the results of this assessment may provide an initial hazard screening for these other purposes, with more detailed analysis then undertaken for specific locations and scenarios of interest.

It is important to note this assessment is not intended to map out a hazard overlay for inclusion in the District Plan, but provides information about hazards (and the uncertainty in our understanding of those hazards), which may be subject to further analysis and consultation to eventually determine if and where a hazard overlay should apply.

The assessment area covers the entire coastline of the Christchurch District extending from the Waimakariri River mouth in the north to the entrance of Te Waihora (Lake Ellesmere) in the south (refer to Figure 1.1). The assessment includes open coast and pocket beaches, estuaries and lagoons and cliffs and banks. The assessment area within the estuary and lagoons is limited to the area directly attached to the Coastal Marine Area (CMA) boundary.

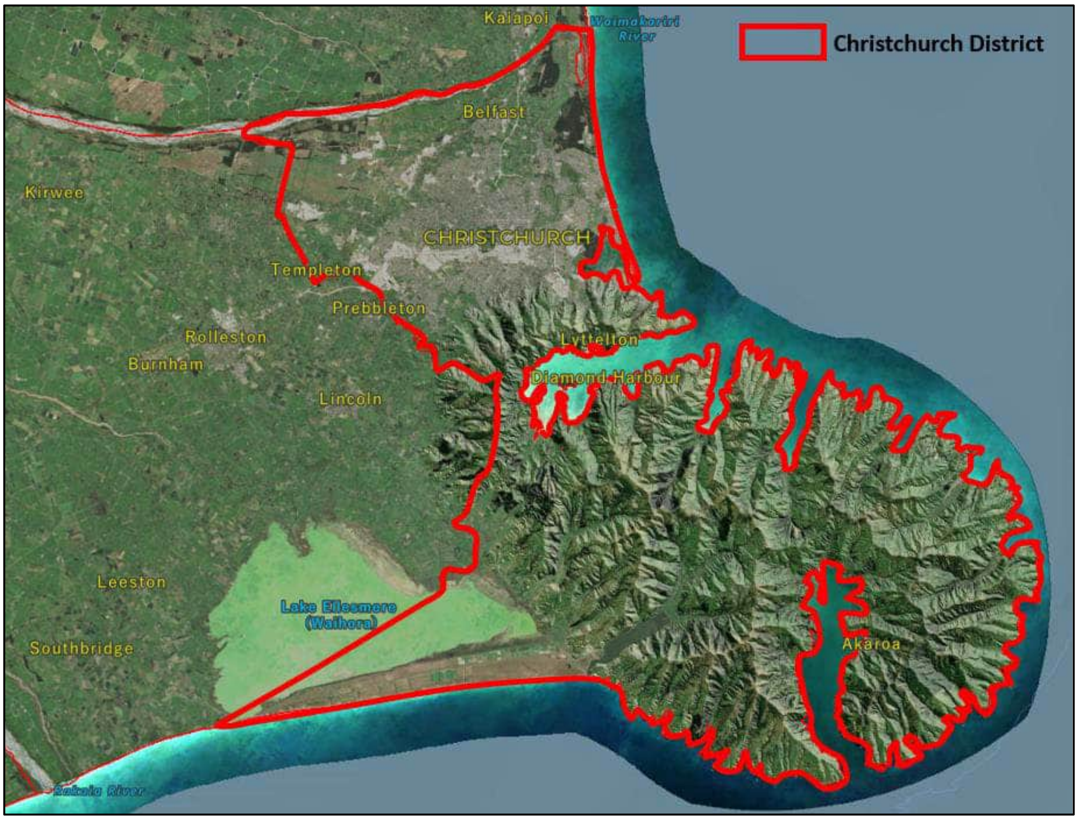

Figure 1.1: Christchurch district indicated by red polygon (source: Canterbury Maps).

1.3 Scope

The project has been undertaken in three stages:

Stage 1: Scoping and initial technical reporting

This initial scoping stage involved undertaking a review of the previous Christchurch coastal hazard assessment as well as assessments completed for the wider Canterbury region and New Zealand to inform a consistent approach. Available data sources were collated to facilitate technical discussion between T+T, CCC, ECan and the technical reviewer. Appropriate methodologies were developed to allow consistent identification of both coastal erosion and inundation hazards for the entire Christchurch District.

Stage 2: Technical assessment (this report)

This report includes a comprehensive assessment of coastal erosion and inundation hazard, and associated groundwater information for the Christchurch District, which is based on the methodologies agreed upon in Stage 1. This report sets out available data that has been used, methodologies, analyses and results of both erosion and inundation hazards.

Stage 3: Communicating the hazard information

As part of Stage 3 the raw hazard information from the technical assessment has been translated into various more accessible forms to support community engagement and public awareness efforts. This includes a public-facing report and interactive website. The purpose of the website is to allow those with a particular interest to explore the results in more detail than is possible with the printed maps in this report. The interactive online map format makes it easy for users to explore the wide range of scenarios considered in the assessment (e.g., with slider controls to adjust sea level rise), and to zoom in to particular locations of interest. The online viewer can be accessed at https://ccc.govt.nz/environment/coast/coastalhazards/2021-coastal-hazards-assessment

1.4 Report layout

This report is structured as follows:

- Environmental data that has been used for this study is set out in Section 2.
- Coastal erosion methodology, analysis and results are set out in Sections 3 to 5.
- Coastal inundation approach, analysis and results are set out in Sections 6 to 8.
- Groundwater approach, analysis and results are set out in Section 9.

1.5 Reference levels

The vertical elevation or reference levels in this report are with respect to New Zealand Vertical Datum (NZVD2016) unless otherwise specified. As illustrated in Figure 1.2, NZVD2016 is 1.648 m above Chart Datum (CD) at Lyttelton based on LINZ (2021) and 0.35 – 0.4 m above Lyttelton Vertical Datum 1937 (LVD-37) depending on the exact location based on the spatial difference grid by LINZ (2021). Christchurch City Drainage Datum (CDD) is 9.043 m above LVD-37 based on NIWA (2011) and therefore 8.64-8.69 m above NZVD2016.

For example, a MHWS high tide water level at Lyttelton of 0.84m (NZVD2016) is equivalent to a level of 1.23m (LVD1937) or 10.28m (CDD.)

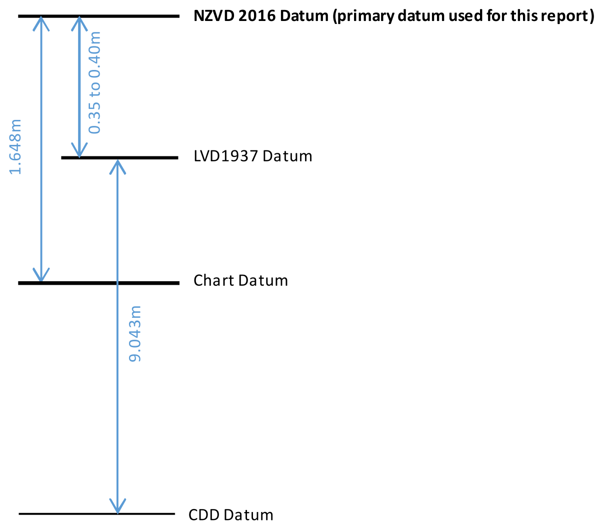

Figure 1.2: Relationship between vertical datums commonly used in Christchurch district

2 Environmental data

2.1 Topography and bathymetry

The following assessment uses the latest available LiDAR which for most of the region is a 1 m DEM flown in 2018 sourced from ECan (Figure 2.1). The most recently available LiDAR for Kaitorete Spit is a 0.45 m DEM LiDAR flown in 2008. Because two different surveys have been used there is a slight mismatch in levels at the join between surveys, which results in some minor artefacts in the inundation maps in the vicinity of Te Waihora (Lake Ellesmere).

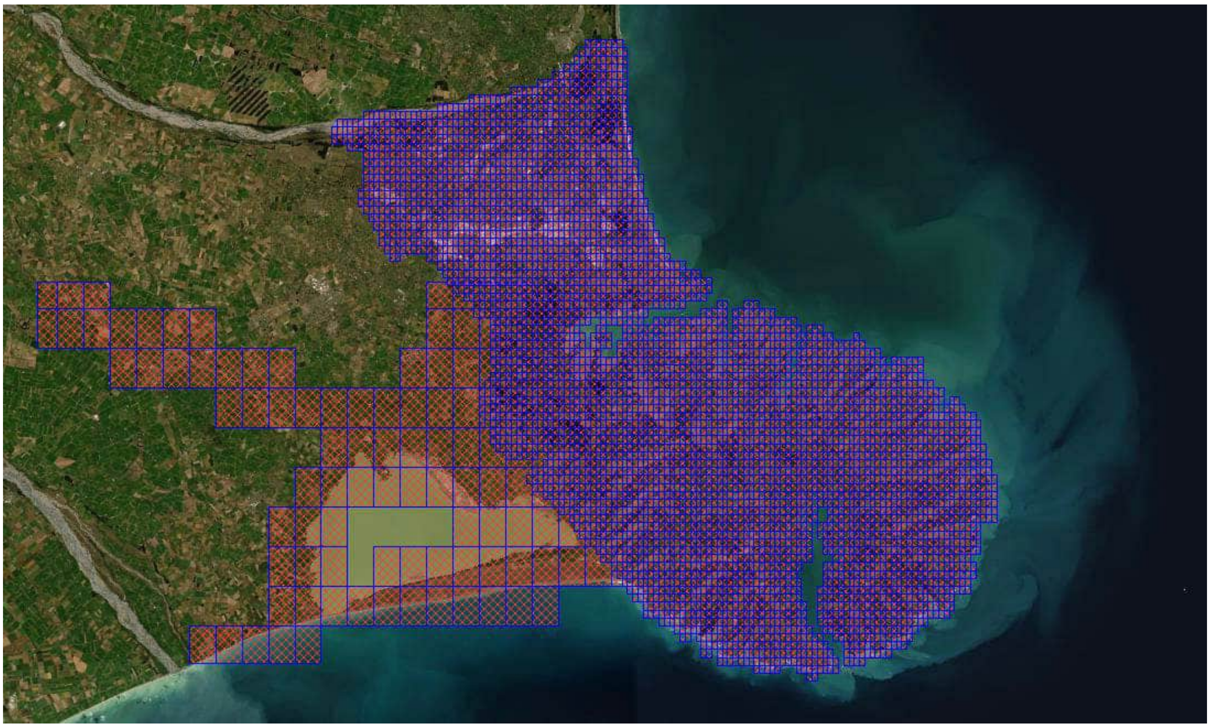

Figure 2.1: Extent of topography datasets. (Purple) 2018 1 m DEM including Christchurch City and Banks Peninsula. (Red) 2008 0.45 m DEM for available for Kaitorete Spit.

Relevant bathymetric surveys are summarised in Table 2.1. The recent 2018 LiDAR captures some of the intertidal flats in the Avon-Heathcote Estuary, however the tidal channels are excluded (Figure 2.2). Rogers et al. (2020) collected RTK surveys and single-beam echosounder data across the estuary mouth in April/May 2019.

There have been bathymetric studies completed for Upper Akaroa Harbour and Lyttelton Harbour (Hart et al., 2009 and Hart et al., 2008). The 2008/2009 bathymetries have been compared against 1952 bathymetric surveys. Hart et al. (2009) provides a 1 m contour map for entire Akaroa Harbour and 0.25 m contour maps for Wainui Bay, French Farm Bay, Barrys Bay, Duvauchelle Bay, Robinsons Bay, Takamatua Bay and Akaroa Inlet.

Table 2.1: Bathymetry sources

Location	Bathymetric surveys
CHCH open coast	Chart NZ 63 Kaikoura Peninsula to Banks Peninsula (1:200000)
Avon-Heathcote Estuary	April 2011 (Measures et al. 2011) January 2013 survey (NIWA) 2018 LiDAR (partial coverage on intertidal flats) Single-beam echosounder surveys (estuary mouth) collected by Rogers et al. (2020)
Banks Peninsula	Chart NZ 632 Banks Peninsula (1:75000)
Lyttelton Harbour	Chart NZ 6321 Lyttelton Harbour / Whakaraupō (1:25000)
Akaroa Harbour	Chart NZ 6324 Akaroa Harbour (1:30000) Chart NZ 6324 Akaroa Harbour: French Bay (1:15000) Hart et al. (2009)
Kaitorete Spit	Chart NZ 632 Banks Peninsula (extends partially)

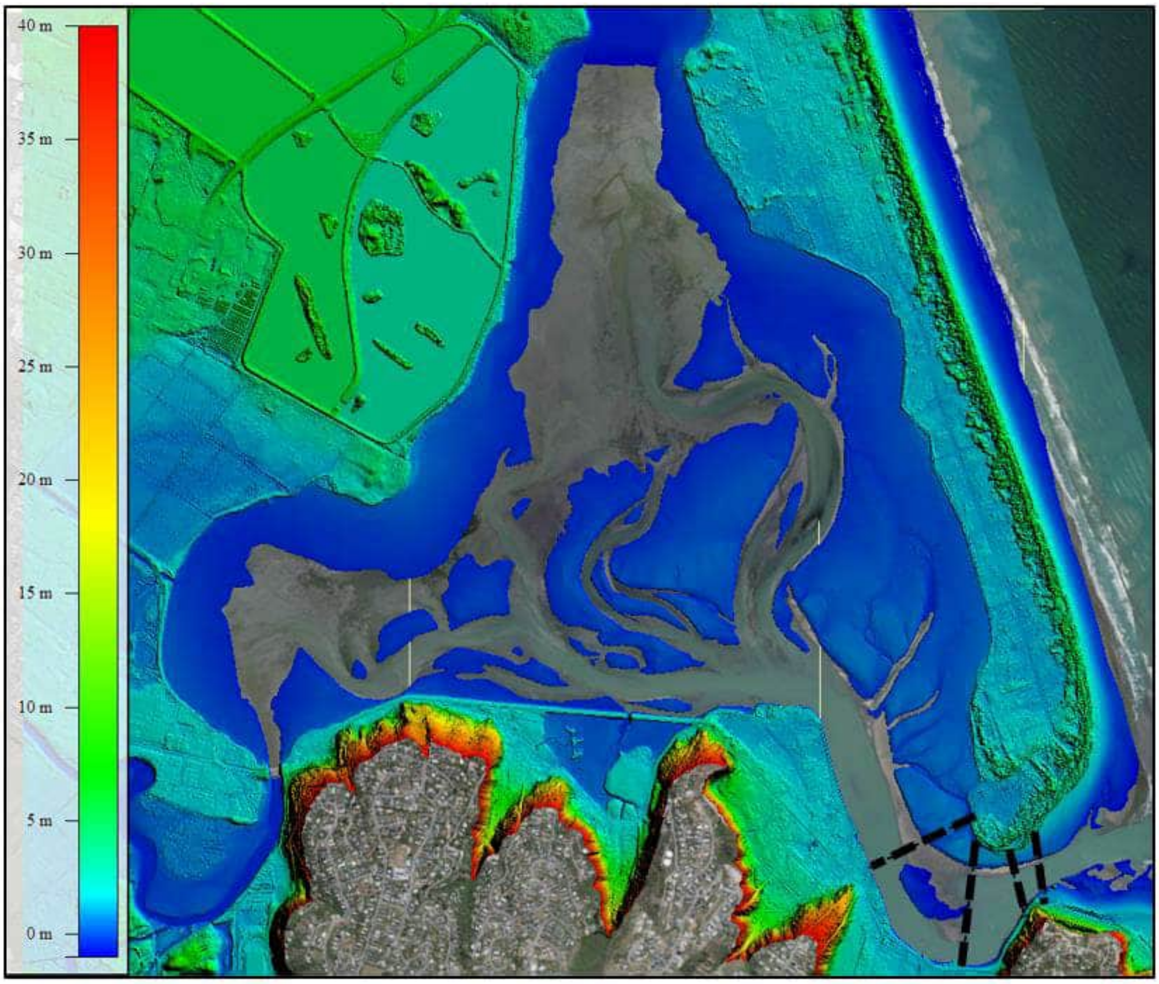

Figure 2.2: 2018 LiDAR extent across the Avon-Heathcote estuary. Dashed lines overlaid to show approximate location of survey transects reported by Rogers et al. (2020).

The DEM represents a bare earth terrain, with all buildings and above-ground features detected having been removed. Using this approach, it is sometimes possible that flooding is shown to occur through the area occupied by large buildings. This is because the model does not recognise these as buildings and works only off the (interpolated) DEM. Care should therefore be exercised in the interpretation of results, particularly in areas where there is a high percentage of ground area covered by above-ground features (trees, buildings, etc). The same is also true of bridges that cross open waterways. In some cases the DEM excludes the bridge deck, and flooding is shown to exist over the bridge where, in reality, the DEM has ignored the bridge.

As can be seen in Figure 2.2 ground elevation from the DEM exists in the area covered by the wastewater treatment ponds at Bromley. It should be noted that elevation in these water bodies will not be invert levels as LiDAR does not penetrate water. As such any inundation shown over areas such as these, which are permanently covered in water, will need to be viewed in this context.

2.2 Aerial imagery

2.2.1 Latest available imagery

The most recently available aerial photography is 2019 imagery available for the entire Christchurch coastline sourced from ECan (Figure 2.3).

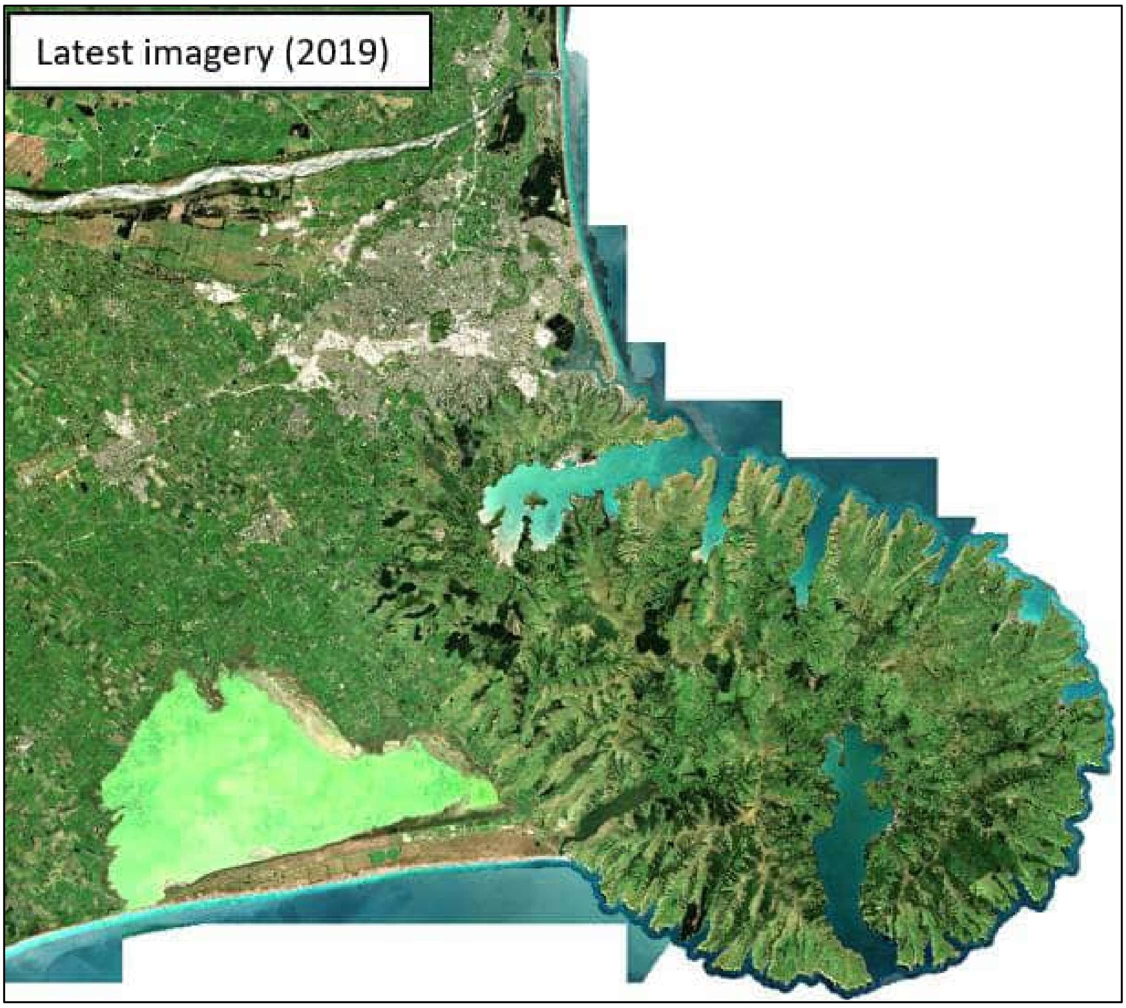

Figure 2.3: Latest available imagery sourced from ECan (2019).

2.2.2 Historic imagery

A summary of the historic aerial imagery available for the region is provided in Table 2.2. The earliest aerials for Christchurch City are from 1941. The earliest aerials available for the outer Banks Peninsula shoreline are from 1995.

Table 2.2: Summary of historic aerial imagery available

Location	Years available	Source
Christchurch open coast	1941, 1955, 1979, 1994, 2011, 2016, 2019	ECan GIS Server
Avon-Heathcote Estuary	1941, 1955, 1979, 1994, 2011, 2016, 2019	ECan GIS Server
Taylors Mistake	1941, 1945-1949, 1955, 1965-1969, 1970-1974, 1980-1984, 1995-1999, 2000-2004, 2016, 2019	ECan GIS Server
Lyttelton Harbour	1965-1969, 1970-1974, 1980-1984, 1995-1999, 2000-2004, 2010-2015, 2016, 2019	ECan GIS Server
Outer Banks Peninsula	1995-1999, 1980-1984, 2000-2004, 2016, 2019	ECan GIS Server
Akaroa Harbour	1980-1984, 1995-1999, 2000-2004, 2016, 2019	ECan GIS Server
Kaitorete Spit	1980-1984, 1990-1994, 1995-1999, 2010-2015, 2016, 2019	ECan GIS Server

2.2.3 Digitised shorelines

Digitised shorelines for the open coast, Avon-Heathcote Estuary and some of the Lyttelton and Akaroa Harbour beaches were previously provided by CCC for the T+T (2017) study. The 2017 study also included two shorelines for each of the harbour sites. Additional shoreline data has been digitised using the more recently available 2019 aerial imagery. A summary of digitised shorelines is provided in Table 2.3.

Table 2.3: Summary of digitised shorelines

Location		Years available
Christchurch open coast		1941, 1955, 1979, 1994, 2011,2016, 2019
Avon-Heathcote Estuary		1941, 1955, 1979, 1994, 2011, 2016, 2019
Lyttelton Harbour	Allandale	1973, 2016, 2019
	Teddington	1973, 2016, 2019
	Charteris Bay	1973, 2016, 2019
	Purau Bay	1973, 2016, 2019
Akaroa Harbour	Takamatua Bay	1980-1984, 2016, 2019
	Duvauchelle Bay	1980-1984, 2016, 2019
	Wainui	1980-1984, 2016, 2019

2.3 Beach profiles

ECan have collected beach profile data for a total of 57 locations along the Christchurch District coastline (Figure 2.4). The earliest of these surveys was completed in 1970. Majority of the Christchurch open coast profiles have been surveyed on a bi-annual basis since the 1990's, with additional surveys as necessary. Profiles along Kaitorete Spit have been surveyed on an annual basis. Beach profiles have also been collected, biannually since 2017, at four sites within Lyttelton Harbour by the Lyttelton Port Company as part of coastal monitoring for their dredging consents. A summary of the beach profile data available is provided in Table 2.4.

Table 2.4: Summary of beach profile data along the Christchurch coastline

Beach Profile Description		First survey date	Last survey date	Survey period (yr)	No. of Surveys
Code	Name				
C2200	Waimakariri River	11/03/1994	20/05/2015	21.2	34
C2070	Brooklands	22/06/1990	27/01/2020	29.6	63
C1972	Brooklands	22/06/1990	27/01/2020	29.6	62
C1891	Brooklands	22/06/1990	27/01/2020	29.6	62
C1755	Spencerville (Heyders Road)	22/06/1990	27/01/2020	29.6	62
C1565	Spencerville	22/06/1990	27/01/2020	29.6	61
C1400	Bottle Lake Forest	22/06/1990	27/01/2020	29.6	62
C1273	Bottle Lake Forest	22/06/1990	27/01/2020	29.6	60
C1130	Waimairi Beach (Larnach Street)	9/05/1990	31/01/2020	29.8	61
C1111	Waimairi Beach (Beach Road)	7/08/2008	31/01/2020	11.5	23
C1100	North New Brighton (Pandora Street)	9/05/1990	31/01/2020	41.2	61
C1086	North New Brighton (Pacific Road)	9/05/1990	31/01/2020	41.5	64
C1065	North New Brighton (Effingham St)	9/05/1990	30/01/2020	41.5	59
C1041	North New Brighton (Cygnet Street)	9/05/1990	30/01/2020	41.5	62
C1011	North New Brighton (Bowhill Road)	9/05/1990	26/07/2020	30.2	59
C0952	New Brighton (Rawhiti Street)	9/05/1990	30/01/2020	41.5	63
C0924	New Brighton (Lonsdale Street)	9/05/1990	30/01/2020	41.5	62
C0889	New Brighton (Hawke Street)	9/05/1990	30/01/2020	29.7	60
C0863	New Brighton 226 Marine Parade)	1/12/2000	30/01/2020	19.2	35
C0856	New Brighton 231 Marine Parade)	21/07/2004	30/01/2020	15.5	31
C0853	New Brighton 233 Marine Parade)	21/07/2004	30/01/2020	15.5	31
C0848	New Brighton (Hood Street)	9/05/1990	30/01/2020	29.7	60
C0815	New Brighton (Rodney Street)	9/05/1990	30/01/2020	41.5	61
C0781	New Brighton (Mountbatten Street)	9/05/1990	30/01/2020	41.5	61
C0748	South New Brighton (Jervois Street)	9/05/1990	28/01/2020	41.5	62
C0703	South New Brighton (Bridge Street)	1/08/1978	27/01/2020	41.5	62
C0650	South New Brighton (Beatty Street)	1/08/1978	28/01/2020	41.5	62
C0600	South New Brighton (Jellicoe Street)	1/08/1978	28/01/2020	41.5	57
C0531	South New Brighton (Halsey Street)	19/12/1978	28/01/2020	41.5	61
C0513	South New Brighton (Caspian Street)	18/12/1978	28/01/2020	41.5	63
C0471	South Shore (Heron Street)	31/07/1978	28/01/2020	41.5	62
C0431	Southshore (Penguin Street)	1/08/1978	27/01/2020	41.5	63
C0396	South Shore (Plover Street)	9/05/1990	27/01/2020	29.7	61
C0362	South Shore (Tern Street)	1/08/1978	27/01/2020	41.5	62
C0350	South Shore (Torea Street)	9/05/1990	27/01/2020	29.2	60
C0300	South Shore (South of Pukeko Place)	9/05/1990	27/01/2020	29.7	64
C0271	South Shore (End Rockinghorse Road)	9/05/1990	27/01/2020	29.7	65

Table 2.4 (continued): Summary of beach profile data along the Christchurch coastline

Beach Profile Description		First survey date	Last survey date	Survey period (yr)	No. of Surveys
Code	Name				
C0070	Sumner	9/05/1990	23/01/2020	29.7	59
C0112	Sumner	9/05/1990	23/01/2020	29.7	59
C0150	Sumner	9/05/1990	23/01/2020	29.7	59
C0180	Clifton	9/05/1990	24/01/2020	29.7	66
C0190	Clifton	9/05/1990	24/01/2020	29.7	60
C0221	Clifton	9/05/1990	24/01/2020	29.7	64
BPN8010	Taylors Mistake	21/07/1993	23/01/2020	26.5	53
BPN7998	Taylors Mistake	21/07/1993	23/01/2020	26.5	53
BPN7985	Taylors Mistake	21/07/1993	23/01/2020	26.5	53
BPN7975	Taylors Mistake	21/07/1993	23/01/2020	26.5	53
ECE3800	Birdlings Flat	04/03/1991	28/05/2020	29.3	30
ECE3755	Birdlings Flat	04/03/1991	26/06/2019	29.3	29
ECE3560	Kaitorete Spit	04/03/1991	28/05/2020	29.3	30
ECE2995	Kaitorete Spit	04/03/1991	28/05/2020	29.3	30
ECE2515	Kaitorete Spit	04/03/1991	28/05/2020	29.3	30
ECE1980	Kaitorete Spit	04/03/1991	28/05/2020	29.3	30
ECE1620	Kaitorete Spit	04/03/1991	28/05/2020	29.3	30
ECE1320	Kaitorete Spit	01/03/1991	27/05/2020	29.3	30
ECE1183	Kaitorete Spit	02/06/1970	27/05/2020	50	51
ECE1172	Kaitorete Spit	02/06/1970	27/05/2020	50	39
LPC	Corsair Bay	03/02/2017	27/01/2021	4	9
LPC	Rapaki	03/02/2017	27/01/2021	4	9
LPC	Purau Bay	03/02/2017	27/01/2021	4	9
LPC	Camp Bay	03/02/2017	27/01/2021	4	9

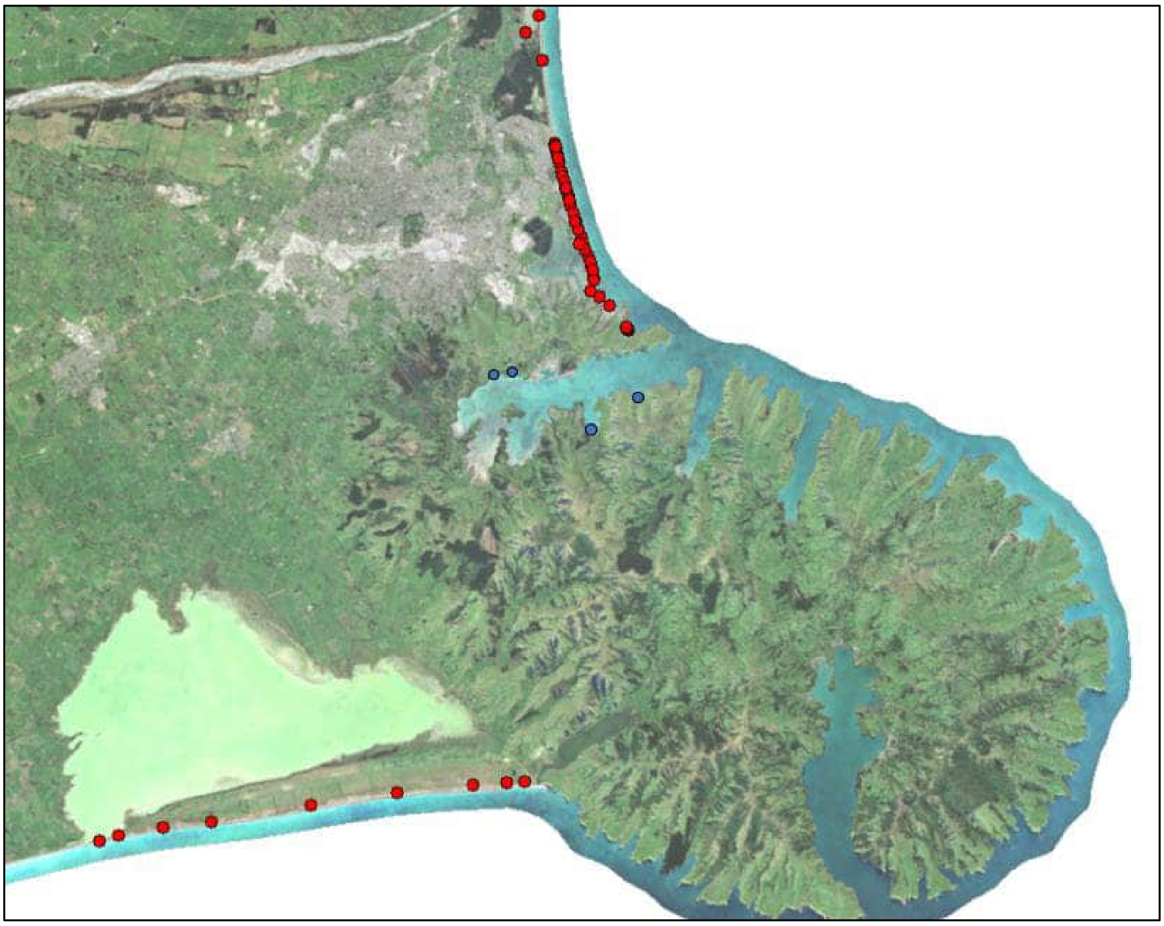

Figure 2.4: Location of ECan beach profile datasets (red dots) and LPC monitoring profiles (blue dots).

2.4 Water levels

2.4.1 Tide levels

Tidal levels for New Zealand ports are provided by Land Information New Zealand (LINZ) based on average predicted values over the 18.6 yr tidal cycle. Values for Lyttelton are presented in Table 2.5. The spring tidal range is approximately 2.2 m and the mean sea level is -0.22 m NZVD2016.

Table 2.5: Astronomical tide levels at Lyttelton Port (Source: LINZ, 2021)

Tide state	m NZVD2016
Highest Astronomical Tide (HAT)	1.07
Mean High Water Springs (MHWS)	0.84
Mean Sea Level (MSL)	-0.22
Mean Low Water Springs (MLWS)	-1.38
Lowest Astronomical Tide (LAT)	-1.49

MHWS levels for other locations within Christchurch included in LINZ (2021) are Sumner (0.76 m NZVD2016) and Akaroa (1.08 m NZVD2016), which are based on offsets derived by LINZ (2021) and converted to NZVD2016. This shows that the MHWS at Sumner is 0.08 m lower and at Akaroa (Tikao Bay) is 0.24 m higher compared with Lyttelton Port. The higher MHWS level in Akaroa is likely a result of tidal amplification, which increases towards the head of the harbour.

NIWA (2015) include MHWS and MHWPS levels for multiple locations within Christchurch the levels seem to be consistent along the Christchurch open coast (i.e. within 2 cm). The difference between MHWS and MHWPS is approximately 0.2 m. Refer to NIWA (2015) for a detailed description of different MHWS definitions in Canterbury.

2.4.2 Water level gauges

CCC and ECan have water level gauges across most of the rivers, harbours and lakes in Christchurch. The water level gauges relevant for this study are shown in Figure 2.5. A summary of the gauge information is provided in Table 2.6.

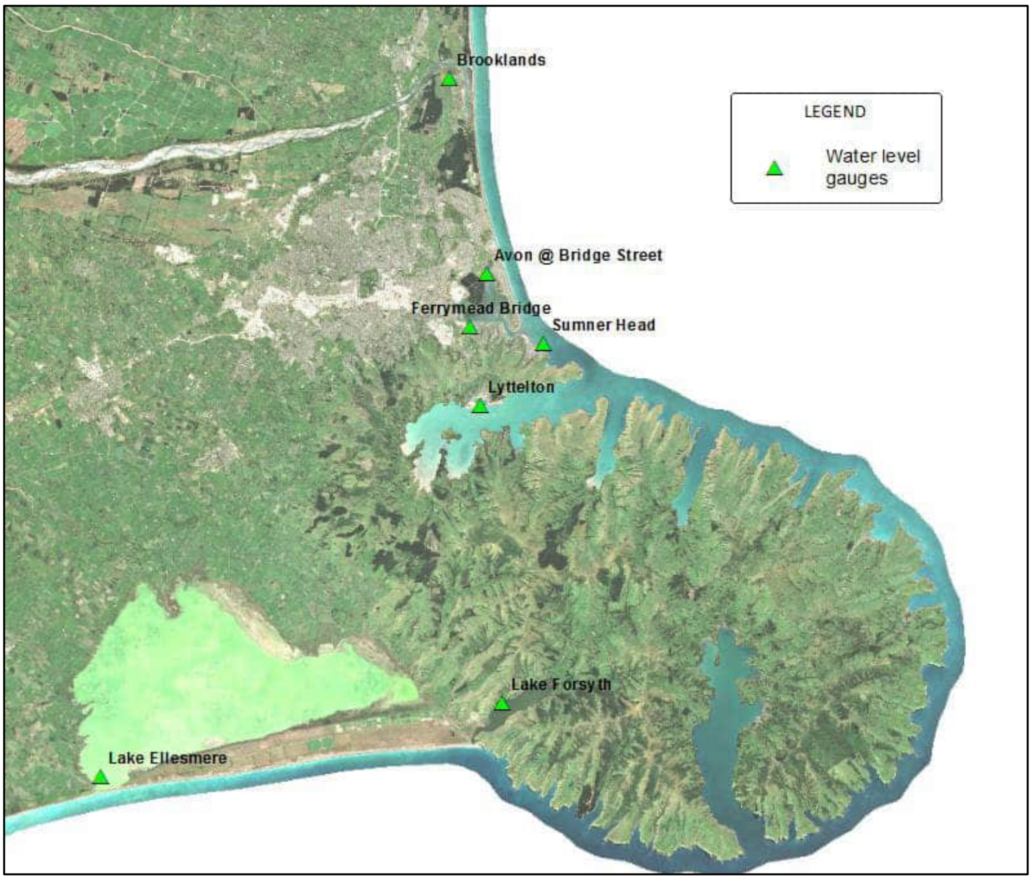

Figure 2.5: Location of relevant water level gauges.

Table 2.6: Summary of water level gauge data available

Location	Type	Start of data	Source
Brooklands (Styx tide gates)	Tidal	1990	CCC
Avon River at Bridge St	Tidal (with river influence)	1997	CCC
Ferrymead Bridge	Tidal (with river influence)	1974	CCC
Sumner Head	Tidal	1994	NIWA/ECan
Lyttelton Standard Port Gauge	Tidal	1998	LINZ/LPC
Wairewa (Lake Forsyth)	Lake level	1995	ECan
Te Waihora (Lake Ellesmere)	Lake level	1994	ECan

There have been several water level analyses completed using the Christchurch tide gauge data, such as NIWA (2015) and Goring (2018), with the latest analysis undertaken by GHD (2021). The resulting extreme water levels for the analysed gauges are shown in Table 2.7. The Styx water level is taken below the tide gates and represents the level in the Brooklands Lagoon. Bridge St and Ferrymead are within the Avon-Heathcote estuary.

Table 2.7: Extreme water levels (m NZVD2016) based on tide gauge analysis (excl. wave effects)

Site	ARI							
	1 year	**2 year**	**5 year**	**10 year**	**20 year**	**50 year**	**100 year**	**200 year**
Sumner[1]	1.37	1.44	1.52	1.59	1.65	1.74	1.80	1.87
Bridge St	1.33	1.40	1.49	1.56	1.64	1.73	1.80	1.87
Ferrymead	1.31	1.36	1.44	1.50	1.56	1.63	1.69	1.75
Styx	1.44	1.50	1.58	1.64	1.69	1.77	1.83	1.89
Lyttelton	1.31	1.36	1.41	1.45	1.49	1.54	1.58	1.62

Source: GHD (2021), converted from CCC Datum to LVD-37 (-9.043 m) and then converted to NZVD2016 using difference grid from LINZ (2016).
[1]Levels include effects of infra-gravity (IG) waves.

2.4.3 Long-term sea levels

Historic rise in mean sea level around New Zealand has averaged 1.7 ± 0.1 mm/year with Christchurch exhibiting a higher rate of 2.12 ± 0.09 mm/year (MfE, 2017).

Climate change is predicted to accelerate this rate of sea level rise. The Ministry for the Environment (MfE, 2017) guideline recommends using four scenarios to cover a range of predicted future sea levels that reflect the inherent uncertainty.

1. NZ RCP2.6 M (Low to eventual net-zero emission scenario).
2. NZ RCP 4.5 M (Intermediate-low scenario).
3. NZ RCP 8.5 M (High-emissions scenario).
4. NZ RCP 8.5 H+ (Higher extreme RCP8.5H+ scenario, based on the RCP8.5 83rd percentile projection from Kopp et al. (2014)).

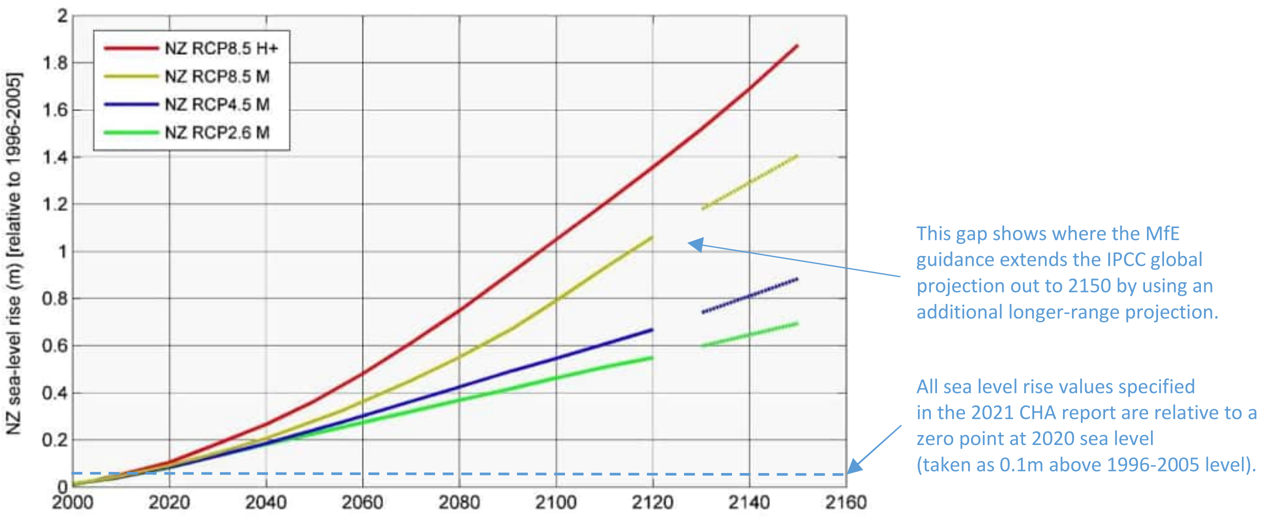

Figure 2.6: Four scenarios of New Zealand-wide regional sea-level rise projections as presented within the MfE 2017 guidance, with extensions to 2150 based on Kopp et al. (2014) (Adapted from MfE, 2017).

The MfE guidance scenarios shown in Figure 2.6 were based on IPCC (2013). As the 2021 CHA report was being finalised, IPCC (2021) was released. IPCC (2021) provides an updated suite of sea level rise projections, which differ from the IPCC (2013) projections in some details. However, the various increments of sea level rise adopted for the 2021 CHA (refer Sections 3.5 & 6.3) still provide good coverage across the range of updated sea level rise projections. This adaptability is one reason why a wide range of sea level rise increments were adopted for the 2021 CHA, rather than fixing the analysis to specific RCP projections.

2.5 Waves

MetOcean Solutions Ltd. have New Zealand-wide and nested wave hindcast models available from 1979 to 2020, with a Canterbury-wide hindcast (400 m domain) specifically for the Christchurch region. Wave timeseries including 3-hourly data from 1979 to 2020 extracted at the -10 m depth contour have been provided by MetOcean for several locations along the shoreline (refer to Figure 2.7). Extreme value analyses have been undertaken for the available timeseries to derive extreme wave heights. Table 2.8.shows the extreme significant wave heights at several locations along the open coast.

Table 2.8: Extreme open coast wave heights (H_s) (m) derived from MetOcean hindcast data

Site	Average Recurrence Interval (ARI)		
	1 year	**10 year**	**100 year**
Waimairi Beach	3	3.8	4.2
North New Brighton	3.2	3.9	4.3
South New Brighton	3.2	3.9	4.3
Sumner	3.3	3.9	4.2
Lyttelton Harbour Entrance	3.4	4.0	4.3
Akaroa Harbour Entrance	5.8	7.2	8.5
Kaitorete Spit	4.4	4.9	5.6

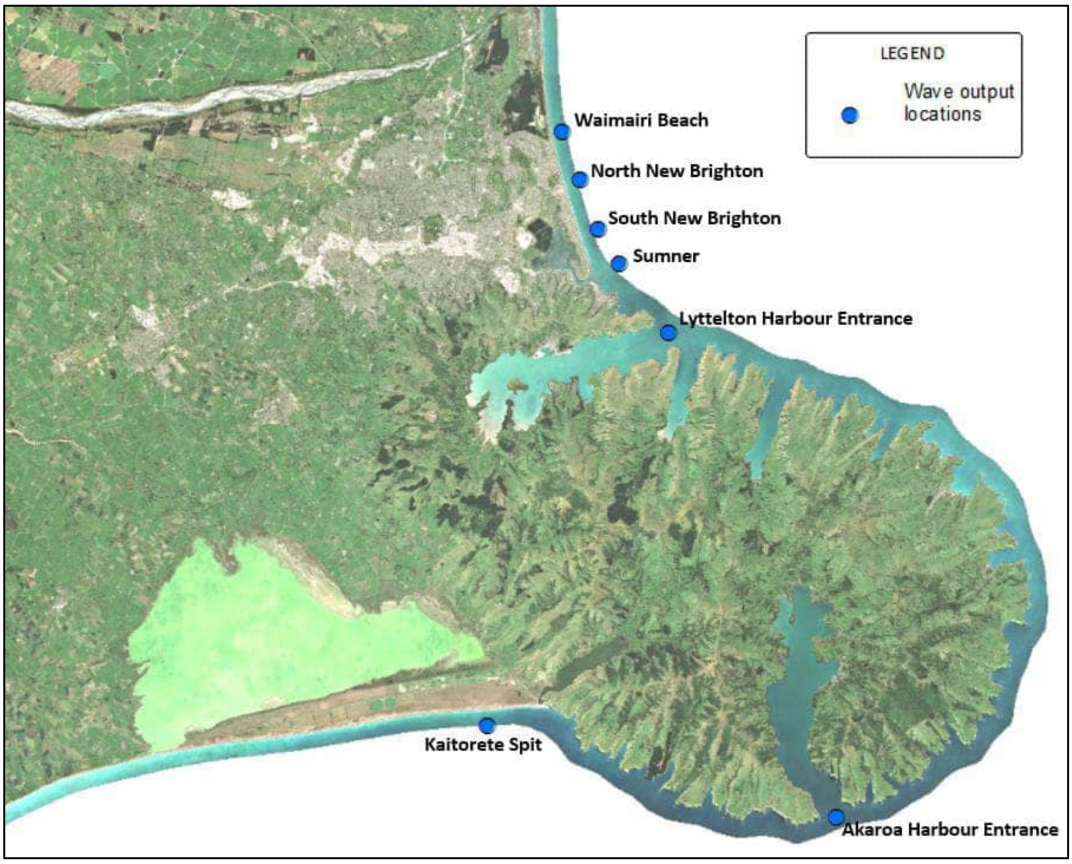

Figure 2.7: Wave output locations.

2.6 Winds

Wind data is available from the NIWA National Climate Database (CliFlo) and Metservice. The list of relevant weather stations is provided in Table 2.9 and shown in Figure 2.8. Other existing wind data records such as data from New Brighton Pier AWS (2009-2016) and wind data discussed by Goring (2008) including Oxidation Pond No. 3 (1993-1998) and Bottle Lake Forest (1997-2008), but have not been considered in this assessment due to their relative short lengths.

Table 2.9: Available weather stations around Christchurch region

Station name	Agent Number	Owner	Start of data	End of data
Christchurch Aero	4843	Metservice	31/12/1959	1/06/2020 (present)
Le Bons Bay Aws	4960	Metservice	18/01/1984	1/06/2020 (present)
Lyttelton Harbour	4903		27/07/1978	13/09/2013
Akaroa Ews	36593	NIWA	18/12/2008	1/06/2020 (present)
Akaroa Rue Lavaud	4951	Metservice	8/12/1977	11/05/2001
Bromley Ews	43967	NIWA	1/4/1967	31/7/1988

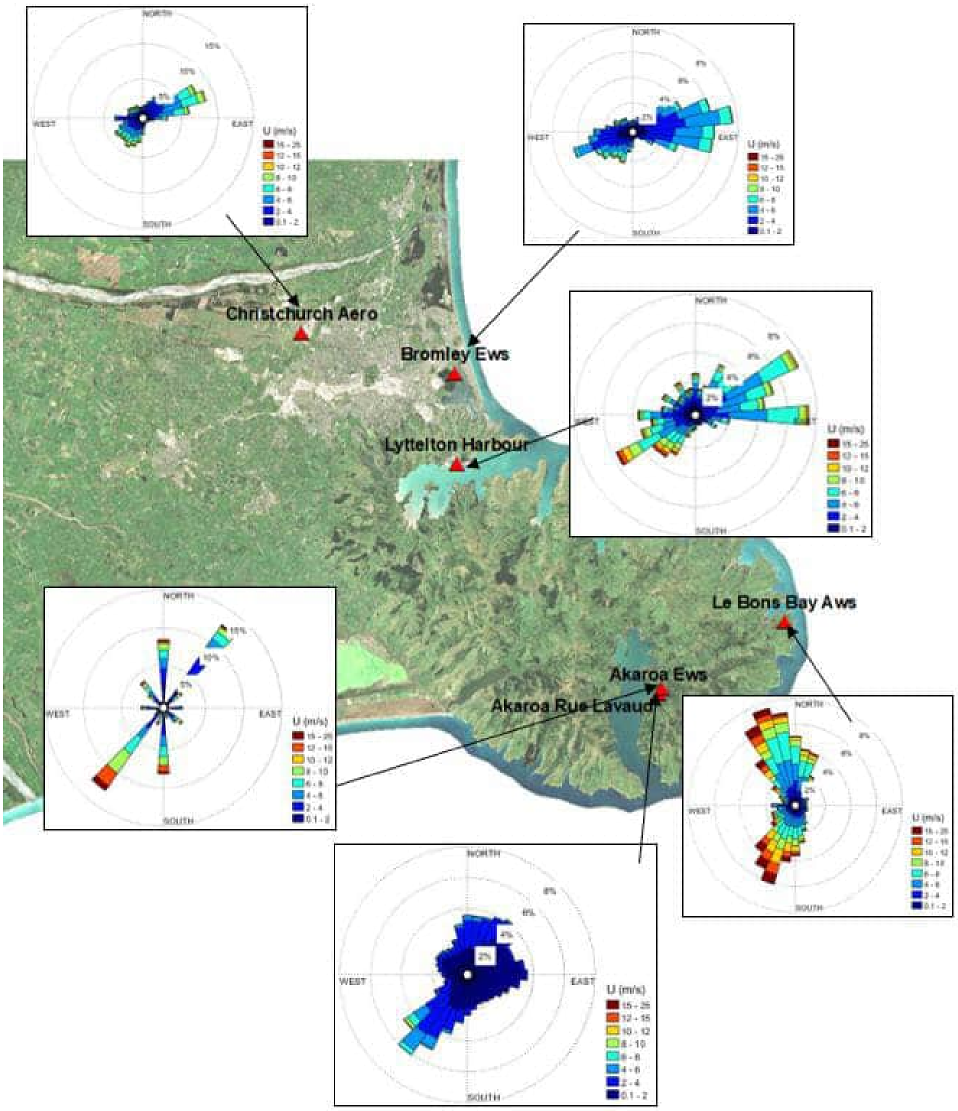

Figure 2.8: Locations of relevant weather stations around Christchurch region including wind roses.

At Christchurch Airport, winds are predominately from the northeast and the southwest quadrants (Figure 2.8). Winds at Bromley and Lyttelton Harbour are slightly more shore normal and predominantly from east-northeast and west-southwest. At Akaroa wind is predominantly from the southwest and north-northeast, and at Le Bons Bay the wind speed is significantly higher with the predominant directions from north-northwest and south-southwest. The higher wind speeds at Le Bons Bay are likely due to the exposed location and height of 236 m above mean sea level. At Akaroa Ews the wind speed is low likely due to its sheltered location.

Goring (2008) assessed whether the wind record at Christchurch Aero is representative for the Avon-Heathcote Estuary. He reviewed a relatively short dataset and compared this with wind data from the oxidation pond (i.e. at the north-western side of the estuary). He found that the southerly winds recorded at the airport are much smaller than those experienced over the estuary and may therefore not be representative for the estuary. The wind data from Bromley EWS is representative for the Avon-Heathcote Estuary based on Goring (2008).

2.7 Sediment supply

As part of Council's Multi-Hazards Study (LDRP 97, Jacobs (2017)), Hicks (2018a) assessed the current coastal sand budget for Southern Pegasus Bay, as summarised in Figure 2.9. The key sediment supply to the coast is sand from the Waimakariri River, which is estimated to be 745,000 m^3/yr. The assessment includes potential sand losses from the Waimakariri River such as loss associated with irrigation water abstraction, gravel extraction and entrapment in Brooklands Lagoon. Loss of sand through irrigation abstraction and gravel extraction is considered to have minor impact on the supply at the coast.

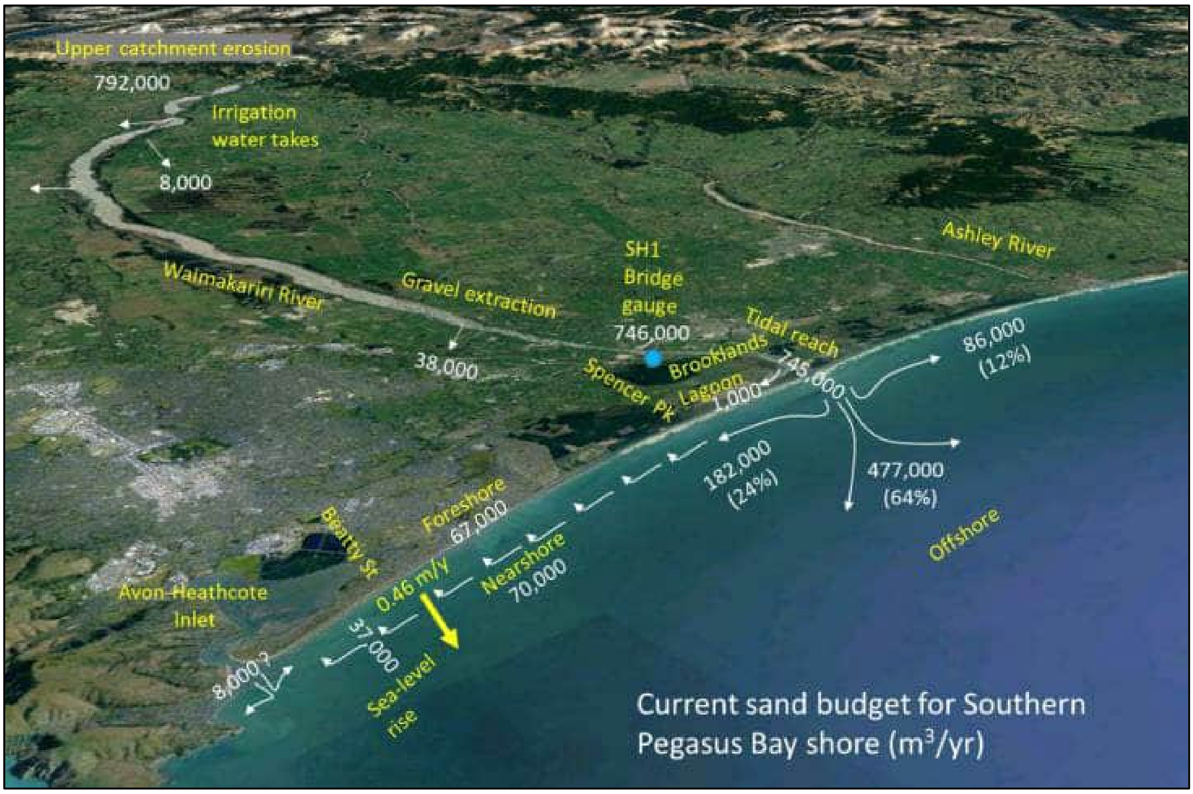

Figure 2.9: Current sand budget for Southern Pegasus Bay (sourced from Hicks (2018a).

Hicks (2018a) assessed longshore transport rates using a SWAN model based on the wave record from the Banks Peninsula buoy for the period September 2000 to December 2017. Results indicate the river sand enters a bi-directional longshore transport system, with approximately 24% transported southwards.

The study includes assessment of the sand volume changes along the Christchurch city beaches, sand exchange with the Avon-Heathcote Estuary and the beach 'demand' for sediment south of the Waimakariri River mouth.

Hicks (2018b) assesses the future sediment budget for Southern Pegasus Bay. The assessment includes a range of future scenarios (Table 2.10) including climate change effects on Waimakariri sand supply and effects of wave climate change and sea level rise.

Key findings from the study include:

- Changes in the Waimakariri sediment supply to the coast could vary from an 11% reduction in supply to a 28% increase.
- Climate-change-altered nearshore wave climate could alter the volume of sediment supply transported southwards:
  - The proportion of sediment transported southwards may reduce due to a reduction in wave energy from the NE quarter. For example, the proportion of sediment transported southwards may reduce by 10% under the RCP6.0M wave climate and by 25% under the RCP8.5M wave climate.
- SLR by itself with no change in offshore wave climate would increase the proportion of sand transported southwards.
- SLR and wave climate change would have compensating effects, however the wave climate change would prevail, resulting in reduced proportions transported south.

The study assesses the impacts of future sand budget on beach volumes and shoreline position and concludes that at least until 2120, the city shore sand budget should remain in surplus except under the RCP8.5M climate change scenario.

Table 2.10: Summary of future scenarios assessed by Hicks (2018b)

Scenario	Description	River load scenario	Wave scenario	SLR by 2120 (m)
A	Worst case independent combination	Total 11% reduction (8% by climate change, 3% by irrigation)	Wave climate aligning with RCP6.0	1.36
B	Worst case independent combination	Total 11% reduction (8% by climate change, 3% by irrigation)	Wave climate aligning with RCP8.5	1.36
C	RCP8.5+ SLR	Increased 28% by climate change, reduced 3% by irrigation	Wave climate aligning with RCP8.5	1.36
D	RCP8.5+ SLR, no wave change, inlet loss	Increased 28% by climate change, zero irrigation effect	Baseline	1.36
E	RCP8.5 Median* + ebb delta losses	Increased 28% by climate change, reduced 3% by irrigation	Wave climate aligning with RCP8.5	1
F	RCP8.5 Median*	Increased 28% by climate change, zero irrigation effect	Wave climate aligning with RCP8.5	1
G	RCP6.0	Increased by 9%	Wave climate aligning with RCP6.0	0.63
H	RCP2.6*	Total 11% reduction (8% by climate change, 3% irrigation)	Baseline	0.55
I	Landslide doubles river load	Load doubled	Wave climate aligning with RCP8.5	
J	Status quo	Baseline	Baseline	Baseline
K	Landslide doubles river load, no CC	Load doubled	Baseline	Baseline

Another study which includes sediment budget for the Canterbury region is Single (2006). Single (2006) investigated the gravel budget along the Canterbury Bight and determined that the Canterbury Bight is nearly in a state of gravel budget balance. The total river supply of gravel to the Canterbury Bight coast is about 176,700 m^3/yr (comprising Opihi/Temuka 19,400 m^3/yr; Orari 12,500 m^3/yr; Rangitata 28,000 m^3/yr; Hinds 16,000 m^3/yr; Ashburton 27,300 m^3/yr; Rakaia 73,500 m^3/yr).

2.8 Vertical land movement

2.8.1 Earthquake movement

The ground around Canterbury has experienced regional scale tectonic movements caused by the 2010 – 2011 Canterbury Earthquake Sequence (CES). These movements comprise both translation and elevation change which have deformed the ground surface. T+T (2013) analysed seven LiDAR datasets and ground-based survey points collected between 6 July 2003 and 17 February 2012 to quantify vertical ground displacement throughout Christchurch City, parts of the Port Hills and Sumner.

By separating regional-scale tectonic movement from total elevation change, the local effects of liquefaction induced elevation change (the ejection of sand, lateral spreading, topographic effects and the settlement of liquefied soils) could be isolated from tectonic ground movements.

Results show general subsidence across the city with subsidence from 0.1 m to more than 0.5 m (Figure 2.10) with the most pronounced subsidence occurring along the banks of the Avon River in the city's northeast. At the same time, the southeast of the city including the southern margins of the Avon-Heathcote Estuary and the Ferrymead area experienced uplift of up to 0.45 m, which can be attributed to tectonic related movement.

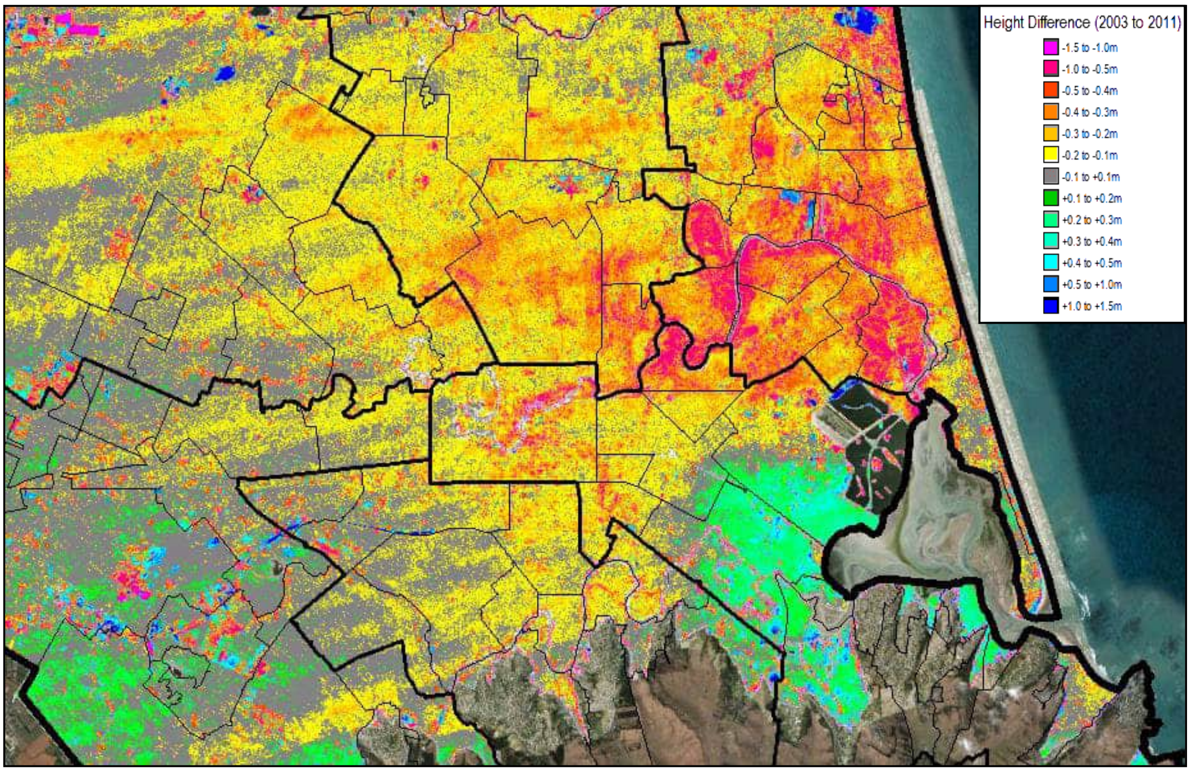

Figure 2.10: Summary of changes in ground elevation between 2003 and 2011 (source T+T, 2013).

Using pre and post-earthquake LiDAR surveys, Measures et al. (2011) calculated vertical change across the estuary and found that the northern part of the estuary subsided by 0.2 to 0.5 m while the southern part of the estuary rose by 0.3 to 0.5 m (Figure 2.11).

Beavan and Litchfield (2012) summarise 2010-2011 earthquake-induced changes along the Christchurch coastline as uplift of more than 0.05 m along the coastline from New Brighton to just south of Lyttelton Harbour. The maximum uplift of more than 0.4 m occurred within the Avon-Heathcote Estuary and coastal subsidence of more than 0.05 m from about New Brighton northwards towards Kaiapoi.

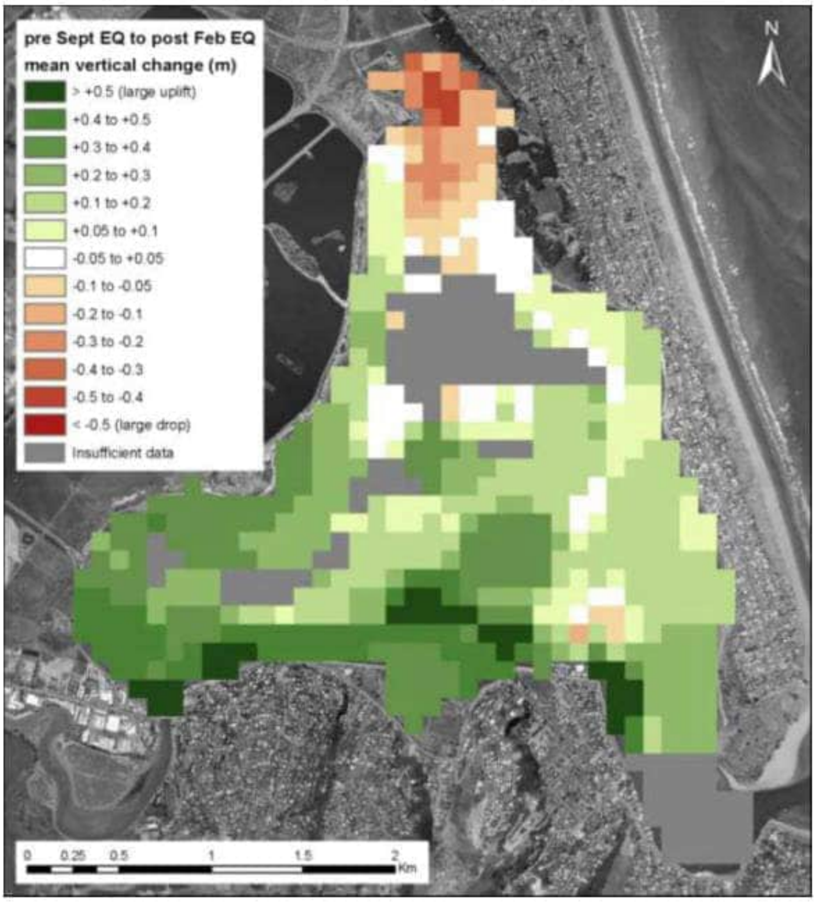

Figure 2.11: Vertical change pre-September 2010 earthquake to post February 2011 earthquake (figure sourced from Measures 2011).

2.8.2 Long-term vertical movement

Long term changes in land elevation may be caused by a number of processes including isostatic adjustment due to changes in mass loading on the Earth's-surface, long-term changes due to plate-tectonics, subsidence due to withdraw of fluids and subsidence due to the natural compaction of sediments (Beavan and Litchfield, 2012). Long-term tectonic movement in the Christchurch area includes tectonic uplift and strike-slip faulting producing the range and basin topography of northern and inland central Canterbury and subsidence of the braidplain (Forsyth *et al.,* 2008).

The School of Surveying at the University of Otago have recently assessed the vertical ground motion around Christchurch City based on the semi-continuous GNSS sites and continuous station (SMNT) at the Sumner tide gauge (Pearson et al., 2019). The assessment includes consideration of the co-seismic offsets and post seismic relaxation from the February 2016 Christchurch earthquake and the November 2016 Kaikoura earthquakes (Figure 2.12). Vertical velocities are corrected for the coseismic offsets to estimate the long term rates shown in Figure 2.13. Rates of land subsidence over the 4-year data period range from 0.23 to 7.97 mm/yr near the Christchurch city coast. However, the length of data is short and Pearson et al. (2019) state that further monitoring is required to monitor the subsidence across eastern Christchurch.

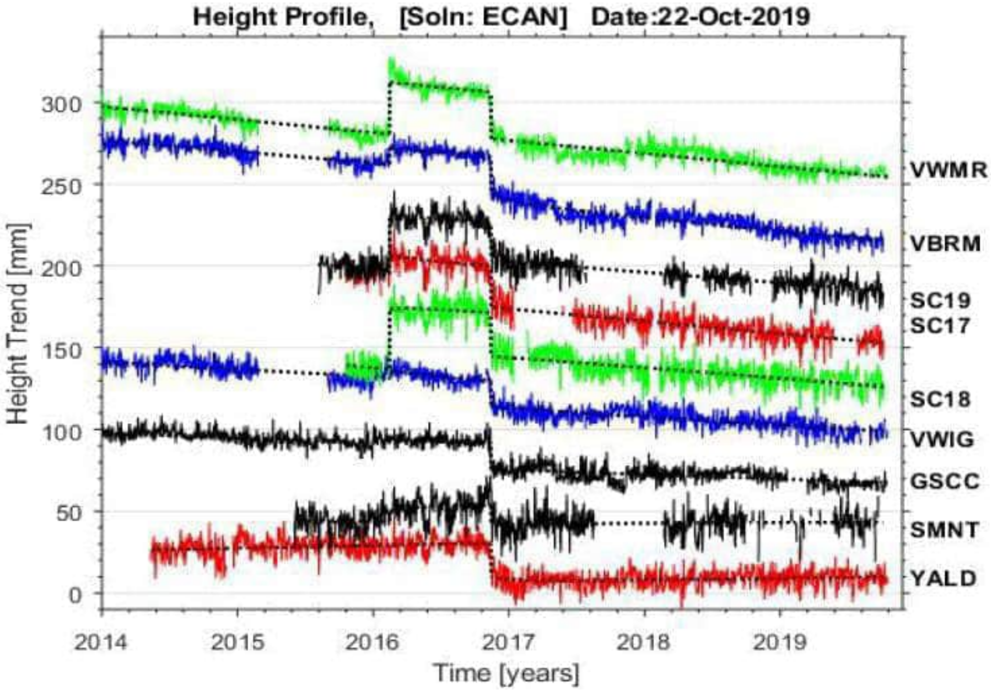

Figure 2.12: Height timeseries including the co-seismic offsets and post seismic relaxation for all sites (source Pearson et al. 2019).

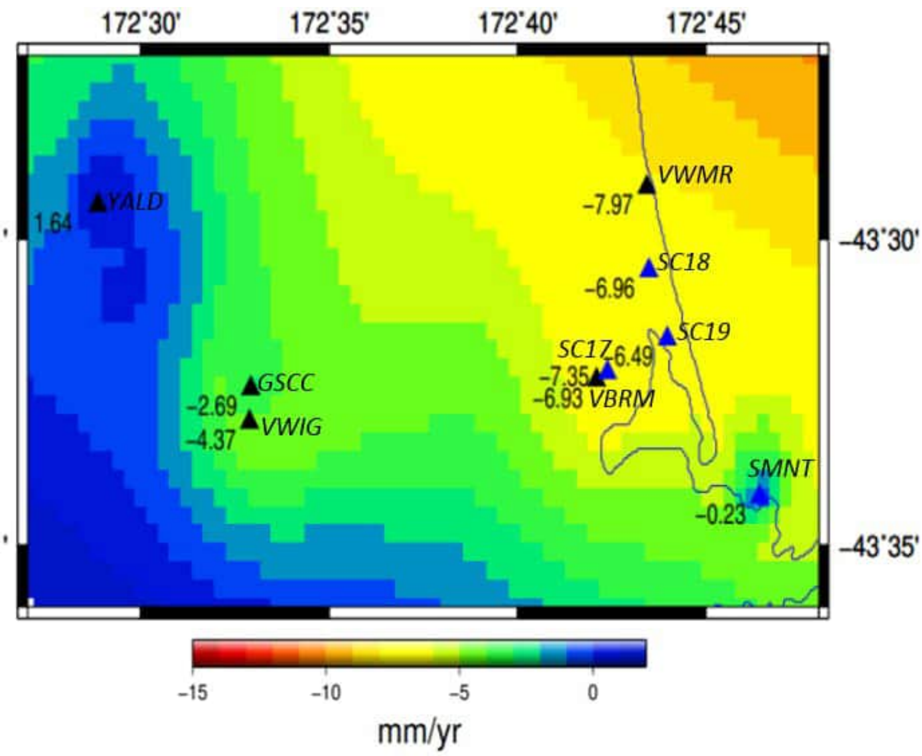

Figure 2.13: Contour map showing estimated long term vertical velocities (mm/yr), uplift (positive, blue) and subsidence (negative, green to orange) (sourced from Pearson et al., 2019). Estimated long term velocities are based on timeseries (2015 to 2019) corrected for coseismic offsets Coastal erosion methodology.

2.9 Anthropogenic influences

2.9.1 Dredging

March (2018) Lyttelton Port Company was granted resource consent to dredge the harbour shipping channel to increase its draught. The recent capital dredge included up to 18M m^3 of material deposited at an offshore disposal site located 6 km off Godley Head in 20m water depth (Figure 2.14). Ongoing maintenance dredging of some 0.9M m^3 per annum is deposited at existing disposal ground within the harbour. MetOcean Solutions Ltd (2016) undertook numerical modelling to investigate the morphological effects and sediment transport patterns associated with the disposal of capital dredged material at the offshore disposal site and the effects of the mound on the offshore wave height gradient.

T+T (2016) review and summarise the effects of the dredging on coastal process and note that the modelling (Figure 2.14) shows a small amount of wave focussing in the lee of the disposal site mound and defocussing on either side. Focussing of up to 4% may occur along South New Brighton with mean reductions of up to 2% between Sumner and Lyttelton Harbour. These changes are expected to diminish as the mound is eroded and seabed returns to its previous near horizontal form.

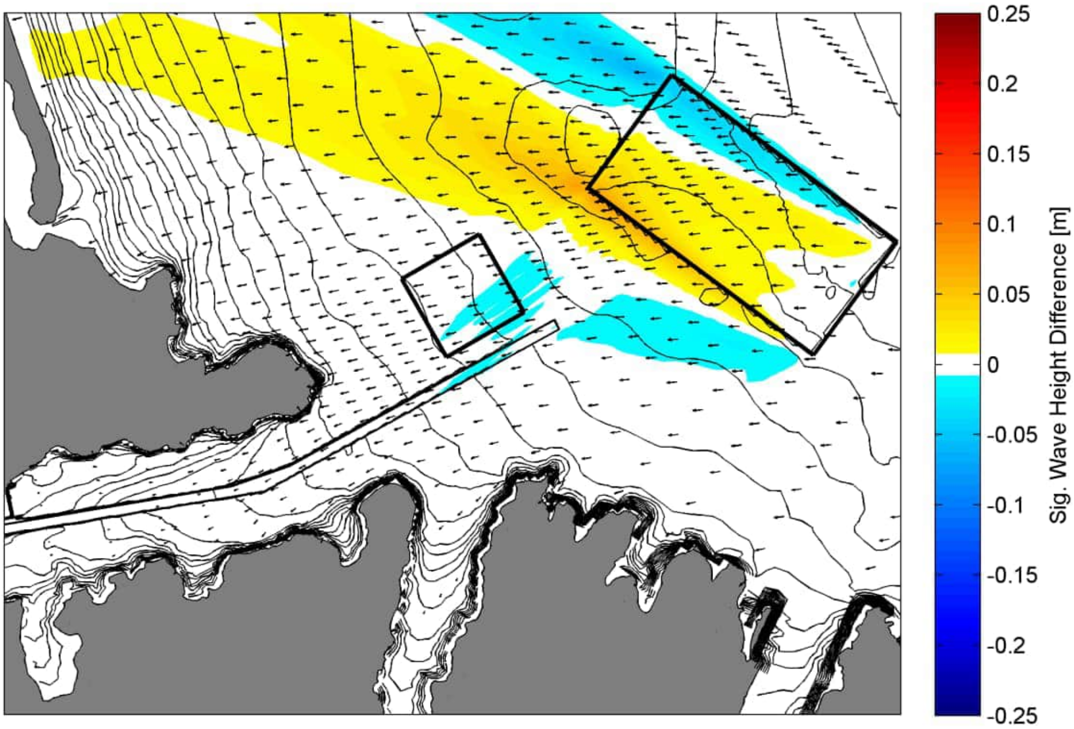

Figure 2.14: Difference in a weighted mean significant wave height (m) between the existing and with the elevated capital disposal ground (top) (image sourced from MetOcean Solutions Ltd (2016)

2.9.2 Gravel extraction

Single (2006) describes the gravel management within the Canterbury Bight. Historically sand has been mined from Kaitorete Spit (1952 to 1984). Peak annual extraction volumes of about 312,000m^3 occurred in the mid-1970s. Sediment is often excavated to open river channels to sea to prevent flooding. This occurs at Taumutu and Birdlings Flat. Due to the northwards sediment transport, excavated material is placed on the active beach north of the channels.

Gravel extraction operations from the lower Waimakariri River channel remove about 38,000 m^3/yr of sand. Most of the extraction occurs in the reach between 18 and 4 km upstream from the coast, where the river's gradient starts to reduce, diminishing the river's capacity to transport gravel and prompting deposition. A gravel/sand transition occurs in the tidally influenced zone approximately 4 km from the coast, and from there downstream the Waimakariri River is a single-thread sand-bed river and carries no gravel bedload.

Hicks (2018a) indicates that gravel extraction from Waimakariri River has minimal impact on coastal sand budget. Even if extraction stopped, most of the extracted sand would not reach the coast as it would remain locked up in river-bed gravel deposits. (Hicks, 2018a).

2.9.3 Dune restoration

Dune enhancement measures have been applied along CHCH open coast since the 1870s when Marram grass was introduced with more enhanced measures such as dune reshaping and foredune planting of native sand-binding species applied since the 1990s. It is likely that the larger seaward growth of the dunes is a result of dune management. Figure 2.15 shows an example of dune management along North New Brighton.

Figure 2.15: Dune management along North New Brighton in February 1992

2.9.4 Artificial lake opening

Te Waihora (Lake Ellesmere) is intermittently closed and open to the sea. The lake is mechanically opened to the sea primarily to minimize flooding of adjacent agricultural land, flush poor quality water, and provide passage for migrating fish such as founder and eel (Measures et al., 2014). Since the mid 1850's there have been numerous schemes and proposals for how to open the lake.

Figure 2.16: Bulldozers removing the 'scab' to make the connection between the cut and sea (top). Excavator working to enlarge the freshly open cut (sourced from Measures et al., 2014)

Wairewa (Lake Forsyth) is also artificially controlled to reduce flooding. While it is closed due to the substantial accumulation of gravel, there is evidence that it was probably permanently open until about the middle of last century (Soons et al., 1997). The Lake has been artificially opened from time to time for more than 140 years. Lake openings have included beach and canal openings.

- Beach openings involve excavation of a 4 m wide channel dug through the gravel on the shortest route to the sea, typically angled towards the south-east. The removed gravel is generally deposited on the eastern side of the beach so that it is less likely to be deposited back into the channel by littoral drift processes.
- Canal openings occur through the canal which was constructed in 2009. The canal is approximately 20 to 30 m wide and 900 m long and runs along the toe of the cliff at the eastern end of the beach. A rock groyne (70 m long) has been constructed at the mouth of the canal using local boulders. This structure provides some protection from wave action and limits the gravel close-off of the canal. Opening of the canal typically involves an excavator removing gravel from the blocked canal outlet (Wairewa Rūnanga Incorporated, 2013).

3 Coastal erosion methodology

3.1 Conceptual models for coastal types

Areas Susceptible to Coastal Erosion (ASCE) varies depending on the coastal type and the key drivers of erosion and instability for those coastal types. In the Christchurch district, these coastal types include unconsolidated sandy beaches and gravel barriers, consolidated banks and harder cliffs. The conceptual models proposed for each of these coastal types is set out below.

3.1.1 Sandy beaches

The ASCE for sandy beaches accounts for short-term, storm induced erosion (either singular or a series) and the response of an over-steepened dune as it regresses back to a stable slope. Additionally, longer term change is accounted for as the position of the coastline may change as a result of imbalances in the sediment budget (both positive and negative) and changes in the relative sea level due (a combination of regional sea level and local land level).

Methods for assessing and combining these parameters are shown in Equation 2.1 (Current ASCE) and Equation 2.2 (Future ASCE) and in Figure 3.1 and have been widely used in New Zealand since Gibb (1998) and are used in most contemporary assessments. This model as was used by T+T (2017) which the peer review panel (Kenderdine et al., 2016) found generally acceptable once the methods of component derivation were refined.

$$Current\ ASCE_{Beach} = ST + DS \quad (3.1)$$

$$Future\ ASCE_{Beach} = (LT \times T) + SL + ST + DS \quad (3.2)$$

Where:

ST = Short-term changes in horizontal shoreline position related to storm erosion due to singular or a cluster of storm events or short-term fluctuations in sediment supply and demand, beach rotation and changes in wave climate (m).

DS = Dune stability allowance. This is the horizontal distance from the base of the eroded dune to the dune crest at a stable angle of repose (m).

LT = Long-term erosion rate of horizontal shoreline movement (m/year).

T = Timeframe (years).

SL = Horizontal shoreline retreat caused by increased in mean sea level (m).

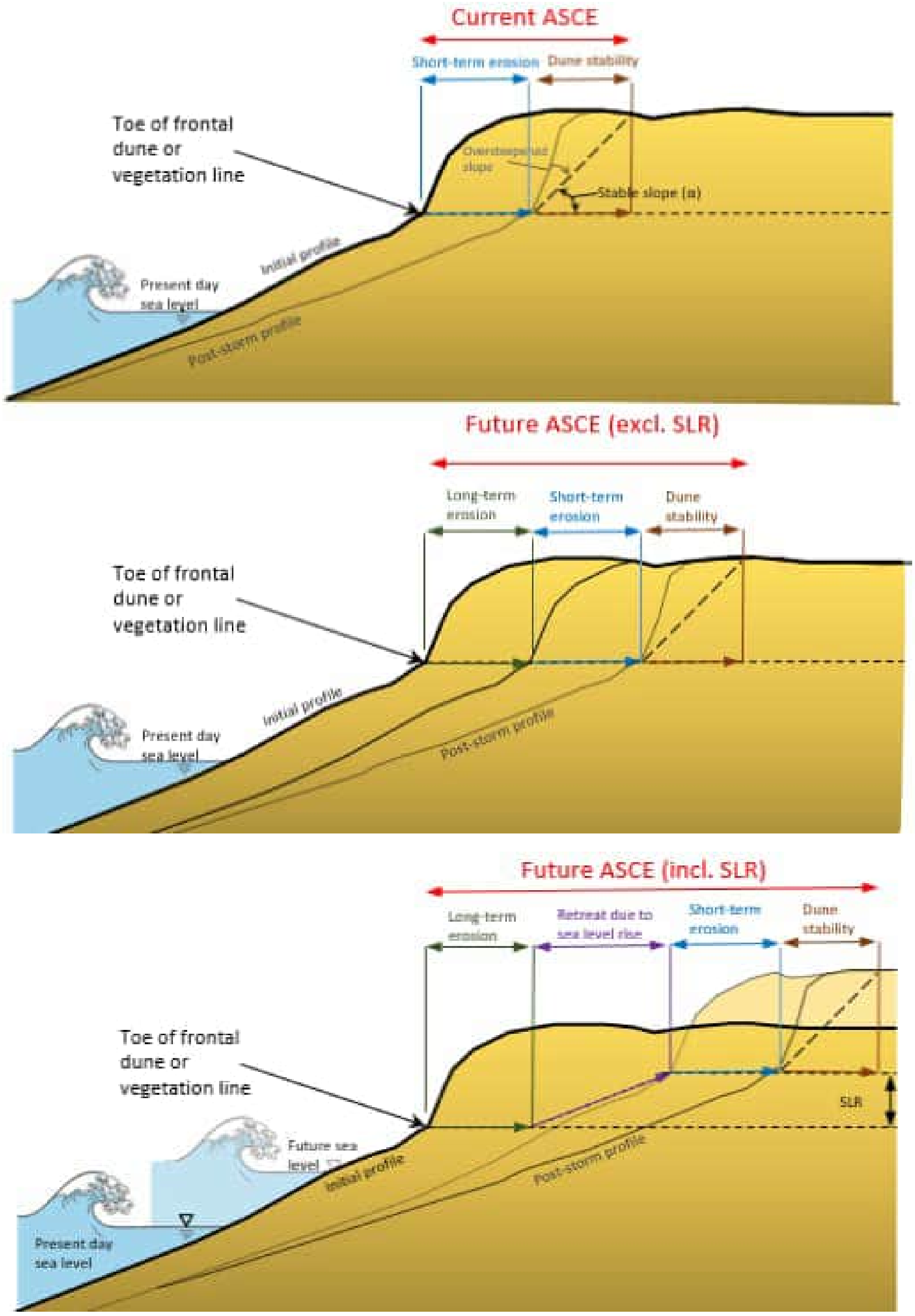

Figure 3.1: Definition sketch for Areas Susceptible to Coastal Erosion on open coast sand beach shoreline.

3.1.2 Mixed sand gravel beaches

Erosion processes along mixed sand gravel beaches can be complex and differ depending on the proportion of sand and gravel. Some gravel barriers can be dominated by erosion due to rollover, where the barrier is overwashed by storm waves and subsequently gravel is shifted landward. This process occurs at the southern end of Kaitorete Spit. However, along majority of Kaitorete Spit erosion is dominated by storm waves moving sediment offshore from the beach face. The ASCE for the mixed sand gravel beach along Kaitorete Spit has been established from the cumulative effect of four main parameters as shown in Figure 3.2 and Equation 2.3 and 2.4.

$$Current\ ASCE_{Gravel} = ST + SS \quad (3.3)$$

$$Future\ ASCE_{Gravel} = (LT \times T) + SL + ST + SS \quad (3.4)$$

Where:

ST	=	Short-term changes in horizontal shoreline position related to storm erosion.
SS	=	Slope stability.
LT	=	Long term rate of horizontal shoreline movement (m/yr).
T	=	Timeframe (years).
SL	=	Horizontal shoreline retreat caused by increased mean sea level (m).

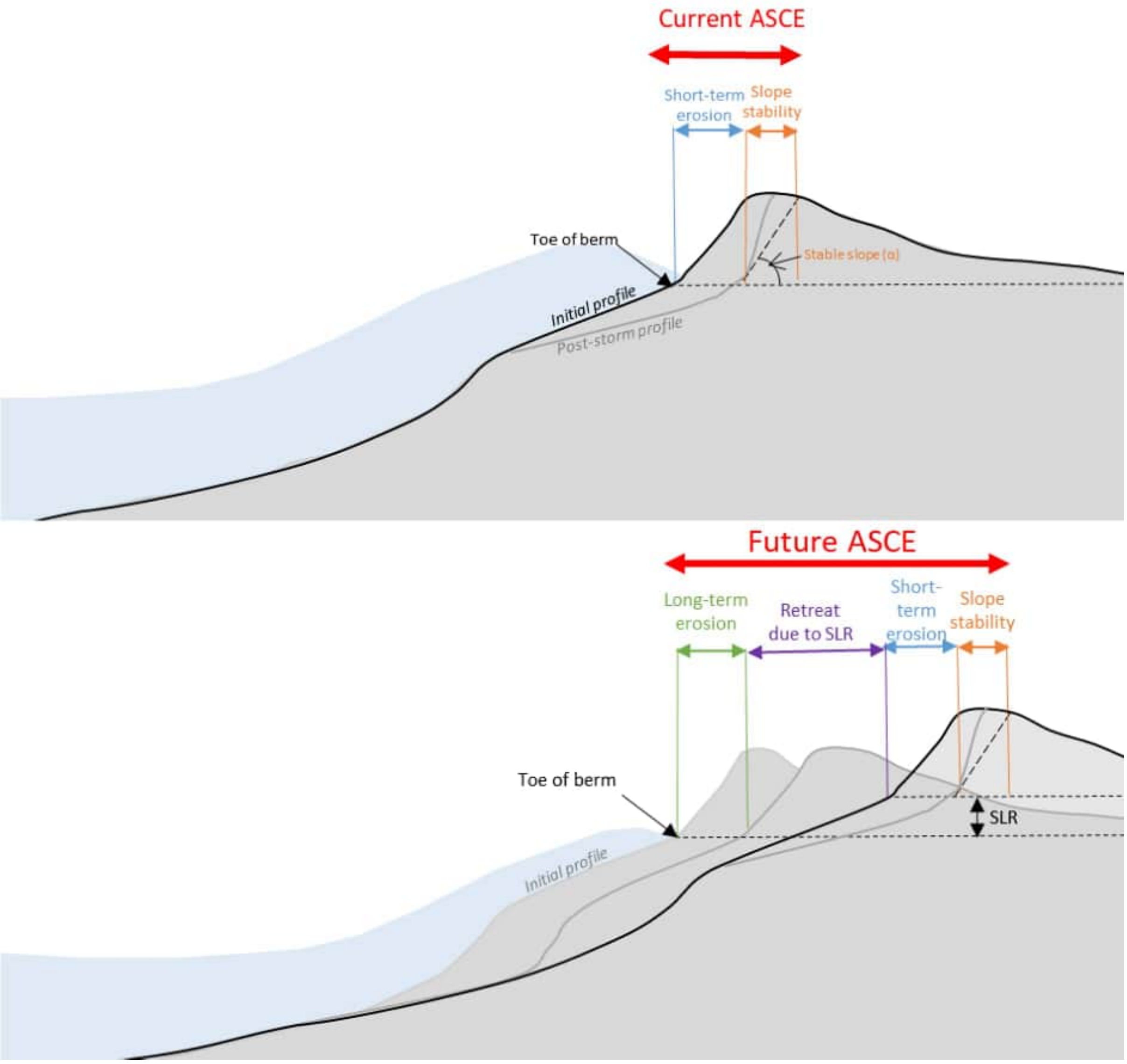

Figure 3.2: Definition sketch for Areas Susceptible to Coastal Erosion on mixed sand gravel beaches.

3.1.3 Banks

Banks, comprising weakly consolidated materials generally along estuary and sheltered harbour environments, are not able to rebuild following periods of erosion but rather are subject to a one-way process of retreat. Coastal erosion of harbour banks typically has two components:

- **Toe erosion**

  A gradual retreat of the bank toe caused by weathering, marine and bio-erosion processes. This retreat will be affected by global process such as SLR and potential increases in soil moisture.

- **Slope instability**

  Episodic instability events are predominately due to the decrease in material properties of the bank or yielding along a geological structure. Instability causes the slope to flatten to an angle under which it is 'stable'. Slope instabilities are influenced by processes that erode and destabilise the bank toe, including marine processes, weathering and biological erosion or change the stress within the slope.

The conceptual model for bank erosion is shown in Equations 2.5 and 2.6 and in Figure 3.3. This is the same model as was used by T+T (2017) which the peer review panel found generally acceptable after modifications.

$$Current\ ASCE_{Bank} = (H_C/tan\alpha) \quad (3.5)$$

$$Future\ ASCE_{Bank} = (LT\ x\ T)\ x\ SL + (HC/tan\alpha) \quad (3.6)$$

Where:

H_C	=	Height (m) of bank.
α	=	The characteristic stable slope angle (°).
LT	=	Long-term retreat (regression rate), (m/year).
SL	=	Factor for the potential increase in future long-term retreat due to SLR effects.
T	=	Timeframe over which erosion occurs (years).

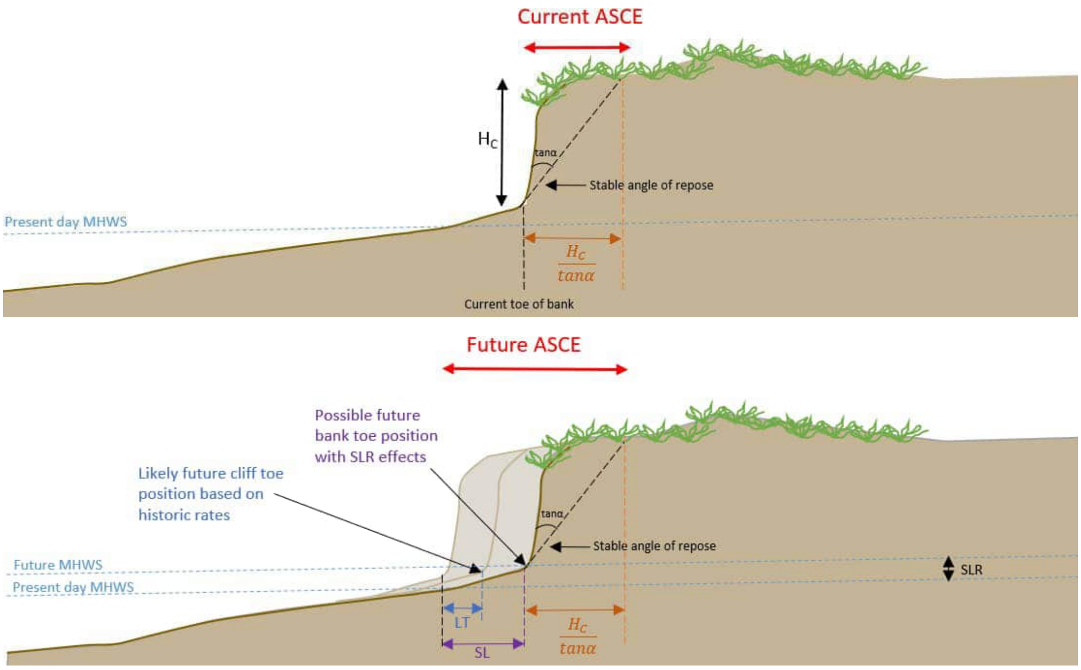

Figure 3.3: Definition sketch for Areas Susceptible to Coastal Erosion on bank coastlines.

3.1.4 Hard cliffs

Cliffed coasts around Banks Peninsula typically comprised of harder volcanic rock and like the bank shorelines are not able to rebuild following periods of erosion but rather are subject to a one-way process of retreat.

Due to the scale of assessment and minimal coastal erosion rates along the volcanic cliffs around Christchurch District, the cliffs have been assessed based on a simplified conceptual model (Figure 3.4). The model identifies the steep coastal edge which is potentially unstable due to coastal processes (assumed to be 1(H):1(V) and includes a setback which accounts for a range of factors including the physical scale of potential cliff failure mechanisms, long-term toe erosion and precision limitations involved with defining the unstable slope area. Where the coastal cliff edge is flatter than 1(H):1(V), a setback, based on the upper ASCE calculated for harbour beaches and banks, has been applied from the coastal edge. While this method is not a detailed cliff projection method, it is suitable for a regional coastal hazard screening assessment.

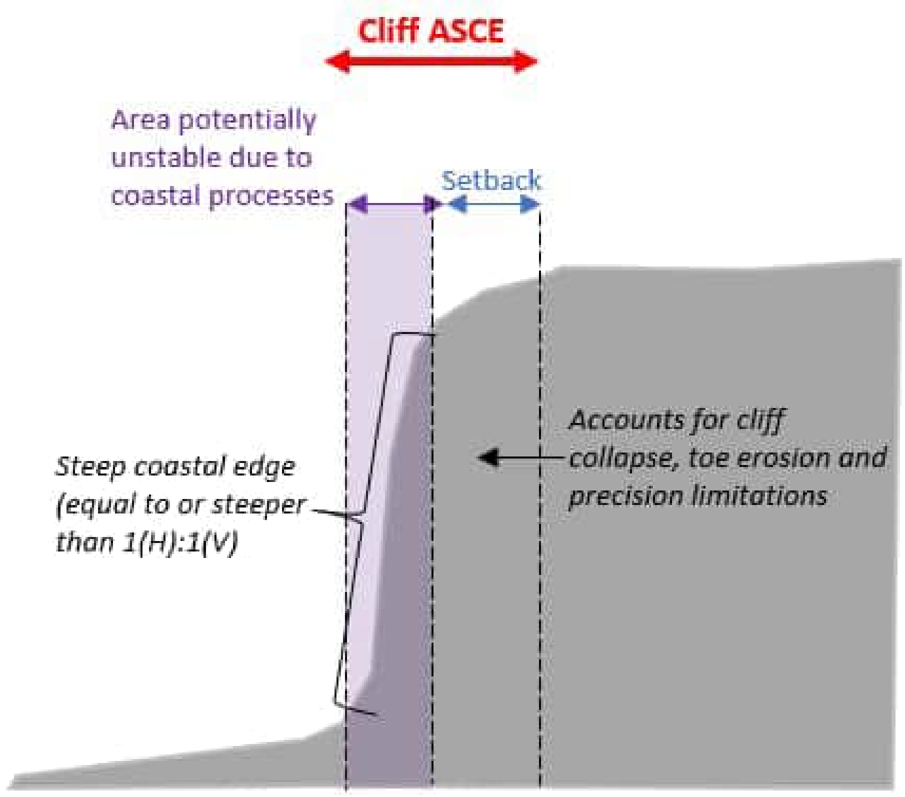

Figure 3.4: Conceptual model for ASCE along hard cliff shorelines.

3.1.5 Protected shorelines

Coastal erosion protection structures around Christchurch City district have been classified into three different categories:

Class 1 – Significantly modified shorelines

There are three locations where the shoreline has been significantly modified with land reclamation and hard protection structures. These locations include the southern shore of the Avon-Heathcote estuary, Sumner Beach, Lyttelton Port and Akaroa township (refer Figure 3.5).

These structures (or previous iterations) have generally been present since at least the 1940s. Because these shoreline modifications are so extensive and have been in place for so long, it has not been feasible to use past observations of erosion rates to estimate what the long-term erosion rates would be in the absence of structures so a different approach is required.

In many instances, significant development has since occurred behind these structures, which has historically relied upon the protection provided. Failure of these structures would likely cause significant disruption to the wider community or city. Considering these wider implications, the New Zealand Coastal Policy Statement recognises that hard protection structures may be the only practical means to protect existing infrastructure of national and regional importance, increasing the likelihood that the structures in some of these areas may be maintained or immediately repaired if damaged.

For the coastal erosion assessment, the current (short-term) hazard area represents the immediate hazard if the structure were to fail, considering the structure height and characteristic stable angle of fill material (i.e. 2H:1V) (Figure 3.7).

The future (long-term) hazard area has been set equivalent to the current hazard area, which would be the case if the structure was promptly repaired if damaged (Figure 3.7). However, if the protection structure fails and is not promptly repaired then it is likely the fill material will rapidly erode, and the shoreline will eventually move back towards its ‘original’ natural position (this scenario has not been modelled in this study but could be assessed in future as part of adaptation planning if relevant).

Figure 3.5: Extent of significantly modified shorelines.

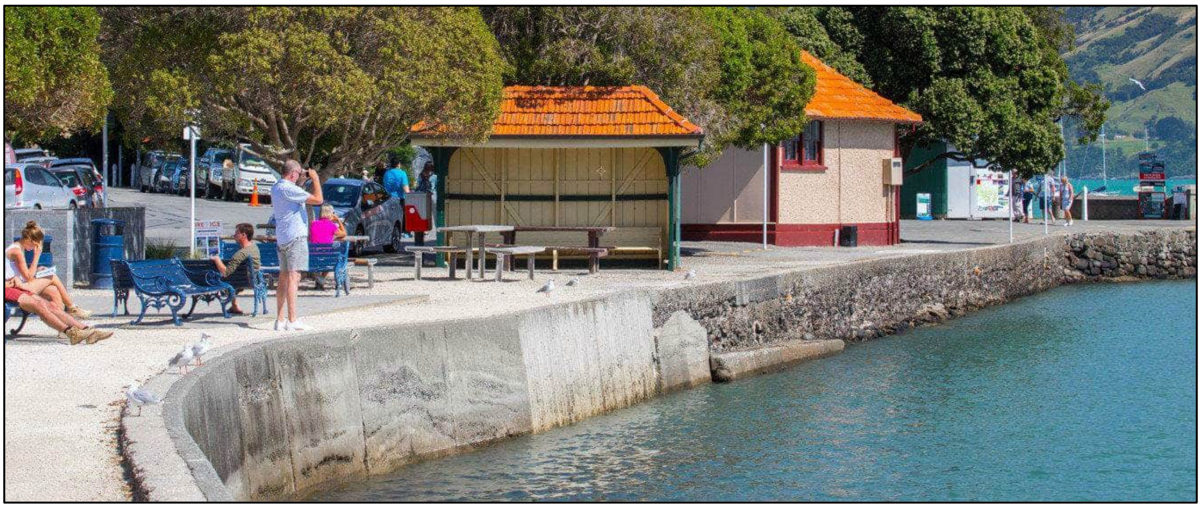

Figure 3.6: Example of significantly modified shoreline in Akaroa.

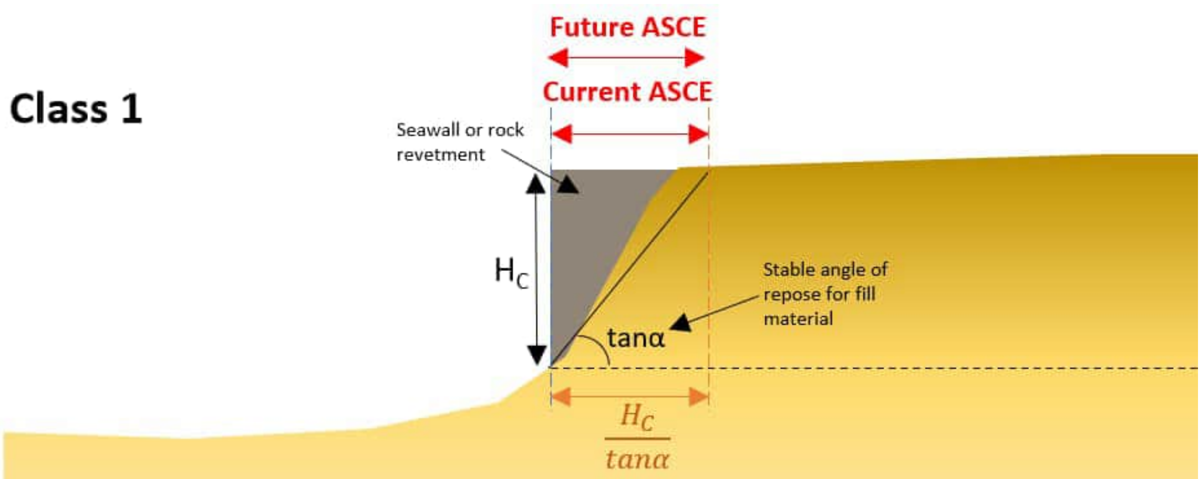

Figure 3.7: Schematic of ASCE for Class 1 structures.

Class 2 – Functional private and public structures

These include functional, consented private structures and functional public structures. The consent status has been chosen as a key factor for the private structures as it relates to the legal ability to undertake repair if damaged and reflects on the degree of engineering involved in their design and construction. If they fail or are damaged, these may be able to be repaired during the consent term. However, it is unknown if they will be re-consented at the end of consent term so the degree of protection in the long term is uncertain. For public structures, the consent status is a less relevant classification factor because many of these structures pre-date the Resource Management Act and so will not have resource consent for their construction.

Another relevant consideration is the condition of the structure, however this was more difficult to consistently determine and incorporate into the assessment. For example, there are consented private structures along the eastern margin of Avon-Heathcote estuary which have been damaged, resulting in some no longer being functional.

Figure 3.8: Example of functional public structures (left) Corsair Bay (right) French Farm Bay.

Class 3 - Informal, non-consented structures

These include all non-consented and/or informal structures. They may have limited effectiveness at reducing erosion and are less likely to be repaired if damaged. This means the long-term erosion (and effects of sea level rise) could be similar to the adjacent unprotected coast (i.e. as if the structure was not present).

Figure 3.9: Example of informal, non-consented structures along the Avon-Heathcote Estuary.

It is not possible to reliably distinguish between Class 2 and Class 3 structures using the currently-available information, and it would still be difficult even if more detailed information was collated. Long-term erosion effects may also be similar for both classes. Therefore Class 2 and Class 3 structures are treated in the same way for this study.

Known structures are shown on the hazard map for context. However, the impact of Class 2 and 3 structures on future erosion was not considered in the assessment and the mapped erosion hazard was based on the characteristics of the adjacent unprotected shoreline (i.e. as if the structure was not present). This allows the long-term importance of these structures to be considered as part of adaptation planning, acknowledging they may provide some degree of protection against erosion now and into the future but also showing what could be at risk if they were to fail.

3.2 Baseline derivation

The baseline is the shoreline to which ASCE values are referenced and mapped from. This is the dune toe or seaward edge of vegetation for beach shorelines, the cliff/bank toe for consolidated shorelines and the toe of the structure for Class 1 structures (significantly modified shorelines). The baseline has been derived using a combination of the most recently available LiDAR (2018) and most recently available aerial imagery (2019).

3.3 Defining coastal behaviour cells

Each site has been divided into coastal cells based on the shoreline composition and behaviour which can influence the resultant hazard. Factors which may influence the behaviour of a cell include:

- Morphology and lithology.
- Exposure to waves.
- Profile geometry.
- Backshore elevation.
- Historical shoreline trends.

3.4 Assessment level

Coastal erosion hazard across the Christchurch City District has been assessed at either a regional hazard screening level or a detailed level. The adopted level of assessment varies to suit the context and available information. Report 1 includes further detail on the rationale of the assessment level for each area. The two approaches are outlined below.

3.4.1 Regional hazard screening (deterministic approach)

Regional hazard screening is intended to identify areas that are potentially exposed to coastal hazards and show where more detailed hazard (and eventually risk and vulnerability) assessments should be focussed. Regional assessments are typically undertaken at a coarse spatial resolution, are often based on limited data and therefore derive simpler or generic hazard component values. The hazard values are assessed by combining the individual parameters using a deterministic ('building-block') approach, with uncertainty incorporated into the derived values. A deterministic calculation assumes fixed values for the input parameters. Each individual parameter is usually selected conservatively (to give a less favourable outcome than average), which means that when these multiple unfavourable assumptions are added it represents an "upper end" scenario (Figure 3.10).

The spatial scale of this level of assessment is relatively coarse (i.e. 1 – 10km resolution), with mapping appropriate for the level of detail and spatial scale.

3.4.2 Detailed hazard assessment (probabilistic approach)

Detailed hazard assessments are intended to provide a more thorough understanding of the coastal processes, uncertainties, and the effects of different future sea level rise scenarios. Therefore, the individual processes, likelihood of occurrence, uncertainty and inter-relationship should be more thoroughly understood and combined in a robust manner (e.g. probabilistic approach) (Cowell et al. 2006, Shand et al. 2015, T+T, 2017).

A probabilistic calculation assumes a range of values for each input parameter with probability distribution functions in the form of either a normal distribution, a triangular distribution or extreme value distribution. A normal distribution is used where sufficient data is available and this data is (near) normally distributed. A triangular distribution is used where limited data is available. The triangular distribution contains the best estimate (mode), lower and upper bounds of the component based on either available data or heuristic reasoning based on experience. An extreme value distribution has been used where extreme values are not included in the available data and should be included.

Probability distributions constructed for each component are randomly sampled and the extracted values used to define a potential ASCE distance. This process is repeated 10,000 times using a Monte Carlo technique. An example of a probability distribution of the resultant ASCE width is shown in Figure 3.10.

The probabilistic approach provides both a “best-estimate” and an understanding of the potential range of outcomes as well as a more transparent way of capturing and presenting statistical viability and uncertainty.

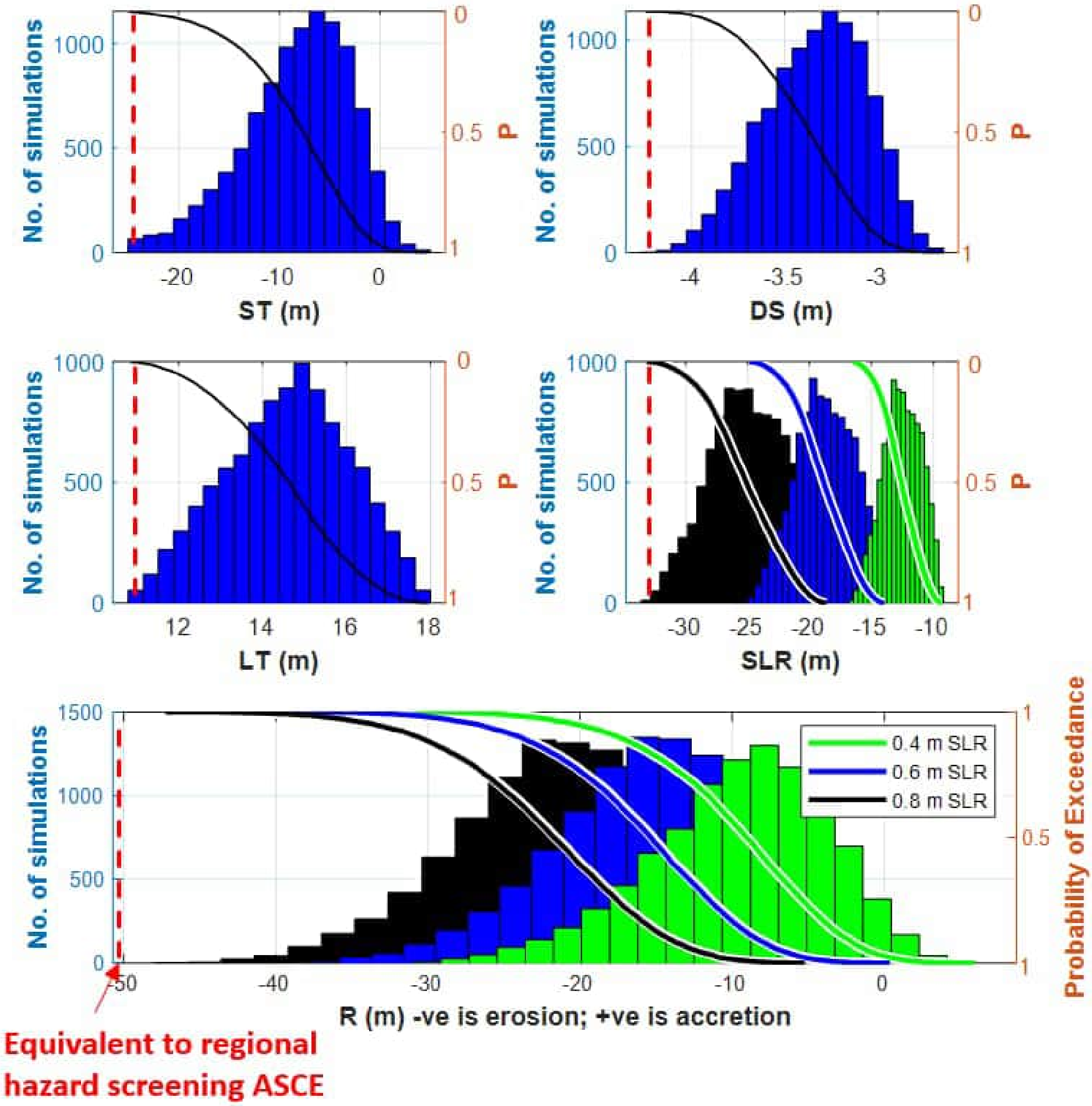

Figure 3.10: Example of component and ASCE histogram cumulative distribution functions of parameter samples and resultant ASCE distances for the probabilistic approach. Red dashed lines demonstrate upper bound component values added together to get the resultant regional hazard screening (deterministic) ASCE.

3.4.3 Spatial extent

3.4.3.1 Detailed erosion assessment

Detailed erosion assessment has been completed for the Christchurch open coast beaches and selected areas within Lyttelton and Akaroa Harbours. Due to different data availability slightly different levels of detailed probabilistic assessment have been completed for each area.

Full probabilistic approach

Where there is sufficient data including historic shorelines and beach profile datasets, full probabilistic analysis has been completed, including statistical analysis of shoreline position and profiles. The full probabilistic approach has been completed for the Christchurch open coast beaches:

- Waimakariri to Southshore.
- Sumner.
- Taylors Mistake.

Quasi-probabilistic approach

Where there are data limitations (i.e. no beach profiles or limited historic aerial imagery), a more detailed assessment was still feasible, however some generic assumptions have been made around parameter bounds, including short term and long term components. This approach has been adopted for the following areas:

- Avon-Heathcote estuary.
- Beach and bank shorelines along existing major settlements within Lyttelton and Akaroa harbours (refer Figure 3.11 and Figure 3.12).

3.4.3.2 Regional hazard screening erosion assessment

The regional hazard screening assessment includes a deterministic approach where the upper bound parameters are adopted for each cell. Regional hazard screening assessment has been completed for the following areas:

- All hard cliffs.
- Beaches and banks within Lyttelton and Akaroa harbours away from major settlements.
- All beaches and banks around Outer Banks Peninsula.
- Kaitorete Spit.

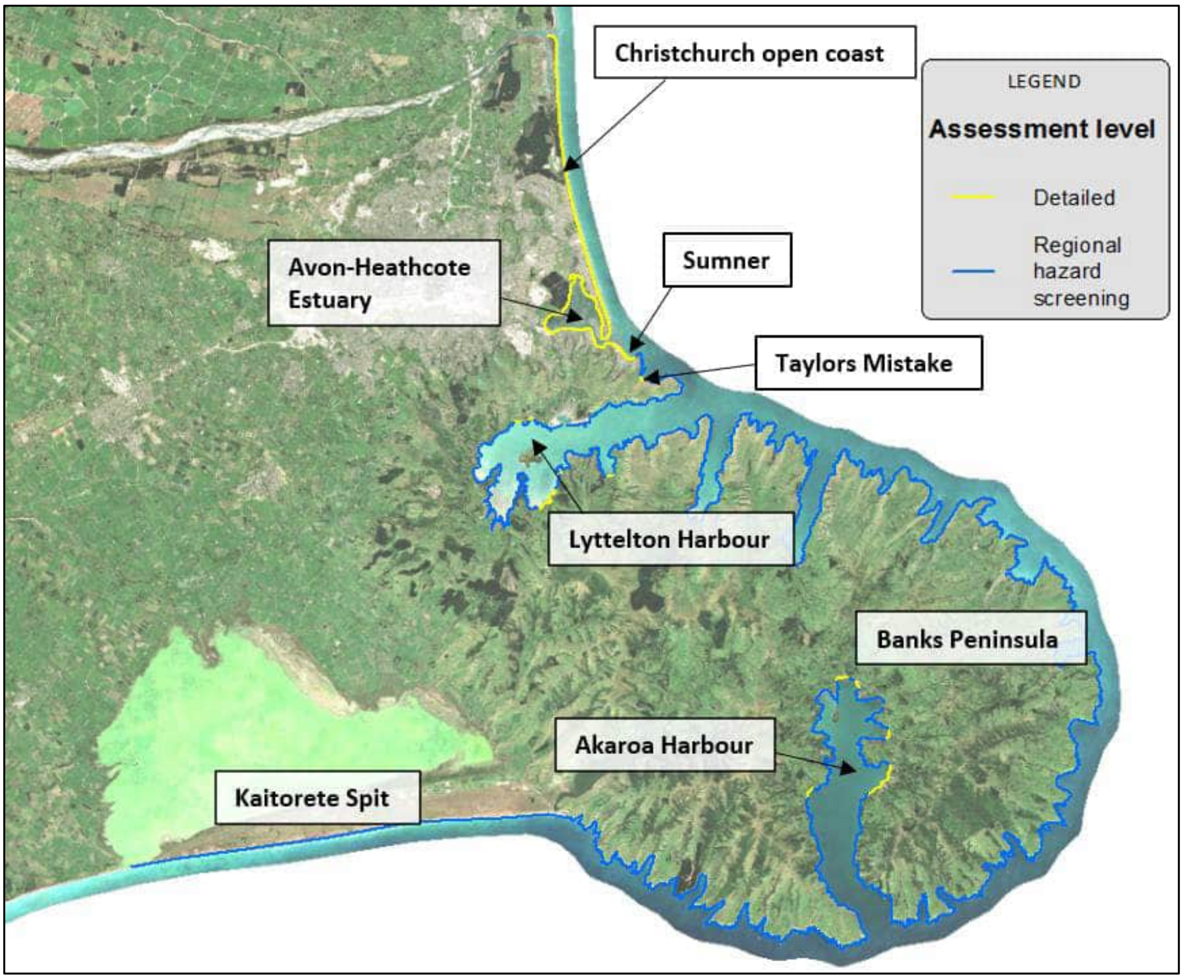

Figure 3.11: Christchurch district showing extents and level of detail for the coastal erosion assessment.

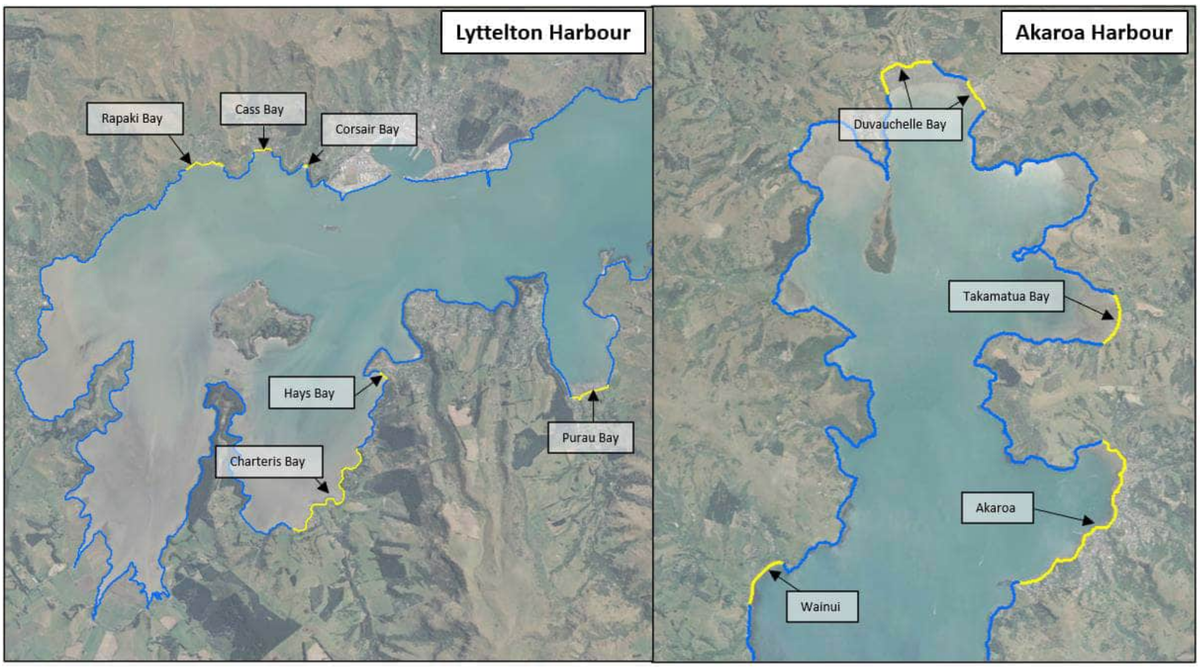

Figure 3.12: Location of detailed (yellow) and regional hazard screening (blue) coastal erosion assessments within Lyttelton and Akaroa Harbours.

3.5 Scenarios

The MfE (2017) guidance recommends either direct usage of RCP scenarios or increments of sea level rise to inform adaptation planning. For this assessment, increments of sea level rise have been adopted which can be aligned with timeframes, approximate RCP scenarios and allowance for vertical land movement. Erosion assessment scenarios are summarised in Table 3.1.

Table 3.1: Erosion assessment scenarios

Assessment	**Timeframe**	**Relative sea level increment[2] (m)**	**Likelihood scenarios[3]**	**Sediment supply reaching beaches[4]**
Detailed[1]	Current – 2030	0	The following range of likelihoods mapped as a gradient: Pmin P99% P95% P85% P66% P50% P33% P15% P5% P1% Pmax	N/A
	2050	+0.2		Scenario 1 No change to sediment supply
		+0.4		
	2080	+0.4		
		+0.6		
		+0.8		
	2130	+0.4		
		+0.6		
		+0.8		
		+1.0		
		+1.2		
		+1.5		
	2150	+2.0		
	2130	+1.5		Scenario 2 Reduced supply (11% reduction)
	2130	+1.5		Scenario 3 (Increased supply 28% increase)
Regional screening assessment	Current – 2030	0	Upper bound (assumed)	-
	2080	+0.4		
	2130	+0.4		
		+1.5		

1 Both full probabilistic and quasi-probabilistic.

2 Relative sea level combines the effect of both rising sea level and allowance for vertical land movement. Increments are specified relative to 2020 sea level.

3 This provides an indication of the probability of a modelled erosion extent occurring for a particular storm event. For example, land mapped within the P95% extent is very likely to be eroded in the type of event being modelled, whereas erosion of land within the P5% extent is very unlikely (but not impossible) in that type of event.

4 The sediment supply reaching the beaches depends on both the amount of sediment discharged by the Waimakariri River, and the amount of this sediment which is transported southwards along the coast. This was assessed for Christchurch open coast beaches only, as it is not relevant for other beaches.

3.5.1 Long-term vertical land movement

MfE (2017) recommends consideration of vertical land movement (VLM), such as uplift or subsidence caused by creeping tectonic plates, because changes in land level can accelerate or decelerate the local effects of a rise in absolute sea level. It is recommended that any significant long-term VLM (>10 years) should be factored into local predictions of future relative sea level[1].

Long-term records of VLM are limited for Christchurch region. The recent work completed by Pearson et al (2019) shows notable subsidence on the eastern side of Christchurch (-0.2 to -0.7 mm/yr) (see Section 2.8). However, as the ground level monitoring covers only a short period after the Canterbury earthquakes (2015 to 2019) and has limited spatial coverage across the city, this data does not provide a reliable basis for extrapolating VLM for decades into the future or defining a pattern of movement across the district.

Therefore, rather than "locking in" a specific VLM rate and spatial pattern in the assessment, land movement will be treated as another source of uncertainty in the prediction of future relative sea level at a particular location. This means that different combinations of absolute sea level rise and local land subsidence can be explored, to give a better understanding of the range of possible future conditions.

The incremental analysis approach is preferred over selection of a specific combination of timeframe, sea level and vertical land movement as it provides a more nuanced understanding of potential effects over a range of future conditions, which is more useful for adaptation planning purposes. An additional high-end scenario has been included in each series of erosion and inundation analyses to provide sufficient "headroom" for the most unfavourable combinations of absolute sea level rise and vertical land movement estimates to be considered.

3.6 Mapping methodology

3.6.1 Regional hazard screening maps

For the regional hazard screening sites, where there is a single ASCE distance for each assessment scenario, the ASCE have been mapped as a polygon, offset horizontally from the baseline. The width of the polygon represents the calculated ASCE distance. For the cliff shorelines, the ASCE has been mapped based on the method described in Section 4.6.5. An example of the mapping for the regional hazard screening ASCE is provided in Figure 3.13.

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1 Relative sea level is measured relative to a fixed surface point on land (e.g. a tide gauge), whereas absolute sea level is measured relative to the centre of the earth. Any changes in relative sea level at a particular location represent the combined effect of vertical land movement and changes in absolute sea level. It is this relative sea level rise which is most relevant for community adaptation planning.

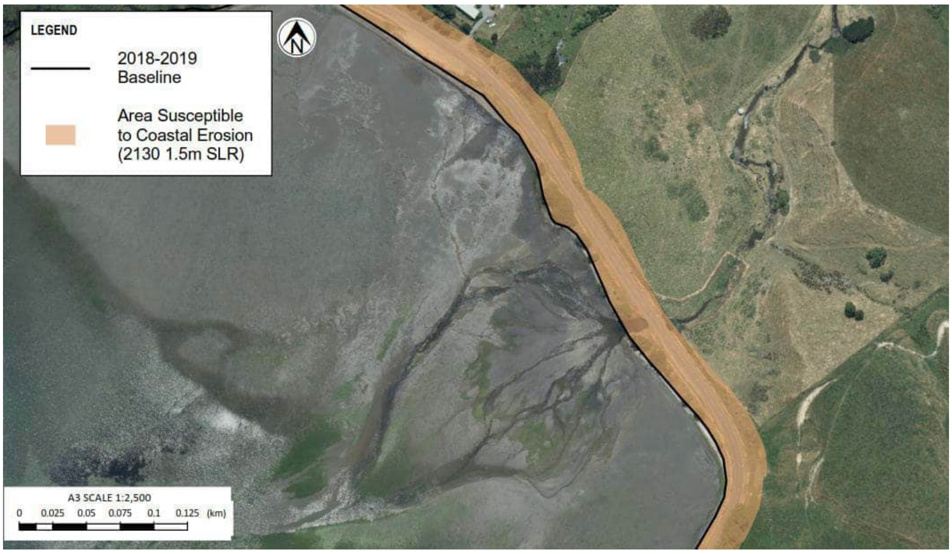

Figure 3.13: Example ASCE map for the regional hazard screening sites.

3.6.2 Detailed hazard assessment maps

For the detailed sites where ASCE have been assessed probabilistically, a raster-based mapping approach has been adopted. The rasters comprise of 1 m grid cells which include information on exceedance probability in every grid cell and show the full probabilistic range of the resulting ASCE across shore. An example of the raster map is shown in Figure 3.14.

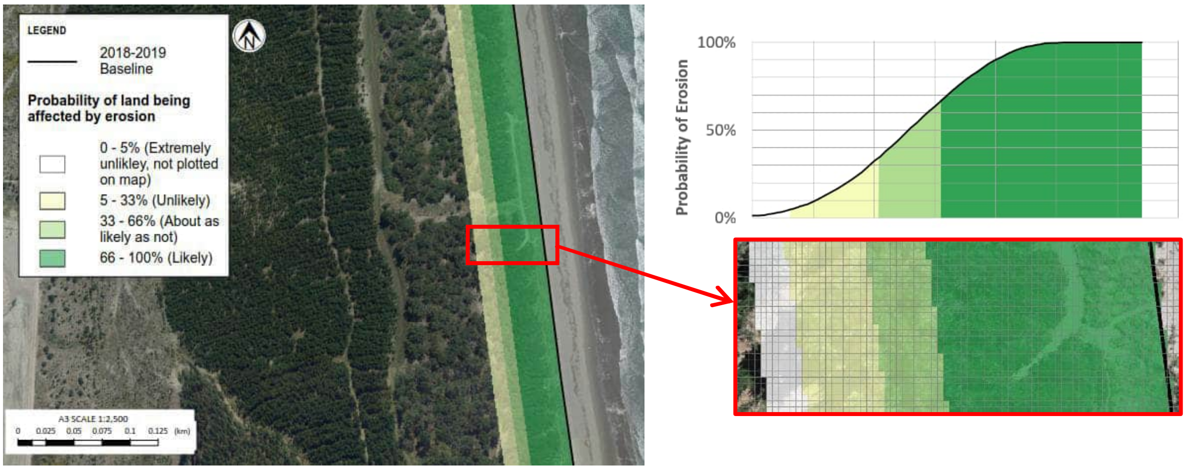

Figure 3.14: Example of raster ASCE mapped for a detailed site showing spatial extent of erosion and corresponding probabilities of occurrence.

4 Coastal erosion analysis

4.1 Christchurch open coast

The Christchurch open coast is located at the southern end of Pegasus Bay on the eastern edge of extensive gravel outwash plains derived from the Southern Alps. At the northern extent, is the mouth of the wide, braided, Waimakariri River and at the southern extent is the inlet to the Avon-Heathcote Estuary. The shoreline predominately faces east and is sheltered from southerly swell due to the presence of Banks Peninsula to the south.

At the end of the last glaciation period, sea level rose several meters until about 6000 years ago, when it reached approximately the present-day level. Since then, the sea level has been relatively static, however, the coastline has prograded seaward several kilometres as a result of fluvial and marine deposition (Brown and Weeber, 1992). Succession of beach deposits, sand dunes, estuaries and lagoons has since occurred, and the current eastern suburbs of Christchurch are located on extensive areas of sand dunes and old dune ridges.

Kirk (1987) suggests that this progradation material has been predominantly supplied by material from south of Banks Peninsula, which has moved northward around the peninsula and onto the Banner Bank before being reworked landward. Kirk considers that this reworking has now ceased, and that the coastline has reached equilibrium with sand supplied by the Waimakariri River replacing sand removed offshore and south of the open coast by current coastal processes.

The present-day shoreline generally has similar morphology with a dune backshore and a relatively flat, fine sand beach (Figure 4.1). There are several locations where the backshore has been modified including the Brighton Pier seawall and North New Brighton seawall.

Figure 4.1: Site photos along Christchurch open coast. (Top left) Erosion scarp on Southshore Spit, (top right) vegetated, accreting dunes near Waimairi, (bottom left) dune planting and fencing near Waimairi, (bottom right) seawall at New Brighton.

4.1.1 Cell splits

The Christchurch open coast has been divided into 14 coastal cells (1 to 14) based on the shoreline behaviour which can influence the resultant hazard (Figure 4.2). Cell 1 includes the northern tip of the Brooklands Spit which is influenced by the dynamics of the Waimakariri River mouth. Cell 14 includes the southern tip of the Southshore Spit which is influenced by dynamics of the Avon-Heathcote estuary mouth. Cells 7 and 9 have partially modified dunes due to the presence of the

North New Brighton and New Brighton seawalls. A key factor influencing the remaining cell splits is the variation in historic shoreline trends.

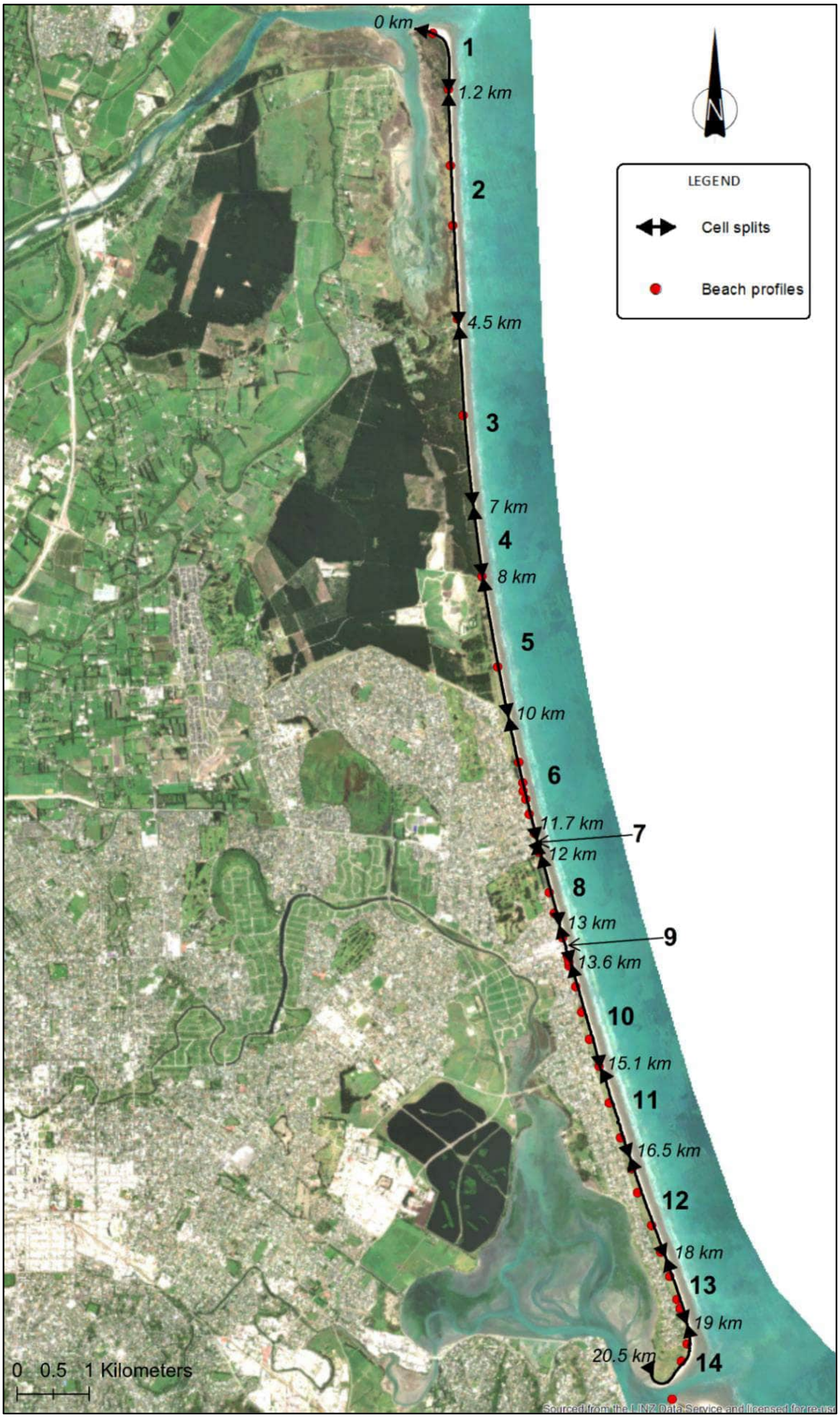

Figure 4.2: Overview of cell extents with cell numbers and chainages along the Christchurch open coast.

4.1.2 Short term component (ST)

Unconsolidated coastlines (beaches) undergo short-term cycles of storm-induced erosion (i.e. storm cut) due to single or clusters of storms followed by periods of re-building. The erosional component of these cycles (i.e. landward movements) needs to be accounted for in the coastal hazard assessment.

4.1.2.1 Approach

The short-term component along the Christchurch open coast has been assessed based on the beach profile datasets (see Appendix A). The profile data provides information on both the long-term movement of the dune toe (see Section 4.1.4) as well as the short-term storm fluctuations.

Based on visual inspection of the beach profiles the dune toe level (i.e. the baseline to which ASCE is offset from) was estimated to be around 2.5 m RL. The short-term component has been quantified using statistical analysis of the inter-survey storm cut distances. The inter-survey storm cut distance is the horizontal landward retreat distance measured between two consecutive surveys (Figure 4.3). We note that due to the relatively long period between surveys the distances may not represent the maximum excursion that may have occurred between the time periods. However, the data set provides the best source of information to analyse.

Figure 4.4 shows that while there has been net accretion at the dune toe, the dune toe position fluctuates over time with periods of erosion and accretion. The profile data shows several stormy periods where the dune toe has retreated a significant distance landward (i.e. up to 15 m retreat at profile CCC1041 during the 1992 storms) (Figure 4.5). Following the storm events, the dune tends to show gradual recovery and accretion (Figure 4.4).

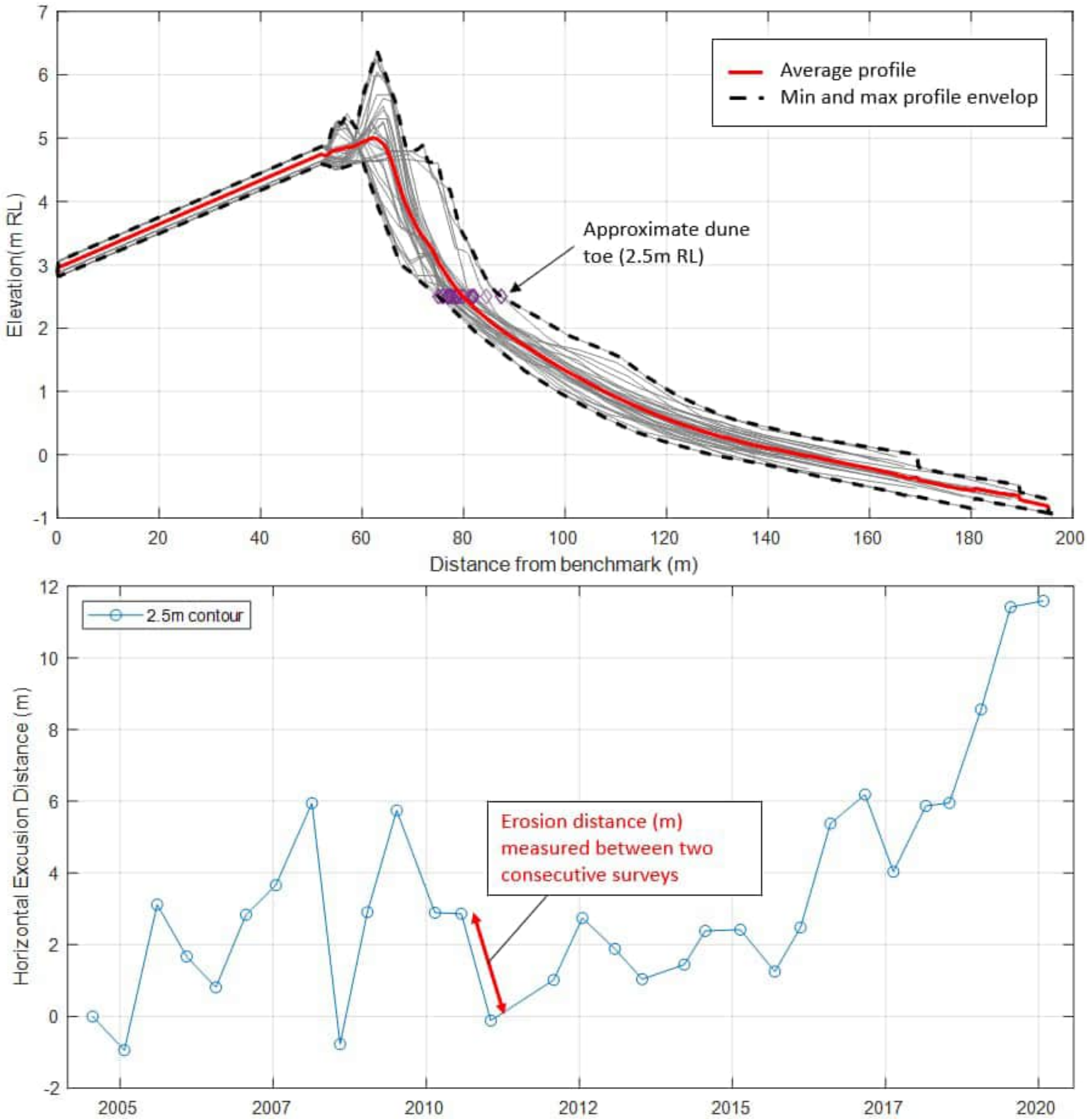

Figure 4.3: Example of beach profile data (CCC0856) used to assess the short term component. (Top) Beach profiles showing the average profile and envelop of change. The dune toe position (2.5 m RL) contour is marked with a purple diamond on each profile. (Bottom) horizontal excursion distance measured at the 2.5 m RL contour.

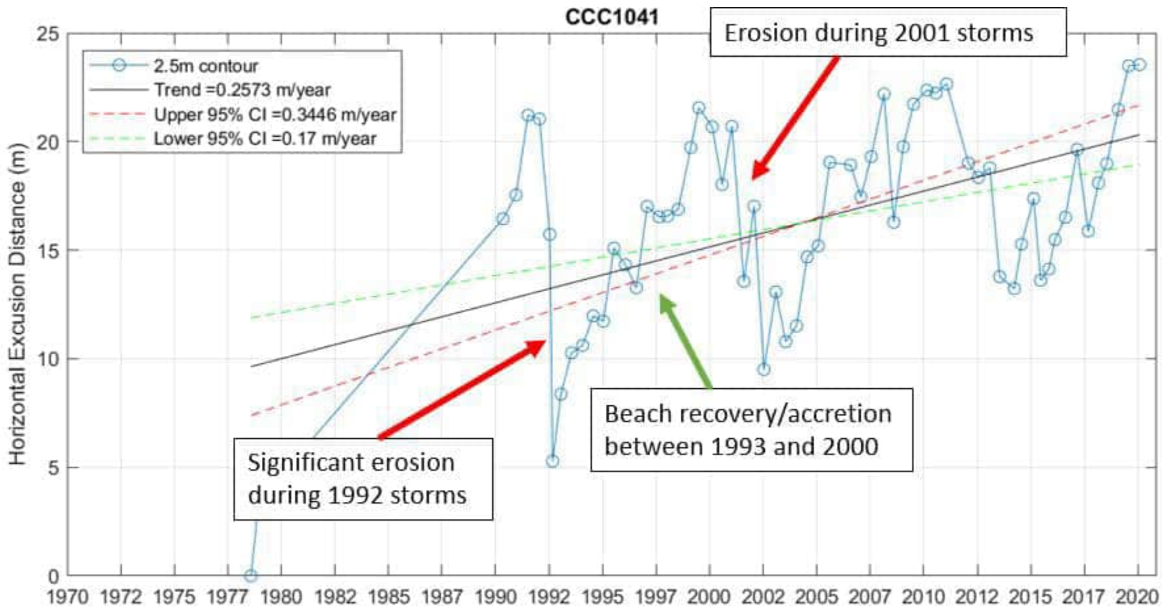

Figure 4.4: Horizontal excursion plot for profile CCC1041 showing significant retreat during stormy years followed by periods of gradual beach recovery and accretion.

Figure 4.5: Photograph taken in vicinity of CCC1041 in August 1992, showing the post-storm dune (source: Justin Cope, ECan).

The mean and maximum inter-survey storm cut distances for all profiles along the open coast have been derived and are shown in Table 4.1. A full set of excursion distances and profile plots for all profiles is presented in Appendix A. Figure 4.6 shows a temporal-spatial plot of the dune toe movements for each alongshore beach profile and for each survey date. The dune toe movements measured at profile CCC0889 are likely influenced by the backshore seawall and has therefore been omitted from the analysis. The matrix shows 4 major storm events/periods (1992, 2001, 2008 and 2014) where erosion was measured at almost each profile along the coast (Figure 4.6). There are two events (2015 and 2017) where only the northern end of the coast has shown erosion with minimal movement at the southern end. While the beach generally has similar exposure, the response to storms may differ slightly at the northern and southern ends.

Based on spatial variation in inter-survey distances, the coast can be broadly divided into four areas: the northern end (Cells 2 to 4), the southern end (Cells 5 to 13) and the distal ends of the Brooklands spit (Cell 1) and the Southshore spit (Cell 14). Average storm cut distances appear to be slightly larger at the northern end of the shoreline compared to the southern end. The distal ends of the two spits (profiles C2200 and C0271) show large fluctuations, with up to -19.4 m inter-survey storm cut at the Brooklands Spit and -38.4 m inter-survey storm cut at the end of Southshore Spit (Table 4.1).

Table 4.1: Mean and maximum inter-survey storm cut distances for each beach profile

Cell	Profile	Chainage (km)	Mean inter-survey storm cut (m)	Maximum inter-survey storm cut (m)
1	C2200	0.25	-4.9	-19.4
2	C2070	1.15	-5.1	-17.8
	C1972	2.2	-4.9	-13.1
	C1891	3.06	-3.7	-10.4
	C1755	4.4	-4.0	-15.8
3	C1565	5.75	-3.4	-10.5
4	C1400	8.0	-3.2	-13.8
5	C1273	9.3	-3.3	-12.2
6	C1130	10.65	-2.9	-11.2
	C1111	10.95	-2.2	-4.3
	C1100	11.05	-2.4	-9.6
	C1086	11.18	-2.8	-9.8
	C1065	11.4	-2.1	-10.7
	C1041	11.67	-2.9	-10.4
7	C1011	11.95	-3.7	-11.3
8	C0952	12.53	-2.4	-10.6
	C0924	12.83	-2.2	-8.8
9	C0889	13.2	-5.6	-22.2
	C0863	13.48	-3.3	-8.0
	C0856	13.55	-2.1	-6.1
	C0853	13.58	-1.9	-6.7
10	C0848	13.63	-2.7	-9.0
	C0815	13.93	-2.7	-13.5
	C0748	14.68	-2.3	-10.2
	C0703	15.08	-3.1	-10.7
11	C0650	15.6	-2.0	-12.9
	C0600	16.14	-2.5	-9.9
12	C0531	16.6	-2.1	-8.3
	C0513	16.94	-1.9	-9.4
	C0471	17.44	-2.4	-8.9
	C0431	17.83	-2.5	-8.0
13	C0396	18.18	-2.3	-15.4
	C0362	18.52	-2.3	-12.4
	C0350	18.65	-2.5	-9.8
14	C0300	19.15	-4.1	-11.6
	C0271	19.45	-6.1	-38.4

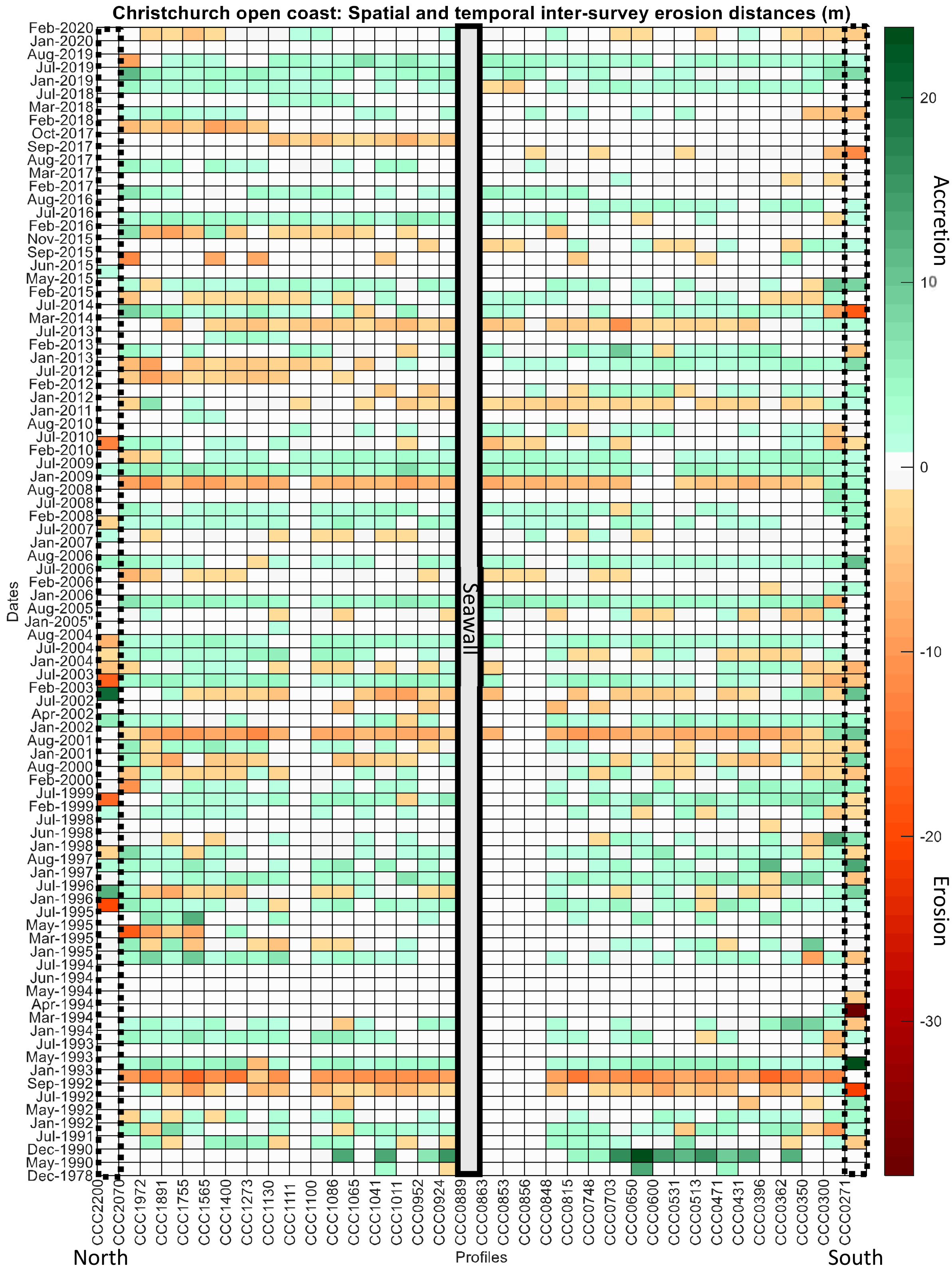

Figure 4.6: Matrix showing inter-survey changes in dune toe position for each profile through time. Dashed lines show the profiles influenced by spit dynamics at either end of the coast. Profile CCC0889 is influenced by the New Brighton seawall and therefore has been excluded from the analysis.

4.1.2.2 Adopted values and distribution

The inter-survey storm cut distances are based on a 30-year dataset of 6-monthly surveys, with maximum possible/extreme distance possibly not measured. In order to derive extreme values from a limited number of observations (i.e. 30 years of 6-monthly surveys), an extreme value analysis has been undertaken.

T+T (2017) reviewed a range of data selection methods including Peaks Over Threshold (POT) and Annual Maximum (AM) approaches. The POT method includes a threshold level (i.e. minimum storm cut distance) that can be used to increase the population size of shorter datasets and/or omit smaller events which may not belong to the same statistical population. The AM method selects the maximum inter-survey erosion distances for each year (i.e. if two surveys are carried out within a year, the largest inter-survey erosion distance is selected) within a time series and for a particular coastal cell. Note that as a result of inter-survey erosion distances the largest cumulative erosion across a series of storms (for example the 1992 storms) may not always be captured and therefore the resulting erosion may potentially be less than possible on an annual basis. The AM method was previously adopted in T+T (2017) and was agreed with the peer review panel and therefore has been adopted within this assessment.

At the distal end of the spits (Cells 1 and 14) there is limited profile data (i.e. one to two profiles). Due to the limited data points within these cells, the AM method is less appropriate as the resulting extreme value curve becomes skewed to the small, normal fluctuations that occur in beach position at the distal end of the spit and results in unrealistic storm cut values. Subsequently for Cells 1 and 14 the POT approach has been adopted for selecting storm cut distances. A threshold of -4 m was adopted for the spits, which is equivalent to approximately the average standard deviation of the open coast and represents the day-to-day fluctuations. Therefore, this approach would filter out the small day-to-day fluctuations and would result in a more realistic extreme value distribution of storm cut.

T+T (2017) tested a range of distributions and found a Generalized Extreme Value (GEV) Type 1 (Gumbel) distribution to have the best fit to the observed data. Therefore, for this assessment the Gumbel distribution has been adopted.

An example of the extreme value distribution for the inter-survey storm cut along the southern profiles is shown in Figure 4.7. Based on the distribution the 5 year ARI storm cut equates to -8 m and the 100 year ARI storm cut equates to -29 m (Figure 4.7). A summary of the extreme value distributions which have been adopted for the cells along the open coast is provided in Table 4.2. The 100 year ARI storm cut distance is also included for context.

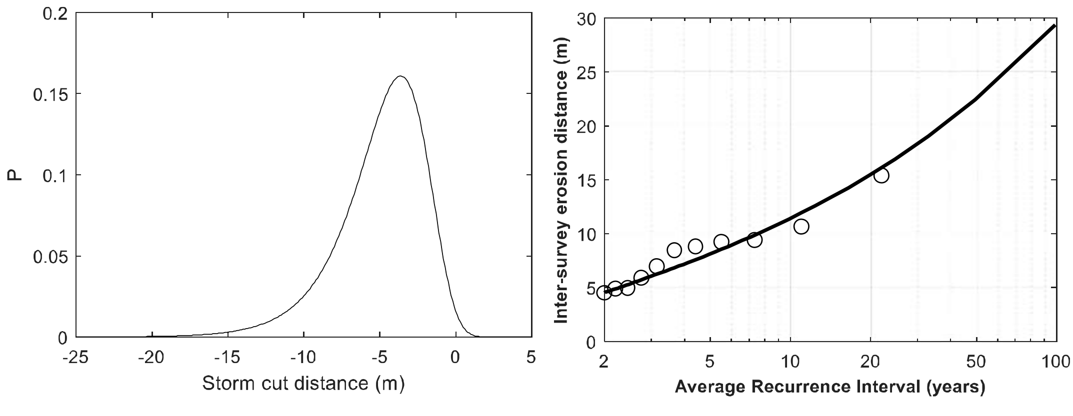

Figure 4.7: Example of extreme value distribution and curve for the profiles along the southern section of shoreline (Cells 9 to 13).

Table 4.2: Summary of extreme value distributions for inter-survey storm cut distances along the Christchurch open coast

Cells	Profiles	Mean alongshore inter-survey storm cut (μ) (m)	Shape parameter (σ)[1]	Resultant 100 year ARI storm cut (m)
1	Brooklands Spit (CCC200)	-11	7	-22
2 to 4	Northern profiles (CCC2070 to CCC1273)	-5.9	4.7	-22
5 to 13	Southern profiles (CCC1130 to CCC0300)	-3.6	2.3	-29
14	Southshore Spit (CC0271)	-5.5	1.9	-41

[1] Shape parameter describes the shape of the distribution (e.g., a larger shape parameter results in a wider distribution).

4.1.3 Dune stability (DS)

The dune stability factor delineates the area potentially susceptible to erosion landward of the erosion scarp. The parameter assumes that storm erosion results in an over-steepened scarp which must adjust to a stable angle of response for loose sand. The dune stability width is dependent on the height of the existing dune and the angle of repose for loose sand. The dune stability factor is outlined in Equation 4.1.

$$DS = \frac{H}{2(tan\alpha_{sand})} \quad (4.1)$$

Where H is the dune height from the eroded base to the crest and α_{sand} is the stable angle of repose for beach sand (ranging from 30 to 34 degrees). In reality, the formation of a talus slope at the toe will allow the scarp to stand at steeper slopes (unless subsequently removed), hence the dune height is divided by 2.

Dune heights were obtained from 2018-2019 LiDAR and checked against beach profile data. Dune crest elevations were extracted at 100 m intervals along the coast. The average dune toe elevation (2.5 m RL) was subtracted from the dune crest elevations, resulting in the dune height. Parameter bounds have been defined based on the variation in dune height within the coastal cell and potential range in stable angle of repose (Table 4.3 and Table 4.4).

Table 4.3: Dune stability component values

Cell	Dune stability component values		
	Lower (degrees)	**Mode (degrees)**	**Upper (degrees)**
1 to 14	30	32	34

Table 4.4: Dune height component values

Cell	Dune height component values		
	Lower (m)	Mode (m)	Upper (m)
1	1	2	3
2	4	5	7.5
3	3.5	4	5
4	3	4	5
5	4.5	5.5	6.5
6	4	5	7
7[1]	0.5	0.8	1
8	4	5	6
9[2]	1	1.5	2
10	4	5	6
11	3	3.5	4.5
12	2.5	3	5
13	1.8	2	3
14	2	3	4

[1] North New Brighton seawall.

[2] New Brighton seawall.

4.1.4 Long-term trends (LT)

The long-term rate of horizontal coastline movement includes both ongoing trends and long-term cyclical fluctuations. These may be due to changes in sea level, fluctuations in coastal sediment supply or associated with long-term climatic cycles such as IPO (Interdecadal Pacific Oscillation).

4.1.4.1 Methodology

Long-term trends have been evaluated by the analysis of historic shoreline positions. Beach profile data has also been assessed; however the profile datasets are shorter than historic shorelines (i.e. 1990 to 2020) and subsequently are less suitable for interring long-term rates.

Shoreline data has been derived from geo-referenced historical aerial photographs. Software developed by T+T has been used to measure the distance to each shoreline from an assumed baseline at 50 m increments alongshore. A weighted linear regression analysis has then been undertaken on each set of shoreline measurements to estimate long-term rates between 1941 and 2019. In weighted linear regression, more reliable data (lower error values) are given greater emphasis or weight towards determining a best-fit line. Weighting of the shoreline data was estimated based on the Root Mean Square (RMS) Error associated with georeferencing and digitising. The older shorelines are typically weighted lower than the more recent shorelines. By calculating trends along the entire shoreline, rather than at a low number of discrete points (i.e. beach profile surveys), alongshore variation in long-term trends can be determined more accurately and either be used to inform parameter bounds or to separate the site into coastal behaviour cells.

Regression rates have been calculated both including and excluding the 1941 and 1955 shorelines (Figure 4.8). The 1941 and 1955 shorelines were excluded due to the significant changes in the Waimakariri River mouth and development of the Brooklands spit during this period. The average long-term rates measured from the beach profiles have also been plotted for comparison with the historic shoreline trends (Figure 4.8).

The data shows that majority of the shoreline has experienced net accretion between 1941 and 2019. Since 1974, the shoreline has generally shown a trend of increased accretion from north to south, with largest fluctuations around the spits. Based on the 95% confidence intervals, the uncertainty in long-term trends is largest near the spits and smallest near New Brighton (Cells 6 to 9). It should be noted that while the shoreline has shown historic accretion, significant storm cuts have also been experienced during this time. For example, up to 15 m retreat near North New Brighton during 1992 and approximately 10 m retreat near South New Brighton during 2013 (see Section 4.1.2)

Brooklands Spit to Bottle Lake Forest (cells 1 to 5)

There are no digitised shorelines along the Brooklands Spit for 1941 and 1955 as the Spit was only partially formed and there was minimal vegetation established (Figure 4.9).

Prior to 1940, the Waimakariri River mouth opened to the sea approximately 3 km south from its current position. During a flood event in 1940 the river mouth shifted north to its present position and the old river channel infilled. By the 1970s the Brooklands Spit had formed, and marram grass and pine trees were planted to stabilise the shifting dune sands. Between 1973 and 1977 a series of storms washed away 15 to 18 m of dune and in 1978 storm waves breached the spit resulting in a 250 m wide gap approximately 3 km south of the river mouth (cell 2).

The rock bank on the northern side of the river mouth was constructed to help keep the mouth in its current position. The historic shorelines show that between 1979 and 2011 there was significant erosion at the tip of the spit. Boyle (2017) also report that in 2012 there was concern around rapid erosion at the tip of Brooklands Spit. Continued monitoring and analysis completed by Boyle (2017) found the erosion ceased in 2013 and the Spit has since started migrating northwards.

From 1940s to 1970s the significant river mouth changes and formation of the spit appeared to have impact on the adjacent shoreline. For example, through Bottle Lake Forest (cells 3 to 5) there was rapid shoreline accretion between 1941 and 1974 as the shoreline re-adjusted (Figure 4.10). Since the 1970s the river mouth and spit have been 'relatively' stable. Therefore, long-term rates post 1970s are likely to be a more accurate representation of future rates and subsequently have been adopted (Table 4.5).

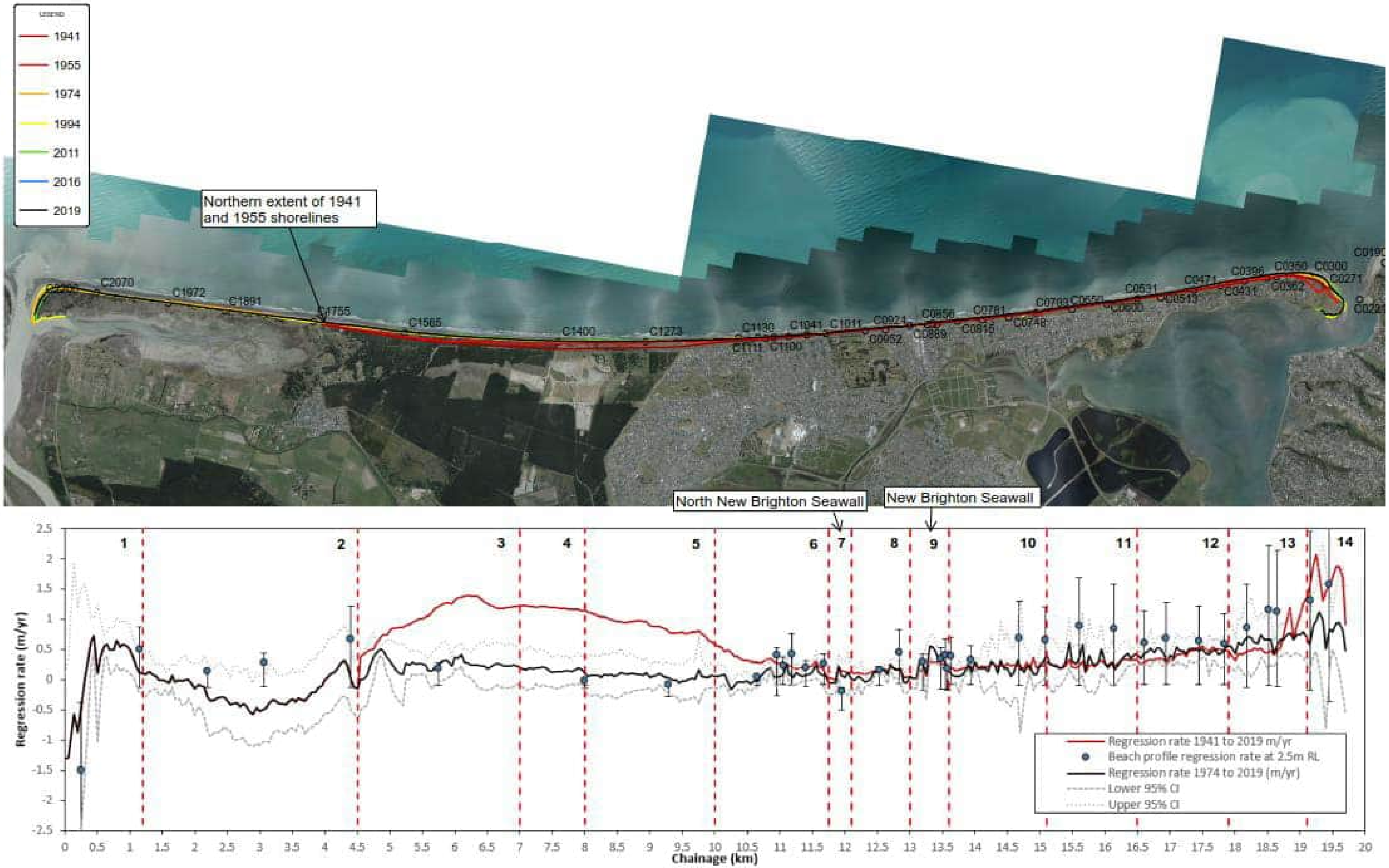

Figure 4.8: Regression analysis of historic shorelines. 95% confidence intervals included for regression rates between 1941 and 2019 (red) and 1974 and 2019 (black). Profile regression rates overlaid with error bars based on 95% confidence intervals. Refer to Table 4.1 for profile chainage locations.

Figure 4.9: Historic aerials showing growth of the Brooklands Spit.

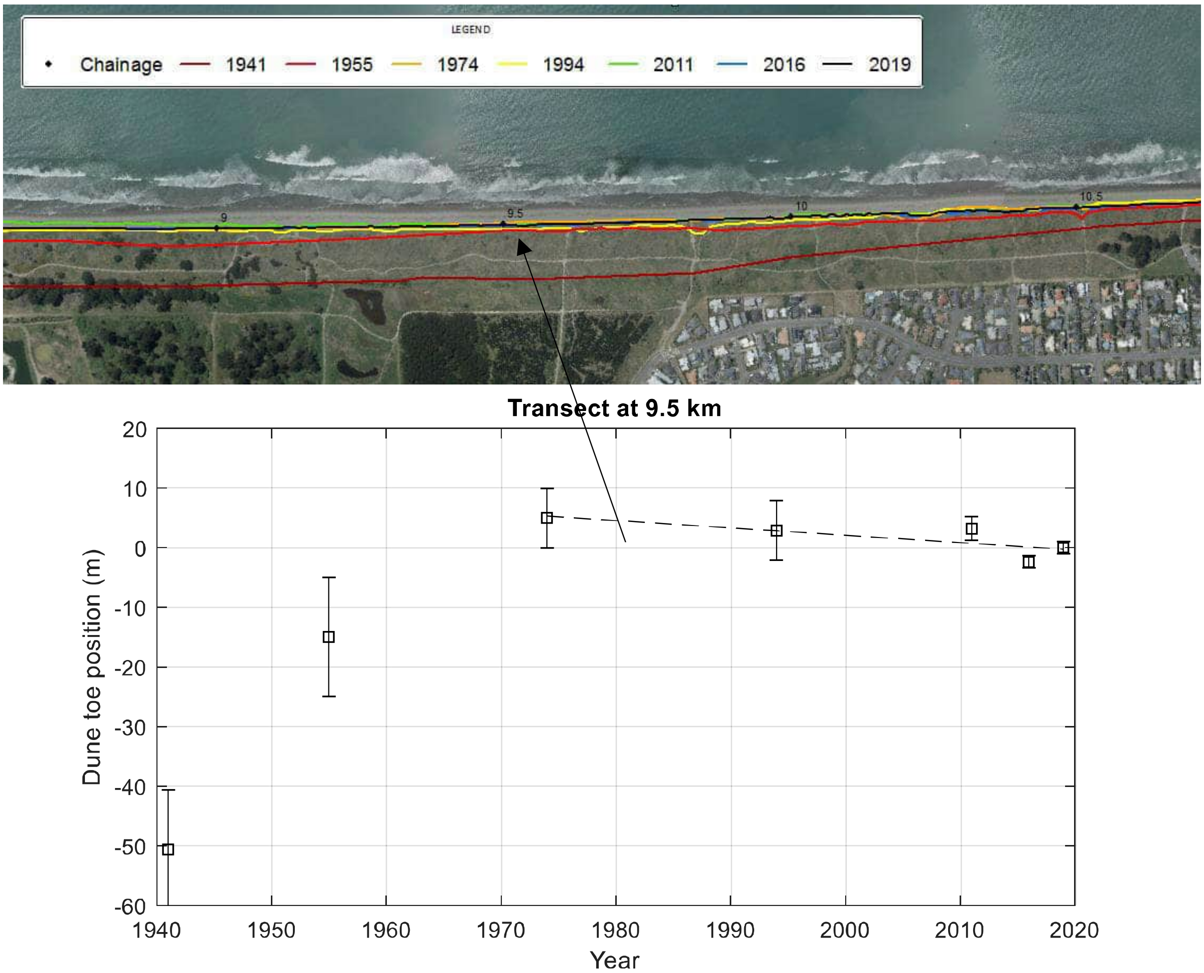

Figure 4.10: Historic shorelines and regression plot at chainage 9.5 km (Bottle Lake Forest, Cell 5). Distances are relative to 2019 shoreline position.

Waimairi to Southshore (city shoreline)

The city shoreline (i.e. Cells 6 to 13) shows average accretion rates ranging from 0.1 m/yr near Waimairi and up to 0.7 m/yr along Southshore. Recent accretion rates have been high near New Brighton and Southshore (Cells 10 to 13) and hence the regression rates from the beach profile dataset (1990 to 2020) are higher compared to the regression rates from the historic shorelines (Figure 4.8). Figure 4.11 shows how the shoreline near South New Brighton (Cell 10) experienced accretion between 1941 and 1974, followed by erosion until 1994 and then accretion until 2019. Profile data indicates that the erosion between 1974 and 1994 shorelines is likely the result of the 1992 storm event.

Hicks et al (2018a) noted that the phase of accretion since 2011, along Cells 10 to 13, may be associated with effects from the earthquakes. Following the earthquake there was a reduction in the tidal prism of the Avon-Heathcote estuary and subsequently a reduced volume on both the ebb and flood tidal deltas at the inlet entrance. This reduction in delta size has potentially resulted in a surplus of sand being supplied to the adjacent shoreline and hence the period of increased accretion following 2011.

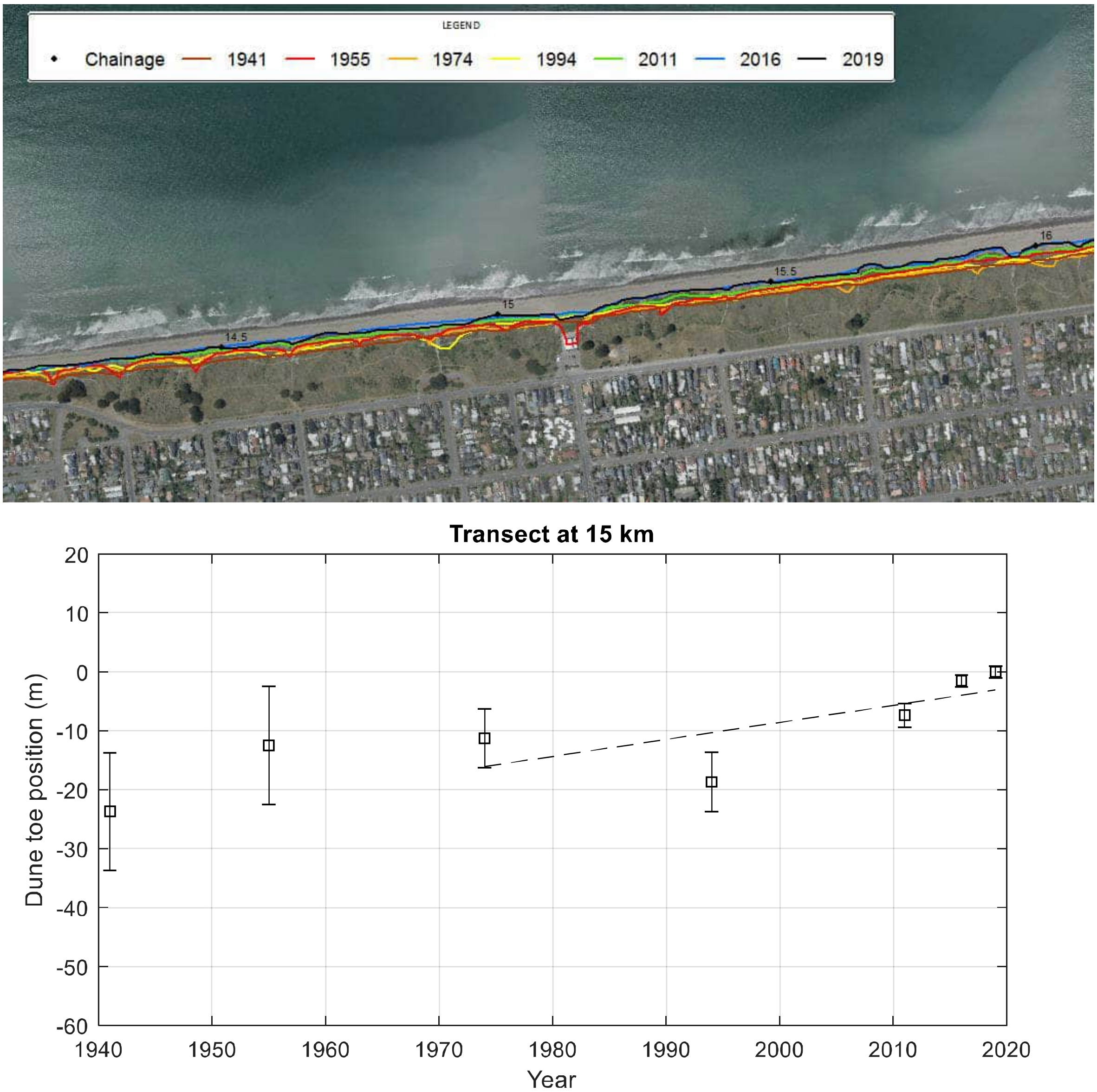

Figure 4.11: Historic shorelines and regression plot at chainage 15 km (South New Brighton, Cell 10). Distances are relative to 2019 shoreline position.

Distal end of Southshore Spit (Cell 14)

The distal end of the Southshore Spit is very dynamic and is largely influenced by changes in the adjacent inlet delta system.

Historic shorelines mapped from aerial photographs indicates the spit has shown net accretion since 1941 (Figure 4.12). However, previous studies indicate that there were three periods of erosion along the spit between 1918 and 1949. Findlay and Kirk (1988) reported an erosional phase occurred between 1918 and 1922 and then again between 1930 and 1937. The most significant erosion occurred between 1940 and 1949 where the spit eroded up to 500 m. This erosion is evident in the shoreline data shown in Figure 4.12. Following this significant erosion, a sandbag groyne was constructed and later upgraded in the 1950s. The period from 1950s to 1974 was generally dominated by accretion and then followed by a small period of erosion from the 1980s to 1994. Between 1994 and 2016 the shoreline continued to accrete and then between 2016 to 2019 there has been erosion (Figure 4.12).

Findlay and Kirk (1988) note that the main ebb channel from the Avon-Heathcote estuary historically flowed south-east past Shag Rock to an outlet near Cave Rock (Sumner). The channel shifted to its current position during 1938 and it is understood that this shift was an important factor contributing to the extensive erosion of the spit during the 1940s.

Due to the dynamic interactions with the inlet delta system, there is uncertainty in the future long-term rates around the spit. For example, an increased tidal prism within the Avon-Heathcote is likely to result in an enlarged ebb tidal delta, widening of the inlet and subsequently erosion of the spit.

The Canterbury Earthquake Sequence (CES) resulted in 0 to 0.4 m uplift across the estuary which reduced the tidal prism by ~12 to 18% (Measures et al 2011). This reduced tidal prism may have contributed to the flux of sediment which was observed on the adjacent spit following 2011.

Prior to CES, Rodgers et al (2020) state that there was a theorized 400-year period of gradual subsidence and tidal prism increase. Rodgers et al., (2020) concluded that while the long-term increase in tidal prism was interrupted with the earthquake uplift, it appears to have resumed.

Future changes in relative sea level are likely to affect the tidal prism of the estuary and subsequently the volume of sand stored in the ebb tidal delta and the adjacent spit. Hicks et al., (2018b) suggest that the tidal inlet is likely to enlarge in the future, resulting in an increased tidal prism and potentially increased erosion on the spit. Quantification of this is, however, beyond the scope of this assessment.