Waimakariri District Plan Review -Natural Hazards

Waimakariri District Council

Coastal Erosion and Sea Water Inundation Assessment Technical Report

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Executive Summary

Waimakariri District Council (WDC) as part of its review of the 2005 operative District Plan has requested technical information on the extent of future coastal erosion and sea water inundation hazards including the impacts of sea level rise and other climate change effects on coastal processes (e.g. wave climate, sediment budget). This information will help inform the District's overall approach to managing natural hazards within a multi-hazard context under the direction given in the Canterbury Regional Policy Statement (CRPS).

This report documents a number of investigation that have been carried out by Jacobs to assess the extent of the existing and potential future coastal erosion and sea water inundation hazards and confirm whether or not the settlements of Kairaki, The Pines, Kaiapoi, Woodend Beach, Pegasus, and Waikuku and other identified future development areas within the coastal environment may become subject to coastal hazards over a 50 and 100-year time frame.

The methodology used in the investigations meets the requirements of the NZCPS and CRPS for identification of coastal hazards, and follows the guidance for inclusion of sea level rise (SLR) given in MfE(2017).

The Coastal Erosion Hazard Zone (CEHZ) mapping indicates that for the majority of the district's coastline, the continued Waimakariri River sand supply will dominate over SLR induced erosion for over 100 years under all SLR scenarios. Only at the northern end of the district around Waikuku would a CEHZ be required to be located landward of the existing dune vegetation limit, and then only most likely by around 20 m under the most extreme RCP8.5+ SLR scenario. In no location under any SLR scenario over the next 130 years does the projected erosion extend into developed areas landward of the existing dune at Waikuku and Kairaki.

Although the results indicate that coastal erosion only likely to cause limited issues to the current dune environment in around the Waikuku area, there are other valid stability, landscape and ecology reasons to limit land use activities in the dune environment over the whole length of the district's coast. Under this approach, the back of the dune position would be considered an appropriate boundary on which to base land-use conditions to protect the dunes from inappropriate development and to protect existing and future developments from coastal erosion hazards.

The bathtub inundation mapping of the 1% AEP coastal water level with SLR indicates that least 3500 hectares and possibly up to 4700 hectares may potentially be at risk from coastal inundation in 50-years' time, due to overtopping in Kairaki Creek, the lower Kaiapoi river drain and the Waikuku Drain. Inundation areas would include settlements at Pines, Woodend Beach and Waikuku and the Kaiapoi Red zone north of the river. No inundation is shown as being sourced through the sand dunes from the open coast.

For SLR over 100-year period, inundation areas are mapped as being in the order of 5600 hectares with a 1 m SLR under RCP8.5, and 6500 hectares with a SLR of 1.36 m under RCP8.5+. Additional inundation areas of existing development at these higher SLR scenarios include central and south-east Kaiapoi to the south of the River, encroachment into west Kaiapoi sub division, Kairaki, and the east side of Pegasus. Again, no inundation is shown as being sourced through the sand dunes from the open coast with all dune areas being above run-up level of 3.6 m NZVD2016.

Under the 130 year RCP8.5+ scenario of SLR by 1.88 m, the total coastal inundation area in a 1% AEP event is mapped as being in the order of 7500 hectares, with additional inundation areas including west of SH1 at Kaiapoi in association with coastal water levels up the Kaiapoi River, and extension of inundation areas further west at Waikuku and Pegasus Township.

Given the extensive inundation areas identified by the bathtub mapping, particularly around Kaiapoi, Kairaki-Pines and Waikuku, it is recommended that further modelling with more complex hydrodynamic models be undertaken to examine the susceptibility of those areas. The additional modelling should include focus on better definition of the role of set-up on river mouth water levels, the interaction extreme sea levels with river flows particularly backwater effects during catchment flood events, the hydraulic connectivity of low-lying areas with the sea and the dynamic effects of storm tide propagation including the attenuation of flood waves in estuaries and overland flow areas.

1. Introduction

1.1 Project Background

Waimakariri District Council (WDC) as part of its review of the 2005 operative District Plan has requested technical information on the extent of future coastal erosion and sea water inundation hazards including the impacts of sea level rise and other climate change effects on coastal processes (e.g. wave climate, sediment budget). This information will help inform the District's overall approach to managing natural hazards within a multi-hazard context under the direction given in the Canterbury Regional Policy Statement (CRPS).

Chapter 8 of the 2005 Operative District Plan covers Natural Hazards. Although coastal erosion can be included under general natural hazard policies 8.1.1.1 and 8.1.1.2, and sea water inundation under flooding policies 8.2.1.1 to 8.2.1.4, they are not covered under more specific policies. This is due to coastal hazards being included in the 2005 Canterbury Coastal Environment Regional Plan (CCERP) which includes policies and rules to control development in erosion prone areas within Coastal Hazard Zones and identifies Sea Water Inundation Zones where territorial authorities may establish policies and rules. These Coastal Hazard Zones have been defined without consideration of the impacts of climate change effects on coastal erosion.

However, under the 2013 CRPS, the responsibility for specifying objectives, policies and methods for the control of land subject to coastal erosion and sea water inundation - including the cumulative effects of sea level rise over the next 100 years within greater Christchurch, which includes Waimakariri District – has been passed to operative District Plans. Therefore, WDC is now required to include these provisions in the review of its District Plan.

The existing Coastal Hazard Zones in the CCERP for the District are largely restricted to the active beach due to historical shoreline accretion and the exclusion of sea water inundation hazards in the definition of these zones. However, the extent of these zones needs to be reassessed for the impacts of sea level rise to meet the requirements of the NZCPS and the CRPS. Existing settlements potentially affected by either coastal erosion or sea water inundation include Kairaki, The Pines, Kaiapoi, Woodend Beach, Pegasus, and Waikuku.

This report documents a number of investigation that have been carried out by Jacobs to assess the extent of the existing and potential future coastal erosion and sea water inundation hazards and confirm whether or not these settlements and other identified future development areas within the coastal environment may become subject to coastal hazards over a 50 and 100-year time frame.

Jacobs understands that the ultimate objectives of this assessment to inform land use planning within the District, including control of development on land that is subject to coastal hazards, as well as the use, development and maintenance of Council-owned land and infrastructure in these areas.

1.2 Pegasus Bay Coast

As shown in Figure 1.1, the Waimakariri District has a short coast line (approximately 18km) in central Pegasus Bay between the Waimakariri and Ashley Rivers and includes the north bank of the Waimakariri River mouth environment and both banks of the Ashley River mouth.

1.2.1 Shoreline Accretion

The Waimakariri coast is part of the Holocene prograded sand wedge of southern and central Pegasus Bay, having undergone shoreline accretion over the last 10,000 years in the lee of Banks Peninsula. This progradation has been greatest at the southern end and tapers towards the northern end of Pegasus Bay where the beach changes to a mixed sand and gravel system north of Leithfield. The sediment sources that have been feeding this Holocene progradation of Pegasus Bay are generally regarded as being the Waimakariri, Ashley, Waipara and Kowhai Rivers, in descending order of importance (Hicks, 1998 compiled from numerous order authors) and Hicks *et al* (2018a) – See also section 3.6. Kirk (1979) suggested an additional major source that has now ceased as being the onshore movement of sand from the Banner Bank streaming north from the seaward tip of Banks Peninsula.

Figure 1.1: Location of Waimakariri District Council within Pegasus Bay, Canterbury

From historical survey plans and aerial photographs, this progradation has been continuing over the last 150 years for the Christchurch City and Waimakariri District coast lines, while the northern end within the Hurunui District has been retreating over the last 50 years.

For the Christchurch City Coast, from the comparison of shorelines in historical cadastral plans (1879, 1884 – MHWS position) with 1988 photographs (wetted line), Worthington (1991) presented net shoreline advance of +0.24 m/yr to +0.90 m/yr for the 100 year+ period for selected sites from South Shore to Bottle Lake Forest Park. In general, the rate of accretion increased in a northward direction along the Christchurch City coastline. A more recent analysis, Tonkin & Taylor (2017), presented the results of linear regression analysis of the dune vegetation limit from five aerial photograph dates between 1941 and 2011 which showed that all of the city's shoreline from Parklands to South Shore had experienced net dune toe accretion over the 70-year period at rates ranging from +0.1 m/yr to +0.55 m/yr. In general, the analysis showed that the highest rates of accretion have occurred at South Shore section (mean +0.44 m/yr), followed by the Parklands section (mean +0.38m/yr), with the most parts of this section (approximately 9.5 km south of the Waimakariri River) having accretion rates in excess of 0.5 m/yr. The lowest rates occurred in the North Brighton to New Brighton section (mean +0.14 m/yr) due to the presence of sea walls and dune modifications.

For the Waimakariri District coast, Worthington's (1991) study obtained the following long-term (e.g. 100 years+) accretion rates for sites within the district (See Figure 1.2 for locations). Note that the Pines Beach rate on the north side of the Waimakariri River is similar to the Bottle Lake Forest rate on the south side over the same time frame.

- Beach Rd, Pines Beach: 1857-1988: +0.89 m/yr
- Woodend Beach Rd: 1857-1984: +0.32 m/yr
- Waikuku Beach Rd: 1857-1984: +0.84 m/yr
- South side Ashley River: 1857-1984: +1.13 m/yr

Figure 1.2: Waimakariri District Coastal Features.

For the current study, as detailed further in section 3.4, linear regression analysis of dune toe vegetation at 100m longshore intervals from ten aerial photographs dating from 1941 to 2017 showed accretion rates from Kairaki to Waikuku of between 0.39 m/yr and 4.02 m/yr, and mean rate over the whole district of 2.11 m/yr. The greatest rates were to the south of Woodend Beach, decreasing northward to Waikuku. Only at access locations and immediately to the south of the Ashley River were rates less than 1 m/yr. It is noticeable that these accretion rates obtained from mapping the dune toe vegetation are considerably greater than those obtained by Worthington (1991) from mapping the MHWM (historical cadastral surveys) and wetted line on aerial photographs.

Annual ECan beach profiles since 1991, presented in Appendix A, show fore dune growth and beach accretion at all sites except PCC3340 at Waikuku Surf Club (therefore may not be representative of dune environment – see comparison with profile PCC3400). Linear regression analysis of the 3 m contour (LVD1937), taken as a proxy for the dune toe, revealed the following advance rates over the last 26 years, which support the rates obtained from the above aerial photograph analysis.

- PCC2300 (Pines Beach): 1991-2017; +1.77 m/yr
- PCC2545 North Pines: 1991-2017; +1.81 m/yr
- PCC2755 Woodend Beach: 1991-2017; +1.20 m/yr
- PCC3100 Pegasus: 1991-2017; +0.97 m/yr m/yr
- PCC3340 Waikuku Surf Club: 1991-2017; -0.09 m/yr
- PCC3400 Waikuku Dunes: 1996-2017; +1.24 m/yr

For the Hurunui District to the north of Waimakariri District, Worthington (1991) showed long-term beach accretion at Amberley Beach Rd from 1862 to 1988 at an average rate of 0.32 m/yr. However, DTec (2002, 2009), in breaking down this long-term rate found the following trend of reducing accretion changing to erosion over the last 50 years.

- 1862-1950: +0.46 m/yr
- 1950-1968: +0.19 m/yr
- 1968-1988: -0.20 m/yr
- 1991-2008: -0.82 m/yr

DTec (2002) reported a similar trend of decreasing accretion rates since the 1950's at Leithfield and Waikuku Beach settlements nearer to the centre of Pegasus Bay. However, these beaches had not converted to an erosion phase in the 1970's and 1980's.

1.2.2 Waimakariri District Coastal Characteristics

Within the Waimakairi District, there is generally a well-developed dune field behind the beach, with the location of the inferred landward limit of this dune field based on contours (2m NZVD2016), vegetation type, and development being shown in Figure 1.2. Total dune field widths from this back dune location to the 2017 vegetation line are in the order of 100-500 m. Within the dune field there are generally two to three rows of dunes running parallel to the shoreline, with the fore dune generally being well vegetated with marram grasses and the back dunes generally being covered in pine trees. Noticeable gaps in dune vegetation are restricted to historical beach access locations at Pines Beach, Woodend Beach and Waikuku Surf Club. Fore dune crest elevations are in the order of 6-10 m RL[1] , even at these access locations. Examples of beach and dune profiles from annual surveys of six ECan long-term beach monitoring sites (1991-2017) are presented in Appendix A.

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[1] RL is terms of Lyttelton Vertical Datum 1937, for which MSL is +0.165 m.

Behind the dune field, the land surface is dominated by a low lying poorly drained coastal plain with several wetlands. Although this coastal plain is pre-dominantly in agricultural production, it also features the settlements of Kairaki, The Pines, Woodend Beach, Pegasus, and Waikuku.

The Waimakariri River, at the south end of the Waimakariri District has a mouth position fixed by heavy rock protection and stopbanks at Kairaki since 1940 (Boyle, 2016). Prior to this the mouth position could fluctuate, but was generally located approximately 3km further south within the current Brooklands Lagoon. On the north bank of the river mouth, the Kairaki Creek exits to the lower river at the Waimakariri Sailing and Power Boat Club approximately 750 m upstream from the sea, and the Kaiapoi River enters the main river a further 1.8 km upstream.

The Ashley river mouth at the northern end of district is restricted by lower river stopbanks, but the entrance to the sea, which is combined with the mouth of Saltwater Water Creek, can be up to 5 km north of the main river channel. On the south side of the river mouth a 5 km long drainage network from Tūtaepatu Lagoon enters the river via a culvert approximately 950 m upstream from the ocean at Waikuku Beach.

No other water bodies exit to the sea along the Waimakariri District coast.

2. Methodology

The Coastal Hazard Mapping has been undertaken to meet the requirements of the NZCPS and the CRPS.

Policy 24 of the NZCPS provides national direction for the identification of coastal hazards, and requires hazard risks over at least 100 years be assessed with regard to the following:

(a) physical drivers and processes that cause coastal change including sea level rise;

(b) short-term and long-term natural dynamic fluctuations of erosion and accretion;

(c) geomorphological character;

(d) the potential for inundation of the coastal environment, taking into account potential sources, inundation pathways and overland extent;

(e) cumulative effects of sea level rise, storm surge and wave height under storm conditions;

(f) influences that humans have had or are having on the coast;

(g) the extent and permanence of built development; and

(h) the effects of climate change on:

  i. matters (a) to (g) above;

  ii. storm frequency, intensity and surges; and

  iii. coastal sediment dynamics;

taking into account national guidance and the best available information on the likely effects of climate change on the region or district.

The methodology used in this assessment address the hazard factors outlined above from Policy 24 of the NZCPS. This alignment allows this assessment to be consistent with not only the national policy on coastal hazard management, but also the regional policies within the CRPS that the NZCPS informs.

2.1 Coastal Erosion Hazard Mapping

Coastal Erosion Hazard Zones (CEHZ) are usually calculated from the following formula to meet the requirements of NZCPS Policy 24:

CEHZ = (LT X T) + SL + ST + DS
Where
LT = Rate of long-term shoreline movement
T = Time frame (e.g. 50 & 100 years)
SL = Sea level rise erosion over time frame for each agreed projection of sea level rise to be used
ST = Storm term storm erosion
DS = Dune stability factor

GIS is used to map the resulting CEHZ for each time frame and sea level rise projection. Manual interpretation and smoothing of the resulting zones is then applied to obtain zones appropriate for planning purposes.

Since the Waimakariri Coast has been accreting in the past, even with current SLR, the key question for the width and direction (i.e. landward or seaward) of the CEHZ zone in relation to the current shoreline position is whether and when the SLR induced beach erosion will dominant over accretion from Waimakariri sand supply. Within the 100-year time period being considered, the results could be that the accretion is merely slowed, or that the shoreline converts to a long-term erosional state.

A deterministic rather than probabilistic approach to long-term shoreline movements and sea level rise (SLR) erosion was used in this assessment, using actual measured shoreline change and accepted most likely SLR scenarios applied to average dune/beach parameters in each shoreline section to calculate SLR erosion effects. It is recognised that that there are uncertainties in the deterministic calculation of each parameter, however, to provide for an upper bound of zone width estimates, a conservative sensitivity approach was also applied, in which the combination of minimum historical accretion rate and dune/beach parameters giving the largest SLR erosion were used to calculate the most landward possible shoreline position. No probability was applied to this most landward possible position.

2.1.1 Long-term Historical Shoreline Movements

Long-term historical shoreline movements were determined from digitizing the seaward dune edge determined from dune form and vegetation limit on georeferenced aerial imagery acquired from Environment Canterbury (ECan) imagery service, captured on the following dates:

14 October 1941
7 October 1955
14 May 1963
29 October 1965
26 September 1973
1 October 1976
28 September 1984
26 November 1994
5 December 2000
24 February 2017

The seaward dune edge is considered to be an appropriate shoreline reference, being recognisable on most of the imagery and a good indicator of both landward (erosion) and seaward (accretion) shoreline movements. The digitised dune edge extent for the entire district coastline from each photograph run were captured into a geodatabase using ArcGIS. In some instances, the quality of the imagery made accurate interpretation of the vegetation line difficult, particularly in older black & white images and where vegetation cover was limited, however, the resulting expected confidence interval of the digitised dune edge position is ±5m. The resulting shoreline locations at the time of each photograph run is presented in the maps in Appendix B.

In addition to the shorelines, a constant baseline was also digitised from each photograph run, which was used in the GIS based DSAS (Digital Shoreline Analysis System) to calculate net shoreline change and linear regression rates of shoreline movements at 100 m spaced transects since 1941. A total of 162 DSAS transects were generated along the District's shoreline, with their locations being shown in maps presented in Appendix B.

A second DSAS run was carried out removing the 1941 and 1955 photographs from the analysis, as the large magnitude of observed shoreline change for the southern sections over the period up to 1963 appeared to be aided by anthropogenic influences of the stabilization of the Waimakariri River mouth, and possibly dune stabilisation planting by the former Catchment Board, therefore the resulting movement statistics are unlikely to be appropriate for use in projecting future trends.

For interpretation of the DSAS results, the transects were grouped into the following coastal sections, the location of which are shown in Appendix B, with the shoreline changes being presented as averages and minimums within each section. Since the Waimakariri coast is relatively homogenous, the sections are based on settlement locations behind the beach with the boundary locations between each section being set arbitrarily. This approach has resulted in some dis-continuities between sections for mapping future shoreline positions.

Table 2.1: Shoreline Sections used in coastal erosion hazard mapping

Shoreline Section	Section Name	DSAS transect numbers
1	Kairaki	2-11
2	Pines	12-21
3	North Pines	22-33
4	South Woodend	34-49
5	Woodend Beach	50-62
6	North Woodend	63-75
7	Pegasus Township	76-97
8	North Pegasus	98-109
9	Waikuku Township	110-119

For the most likely deterministic approach, the average DSAS transect shoreline movement in each coastal section were used in the calculation of coastal hazard zones. For the conservative sensitivity approach, the minimum individual DSAS transect shoreline movement within each coastal section was used.

2.1.2 Sea Level Rise Impacts

IPCC AR5 (2014) developed four climate change and sea level rise (SLR) projections, termed RCPs (Representative Concentration Pathways), based on different global emissions scenarios. Within each RCP, percentiles are used to quantify the distribution of the sea level rise projection with the median (50th percentile) plotted as the main curve.

Within MfE (2017) *Coastal Hazards and Climate Change: Guidance for Local Government*, four sea level rise scenarios are developed based on the 3 of the IPCC RCP scenarios (RCP2.6 – low emission, RCP4.5 – moderate then declining emissions, RCP8.5 – continuing status quo high emissions) and a higher RCP8.5+ scenario taking into account possible instabilities in the polar ice sheets. The resulting SLR projections from these scenarios extended out to 2150 and including a small additional sea level rise above the global projections to account for NZ wide regional offset in rates of historical rise are presented in Figure 2.1. The use of the RCP8.5+ projection to 2150 corresponds to the recommended minimum transitional SLR allowance in MfE (2017) to avoid hazard risk for coastal subdivisions, greenfield developments and new major infrastructure (MfE 2017, Table 12).

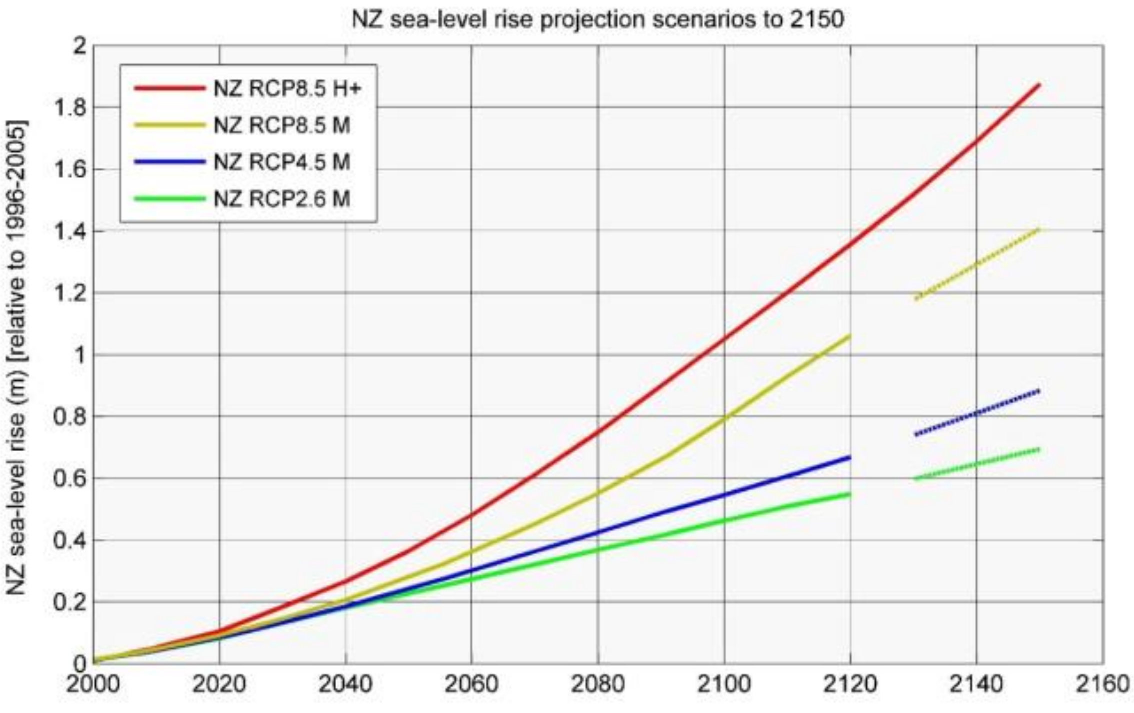

Figure 2.1: MfE(2017, Figure 27) Four scenarios of New Zealand-wide regional sea-level rise projections based on IPCC (2014)

For this assessment, the RCP4.5 and RCP8.5 and RCP8.5+ SLR projections presented in Table 2.2 are used. Since the IPCC (2014) and MfE (2017) rise figures are based on rise above a 1986-2005 baseline, the projections presented in this table and used in the assessment include a second offset of -0.05 m to bring the projected rise to being from a more recent 2015 baseline.

For simplicity, the projections to 2070 are taken as being 50 year projects, 2120 as 100 year projections, and 2150 as 130 year projections.

Table 2.2: Sea Level Rise Scenarios used in this Coastal Hazards Assessment

Scenario	**Year and time scan**	**Sea Level Rise from 2015** (-0.05 from MfE 2017 figures)
Medium NZ RCP4.5 (moderate then declining emissions)	2070 (50 years)	+0.31 m
	2120 (100 years)	+0.62 m
Medium RCP8.5 ('business-as-usual' growth in emissions)	2070 (50 years)	+0.40 m
	2120 (100 years)	+1.01 m
RCP8.5+ (83th percentile RCP8.5 to account for possible instabilities in polar ice sheets	2070 (50 years)	+0.56 m
	2120 (100 years)	+1.31 m
	2150 (130 years)	+1.83 m

The potential erosion impacts of sea level rise on sand beaches were estimated using the Bruun Rule (Bruun, 1962, 1988) geometric response model, which is considered to provide an acceptable 'order of magnitude' estimate of shoreline retreat distance due to sea level rise on sand beaches (Ramsay *et al* 2012), has been accepted in the Environment Court as a suitable precautionary approach to predict beach response to sea level rise (*Skinner v Tauranga District Council A163/02*), and was used by Tonkin & Taylor (2017) in their Christchurch Coastal Hazards assessment.

The Bruun Rule is governed by a simple two-dimension conservation of mass principle – with the volume of material eroded from the shoreline being equivalent to that required to raise the sea bed to keep pace with the rise in sea level (Figure 2.2). The rule is expressed as:

$$R = \frac{L}{B+h}\,SLR$$

Where: *R* is the shoreline retreat
L is the horizontal distance from the shoreline to the offshore position where sediment transfers between the shore and sea bed cease (e.g. where the seabed stops responding to sea level). This limit is referred to as the "closure depth".
h is the water depth at the above position where offshore sediment transfers cease.
B is the height of the berm or dune where erosion takes places, and
SLR is the magnitude of sea level rise.

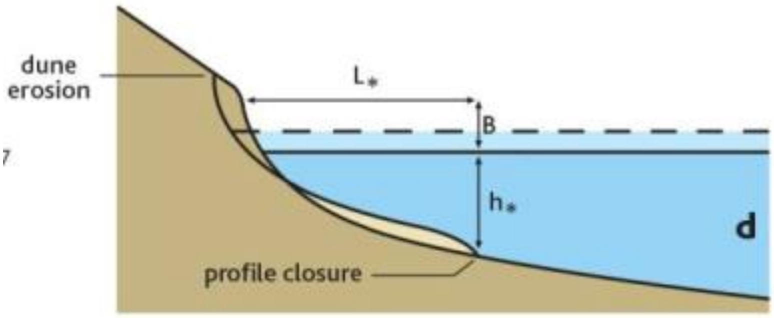

Figure 2.2: Schematic diagram of Bruun rule parameters for dune response to SLR (from Cowell and Kench 2001)

Closure depth was determined from the outer Hallermeier's limit (Hallermeier 1978) given by Hicks *et al* (2018a) for Pines Beach, which was calculated from wave statistics at the 10m depth at this site determined from 2000-2017 time-series output of SWAN modelling of the Banks Peninsula wave buoy record. Tonkin and Taylor (2017) similarly used Hallermeier's limits to calculate closure depth for the Christchurch coastal hazards study, noting that the outer limit was adopted as the upper bound, with the inner closure providing the most likely values. Therefore, it is considered that the use of the outer limit fits will provide a conservative SLR erosion estimate. The outer closure depth (D_o) at Pines Beach given as being 7.89 m below MSL (Hicks *et al*, 2018a, Table 3.6) was used at all locations along the Waimakariri coast, with distance to this depth being interpolated from LINZ bathymetric chart NZ63. Based on the comparison of wave climate at Pines Beach to Waikuku (Table 3.2), the use of a common closure depth is considered appropriate, and will again result in conservative estimates SLR induced erosion for the northern parts of the Waimakariri coast. For sensitivity, the use of the inner closure depth (5.6 m) resulted in a reduction in erosion of 5m over 100 years, and the use of a 10 m depth in an increase of 3 m over 100 years.

Dune heights were taken as the fore dune elevation at each of DSAS transects determined from LIDAR survey captured in 2014, with average and minimum elevations within each coastal section being used to calculate average and maximum SLR erosion distances respectively.

Commonly listed limitations of the Bruun Rule relevant to the Waimakariri coast include:

- Assumes no offshore or onshore losses or gains;
- Assumes an equilibrium beach profile; and

Since the Waimakariri District coast is clearly accreting as a result of sediment input from the Waimakariri River, the above assumptions suggest that the Bruun Rule results are not valid. However, this can be rectified by:

1. Discounted the rate of projected future SLR for the rate of historical rise associated with shoreline accretion rates over the period of historical assessment, so that the change in rate of SLR rise is from used rather the absolute projected rate. For this assessment the rate of historical rise discounted for was 2.54 mm/yr, being the rate of rise at Lyttelton Port since 1961 (Hannah 2016).
2. Within the CEHZ calculation, offsetting the estimated erosion from SLR by the projected future accretion from continuation of current rates. Assessment of the impact of potential future changes in the Waimakariri River supply to this coast with climate change was also carried out using the findings of Hicks *et al* (2018b) to confirm that current supply is a reasonable assumption.

2.1.3 Short-term Storm Erosion.

The assumption for inclusion of this component in Coastal Erosion Hazard Zones is that the storm resulting in this erosion will occur at or near the end of the planning time frame under consideration (e.g. 50 or 100 years), therefore the beach will not have the opportunity for recovery within the designated time frame.

Our proposal was to calculate this storm erosion component using the results of SBEACH[2] (Storm-induced BEAch CHange) numerical modelling for predicting beach, berm and dune erosion due to storm waves and water levels, generated by the 100 year ARI combined wave and water level storm sourced from Stephens *et al* (2015). However, the modelling results did not yield erosion of the beach and dune profile, therefore were not used.

Instead, the maximum horizontal retreat of the 4m contour between annual ECan beach profiles (and some more frequent surveys) was used as the mean short-term erosion component. It is recognised that as annual surveys, the magnitude of measured retreat in likely to be less that occurred in storm events, but since the 4 m contour is located on the dune scarp face, any post-storm recovery would be reduced and lagged from the erosion, so is considered a reasonable indicator of storm effects.

For sensitivity analysis of the results, a standard maximum arbitrary short-term retreat of -10 m was also applied to each coastal section. This arbitrary maximum ranged from 2 m (south Woodend) to 8.5 m (Pegasus) above the maximum survey retreat relevant to each section. As a second sensitivity test, the geometric profile model for maximum dune recession due to storm tide (Komar *et al* 1999), was also applied to the surveyed beach profiles. The results, which are recognised as being precautionary as does not account for storms being duration limited, showed 3.5 m of dune toe retreat at Pines Beach and 8 m at Waikuku. It is therefore considered that the -10m maximum storm effect as being very conservative at Pines Beach, and a reasonable conservative estimate for the steeper beaches and larger run-up experienced at Waikuku.

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[2] Larsen M & Kraus N.C 1989 SBEACH: Numerical model for simulating storm induced beach changes, Report 1: Empirical Foundation and Model Development. Technical Report CERC 89-9. US Army Corps of Engineers.

2.1.4 Dune Stability Factor

The dune stability factor delineates the area of potential slumping risk landward of a dune erosion scarp due to reduced bearing capacity from the presence of an over-steepened scarp. The additional of this component in the Coastal Erosion Hazard Zone reflects that structures should not be located within this distance of the erosion scarp at the end of the planning timeframes under consideration (50 and 100 years).

The dune stability factor was calculated by the following formula applied by Tonkin & Taylor (2017) for the Christchurch coastal hazard assessment:

$$DS = \frac{H_{dune}}{2(\tan\alpha_{sand})}$$

Where H_{dune} is the dune height from base to crest, and α_{sand} is the stable angle of repose for beach sand, which has values of 30 to 34 degrees (adopted from Tonkin & Taylor, 2017).

2.2 Coastal Inundation Hazard Mapping

Our approach to mapping of the Sea Water Inundation Areas (SWIA) involved a two pass approach, firstly using GIS to undertake "Bathtub" type inundation method that would provide a conservatively high area of potential inundation, and secondly recommending inundation areas that may require future more accurate more hydrodynamic modelling to better define sea water inundation risks.

In the "bathtub" approach, LiDAR data of the Waimakariri District coastal dune field and hinterland was acquired via the LINZ data service in the form of a one metre digital elevation model (DEM) captured in 2014. The DEM tiles were mosaicked together to form one contiguous surface in the New Zealand Transverse Mercator projection and the New Zealand Vertical Datum 2016 (NZVD2016).

For open coast locations, the current coastal water level used in the analysis was the joint probability 1% AEP level from combined storm tide (e.g. astronomical tide, storm surge & wind set-up), wave set-up (super elevation of water level close to shore due to wave breaking process) and run-up (maximum vertical extent of wave "up-rush" on a beach above storm-tide level) from Stephens *et al* (2015)[3]. The use of 1% AEP water level is consistent with the guidance in MfE (2017), being an event that is rare on an annual basis (e.g. 1% change of occurring or being exceeded in any one year), but is increasing likely over longer timeframes (e.g 63% change of occurring at least once over a 100-year timeframe). The joint probability approach is also recommended in MfE (2017) as it overcomes the potential over-prediction from treating storm surge and storm wave effects as independent components of extreme water levels (Stephens *et al*, 2015).

For the inside or estuary components of the river mouth environments, due to short fetch lengths, wave run-up and wind set-up is not considered to be significant contributions to water levels on the lower river/estuary banks, so the critical water level for inundation is a combination of storm tide, wave set-up from waves breaking on the ebb tide delta and river flow. The international literature on wave set-up effects on water levels in river entrances and estuaries suggests that the magnitude of set-up is up to 2-14% of the offshore wave height (Tanaka & Tinh, 2008; Zaki *et al*, 2015) for untrained river mouths and less for mouths entrances with training walls (Hanslow *et al*, 1996). From the components of the joint probability 1% AEP storm tide and wave set-up water levels presented by Stephens *et al* (2015) via the coastal calculator, the percentage of wave set-up to offshore wave height was 14%, hence it is considered that this level is an appropriate conservative value of extreme coastal water level entering the river mouths that is suitable for use in the first pass bathtub approach. It is noted that the literature also indicates that the wave set-up is lower for deeper estuaries, and reduces with increased magnitudes of flood flow, therefore further consideration of these input levels should be undertaken should hydrodynamic modelling be undertaken, particularly for the Waimakariri River mouth area due to the deeper bed levels and larger flood flows.

Modelled extreme lower river flood level distributions for the Waimakariri River and discussions with ECan staff indicated that coastal water levels dominated over fluvial flood levels up to Kairaki, therefore no river flood effects

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[3] Wave set-up and run-up calculated in Stephens *et al* (2015) by formula presented by Stockdon *et al* (2016).

on the mouth environment water levels are included in the bathtub modelling, with the coastal water level being extrapolated up the river channels until they intersect the bed and bank levels. However, it is recognised that the coincidence of flood flows and elevated sea levels from storm surge & large waves is possible, which may result in inundation around the mouth environment from backwater effects on the river flow. These effects could also be examined further should hydrodynamic modelling be undertaken. The lower Ashley River is steeper gradient, resulting in limited potential flood backwater effects from super-elevated coastal water levels.

For the mapping of SLR scenarios, 0.1 m increment of rise up to 1 m were run in ArcGIS using the map algebra geoprocessing tools, which essentially identified land in the dune field and coastal hinterland lower than the inundation scenario increment as being potentially inundated. Two additional scenarios of 1.36m and 1.88m were run to align with guidance from MfE (2017). All water levels were converted to NZVD2016 to tie into the DEM developed from the LIDAR data. The resulting inundation raster outputs were then converted to polygon feature classes and analysed against the NZ coastline dataset to identify those areas of inundation that are connected to the coast and those that are not.

An additional step in the analysis was carried out using WDC’s stormwater dataset in order to give some confidence to the connected inundation areas and helped to include additional areas that may have been missed in the original analysis. The principal reason for inundation not being connected in the original analysis was due to the DEM containing highpoints or bunds where water would likely flow i.e. a bridge, culvert or channel surrounded by vegetation. In these cases, the aerial imagery was used in conjunction with the council stormwater asset data, the DEM and site visit notes to identify any areas of inundation that should also be considered connected to the coast.

3. Coastal Process Inputs

3.1 Storm Tide Levels

Astronomical and storm tide levels for Waimakariri District open coast sites from the Canterbury Coastal Calculator (Stephens *et al*, 2015) are presented in Table 3.1. Since east coast locations have a monthly dominant perigean and apogean tides rather than fortnightly spring and neap tides, the mean high water perigean spring tide (MHWPS) is more relevant that the conventional MHWS for defining high astronomical tide levels, and providing a point of reference for storm tide elevations that include storm surge.

The tidal components of the water levels are based on records from the Lyttleton Harbour Tide gauge, with the storm tide distributions being calculated by a Monte Carlo Joint-Probability method (Stephens *et al*, 2015). Due to different datum's used in different reports, the tide elevations in Table 3.1 are given in terms of MSL, LVD1937 and NZVD2016.

Table 3.1: MHWPS and extreme storm tide level distributions for Waimakariri District as presented in Canterbury Coastal Calculator (Stephens *et al,* 2015).

Datum	MHWPS	%AEP (Annual Exceedance Probability)							
		63	39	18	10	5	2	1	0.5
Current MSL	1.06	1.52	1.55	1.60	1.63	1.65	1.69	1.72	1.74
LVD1937	1.22	1.68	1.71	1.76	1.79	1.81	1.85	1.88	1.90
NZVD2016	0.86	1.32	1.35	1.40	1.43	1.45	1.49	1.52	1.54
Current MSL = +0.165 LVD1937 (from Stephens *et al*, 2015) NZVD2016 = +0.356 LVD1937 (from LINZ) Current MSL = -0.191 NZVD2016									

For this assessment the 1%AEP (e.g. 100 yr ARI) storm tide level was used for base current conditions. From Table 3.1 this level is 0.66 m above the MHWPS level.

3.1.1 Sea level Rise

Sea level rise scenarios (RCP4.5, RCP8.5, RCP8.5+) consistent with mfE (2017) guidance as presented in Table 2.2 were applied to the above storm tides to obtain range of possible storm tides for 50 years (2070 projections) and 100 years (2120 projections) time frames. Addition assessment of 130-year time frame (2150) for the RCP8.5+ scenario was also undertaken.

MfE (2017) reported that projected future storm surge peaks with climate change were similar to current hindcast peaks for the majority of New Zealand including Pegasus Bay, therefore it is appropriate that the above SLR magnitudes can be added directly to the storm tides in Table 3.1.

3.2 Waves

Stephens *et al* (2015) presents a statistical extreme wave data analysis for the Canterbury coast that involved using SWAN modelling to transform 30 years (1970-2000) of hindcast of storm surge and waves at 50m water depth (WASP data) to 29 inshore locations at 10 m water depth along the Canterbury coast, including Pines Beach and Waikuku on the Waimakariri District coast. Stephens *et al* (2015) noted that the hindcast records are approaching sufficient duration to generate robust extreme wave distributions from a statistical perspective, but, these generated wave distributions typical suffer from under-prediction of the most extreme events. However, for the Canterbury data this is addressed by calibration against overlapping collected wave data from the Banks Peninsula wave buoy in 1999-2000. The resulting stimulated extreme wave heights for Pines Beach and Waikuku inshore site are presented in Table 3.2.

Table 3.2: Simulated most likely extreme significant wave height distributions along Waimakariri District coast (from Stephens *et al,* 2015)

Site	%AEP (Annual Exceedance Probability)							
	63	**39**	**18**	**10**	**5**	**2**	**1**	**0.5**
Pines Beach	2.29	2.55	2.84	3.02	3.17	3.33	3.43	3.51
Waikuku	2.25	2.48	2.72	2.87	2.98	3.11	3.18	3.24

With climate change, MfE (2017) suggest that generally an increase of 0-10% in heights of large waves (99th percentile) would apply around New Zealand out to 2100 with maximum increases on exposed west and south coasts. More specifically to Pegasus Bay, Hicks *et al* (2018b) used the SWAN modelling with future sea level and wind climate scenarios to determine 'broad-brush' potential changes in the future local wave climate. The key result was that for a 1.36 m SLR and a RCP8.5 wind climate was that the general increase in wave energy associated with SLR is substantially offset by reduction in high north-east quarter winds and therefore waves, which results in a 10% increase in northward sediment transport compared to the current baseline.

3.2.1 Wave Set-up and run-up components of water levels

Wave set-up, the temporarily increases the mean still water level at the coast due to release of wave energy in the surf zone as waves break, and wave run-up, the maximum vertical extent of wave 'up-rush' on a beach above the still-water level, are also important considerations for coastal inundation and erosion processes on the open coast, while set-up also effects water levels entering river mouth environments. Both set-up and run-up are dependent on wave characteristics (heights and period), and the beach or ebb tide bar on which the waves are breaking.

Since there is a degree of dependence of storm surge and extreme wave heights, the addition of storm tide plus wave set-up and run-up as independent components of storm sea levels are likely to result in over prediction of these levels to be used in design. To overcome this likely over prediction, the coastal run-up calculator in Stephens *et al* (2015) presents predictions of the extreme storm water levels using joint probability of extreme storm tide, wave set-up and run-up elevations. It is noted that under the joint probability the wave height producing the run-up and set-up components are a lower probability that the extreme water level (e.g. 1% AEP water level including set-up and run-up does not require 1% AEP wave heights).

The resulting most likely highest joint 1% and 2% AEP storm tide, wave set-up and run-up water levels for Pines Beach and Waikuku from Stephens *et al* (2015) coastal calculator applying the given storm beach profile gradient for each location are presented in Table 3.3. For the assessment of coastal inundation, the 1%AEP levels are used to be consistent with the recommendations in MfE (2017).

Table 3.3: Estimated most likely highest combined storm tide, wave set-up and run-up from Stephens *et al (*2015) for Waimakariri District Sites. Elevations have been converted to NZVD2016.

Site	Storm beach slope	AEP Event	Combined Water levels (ST & total in NZVD2016)								
			Storm tide + Set-up				Storm tide + Set-up + Run-up				
			Wave Height	ST	SU	Total	Wave Height	ST	SU	RU	Total
Pines Beach	1:17	1%	1.82	1.31	0.26	1.57	2.82	1.03	0.41	0.88	2.32
		2%	1.94	1.23	0.28	1.51	2.32	1.17	0.33	0.73	2.23
Waikuku	1:10	1%	2.37	1.25	0.61	1.86	2.67	1.11	0.69	1.11	2.91
		2%	2.39	1.34	0.22	1.56	2.71	1.10	0.37	0.80	2.27
Note: Add 0.356 m to NZVD2016 levels for elevations in terms of LVD1937 datum.											

It is noted that the differences in the set-up and run-up levels between the two sites is primarily due to differences in the beach slope, with foreshore slopes being steeper in the northern part of the district as shown by the profiles in Appendix A. As a result, open coast run-up is higher at Waikuku than at Kairaki, contributing to greater erosion scarps being evident along the dune toe at northern sites following storm events.

As stated in section 2.2, for river mouth locations, the storm tide + set-up levels are appropriate for defining the coastal water levels inside the mouth environment. However, given the steepness of the Waikuku beach slope, it is considered that the set-up level at Pines Beach is more appropriate for the inside of both river mouths, therefore the combined storm tide and set up levels from this site have been used at the Ashley as well as the Waimakariri mouth.

3.3 River Flood Levels and Bank Heights

Modelled extreme river flood levels supplied by ECan, converted to NZVD2016 from LVD1937, for river mouth cross sections are given in Table 3.4. The location of these cross-sections are presented in Appendix C.

Table 3.4: Lower Waimakariri and Ashley flood levels supplied by ECan. Elevations have been converted to NZVD2016.

Waimakariri River			**Ashley River**		
X-section	2% AEP (3500m^3/s)	1% AEP (4000m^3/s)	X-section	2% AEP (3000m^3/s)	1% AEP (3250m^3/s)
0.00 km	1.144	1.144	0.00 km	1.114	1.114
0.53 km	1.503	1.607	0.80 km	3.168	3.245
1.18 km	1.962	2.134	1.61 km	5.078	5.214
Note: Add 0.356 m to NZVD2016 levels for elevations in terms of LVD1937 datum.					

It is noted that for both rivers the modelled coastal water level at the mouth is a fixed level of 1.144 m NZVD2016, being around the HAT (highest astronomical tide) level, which is 0.43 m below the 1% AEP coastal water level (1.57 m NZVD2016 from storm tide + set-up) used in this assessment. It is unclear how these modelled levels would response to backwater effects from this higher coastal boundary conditions and sea level rise. However, for the Waimakariri River, ECan staff indicated that even in flood events the water levels at the mouth and in Brooklands Lagoon are determined by the coastal water levels (Tony Boyle, *pers com*). On this basis, the “bathtub” coastal inundation method involved extrapolating the 1% AEP coastal water level + SLR up the river channel without consideration of flood backwater effects. It is further noted that from the LiDAR data, river bank elevations along the mouth channel at Kairaki (0 km river cross-section) are around 0.5 m above the current 1% AEP coastal level, hence are mapped to be overtopped with SLR above this level. The banks along the east side of Kairaki Creek are lower, therefore will be overtopped in higher frequency coastal storms or lower magnitude SLR.

For the Ashley River, the flood levels at the 0.8 and 1.6 km cross-section indicate the steepest of the catchment, which in flood events results in the flow rapidly breaching the mouth spit opposite the river channel (Tony Boyle, *pers com*), and would result in minimal flood backwater effects from super-elevated coastal levels. Stopbank levels at the 0.8 km cross-section are in the order of 3.8 m NZVD2016 reducing to a minimum of 2.7 m NZVD2016 on the south bank downstream of this location, above the modelled flood levels and only susceptible to overtopping from extreme coastal water levels with SLR greater than 1m. However, land levels downstream of the northern stopbank around to Saltwater Creek are lower, resulting in potential coastal inundation in coastal storms with lower levels of SLR.

3.4 Historical Shoreline Movements

The historical shoreline positions from the aerial photograph analysis are shown in Appendix B. As can be seen from these plots there has been continuous seaward advance of the dune vegetation line over the whole the district’s coastline south of the Ashley River mouth since 1941. Table 3.5 summarises the accretion distances and linear regression rates from the DSAS for the 8-10 photograph dates used in the linear regression.

A notable feature of the results is the northward reduction in rate of accretion, with the average advance decreasing from over 2.5 m/yr at Kaikaki - Pines to around 1 m/yr at Waikuku. This trend emphasises the importance of the Waimakariri River in supplying sand to the coastal sediment budget and increasing efficiency for northward wave transport away from the mouth due to reduction in the sheltering effect of Banks Peninsula on southerly waves. It is also notable that all DSAS transects experienced accretion, with only Transect 58 at Woodend Beach access way and transects 117-119 at at the north end of Waikuku Beach adjacent to the Ashley River having retreat rates of less than 1 m/yr.

Table 3.5: Results of historical shoreline movement analysis from aerial photographs 1941 - 2017

Shoreline Section	DSAS transects	Average Advance Dist (m)	Linear Regression Advance Rates 1941—2017 (m/yr)			Avg R^2 for lin. Reg.	Avg Std Error for Lin. Reg.
			Average	Max	Min		
Kairaki	2-11	205.3	2.87	3.47	1.30	0.82	28.10
Pines	12-21	175.4	3.20	4.02	2.64	0.61	62.27
North Pines	22-33	182.8	2.52	2.81	2.20	0.90	20.33
South Woodend	34-49	171.6	2.31	2.93	2.00	0.85	23.88
Woodend Beach	50-62	148.2	2.09	2.49	0.39	0.76	26.82
North Woodend	63-75	138.3	2.11	2.59	1.71	0.86	20.72
Pegasus Township	76-97	122.1	1.69	2.42	1.45	0.81	20.24
North Pegasus	98-109	127.2	1.55	1.71	1.30	0.69	26.17
Waikuku Township	110-119	89.4	1.06	1.56	0.51	0.53	24.52

However, from the shoreline positions presented in Appendix B it is also noticeable that for 65% of the shoreline, accretion distances were considerably higher in the 1941-1963 period compared to the post 1963 rates. Except for the Pines shoreline section (where vegetation cover over a large bare fore dune area only occurred since the 1984 photograph), the sections from Woodend Beach south accreted at rates of 3 to 4 m/yr between 1941 and 1963, compared to 1-2 m/yr post 1963. These extreme 1941-1963 accretion rates are likely to be linked to fixing the mouth of the Waimakariri River in 1940 way from its more southerly historical position, and possibly dune stabilisation planting in the 1940’s and 1950’s as part of Catchment Board activities. The other area of noticeable rapid de-acceleration of shoreline advance was the northern sections of North Pegasus and Waikuku where advance rates of 3 – 4 m/yr in the 1941-1963 period have reduced to less than 1 m/yr since 1963. This is consistent with trends of shoreline movement in the Hurunui coast.

Due to likely anthropogenic influences on the historical shoreline movements in the 1940’s and 1950’s, it is considered that the 1941-1963 rates are not appropriate to extrapolate into the future within the CEHZ calculations. Therefore, a second DSAS analysis was undertaken using the 7-8 photographs since 1963 for use in the CEHZ calculations.

Table 3.6: Results of historical shoreline movement analysis for the southern sections from aerial photographs 1963 – 2017

Shoreline Section	DSAS transects	Average Advance Dist (m)	Linear Regression Advance Rates 1963-2017 (m/yr)			Avg R^2 for lin. Reg.	Avg Std Error for Lin. Reg.
			Average	Max	Min		
Kairaki	2-11	115.1	2.18	2.94	0.77	0.80	20.02
Pines	12-21	198.5	4.69	6.20	3.39	0.75	54.22
North Pines	22-33	115.6	2.06	3.56	1.62	0.91	13.49
South Woodend	34-49	71.7	1.36	2.03	1.01	0.98	3.86
Woodend Beach	50-62	56.6	1.19	1.77	0.67	0.87	8.58
North Woodend	63-75	124.0	2.42	3.27	1.20	0.87	18.77
Pegasus Township	76-97	83.3	1.67	3.34	0.60	0.81	14.51
North Pegasus	98-109	31.5	0.64	0.74	0.54	0.57	10.97
Waikuku Township	110-119	15.6	0.43	0.81	0.11	0.27	16.41

It is notable from these results that as well as reduced accretion rates, the majority of sections, except North Pegasus Waikuku had a better regression fit (e.g. higher R^2 value) that for the longer period, giving more confidence in the results from this analysis. However, it is noted that the range of accretion rates within each sections is still high, reflecting the variability in the mapping of dune toe position.

Importantly, it is also noted that the only DSAS transect to experience net erosion over this period was located at the Waikuku surf club (DSAS 114), therefore not representative of the general dune environment and excluded from consideration of the minimum shoreline movement for this shoreline section.

3.5 Dune Parameters

Table 3.7 presents the current (e.g. from 2017 aerial photographs) dune parameters required for the Bruun calculations summarised for each coastal section extracted by GIS from the LiDAR data at each of the DSAS transects. Again these results demonstrate the high degree of variability in the dune parameters within each shoreline section.

The current total dune field width from the landward 2 m contour to the seaward vegetation limit extracted by the same method is also presented in Table 3.7, with the trend of narrower dunes to the north being evident, which is constant with longshore shoreline accretion trends and hind dune removal for development at Waikuku.

Table 3.7: Current dune parameter measured by GIS from 2017 aerial photographs

Shoreline Section	DSAS transects	Foredune Elevation			Width foredune crest to sea			Total dune field width		
		Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
Kairaki	2-11	5.62	8.53	3.01	125.0	170.8	109.5	451.2	502.9	355.3
Pines	12-21	7.25	9.86	3.58	88.7	99.9	75.4	292.7	368.4	235.4
North Pines	22-33	7.73	8.48	6.43	74.6	93.0	60.1	236.5	292.7	204.4
South Woodend	34-49	6.90	8.09	4.19	88.4	104.0	75.0	258.8	332.3	216.6
Woodend Beach	50-62	7.50	9.92	6.36	93.6	209.7	71.6	223.6	260.7	103.9
North Woodend	63-75	7.77	8.63	6.72	94.6	115.1	88.4	220.3	252.5	169.8
Pegasus Township	76-97	8.32	9.65	6.93	96.9	121.1	66.7	193.5	246.6	165.4
North Pegasus	98-109	7.72	8.92	6.82	76.8	78.4	69.6	191.1	211.3	179.0
Waikuku Township	110-119	6.65	8.25	4.85	68.8	103.0	48.5	188.9	227.1	148.2

3.6 Sediment Budget

Hicks *et al* (2018a) produced an updated sediment budget for the Christchurch coast, from which the following components are relevant for a sediment budget for the Waimakariri District coast:

- Sand supply rate from the Waimakariri River: 745,000 m^3/yr
- Percentage of Waimakariri river supply transported north: 32% (86,000 m^3/yr)

Using the foredunes and beach volume gains from the ECan profiles (1991-2017), it is estimated that up to 48% of this sand supply is being retained on the beaches between the Waimakariri and Ashley Rivers.

Hicks *et al* (2018b) examined the potential effects on climate change and sea level rise over the next 100 years on the sediment supply and transport rates. The conclusions of this study for the Waimakariri coast included:

- The river's sand delivery to the coast could potentially vary between a reduction of 11% and an increase of 28%
- Sea level rise by 1.36m and change in the wave climate associated with a RCP8.5 scenario climate change would result in a small decrease (up to 5%) in sand transported southwards towards

Christchurch City beaches due to decreased north-east wave energy, therefore a corresponding increase in northward transport towards the Waimakariri coast.

- Beach closure depth is unlikely to change much under combined sea level rise and wave climate change scenarios.

Although these results demonstrate uncertainty weather the future sand supply will decrease or increase, it is considered that these results indicate that there is unlikely to be a significant reduction in future sediment supply to Waimakariri beaches, with a more likely possibility of increased supply. Therefore, the assumption of continuation of existing supply used in this assessment is considered to be valid.

4. Coastal Erosion Hazard Results

4.1 Historical Long-Term Shoreline Movements

Based on the results presented in Section 3.4, and the findings of Hicks *et al* (2018) for continued Waimakariri sediment supply, extrapolation of the historical shoreline movements since 1963 are presented in Table 4.1 for 50, 100 and 130 year periods. For a conservative approach to testing the sensitivity of the magnitude of accretion, both the average and minimum individual DSAS transect shoreline movement in each coastal section are presented. The average value representing the most likely accretion and the minimum values representing the absolute lower limit of accretion within each section which correspondingly would result in a more rapid change to erosion with SLR. For the Pines and North Woodend shoreline sections, the accelerated post 1963 accretion rates have been disregarded and the average from the two adjoining sections used instead to provide a smoother and more realistic projection of continued future accretion.

Table 4.1: Extrapolation of historical shoreline change for input into CEHZ calculations

Shoreline Section	Period	Past rate (m/yr)		Extrapolated future shoreline movement (m)					
		Average	Minimum	50 years		100 years		130 years	
				Avg	Min	Avg	Min	Avg	Min
Kairaki	1963-2017	2.18	0.77	109.0	38.5	218.0	77.0	283.1	100.1
Pines		2.12(1)	1.20(1)	106.0	60.0	212.0	120.0	275.6	156.0
North Pines	1963-2017	2.06	1.62	103.0	81.0	206.0	162.0	267.8	210.6
South Woodend	1963-2017	1.36	1.01	68.0	50.5	136.0	101.0	176.8	131.3
Woodend Beach	1963-2017	1.19	0.67	59.5	33.5	119.0	67.0	154.7	87.1
North Woodend		1.43(1)	0.63(1)	71.5	31.5	143.0	63.0	185.9	81.9
Pegasus Township	1963-2017	1.67	0.60	83.5	30.0	167.0	60.0	217.1	78.0
North Pegasus	1963-2017	0.64	0.54	32.0	27.0	64.0	54.0	83.2	70.2
Waikuku Township	1963-2017	0.43	0.11	21.5	5.5	43.0	11.0	55.9	14.3
Notes: (1) Averaged from adjoining shoreline sections.									

4.2 Sea Level Rise Effects

As indicated in Section 2.1.2, under the equilibrium profile assumption of the Bruun Rule, the historical rise in sea level already experienced over the last century should have resulted in shoreline retreat as the beach moves to a new equilibrium position with the increased sea level. However, the fact that this has not occurred on southern Pegasus Bay beaches, indicates that this coast is not in equilibrium, with the sediment supply rate from the Waimakariri River being sufficient to negate the effects of historical/current rises in sea level. As also outlined in Section 3.6, the recent NIWA sediment budget study (Hicks *et al*, 2018b) indicated that there is unlikely to be a significant reduction in future Waimakariri sediment supply to Pegasus Bay beaches. Therefore, in estimating the effect of future sea level rise on shoreline erosion we need to discount the effect by the rate of historical rise already experienced over the period of known accretion rate, and focus on the theoretical erosion effects from an increase in rate of SLR above current rates rather that the absolute projected rate of raise.

Applying a historical discount rate of 2.54 mm/yr, being the rate of rise at Lyttelton Port since 1961 (Hannah 2016), The resulting adopted rates of SLR to be used in the Bruun Rule calculations are presented in Table 4.2, with the resulting theoretical shoreline retreat distances due to SLR to 2070 calculated by the Bruun Rule for each coastal section being presented in Table 4.3, and to 2120-2150 in Table 4.4.

To account for accelerating rates of rise with time, the retreat to 2120 is calculated from the sum of retreat from the rate of rise over two periods; 2015 to 2070 and 2070 to 2120. Similarly, the retreat to 2150 is calculated by adding the retreat from the rate of rise from 2120 to 2150 to the retreat for the two periods up to 2120. For conservative sensitivity, the presented results include both the average retreat calculated from the average dune heights and dune/beach slope for each shoreline section, which are considered to be the most likely SLR effects, and the likely absolute maximum retreat distances for each shoreline section calculated from a combination of the minimum dune height and longest beach/dune distances (e.g. flattest slopes. For all calculations the closure depth used was held constant as the outer Hallermeier's limit (D_0) of 7.89 m for Pines Beach as given by Hicks *et al* (2018a).

Table 4.2: Adopted rates of SLR for Bruun Rule Calculations

RCP	Years	Projected SLR (m)	Projected Rate of SLR (mm/yr)	Historical Discount SLR Rate (mm/yr)	Adopted SLR rate for Bruun Rule Calcs (mm/yr)
RCP4.5	2015-2070	0.31	5.64	2.54	3.10
	2070-2120	0.31	6.20	2.54	3.66
RCP8.5	2015-2070	0.40	7.27	2.54	4.73
	2070-2120	0.61	12.20	2.54	9.66
RCP8.5+	2015-2070	0.52	10.18	2.54	7.64
	2070-2120	0.79	15.00	2.54	12.46
	2120-2150	0.52	17.33	2.54	14.79

Table 4.3: Theoretical shoreline erosion distances due to sea level rise to 2070 calculated by the Bruun Rule

	Shoreline Erosion Distances (m)					
	RCP4.5		RCP8.5		RCP8.5+	
Shoreline Section	Avg	Max	Avg	Max	Avg	Max
Kairaki	-8.3	-13.9	-12.7	-21.2	-20.5	-34.2
Pines	-7.4	-12.3	-11.3	-18.9	-18.2	-30.5
North Pines	-7.0	-9.3	-10.7	-14.3	-17.3	-23.0
South Woodend	-7.0	-10.9	-10.8	-16.7	-17.4	-26.9
Woodend Beach	-7.3	-10.9	-11.2	-16.7	-18.0	-26.9
North Woodend	-7.9	-10.2	-12.0	-15.6	-19.4	-25.2
Pegasus Township	-9.0	-11.9	-13.8	-18.3	-22.2	-29.5
North Pegasus	-8.0	-10.0	-12.2	-15.3	-19.6	-24.7
Waikuku Township	-8.1	-11.8	-12.4	-18.0	-20.2	-29.1

Table 4.4: Theoretical shoreline erosion distances due to sea level rise to 2120 and 2150 calculated by the Bruun Rule

	Shoreline Erosion Distances (m) with Sea Level Rise							
	2120						2150	
	RCP4.5		RCP8.5		RCP8.5+		RCP8.5+	
Shoreline Section	Avg	Max	Avg	Max	Avg	Max	Avg	Max
Kairaki	-18.1	-30.2	-38.6	-64.4	54.0	90.0	-77.8	-129.7
Pines	-16.1	-26.9	-34.3	-57.4	47.8	80.1	-69.0	-115.5
North Pines	-15.3	-20.4	-32.5	-43.4	45.5	60.6	-65.5	-87.3
South Woodend	-15.4	-23.8	-32.7	-50.6	45.7	70.7	-65.9	-101.9
Woodend Beach	-15.9	-23.8	-33.9	-50.6	47.4	70.7	-68.3	-101.9
North Woodend	-17.1	-22.3	-36.5	-47.5	50.9	66.4	-73.4	-95.7
Pegasus Township	-19.6	-26.0	-41.8	-55.5	58.4	77.5	-84.2	-111.7
North Pegasus	-17.4	-21.9	-37.0	-46.6	51.6	65.0	-74.4	-93.7
Waikuku Township	-17.7	-25.7	-37.7	-54.8	52.7	76.6	-75.9	-110.4

4.3 Short-term Storm Effects

The maximum inter-survey horizontal retreat of the 4m contour from the annual ECan beach profile record used as the mean short-term erosion component for each coastal section is presented in Table 4.5 along with the standard maximum arbitrary short-term retreat of -10 m.

Table 4.5: Estimated Mean and Maximum short erosion effects applied in CEHZ's. The mean effect is from the maximum inter-survey horizontal retreat of the 4m contour from the annual ECan beach profiles.

Shoreline Section	Mean short-term erosion (m)	Arbitrary Max short-term erosion (m)
Kairaki	-7.70	-10.00
Pines	-7.70	-10.00
North Pines	-7.70	-10.00
South Woodend	-8.00	-10.00
Woodend Beach	-3.30	-10.00
North Woodend	-2.40	-10.00
Pegasus Township	-1.50	-10.00
North Pegasus	-3.50	-10.00
Waikuku Township	-5.50	-10.00

4.4 Dune Stability Factor

Table 4.6 presents the average and maximum dune stability factors for each coastal section calculated by the equation given in Section 2.1.4 and for the range of dune heights given in Table 3.7.

Table 4.6: Average and Maximum Dune Stability Factors applied in CEHZ's.

Shoreline Section	Average Dune Stability Factor (m) (for dune slope = 32 deg)	Max Dune Stability Factor (m) (for dune slope = 30 deg)
Kairaki	-4.50	-7.39
Pines	-5.80	-8.53
North Pines	-6.19	-7.34
South Woodend	-5.52	-7.00
Woodend Beach	-6.00	-8.59
North Woodend	-6.22	-7.47
Pegasus Township	-6.66	-8.36

4.5 Coastal Hazard Erosion Zones

As set out in Section 2.1, the width of the CEHZ is calculated by:

CEHZ = (LT X T) + SL + ST + DS
Where
LT = Rate of long-term shoreline movement
T = Time frame (e.g. 50 & 100 years)
SL = Sea level rise erosion over time frame for each agreed projection of sea level rise to be used
ST = Storm term storm erosion
DS = Dune stability factor

The reference position for the calculation is usually taken as the seaward dune toe, which translates into the landward boundary of the CEHZ. For eroding coasts, this position is landward of the current dune vegetation limit, and is often used in planning documents (such as District Plans) as the setback distance for development controls. However, from the information presented in the above sections for the Waimakariri coast, the most likely projections are that continued accretion at current rates of sand supply from the Waimakariri River will be sufficient to dominant over the erosion required to achieve beach and nearshore profile equilibrium under SLR. Therefore, the CEHZ widths are positive distances seaward of the current dune vegetation limit.

Although the CEHZ's include consideration of the short-term and dune stability factors, for the following discussion the zone widths are referenced as projecting distances of shoreline movements, of which a maximum of 20 m erosion would be due to these two parameters.

4.5.1 50-year CEHZ Widths to 2070

The resulting CEHZ widths for the close to 50-year period for the SLR scenarios to 2070 are given in Table 4.7. As per the conservative approach to testing the sensitivity of the zone widths, both the average (most likely) and absolute minimum CEHZ widths are presented in the Table. The position of the calculated CEHZ relative to the current dune vegetation limit (2017) in each shoreline section for the more extreme RCP8.5 and RCP8.5+ SLR scenarios are shown in Appendix D. As noted in section 2.1.1, the averaging of results within shoreline sections has resulted in some dis-continuities between sections for mapping of the CEHZ positions.

Table 4.7: Average (most likely) and Minimum CEHZ widths to 2070 (50 years).

	50 year CEHZ widths (m)					
	RCP4.5 (SLR 0.31m)		**RCP8.5 (SLR 0.4 m)**		**RCP8.5+ (SLR 0.56 m)**	
Shoreline Section	**Avg**	**Min**	**Avg**	**Min**	**Avg**	**Min**
Kairaki	88.4	7.2	84.0	-0.1	76.2	-13.1
Pines	85.1	29.1	81.2	22.6	74.3	11.0
North Pines	82.1	54.3	78.4	49.4	71.8	40.6
South Woodend	47.4	22.6	43.7	16.8	37.1	6.6
Woodend Beach	42.9	4.0	39.0	-1.7	32.2	-12.0
North Woodend	55.0	3.8	50.9	-1.6	43.5	-11.2
Pegasus Township	66.3	-0.3	61.6	-6.6	53.1	-17.8
North Pegasus	14.4	-0.7	10.2	-6.0	2.7	-15.4
Waikuku Township	2.6	-23.4	-1.7	-29.7	-9.3	-40.8

The average results of positive CEHZ widths relative to the dune tow position indicate that the dominance of Waimakariri River sediment supply over SLR erosion will most likely continue over this 50-year time period under all SLR scenarios including an addition rise of 7.64 mm/yr (0.56 m) under the RCP8.5+ scenario. Accretion will be reduced from rates experienced over the last 50 years, but is projected to continue in the order of 70-90 m (1.4-1.8 m/yr) up to 3km north of the river mouth (Kairaki to North Pines sections), and 30-60 m (0.6 -1.2 m/yr) for the Woodend to Pegasus township areas. For the northern areas (North Pegasus and Waikuku), the most likely shoreline advance is projected to be much lower, at around 2-15 m (up to 0.3 m/yr) over the 50-year period.

Applying the absolute minimum accretion and maximum SLR effects, the worst case CEHZ would still be positive to the South of Woodend, but convert to negative widths (e.g. erosion) in north from Pegasus under the RCP4.5 scenario, and north from Woodend Beach under RCP8.5 and RCP8.5+ scenarios. Apart from Waikuku, the projected erosion distances are generally as a result of the short-term erosion and dune stability factors, whereas at Waikuku dune erosion of around 20 m is projected to occur due to dominance of SLR erosion over Waimakariri sand supply accretion resulting in the Waikuku Surf Club being in the CEHZ.

4.5.2 100-year CEHZ Widths to 2120

The resulting CEHZ widths for the 100-year period for the SLR scenarios to 2120 and 130 years to 2150 are given in Table 4.8. As per the conservative approach to testing the sensitivity of the zone widths, both the average (most likely) and absolute minimum (or negative) CEHZ widths are presented in the Table. The position of the CEHZ relative to the current dune vegetation limit (2017) for the more extreme RCP8.5 and RCP8.5+ SLR scenarios to 2120 is shown in Appendix E, with the same discontinuities between shoreline sections as discussed in section 4.5.1.

Table 4.8: Average (most likely) and Minimum CEHZ widths to 2120 (100 years) and 2150 (130 years)

	CEHZ widths (m)							
	To 2120						To 2150	
	RCP4.5		RCP8.5		RCP8.5+		RCP8.5+	
Shoreline Section	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**	**Avg**	**Max**
Kairaki	187.5	29.4	167.0	-4.8	151.6	-30.4	193.1	-47.0
Pines	182.4	74.5	164.2	44.1	150.7	21.3	193.1	22.0
North Pines	176.8	124.3	159.6	101.3	146.7	84.1	188.4	105.9
South Woodend	107.1	60.2	89.7	33.4	76.8	13.3	97.4	12.4
Woodend Beach	93.8	24.6	75.8	-2.2	62.3	-22.3	77.1	-33.4
North Woodend	117.3	23.2	97.9	-2.0	83.4	-20.9	103.8	-31.3
Pegasus Township	139.2	15.6	117.0	-13.8	100.4	-35.9	124.7	-52.1
North Pegasus	37.0	14.4	17.4	-10.3	2.7	-28.7	-0.9	-41.3
Waikuku Township	14.5	-31.9	-5.5	-61.0	-20.5	-82.7	-30.8	-113.2

As with the 50-year results, the most likely future under all 100-year SLR scenarios is for continued accretion from Waimakariri River sediment supply dominating over SLR induced erosion in the southern shoreline sections with shoreline advance in the Kairaki – North Pines projected to be up 150 m (average 1.50 m/yr) even under the extreme RCP8.5+ SLR scenario. But, at Waikuku, the CEHZ is projected to most likely be the range of 5-20 m landward of the existing dune vegetation position depending on the magnitude of SLR experienced over this 100-year time frame. This erosion distance is due to the inclusion of the short-term and dune stability parameters in the CEHZ, and in the context of the total dune width, is low level (in the order of 2 - 10% of the average width (189 m), or 3 - 14% of the minimum width (148 m)). Even accounting for these factors, would still be a minimum dune width of over 100 m outside of the CEHZ across the whole township frontage

For the absolute minimum accretion and maximum SLR effects, the pattern of the results are similar to those over 50 years, with the CEHZ converting to negative widths (e.g. erosion of the fore dune) in the northern part of the district under the RCP4.5 scenario, and from Woodend Beach to Waikuku under RCP8.5 and RCP8.5+ scenarios. However, the greater negative zone widths reflect the potential for maximum SLR erosion to dominant over minimum continued accretion. At Waikuku, maximum CEHZ widths into the dunes of over 80 m is projected under RCP8.5+ SLR scenario, which would account for 40 - 55% of the total dune field width, and leave less 100 m dune width at some locations.

It is also noted that in plan shape, the projected shoreline changes of +150 m at the southern end and -20 m at the northern end, would result in a slight shift in beach orientation to be more easterly, which it occurred could influence longshore sand transport rates. Consideration of whether coastal process would result in this re-orientation of the shoreline actually occurring is beyond the scope of this investigation.

4.5.3 130-year CEHZ Widths to 2150

As indicated in Section 2.1.2 the 130 year projections under the RCP8.5+ SLR scenario corresponds to the recommended minimum transitional SLR allowance in MfE (2017) to avoid hazard risk for coastal subdivisions, greenfield developments and new major infrastructure. As presented in Table 4.8, and shown on the maps in Appendix F, the resulting most likely CEHZ widths under this projection are for continued accretion from

Waimakariri sand supply in the south of the district and erosion north from Woodend Beach. At Waikuku the most likely CEHZ position is mapped to be in the order of 30 m landward of the current dune edge position, of which 60% is accounted for by short-term erosion effects and dune stability parameter. For the worst case scenario (e.g. minimum accretion and maximum SLR effect), the erosion distances are estimated to be up to 100 m, which would be 60-75 % of the current total dune width. Under this scenario the CEHZ would be very close to existing residential developments at DSAS transects 117 and 118.

4.5.4 Sediment Budget Check

To provide a check on the above shoreline movement projections, a future sediment budget assessment from Hick *et al* (2018b) was also undertaken to calculate the sea level rise required for a stable shoreline to occur. As presented by Hicks, the equation of this to occur is:

$$S=Q_sT_eP_s/BL$$

Where S is SLR (m/yr), Q_s is Waimakariri River sediment supply (m^3/yr), T_e is the beach trapping efficiency, P_s is the percentage of longshore transport supply to the north, B is longshore length of coast (12 km), and L is the cross shore width from crest of dune to closure depth.

The results of these check calculations applying continuation of the existing Q_s, T_e, and P_s values from section 3.6, along with the maximum and minimum values for Q_s and P_s from Hicks *et al* (2018b) are presented in Table 4.9.

Table 4.9: Sea level rise required for stable shore from sediment budget approach

	River Supply (Qs) (mill m^3/yr)	Trapping Efficiency (Te)	North Longshore Trans (Ps)	Shore length (B) (km)	Cross shore Width (L) (m)	Rate of SLR for stability (mm/yr)
Average Conditions	0.744	0.48	0.32	12.0	725	**13.11**
Minimum Conditions	0.656	0.48	0.38	12.0	771	**9.53**
Maximum conditions	0.953	0.48	0.39	12.0	535	**27.78**

These results indicate that averaged over the whole district shoreline over a 100-year period, erosion will only begin to occur with minimum projected future sand supply erosion as SLR approaches 0.95 m, similar to RCP8.5 projected rise. For most likely supply rates, erosion should only begin to occur in 100 years under the RCP8.5+ scenario, and for maximum projected supply rates, sometime well beyond 2150.

Although these results are generalised for the whole district's coast, they confirm the findings from the shoreline movement projections that sediment supply from the Waimakariri River will most likely continue to dominant over shoreline erosion as a result of SLR for the majority of the next 100 years.

4.5.5 Dune Width Approach to Land Use Zone

Although the above results indicate that coastal erosion over the next 100 years is only likely to cause limited issues to the current dune environment in around the Waikuku area, there are other valid stability, landscape and ecology reasons to limit land use activities in the dune environment over the whole length of the district's coast. Under this approach, the back of the dune position as shown in Appendix D is considered an appropriate boundary on which to base land-use conditions to protect the dunes from inappropriate development and to protect existing and future developments from coastal erosion hazards.

5. Coastal Inundation Hazard Results

As detailed in section 2.2, the coastal inundation mapping combines the 1% AEP sea level with the projected SLR. For river mouths the 1% AEP sea level is the joint probability storm surge and set-up, while for the open coast the run-up is also included. The values for these water levels are as follows (from Table 3.3)

- 1% AEP Joint Probability Storm Tide + Set-up: 1.57 m NZVD2016 (for river mouths)
- 1% AEP Joint Probability Storm Tide + Set-up + Run-up: 2.32 m NZVD2016 (for open coast)

SLR increments of 0.1m are added to these levels for the bathtub inundation mapping. Three types of areas were mapped:

- Those areas below the water levels that are definitely connected to the open coast or river mouth
- Those areas below the water levels that are likely to be connected to the open coast or river mouth but require further work for this to be confirmed.
- Those areas below the water levels that are not connected to the open coast or river mouth, therefore while may be subject to poor drainage and high ground water levels, any inundation will not be from a marine source.

5.1 2070 Sea Level Rise Results

The range of projected SLR rise over the next 50-year to 2070 considered for this assessment is 0.31 m (RCP4.5) to 0.56 m (RCP8.5+). The bathtub inundation mapping for increments of SLR from 0.3 to 0.6 m combined with the 1% AEP sea levels are presented in Appendix G.

The mapping identifies that the majority of the coastal inundation is on the low lying areas between Kairaki/Pines and Kaiapoi, from water entering Kairaki Creek and the drain on the lower Kaiapoi River just upstream from the confluence with the Waimakariri. Settlements at Pines, Woodend Beach and Waikuku and the Kaiapoi Red zone north of the river are shown as being at risk of some level of coastal inundation during a 1% AEP coastal event under all 50-year SLR scenarios.

A further area of low lying land to the north-west of Kaiapoi, including SH1, is projected to be influenced by coastal inundation once SLR reaches 0.5 m. Coastal inundation in the central and northern parts of the district appear to be sourced from drain into the Ashley Mouth at Waikuku, and from Saltwater Creek to the north of the Ashley River. No inundation is shown as being sourced through the sand dunes from the open coast.

The total land area in each inundation class for the different SLR increments are presented in Table 5.1. The results show similar coastal inundation area for SLR of 0.3 m and 0.4 m under RCP4.5 and RCP8.5 respectively, but over 1000 hectares increase for SLR of 0.5 m under RCP8.5+. The depth of inundation across this addition area would be a maximum of 0.1 m.

Table 5.1: Coastal Inundation areas for a 1 % AEP coastal storm with 50-year SLR projections

	Resulting 1%AEP storm Tide + set-up water level (NZVD2016)	Coastal Inundation Areas (hectares)		
SLR Increment		Coastal Connection	Likely Coastal Connection	Below water level but no coastal connection
0.3 m	1.87	3423.588	168.4725	1026.051
0.4 m	1.97	3616.108	190.2535	1074.524
0.5 m	2.07	4768.812	229.9482	532.3295
0.6 m	2.17	4768.812	229.9482	532.3295

5.2 2120 Sea Level Rise Results

The range of projected SLR rise over the next 100-year to 2120 considered for this assessment is 0.6 m (RCP4.5), 1.01 m (RCP8.5) and 1.36 m (RCP8.5+). The bathtub inundation mapping for this range of SLR combined with the 1% AEP sea levels are presented in Appendix H, and the total land area in each inundation class for the different SLR levels are presented in Table 5.2.

Table 5.2: Coastal Inundation areas for a 1 % AEP coastal storm with 100-year SLR projections

	Resulting 1%AEP storm Tide + set-up water level (NZVD2016)	Coastal Inundation Areas (hectares)		
SLR Increment		Coastal Connection	Likely Coastal Connection	Below water level but no coastal connection
0.6 m	2.17	4768.812	229.9482	532.3295
1.0 m	2.57	5665.303	1.1125	462.3426
1.36 m	2.93	6487.736	2.2054	315.6655

The results indicate that approximately another 1000 hectares of land will be subject to coastal inundation for each of the SLR scenarios, with a corresponding drop in the likely and non-connected areas as water levels increase. There would also be corresponding increasing inundation depths with higher sea levels. Additional inundation areas of existing development at these higher SLR scenarios include central and south-east Kaiapoi to the south of the River, encroachment into west Kaiapoi sub division, Kairaki, and the east side of Pegasus. The banks around the Kaiapoi waste water treatment ponds are shown as being of sufficient height to prevent inundation of the ponds.

No inundation is shown as being sourced through the sand dunes from the open coast with all dune areas being above run-up level 3.6 m NZVD2016.

5.3 2150 Sea Level Rise Results

The coastal inundation from the 130-year SLR scenario to 2150 mapped in Appendix I is for the most extreme RCP8.5+ scenario to comply with the recommendations in MfE (2017) for new subdivisions and greenfield developments. The mapping indicates that at this sea level nearly 7,500 hectares will be subject to coastal inundation in a 1% AEP coastal event, an increase of approximately 1000 hectares of the 100-year inundation under the same SLR scenario. Additional inundation areas include west of SH1 at Kaiapoi in association with coastal water levels up the Kaiapoi River, and extension of inundation areas further west at Waikuku and Pegasus Township.

5.4 Further Modelling Recommendations

Given the extensive inundation areas identified by the bathtub mapping, particularly around Kaiapoi, Kairaki-Pines and Waikuku, it is recommended that further modelling with more complex hydrodynamic models be undertaken to examine the susceptibility of those areas. The additional modelling should include focus on better definition of the role of set-up on river mouth water levels, the interaction extreme sea levels with river flows particularly backwater effects during catchment flood events, the hydraulic connectivity of low-lying areas with the sea and the dynamic effects of storm tide propagation including the attenuation of flood waves in estuaries and overland flow areas.

6. Conclusions

6.1 Coastal Erosion

The CHEZ mapping indicates that for the majority of the district's coastline, the continued Waimakariri River sand supply will dominate over SLR induced erosion for over 100 years under all SLR scenarios. Only at the northern end around Waikuku would a CEHZ be required to be located landward of the existing dune vegetation limit, and then only most likely by around 20 m under the most extreme RCP8.5+ SLR scenario. Maximum 100-year retreat under this scenario is projected to be around 80 m, and up to 115 m by 2150.

In no location under any SLR scenario over the next 130 years does the projected erosion extend into developed areas landward of the existing dune at Waikuku and Kairaki.

Although the results indicate that coastal erosion only likely to cause limited issues to the current dune environment in around the Waikuku area, there are other valid stability, landscape and ecology reasons to limit land use activities in the dune environment over the whole length of the district's coast. Under this approach, the back of the dune position would be considered an appropriate boundary on which to base land-use conditions to protect the dunes from inappropriate development and to protect existing and future developments from coastal erosion hazards.

6.2 Coastal Inundation

The bathtub inundation mapping of the 1% AEP coastal water level with SLR indicates that least 3500 hectares and possibly up to 4700 hectares may potentially be at risk from coastal inundation in 50-years' time, due to overtopping in Kairaki Creek, the lower Kaiapoi river drain and the Waikuku Drain. Inundation areas would include settlements at Pines, Woodend Beach and Waikuku and the Kaiapoi Red zone north of the river. No inundation is shown as being sourced through the sand dunes from the open coast.

For SLR over 100-year period, inundation areas are mapped as being in the order of 5600 hectares with a 1 m SLR under RCP8.5, and 6500 hectares with a SLR of 1.36 m under RCP8.5+. Additional inundation areas of existing development at these higher SLR scenarios include central and south-east Kaiapoi to the south of the River, encroachment into west Kaiapoi sub division, Kairaki, and the east side of Pegasus. Again, no inundation is shown as being sourced through the sand dunes from the open coast with all dune areas being above run-up level of 3.6 m NZVD2016.

Under the 130 year RCP8.5+ scenario of SLR by 1.88 m, the total coastal inundation area in a 1% AEP event is mapped as being in the order of 7500 hectares, with additional inundation areas including west of SH1 at Kaiapoi in association with coastal water levels up the Kaiapoi River, and extension of inundation areas further west at Waikuku and Pegasus Township.

Given the extensive inundation areas identified by the bathtub mapping, particularly around Kaiapoi, Kairaki-Pines and Waikuku, it is recommended that further modelling with more complex hydrodynamic models be undertaken to examine the susceptibility of those areas. The additional modelling should include focus on better definition of the role of set-up on river mouth water levels, the interaction extreme sea levels with river flows particularly backwater effects during catchment flood events, the hydraulic connectivity of low-lying areas with the sea and the dynamic effects of storm tide propagation including the attenuation of flood waves in estuaries and overland flow areas.

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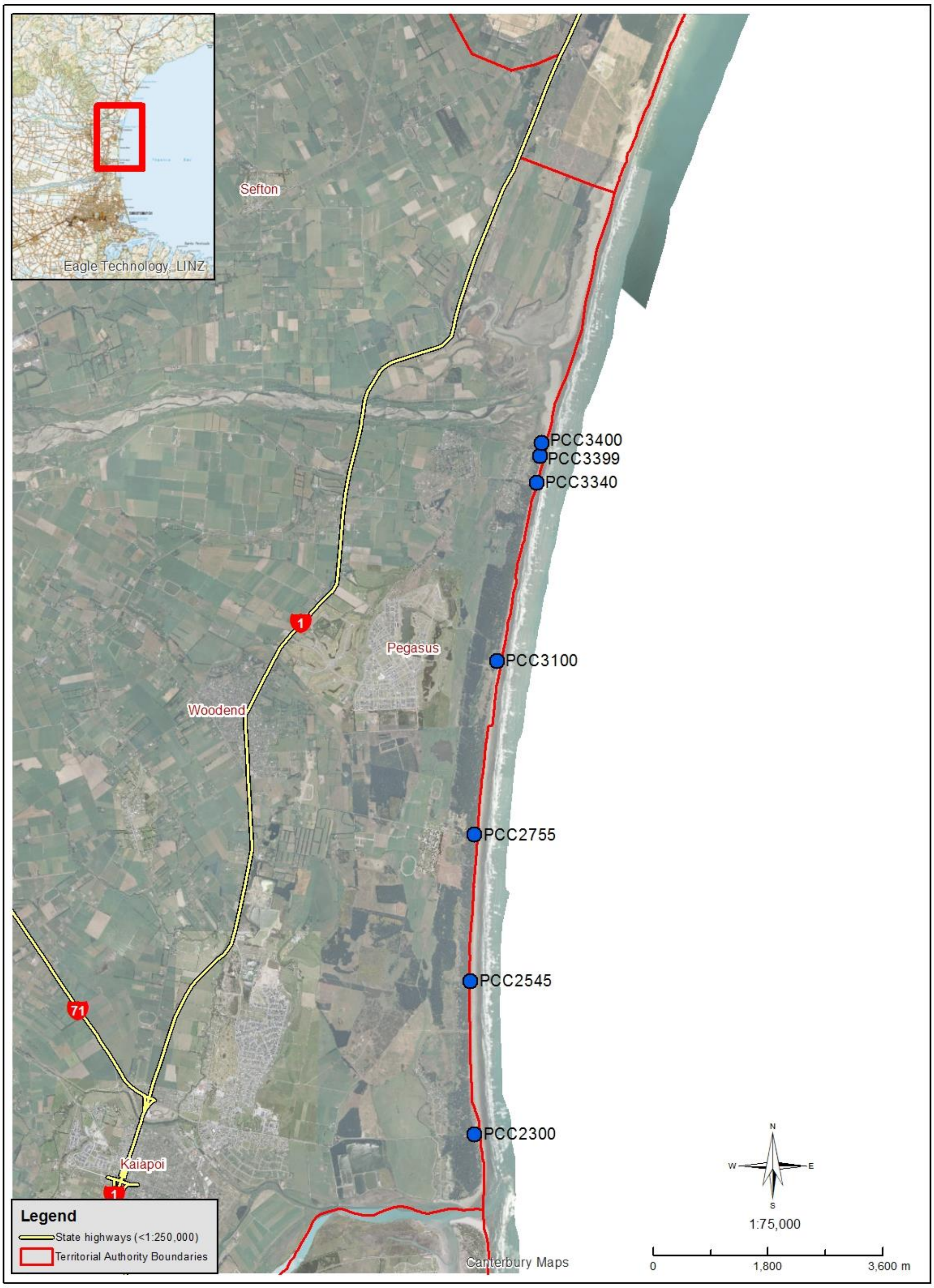
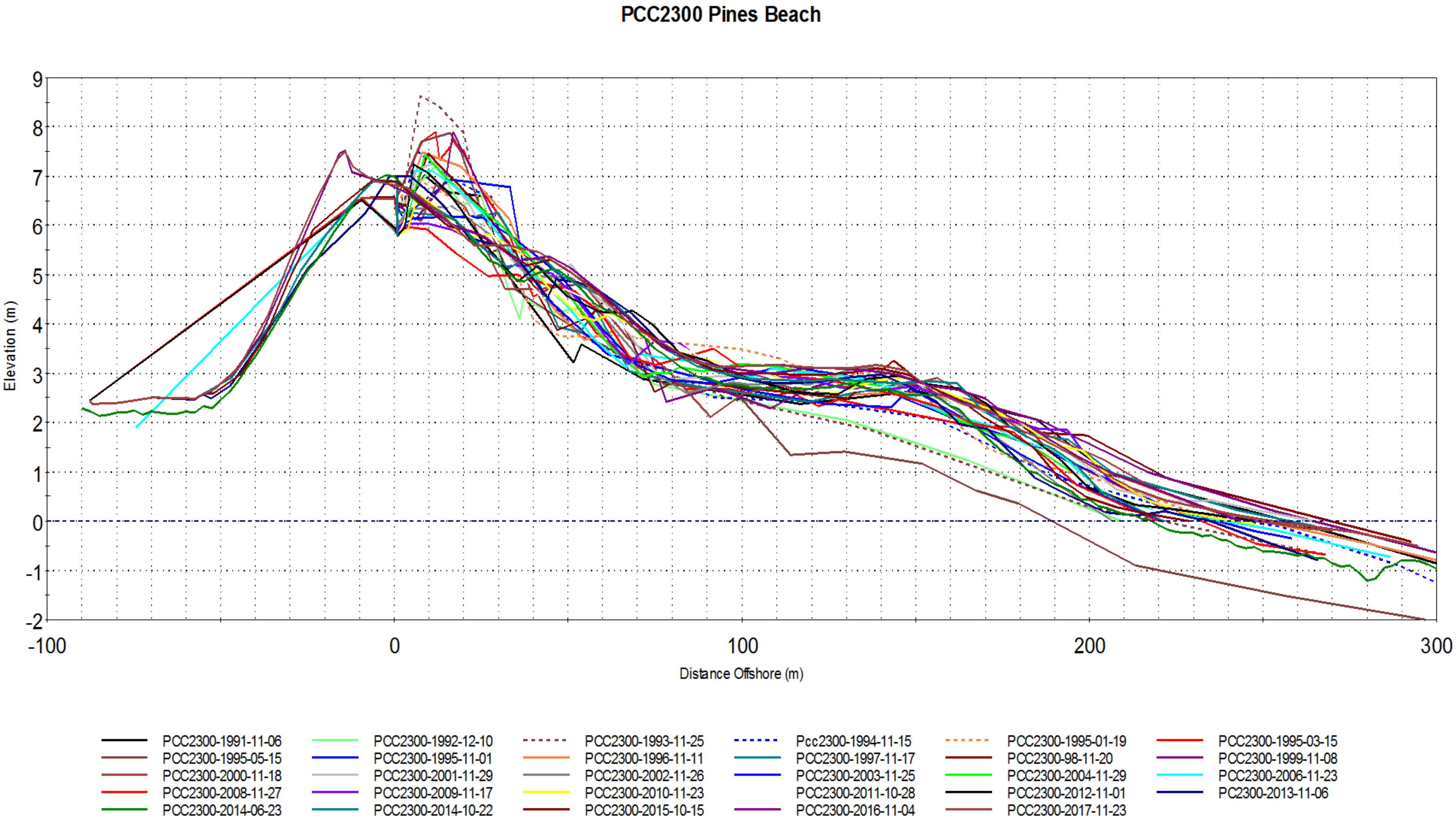
Zaki *et al* (2015) 2_D investigation of river flow on wave setup in estuaries. 22nd Australasian Coastal and Ocan Engineering Conference, Sydney, 2015 p578-581.

Appendix A: Beach and dune profiles from ECan Monitoring sites

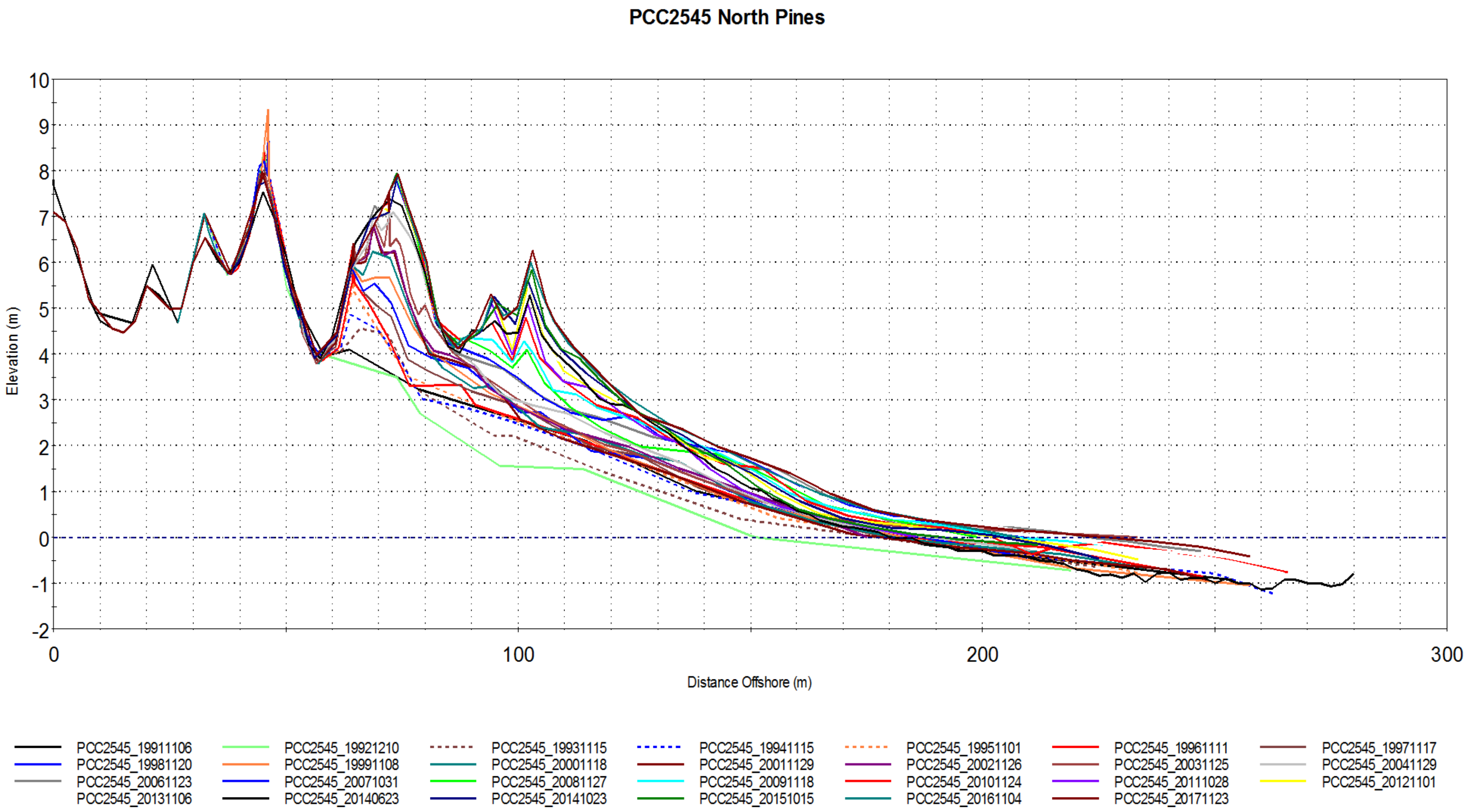


Environment Canterbury coastal monitoring sites within Waimakariri District

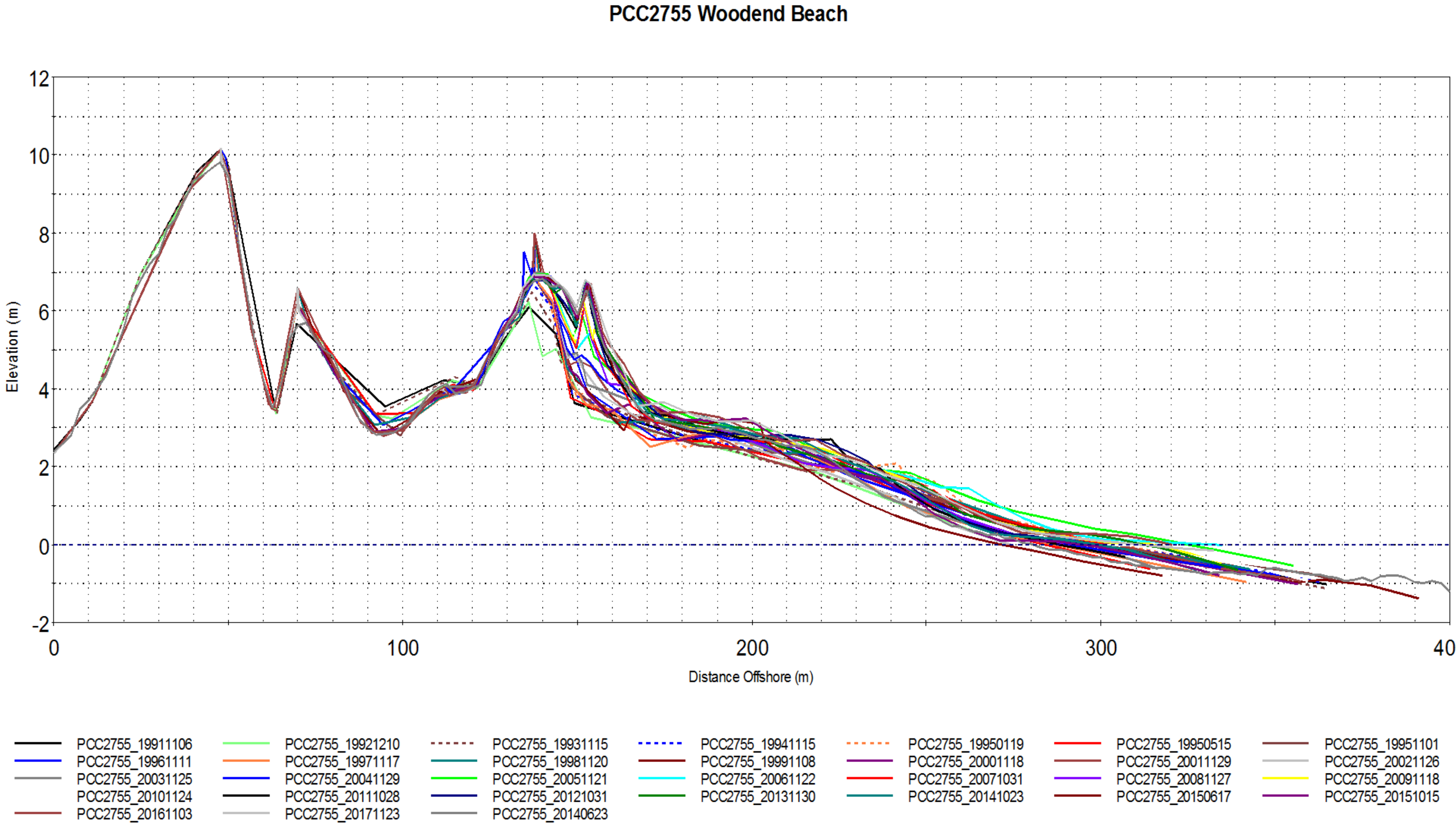


Elevations are in terms of LVD1937

Elevations are in terms of LVD1937



Elevations are in terms of LVD1937



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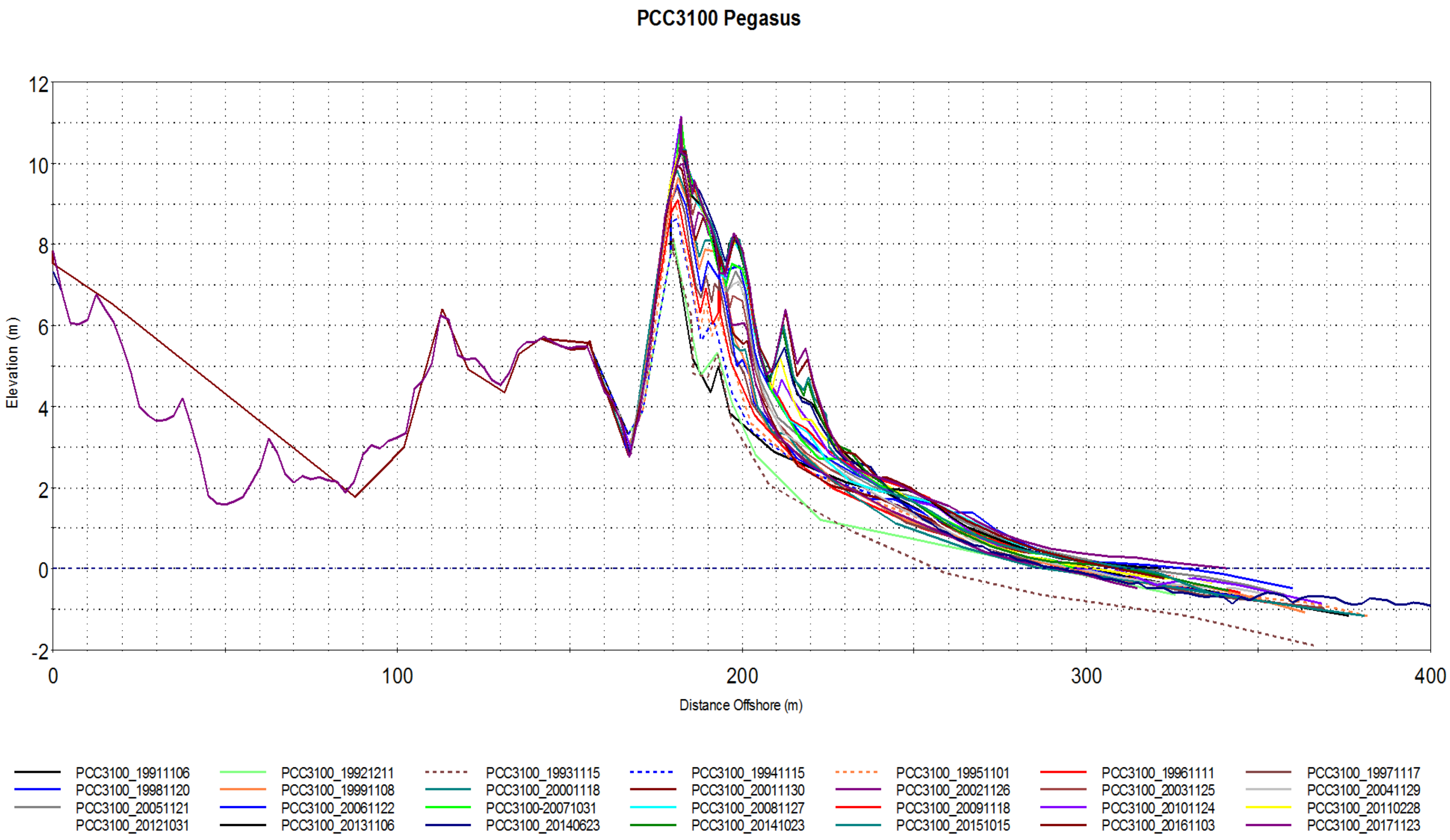

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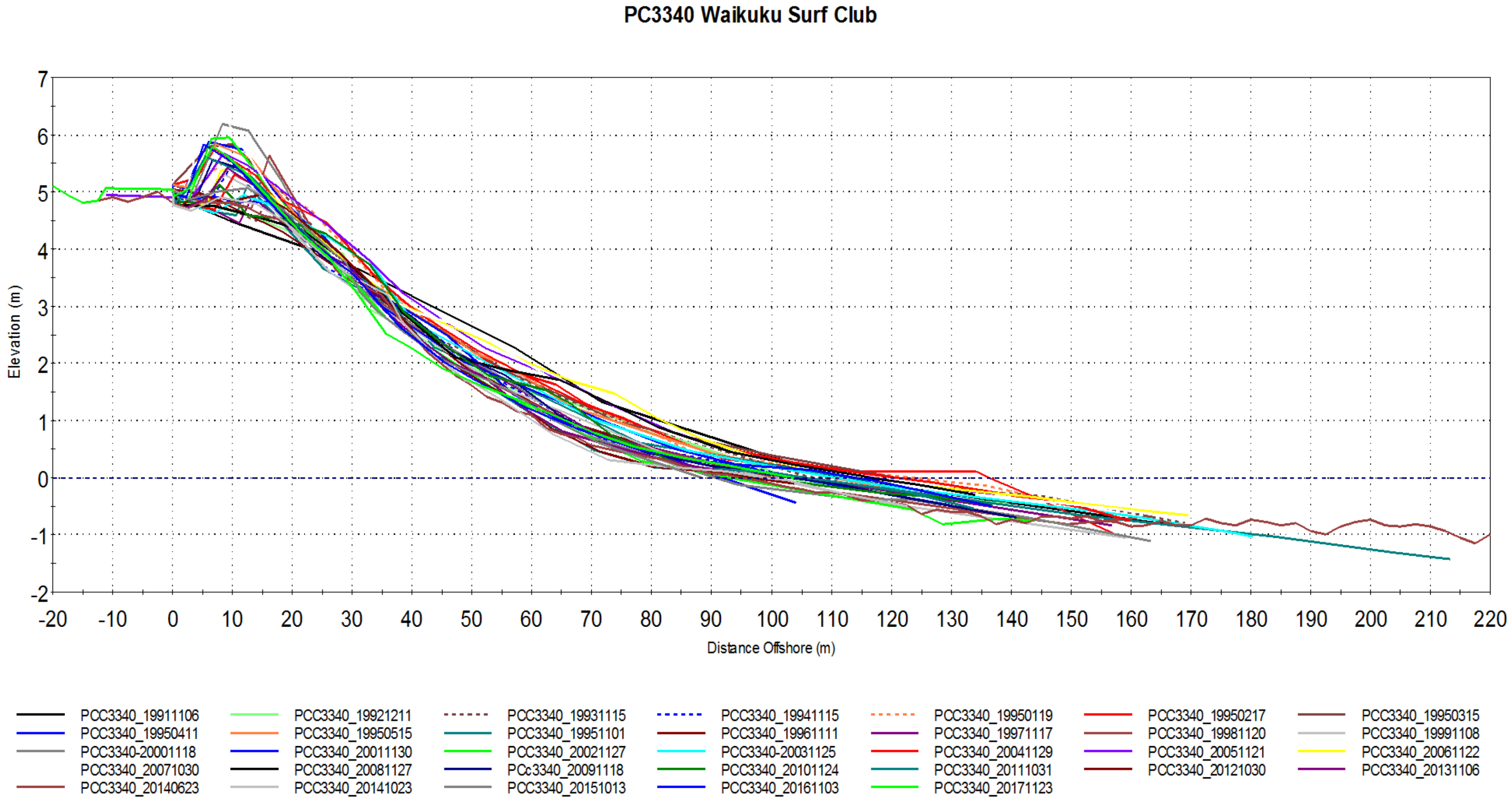
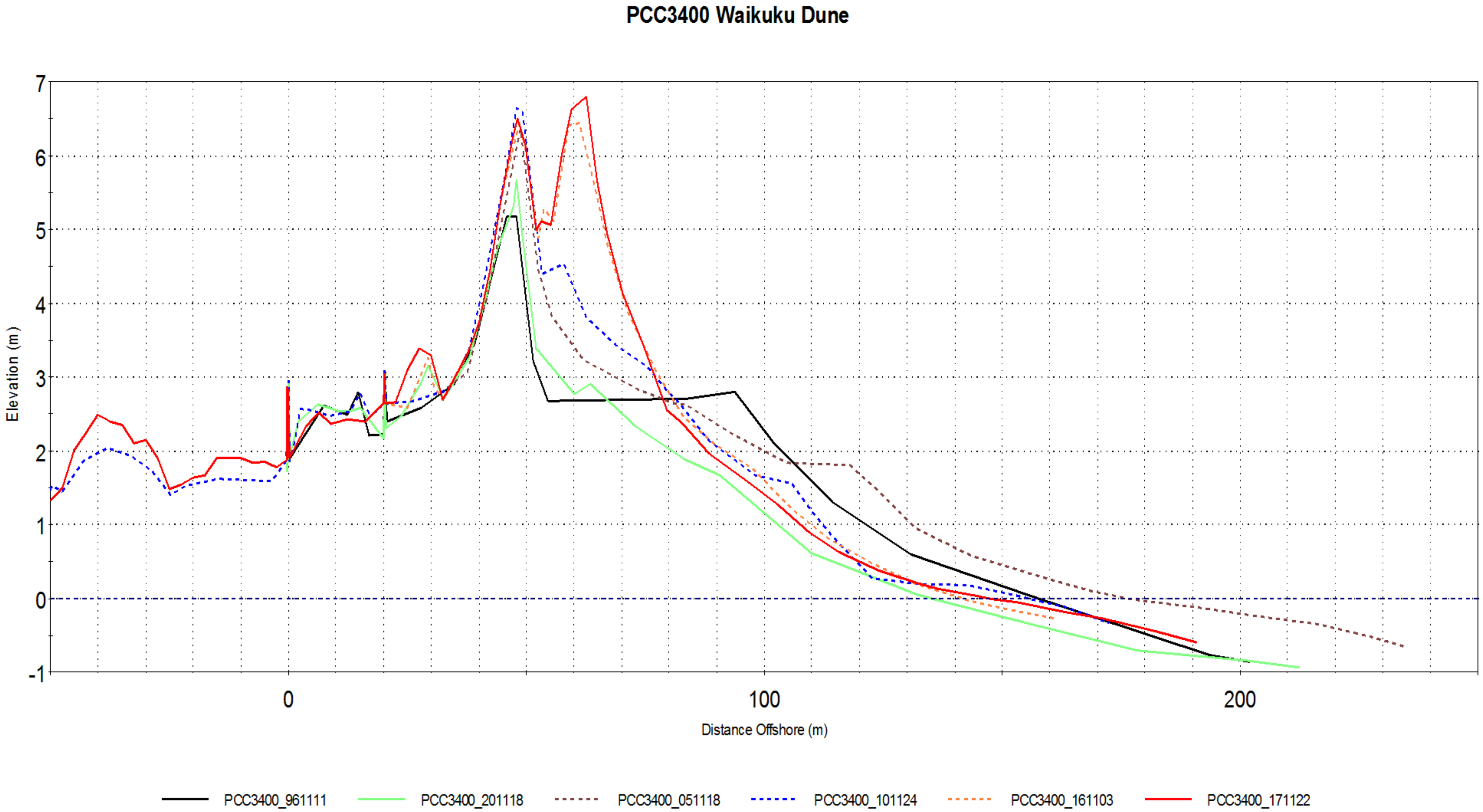
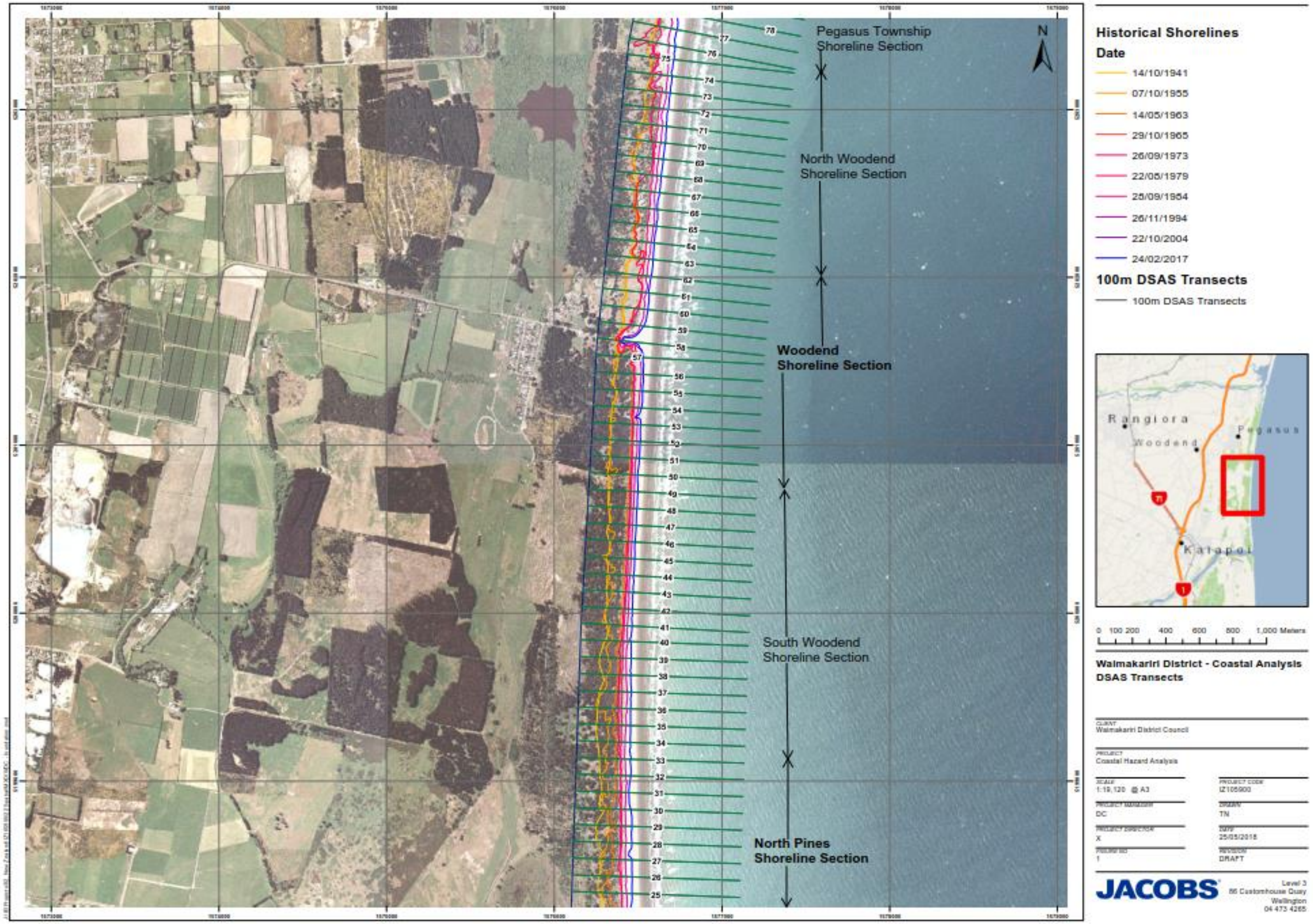


Elevations are in terms of LVD1937



Appendix B: Historical shoreline and DSAS transect locations


Pegasus Township Shoreline Section
North Woodend Shoreline Section
Woodend Shoreline Section
South Woodend Shoreline Section
North Pines Shoreline Section
N
78
77
76
75
74
73
72
71
70
69
68
67
66
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64
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62
61
60
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46
45
44
43
42
41
40
39
38
37
36
35
34
33
32
31
30
29
28
27
26
25
Historical Shorelines
Date
14/10/1941
07/10/1955
14/05/1963
29/10/1965
26/09/1973
22/05/1979
25/09/1984
26/11/1994
22/10/2004
24/02/2017
100m DSAS Transects
100m DSAS Transects
Rangiora
Woodend
Pegasus
Kaiapoi
71
1
0 100 200 400 600 800 1,000 Meters
Waimakariri District - Coastal Analysis
DSAS Transects
CLIENT
Waimakariri District Council
PROJECT
Coastal Hazard Analysis
SCALE
1:19,120 @ A3
PROJECT CODE
IZ105900
PROJECT MANAGER
DC
DRAWN
TN
PROJECT DIRECTOR
X
DATE
25/05/2018
FIGURE NO
1
REVISION
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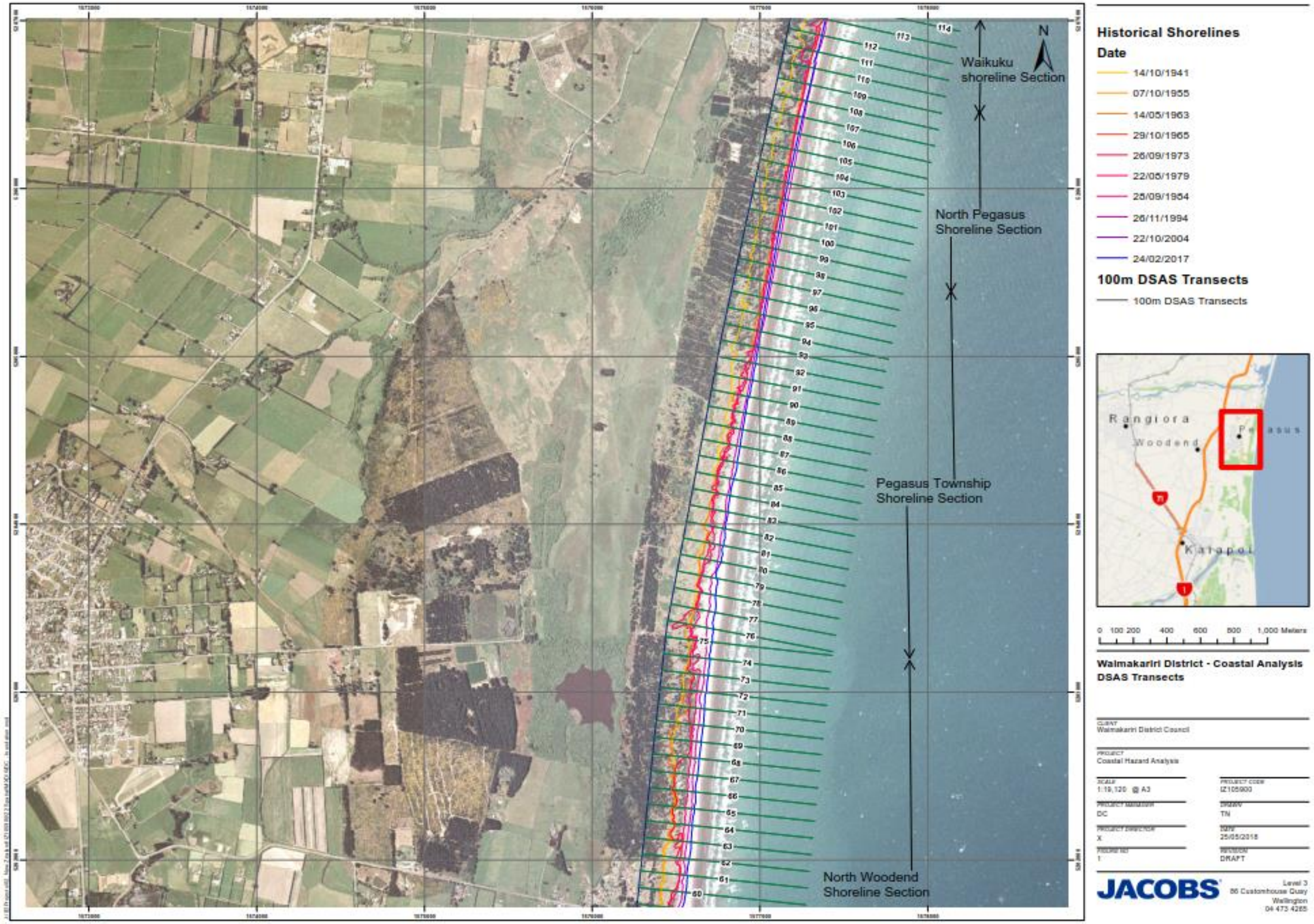
Level 3
86 Customhouse Quay
Wellington
04 473 4265



Waimakariri District - Coastal Analysis DSAS Transects

CLIENT
Waimakariri District Council

PROJECT
Coastal Hazard Analysis

SCALE 1:19,120 @ A3	PROJECT CODE IZ105900
PROJECT MANAGER DC	DRAWN TN
PROJECT DIRECTOR X	DATE 25/05/2018
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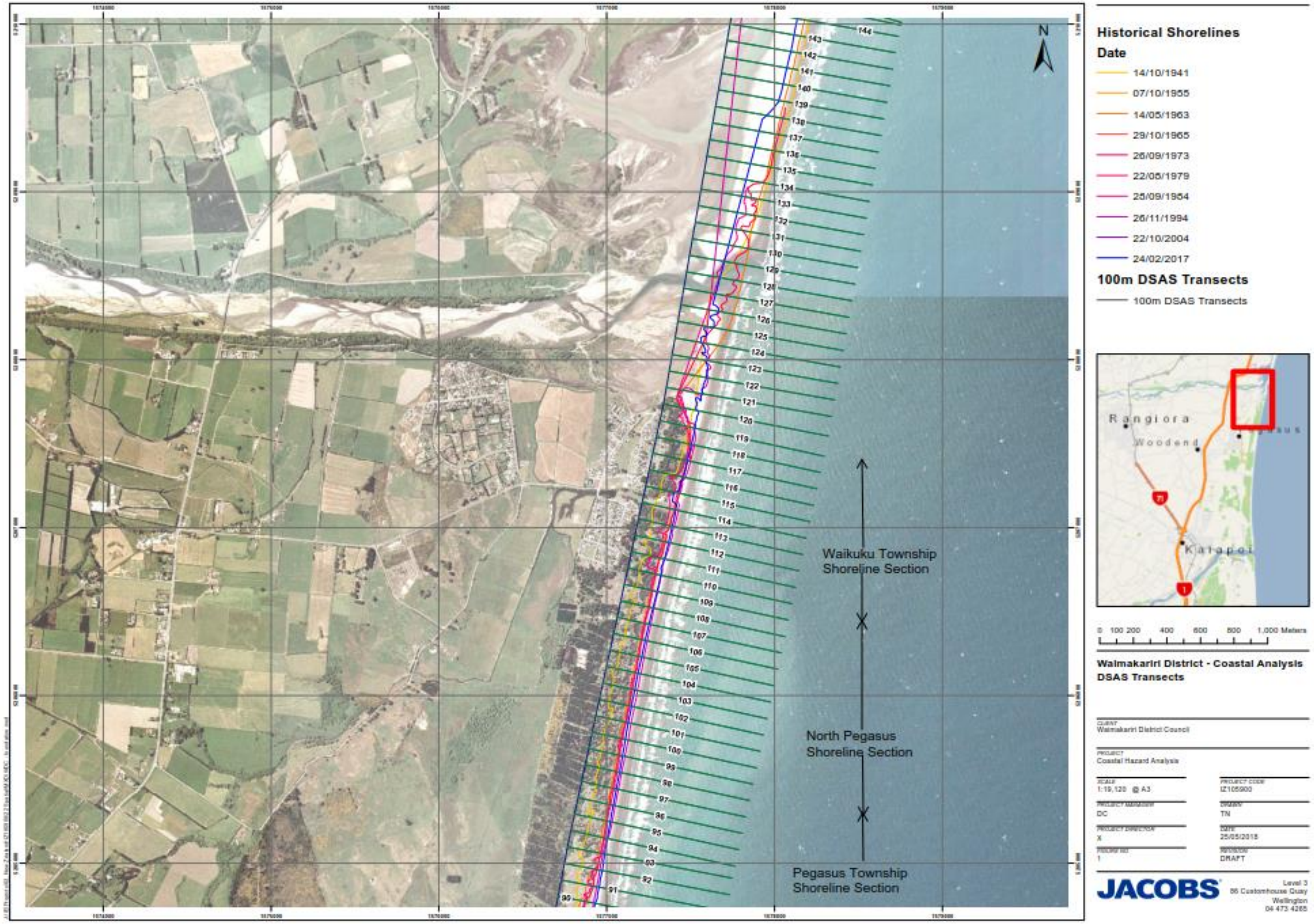
Level 3
86 Customhouse Quay
Wellington
04 473 4265


N
Historical Shorelines
Date
14/10/1941
07/10/1955
14/05/1963
29/10/1965
26/09/1973
22/06/1979
25/09/1984
26/11/1994
22/10/2004
24/02/2017
100m DSAS Transects
100m DSAS Transects
Rangiora
Woodend
Pegasus
Kaiapoi
0 100 200 400 600 800 1,000 Meters
Waikuku Township Shoreline Section
North Pegasus Shoreline Section
Pegasus Township Shoreline Section
Walmakariri District - Coastal Analysis
DSAS Transects
CLIENT
Waimakariri District Council
PROJECT
Coastal Hazard Analysis
SCALE
1:19,120 @ A3
PROJECT CODE
IZ105900
PROJECT MANAGER
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PROJECT DIRECTOR
X
DATE
25/05/2018
FIGURE NO
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REVISION
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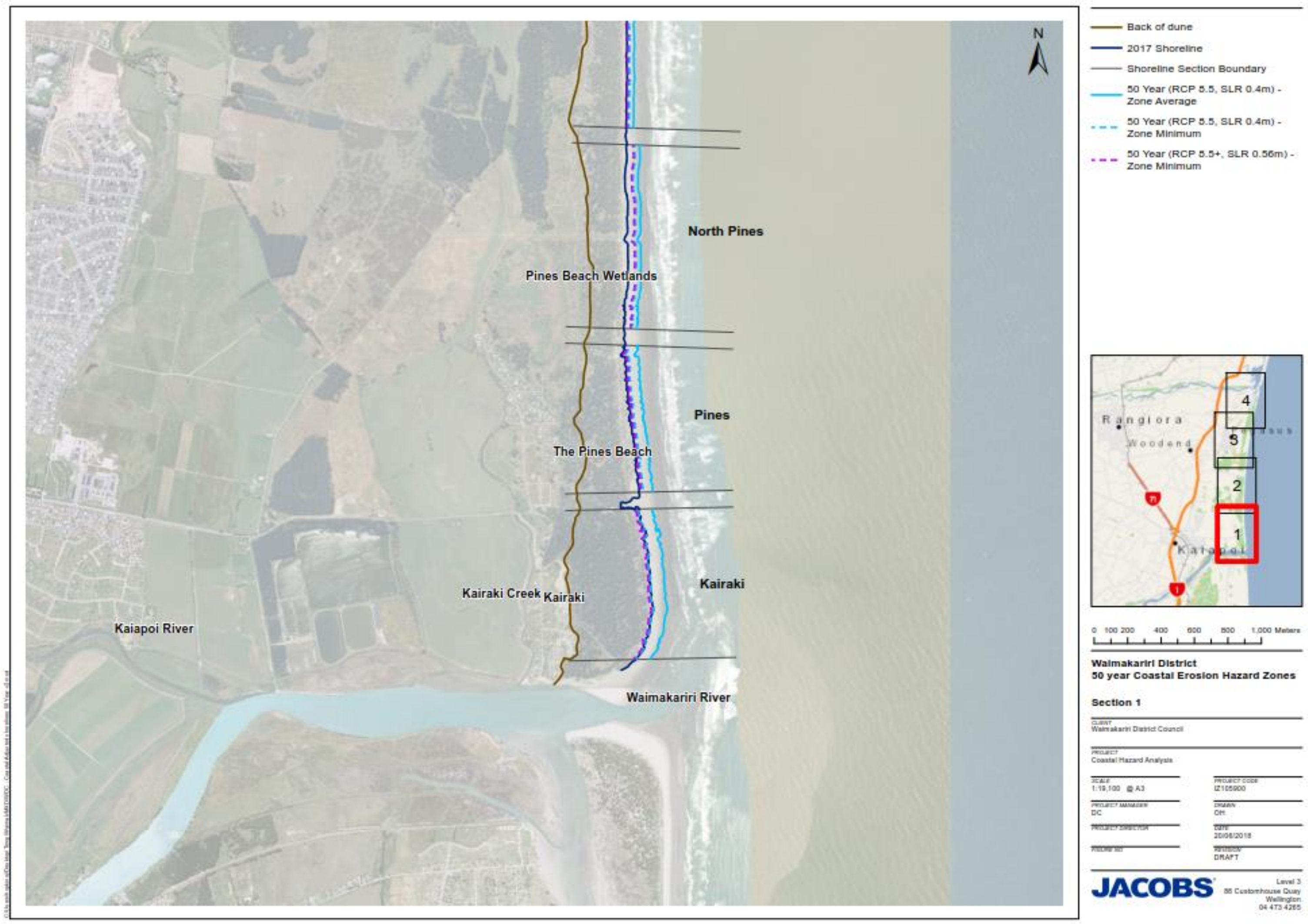
Wellington
04 473 4265

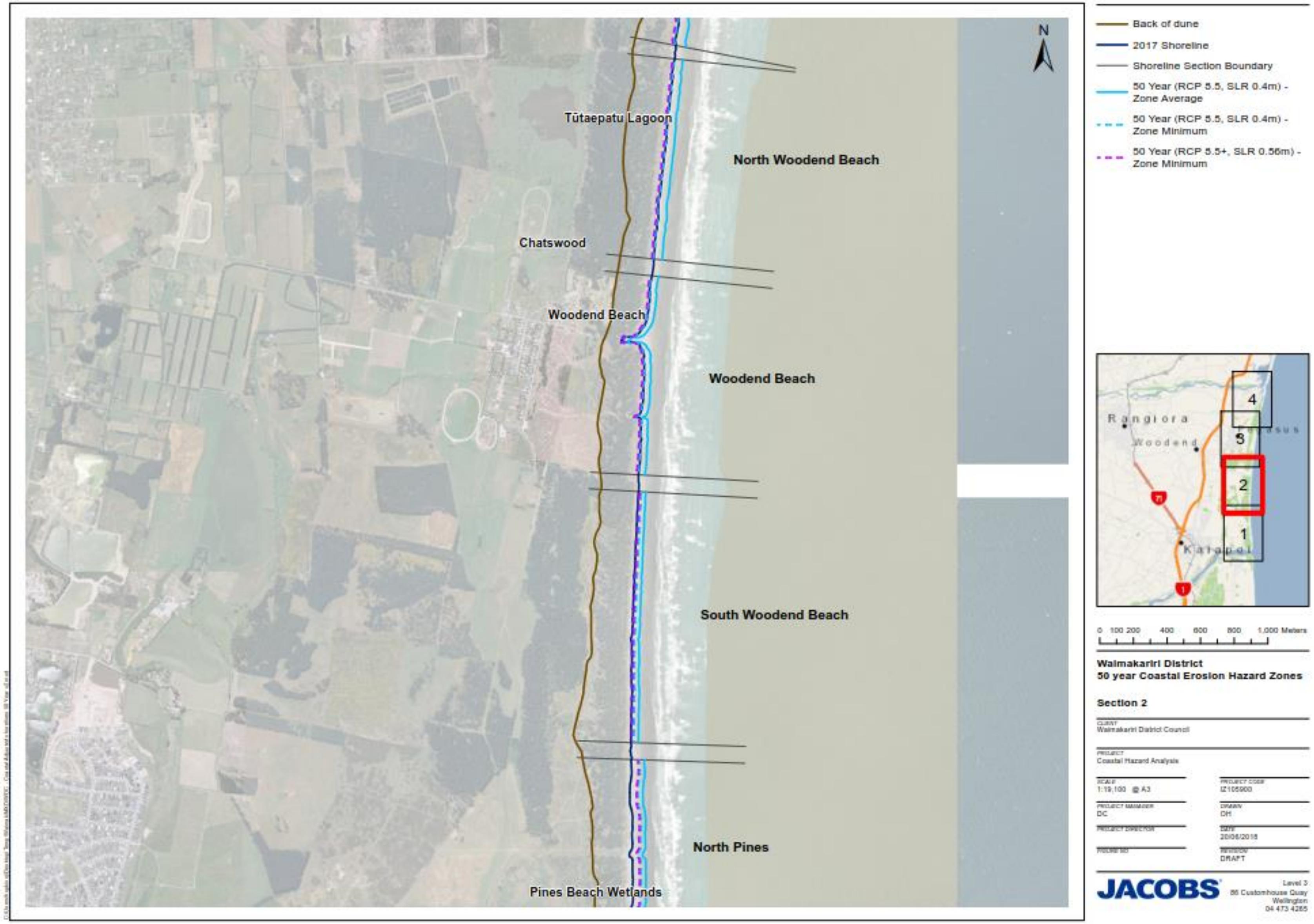
Appendix C: River Cross-section Locations

Waimakariri River cross-section locations

Ashley River cross-section locations

Appendix D: 50-year (2070) Coastal Erosion Hazard Zone Positions




N
Tūtaepatu Lagoon
North Woodend Beach
Chatswood
Woodend Beach
Woodend Beach
South Woodend Beach
North Pines
Pines Beach Wetlands
Back of dune
2017 Shoreline
Shoreline Section Boundary
50 Year (RCP 8.5, SLR 0.4m) - Zone Average
50 Year (RCP 8.5, SLR 0.4m) - Zone Minimum
50 Year (RCP 8.5+, SLR 0.56m) - Zone Minimum
Rangiora
Woodend
Pegasus
Kaiapoi
1
2
3
4
71
1
0 100 200 400 600 800 1,000 Meters
Walmakariri District
50 year Coastal Erosion Hazard Zones
Section 2
CLIENT
Waimakariri District Council
PROJECT
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PROJECT CODE
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PROJECT MANAGER
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PROJECT DIRECTOR
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Waimakariri District
50 year Coastal Erosion Hazard Zones

Section 3

CLIENT
Waimakariri District Council

PROJECT
Coastal Hazard Analysis

SCALE
1:19,100 @ A3

PROJECT CODE
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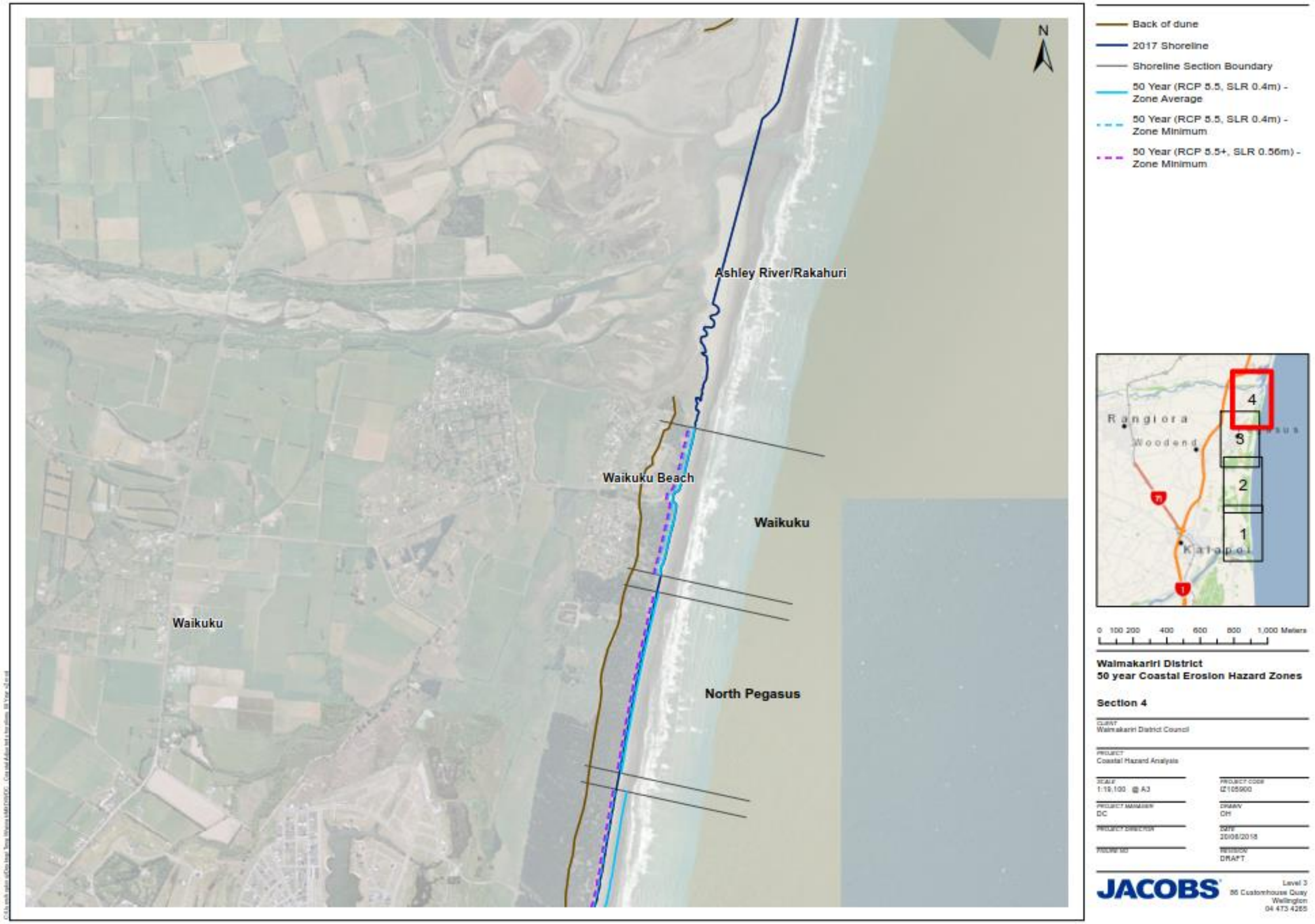

Waimakariri District
50 year Coastal Erosion Hazard Zones

Section 4

CLIENT
Waimakariri District Council

PROJECT
Coastal Hazard Analysis

SCALE
1:19,100 @ A3

PROJECT CODE
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PROJECT MANAGER
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PROJECT DIRECTOR

DATE
20/08/2018

REVISION
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Level 3
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Wellington
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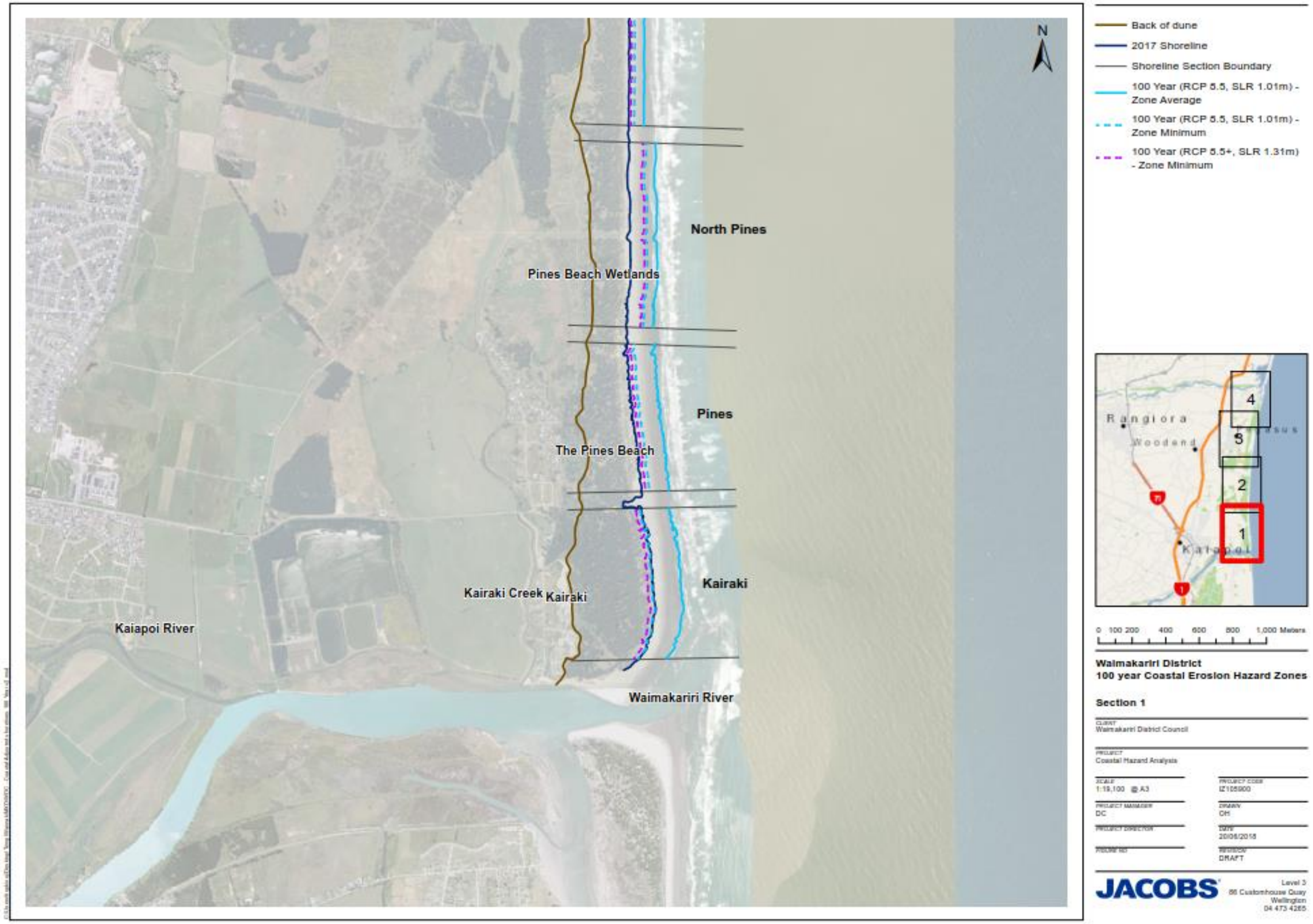
Appendix E: 100-year (2120) Coastal Erosion Hazard Zone Positions



Waimakariri District
100 year Coastal Erosion Hazard Zones

Section 1

CLIENT
Waimakariri District Council

PROJECT
Coastal Hazard Analysis

SCALE
1:19,100 @ A3

PROJECT CODE
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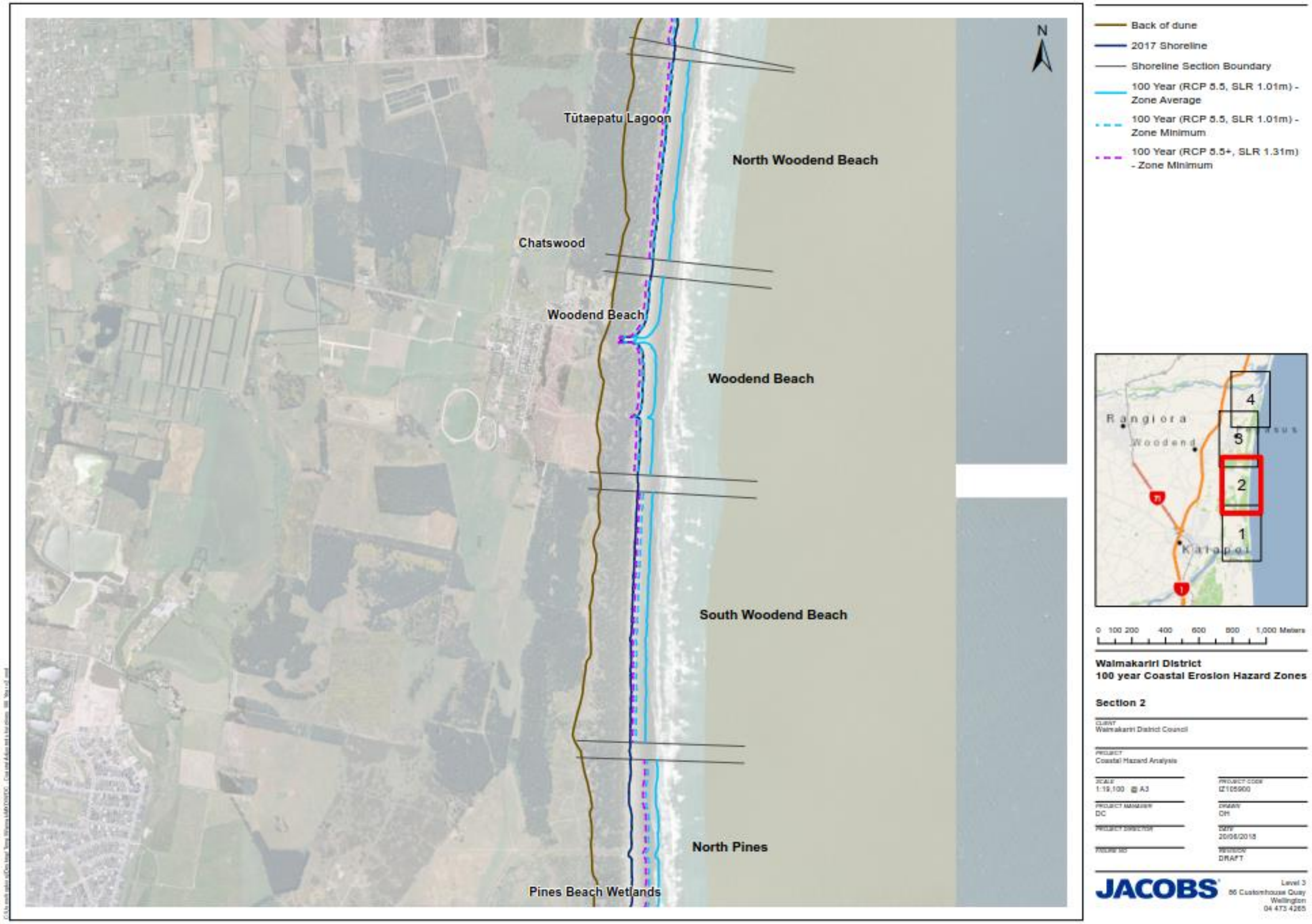
04 473 4265



Waimakariri District
100 year Coastal Erosion Hazard Zones

Section 2

CLIENT
Waimakariri District Council

PROJECT
Coastal Hazard Analysis

SCALE
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PROJECT CODE
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PROJECT MANAGER
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Wellington
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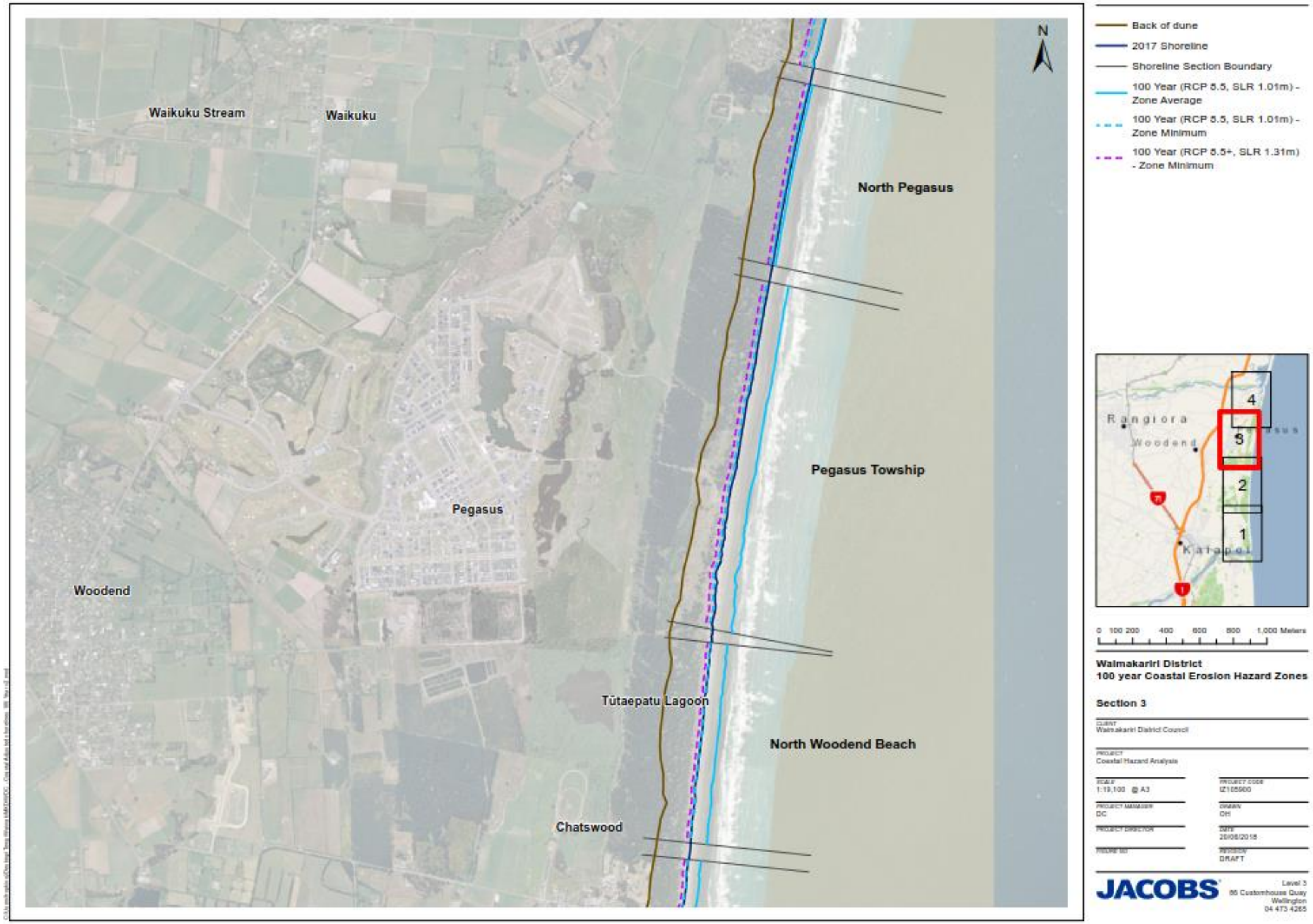

Waimakariri District
100 year Coastal Erosion Hazard Zones

Section 3

CLIENT
Waimakariri District Council

PROJECT
Coastal Hazard Analysis

SCALE
1:19,100 @ A3

PROJECT CODE
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PROJECT MANAGER
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PROJECT DIRECTOR

DATE
20/08/2018

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Waimakariri District
100 year Coastal Erosion Hazard Zones

Section 4

CLIENT
Waimakariri District Council

PROJECT
Coastal Hazard Analysis

SCALE
1:19,100 @ A3

PROJECT CODE
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PROJECT MANAGER
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PROJECT DIRECTOR

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20/06/2018

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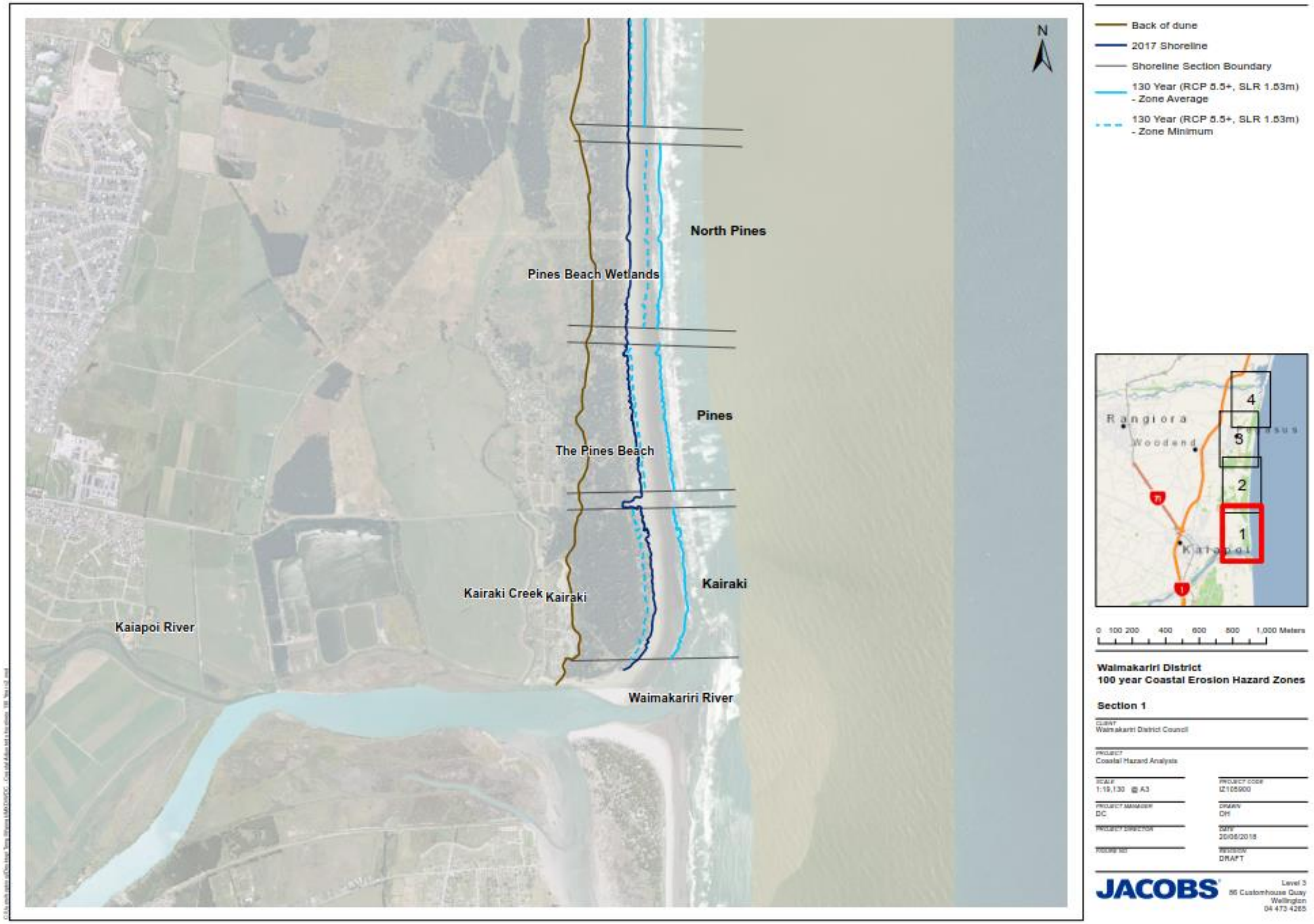
Wellington
04 473 4265

Appendix F: 100-year (2120) Coastal Erosion Hazard Zone Positions


N
Back of dune
2017 Shoreline
Shoreline Section Boundary
130 Year (RCP 8.5+, SLR 1.53m) - Zone Average
130 Year (RCP 8.5+, SLR 1.53m) - Zone Minimum
North Pines
Pines Beach Wetlands
Pines
The Pines Beach
Kairaki
Kairaki Creek
Kairaki
Kaiapoi River
Waimakariri River
4
Rangiora
3
Pegasus
Woodend
2
1
Kaiapoi
0 100 200 400 600 800 1,000 Meters
Waimakariri District
100 year Coastal Erosion Hazard Zones
Section 1
CLIENT
Waimakariri District Council
PROJECT
Coastal Hazard Analysis
SCALE
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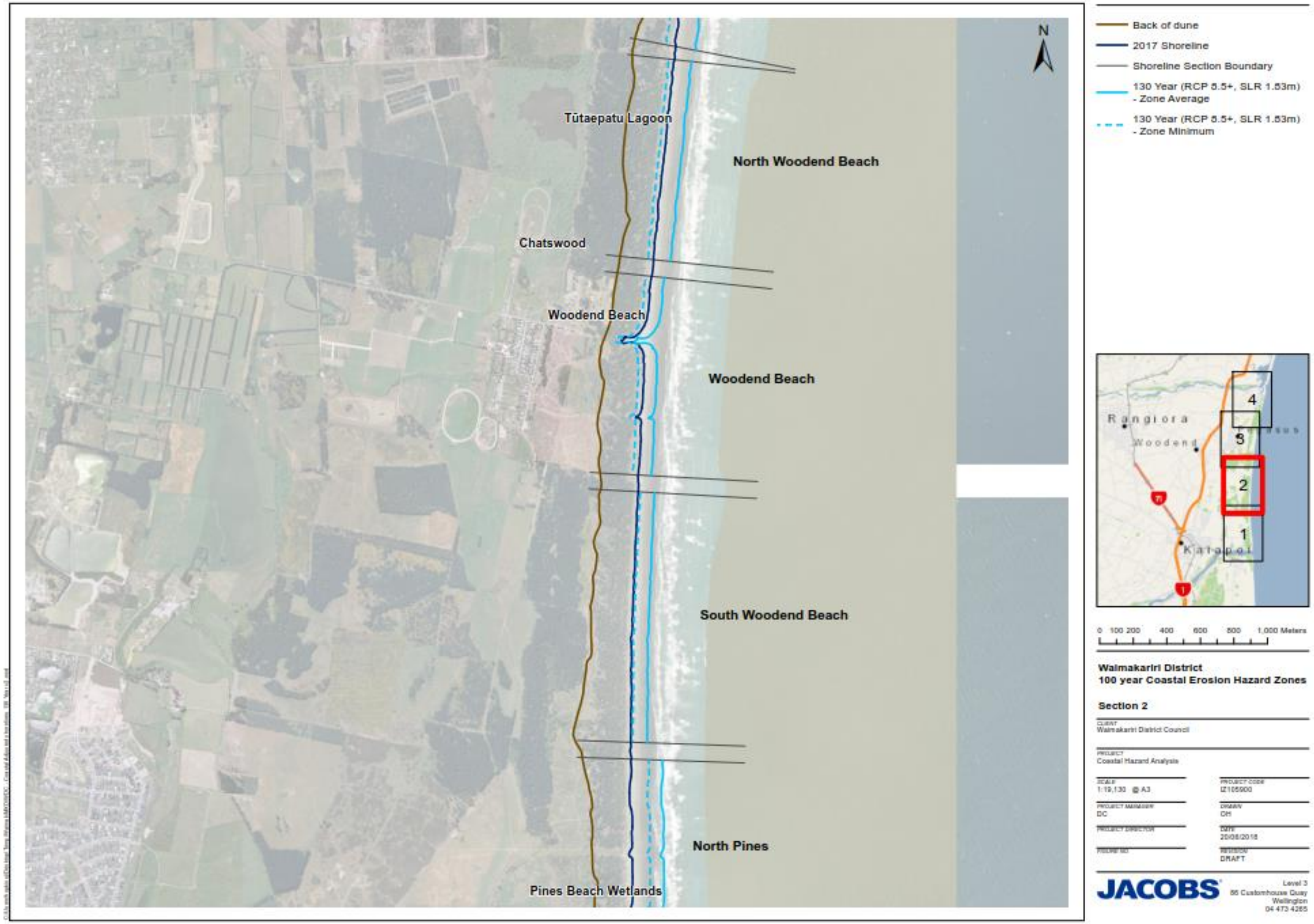

Waimakariri District
100 year Coastal Erosion Hazard Zones

Section 2

Waimakariri District
100 year Coastal Erosion Hazard Zones

Section 3

CLIENT
Waimakariri District Council

PROJECT
Coastal Hazard Analysis

SCALE
1:19,130 @ A3

PROJECT CODE
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20/06/2018

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Level 3
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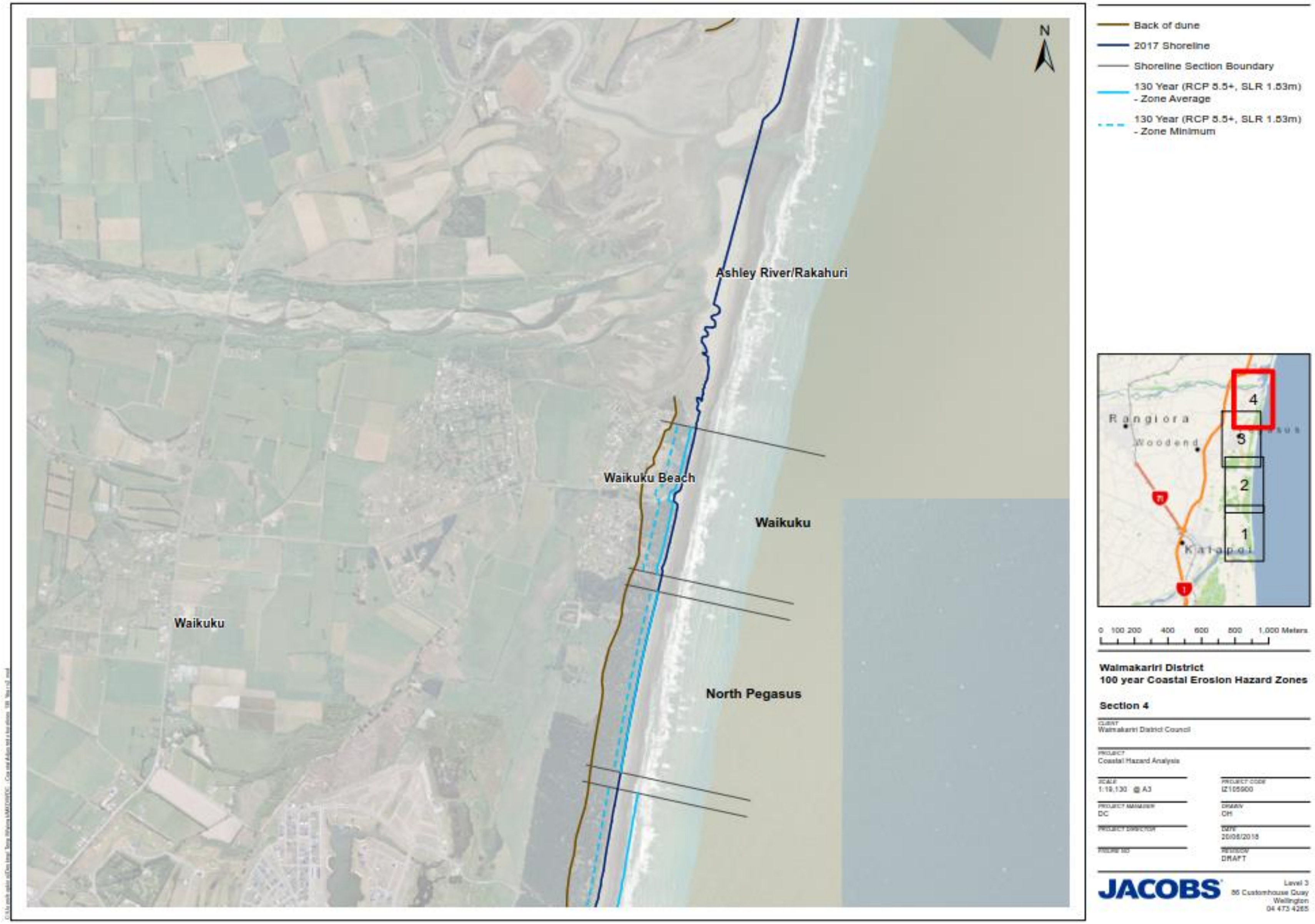
N
Ashley River/Rakahuri
Waikuku Beach
Waikuku
Waikuku
North Pegasus
Back of dune
2017 Shoreline
Shoreline Section Boundary
130 Year (RCP 8.5+, SLR 1.53m) - Zone Average
130 Year (RCP 8.5+, SLR 1.53m) - Zone Minimum
Rangiora
Woodend
Kaiapoi
Pegasus
1
2
3
4
0 100 200 400 600 800 1,000 Meters
Waimakariri District
100 year Coastal Erosion Hazard Zones
Section 4
CLIENT
Waimakariri District Council
PROJECT
Coastal Hazard Analysis
SCALE
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PROJECT DIRECTOR
DATE
20/08/2018
FIGURE NO
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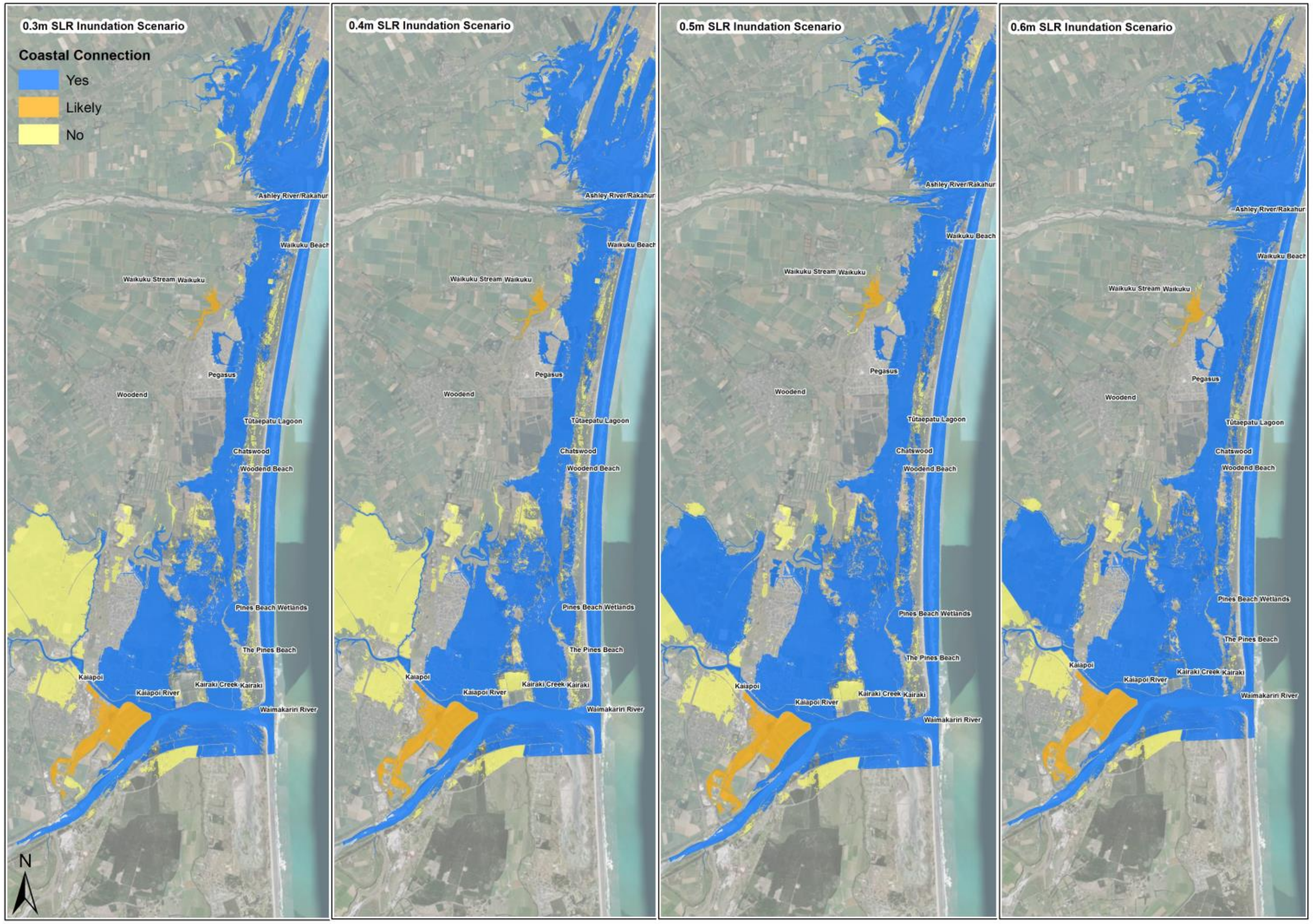
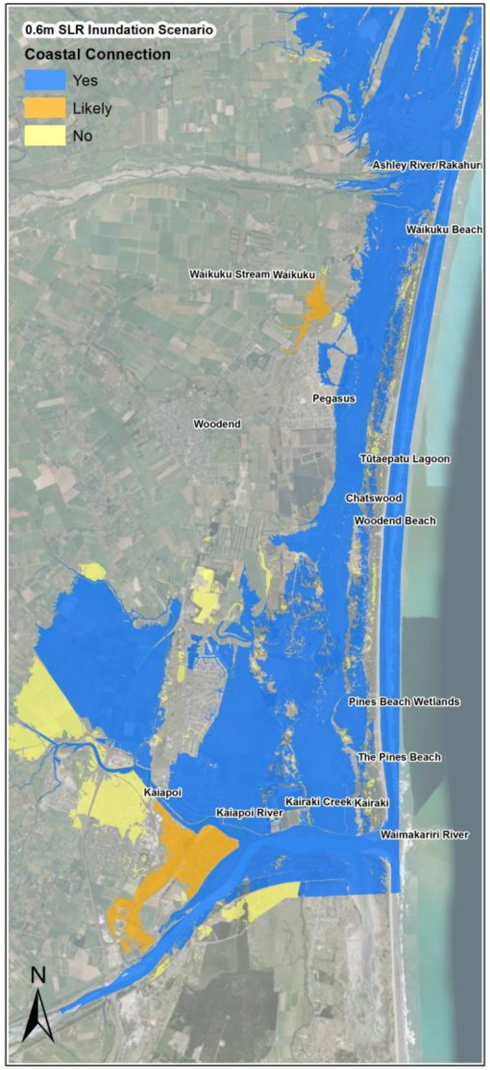
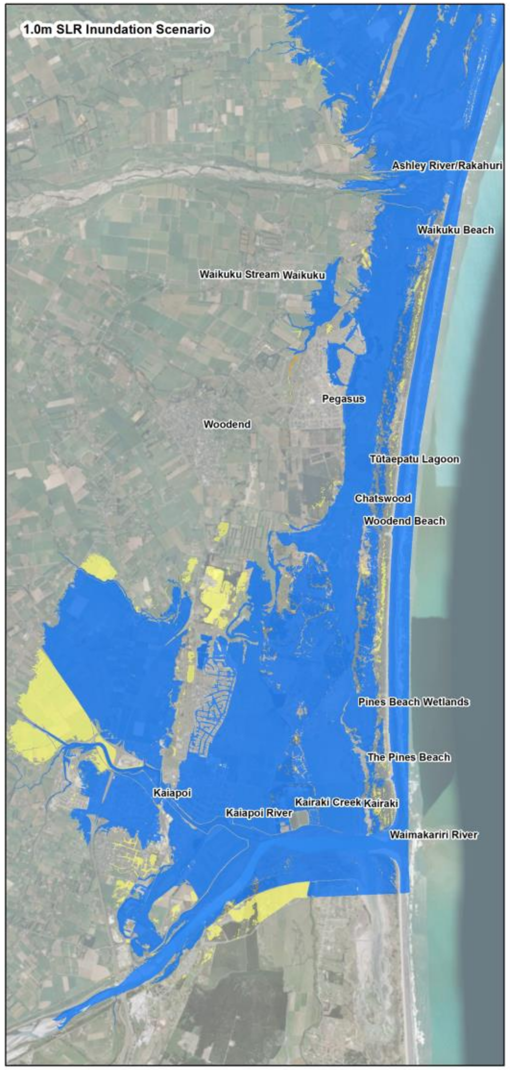
86 Customhouse Quay
Wellington
04 473 4265

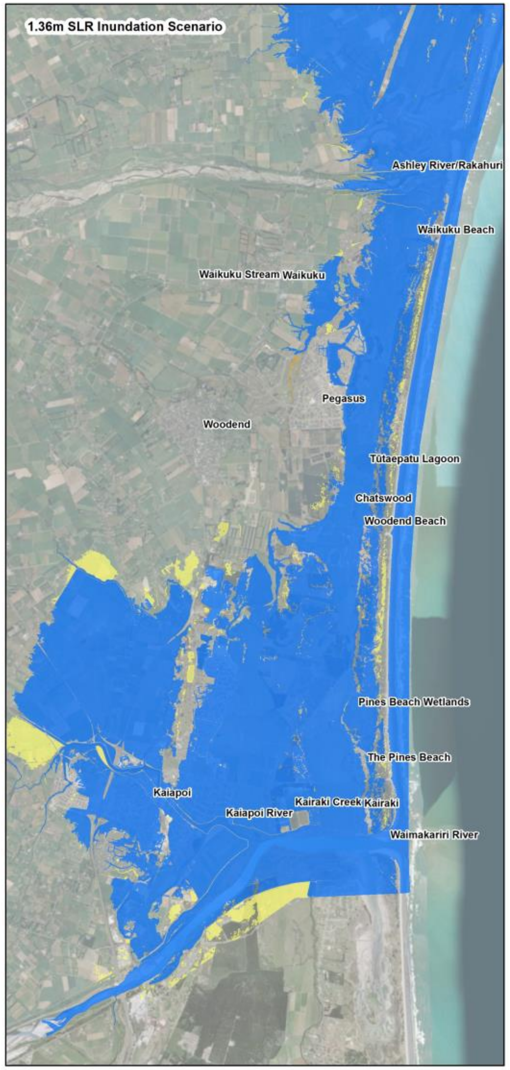
Appendix G: 50-year Coastal Inundation Maps



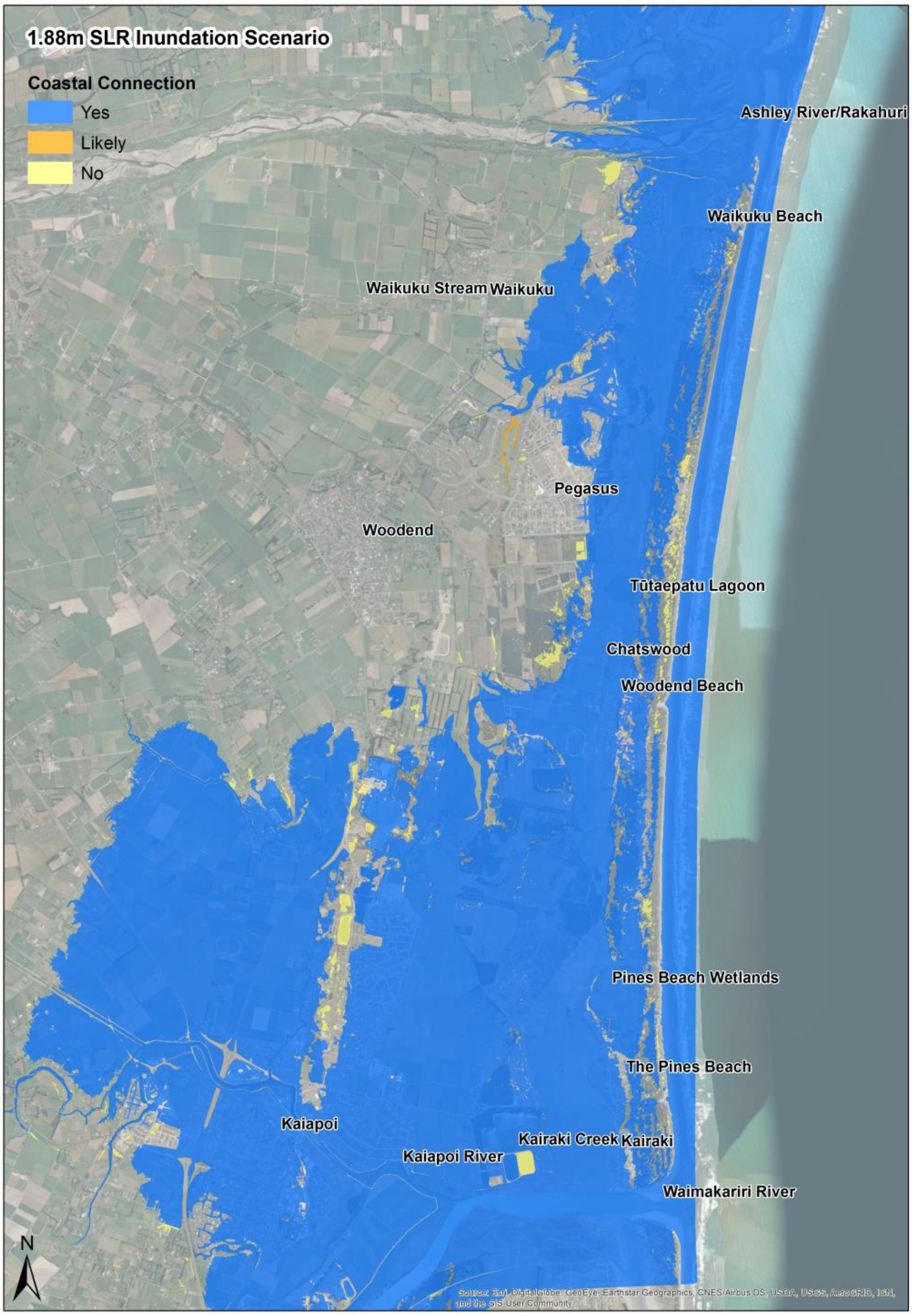
Appendix H: 100-year Coastal Inundation Maps







Appendix I: 130-year Coastal Inundation Maps



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community