Mapping for priority coastal hazard areas in the West Coast Region

Supporting Te Tai o Poutini

Prepared for West Coast Regional Council

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Executive summary

This project is to assess a specific subset of 'priority' coastal hazard areas (pCHA) provided by West Coast Regional Council for Granity-Hector-Ngakawau, Orowaiti, Punakaiki Village, Punakaiki Beach, Rapahoe, Haast Beach to Waiatoto, Neils Beach to Jackson Bay. This study maps areas susceptible to coastal erosion and inundation, it does not include other hazards such as tsunami or river flooding. Coastal erosion and inundation hazards were assessed, and hazard area mapped for each pCHA.

The erosion hazard assessment is completed using a hybrid-probabilistic approach that accounts for available shoreline data and derived trends but also allow for expert judgment to account for effect that are difficult to quantify and/or where no/limited data is available.

The study also mapped land exposed to coastal flood inundation from extreme storm-tides, wave setup and sea level rise. Inundation hazard assessment is completed using a hydrodynamics model for Westport/Orowaiti area and static ("bathtub") for other pCHA. For Westport and Rapahoe high resolution LiDAR topography data was used for this analysis, but for other areas this data is not yet available so the analysis utilised the less accurate SRTM dataset. There is much higher uncertainty in this data and it is recommended that inundation hazard should be re-analysed to confirm/update the results once LiDAR data is released for these areas.

Accompanying this report are GIS layers showing potential inundation for 1% annual exceedance probability (AEP) flood events for a range of sea-level rise (SLR) steps, and erosion hazard for 50-year and 100-year outlooks. These layers will inform WCRC in the development of Te Tai Poutini plan.

1 Introduction

The scope of this project is to assess a specific subset of 'priority' coastal hazard areas (pCHA) (Table 1-1) provided by West Coast Regional Council (WCRC) and defined in the CHA report (Measures and Rouse 2022).

Table 1-1: Priority Coastal Hazard Areas for this study. See Measures and Rouse (2022) for further details on other coastal hazard areas.

CHA	Location	Priority 2022	Status in 2022
CHA 3	Hector, Ngakawau and Granity	High	Existing
CHA 4	Orowaiti Lagoon	High	New
CHA 12	Punakaiki Village (Pororari Beach)	High	Existing
CHA 13	Punakaiki River Beach	Medium	Existing
CHA 16	Rapahoe	High	Existing
CHA 25	Okuru to Waiatoto (renamed) Haast Beach to Waiatoto	Medium	Extended 2021
CHA 26	Neils Beach (renamed) Neils Beach to Jackson Bay	Medium	Extended 2021

This study comprises assessments for the two main coastal hazards, erosion and inundation. These hazards were addressed within specific methods based on the information available in the areas of the West Coast. Other hazards such as tsunami and river flooding are outside the scope of this study.

The erosion hazard assessment is completed using a hybrid-probabilistic approach that accounts for available shoreline data and derived trends but also allow for expert judgment to account for effects that are difficult to quantify and/or where no/limited data is available.

Inundation hazard assessment is completed using a hydrodynamics model for Westport/Orowaiti area and static ("bathtub") for other pCHA.

The assessment is supplemented by observations from a walkover site inspection of the pCHAs, a brief literature review of each area, and compilation of aerial photography and other cadastral maps.

1.1 Purpose of this report

This study is to provide coastal hazard (storm inundation and erosion) information for WCRC who are developing Te Tai Poutini plan, a combined district plan for the West Coast (Buller, Grey and Westland District Councils). The report documents the technical details of the methodology used to develop the hazard areas for the priority CHAs. It also provides discussion on hazard mechanisms and uncertainties in each of the CHAs.

1.2 Exceedances and return periods

The likelihoods associated with extreme storm-tides and/or waves, are reported in terms of their probability of occurrence. The annual exceedance probability (AEP) describes the chance of an event reaching or exceeding a certain water level in any given year. For example, if a storm-tide of 1.5 m has a 5% AEP, then there is a 5% chance of a storm-tide this high, or higher, occurring in any 1-year period. Such an event is an outside chance in any year, but it can still happen and should be planned for. Furthermore, although the occurrence probability is only 5% for any year, more than one storm-tide this high or higher could occur in any given year. Integrated over a planning timeframe of say 100 years, a 5% AEP event has a 99% chance of occurring or being exceeded, i.e.,, it is almost certain (see discussion below on exceedances).

Alongside AEP, the likelihood of extreme events can also be described in terms of their average recurrence interval (ARI), which is the average time interval between events of a specified magnitude (or larger), when averaged over many occurrences i.e.,, a very long period of time. Table 1-2 shows the relationship between AEP and ARI, small relatively common events have a high annual exceedance probability and a low average recurrence interval, and *vice versa* for large, rare events.

Table 1-2: Relationship between annual exceedance probability (AEP) and average recurrence interval (ARI). AEP = $1 - e^{(-1/ARI)}$.

AEP (%)	99%	86%	63%	39%	18%	10%	5%	2%	1%	0.5%
ARI .(years)	0.2	0.5	1	2	5	10	20	50	100	200

ARI (or its often used surrogate "return period") is an easily misinterpreted term, with the public often assuming that because one large event has just occurred, then the average recurrence interval will pass before another such event. We therefore prefer the term AEP for weather-related hazards (unlike perhaps earthquakes on a particular section of a fault), because it conveys the continuous probability that large events could occur at any time.

This report provides occurrence likelihoods for extreme storm-tide and wave height magnitudes and their joint occurrences. This knowledge is only one aspect of the planning process. Another essential planning component is to consider the planning timeframe, or lifetime, of interest. For example, a typical planning lifetime for residential housing development is greater than 50 years, the NZ Coastal Policy Statement requires assessment of coastal hazard risk over at least 100 years (e.g., Policy 24)(MfE 2017), whereas mortgage timeframes are usually only 30-years duration.

Table 1-3 presents the likelihood that events with various occurrence probabilities will occur, *at least once*, within a specified planning lifetime.

The likelihoods are shaded according to their chance of occurring or being exceeded in the specified timeframe:

- > 85% Almost certain (red)
- 60%–84% Likely (orange)
- 36%–59% Possible (green)
- 16%–35% Unlikely (yellow)
- < 15% Rare (blue)

For example, a relatively common (smaller) event with a 39% AEP is *almost certain* to occur or be exceeded over a 20-year lifetime. However, a rare (larger) 2% AEP event is *unlikely* to occur or be exceeded over the same 20-year lifetime. 1% AEP's are a commonly used planning or engineering design event magnitude, and 100-year planning lifetimes are common for affected infrastructure or for coastal hazard risk assessments, Table 1-3 shows that a 1% AEP event is *likely* to occur or be exceeded over a 100-year planning lifetime with a 63% probability.

Table 1-3: Likelihood of *at least one exceedance* event occurring within planning lifetimes The likelihood of occurrence is described by AEP and/or ARI. $P = 1 - e^{-L/ARI}$, where L = planning lifetime and P = probability of at least one exceedance event occurring within the planning lifetime.

		Planning lifetime (years)						
AEP (%)	ARI (years)	2	5	10	20	50	100	200
39%	2	63%	92%	99%	100%	100%	100%	100%
18%	5	33%	63%	86%	98%	100%	100%	100%
10%	10	18%	39%	63%	86%	99%	100%	100%
5%	20	10%	22%	39%	63%	92%	99%	100%
2%	50	4%	10%	18%	33%	63%	86%	98%
1%	100	2%	5%	10%	18%	39%	63%	86%
0.5%	200	1%	2%	5%	10%	22%	39%	63%

In this report, we include large wave heights combined with high storm-tides because coastal flooding, or other hazards such as erosion or structural damage to coastal defences, roads or buildings, is worse when high storm-tides and large waves occur together.

1.3 West Coast wave climate

Coastal hazards are tightly related to the wave climate and the occurrence of extreme events. The offshore area of the West Coast is exposed to the larges southwesterly swells and seas generated in the Southern Ocean and Tasman Sea. However, in the coastal area, the continental shelf and New Zealand landmass force the southwest waves to refract resulting in a strong reduction in wave height and a lower-energy wave climate in the bays and bights along the coast of the West Coast region (Godoi et al. 2017). Extreme wave events on the wave coast can also result from tropical cyclones and tropical storm moving towards the shore of the West Coast region as occurred in 2018 with ex-Tropical Cyclone Fehi (hereafter exTC Fehi) which caused much damage from erosion and inundation. Estimating the probability of occurrence of such extreme event as exTC Fehi is complicated by the fact that these occurrence are rare but corelated to marine heat wave and the warming of the Tasman Sea.

1.4 Field visit

A field visit to the seven priority areas took place from 12-15 August 2021.

The purpose of the field visit was to:

- Observe each site; interpret changes since earlier photographs, previous inspections, and reports.
- Qualitatively identify the potential for erosion and inundation hazards to affect the areas the assessment timeframe.
- Identify the different site morphologies to inform the quantitative future shoreline and inundation hazard predictions.

Coastal areas were inspected by foot and public vehicle access. Some areas of CHA25 could not be readily accessed due to lack of road access to the beach (e.g., North Bank of Arawhata River to northern extent of Waiatoto Lagoon, south bank of Okuru Lagoon to Mussel Rock). However, these inaccessible areas are potentially subject to coastal hazards, and aerial photographs show they appear consistent with adjacent areas of coast which were inspected.

The photographs and observations from the field visit are included throughout this report. Observations from the field visit are presented alongside the results of the coastal inundation and erosion analysis in Section 4.

2 Coastal Inundation methodology

The study splits analysis of coastal hazard into a coastal inundation component and a coastal erosion component. This section describes the methods used to assess the coastal inundation hazards.

Mapping land exposed to coastal flood inundation from extreme storm-tides involves the following steps which are elaborated further below:

1. Source digital elevation models (DEMs) of land topography (Section 2.1) suitable for inundation assessments.
2. Estimate extreme sea-level elevations around the coastline, including the effects of storm-tides (*ST*) and wave setup (*WS*) (Section 2.3.3) as well as tidal elevations (e.g., mean high water springs) (Section 2.3.6).
3. Add sea-level rise (SLR) to extreme sea levels (Section 2.4).
4. Adjust for mean sea-level (MSL) offset and vertical land motion (Section 2.3.5).
5. Spatial mapping of extreme sea-level + SLR elevations onto land to identify future coastal flood inundation areas (Section 4).

The inundation hazard assessment is supplemented and informed by the brief walkover site inspection and literature review.

2.1 Digital elevation models and LiDAR availability

Digital elevation models (DEMS) are measurements of land elevation. DEMs are used in conjunction with extreme water level analysis to map coastal flood inundation hazard areas.

For this study we used a combination of aerial survey (LiDAR) and satellite DEM products.

2.1.1 LiDAR

Airborne light detection and ranging (LiDAR) topography surveys are the best available DEMs for coastal storm-tide and SLR flood mapping. These provide vertical elevation accuracy down to 0.10–0.15 m and can include derivate datasets of digital surface models, building outlines and simultaneous aerial photography.

LINZ manage LiDAR datasets[1] for New Zealand and have a programme to obtain complete coverage of LiDAR around New Zealand's coastal areas by 2024[2]. At the time of writing LINZ are actively surveying the West Coast and recently (August 2021) released LiDAR for the Westport area including CHA3 (Westport/Orowaiti) and most of CHA4 (Granity and Ngakawau but not Hector).

LiDAR DEMs on the West Coast are generally available for larger urban areas (Greymouth, Hokitika, Westport) with a small number of additional villages (e.g., Rapahoe) and riverbeds (e.g.,Waiho).

Table 2-1 below outlines the areas of LiDAR available for the present study of priority CHAs

[1] https://data.linz.govt.nz/
[2] https://linz.maps.arcgis.com/apps/MapSeries/index.html?appid=2552c3a5cee24f7b87806b085c3fee8a

Table 2-1: Digital elevation model availability for priority CHAs.

CHA	Name	DEM sources
3	Granity, Ngakawau, Hector	LiDAR (2021) with bias-corrected SRTM north of Ngakawau River
4	Westport/Orowaiti River	LiDAR (2021)
12, 13	Punakaiki Village, Punakaiki River Mouth	satellite DEM (bias-corrected SRTM)
16	Rapahoe	LiDAR (2016 Grey District Council Hokitika)
25	Haast Beach to Arawhata River Mouth	satellite DEM (bias-corrected SRTM)
26	Jackson Bay to Neils Beach	satellite DEM (bias-corrected SRTM)

2.1.2 Areas without LiDAR

Where LiDAR is yet to be flown or released, we have use satellite-based elevation measurements of the land. A number of satellite DEMs have coverage of near coast areas and are available publicly or via data subscription. For this study we evaluated which of CoastalDEM[3], SRTM[4] (original, rereleased or modified) or MERIT[5] would be most appropriate for the West Coast inundation assessments.

These DEMs are based on satellite topography measurements such as NASA's Space Shuttle Radar Topography Missions (SRTM), the Japanese Space agency (JAXA) AW3D missions[6] and other commercial satellite sources. CoastalDEM and MERIT are based on the original public releases of SRTM at 3 arc-seconds or about 90 meters with a number of corrections (e.g., absolute bias, stripe noise, speckle noise, and global tree height bias). The SRTM was subsequently re-released with full worldwide resolution of 1 arc-second, or about 30 meters, including other corrections. NIWA reprocessed[7] the SRTM data following Meadows & Wilson (2021) to further remove landcover bias around NZ and compare the SRTM elevation bias to available LiDAR data NZ-wide. These datasets, are an intermediate between the LINZ 8m topomap and LiDAR survey.

Figure 2-1 demonstrates the result of the NZ-wide bias correction process when comparing only the overlapping West Coast LiDAR datasets. The result show the STRM data used for this study have a mean bias of -0.27 m and a Standard Deviation of 1.55 m. LiDAR (at < 1m spatial resolution) would still be preferred however the bias-corrected SRTM DEM is a reliable DEM suitable for district scale coastal inundation assessments where LiDAR is unavailable (Figure 2-2, Figure 2-3).

[3] https://go.climatecentral.org/coastaldem/
[4] https://srtm.csi.cgiar.org/srtmdata/
[5] http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/
[6] https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm
[7] As part of Deep South National Science Challange: *Adapting to -Compound Flood Hazards* 2020-2023

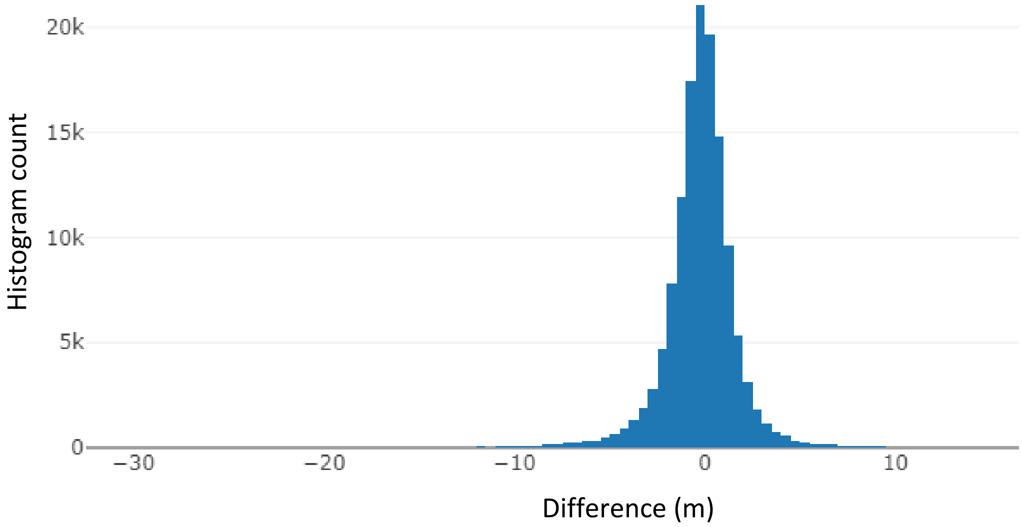

Figure 2-1: histogram of calculated elevation difference between SRTM and LiDAR for the West Coast. The mean bias is -0.27 m with a standard deviation of 2.01 m.

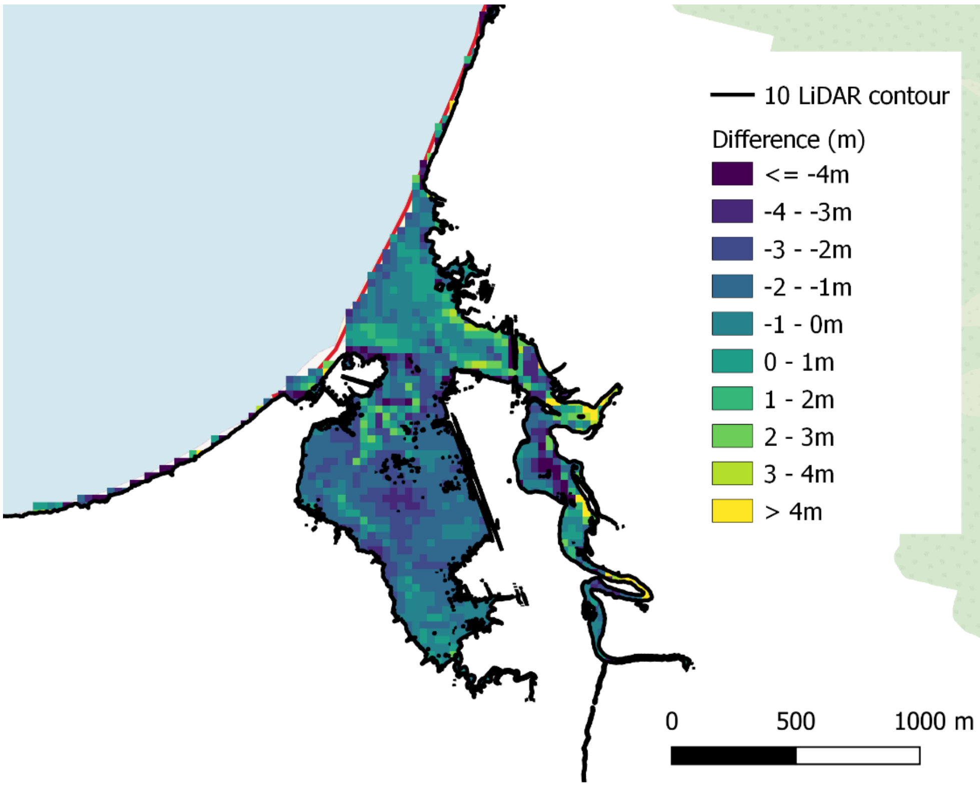

Figure 2-2: Map of elevation differences between LiDAR and SRTM at Rapahoe for elevations<10 m. Difference is calculated as SRTM elevation minus LIDAR elevation.

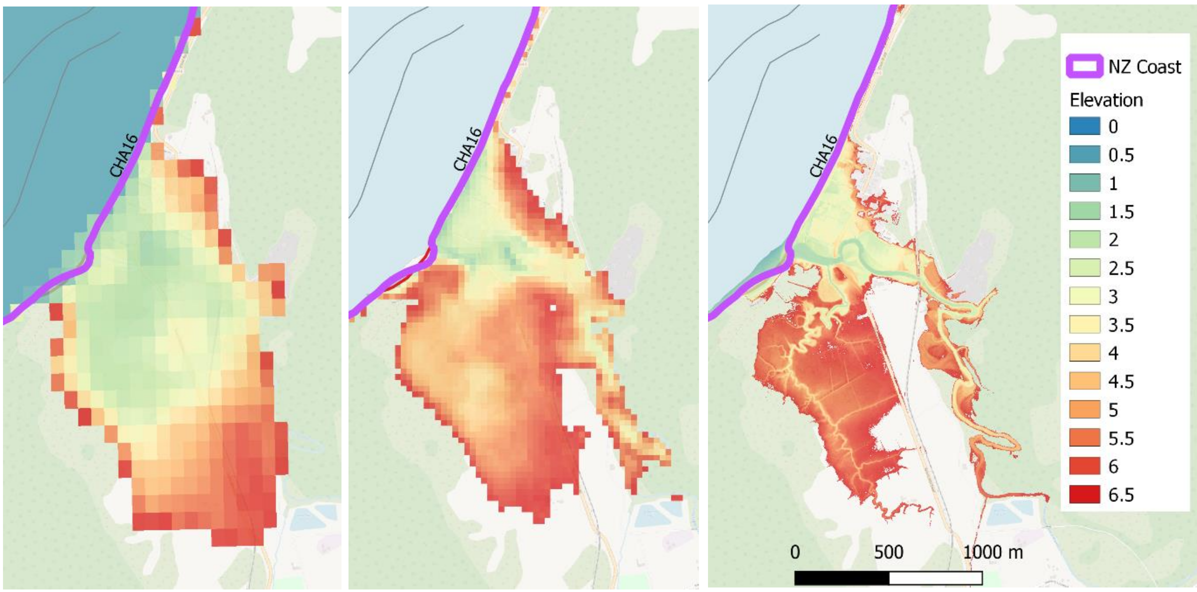

Figure 2-3: Example comparison of digital land elevation at Rapahoe from sources considered for this study. A) CoastalDEM, B) bias corrected SRTM and C) LiDAR. Scale and colour graduations the same for all. Elevation data clipped at + 6.5 m.

Figure 2-3 illustrates the same area of Rapahoe and the Waimatuku/Seven Mile Creek using the CoastalDEM, bias-corrected SRTM, and LiDAR. The improved in spatial resolution from CoastalDEM to SRTM is seen in the reduced grid size and resolution of smaller topographic features, however it is clear that LiDAR is the most suitable for coastal hazard mapping where available.

The bias-corrected SRTM offers an opportunity to proceed with the analysis of static coastal inundation and produce results that are useful at the scale of the CHA but are not suitable for analysing the inundation hazard at a property scale. We note that the static inundation mapping may be updated relatively easily when LiDAR is released for the other priority CHAs.

NIWA's bias-corrected SRTM is hereafter referred to as SRTM.

2.2 Vertical datum

NZVD2016 is used throughout this report. Any conversions between local vertical datums (e.g., Lyttleton Vertical Datum 1937, LVD-37) were undertaken using the LINZ online coordinate converter.

Note that the offsets between LVD-37 and NZVD2016 are not spatially uniform. The offsets determined at the tide gauge locations are specific to that locality.

2.3 Extreme sea levels

The present study estimated storm-tide-driven extreme sea levels (ESLs) along the New Zealand coastline. ESL elevations were calculated using the formula:

$$\mathrm{ESL} = \mathrm{MSL} + ST + WS + \mathrm{SLR} \qquad (1)$$

where:

- MSL is mean sea level relative to local vertical datum calculated from sea-level gauge records over (approximately) a recent decade,

- *ST* is the storm-tide combination of high tide, meteorological effects (storm-surge) and monthly sea-level anomaly, affected by both seasonal heating and cooling and interannual and inter-decadal climate variability such as the El Niño Southern Oscillation (ENSO) and the 20-30 year Interdecadal Pacific Oscillation (IPO),
- *WS* is the additional wave setup (over and above *ST*) at the shoreline where breaking waves are present, and
- SLR is relative sea-level rise including the effect of regional sea level rise and local effects of background vertical land motion.

For this study, extreme sea level inundation maps for the West Coast were extracted from a series of pre-mapped national-scale inundation assessments by NIWA (as outlined in Section 2.3.1 below). However, these ESLs and inundation maps require small additional offsets to account for updated measurements or processes that were not included in the national assessments. The offsets include:

- Update of MSL offset in ESL calculation based on recent tide gauge measurements. The change associated with this update is generally <0.1 m (see Section 2.3.5).
- Adjustment of future sea levels to account for background vertical land motion across the region (i.e., interseismic subsidence or uplift) and extrapolated to a 100-year timeframe. This offset is generally <0.2 m over a 100-year timeframe and only for sites near Westport (see Section 2.4.1).

2.3.1 Context

This study uses extreme sea levels produced by NIWA within a sequence of recent and ongoing research projects.

Originally, 1% annual exceedance probability (AEP) extreme storm-tide + wave setup elevations were calculated as part of a Deep South Challenge research project "*Coastal Flooding Exposure Under Future Sea-level Rise for New Zealand*" (Paulik et al. 2019). In that study, storm-tide elevations were estimated from a mixture of sea-level gauges and the NIWA tide forecaster (Goring 2001), with storm-tide relationships to MHWS given in Stephens et al. (2020). The treatment of wave setup is relatively crude, being a simple allowance of +0.5 or +1.5 m depending on perceived energy exposure (Paulik et al. 2019, Paulik et al. 2020).

While improvement in the method are part of current research projects (Deep South Challenge: *Adapting to -Compound Flood Hazard* 2020-2023 and the University of Victoria Endeavour Programme: *NZ SeaRise* 2017-2022), output from these projects have not yet produced usable results for this West Coast study.

2.3.2 Extreme storm-tides

Extreme storm-tide is calculated using relationships between tide and extreme storm-tide from by Stephens et al. (2020). They showed the existence of a linear relationship existed between MHWS7 and extreme storm-tide levels by fitting extreme-value models to the measured sea levels in regions with a sea-level gauge record. .

In regions with no sea-level gauge record, storm-tide elevations can be calculated using the same linear relationships between MHWS-7 and extreme storm-tide elevations (Figure 2-4).

Table 2-2 illustrates the linear fit coefficients and Figure 2-4 provides examples.

Table 2-2: Storm-tide linear fit coefficients—relationship to MHWS-7 (m).

Storm-tide ARI (years)	y-intercept	Scalar (× MHWS-7)	*r* fit coefficient
1	0.19	1.15	0.99
2	0.21	1.17	0.99
5	0.23	1.20	0.98
10	0.25	1.23	0.98
20	0.26	1.25	0.97
50	0.28	1.29	0.97
100	0.28	1.32	0.96

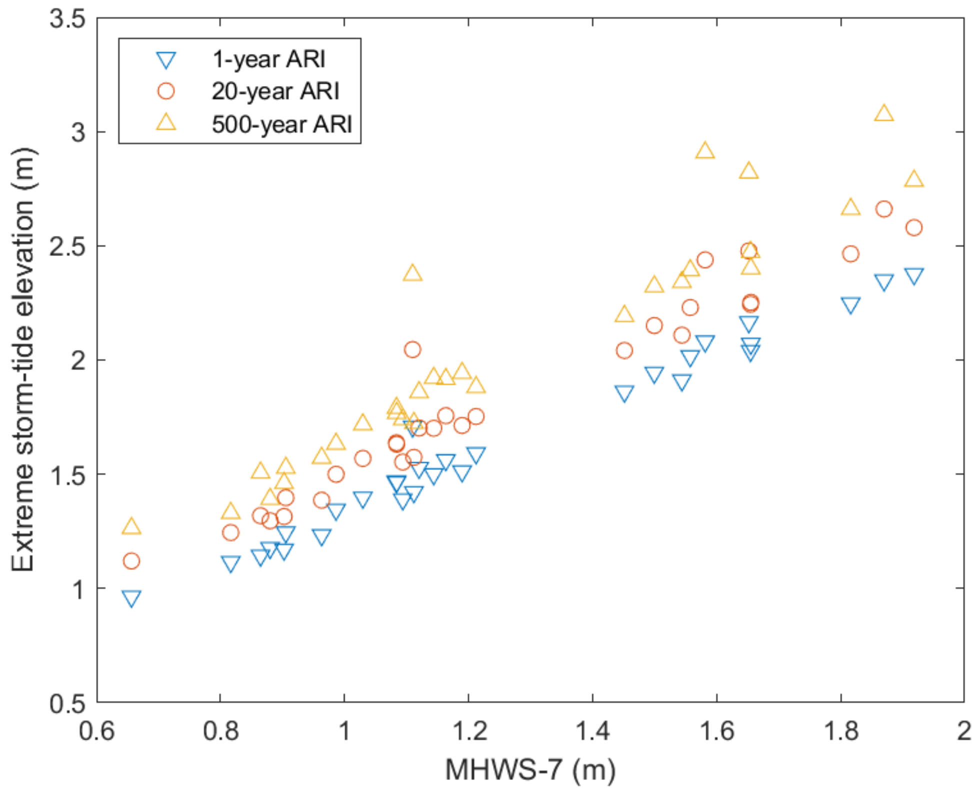

Figure 2-4: Linear relationship of storm tide and MHWS-7. Data point are from tide analysis and extreme value analysis of individual tide gauge record from around NZ.

2.3.3 Wave setup

The contribution of waves to extreme water levels was determined by estimating wave setup. Wave setup is highly dependent on the local bathymetry and exposure to wave energy and difficult to estimate in non-uniform bathymetry and topography. In addition, there are no direct records of wave setup on the West Coast. However, inundation water levels in the Orowaiti lagoon during exTC Fehi were surveyed and provide a benchmark for the combined storm-tide and wave setup.

Because a joint probability between storm-tide and wave setup is not available, a single value of wave setup has to be selected so that (1) it is applicable for the whole West Coast and (2) the resulting total water level is equal or larger than the value predicted for exTC Fehi but lower than the combined 1% AEP storm tide and 1% AEP wave setup (calculated from the 1% AEP significant wave height and period). Wave setup value of 0.8m corresponds to the wave setup resulting from 4.5 m significant wave height with a 10s peak wave period travelling directly towards the coast with a surf-zone slope of 1/60 (based on CEM formulation, USACE (2012)). The wave condition of 4.5 m significant wave height with a 10s peak wave period corresponds to the mean annual maxima significant wave height and mean wave period associated with annual maxima significant wave heigh for most of the West Coast region (Godoi et al. 2017) and is lower than the 1%AEP significant wave height for the region (5—6 m; Godoi et al. 2017). The value of wave setup is comparable to the wave setup at high tide during exTC Fehi on the open coast near Westport (0.75 m based on hindcast wave condition). The spatial variation in extreme wave setup is unclear. Large variation in wave setup in expected near small scale (10 – 100 m) bathymetric features that affect wave breaking and propagation but overall a small variation in wave height is expected in the extreme wave forcing outside the surf zone. Therefore, wave setup value of 0.8 m is applied for all CHA and for all the extreme water level calculations.

2.3.4 Extreme storm tide + wave setup elevations

The estimated ESL are consistent with the original analysis from Paulik et al. (2019) for the West Coast.

The 1% AEP Storm tide + wave setup elevations are shown in Figure 2-5. The ESLs for this large and infrequent event are generally in the range of 2.8 – 3.3 m above MSL. Table 2-3 contains the extreme sea levels for more frequent events near priority CHA locations.

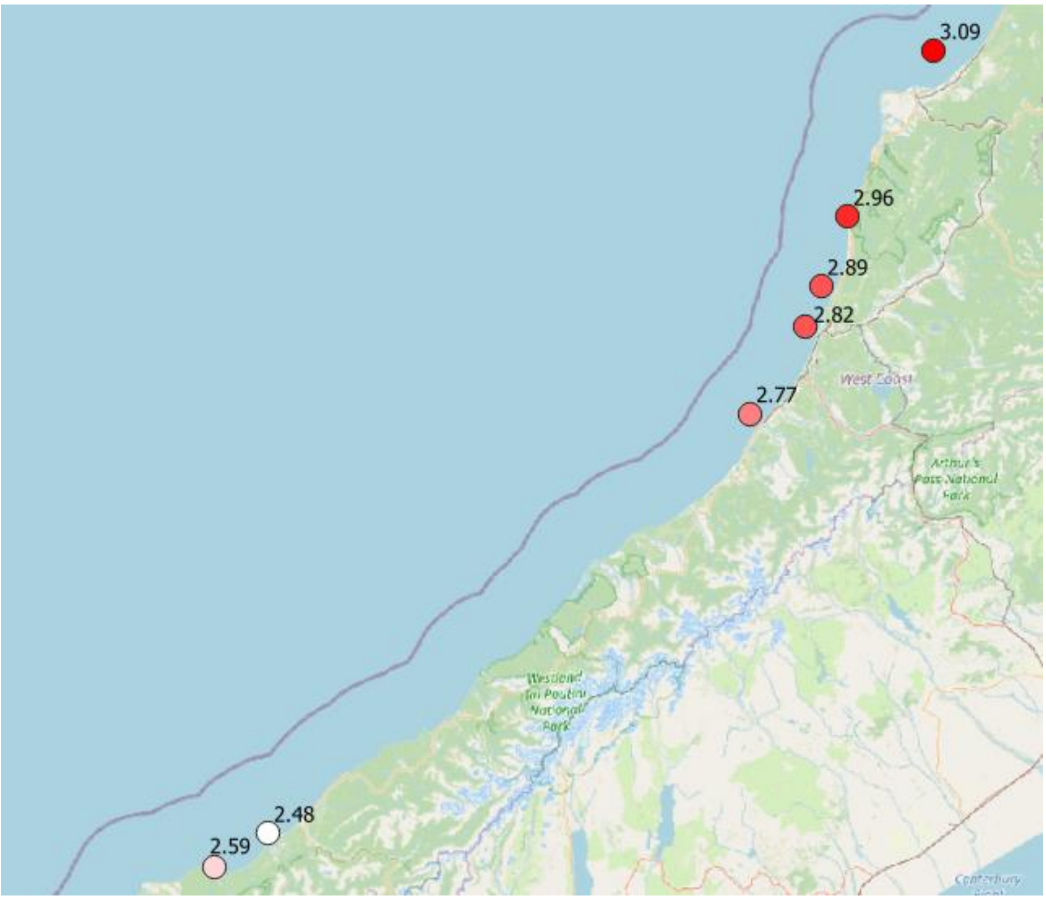

Figure 2-5: Output of 1% AEP storm-tide + wave-setup elevations above NZVD2016 along the West Coast used in this study. **Table 2-3: Extreme storm-tide + wave setup elevations on the open coast as mapped for Priority CHA assessment.** Elevations in NZVD2016 including CHA specific MSL offset. Coordinates in NZ Transverse Mercator (NZTM).

Site name	CHA	Easting	Northing	Storm-tide + wave setup elevation (m NZVD2016)					
				AEP: 39%	18%	10%	5%	2%	1%
				ARI: 2-year	5-year	10-year	20-year	50-year	100-year
Westport	3, 4	1499608	5390870	2.775	2.843	2.911	2.953	3.037	3.085
Punakaiki	12, 13	1464850	5336372	2.6643	2.729	2.7937	2.8335	2.9131	2.9578
Rapahoe	16	1455269	5307735	2.5995	2.663	2.7265	2.7655	2.8435	2.887
Greymouth	17, 18	1446107	5293434	2.5417	2.604	2.6663	2.7045	2.7809	2.8232
Hokitika	21	1432634	5268459	2.4923	2.554	2.6157	2.6535	2.7291	2.7708
Okuru	25	1270468	5130759	2.2357	2.292	2.3483	2.3825	2.4509	2.4872
Jackson Bay	26	1255444	5123506	2.3432	2.398	2.4528	2.486	2.5524	2.5872

2.3.5 Mean sea level offsets

The level of the sea is recorded at a number of tide gauges along the West Coast. These are located at or near Ports and Harbours, and are operated by the Regional Council or NIWA. Tide gauges record the level of the sea and are sheltered from the waves or rely on filtering to eliminate the temporary rise and fall in sea level with the passing of a wave.

Recent studies of national-scale assessment of extreme water levels (e.g. Paulik et al. 2019) included MSL offsets relative to local vertical datums as calculated and presented in Table S1 of Bell et al. (2015). For the West Coast Bell et al. (2015) applied a uniform 0.14 m offset which was carried through to the Stephens et al (2020) analysis and mapping extracted for this study.

However, these earlier studies did not have access to the recent tide gauge measurements made by LINZ at various locations and times from 2019-2021, nor the recent efforts of LINZ to survey the gauges into known vertical datums. Hence, we can now update the MSL offsets as provided to NIWA by the Technical Leader for Sea-Level Data at LINZ (pers. comm. Glen Rowe) for Westport, Greymouth and Jackson Bay (Table 2-4).

MSL for each priority CHA between LINZ MSL locations was approximated by manual interpolation of the MSL elevation with distance from the LINZ locations and following the apparent[8] trend of declining MSL elevation by approximately 100 mm from Westport to Jackson Bay.

These MSL elevation elevations are provided in Table 2-4 as reference sea levels underpinning the coastal hazard assessment but may be updated in time if LINZ update the data.

Table 2-4: Mean sea levels for coastal hazard assessment. MSL elevations from LINZ measurements pers. comm[9] MHWS-7 heights at nearest location Stephens et al. 2020. Manual interpolation between MSL locations indicated by *. Conversion from local vertical datum to NZVD via LINZ online converter[10]. Coordinates in NZ Transverse Mercator (NZTM)

Location	CHA No.	Easting	Northing	LVD-37 to NZVD2016 offset[10] at coordinates	MSL offset used in Paulik et al. (2019) national scale mapping	Updated MSL offset used in this study		Difference in MSL offsets (new – old)
				(m)	(m LVD-37)	Elevation (m LVD-37)	Elevation (m NZVD2016)	m
Westport[1]	3, 4	1499608	5390870	0.368	0.14	0.261	-0.107	0.121
Punakaiki	12, 13	1464850	5336372	0.319	0.14	0.23*	-0.089	0.09
Rapahoe	16	1455269	5307735	0.317	0.14	0.21*	-0.107	0.07
Greymouth[1]	17, 18	1446107	5293434	0.32	0.14	0.202	-0.118	0.062
Hokitika	21	1432634	5268459	0.346	0.14	0.202*	-0.144	0.062
Okuru	25	1270468	5130759	0.32	0.14	0.13*	-0.19	-0.01
Jackson Bay[1]	26	1255444	5123506	0.318	0.14	0.116	-0.202	-0.024

The effect of updated MSLs is that the extreme storm-tide + wave setup elevations that were inundation mapped are marginally lower or higher depending on the area of the West Coast. The largest difference is Westport where the updated MSL is now 0.121 m higher than previously used so the extreme sea level elevations and inundation mapping are underestimated by this amount. Table 2-4 demonstrates that other priority CHA sites have smaller underestimates (e.g., 0.09 m at Punakaiki), or very small overestimates (e.g., -0.024 m at Jackson Bay).

[8] Longer durations of measurements at intermediate locations is required to confirm the uniformity of this trend.
[9] MSL elevations: pers. comm. Glen Rowe, LINZ Technical Leader Sea-Level Data (email 2-Sept-2021)
[10] https://www.geodesy.linz.govt.nz/concord/

The WCRC should be aware of these updated offsets. However, MSL offsets of this magnitude are small compared to the combined potential uncertainties and limitations in the analysis and mapping methodology (refer Section 2.8).

Local offsets of this magnitude are relevant and may be applied to the dynamic process-based coastal/river modelling at Westport (this study) and Hokitika and Greymouth (as being completed concurrently by LandRiverSea consulting). This may be revisited when LiDAR is available region-wide.

2.3.6 Tides

This CHA analysis and underpinning extreme storm-tide analysis includes astronomical tide forecasts. High tide heights along the open coast, outside of estuaries, Mean High-Water Springs-7 (MHWS-7, representing the highest 7% of all astronomical high tides) were calculated from the NZ tidal model (Walters et al. 2001). These MHWS-7 values are heights above mean sea level.

This method of deriving MHWS differs from the LINZ method which is based on summing $M_2 + S_2 + N_2$ tidal constituents (i.e.,, lunar and solar tides) and gives results that are close to the LINZ method while providing a consistent measure around NZ in terms of the percent of high tides that exceed MHWS. The MHWS-7 elevation includes geographic tide variations, such as west coast spring-neap tides and east coast monthly perigean-apogean tides

MHWS-7 elevations were available from Stephens et al. (2020), and with readjustment to the local MSL elevations (Section 2.3.5 above), are provided relative to NZVD2016 in Table 2-4 and illustrated in Figure 2-6. These elevations are used within the underpinning tidal elevations for dynamic coast/river modelling at Westport, Hokitika and Greymouth.

The MHWS-7 elevations show a declining trend of approximately 0.5 m from Westport to Jackson Bay which is consistent with the declining amplitude of the major tidal constituents along this coastline (the M_2 and S_2 tides rise to the north).

Table 2-5: MHWS7 is the high-tide elevation exceeded by only 7% of high tides.

Location	CHA No.	Easting	Northing	MHWS-7		
				Height above MSL (m)	Elevation (m LVD-37)	Elevation (m NZVD2016)
Westport[1]	3, 4	1499608	5390870	1.60	1.86	1.49
Punakaiki	12, 13	1464850	5336372	1.49	1.72	1.40
Rapahoe	16	1455269	5307735	1.45	1.66	1.34
Greymouth[1]	17, 18	1446107	5293434	1.41	1.61	1.29
Hokitika	21	1432634	5268459	1.39	1.59	1.25
Okuru	25	1270468	5130759	1.21	1.34	1.02
Jackson Bay[1]	26	1255444	5123506	1.16	1.28	0.96

The intersection of the MHWS7 elevations with the land approximates the position of the Coastal Marine Area (CMA) boundary. There are a number of methods to estimate and map this jurisdictional boundary (e.g., Allis et al. 2021) and this may be used to approximate future CMA areas after increments of SLR. This mapping is not included in this study.

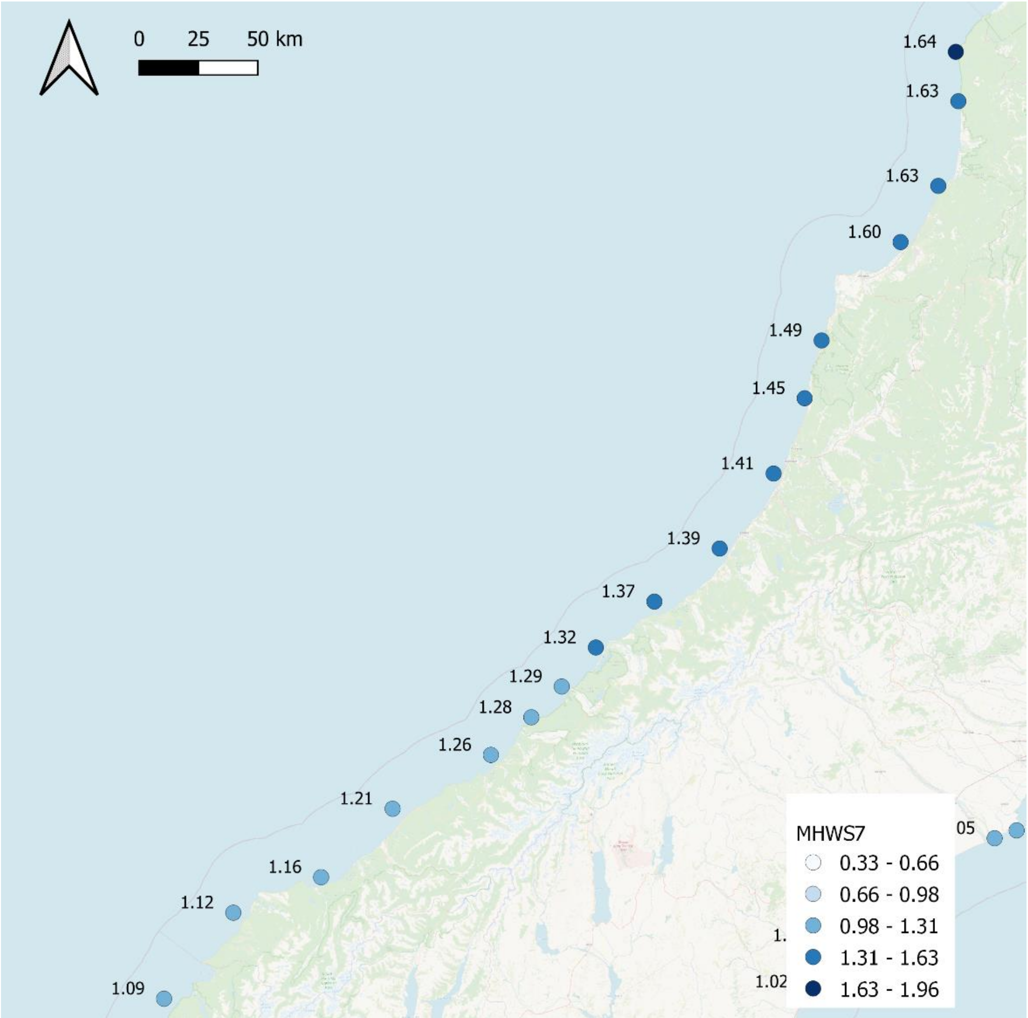

Figure 2-6: MHWS-7 heights (above MSL) along the West Coast. [Source: Stephens et al. (2020), Walters et al. (2001)].

2.3.7 Validation of storm tide and storm tide + wave setup

exTC Fehi was a notable storm event (Stephen et al. 2020) that produced highest storm tide on record at Jackson Bay and caused unprecedented coastal flooding in and near Westport. Storm-tide records from exTC Fehi in Westport and Jackson Bay provide an important data point for validating the values calculated in this study. In addition, recorded inundation levels in Westport following the event provide a robust validation for hydrodynamics)

Westport tide gauge is located well inside the Buller training wall which extend far beyond the breaking depth of large waves and as such is considered to be free of the influence of wave setup. The storm-tide recorded during exTC Fehi is 2.29 m LVD which is 0.11 m below the estimated 1% AEP storm-tide and 0.05 m below the 2% AEP storm-tide for Westport. Considering the uncertainties with the extreme analysis this comparison validates the storm-tide analysis.

In Jackson Bay, the tide gauge reached 2.33m above LVD, 0.4 m above the 1% AEP storm-tide and 0.4m below the 1% AEP storm-tide + wave setup. The tide gauge is located approximately 150m from the shore, so it was likely in the surf-zone during the event but not recording the full range of wave setup (which would occur at the shore).

Considering the uncertainties with the extreme analysis this comparison validates the storm-tide analysis.

2.4 Future sea levels

Climate change is causing the elevation of mean sea level to increase. All wave and tide processes are superelevated above this rising level.

Following the Ministry for the Environment (MfE) Coastal Hazards and Climate Change Guidance (MfE, 2017), we applied a series of SLR increments to forecast future coastal hazards which encompass a range of future sea-level scenarios. The increments selected range from 0 m to 2 m above present day mean sea levels in 0.2 m increments.

Simulating a range of sea level rise increments rather than SLR values linked to specific projections under different emission scenarios has a number of benefits has a number of benefits:

- The equivalent increment recommended in MfE (2017) or identified in IPCC AR6 projections can be easily identified.
- Local vertical land motions (VLM) which contribute to *relative* sea-level rise (RSLR) can be coupled to the future SLR projections and hence to the equivalent increment tie-ins. VLM is either subsidence of the land relative to the sea resulting in an additional sea-level rise relative to the land, or conversely uplift of the land results in a reduced relative sea-level rise. (VLM is detailed in Section 2.4.1).
- Future updates to SLR and VLM do not require new model scenarios as the any updated in sea level rise prediction can be tied to the nearest existing scenarios.
- Increments allow a look into the future without getting bogged down in the details of future projections which are expected to change.
- Increments are emission scenario neutral – hence allow for other climate change trajectories to be included.

One utility of incremental SLR mapping is also in that it can be repurposed for coastal adaptation management with communities. This approach involves considering a range of scenarios and pathways using the incremental SLR maps as resources. Triggers and decision points in a Dynamic adaptive planning pathways (DAPP) process.

2.4.1 Vertical land motion

Vertical land motion is the geological background trend of vertical land movement at a rate *independent* of the active seismic motion (i.e. earthquakes) and interseismic rates (Figure 2-7).

VLM combined with sea-level rise rates becomes *relative* sea-level rise (RSLR) as it includes the relative motion of the land as well as the rising sea level. If the land is subsiding (a negative VLM) the effect is a local acceleration of SLR, and the inverse for uplift (a positive VLM).

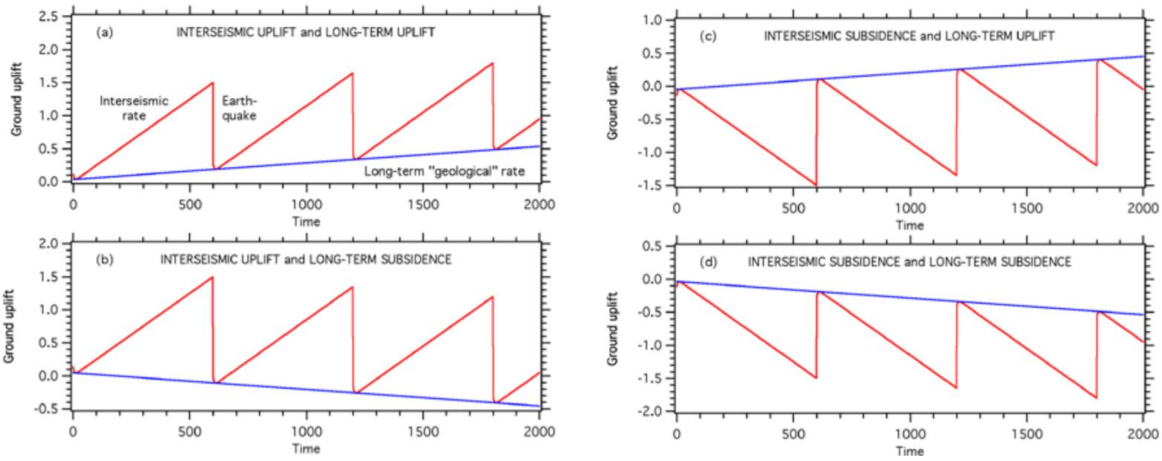

Figure 2-7: Explanation of vertical land motion rates. [Source: Beaven & Litchfield (2012)].

Continuous GPS (cGPS) sensors are operated by Geonet[11] at Westport, Hokitika and Karangarua and can be used to observe the different components of land motion such as uplift/subsidence, (Figure 2-7). Beaven and Litchfield (2012) determined local VLM rates on the West Coast from three continuous GPS gauges located near to the coast (Table 2-6). In 2012, these gauges showed slow subsidence (-0.8 mm/year over 8 years of data) at Westport and slower uplift (+0.3 mm over 10.5 years) at both Hokitika and Karangarua.

Table 2-6: Vertical land motion rates on the West Coast. Rates reported by Beaven & Litchfield (2012) and reanalysed for this study with simple least-squares linear trend from the start of the cGPS data to the end date before active seismic activity.

Name	Location	Easting	Northing	cGPS Start date	VLM (Beaven & Litchfield, 2012) mm/year	End date of linear trend (this study)	VLM (this study) mm/year
WEST	Westport	-41.7447	171.8062	01/01/2000	-0.8	1/10/2016	-1.47
HOKI	Hokitika	-42.7129	170.9843	23/09/2004	0.3	13/11/2016	0.16
QUAR	Karangarua	-43.5317	169.8158	05/02/2000	0.3	1/04/2015	0.25

Producing updated national estimates of past and future VLM is an active research task being undertaken by *NZSeaRise*[12]. However, until *NZseaRISE* produces[13] local VLM estimates, a linear trend estimation is appropriate to infer trends and has been used elsewhere for district plan assessments (e.g., for Wellington City Council in Bell & Allis, 2021).

Here we have estimated the background trend in the VLM from the beginning of the cGPS record through to a nominated end date (Table 2-6) which corresponds with a shift to active vertical land motion from (e.g., 14 Nov 2016 Kaikoura earthquake for HOKI) which is at the beginning of a recent period of seismic fluctuations (Figure 2-8). This is different from the rate of suggested in Figure 2-7 but for the relatively short record (relative to the seismic cycle) this provides a conservative rate.

[11] https://www.geonet.org.nz/data/types/geodetic
[12] https://www.searise.nz/
[13] Publication of the NZ SeaRise local projections of relative SLR projections is expected in early 2022.

The updated rates estimated here are consistent with the magnitude and trend of Beaven & Litchfield (2012) and show an acceleration of subsidence to 1.47 mm/year subsidence at Westport, and slightly reduced uplift of 0.16-0.25 mm/year uplift at Hokitika and Karangarua.

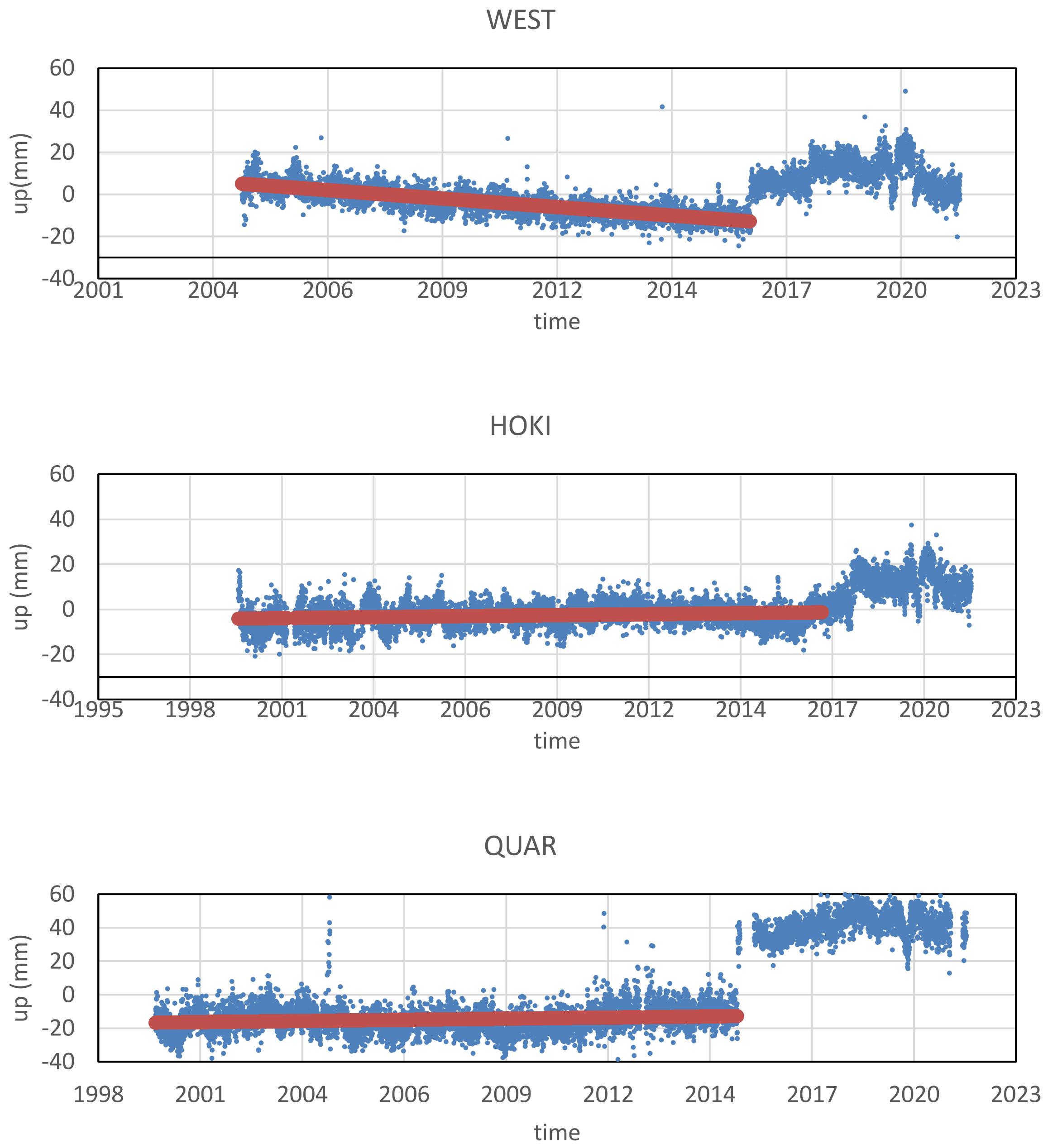

Figure 2-8: Vertical land motions recorded by cGPS sensors along the West Coast. Data shown for Westport (WEST), Hokitika (HOKI) and Karangarua (QUAR). Uplift = positive on the y-axis. Least-squares linear trend calculated from start of data to date reported in Table 2-6. [Data source: geonet.org.nz].

Extrapolating these rates out to 100-years to align with the district planning time scales, the VLM estimates would contribute an additional 0.147 m to relative sea-level rise at Westport, but only 16-25 mm at Hokitika and Karangarua (Table 2-7). This linear extrapolation assumes the ~14-year trend at each site will continue over the coming century which is deeply uncertain.

However, over this time period the 0.147 m is a non-negligible addition that MfE (2017) suggests should be considered in future planning.

Table 2-7: VLM extrapolated over 100-years for district plan timeframe.

Name	Location	CHA	VLM (this study) mm/year	VLM over 100-years mm	VLM over 100-years + 50% acceleration of trend mm
WEST	Westport	3, 4	-1.47	-147	-220
HOKI	Hokitika		0.16	16	24
QUAR	Karangarua		0.25	25	37

Taking a precautionary approach (c.f. NZCPS Policy 3) we have estimated VLM if the recent regional VLM trends were to accelerate by 50% over this timeframe. A 50% acceleration would lead to potentially 0.220 m subsidence at Westport at the end of 100-years, but still only 24 to 37 mm at Hokitika and Karangarua respectively (Table 2-7).

However, similar to the discussion about local MSL offsets (Section 2.3.5), the extrapolated VLM estimates must be considered in the context of the inherent uncertainties and limitations of the CHA inundation analysis, underpinning land DEMs, mapping method and SLR timeframes. Refer to Section 2.8 for an overview of methodological limitations.

Here, we have mapped future SLR increments at 0.2 m intervals, if the council wishes to include relative land motion in addition to SLR over the district planning timescale, then the recent or accelerated VLM rates effectively means the hazard map implementation should the *next highest increment* of mapped SLR for CHA which are closest to Westport. The VLM for the other cGPS sites appears small compared to SLR and may be neglected unless trends change.

These values should be updated, and hazard increment re-evaluated when the *NZSeaRise* results are released in 2022.

2.4.2 Sea-level rise

Sea-level rise is mapped on the land via increments of 0.2 m above present day sea levels. These increments are not tied to assumptions about any specific trajectory occurring, rather the *timing* that they occur is identified from the global projections. This is the approach recommended in MfE(2017) as part of a Dynamic Adaptive Planning Pathways (DAPP) approach because there is deep uncertainty about the actual trajectory of SLR because it depends on political and public efforts to restrain emissions globally.

We used the four SLR scenarios from MfE (2017), which are based around three greenhouse gas representative concentration pathways[14] (RCP2.6, RCP4.5 and RCP8.5). Three of the scenarios are derived from the median projections of global SLR for the RCPs presented by IPCC in their Fifth Assessment Report (IPCC (2019)) and extended out to 2130.

[14] Note that since NIWA was awarded this contract the IPCC produced new estimates of SLR in the Sixth Assessment Report (AR6). Note that AR6 uses new terminology of Shared Socio-economic Pathways (SSPs) to represent future SLR. The new SSPs have similar notation to RCP 2.6, 4.5, 8.5 with the equivalent SSP being between 0.04 - 0.12 m higher SLR at 2120 (100-year timeframe). The use of SLR increments for hazard mapping means this analysis is independent of SLR trajectory as the equivalent tie-in to SSP can be established.

The fourth higher scenario is at the upper-end of the "likely range" (i.e.,, 83rd-percentile) of the wide ensemble of SLR projections (from Kopp et al. (2014)) based on emission scenario RCP8.5—this scenario is called '*H+*'. This higher *H+* scenario reflects the possibility of future surprises (deep uncertainty) towards the upper range in SLR projections of an RCP8.5 scenario.

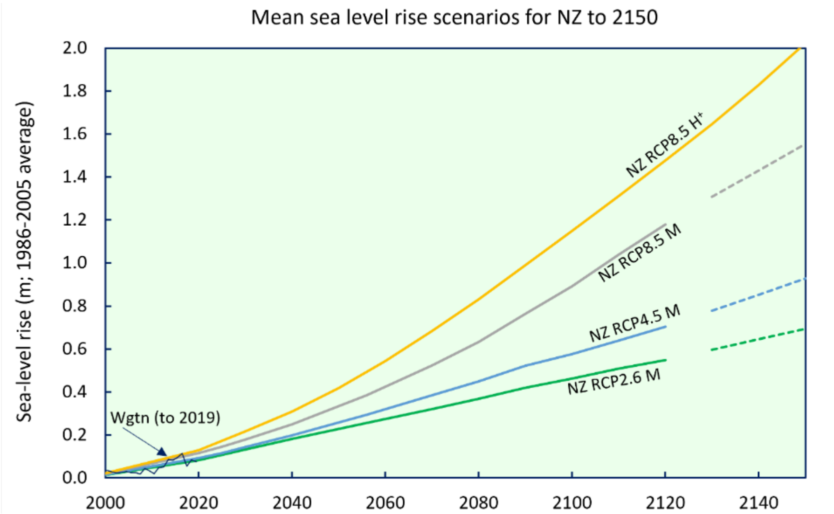

Figure 2-9: The four SLR scenarios for NZ (excluding VLM) from the MfE coastal guidance (MfE 2017) out to 2150 overlain by the annual MSL series from Wellington Harbour for 2000–2019. Note: SLR is relative to the 1986–2005 average MSL. Source: Projections - MfE 2017, tide gauge data – GWRC.

The scenarios in Table 2-8 and Table 2-9 have been adjusted to 2020 mean sea levels using the assumption that the sea-level rise trajectory lies exactly on the projected scenario at year 2020 and would follow that projected trajectory forward in time.

Table 2-8: 5-yearly increments for projections of sea-level rise for the wider New Zealand region. SLR listed in metres above 2020 mean sea level. (Adapted from MfE 2017)

Sea-level rise	NZ RCP2.6 *M* (median)	NZ RCP4.5 *M* (median)	NZ RCP8.5 *M* (median)	NZ RCP8.5 H+ (85th percentile)
2020	0	0	0	0
2025	0.025	0.025	0.03	0.035
2030	0.05	0.05	0.06	0.07
2035	0.075	0.08	0.09	0.115
2040	0.1	0.11	0.12	0.16
2045	0.125	0.135	0.155	0.21
2050	0.15	0.16	0.19	0.26
2055	0.17	0.19	0.23	0.315
2060	0.19	0.22	0.27	0.37
2065	0.215	0.25	0.315	0.435
2070	0.24	0.28	0.36	0.5
2075	0.265	0.31	0.41	0.57
2080	0.29	0.34	0.46	0.64
2085	0.315	0.375	0.52	0.715
2090	0.34	0.41	0.58	0.79
2095	0.36	0.44	0.64	0.865
2100	0.38	0.47	0.7	0.94
2105	0.405	0.5	0.77	1.015
2110	0.43	0.53	0.84	1.09
2115	0.45	0.56	0.905	1.17
2120	**0.47**	**0.59**	**0.97**	**1.25**
2125	0.495	0.625	1.03	1.33
2130	0.52	0.66	1.09	1.41
2135	0.545	0.695	1.145	1.495
2140	0.57	0.73	1.2	1.58
2145	0.59	0.765	1.26	1.675
2150	0.61	0.8	1.32	1.77

Table 2-9: Approximate years when specific sea-level rise increments could be reached for various projected scenarios of sea-level rise for the wider New Zealand region. SLR expressed in metres above 2020 mean sea level. Bold shows SLR increments mapped in this project. Adapted from (MfE 2017, Stephens et al. 2017).

SLR	NZ RCP2.6 (median)	*M*NZ RCP4.5 (median)	*M*NZ RCP8.5 (median)	*M*NZ *H*+
0	2020	2020	2020	2020
0.1	2040	2038	2037	2033
0.2	**2062**	**2057**	**2051**	**2044**
0.3	2082	2073	2063	2054
0.4	**2104**	**2089**	**2074**	**2062**
0.5	2126	2105	2083	2070
0.6	**2148**	**2121**	**2092**	**2077**
0.7	>2150	2136	2100	2084
0.8		**2150**	**2107**	**2091**
0.9		>2150	2115	2097
1.0			**2123**	**2104**
1.1			2131	2111
1.2			**2140**	**2117**
1.3			2148	2123
1.4			**>2150**	**2129**
1.5				2135
1.6				**2141**
1.7				2146
1.8 – 2.0	>2150	>2150	>2150	**>2150**

2.5 Tie in of mapped SLR scenarios to priority CHAs

The utility of using pre-mapped SLR increments to communicate future potential coastal hazard areas is that it doesn't tie the Council to a choosing a *single* SLR trajectory (e.g., one of those in Section 2.4.2), rather it enables the council to test exposure and risk using any trajectory, and also to see beyond the 100-year timeframe. This approach allows the council to include local adjustments based on information available at the time of assessment and update the mapping as new information comes to hand (e.g., LiDAR). However, this approach does require a process to systematically decide which mapped increment to use for specific mapping scenarios. The below diagram indicates the basic information process for the map of each area (Figure 2-10).

We also note that other council initiatives and preferences may also adjust the selection of mapped SLR increments; this could include taking a precautionary approach to accommodate potential uncertainties in underlying DEM or mapping method and selecting the next highest increment.

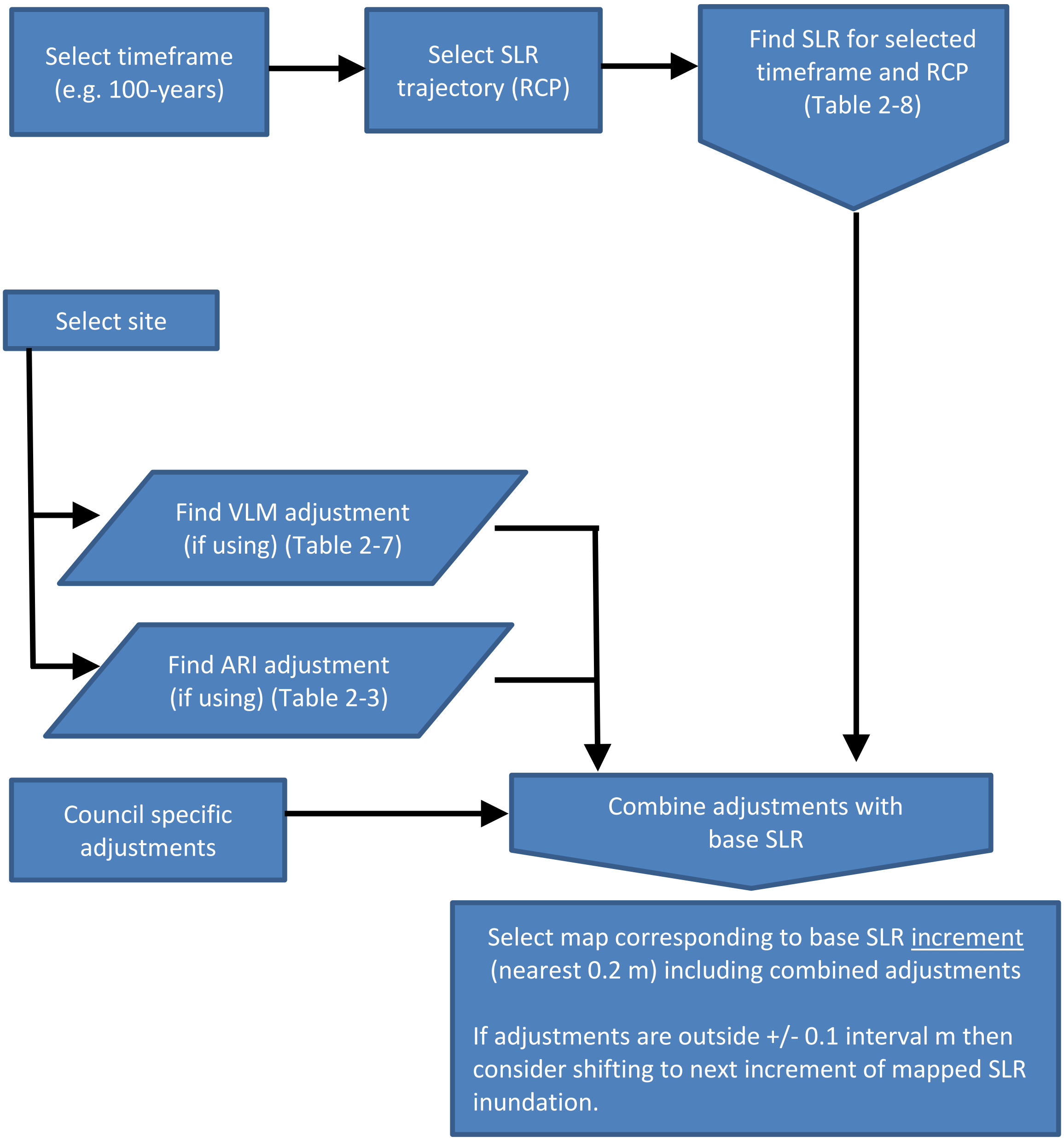

Figure 2-10: Flow chart for determining mapped SLR increment to use.

A worked example for the Westport area (CHA 3, 4) would include the following steps to establish that the mapped 1.2 m increment is the one to use for 100-year ARI maps for Westport area under the RCP8.5M scenario in 2120. But it would also be appropriate to check the 1.4 and 1.6 m mapped increments for potential emergence of hazards or hazard areas.

Table 2-10: Worked sequence for selecting mapped SLR increments. Refer to Figure 2-10.

Step	Selection
Site	Westport north area; CHA3 and 4
Select timeframe/AEP	100 years
Select SLR trajectory	RCP8.5 M => 0.97 m SLR in 2120. Also check if any key assets become exposed in RCP8.5 H+ scenario (1.25 m in 2120) as a stress test for the CHAs.
Find MSL adjustment	Potential MSL underestimate at Westport => +0.128 m adjustment
Find VLM adjustment	Potential VLM subsidence over 100-years near Westport (no VLM acceleration) => +0.148 m adjustment
Council adjustments	LiDAR DEM available, topography well defined. No council adjustment
Combine adjustments	MSL + VLM only => + 0.276 m adjustment
Combine adjustments with base SLR	RSLR estimate at 2120 => 1.246 (RCP8.5 M) => 1.526 (RCP 8.5 H+: stress test check)
Select nearest map	Nearest mapped increment to use: 1.2 m (RCP8.5M) 1.6 m (RCP8.5 H+)

2.6 Mapping of inundation (all pCHA except Orowaiti)

The calculated total water level elevations for each pCHA (i.e.,, storm-tide and wave-setup from Table 2-3, combined with SLR increments from 0 to 2 m), were mapped onto the coastline at discreet points along each CHA and extrapolated inland. The DEM (i.e.,, ground elevation) was then subtracted from the maximum water level surfaces to map inundation depth and extent. This static level or “bathtub” flood mapping approach assumes all land below the mapped sea level and connected to the ocean will be entirely inundated.

Coastal flood maps were created for 1%AEP storm-tide scenarios, mapped for the present day and for +0.2 m increments of SLR up to +2 m (i.e.,, 11 maps).

2.6.1 Limitations of bathtub mapping

The static flood mapping technique assumes that all land areas lower than the water levels at the shoreline are flooded to the same height as the shoreline water level. With the following notes

- Only areas that have a direct hydraulic connection to the sea are mapped.

- This excludes the potential for additional flooding effects from streams or drains 'backing-up' behind high coastal floodwaters, higher groundwater levels caused by rise of sea level and/or storm tides, and any terrestrial flooding from rainfall.
- The static flood maps exclude the building footprints. The exclusion does not affect the mapped flood depths as the static flooding does not account for volume continuity or presence/absence of buildings.

The major assumption in the GIS mapping procedure was the "bathtub" method use to map and assign the land area below extreme sea levels as inundated. Storm-tide peaks only last for 1–3 hours close to high tide (Stephens et al. 2016). This duration may not be sufficient to temporally inundate large land areas, particularly if storm-tide flow rates are restricted by a narrow connection to the sea e.g., drainage channels, culverts. The extreme sea level flood area maps therefore do not fully capture the dynamic and time-variant processes that occur during a coastal-storm event, but rather are indicative of areas of coastal flooding from static sea levels, or residual risk behind coastal defences such as stop banks and gravel barriers.

Bathtub flood mapping usually results in an over estimation of coastal flood extents from storm-tide levels where wave processes are less significant, or topography is flat and low lying. This is demonstrated by the comparative flooding extents from 'bathtub' and 'dynamic' models in Figure 2-11 and. Figure 2-12. The bathtub models show that more flooding (depth and extent) is indicated when the dynamics of the flooding process (e.g., variable depth, velocity, duration) are not included. This is illustrated in Figure 2-12 where the bathtub model overestimates flooding north of the main river feature where the topography is relatively flat. Little difference in flooding occurs south of the river where topography is steeper.

Despite its limitations, a bathtub method provides an approximation of coastal flooding extents for identifying key elements at risk e.g., populations, buildings, roads etc.,, More detailed dynamic modelling will produce more accurate flood scenario maps which may be required in areas with potentially high population and/or asset exposure (e.g., 'hotspots'), or where compound flooding hazards (riverine + coastal) are major contributors to flooding hazards (as modelled for Westport/Orowaiti in this study – Section 2.7).

Figure 2-11: Example comparison of dynamic model of flooding (blue) with bathtub model (red) for Tauranga. The scenario modelled was a 1% AEP storm-tide + 1.25 m SLR. In this case the duration of high sea-levels is insufficient to spread floodwater to the full extent predicted by the bathtub model. Source: Reeve et al. 2019.

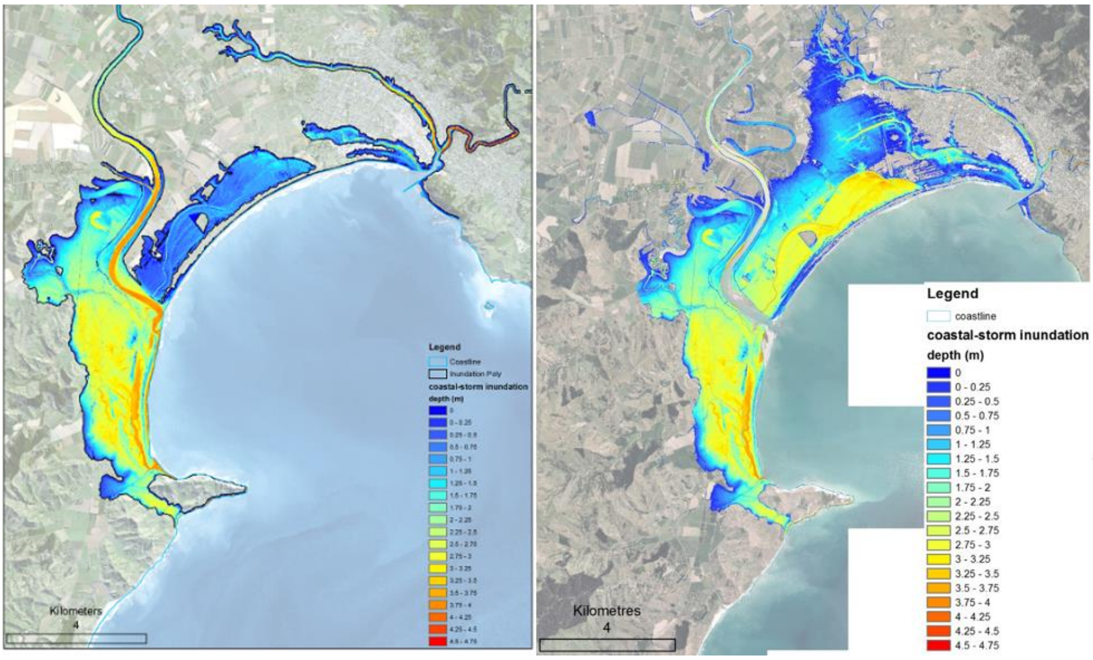

Figure 2-12: Example comparison of dynamic model of coastal flooding (left) with bathtub model (right) for Poverty Bay. Note the larger coastal flood extent created by the bathtub model. Source: Stephens et al. (2018).

2.7 Orowaiti hydrodynamics model

To simulate inundation in and around the Orowaiti, this study re-uses the calibrated Mike-21 hydrodynamic model initially developed for simulating fluvial flood inundation from the Buller River and the Orowaiti (see Gardner 2017 and attached note). Hydrodynamic models require more information than just the maximum ESL to predict the inundation.

2.7.1 Hydrodynamics model forcing

Mike-21 2d hydrodynamics model was used to simulate the inundation. While the model can be coupled to a wave model forcing it cannot simulate wave group forcing that causes infragravity waves. Instead, the model was forced with water level on the offshore boundary that include infragravity waves and wave setup. The Buller River in the model is included as a 1D model coupled to the 2d model. Because the 1D model extend beyond the surf zone, the outlet water level forcing in the Buller 1D model did not include wave setup but included infragravity waves. The wave setup forcing affects the area of the Orowaiti lagoon mouth.

ESL values provided in Table 2-3 for the 1% AEP storm-tide and wave setup represents the maximum water level reached at the coast. For use in a hydrodynamics model, these values have to be converted in a realistic time-varying forcing that includes the general shape of the rising and falling tide as well as high frequency sea level variation (infragravity waves) cause by wave sets.

The model forcing was calculated by generating a pure tidal signal with a single high tide reaching MHWS7 (Figure 2-13). The datum was then corrected to match the hydrodynamics model datum (LVD for the Orowaiti model but the final simulated maximum water level are converted to NZVD16). Storm surge (calculated as difference between storm tide and tide level) was then added as a shift of the tide so that storm surge + MHWS7 tide peak matches the expected storm tide values. The wave setup was then added as an additional shift so that the maximum ESL matches the values in Table 2-3. With the training wall extending beyond the surf-zone, the forcing for the Buller river mouth does not include wave setup.

Infragravity waves (often the leading cause of overwash and flood protection overtopping) were added in the forcing by generating a timeseries of long-bound waves at the boundaries of both the Buller River Mouth and the open-coast of the model. The long-bound waves were generated using XBeach model boundary generator (Roelvink et al. 2009), extracted and added into the ESL level boundaries for the main area offshore forcing and Buller River mouth (Figure 2-14) .

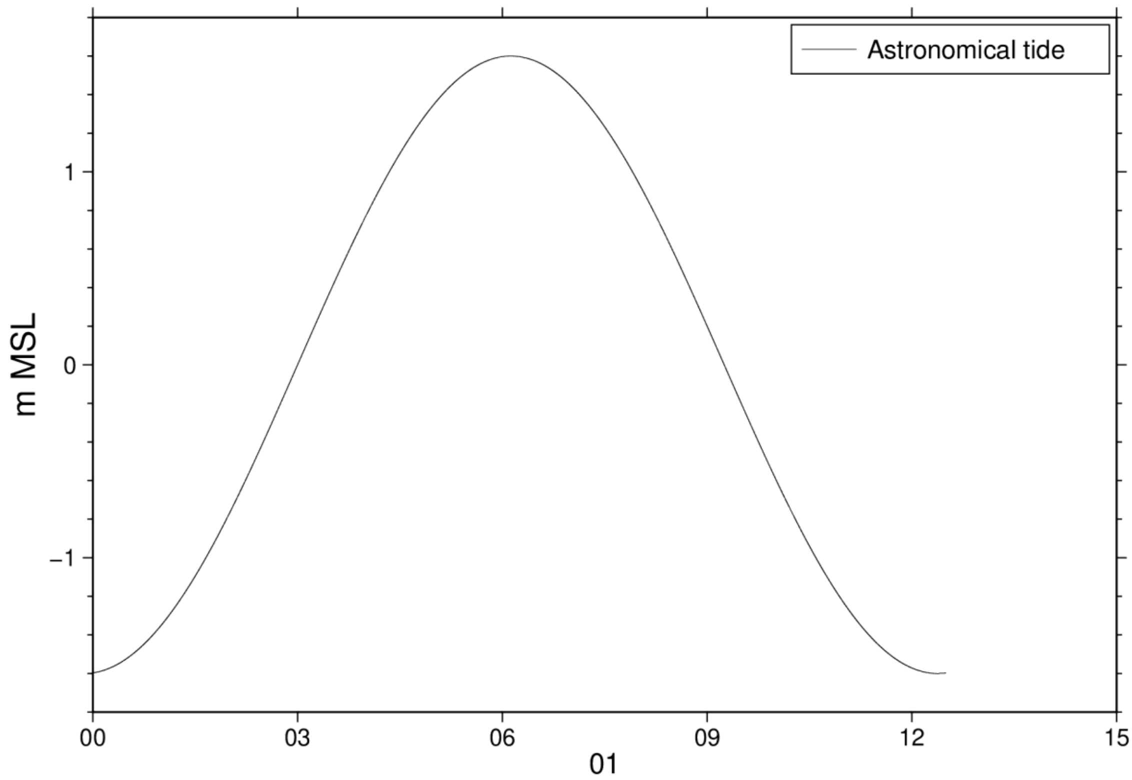

Figure 2-13: Design astronomical tide for the 1% AEP coastal storm for Westport .

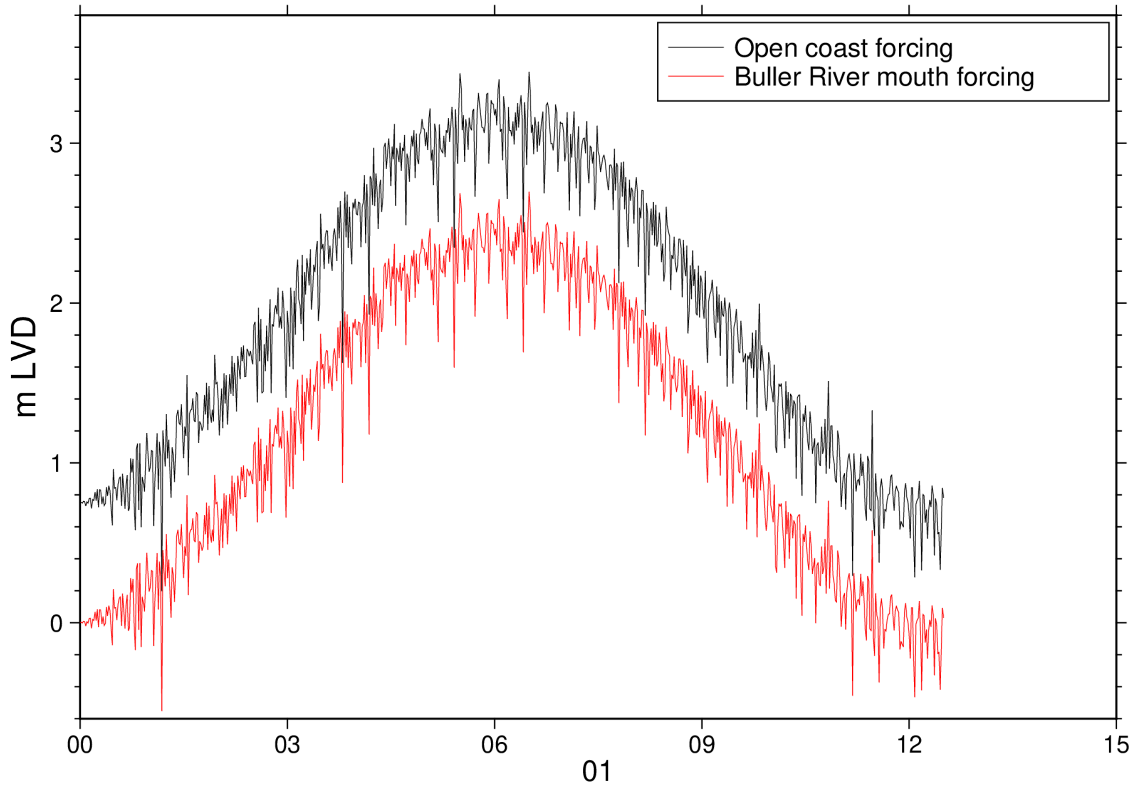

Figure 2-14: Forcing for the 1% AEP coastal storm. For the open coast the forcing includes storm-tide, wave setup and infragravity waves. For the Buller River mouth, the forcing only includes storm-tide and infragravity waves (i.e., no wave setup).

2.7.2 ExTC Fehi validation

In order to verify the validity of the hydrodynamics model, the model was tested by simulating the inundation caused by exTC Fehi.

The forcing of the model for exTC Fehi was generated using the same methodology above but this time using astronomic tide level (NIWA tide forecaster), time-varying predicted storm-surge (NIWA Forecast) and wave setup calculated from predicted offshore wave condition (eco-connect) (Figure 2-15). Infragravity waves calculated from the offshore wave condition as above was also added to ExTC Fehi storm-tide+ wave setup, with the wave energy peaking during low tide (Figure 2-16).

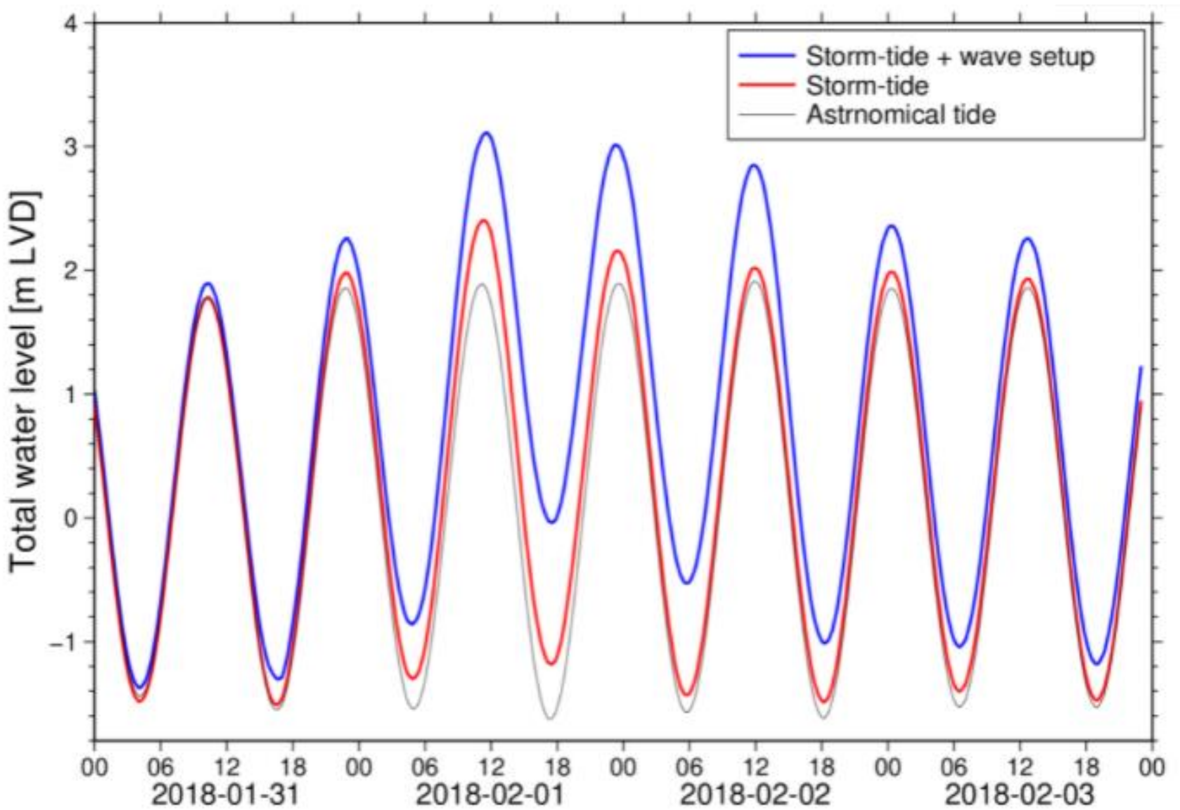

Figure 2-15: Construction of open coast forcing for exTC Fehi. Storm tide was extracted directly from eco-connect. Wave setup was calculated from wave parameters extracted from eco-connect.

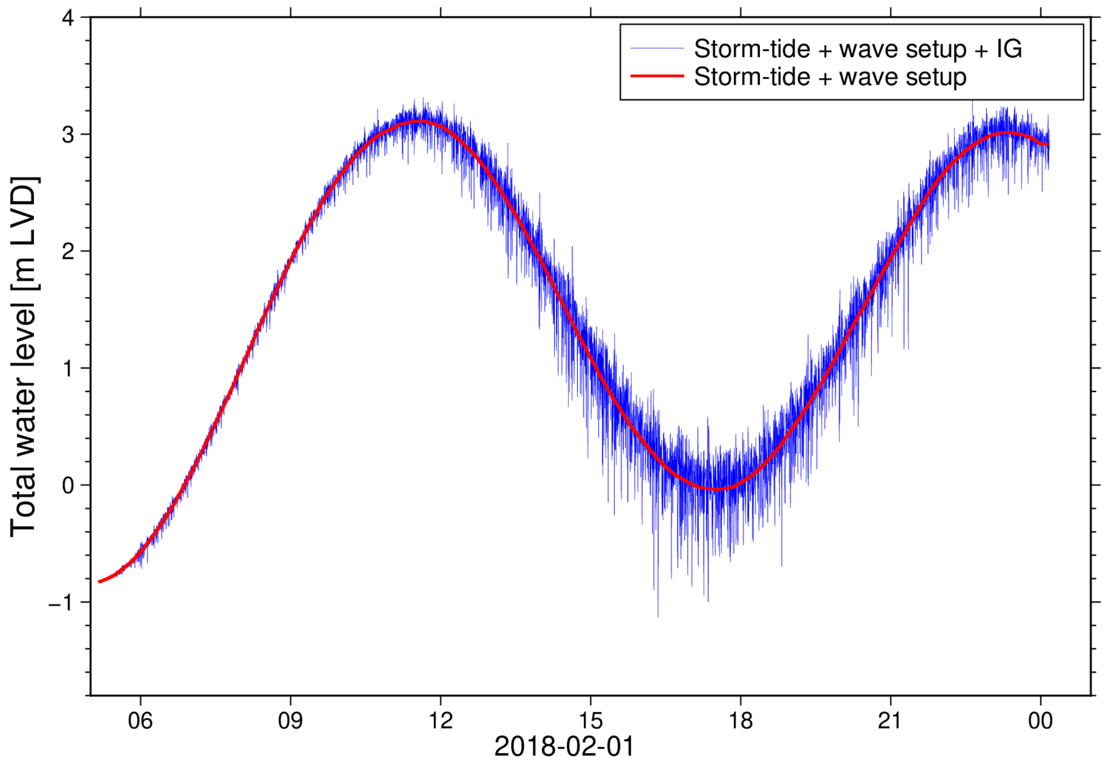

Figure 2-16: Open coast forcing for exTC Fehi including infragravity waves (IG).

The simulated inundation extent for exTC Fehi is remarkably similar to the recorded inundation extent (surveyed flood debris marks and witness accounts) (Figure 2-17). This simulation of exTC Fehi, in addition to previous flood simulation for this model setup confirms that this model is highly suitable for simulating flooding in Orowaiti Lagoon.

Figure 2-17: Validation of coastal inundation model for exTC Fehi. Blue dots show the location of surveyed flood debris marks, the red polygon area represents the inundation extent and flow direction observed by witnesses, blue shading represents simulated flooding from the hydrodynamic model.

2.8 Summary of coastal inundation section limitations

The methodological limitations arise within this work from:

- The generalised wave setup analysis (Section 2.3.3).
- Underpinning land elevation models (especially SRTM, refer Section 2.1.2).
- the uncertainties of the bathtub mapping methodology not including dynamic processes and overland flow dissipation (refer Section 2.6.1).
- The timing of future SLR trends, which depend on global efforts to mitigate carbon emissions (refer Section 2.4.2).

Given the potential uncertainties above, mapping future SLR scenarios in 0.2 m increments is appropriate.

3 Coastal Erosion methodology

This section describes the methodology for evaluating the coastal erosion hazard in unconsolidated shorelines. Coastal erosion has been recorded at all the pCHAs and some coastal protection measures have been put in place to mitigate the hazard. Erosion hazard is the result of complex non-linear interaction between ocean forcing (waves, tides, currents…), sediment supply, transport and the underlying geology and geomorphology. Thus, predicting geomorphological changes is highly uncertain. While some models can predict geomorphological changes with reasonable skill, they rely on a comprehensive knowledge of bathymetry, sediment size and sediment load that is unfortunately unavailable for most/all of the West Coast region. However, analysis of historical imagery can provide a measure of the trend in shoreline position that is a useful empirical proxy for long-term morphological changes that is location specific and accounts for coastal geomorphology and coastal climate (wind, waves, sediment supply, etc…). These historical trends were combined with the theoretical response of shorelines to predicted acceleration in SLR and the potential sudden retreat due to storms, to produce useful erosion hazard areas.

3.1 Erosion zoning methodology

The coastal erosion hazard areas were created from estimates of the future shoreline position combined with an allowance for processes that cause short term shoreline fluctuations and/or backshore slope failure. The base formula used to calculate the coastal hazard area width (Eq. (1)) was adapted from Gibb (1982).

$$W_{CHEZ} = rT + s \qquad (1)$$

Where W_{CHEZ} is a coastal hazard erosion area width (or distance from a reference shoreline); r is a rate of change including historical rate and accelerated future SLR, T is the time span for the hazard area planning period (50 and 100 years in this study), and s is a factor to account for short-term/sudden shoreline change due to storm erosion cycles. The formula has been applied at 20m intervals along the shoreline of each pCHA based on local estimates of the r and s terms (see sections 3.2 and 3.3. The actual hazard area is set back by the width W_{CHEZ} from the most recent shoreline position, which serves as a reference line.

A hybrid-probabilistic approach was used to manage uncertainty in the r and s terms in Equation 3.1. With a conventional probabilistic approach, both r and s in Equation 3.1 are represented by probabilistic distributions and (using what is termed a Monte Carlo approach) 10,000 realisations of W_{CHEZ} are made by drawing values of r and s at random from their respective distributions. The resulting distribution of realisations (e.g., Figure 3-1) shows what the range in projected hazard area width is, which width is most likely, and what the risk is that erosion could extend beyond any given width within the range. For example, if the line was drawn based on the 50th percentile of the realisations, which is the most likely outcome, then there would be a 50% chance that the erosion hazard would extend beyond that line by the end of the planning period. On the other hand, if the line was drawn based on the 95th percentile of the realisations, then there would only be a small (5%) chance that the actual future erosion hazard would extend beyond the line. It follows that for planning purposes, different percentiles may be chosen to match the value of assets and the level of risk.

For example, if the land in the possible hazard area range was farmland, then a reasonable risk of erosion could be accepted and a 50th percentile line might be used. However, in a township (with higher-valued assets), then only a small risk of those assets being eroded could be tolerated and so a 95th percentile line might best be used.

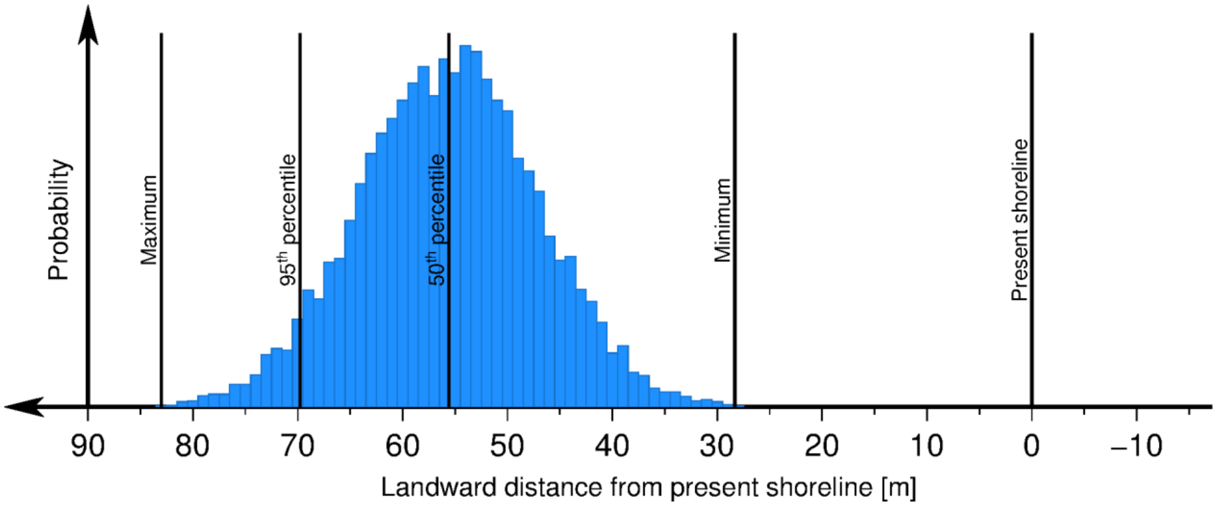

Figure 3-1: Example of probabilistic coastal hazard area prediction. The vertical blue bars show the histogram of 10,000 realisations of the W_{CHEZ} width made by drawing values of r and s at random from their respective distributions. The black bars represent statistical measures of the distribution. Source: Bosserelle et al. (2019).

The approach applied for this study is termed “hybrid-probabilistic” as it differs from a conventional probabilistic approach in two ways (Bosserelle et al. 2019). First, while in an ideal case the type of probabilistic distribution function selected should be the one that best fits the available data, on the West Coast, because of the limited amount of historical data available, a normal distribution was assumed for all terms. A normal distribution is reasonably justified to account for errors in digitization and shoreline detection that affect the estimation of historical shoreline retreat rates, but for short term shoreline fluctuations such as storm cut and slope failure, an extreme-value type of distribution is likely better suited but requires data on past extreme storm cut /slope failure to be fitted and that was not available. Second, in the ideal case, the procedures for determining the r and s terms in Equation 1 are well specified, so that the probability distributions assigned to them relate only to the uncertainties in the parameters used to derive them. This is the case, for example, with sandy beaches backed by dunes, where the effect of accelerated sea-level rise in the term can be calculated from the slope to closure depth using the “Bruun rule”, and the magnitude of short-term erosion “bites” can be assessed from repeated surveys of beach profiles. However, for other shore morphologies (e.g., rocky cliffs, perched beaches) for which neither the response to sea-level rise or the magnitude of shore erosion events are well formulated, the distributions associated with the r and s terms need to be estimated based on expert knowledge and approximation. Significant spans of the West Coast coastal hazard priority areas fall into this latter category because of the nature of the shore morphology and the availability of data. The upshot is that these hybrid modifications introduce additional uncertainty in the hazard area width that is not explicitly captured in the Monte Carlo probabilistic approach used herein. This additional uncertainty is difficult to quantify but can be managed in part at least by making a qualitative assessment of the reliability of the hazard area width for each shore morphology type.

3.1.1 Manual review/correction

All the coastal erosion hazard areas were manually reviewed to account for geomorphological features and underlying geology that the hybrid probabilistic approach cannot take into account. For example, when the probabilistic hazard width extends from a sandy beach system to a bedrock feature, the coastal erosion hazard area was manually corrected to the limit of the beach system. The manual-redraw also helped making transition between morphology so that adjacent hazard areas are consistent. Another correction was applied when the hazard area stops short of a significant geomorphological feature (e.g., the area was in a coastal wetland or across an old channel) that may be reactivated during an extreme event, in such situation the hazard areas was extended to cover the geomorphological feature.

3.2 Rate of shoreline changes (r term)

The shoreline rate of change was calculated according to equation (3.2). It is composed of the historical rate r_H and a term to account for erosion due to an acceleration of SLR (r_R).

$$r = r_H + r_R \tag{3.2}$$

Following the probabilistic approach each of the term of equation above is associated with a statistical distribution sampled accordingly in the Monte Carlo analysis.

3.2.1 Identify historical trends in shoreline movements (r_H term)

Identifying historical shoreline trend in a consistent manner across all the priority area involves the geo-referencing and digitizing of historical shorelines (back of gravel beach, vegetation line).

It is important to find the relevant shoreline markers. In this analysis the closest marker to the ocean were detected from the vegetation line, toe of dune, back of gravel barrier (refer to Boak and Turner 2005 for definitions) for each priority area, to adequately evaluate historical changes. For example, the gravel barrier in Rapahoe rolled over more than 30m since 1939 but the position of the vegetation line has not changed significantly (Figure 3-2). The detection of shorelines, for a range of dates, are necessary for shoreline trend analysis (e.g., Figure 3-3)

Georeferencing and shoreline digitisation can lead to errors that can be quantified using a sample of known points and by estimating the pixel size and sharpness of the feature detected (e.g., vegetation line versus toes of dune). These errors are important to quantify as they are used in the trend analysis and uncertainty estimation (e.g., Figure 3-4). This uncertainty (confidence interval) can then be accounted for in the probabilistic shoreline prediction.

Mean values of r_H are presented in Section 4 for each pCHA.

Figure 3-2: Georeferenced aerial image of Rapahoe in 1939 and the 2020 vegetation line (red line). Note the gravel barrier has rolled over and the narrow lagoon does not exist anymore. The gravel beach lies near the vegetation line and is depleted.

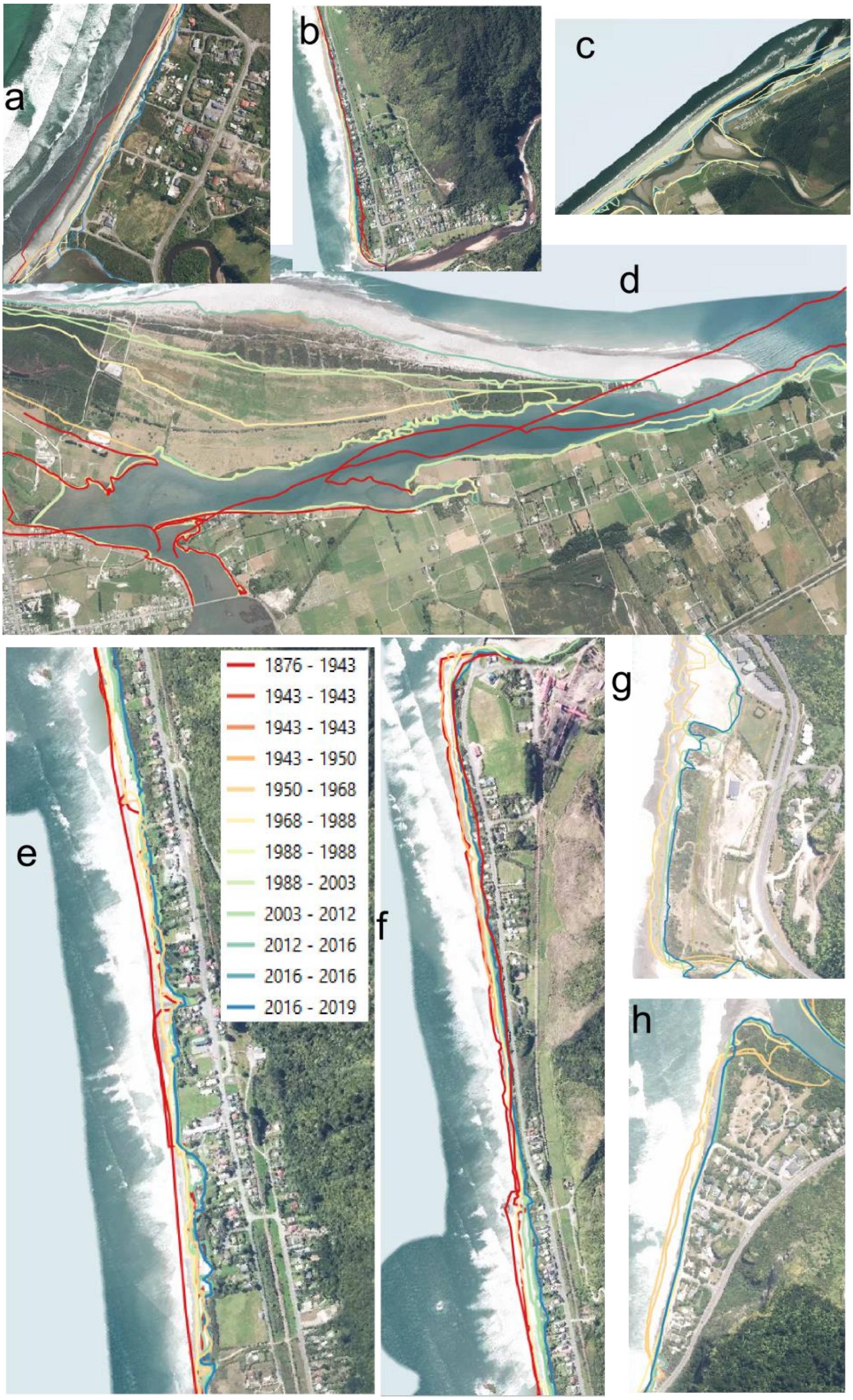

Figure 3-3: Overview of detected shorelines for key parts of the priority areas. The shoreline data has been provided along with this report for details. key areas are a) Rapahoe, b) Hector, c) Okuru settelment, d) Orowaiti lagoon, e) Granity, f) Ngakawau, g) Punakaiki Beach, h) Punakaiki Village..

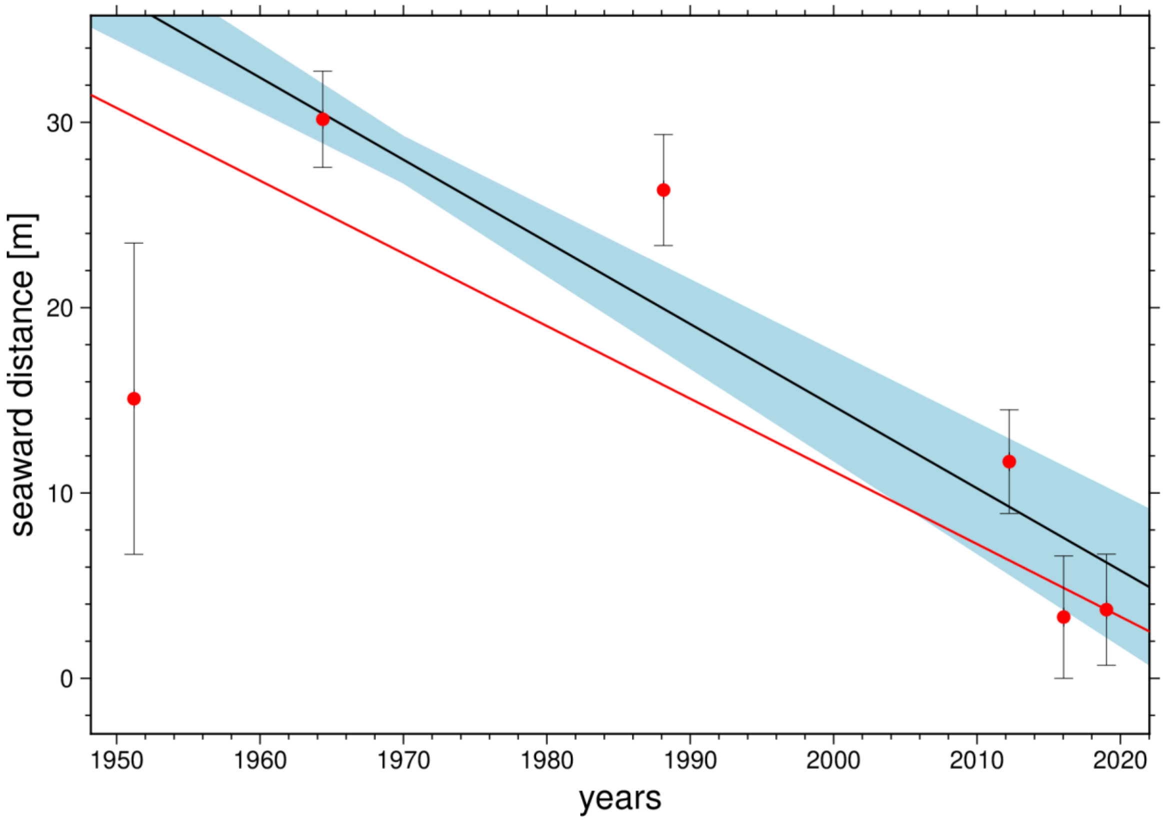

Figure 3-4: Example of shoreline movement trend analysis. Red dots represent shoreline position relative to an arbitrary onshore position. the error bar attached to the dots indicates the cumulated errors in georeferencing and digitisation. the black line is the most likely trend and the shading represents the 95th percentile confidence. The red line is the trend averaged across neighbouring transect and indicates the trend applied to the most recent shoreline.

3.2.2 Erosion due to the acceleration of SLR (r_R)

Erosion due to the acceleration of SLR (r_R) was calculated according to the geomorphology attached to a particular transect following a Bruun type approach. r_R only accounts for the effect of the acceleration of sea-level rise. That is because the historical contribution of SLR is already included in the historical terms. For shoreline geomorpohology dominated by reefs, bedrock (i.e., consolidated geology) or heavily armoured coastal protection, this term was set equal to zero (i.e., no additional erosion due to accelerated sea level rise, Eq. 3a). For sandy beaches and mixed sand and gravel (MSG) beaches (beaches with gravel barriers above sandy beaches), a Bruun rule is applied (Eq. 3b):

$$r_R = \begin{cases} 0 & (a) \\ \frac{Ld + Lb}{Hd - Hb}(r_F - r_H) & (b) \end{cases} \tag{3}$$

Sandy beaches, and mixed sand and gravel beaches

Conceptually, SLR is expected to accelerate shoreline retreat (or slow shoreline accretion) as sediment supply the submerged beach to fill the space made available by SLR. This is a broad definition of the Bruun rule.

While this concept is a simplification of a dynamic and complex natural system it provides a first order assessment of the potential exacerbation of shoreline retreat due to SLR.

The Bruun rule is summarised in eq. (3b) where Ld is the offshore distance to the depth of closure (offshore boundary where waves affect sediment redistribution), Lb is the distance of the dune/barrier crest to the backshore toe, Hd is the depth of closure, and Hb is the elevation of the backshore, r_F is the future rate of SLR (5 mm/y +/- 1mm/y) and $r_H$is the historical rate of SLR (3 mm/y +/- 0.2mm/y). While Hb and Lb can easily be calculated/estimated from Lidar data, the depth of closure is more complicated to calculate. The depth of closure Hd was calculated using Hallermeier (1981) equation but with the parameter derived from Birkemeier (1985) using a naturally distributed significant wave height 6.0m +/- 0.5m and a wave period of 11 s +/- 1 s. The offshore distance (Ld) was calculated assuming a Dean beach equilibrium profile with a Dean profile A value (Eq. (4)) normally distributed centred on 0.1 +/-0.03.

$$y = Ax^{2/3} \tag{4}$$

Using the formulations Birkemeier produces a distribution of closure depth with a peak at 8.7 m and a range of +/- 1.0 m. Using the calculated distribution of closure depth in equation 4 lead to an skewed distribution of offshore distance (Ld) with a peak at 815 m (typically ranging from 500m to 1600).

3.3 Short-term retreat (Roll-over /storm cut/sudden retreat) (s term)

Sudden retreat of shoreline due to storms needs to be accounted when creating coastal erosion hazard areas. For Sandy beach this parameter accounts for the storm cut (i.e. dune erosion/instability) that can occur in a single event. For mixed- sand-gravel beaches and in gravel barriers, the parameter accounts for the roll-over of the whole gravel system and is used to describe the hazard from the back of the gravel barrier. The short-term retreat is observed as a rapid roll-over of the gravel part of the beach and washing-over of material (sediment, driftwood, wrack) into the backshore. Evidence of these processes have been observed on-site during field visit (Figure 4-4, Figure 4-6, Figure 4-20, Figure 4-21, Figure 4-24, Figure 4-25, Figure 4-26, Figure 4-32, Figure 4-37) with short-term retreat distances in excess of 30 m inland observed on exposed coastlines, but short-term retreat observed inside lagoons/river mouths.

Because this process can occur at any time from significant/extreme storms, this process is approximated in Eq.(1) by adding a normally distributed buffer to the prediction of shoreline migration. Values used for different geomorphologies are presented in Table 3-1.

Table 3-1: Roll-over values for different geomorphologies .

Geomorphology type	Mean value	Standard deviation
Open-coast beach/gravel barrier, light—medium armoured shoreline	30.0	10.0

Geomorphology type	Mean value	Standard deviation
Reef protected beaches, heavily armoured shoreline	15.0	10.0
Sheltered beach and lagoon	5.0	1.0

3.4 Treatment of coastal defence structures

Notable coastal defence structures exist in Granity, on the school site and north, in Orowaiti lagoon and in Punakaiki Village. Estimating the coastal changes at the lee of coastal structure is challenging. This is because a residual risk always exists in the lee of structures and because the long-term risk is highly dependent on whether the structure performance will be maintained over time. For example, it is difficult to predict whether existing structure will be raise to match sea level rise and whether/how often the structure will be "topped-up" to compensate for sinking due to on-going erosion process undermining the structure.

In this analysis, only the structure of Granity and north, Orowaiti, Punakaiki Village are considered because these structures have existed and have been somewhat maintained for several years and resisted the erosion of exTC Fehi any other structures have been ignored.

In the analysis the historical shoreline retreat rate at the lee of the structure is lower than in the surrounding (unprotected) area because the structure has halted the erosion there. However, the historical rate of erosion is not null. Using this historical retreat rate provides a proxy for the residual risk in the lee of the structure. For example this term is a good proxy for the impact of the structure fails not because of a specific event but because of acceleration of erosion, or if the structure was abandoned, and the rapid erosion in the lee of the structure could occur in the following years.

The analysis also uses the short-term retreat term in the lee of structures to account for impact of extreme storms that can push debris well beyond the structure especially if part of the structure fails during the event.

No acceleration of the rate of shoreline retreat due to acceleration of SLR is considered in the lee of coastal structures.

4 Results

The scope of this project was to assess coastal hazard areas for a specific subset of pCHA provided by WCRC and defined in the CHA report (Table 4-1). This section contains a brief description of some the hazard area mapping and field observations. The full results of hazard mapping is presented in companion GIS layers.

The CHA report (Measures and Rouse 2022) includes a brief review of literature relevant to the CHAs and prioritises the areas based on a 'first pass' qualitative review of assets at risk and severity of the hazard, with low, medium and high priority assigned.

Here we add to the CHA report literature along with additional notes and observations from the 2021 field visit (see Section 1.4). Each CHA is qualitatively assessed for implications for the inundation and erosion hazard assessments and includes recommendations (e.g., based on morphology or hazards) for the analysis phase in later sections of this report.

Note that the extents of CHA25 and CHA26 were expanded for this Project at the request of WCRC (Table 4-1). The two CHAs have been renamed and extended within the GIS shapefile (see Appendix A) as supplied to WCRC.

Table 4-1: Priority Coastal Hazard Areas for this study. See Measures and Rouse (2022) for further details on other coastal hazard areas.

CHA	Location	Priority 2022	Status in 2022
CHA 3	Hector, Ngakawau and Granity	High	Existing
CHA 4	Orowaiti Lagoon	Low	New
CHA 12	Punakaiki Village (Pororari Beach)	High	Existing
CHA 13	Punakaiki River Beach	Medium	Existing
CHA 16	Rapahoe	High	Existing
CHA 25	Okuru to Waiatoto (renamed) Haast Beach to Waiatoto	Medium	Extended 2021
CHA 26	Neils Beach (renamed) Neils Beach to Jackson Bay	Medium	Extended 2021

4.1 CHA 3: Hector, Ngakawau and Granity

CHA3 extends from 3.5 m north of Hector to the mouth of the Orowaiti Lagoon near the outlet of Deadmans Creek (Figure 4-1).

The CHA shoreline is the edge of the Buller and Westport coastal plain which lies between the sea and the foot of mountain ranges which rise to the Denniston and Stockton plateaus (600-900 m elevation). The coastal plain is narrow (80 m) north of Hector but widens to about 3 km nearer to Westport. Multiple rivers and creeks drain the coastal ranges and discharge to the sea via river mouth lagoons and wetlands, the largest[15] being the Ngakawau River (~197 km^2 catchment), Waimangaroa River (50 km^2) and Whareatea (38 km^2) along with several smaller creeks and agricultural drainage channels. The coastal plain is generally uplifted higher in the south (approx. 4-8 m elevation) compared to the north where it is effectively at present day sea level.

The coastal fringe of the plain has multiple stranded beach ridges which area all aligned approximately shore-parallel from when they were formed e.g., at Jones Creek near Cains Road. Many of the swampy depressions between beach ridges the have been transformed into drainage channels for the adjacent pasture areas and creeks. The ridges generally are low beach ridges, only 2-3 m above the adjacent plains and bisected by creeks draining to the coastal lagoon and the sea.

The CHA includes the small coastal settlements of Hector, Ngakawau and Granity with land use on the coastal fringe plain dominated by dairy pasture with some natural areas of swamp and lowland forest remaining.

[15] https://shiny.niwa.co.nz/nzrivermaps/ -> River Environment Classification , Upstream Catchment Area

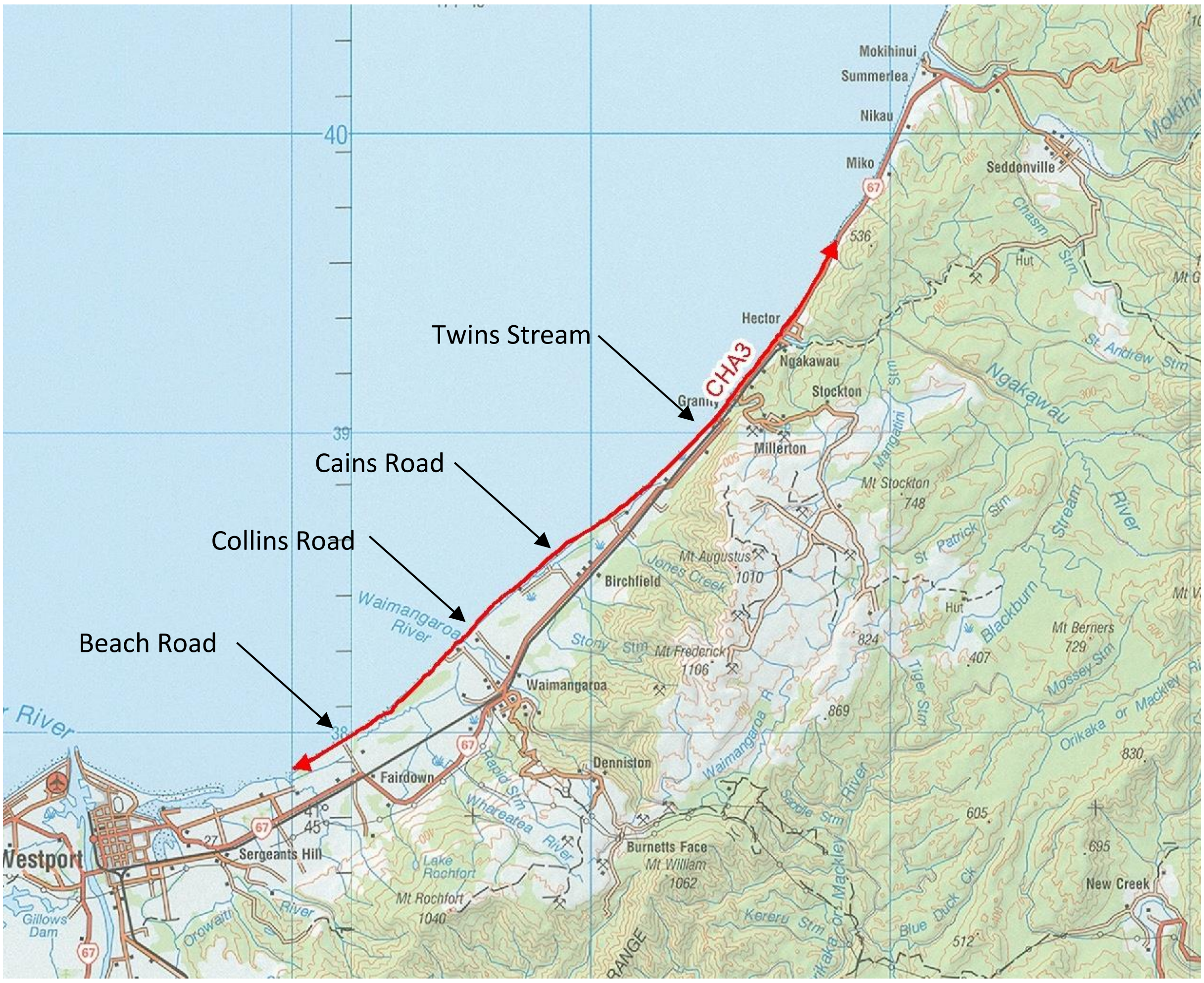

Figure 4-1: CHA3 extents. Annotations indicate locations mentioned in text or photographs.

4.1.1 Erosion

The shoreline in CHA3 is experiencing long term erosion combined with short-medium term (1-20 year time frame) cycles of accretion and erosion. Erosion is caused by wave driven abrasion and transport of material northward exceeding sediment supply from rivers and from the coast to the southwest. Erosion rates vary over the length of the CHA as well as over time due to varying wave conditions and sediment inputs from rivers.

Long-term shoreline retreat is evident for most of the coast northwest from Cape Foulwind and beyond CHA3. This entire coastline is readjusting to two major long-term processes:

1. The 300+ years since an alpine fault earthquake event has resupplied the rivers and beaches with a fresh supply of sands and gravels. Over geological time scales repeated earthquakes will cyclically deposit sands and gravels to build out the shoreline. At 2021 we are at the end of the ~300-400-year earthquake cycle hence beach material supplies from the rivers are reduced compared to the 1800s when the West Coast areas were surveyed and developed, and the coast was flushed with beach material.

2. The 120 years of readjustment to a new equilibrium shoreline position following the major shoreline change when the Buller River training walls were constructed and extended.

The training walls trap sediment either side of the mouth of the Buller River and restrict the flow of sediment reaching CHA3 resulting in erosion. In the 1860s the shoreline at the southern extent of CHA3 was previously 150 m further seaward than the present day with further historic erosion of the Orowaiti Lagoon shoreline and Deadmans Creek area in the late 1800s and early 1900s (see further the maps in Figure 4-10 as part of CHA4 analysis Section 4.2.1).

Most areas of the CHA 3 shoreline show signs of coastal retreat (e.g., Figure 4-2). The retreat is evident in erosion and undermining of the coastal terrace plain which is causing forests and grassland to be lost (Figure 4-3). Erosion and wave overwashing over the low dunes and berm is evident with sandy overwash deposits found in the adjacent paddocks (Figure 4-4). Erosion is creeping closer to private properties along the Granity-Hector shoreline except for where rock revetments and seawalls attempt to hold back the sea (Figure 4-5 and Figure 4-6).

Present-day shoreline variability is greatest near the mouths of the Ngakawau and Waimangaroa Rivers. Erosion rates in this CHA are sensitive to changes in sediment supply from the southwest (for example: sea-level rise resulting in build-up of beaches and storage of sediment west of the Buller River training walls). Any management practices which affect sediment delivery or movement along the shore within this CHA (i.e.,, groynes, beach mining or seawalls) have potential to impact on erosion rates/patterns.

At various properties in Hector, Ngakawau and Granity, sea walls or bunds have been constructed. These are highly variable in design and condition. Whilst somewhat effective at mitigating shoreline retreat and inundation hazards in the short term, these structures will not provide long term protection without substantial reinvestment and upgrades. Vegetated buffer zones have been planted along some parts of the coast to help slow erosion. At some river/creek mouths rip-rap armouring has been used to prevent mouth migration and bank erosion.

Figure 4-2: Shoreline retreat at southern end of CHA 3 (Beach Road) showing 3 m erosion scarp at end with adjacent vegetation loss. Date: 13.8.2021. [Credit: M Allis (NIWA)].

Figure 4-3: Erosion with 2-3 m scarp to the north of Beach Road towards the Whareatea River in CHA3 . Tall trees in distance are located on the north bank of the Whareatea River mouth. Date: 13.8.2021 [Credit: M. Allis (NIWA)]**.**

Figure 4-4: Wave overwashing through dune erosion and blowouts at Collins Rd. Overwashing deposits (sands and gravels) deposited 30 m inland from beach face. Date: 13.8.2021 [Credit: M. Allis (NIWA)].

Figure 4-5: Granity School revetment adjacent to rolling back vegetated gravel barriers. Date: 13.8.2021 [Credit: M Allis (NIWA)].

Figure 4-6: Erosion north of Granity School revetment with drain infilled, berm eroded and vegetation rolling back towards private property. Date: 13.8.2021 [Credit: M Allis (NIWA)].

4.1.2 Flooding

The low-lying coastal land in this CHA is subject to wave washover flooding during storms. This risk is increased by erosion of the gravel barrier at the back of the beach. Extensive property and road flooding occurred during exTC Fehi (Feb 2018). Flooding risk will increase with sea-level rise.

4.1.3 CHA Analysis

Both erosion and inundation will impact the CHA3 shoreline over the coming 100-years. Suitable aerial and satellite imagery was available to provide accurate shoreline detection for 1943, 1950, 1988, 2007, 2011, 2015, 2018. For some part of the CHA, cadastral charts from 1878 was used in the erosion analysis. The Bruun-type approach was applied for the area fronted with gravel barrier (north of Birchfield and north of Hector). No impact of acceleration of SLR is assumed where private coastal defence structures are expected to be maintained at their current location (Granity school, structures near Ngakawau and structures near Hector). In these areas the effective erosion rates are partially obscured by the installation of the structures. However, the hazard area still includes an erosion rate that crudely accounts for failure of the coastal protection.

CHA3 shows a consistent erosion trend apart from the area just north of Birchfield (Jones Creek) where accretion was observed. The most rapid shoreline erosion appears on the southern part of the CHA near Beach Rd, where erosion rates exceed 2.0 m/year (Figure 4-7).

In Granity, the resulting erosion hazard area based on 100-year outlook extends 70 – 90 m inland from the present shoreline (i.e. 20 – 30 m beyond the inundation hazard area for present sea level). In Ngakawau and Hector the erosion hazard area for a 100-year outlook is similar to the inundation hazard area for present day sea level.

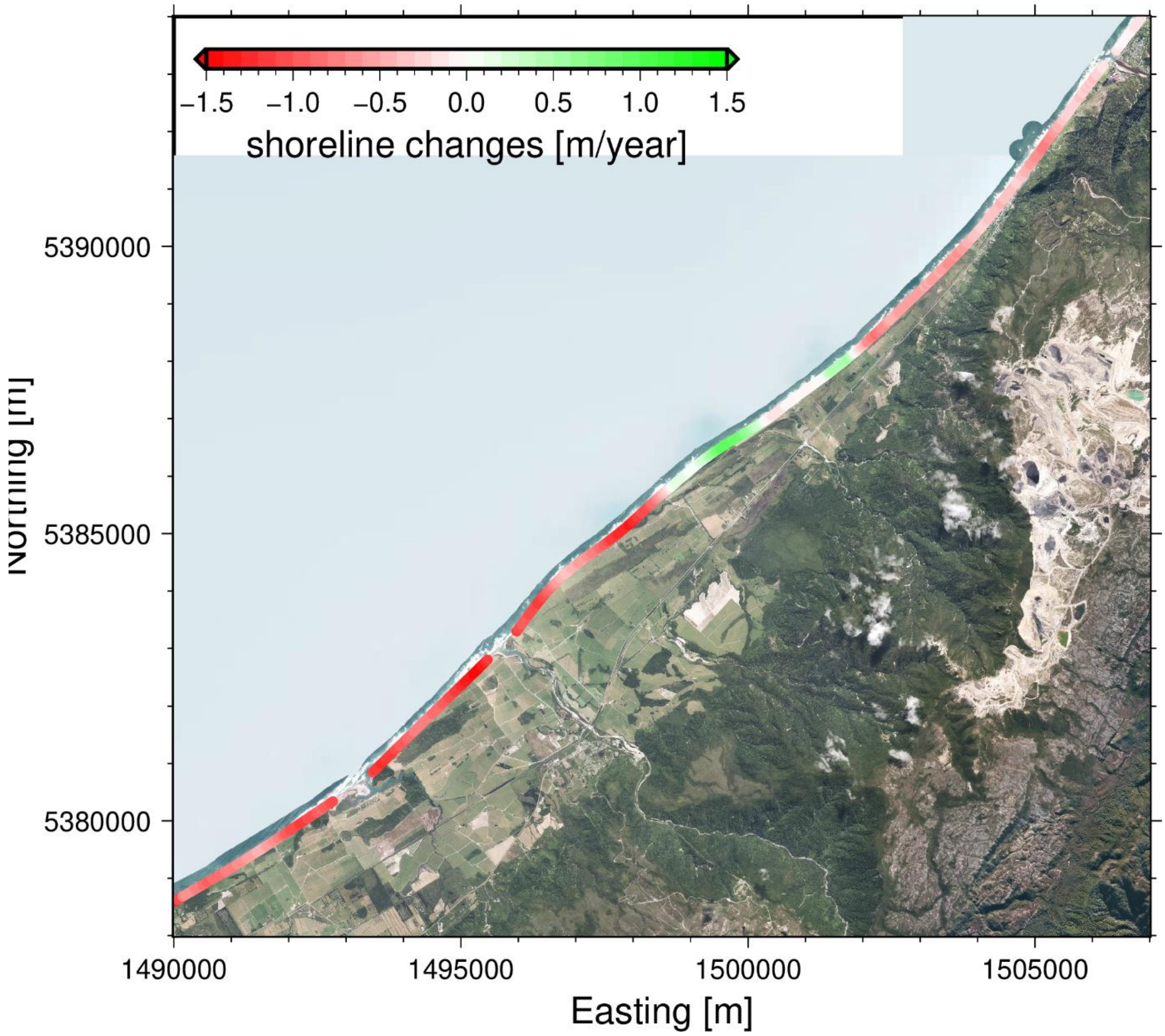

Figure 4-7: Hector to Orowaiti shoreline changes trends. White means no change; red is erosion and green is accretion.

Inundation assessment shows the low-lying land adjoining various river/creek mouths and lagoons and swampy depressions will be subject to increased flooding with sea-level rise. Future rainstorms will also cause increased localised flooding from drains and creeks backing up with sea level rise.

Coastal inundation from the 1%AEP storm-tide + wave-setup at present sea level affects properties only near Granity, Ngakawau and Hector. In these areas, the predicted inundation extends up-to 80m inland in Ngakawau and ranges 50 – 60m inland in Granity (Figure 4-8).

Figure 4-8: 1% AEP storm-tide+wave setup for present sea level in Granity Hector and Ngakawau . Blue shading shows areas at risk of inundation. The dash red line show the area of coastal erosion hazard for a 100-year outlook.

It should be noted that the multiple river/lagoon/beach systems can experience complex interactions between hazards. The interaction of river and coastal flooding and erosion are not covered in the static inundation assessment.

4.1.4 References

Allis, M. (2016a). *Adapting to coastal change at Granity, Ngakawau and Hector*. *NIWA Client Report* HAM2016-012, prepared for West Coast Regional Council.

Allis, M.J. (2016b). Letter note to WCRC (Paulette Birchfield) on advice in *Adapting to coastal change at Granity, Ngakawau and Hector* (NIWA, 2016) for community meeting 22-Nov 2016. 4p.

Benn, J. (2002) *Evaluation of the effects of Stone Removal North of Westport*, prepared for West Coast Regional Council by DTec Consulting Ltd.

Benn, J. and Todd, D. (2005) *Coastal Hazards Assessment: Proposed Fairydown Farm Sub-division; Beach Road, Whareatea River, Buller District*, report for Fairydown Farm Ltd by DTec Consulting Ltd.

Benn, J. and Todd, D. (2007) *Review of Proposed Coastal Protection Works for 12a-14 Main Road, Ngakawau*, report for Alan Merrett by DTec Consulting Ltd.

Benn, J. and Todd, D. (2010) *Updated Coastal Erosion Assessment: Fairydown Farm Sub-division; Beach Road, Whareatea River, Buller District*, report for Fairydown Farm Ltd by DTec Consulting Ltd.

Ramsay, D. (2006) *Managing and Adapting to Coastal Erosion on the West Coast: Granity*. Prepared for West Coast Regional Council*, NIWA Client Report* HAM2006-153.

Ramsay, D. (2007) *Managing and Adapting to Coastal Erosion on the West Coast: Ngakawau and Hector*. Prepared for West Coast Regional Council, NIWA Client Report HAM2007-007.

Single, M. (1999) *Statement of evidence regarding physical coastal processes at the site of the proposed West Coast Coal Terminal*.

Single, M. (2009) Review on the effects on the physical coastal processes of a proposed groyne at Ngakawau, report for Allan Tyler by Shore Processes and Management Ltd.

4.2 CHA 4: Orowaiti Lagoon

This CHA covers the Orowaiti Lagoon and the coastline affected by the Orowaiti River mouth processes (Figure 4-9). The northern limit of this CHA is the same as the southern limit of CHA3.

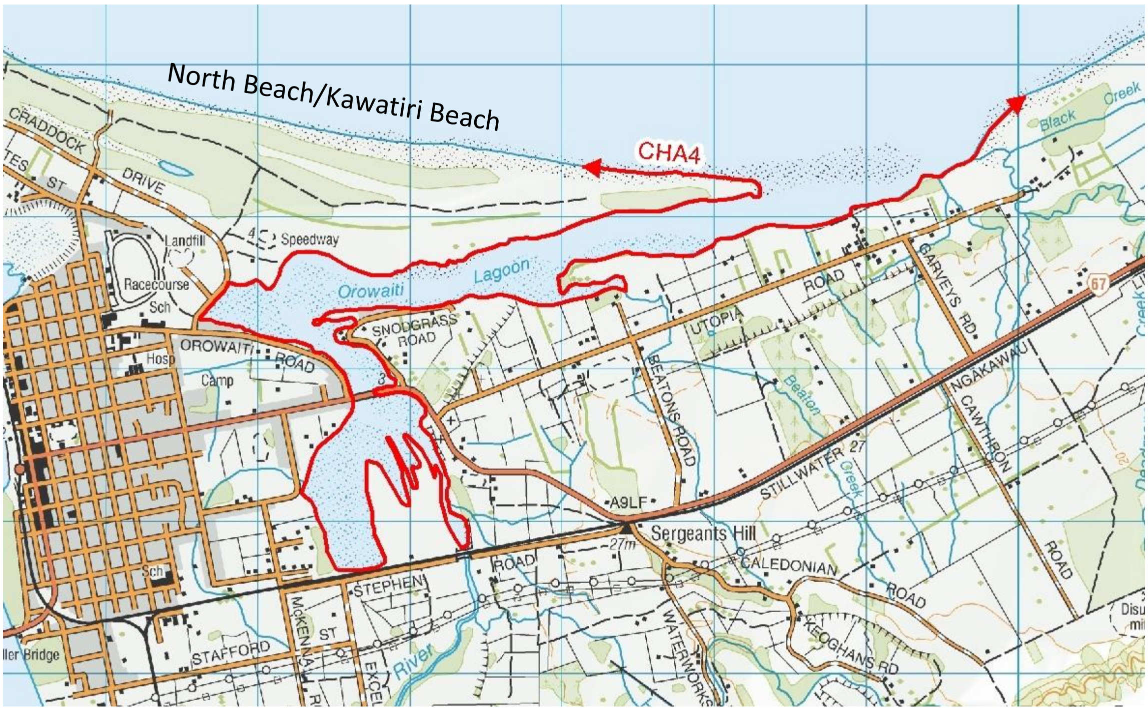

Figure 4-9: CHA4 extents.

4.2.1 Historic shoreline changes

The Westport area has a long history of shoreline change resulting from efforts to control the Buller River and maintain a safe navigable channel to Westport. To achieve this, the then-Harbour Board constructed large river training walls in the late 1800s which were extended several times in response to land accreting around the river and the channel becoming unnavigable. The latest extensions were in the 1970s (Allis, 2015).

The present-day Orowaiti lagoon is separated from the sea by the 300-800 m wide sand spit (named North Beach or Kawatiri Beach, Figure 4-9) which has accreted in the 140 years since the construction and extension of the Buller River training walls began (similar to Carters Beach on the western side of the Buller River).

The 1860s-1880s shoreline, before efforts to control the Buller River began, was a long low sea-cliff approximately 200 m out to sea from the present-day southern bank of the Orowaiti Lagoon (Figure 4-10) and eastwards beyond Deadmans Creek outlet.

West of Beatons Creek the 1860 coastline continued along the present-day lagoon shore, passing a low island (present day Snodgrass Road) and crossed the former mouth of the Orowaiti River 400 m downstream from the Orowaiti Bridge (where the lagoon presently turns 90 degrees east). The shoreline continued west along the line of Orowaiti Road and curved around Bright Street into the river channel where it merged with an extensive river mouth and intertidal bar system with islands (e.g., Martins Island), shingle-spits, sand-banks and river overflow channels (of which the Orowaiti River is one). All the land north of Bright Street was created by sediment accumulating in the lee of the river training walls, this accumulation slowly built up the pre-existing sandbars and sand banks however it remains generally low lying with some low dunes and swampy areas.

The consequence of the growth of Carters Beach and North Beach is that longshore sediment transport was intercepted, and, combined with the river mouth discharging bedload sediment into deeper water, the shoreline downdrift (east and north) was starved of sediment for several decades. Overlaying the 1880 district survey maps illustrates the sediment starvation resulted in 100-200 m of sea-cliff erosion around the Orowaiti Lagoon from Beatons Road north east. Survey records show that the shoreline retreat continued for 15 km north as far as Jones Creek and Cains Road near Birchfield. The persistent beach retreat at Granity, Ngakawau and Hector (20 km north) is also linked to the interruption to longshore sediment transport at Westport/Orowaiti.

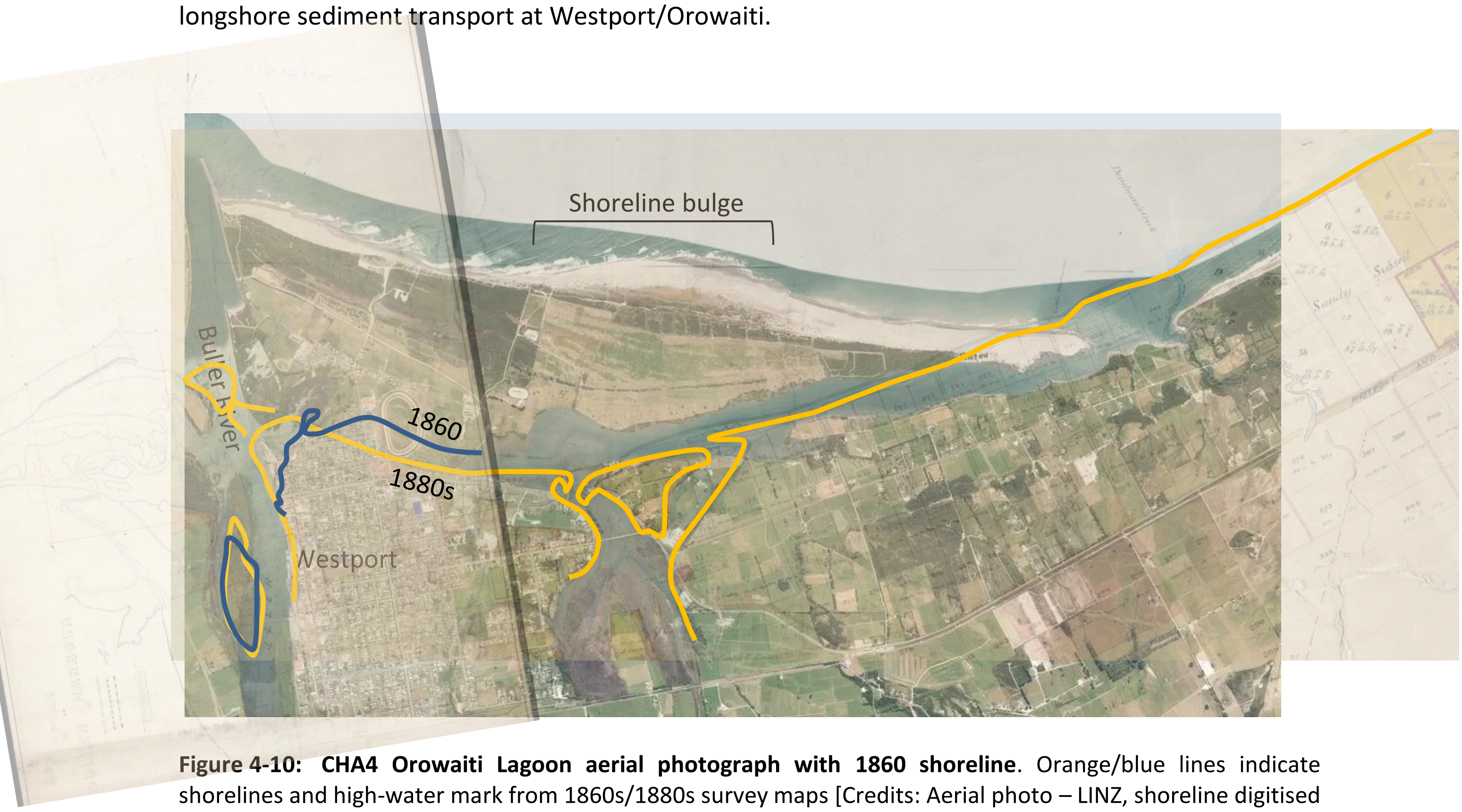

Figure 4-10: CHA4 Orowaiti Lagoon aerial photograph with 1860 shoreline. Orange/blue lines indicate shorelines and high-water mark from 1860s/1880s survey maps [Credits: Aerial photo – LINZ, shoreline digitised from NZ archives (ref: CH1031/SO 159 (1873), and Archway Record Code: R17224538 (1860)].

4.2.2 Erosion

At the eastern end of the lagoon, erosion due to mouth migration of the Orowaiti River (generally eastwards) has caused significant land loss in the past and is on-going at areas between Garveys Road and the outlet of Deadmans Creek/Black Creek. The mouth migration has changed the exposure of the shore to wave action and can also cause erosion by river and tidal flows. At the lagoon mouth several large rock revetments and groynes have been constructed on the South side of the mouth to try and prevent erosion/mouth migration (Figure 4-12). Several of these have already been out-flanked as the Orowaiti River mouth merges with Deadmans Creek and Black Creek (Figure 4-12).

Within the lagoon, local wind-waves and river floods can cause bank erosion and various short sections of shoreline are armoured to prevent erosion.

There is a large sediment bulge migrating slowly along the forebeach at North Beach (Figure 4-10) which will eventually migrate towards the Lagoon mouth. This will result in a phase of additional pressure on the lagoon mouth pushing further eastward. This effect will be temporary (a period of years to decades) as the sediment bulge slowly sweeps north.

4.2.3 Flooding

There are extensive low-lying areas around the lagoon where properties, roads and farmland are threatened by high tides, storm surges and river floods. River flooding is a major driver of inundation as the Orowaiti River is an overflow branch of the Buller River. Sea-level rise will significantly increase flooding risk in the future.

Extensive property flooding occurred during exTC Fehi (Figure 4-11) and during July 2021 Buller River flooding.

Figure 4-11: Flooding of Snodgrass Road during exTC Fehi alongside the Orowaiti River, Westport. [Credit: WCRC].

Figure 4-12: Sand spit and coastal protection rocks at the mouth of the Orowaiti River and Deadmans Creek. Photograph viewing West towards North Beach and Westport from the north bank of Deadmans Creek. Date: 13/8/2021. [Credit: M Allis (NIWA)].

4.2.4 CHA analysis

Both erosion and inundation will impact the land surrounding the Orowaiti Lagoon CHA over the next 100-years. Sea walls and coastal protection structure have been constructed to most of the shorelines used for erosion hazard assessment since early 1900s. Hence, most of the analysis show no trend in shoreline changes. The coastal erosion hazard area there correspond to the short-term erosion cutback. These structures are expected to be maintained in position and upgraded to match rises in sea level. The large-scale shoreline changes from the 1800s were due to the construction of the Buller River training walls. The earliest records are not useful for establishing recent and future shoreline trends in some areas of the Orowaiti Lagoon as they were a consequence of artificial interruption to natural shoreline processes and unlikely to be repeated under the modern resource management framework. Suitable aerial and satellite imagery available for accurate shoreline detection exist for 1943, 1951, 1988, 2000, 2003, 2016, 2018. The analysis accounts for seawall and structures on the shoreline of the lagoon that are expected to be maintained at their current position. Coastal defence structures near the mouth of the Orowaiti are not expected to remain at their current position in the long term because of the fast erosion rate.

The Orowaiti Lagoon shoreline has been generally stable since its original extension/growth following the construction of the Buller River training walls. However, the migration of the mouth towards the north-east is resulting in some severe erosion (up-to 2.0 m/year) of the shores directly east of the mouth. The west side of the lagoon has also shown signs of erosion despite the accretion of Kawatiri Beach (Figure 4-13).

The resulting hazard area for the 100-year outlook for east of Orowaiti Lagoon mouth exceeds 200m but doesn't exceed 20 m in the inner part of the lagoon.

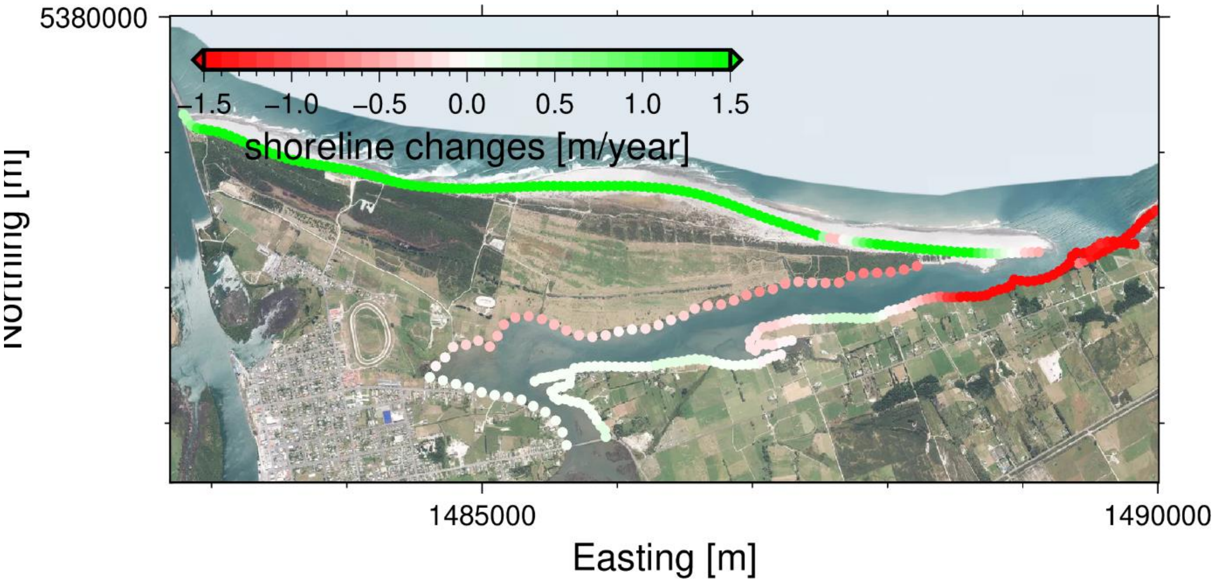

Figure 4-13: Orowaiti shoreline change trends.

Hydrodynamics simulation was used to assess the coastal inundation hazard in Orowaiti Lagoon (see section 2.7 for details). The simulation included combined river and coastal flooding scenarios as these multi-hazard events are expected to increase in the future with SLR and climate change. ExTC Fehi inundation data was used to validate the model.

Overall, inundation and flooding from river/coastal floods is the dominant hazard for the Orowaiti Lagoon CHA. Except for at the lagoon mouth, erosion rates are generally slow due to limited wave fetch and bank protection, whereas widespread areas of land are low lying and flood prone (Figure 4-14). Sea-level rise will significantly increase this risk in the future.

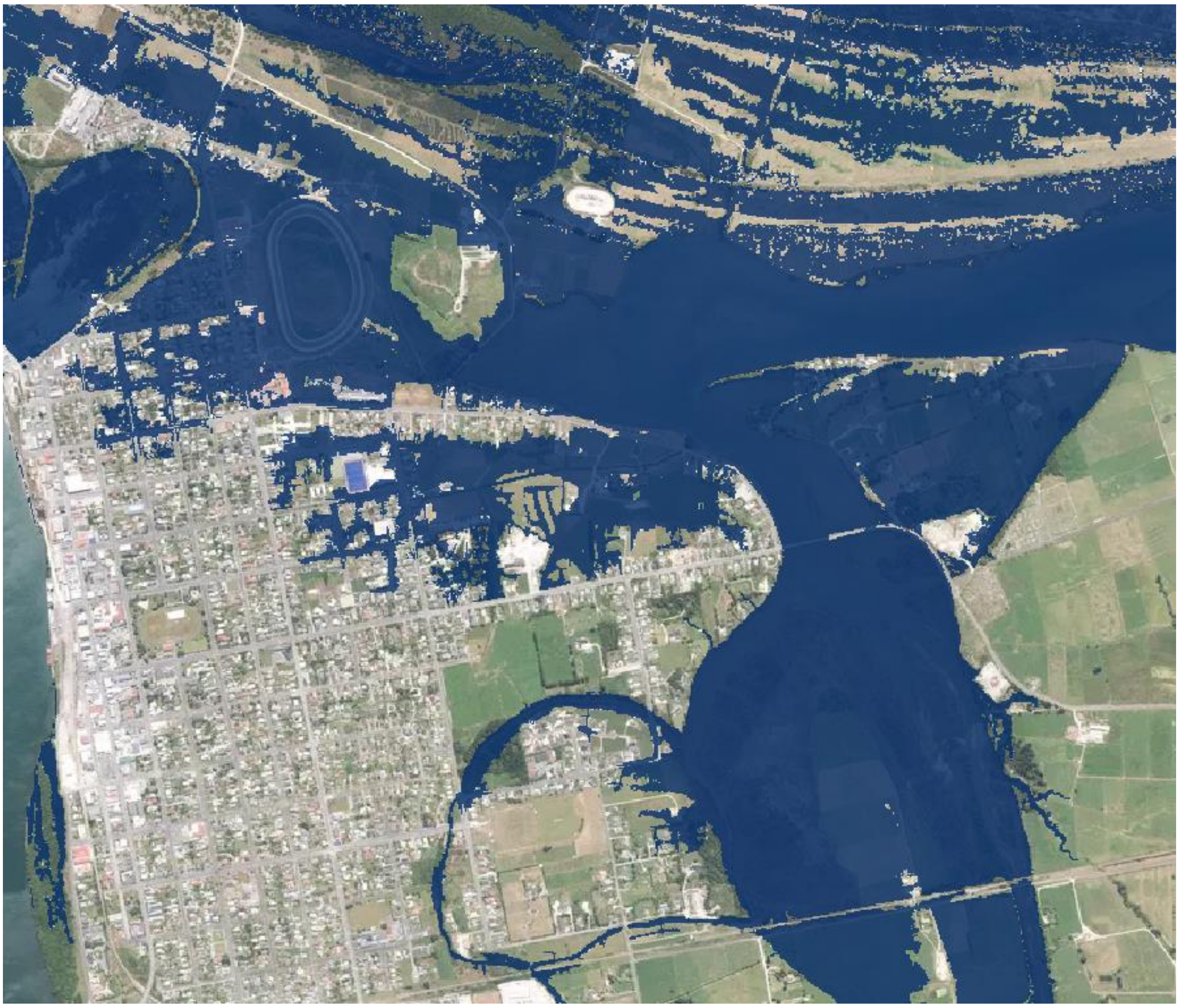

Figure 4-14: 1% AEP inundation from storm-tide, wave setup and infragravity waves for present sea level in Orowaiti. Note this result was produced using a calibrated/validated hydrodynamics model.

4.2.5 References

Allis M. (2015) NIWA letter to Michael Meehan WCRC dated 6 May 2015 providing advice regarding proposed floodway cut options between the Orowaiti Lagoon and Tasman Sea.

Allis, M.J, et al. (2017). *Managing and adapting to coastal erosion on the West Coast: Carters Beach*. *NIWA Client Report* 2017119HN, West Coast Regional Council: 36.

Dennis, F.E. (1996) *Stability of Utopia Road Property*, prepared for Mr G R Millar by OCEL Consultants NZ Ltd.

Goss, I.W. (2011) *Review of coastal hazard as it affects building siting at lot DP 12836, Utopia Road, Westport*, prepared for Mr and Mrs B. J. and L. A. A. Donaldson by OCEL Consultants NZ Ltd.

Gardner M. (2017) Buller River: Update of hydraulic model, *Land River Sea Consulting Ltd Report for West Coast District Council*.

4.3 CHA 12: Punakaiki Village (Pororari Beach)

This CHA covers the length of beach in front of Punakaiki Village including the Pororari River mouth and lagoon. The CHA stretches from cliffs at the northern extent of the Pororari River Mouth embayment towards the southern extend of the bay abutting Dolomite Point.

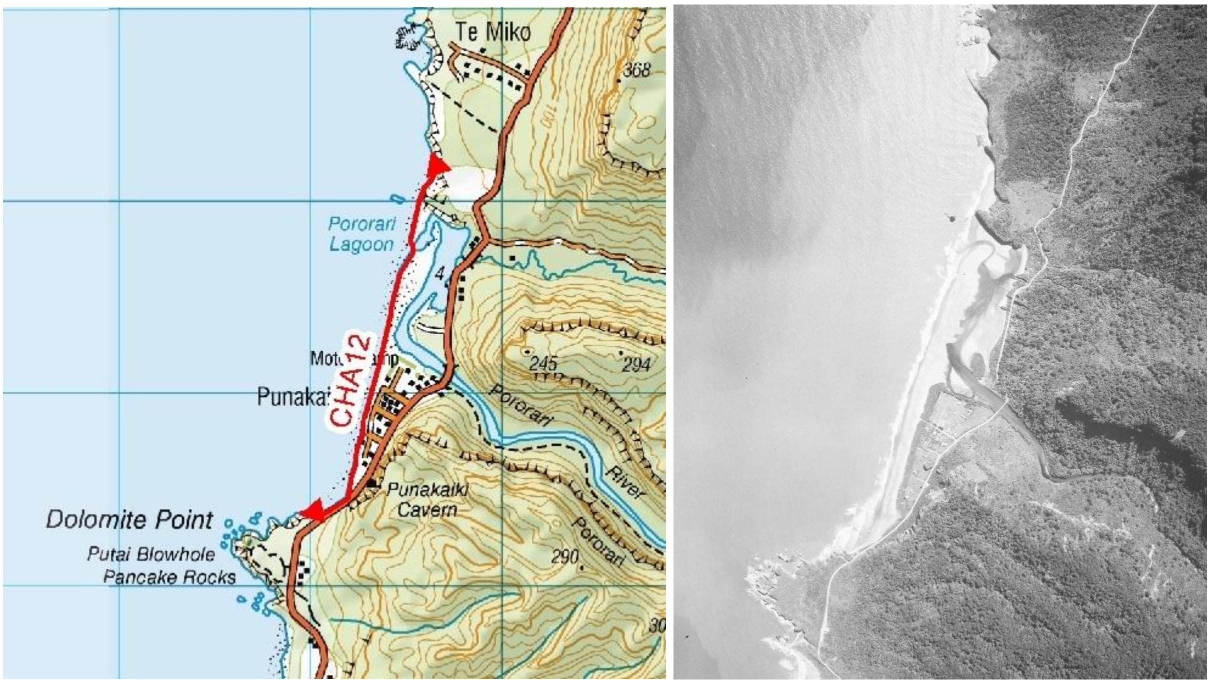

Figure 4-15: Punakaiki Village (Pororari Beach) map and historic aerial photograph (1951). [Credit: LINZ (left), Retrolens (right)].

4.3.1 Erosion

Coastal erosion at the township has been a matter of concern for many years. A series of investigations and reports has been undertaken since 1983 as a result of these concerns (e.g., Hamilton 1983, Kirk 1988, Ramsay 2007, Hicks 2014, Goss 2016). Long term erosion of the beach is occurring in front of the village as a result of wave attack and northward longshore transport. Short term vegetation line retreat of 10-15 m was observed during a March 1983 event (Hamilton 1983).

In response to beach retreat rock revetments have been constructed in front of the village and road at Punakaiki. There are two main bodies of revetment; the 2005 Punakaiki Village revetment which protects the Village (subsequently extended north several times) and the adjoining SH6 revetment to the south of the Village revetment constructed in 2019 after damage to the road during exTC Fehi (Feb 2018).

The river mouth is known to migrate during flood events. The river usually discharges via the lagoon alongside the northern cliffs with Bullock Creek but intermittent breaches of the barrier/spit during river floods allow discharge alongside Punakaiki village (Birchfield 2020). River mouth migration also has the potential to erode the riverbank alongside the village.

4.3.2 Flooding

Storm waves overtopping the beach and barrier can cause flooding. The river mouth migration has the potential to flood the lower campground land and the village if flood waters are backed up on a high tide with large waves.

The few houses around Bullock Creek appear to be elevated on rising terrain so are above river and coastal flood waters.

Figure 4-16: Punakaiki Village with coastal protection structures. Date 13/8/2021. [Credit: M Allis (NIWA)].

4.3.3 CHA analysis

Both erosion and inundation will impact the Punakaiki CHA over the next 100 years. Suitable aerial and satellite imagery were available to provide accurate shoreline detection for 1951, 1964, 1988, 2012, 2019. The recent shoreline erosion rate has been limited by the placement and maintenance of rock armour on the beachfront from 2005 onwards.

The erosion trend at Punakaiki village (based off the analysis of historic imagery) is up to 0.5m/year. The coastal defence structure in place at Punakaiki village and along SH1 are expected to be maintained and upgraded to match raise is relative sea level. For the coastal erosion hazard area, the structure only prevents acceleration in the rate of erosion from acceleration of sea level rise. The recent historical erosion rate is maintained in the calculation to account for failure of the structure.

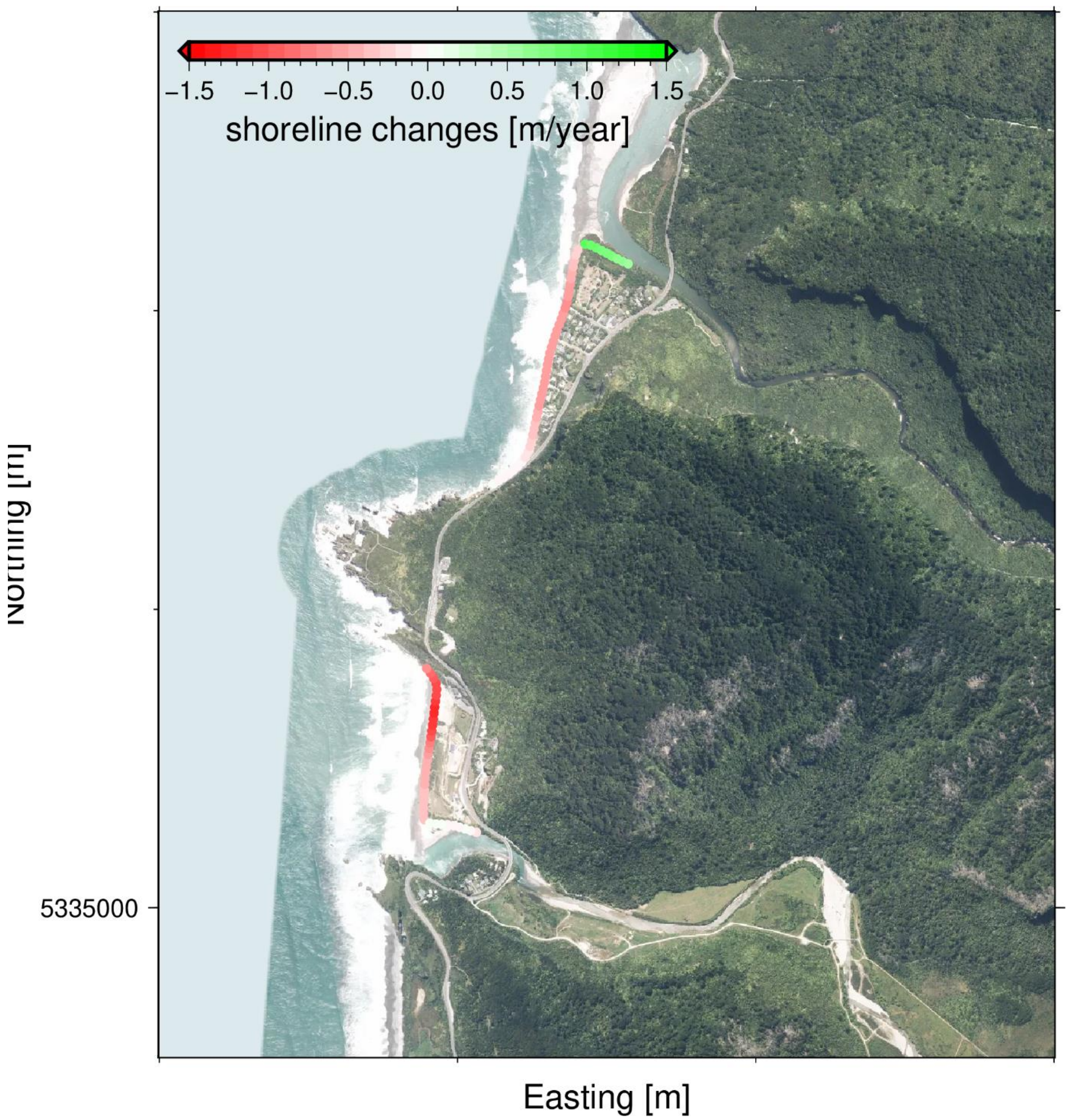

Figure 4-17: shoreline changes trends for CHA 12 Punakaiki Village and CHA 13 Punakaiki River Beach. white mean no changes, red is erosion and green is accretion.

Erosion of the cliffs to the north of the Pororari Lagoon does not present a noteworthy hazard to assets (roads) or property and does not require assessment.

Note the complexity of river/beach/lagoon systems and interactions of multi-hazard river/coastal flood events which can create extreme water levels and erosion which will impact low lying areas of Punakaiki.

Inundation assessment shows the lower elevations of the village and areas within the river valley are exposed to future coastal flooding. Coastal inundation extent from the 1%AEP storm-tide+ wave setup at present sea level affects areas directly behind the coastal protection structure in Punakaiki. In Punakaiki River beach, the inundation reaches the settlement on the south side of the river mouth (Figure 4-18).

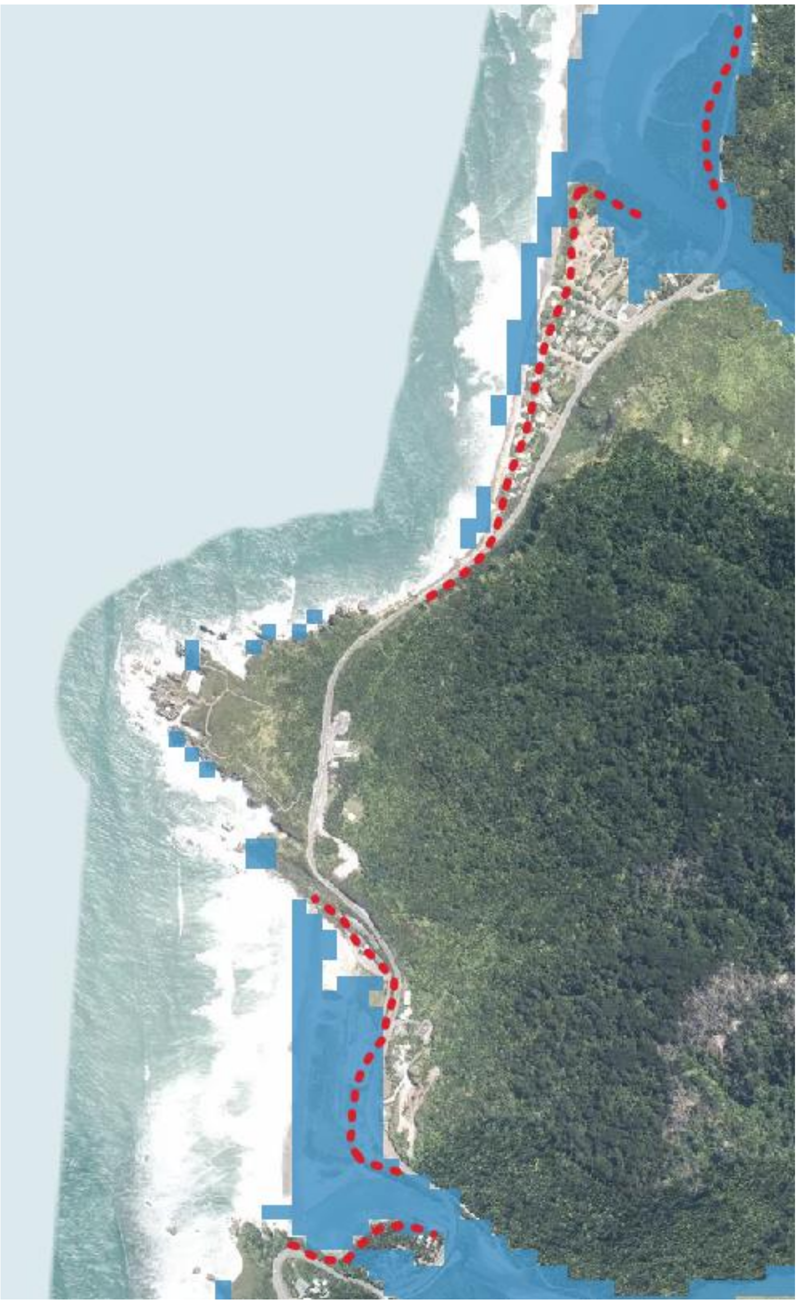

Figure 4-18: inundation extent from the 1%AEP storm-tide+ wave setup at present sea level for CHA 12 Punakaiki Village and CHA 13 Punakaiki River Beach. Blue shading shows the inundation extent and the red line shows the 100-year outlook coastal erosion hazard area limit.

4.3.4 References:

Allis, M. (2020) Coastal changes and future coastal management at Punakaiki. *NIWA Client Report*, 2020236HN: 37.

Birchfield, P (2020). File Note: Pororari River breach– October 2020. West Coast Regional Council. 7 p.

Hamilton, J. McF. 1983. Punakaiki sea erosion. Westland Catchment Board and Regional Water Board Letter, Ref 921000, October 1983

Hicks (2015) Stability of seawall at Punakaiki. NIWA, Technical note for West Coast Regional Council. 8 September 2014.

Coll, C.J. (2019). Punakaiki Township Coastal Erosion Cross Sections. March 2019.

Goss, I.M. 2016. Options and issues regarding extension of Punakaiki Village seawall. Letter report to WCRC, 11 April 2016.

Kirk R. M. (1988) Coastal Erosion and Inundation at Punakaiki Village (Pororari Beach) Westland 1983-1986

Ramsay D., (2007) Punakaiki seawall impacts. NIWA, Technical note for West Coast Regional Council.

4.4 CHA 13: Punakaiki River Beach

CHA 13 covers 700 m of coast from south of Pancake Rocks (Dolomite Point) as far as Razorback Point. The CHA includes the mouth of the Punakaiki River (Figure 4-19). The embayment has a sandy beach with some gravels, a partially vegetated barrier in front of a low-lying former lagoon/swamp (now partially infilled) (Figure 4-20).

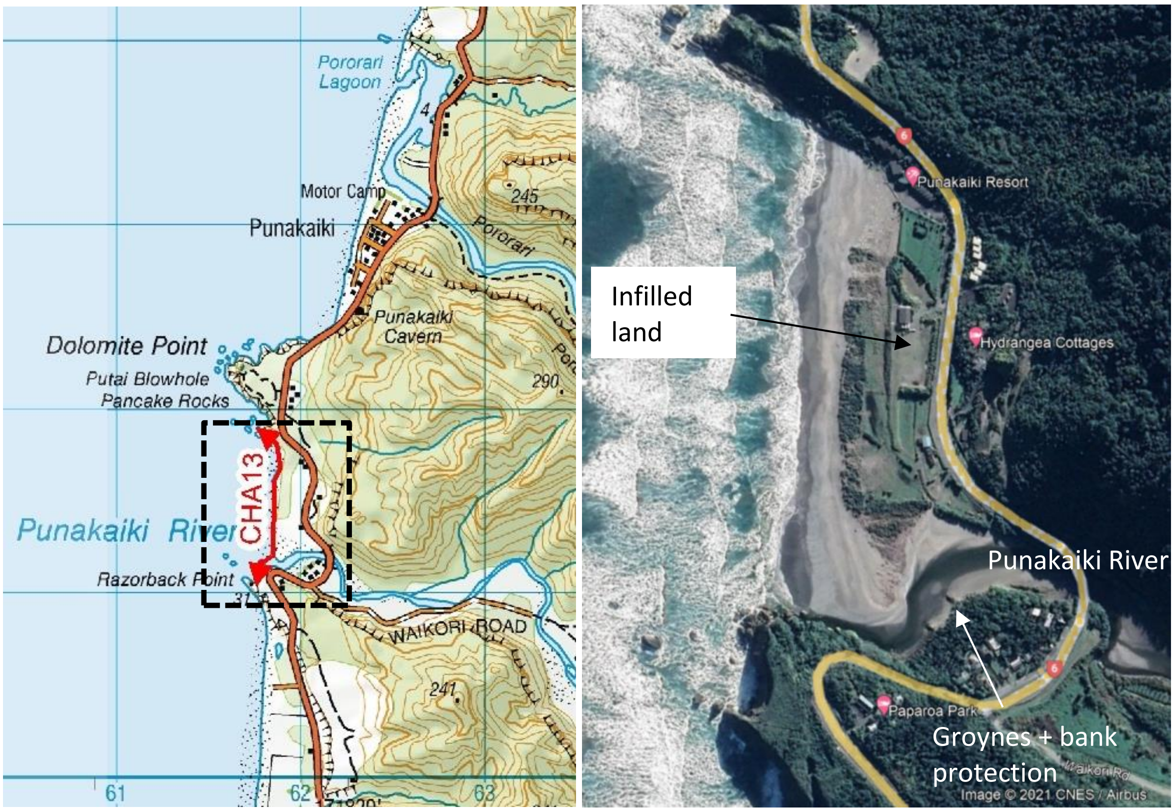

Figure 4-19: CHA 13: Punakaiki River Beach.

Figure 4-20: Punakaiki River beach oblique view. View south over beach towards Razorback Point. Date: 13/08/2021 [Credit: M Allis (NIWA)].

Figure 4-21: Recent erosion of the vegetated barrier (left) at Punakaiki River beach with wave washover depositing sand and driftwood up to 30 m inland from the beach face (right). Date: 13/8/2021. [Credit: M Allis (NIWA)].

4.4.1 Erosion

The beach is in an erosional phase at present with the vegetated barrier/dune recently undercut by waves and wave washover depositing sand and driftwood up to 30 m inland from the beach face (Figure 4-21). The area of low lying beach in front of the Punakaiki Motel Resort is expanding with the fringe of the remaining vegetated barrier slowly retreating (Figure 4-20).

Comparing aerial photos from 1951 and 1964 to the present day, there is little long-term erosion evident but short-term shoreline changes do affect the CHA and it is expected to be sensitive to any changes in external controls (i.e.,, change in sediment supply, rising sea level) which may cause further erosion and rollback.

River mouth migration threatens to erode land at the southern end of the bay between Razorback Point and the Punakaiki River but groynes and rock protection have been installed on the south bank of the mouth of the Punakaiki River to manage the risk of erosion.

4.4.2 Flooding

Wave washover flooding affects low-lying land behind the beach. A small private seawall (concrete blocks + armour stones) has been constructed to reduce wave overwash from flowing into the motel carpark at the northern fringe of the bay. Private property within the centre of the bay has been filled to create an elevated building platform (Figure 4-19).

4.4.3 CHA Analysis

Both erosion and inundation are expected to impact the CHA13 over the next 100 years. The historic erosion trend unlikely to be distinct, but there will be short-term fluctuations with erosion and accretion cycles. A barrier rollover distance of 30 m from the beach face aligns with recent observations. Suitable aerial and satellite imagery was available to provide accurate shoreline detection for 1951, 1964, 1988, 2012, 2016, 2019. The CHA for erosion assumed that the coastal protection structures fronting Punakaiki Motel Resort and the south bank of the mouth of the Punakaiki River will be maintained in position in the long-term future. The coastal erosion hazard area has been manually clipped to account for the limestone outcrop and coastal structures.

Inundation assessments shows the lower elevation land in the centre of the bay and alongside the river valley will be exposed to future coastal flooding.

Punakaiki Beach shows fast retreat of the vegetation line on the northern side of the beach (greater than 1 m/year). The resulting coastal erosion hazard area for 100-year outlook is located just seaward of the main road (Figure 4-18).

4.4.4 References

Goss, I. W. (2011) *Review of coastal hazard – Lot 2 DP 336777*, *Punakaiki Beach*, prepared for Punakaiki Farm Ltd by OCEL Consultants NZ Ltd.

4.5 CHA 16: Rapahoe

The Rapahoe CHA stretches from about 1.5 km north of Rapahoe to south of Seven Mile Creek. The village is built within Seven Mile Creek valley and positioned between eroding mudstone bluffs to the north and south (Nathan et al. 2002). The mudstone cliffs to the north of the village are actively managed by NZTA with rocks and other local material placed at the toe of the cliff to limit erosion and wave undermining. The village sits on several alluvial or gravel/sand terraces which step down towards the shoreline from the hillside and are bisected by the creek.

Figure 4-22: CHA 16: Rapahoe.

4.5.1 Erosion

Long term erosion of the shoreline is occurring as a result of sand and gravel loss (by northward transport and abrasion) exceeding supply (from Seven Mile Creek, cliff erosion and bypassing around Point Elizabeth from the South). Depletion of the beach stocks and wave washover occurs on the remnant beach barrier, while wave attack on the mudstone cliff at the northern end threatens the stability of the road. Creek mouth migration also poses an erosion risk to both the north and south banks of Seven Mile Creek. Over the last 80 years a 60-80 m wide barrier/lagoon system has eroded (Figure 4-23) with the shoreline retreating approximately 80-100 m to the present day, claiming the lagoon and truncating Beach Road, with ongoing washover during storms (Figure 4-24, Figure 4-25) (Allis 2017).

Present day shoreline erosion rates are reduced by placement of rocks along the coastal frontage. They are also reduced by excavating overwashed beach material from the drains and from Beach Road and returning it to the beach after washover events (Figure 4-25 and Figure 4-26).

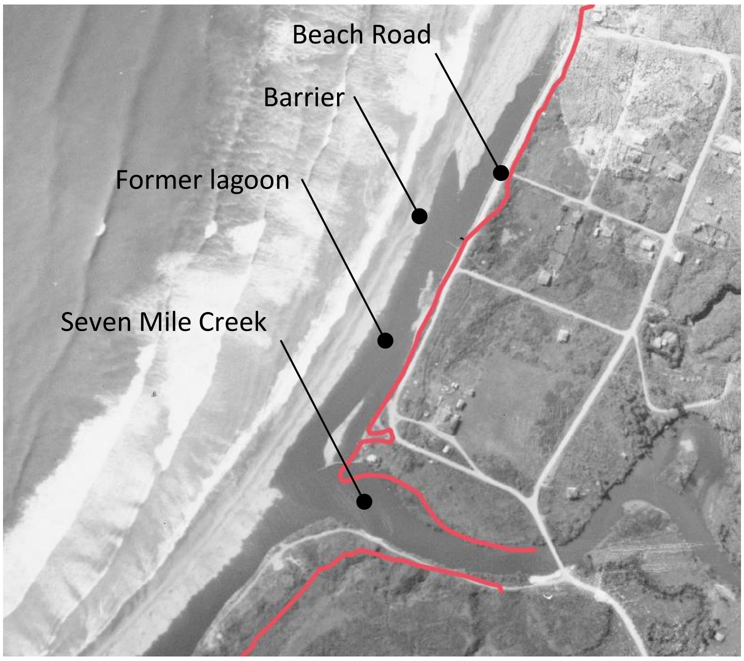

Figure 4-23: Dramatic shoreline change at Rapahoe from 1939 (image) to 2020 shoreline (Red line). The barrier and lagoon system have rolled inland and overwhelmed the beachfront road. [Credit: retrolens].

4.5.2 Flooding

Wave washover flooding occurs during storms when waves overtop the gravel barrier (e.g., exTC Fehi Figure 4-24). In order to mitigate the coastal inundation hazard, some land parcel have been raised and drains have been installed to capture the wave overwash (Figure 4-26). A rock revetment wall was destroyed during exTC Fehi (Figure 4-24).

Figure 4-24: Aftermath of wave overwashing at Rapahoe following exTC Fehi. Note driftwood debris spread up to 50 m inland from the beach face, washover of gravel enveloping Beach road and spreading into flax bushes and flooding inundation of low-lying areas and blocking of drains. Also note the scattered rock from the damaged revetment. Note section with busses since infilled to increase land elevation. [Credit: WCRC].

Figure 4-25: Rapahoe shoreline with infilling of low lying hinterland, retreating gravel barrier (with protective rocks). Date 12/8/2021. [Credit: M Allis (NIWA)].

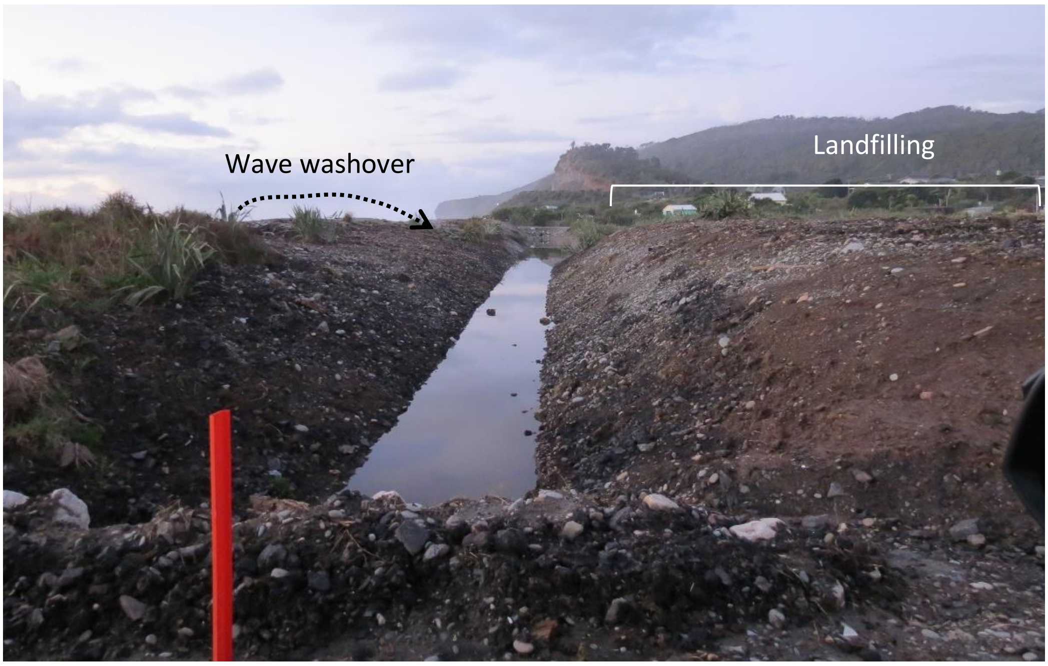

Figure 4-26: Rapahoe drain aimed at capturing wave overwash while infilling of the hindland was used to reduce inundation hazard (right).

4.5.3 CHA Analysis

Both erosion and inundation will impact the Rapahoe CHA over the next 100 years. Suitable aerial and satellite imagery was available to provide accurate shoreline detection for 1939, 1948, 1964, 1970, 1988, 2013, 2017, 2019. It is expected that recent shoreline erosion rates will be diminished by the placement and maintenance of rock rubble on the beachfront from 2008 onwards. However, these rock rubbles are not expected to be maintaining the shoreline position in the future and are ignored in the erosion hazard analysis. Inundation assessments are expected to show the lower elevations of the village and within the creek valley are exposed to future coastal flooding.

Historic shoreline analysis at Rapahoe shows erosion at an average rate of 0.2 m/year (Figure 4-27).. Artificial maintenance and rehabilitation of the gravel barrier has masked the effective erosion rate by holding the vegetation edge position stable while the beach width has dramatically decreased, further exposing the barrier to wave action and overtopping.

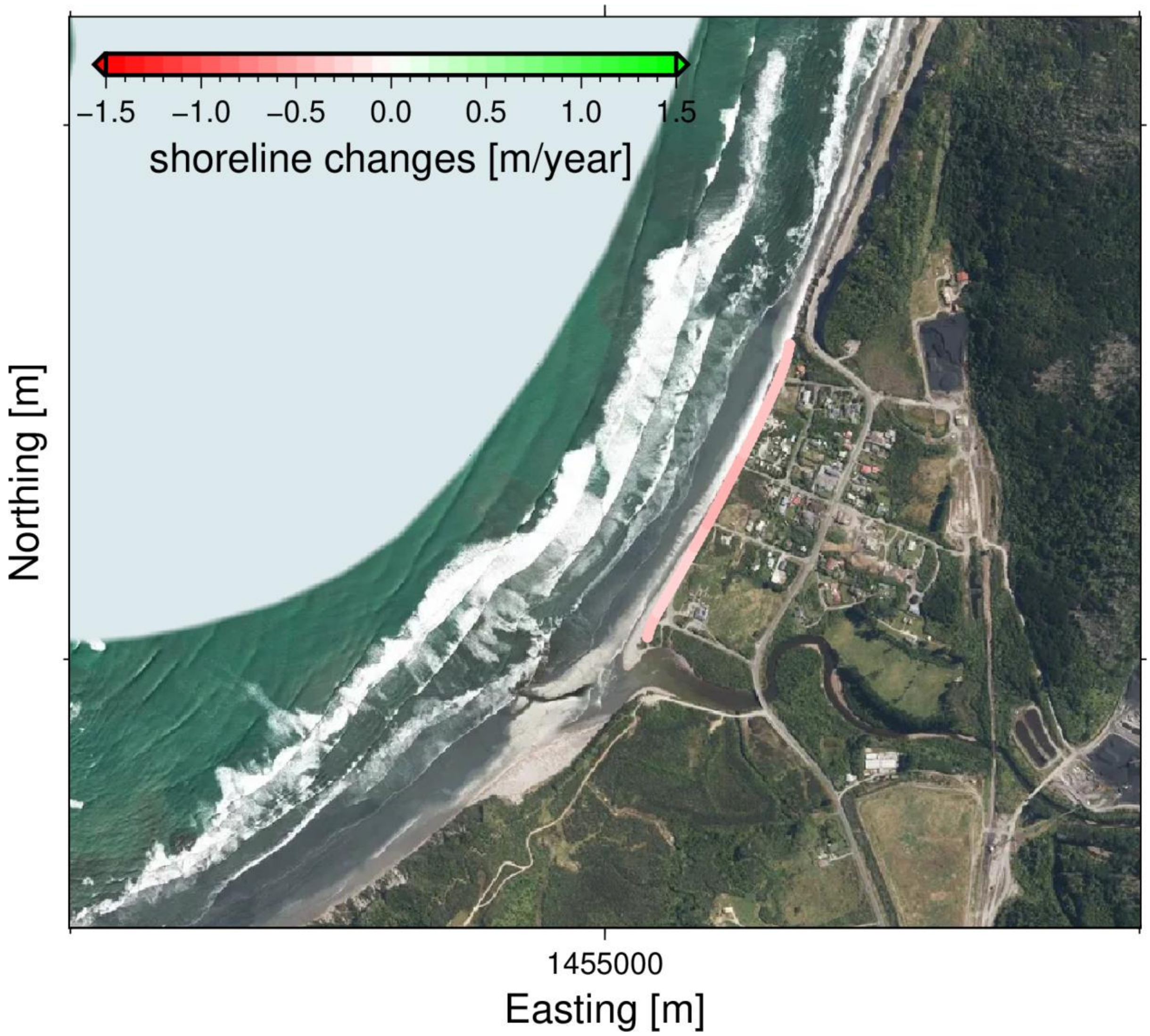

Figure 4-27: Rapahoe shoreline changes trends. white mean no changes, red is erosion and green is accretion.

Inundation from the 1%AEp storm-tide + wave setup at present day sea level reaches 80 to 90 m inland in the southern part of Rapahoe settlement. Inundation extents for higher sea levels is mostly similar until a SLR of 1.60m is reached and inundation water levels exceed the topographic step that makes Hawken St (Figure 4-28).

It should be noted that this analysis does not include the potential for complex river-coastal flood interaction around the mouth of Seven Mile Creek. This interaction could result in additional flood risk to low lying areas of Rapahoe.

Figure 4-28: Rapahoe inundation extent from the 1%AEP storm-tide+ wave setup at present sea level. Blue shading shows the inundation extent and the red line shows the 100-year outlook coastal erosion hazard area limit.

4.5.4 References

Allis, M.J. (2017). Managing and adapting to coastal erosion on the West Coast: Rapahoe 2017 review and update. NIWA Client Report 2017072HN, West Coast Regional Council: 16p.

Ishikawa, R. (2008) Historical Shoreline Change and Beach Morphodynamics at Rapahoe Bay, West Coast, New Zealand. MSc Thesis, Dept. of Geography, University of Canterbury. (peer reviewed for Grey District Council by D Todd).

Nathan, S., Rattenbury, M.S., Suggate, R.P. (compilers) 2002. Geology of the Greymouth area. Institute of Geological and Nuclear Sciences 1:250000 geological map 12. 1 sheet + 58 p. Lower Hutt, New Zealand. Institute of Geological and Nuclear Sciences Limited.

Neale, D. (1999) Shore Protection Options for Rapahoe Beach – Revised Report. Report prepared for discussion by the Department of Conservation, Grey District Council and West Coast Regional Council.

OCEL Consultants NZ Ltd (2006) Coastal Hazards Assessment: Proposed Subdivision south side of Seven Mile Creek, Rapahoe. Prepared for Tiler Bay Holdings Ltd. (Peer reviewed by D. Todd, DTec Consulting Ltd, 2007)

Opus International Consultants (2000) Rapahoe Protection Works Evaluation. Report prepared for Grey District Council. April 2000.

Pfahlert, J.J. (1984) Coastal Dynamics and Sedimentation at Point Elizabeth, West Coast, South Island, New Zealand. MSc Thesis, Dept. of Geography, University of Canterbury.

Ramsay, D. (2006) Managing and adapting to coastal erosion on the West Coast: Rapahoe, NIWA client report HAM2006-154.

4.6 CHA 25: Haast Beach to Waiatoto

CHA 25 extends approximately 25 km from south bank of the Haast River (north of Haast Beach) to the southern limit of the Waiatoto Lagoon. The CHA includes the settlements of Haast Beach, Okuru and Hannahs Clearing as well as the low-lying land at the mouth of the Okuru/Turnbull/Hapuka Lagoon.

Geomorphically, the CHA is dominated by the large salient feature where the shoreline has built out at Okuru through a combination of the wave shadow behind the Open Bay Islands, sediment deposited in the Okuru river lagoon/delta and being tied to bedrock outcrops (e.g., Mussel Point) (Figure 4-29).

This CHA area was extended north to the southern bank of the Haast River at the request of WCRC for this project (see Appendix A).

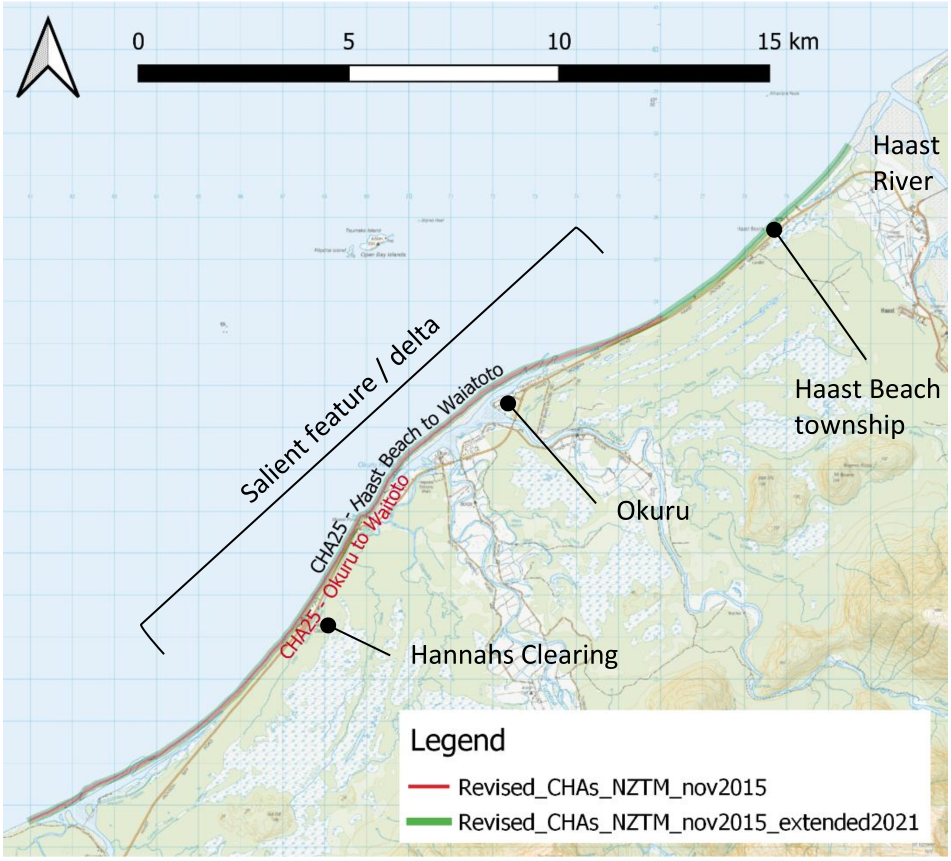

Figure 4-29: CHA25 Haast Beach to Waiatoto.

4.6.1 Erosion

The mouths of the Okuru/Turnbull/Hapuka Rivers and Waiatoto River both migrate over several kilometres of separate sections of this CHA. At both lagoons the position of the river mouth can change the exposure of the lagoon backshore to river flows and wave action which in turn can cause erosion. The lower reaches of the riverbanks are rock-lined where they discharge into the lagoon with stub groynes constraining the river to a channel, directing the flow and providing protection in the case of waves overwashing and breaching the barrier (Figure 4-30).

The open coast is actively eroding along this CHA. South of Hannahs Clearing the erosion has undermined the fringe of an old dump site, with wave washover 10 m into the vegetation causing vegetation dieback (Figure 4-31). The lagoon barrier islands are devoid of most vegetation indicating they are regularly swept clean by wave overwashing (Figure 4-32). Erosion is evident from Okuru Lagoon north to Haast Beach (Figure 4-33).

The beach is backed by sand dunes, and dune blowouts can occur as a result of wave/wind action during storms.

Figure 4-30: Low lying farmland alongside Okuru River and lagoon with low barrier island separating the Tasman Sea from the lagoon. Date 12.8.2021 [Credit: M Allis (NIWA)].

Figure 4-31: Active erosion at old dump site 2 km south of Hannahs Clearing. Erosion has caused vegetation die back, undermined dump (now protected with rock) and exposed the power pole assets. Date 12.8.2021 [Credit: M Allis (NIWA)].

Figure 4-32: Recent rock protection for Haast-Jackson Bay Road alongside cutoff lagoon branch north of Okuru River (at left) with evidence of recent wave washover deposits in filling the lagoon branch (foreground). Date 12.08.2021 [Credit: M Allis (NIWA)].

Figure 4-33: Erosion scarp and vegetation retreat at approximately 1 km south of Haast Beach. Date 11.08.2021 [Credit: M Allis (NIWA)].

4.6.2 Flooding

Lagoon mouth closure can cause flooding of low-lying land and buildings around the lagoons when river water backs up in the lagoon. Wave washover flooding affects parts of this CHA. The farmland and settlements alongside the Okuru lagoon are low-lying and the risk of flooding will increase over time with sea-level rise expected to more frequently to inundate low lying land through wave overwashing, rising groundwater levels and backing up of river flood waters.

4.6.3 CHA analysis

Both erosion and inundation will impact the Haast Beach to Waiatoto area over the coming 100 years. Erosion hazard assessment is complicated by the lagoon barrier and the long-term unknown future of the barrier system with sea-level rise. Therefore, the erosion analysis in the lagoon area was based on the lagoon shoreline rather than the barrier shoreline. In addition, it is possible the lagoon may disappear (at least temporarily). To account for hazard due to the absence of gravel barrier the rollover parameter used in Okuru lagoon area is similar to open coast (average of 30m instead of the approximately 5m in sheltered area). Suitable aerial and satellite imagery was available to provide accurate shoreline detection for 1951, 1969, 1988, 2003, 2006, 2012, 2017, 2019.

Coastal erosion trends for Haast Beach to Waiatoto shows area of accretion and erosion (Figure 4-34). The exposed shoreline near Haast Beach is accreting whereas the area surrounding Okuru Lagoon is eroding. Shorelines in Hannahs Clearing and North do not show trends but have shown cycles of erosion and accretion with an erosion phase starting in the 1950s (30 – 60 m between 1951 – 1969) followed by a full recovery (1969 – 2006) and is ongoing a new erosion phase. South of Hannahs Clearing erosion trend are clearer, exceeding 0.5 m/year (see also Figure 4-31).

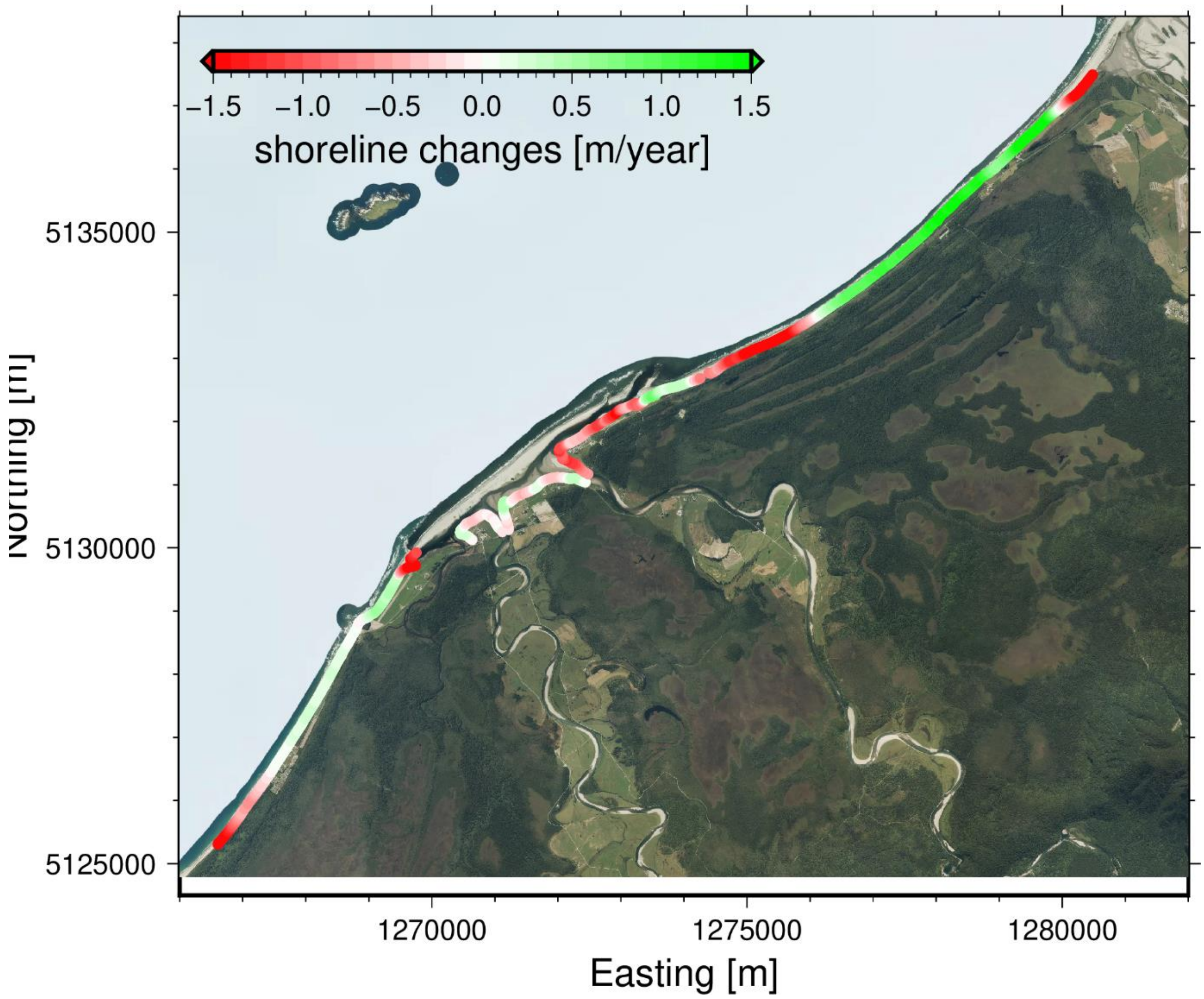

Figure 4-34: Haast shoreline changes trends. White mean no change, red is erosion and green is accretion.

Inundation assessment shows the land adjoining the river flood plain and lagoon will be subject to increased flooding with sea-level rise. Coastal inundation for Haast Beach to Waiatoto from the 1%AEP storm-tide+ wave setup at present sea level affects mostly the area of Okuru River mouth (Figure 4-35). Further SLR increases the area affected by inundation.

It should be noted that this analysis does not include the potential for complex river-coastal flood interaction around the river mouth lagoons. This interaction could result in additional flood risk.

Figure 4-35: Okuru inundation extent from the 1%AEP storm-tide+ wave setup at present sea level. Blue shading shows the inundation extent and the red line shows the 100-year outlook coastal erosion hazard area limit.

4.6.4 References

B F Whitham Ltd and Lakes Consulting Group (2006) *Assessment of Environmental Effects: Rock Seawall at Okuru*. (Peer reviewed for West Coast Regional Council by OCEL Consultants Ltd.)

Moen, W. (2004) *Coastal Hazard Assessment: Mussel Point Okuru.* Report for Cowan & Holmes Ltd by West Coast Regional Council.

MWH (2007) *Waiatoto River Mouth Channel Works, Resource Consent Application and Supporting Information*. Report for New Zealand Energy Ltd.

4.7 CHA 26: Neils Beach to Jackson Bay

CHA 26 extends east from the Arawhata River to Jackson Bay. The area includes the Neils Beach community, the Haast-Jackson Bay Road and Jackson Bay village.

Jackson Bay / Okahu bay is situated at the end of a zetaform shoreline curve (also known as half-hart shape shoreline) which has formed in the lee to the north of Jackson Head and continues north towards the shoreline bulge at Open Bay Islands and Okuru/Turnbull River outlets. Jackson Head itself separates the cliff-fronted sections of the southern Westland coast to its south from the headland-beach coastlines filled with post-glacial alluvial outwash deposits to its north. Longshore drift is predominately to the north except for the Jackson Bay township where a reverse eddy in the lee of Jackson head develops and a weaker net westerly drift develops, as was observed during the site visit (schematised in Figure 4-36). Wave exposure increases to the east of a bifurcation point (where the transport direction switches) but this point is not fixed and moves with oscillation of the climate and in response to trend in wind and wave energy. Inland from the present-day coastline are generally large areas of former beach ridge/swamp depressions (e.g., Burmister Morass) fed by numerous streams and creeks flowing from the southern Alps. The Arawhata River provides an additional sediment source to resupply beaches here and to the northeast.

This CHA area was extended to include Jackson Bay village at the request of WCRC for this project (see Appendix A).

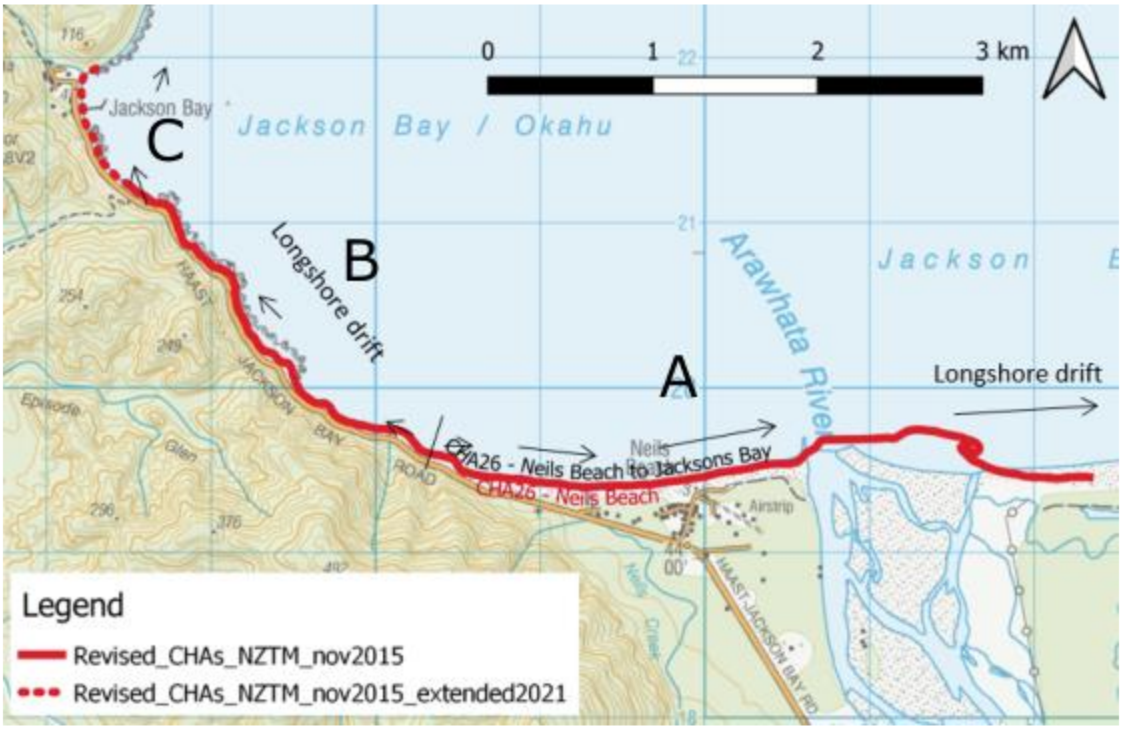

Figure 4-36: CHA26 Neils Beach to Jackson Bay. Arrows schematically indicate prevailing longshore drift direction and magnitude in the lee of Jackson Head. A, B and C correspond to three subsection of CHA26 [Map source: LINZ].

There are three sub-CHA sectors in CHA 26 which are each subject to coastal hazards and processes:

A. Neils Beach and the Arawhata River Mouth

B. Haast-Jackson Bay Road (where alongside the coast)

C. Jackson Bay village

4.7.1 References:

Hicks D.M. (2016) *Rivermouth-related shore erosion at Hokitika and Neils Beach, Westland.* NIWA Client Report CHC2016-002. Prepared for West Coast Regional Council. February 2016. 35 p.

Phelps C., (2016) *Resource Consent Application for West Coast Regional Council – Beach Nourishment and Sacrificial Bund*. VCS Environmental December 2016.

4.7.2 CHA26a: Neils Beach and the Arawhata River Mouth.

Figure 4-37: Neils Beach village with sacrificial bund (foreground) separating the active beach face from the lagoon and low-lying inhabited land. Date 12/8/2021. [Credit. M Allis (NIWA)].

Erosion: The main hazard affecting Neils Beach at the present-day is erosion. Over the period 2010-2015 the shoreline at Neils Beach experienced high erosion rates of 3-4 m per year but prior to this the shoreline was much more stable (Hicks, 2016). This erosion has consumed some 20 m of foreshore and protective dune, and has advanced to the point where continued shore retreat may expose dwellings, roads, and the SW end of the airstrip to damage or loss by erosion, or by increased risk of coastal flooding. The only sediment supplies to this stretch of coastline are from local landslides/streams between Jackson Bay and Neils Beach and the Arawhata River. For this reason the stability of the shoreline is very dependent on the position and orientation of the Arawhata mouth and its recent flood history. A westerly river mouth location appears to encourage sediment storage on Neils Beach while an easterly mouth "drains" this storage and promotes erosion. It is unclear to what extent the current erosion is part of short term variability due to river mouth processes or a longer term trend (e.g., driven by a waning sediment supplies or sea-level rise) (Hicks, 2016).

Flooding: There is likely a risk of flooding in the low-lying areas of Neils Beach and the aerodrome. Flooding is likely from the Arawhata River, particularly if the mouth is constricted by a high beach barrier which is not rapidly eroded on the rising limb of a flood (Measures & Rouse 2022). The risk of flooding will increase over time with sea-level rise expected to more frequently inundate low lying land through wave over washing, rising groundwater levels and backing up of river waters.

A low sacrificial bund was constructed in 2016 to separate the active beach from the lagoon and low-lying inhabited land. The bund is only a stop-gap measure to keep nuisance wave events from filling the lagoon and flooding the inhabited areas. It will not resist a sustained period of erosion during large storms, and does not provide long-term protection against erosion or inundation. For these reasons it is not considered in the presented erosion hazard assessment.

CHA Analysis: Both erosion and inundation will impact the Neils Beach area over the next 100-years. Suitable aerial and satellite imagery was available to provide accurate shoreline detection for 1951, 1988, 2010, 2016, 2021.

Shoreline position indicates that cycles of erosion and accretion can occur in Neils Beach. However, the general trend points to a rapid erosion. Historically variable erosion rates, with recent rapid erosion, increases the uncertainty of the trend analysis resulting in a wide erosion hazard area extending all the way to the SH1.

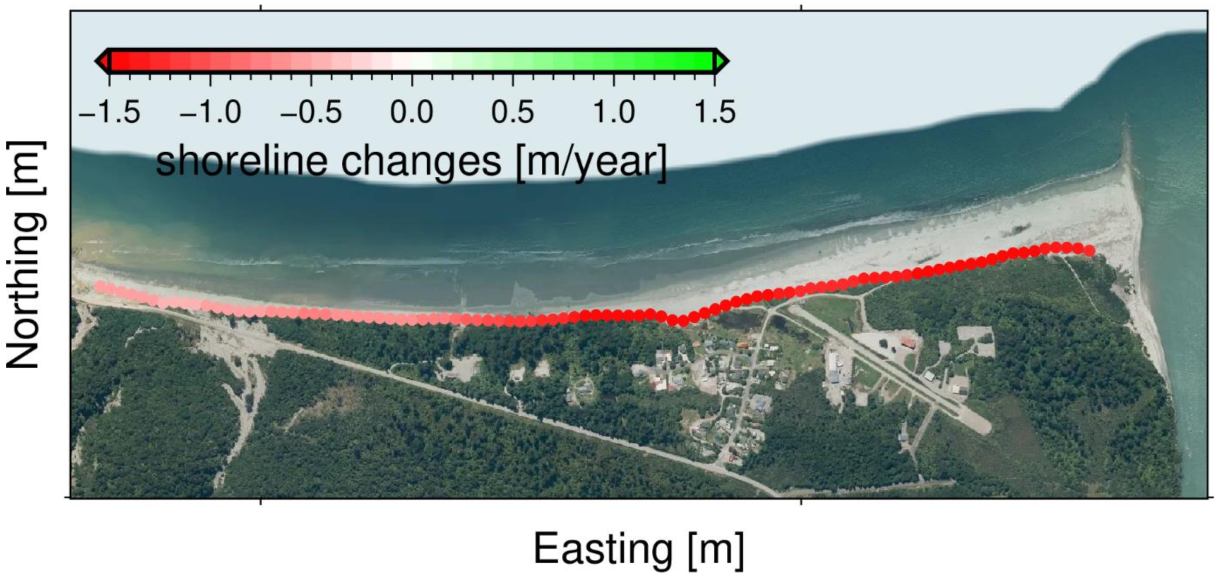

Figure 4-38: Neils Beach shoreline changes trends. White mean no change, red is erosion and green is accretion.

Coastal inundation analysis suggest that the 1%AEP storm-tide + wave setup at present sea level would not affect Neils Beach settlement significantly (Figure 4-39), however this is not consistent with recent observation. The accuracy of the SRTM DEM may be questionable in this area and the coastal inundation assessment should be redone once a LiDAR DEM is available for the area.

Note that the static inundation analysis used for this study does not account for the interaction of river and coastal flooding. Backup of river flooding behind a high beach barrier is a potential source of flooding not included in this hazard mapping approach.

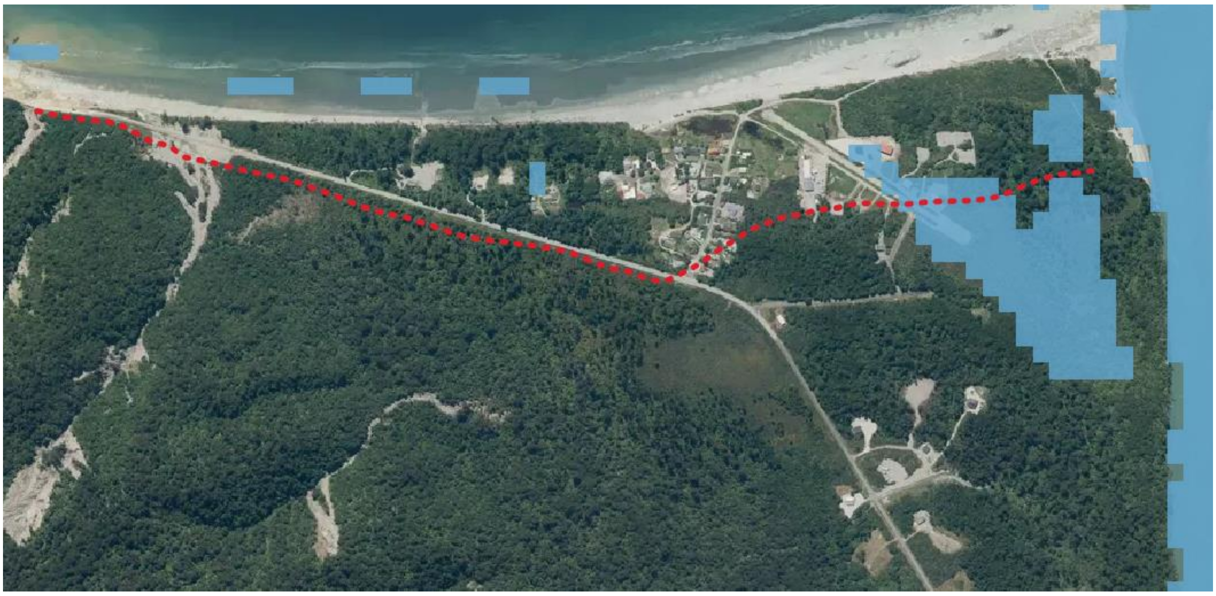

Figure 4-39: Neils Beach inundation extent from the 1%AEP storm-tide+ wave setup at present sea level. Blue shading shows the inundation extent and the red line shows the 100-year outlook coastal erosion hazard area limit.

4.7.3 CHA26b: Haast-Jackson Bay Road

Erosion: The Haast-Jackson Bay Road is situated on a narrow ledge between the beach face and the steep hillside. The ledge consists of unconsolidated sandy-gravel beach deposits mixed with landslide debris bulldozed off the road onto the beach (e.g., Figure 4-40). The road is subject to washouts and undermining/erosion during storms with large waves from the north.

The road is also subject to closure following intense rainfall events when numerous landslides can deposit debris across the road. However, when the landslide debris is pushed onto the beach to clear the road it provides a buffer against further erosion and re-supplies the beach with sediment.

There are no 'formal' shore protection structures along the roadway, instead the landslide debris supplies the material to the beaches between rocky outcrops.

Inundation: The road is elevated 1-3 m above high tide but will still experience flooding by wave washover during storm events which also erode the shoreline.

Figure 4-40: Haast-Jackson Bay Road positioned on narrow ledge between landslide prone hillside and beach face. Date 12/8/2021. [Credit: M. Allis (NIWA)].

CHA analysis: Haast-Jackson Bay Road is already subject to erosion and undermining during large storms and this will increase in frequency and severity with sea-level rise. However, future erosion trends are expected to be offset by the plentiful supply of landslide material which is used to support the road and restock the beach. The status-quo can continue to ensure access to Jackson Bay township, but with a consideration that over time (decades) the low-lying or erosion prone lengths of road could be incrementally built-up to a higher level by spreading landslide debris and keeping the road open and out of reach of the sea (and if the township is abandoned then the road is no longer required).

Probabilistic erosion assessments are unlikely to be advantageous for this coastal road due to the intermittent shoreline changes from isolated erosion/landslide events, the steep topography limiting erosion, and ongoing mechanical interruption to natural shoreline processes. We have instead adopted a 'low-lying / near-coast' hazard area of 45 m wide which indicates the potential for coastal hazards to affect the road due to its proximity and elevation (Figure 4-41).

Figure 4-41: 50 m low lying near coast buffer along Haast-Jackson Bay Road.

4.7.4 CHA26c: Jackson Bay village

Erosion: Erosion potential at the town is managed by rock and concrete rubble walls along the coast (Figure 4-42). Erosion potential will increase with sea-level rise and will result in increased maintenance requirements for the revetment and upgrade of the rubble wall over time.

A rock revetment was constructed by Westland District Council after erosion undermined the road during exTC Fehi (Feb 2018). The new revetment provides some protection to the road and wharf terminus but only extends part-way along the village coastline. The remaining coastline is an ad-hoc rubble/debris wall which fringes the coast and wraps around to the mouth of Seacombe Creek (Figure 4-42).

Figure 4-42: Jackson Bay village coastline with new rock revetment at the terminus of the Wharf transitioning to rubble wall wrapping around to Seacombe Creek. Note low-lying fill area/carpark adjacent to Creek mouth. Date 12.8.2021 [Credit: M Allis (NIWA)].

Inundation: Inundation with sea-level rise is expected to be the main hazard to the low-lying areas of Jackson Bay township and the road. High sea levels will flood up Seacombe Creek onto the adjoining roads, carpark and the private property alongside Peir Street which appears to be backfilled land. Multi-hazard events with large waves and high seas will increasingly overtop the road and rock/rubble walls fronting the village.

CHA analysis: The coastline at Jackson Bay village is not suitable for probabilistic erosion analysis due to the ongoing interruption to natural shoreline processes and revetments which maintain the shoreline position.

We have instead adopted a 'low-lying near-coast' area of 45 m wide which indicates the potential for coastal hazards to affect the road due to its proximity and elevation.

When LiDAR topography is available the area may be updated to include an upper elevation of 5 m above present-day high tide.

Inundation assessment shows the low-lying areas fringing the coast (road, carpark, property) will be increasingly subject to inundation with sea-level rise (Figure 4-43).

Figure 4-43: Jackson Bay inundation extent from the 1%AEP storm-tide+ wave setup at present sea level. Blue shading shows the inundation extent and the red line shows the 100-year outlook coastal erosion hazard area limit.

5 Discussion

This report presents coastal hazard zoning for coastal inundation and erosion. The result of the analysis is generally consistent with observation during field visits.

In several CHAs (e.g., Neils Beach, Rapahoe, Ngakawau) 1% AEP coastal inundation extent appears controlled by the presence of coastal terraces near the shore. In these locations, the 1% AEP inundation extent is only affected by increasing sea level if/when sea-level rise reaches the threshold elevation of the terrace. In these locations sea level rise will still however increase the frequency of flooding within the hazard area.

In all of the pCHA except Granity, Orowaiti and Rapahoe LiDAR topography data is not yet available and SRTM DEM was used instead. SRTM DEM is a crude representation of the ground elevation with lower accuracy and resolution than LiDAR, resulting in high uncertainty for the inundation analysis. With LiDAR survey expected to become available in the near future, the inundation mapping for these areas should be redone to confirm/update the results.

Except for the Orowaiti coastal hazard area, the inundation analysis in this study maps inundation by extrapolating the extreme sea level value including storm tide and wave setup statically across the DEM. While this method is a great first-order assessment of the coastal inundation it doesn't offer the insight of hydrodynamics simulation using a high-resolution DEM such as the model done for Orowaiti Lagoon. Hydrodynamics simulation offer excellent assessment of inundation and can help guide mitigation solutions.

However, there are limited nearshore water level data available on the West Coast which is necessary to validate hydrodynamics model. Water level data on the open coast is also critical for verifying wave setup calculation. This study relies on empirical estimates guided by understanding of surf-zone dynamics from studies of area with a wave climate much more quiescent wave climate then the West Coast. Such data would allow a refinement of the wave setup assessment whole coast.

Storm-tide combined with wave setup represents the maximum still water-level during a storm but does not represent the highest elevation that can be reached by waves (i.e., runup). Records of runup for storm inundation will become a valuable data to monitor how sea level rise will impact the west coast and will provide validation for future coastal inundation analysis.

Uncertainty included in the probabilistic mapping of coastal erosion hazard includes a measure of the uncertainty associated with the data manipulation and in the analysis itself. Improving the data available for evaluating future shoreline changes will reduce the uncertainty in this analysis which may also reduce the width of the mapped erosion hazard area.

However, available information geomorphology of the shore and erosion are limited and assumptions were required to proceed with the coastal erosion hazard analysis. Key assumptions, their implication and CHAs affected are listed in Table 5-1. Further improvement to the understanding of these assumption could lead to refinement of the coastal erosion analysis.

Table 5-1: Summary of assumptions for coastal erosion hazard assessment. Note: this list represent the most significant assumptions and is not exhaustive.

Assumptions	Implications	pCHA affected
Normal distribution of short-term retreat.	Ideally short term retreat follows an extreme distributions in unconsolidated geomorphologies	All
Backshore sediment availability (volume and composition) is not explicitly accounted for	The analysis does not account for the sediment composition of the backshore as erosion progresses. Nor does it take into account the volume of sediment available. However the analysis will stop erosion if the coastal hazard area encounter bedrock (i.e. consolidated geology).	All
Coastal structures (sea wall etc) will be maintained and upgraded as SLR.	The analysis includes a residual risk associated with the historical erosion rate but does not account for any acceleration of the erosion rate due to SLR. The coast associated to any community funded/maintained structure has not been taken into account. The residual risk associated with very recent structure is likely overestimated.	Hector, Ngakawau and Granity. Orowaiti sea walls, and Punakaiki structures
Changes in erosion rate due to changes in wave climate is not accounted for.	The analysis does not account for any changes in erosion due to changes in wave directions. However, we do know that there is likely a trend in the wave climate of the West Coast associated the southward migration of the storm belt.	All
Acceleration of SLR can be represented as a distribution of SLR rates	For the duration of the outlook SRL rate is considered constant (yet greater or equal to the present SLR rate).	All
Error due to georeferencing and digitizing are assumed to be normal	While it is fair to assume georeferencing error follow a normal distribution, errors in digitizing may lead to skewed distribution. This may introduce a bias of 2—5 m in the digitized line.	All

Occurrence of a major earthquake in the next 100 year is not accounted for in the analysis. However, a major earthquake along the Alpine Fault would significantly affect the shoreline. Co-seismic displacement would modify the local shoreline elevation relative to sea level, modifying the inundation and erosion hazard. An earthquake would also cause many landslide and slips in the upper parts of river catchments, resulting in a huge pulse in sediment supply, and consequently a modified response of the shoreline.

6 Summary

Assessment of coastal hazard (inundation and erosion) has been completed for seven priority coastal hazard areas on the West Coast. Accompanying this report are GIS layers showing:

1. Potential inundation for 1%AEP storm events and sea level rise steps from present sea level to 2 m above present sea level. Guidance on selection of the appropriate sea level rise step is given in section 2.5.

2. Erosion hazard for 50-year and 100-year outlooks based on the 95th percentile probable distance onshore.

These layers will inform WCRC in the development of Te Tai Poutini plan.

7 Acknowledgements

The authors would like to thank WCRC, in particular Paulette Birchfield and Edith Bretherton, for onsite walkover meetings, searching the archive for historic aerial photographs, and input on the analysis and the report. We also thank Land River Sea Consulting (Matthew Gardner) for the collaborative approach to this coastal hazard assessment and his aligned work relating to Hokitika and Greymouth. We also acknowledge the excellent historic aerial photography resource at Retrolens.

8 Glossary of abbreviations and terms

Annual Exceedance Probability	Annual Exceedance Probability (AEP) refers to the probability of a flood event occurring in any year. The probability is expressed as a percentage. For example, a storm-tide level which may be calculated to have a 1% chance to occur in any one year, is described as 1% AEP.
Average recurrence interval	Average recurrence interval (ARI) which is the average time interval between events of a specified magnitude (or larger), when averaged over many occurrences.
CHA	Coastal Hazard Areas. Areas of high coastal hazard area identified by Measures and Rouse (2013, updated 2021).
Coastal flooding	Coastal flooding occurs when normally dry, low-lying land is flooded by seawater.
DEM	Digital elevation model, a digital map of ground elevations.
GIS	Geographic information system, software used for spatial mapping and analysis.
LiDAR	Airborne Light Detection and Ranging (LiDAR), is a remote sensing method used for high resolution topographic mapping
LVD or LVD-37	Lyttelton Vertical Datum, the local orthometric height datum used on the West Coast. This datum is based on mean sea level in Lyttelton Harbour and was established in 1937. The preferred datum is now NZVD2016.
MHWS	Mean high-water springs, the average high tide water level.
MHWS–7	MHWS–7 is the level 7% of astronomic high tides exceed
MSL	MSL is the mean level of the sea relative to a vertical datum over a defined epoch, usually of several years.
MSLA	Sea-level anomaly (MSLA) is the variation of the non-tidal sea level about the longer term MSL on time scales ranging from a monthly basis to decades, due to climate variability. This includes the effect of the El Niño-Southern Oscillation (ENSO) and inter-decadal pacific oscillation (IPO) patterns on sea level, winds and sea temperatures, and seasonal effects.
NZVD2016	New Zealand Vertical Datum 2016 is the official national vertical datum for New Zealand.

Present-day MSL	The best estimate of mean sea level for a region at the time of writing, relative to a local vertical datum.
RCP	Representative Concentration Pathways. IPCC and researchers world-wide base their projections for sea-level rise on Representative Pathway Concentrations (RCPs). These scenarios are representative of four different groupings of future radiative forcing (warming) by greenhouse gas emissions and associated social, economic, population and land-use projections. The scenarios used are from the MfE Coastal Guidance (MfE 2017): RCP 2.6, RCP 4.5, RCP 8.5 and RCP 8.5 H+.
Significant wave height	The average height of the highest one-third of waves in the wave record
SLR	Sea-level rise. The rise in mean sea level over time . The main contributors to the global rise in sea level since the 1900 are 1) Warming of ocean waters causing expansion in seawater volume 2) Melting or break-up of land-based ice stores such as glaciers and polar ice sheets (particularly Greenland and West Antarctica), 3) changes in water properties or flowpaths of the main ocean currents, and 4) changes in the net storage of terrestrial freshwater e.g., groundwater/river extraction, reservoirs, changes in rainfall and evaporation from climate variability e.g., El Niño/La Niña. Local processes also contribute to SLR on a local scale, including, for example: subsidence of large river-delta systems or tectonic effects (slow regional uplift/subduction).
Storm surge	The temporary rise in sea level due to storm meteorological effects. Low atmospheric pressure causes the sea-level to rise, and wind stress on the ocean surface pushes water down-wind and, to a lesser extent, to the left up against any adjacent coast.
Storm-tide	Storm-tide is defined as the sea-level peak during a storm event, resulting from a combination of MSL + SLA + astronomic tide + storm surge. In New Zealand this is generally reached around high tide.
Wave runup	The maximum vertical extent of wave “up-rush” on a beach or structure above the still water level, and thus constitutes only a short-term upper-bound fluctuation in water level relative to wave setup
Wave setup	A sustained increase in the mean water level at the shore compared to the level further offshore beyond the surf-zone that is induced by the transfer of momentum from waves as they break over a sloping foreshore. Setup is localised to the surf-zone but is a meaningful addition to the extreme storm-tide levels at the coast
WCRC	West Coast Regional Council

9 References

Allis, M.J., Bell, R.G., Dawe, I., Stephens, S.A., (2021) Determining an objective coastal land-sea boundary zone for jurisdictional clarity. *Proceedings of the Australasian Coasts & Ports 2021 Conference* – Christchurch, 30 November – 3 December 2021.

Beavan, RJ, Litchfield, NJ. (2012) Vertical land movement around the New Zealand coastline: implications for sea-level rise. Lower Hutt: *GNS Science Report No.: 2012/09*.

Bell, R.G., Paulik, R., Wadhwa, S. (2015) National and regional risk exposure in low-lying coastal areas. Areal extent, population, buildings and infrastructure. *NIWA Client report PCE15201*. Prepared for Prepared for Prepared for Prepared for the Parliament.

Bell, R.G., Allis. M.J. (2021) Update on sea-level rise projections for Wellington City. Supporting the 2020–2021 District Plan process. *NIWA Client report 2021051HN*. Prepared for Wellington City Council. March 2021: 25.

Birkemeier, W. A. (1985) Field data on seaward limit of profile change. *Journal of Waterway, Port, Coastal and Ocean Engineering* 111(3): 598-602

Boak, E., Turner, I. (2005) Shoreline Definition and Detection: A Review. *Journal of Coastal Research* 21(4): 688 – 703. https://doi.org/10.2112/03-0071.1.

Bosserelle, C., Hicks, M., Bind, J. (2019) Waitaki District Coastal Hazards. *NIWA Client report 2018035CH.* Prepared for the Otago Regional Council.

Bruun, P. (1962) Sea-level Rise as a Cause of Shore Erosion. Engineering progress at the University of Florida. Florida Engineering and Industrial Experiment Station.

Gibb, J.G. (1978) Rates of Coastal Erosion and Accretion in New Zealand. *New Zealand journal of Marine and freshwater Research* 12 (4): 429-56.

Godoi, V.A., Bryan, K.R., Stephens, S.A., Gorman, R. (2017) Extreme waves in New Zealand waters, Ocean Modelling 117: 97-110

Goring D. (2001) Computer Models Define Tide Variability. The Industrial Physicist, American Institute of Physics, 14—17.

Hallermeier, R. J. (1981) A Profile Zonation for Seasonal Sand Beaches from Wave Climate. *Coastal Engineering*. 4: 253-277.

IPCC (2019) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].

Kopp, R.E., Horton, R.M., Little, C.M., Mitrovica, J.X., Oppenheimer, M., Rasmussen, D.J., Strauss, B.H., Tebaldi, C. (2014) Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future* 2(8): 383–406.

MfE (2017) Coastal hazards and climate change: Guidance for local government. *Ministry for the Environment Publication ME1341*. Wellington, Ministry for the Environment: 279 + Appendices http://www.mfe.govt.nz/publications/climate-change/coastal-hazards-and-climate-change-guidance-local-government. Ministry for the Environment, Wellington.Paulik et al. 2019, Paulik et al. 2020).

Meadows M, Wilson M. (2021) A Comparison of Machine Learning Approaches to Improve Free Topography Data for Flood Modelling. *Remote Sensing*. 13(2):275. https://doi.org/10.3390/rs13020275

Measures, R., Cochrane, T., Caruso, B., Walsh, J., Horrell, G., Hicks, M., Wild, M. (2014) Analysis of Te Waihora lake level control options - A Whakaora Te Waihora science project. *NIWA Client Report CHC2014-076* prepared for Ngāi Tahu and Environment Canterbury, June 2014.

Measures, R., Rouse, H., (2022). Review of West Coast Region Coastal Hazard Areas. *NIWA Client Report CHC2012-081 v2*. Prepared for West Coast Regional Council.

Paulik, R., Stephens, S.A., Wadhwa, S., Bell, R.G., Popovich, B., Robinson, B. (2019) Coastal Flooding Exposure Under Future Sea-level Rise for New Zealand. *NIWA Client report 2019119WN*. Prepared for The Deep South Challenge: 81. March 2019.

Paulik, R., Stephens, S. A., Bell, R. G., Wadhwa, S., and Popovich, B. (2020) National-Scale Built-Environment Exposure to 100-Year Extreme Sea Levels and Sea-Level Rise. *Sustainability*, 12, 1513, https://doi.org/10.3390/su12041513

Roelvink, D., et al. (2009) Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering*, 56(11): 1133-1152.

Stephens, S.A., Wadhwa, S., Tuckey, B. (2016) Coastal inundation by storm-tides and waves in the Auckland Region. Prepared by the National Institute of Water and Atmospheric Research and DHI Ltd for Auckland Council. Auckland Council Technical Report, TR2016/017: 206. https://www.aucklandcouncil.govt.nz/environment/what-we-do-to-help-environment/Documents/coastal-inundation-in-auckland.pdf

Stephens, S.A. (2017) Tauranga Harbour extreme sea level analysis. NIWA Client Report to Bay of Plenty Regional Council, March 2017, 2017035HN: 47.

Stephens, S.A., Ivamy, M., Reeve, G., Wadhwa, S., Popovich, B., Bell, R., Blackwood, P.L. (2018) Is the "bathtub" model adequate for coastal hazard and risk mapping? Oral presentation at The New Zealand Coastal Society Annual Conference "Whiti i te wai - Crossing the Water", 20-23 November 2018, Gisborne.

Stephens, S.A., Bell, R.G., Haigh, I.D. (2020) Spatial and temporal analysis of extreme storm-tide and skew-surge events around the coastline of New Zealand. *Nat. Hazards Earth Syst. Sci.*, 20(3): 783-796. 10.5194/nhess-20-783-2020 https://www.nat-hazards-earth-syst-sci.net/20/783/2020/

USACE (2012). Coastal Engineering Manual Part II: Coastal Hydrodynamics (EM 1110-2-1100). Books Express Publishing.

Walters, R.A., Goring, D.G., Bell, R.G. (2001) Ocean tides around New Zealand. *New Zealand Journal of Marine and Freshwater Research* 35: 567–579.

Appendix A Extended CHAs

The extents of CHA25 and CHA26 were expanded at the request of WCRC. The two CHAs have been renamed and extended within the GIS shapefile (Figure A-1 and Figure A-2) for return back to WCRC with the coastal hazards analysis.

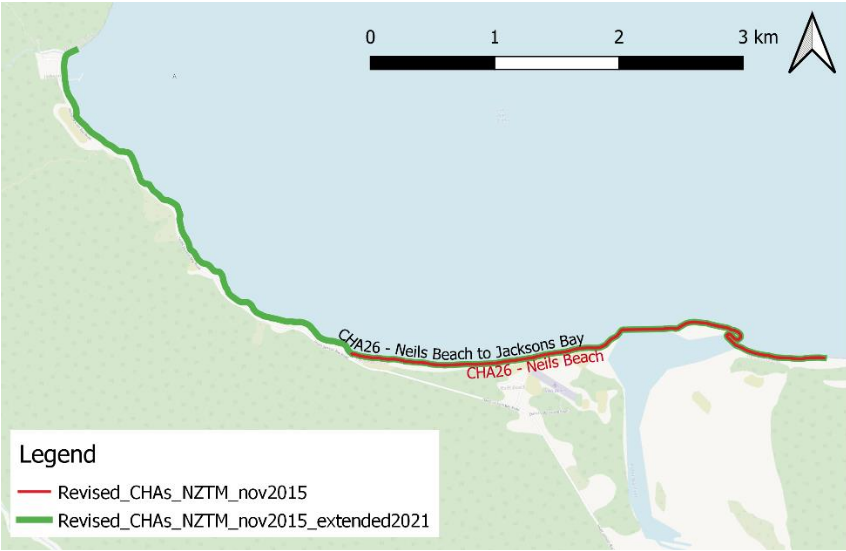

Figure A-1: CHA26 extended to Jackson Bay and renamed *Neils Beach to Jackson Bay*.

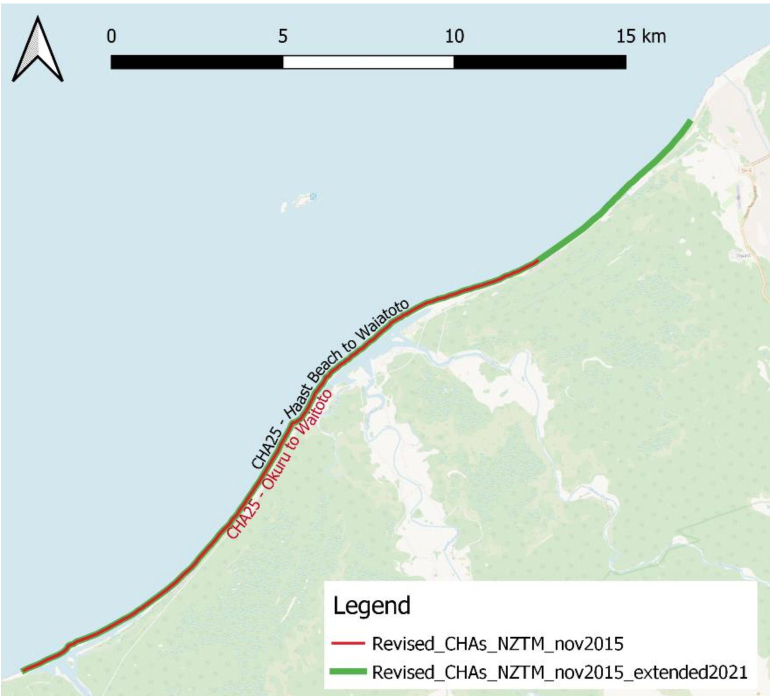

Figure A-2: CHA25 extended to Haast River and renamed *Haast Beach to Waiatoto*.

Appendix B Orowaiti hydrodynamics modelling memo

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1. 3 MARCH 2022

2. **To: Cyprien**
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WESTPORT COASTAL MODELLING

The existing hydraulic model of the Buller River has been used to simulate coastal flooding for the area of interest between the true right bank of the Buller River and the Orowaiti Lagoon mouth. The model is an upgrade to the original 2017 modelling which has the new 2020 LiDAR as its basis for the terrain. The model has been upgraded as part of the ongoing Westport Flood Protection project and is currently being peer reviewed, therefore a final report has not been produced, however it is not expected that there will be any significant changes to the model which will impact on the coastal inundation component as part of the peer review process.

Model Schematic

The model has been built in MIKE Flood software and is a coupled MIKE11 / MIKE21 flexible mesh model with the main Buller River channel being represented using 1d flow equations within MIKE11 and the overland flow component being simulated in MIKE21FM. This setup has the advantage that two separate boundary conditions can be applied – one for the 2D component and a separate boundary condition for the 1D river channel. This is particularly useful for this location as the river moles at the mouth likely provide protection from wave setup inside the river mouth itself.

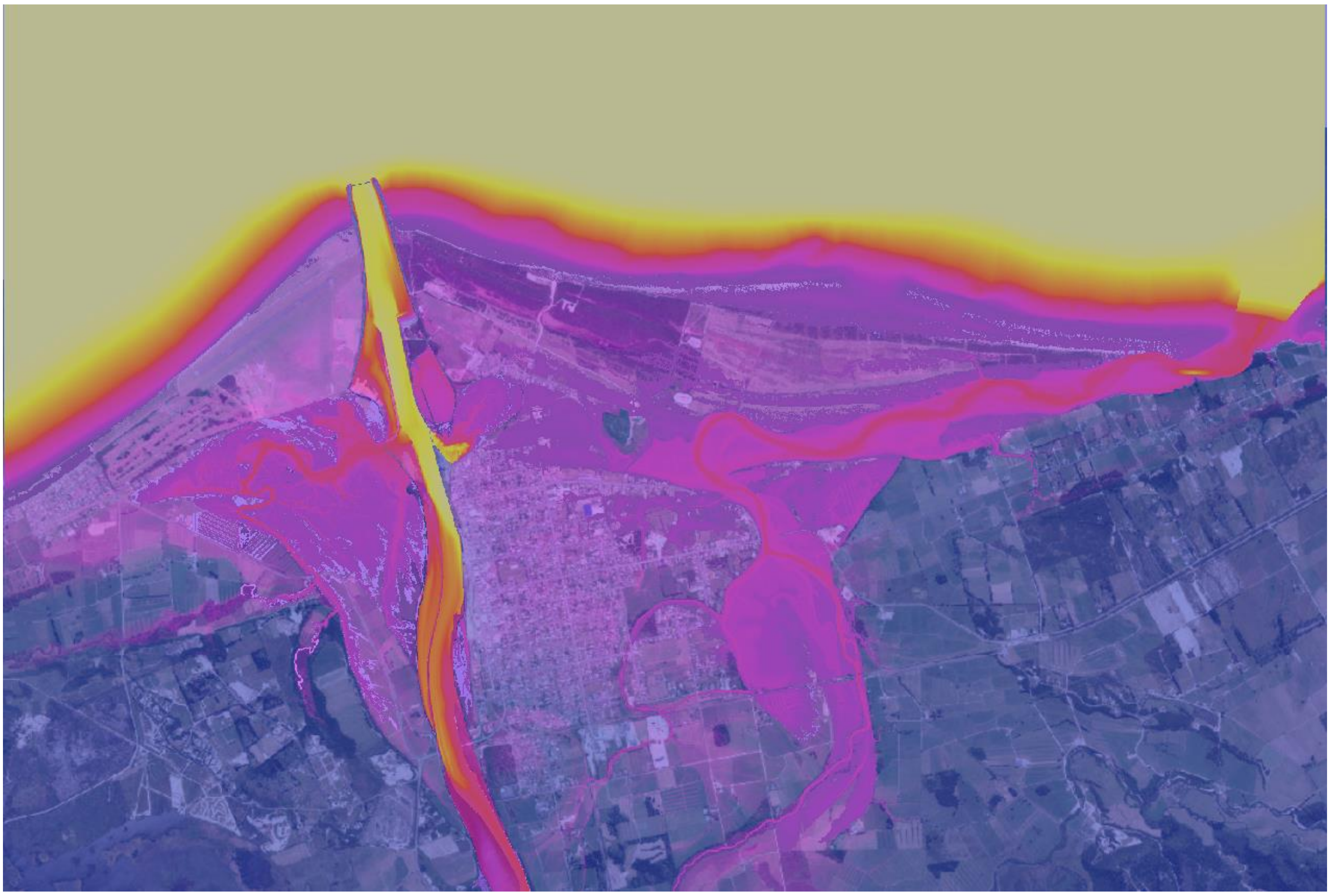

Figure 44 – 2D Model Extent

Model Calibration

Independent to this investigation, the model has already been calibrated to two large river flood events (July 2012, and July 2021) with both events providing a good fit to surveyed debris levels and flood extents.

The February 2018 Cyclone Fehi event has been used as the sole calibration event with coastal boundaries being provided by NIWA to feed into the model.

The model has been run for a 12-hour time period with the provided coastal boundaries with the flood extent and peak elevation data being compared with the modelled water elevation. Results have compared very well with the average error being 0.01m and average absolute error being 0.08m. This is considered an excellent match and gives us confidence that the methodology used to simulate cyclone fehi is fit for purpose. A comparison of the modelled results the estimated flood extent sketched by BDC staff is attached to the end of this memo. The following 3D images (Figure 2 & 3) compare the peak flood extent with photos taken after the event itself (note these photos show less flooding than was experienced at the peak of the flood).

Figure 45 – Comparison of modelled peak extent with flood photo at Orowaiti Lagoon

Figure 46 – Comparison of modelled peak extent with flood photo looking towards Westport

Design Runs

11 simulations have been completed in the model using the provided boundary condition from NIWA as summarised in table 1.

Table 2 – Summary of design runs

SIMULATION	DESCRIPTION
01	100 year ARI Coastal Event - Historic Climate
02	100 year ARI Coastal Event - 0.2m Sea Level Rise
03	100 year ARI Coastal Event - 0.4m Sea Level Rise
04	100 year ARI Coastal Event - 0.6m Sea Level Rise
05	100 year ARI Coastal Event - 0.8m Sea Level Rise
06	100 year ARI Coastal Event - 1.0m Sea Level Rise
07	100 year ARI Coastal Event - 1.2m Sea Level Rise
08	100 year ARI Coastal Event - 1.4m Sea Level Rise
09	100 year ARI Coastal Event - 1.6m Sea Level Rise
10	100 year ARI Coastal Event - 1.8m Sea Level Rise
11	100 year ARI Coastal Event - 2.0m Sea Level Rise

Results have been supplied in geotif format as well as shapefiles of extent.

Kind regards,

Hamilton

CMEngNZ, CPEng

Director, Land River Sea Consulting Ltd