Coastal Flooding Exposure Under Future Sea-level Rise for New Zealand

Prepared for The Deep South Challenge

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Executive summary

This study presents New Zealand's exposure to 1% annual exceedance probability (AEP) coastal flood inundation under present-day and future higher sea levels.

The investigation comprised:

- Estimating 1% AEP extreme sea level elevation (ESL1) at present-day mean sea-level (MSL) around the New Zealand coastline, resulting from combination of tide, storm-surge, mean sea-level anomaly and wave setup.
- Mapping coastal flood inundation on low-lying coastal land by projecting ESL1 onto both high-resolution airborne LIDAR and lower resolution satellite derived MERIT digital elevation models (DEM). On land with LIDAR DEM coverage, inundation is mapped for +0.1 m sea-level rise (SLR) increments up to +3 m above present-day MSL. On land without LIDAR DEM coverage, inundation is mapped for +3 m SLR above present-day MSL. A composite LIDAR and satellite DEM with complete national coverage was used to map land exposed to ESL1 +3 m SLR around the entire New Zealand coastline.
- Mapping "elements at risk" to ESL1 including: population, buildings (count and 2016 NZD replacement value), transport infrastructure (roads, railways, airports), electricity infrastructure (transmission lines, structures, sites), three-waters infrastructure (nodes, pipelines), and land cover (built, production, natural or undeveloped). These elements at risk provide a representative sample of built assets and land cover types exposed within New Zealand's coastal floodplains for each coastal flood inundation scenario.
- Developing national and regional level exposure profiles for elements at risk to ESL1. Exposure for the present-day MSL and with SLR of +0.3 m, +0.6 m, +0.9 m and +1.2 m for areas with LIDAR DEM coverage as presented in Tables 0-1 to Table 1-5. These sea-levels were related to four projected future SLR scenarios for New Zealand beyond 2120 based on three greenhouse gas concentration pathways (RCP2.6, RCP4.5 and RCP8.5).
- Developing combined national and regional level exposure profiles of elements at risk to ESL1 with SLR of +3 m SLR for the composite LIDAR and satellite DEM as presented in Table 1-6.

The exposure mapping results showed that:

- At a national level, elements at risk are subject to a linear ESL1 exposure increase in response to rising sea levels. At region and territory levels, ESL1 exposure of elements exhibits non-linear behaviors, with acceleration or deceleration in response to increasing SLR increments and the characteristics of elements at risk in these areas.
- Population and built assets in some regions and territories with major coastal urban areas experience an initial rapid increase of ESL1 exposure in response to SLR. In Hawkes Bay (i.e. Napier City), Wellington (i.e. Lower Hutt City) and Canterbury (i.e. Christchurch City), exposure of these elements accelerates rapidly to +0.9 m SLR above present-day MSL, before decelerating under higher SLR thereafter. In other populous

regions (e.g. Auckland, Waikato, Bay of Plenty), population and built asset ESL1 exposure increases at an approximately constant rate in response to SLR.

It is also noted that:

- Coastal flooding from ESL1 is considered an unusually large and rare event at present-day MSL, having only a 1% annual exceedance probability. The effect of future rising sea-levels is to increase the frequency of ESL1 being reached or exceeded. This means that elements at risk to present-day ESL1 will be more frequently exposed to coastal flood inundation in future.
- The information presented in this study provides researchers and practitioners with locations to focus more detailed investigation on the potential impacts and management implications of coastal flooding under future sea-level rise.
- It is recommended that coastal flood inundation maps and element at risk exposure information produced in this study should be updated as new LiDAR data are made available.

Table 1-1: National and regional level exposure of elements at risk to ESL1 for present-day MSL on land with available LIDAR DEM coverage.

Region*	Population (#)	Buildings		Transport			Electricity (National Grid)			Three-Waters		Land Cover (km^2)		
		Building (#)	Replacement Value (2016 NZD$ Billion)	Roads (km)	Railway (km)	Airports (#)	Transmission Lines (km)	Structures (#)	Sites (#)	Pipelines (km)	Nodes (#)	Built	Production	Natural or Undeveloped
Northland	2,275	2,645	0.54	74.2	3.8	0	5.8	5	0	93.2	3,047	2.6	61.5	12.7
Auckland	2,837	1,790	0.61	48	10.1	1	21.3	21	0	131.0	5,396	2.2	86.7	21.1
Waikato	7,703	7,184	1.46	342.4	2.6	3	11.6	7	0	141.6	3,540	5.5	540.9	115.7
Bay of Plenty	10,180	8,241	1.84	234.2	10.1	2	30.7	69	0	516.4	15,051	5.2	254.4	32.9
Gisborne	92	159	0.03	13.8	9.2	1	0	0	0	19.7	457	0.4	23	6.6
Hawke's Bay	6,152	4,574	1.02	87.1	1	1	0.8	0	0	484.8	20,711	4.3	38.2	27.4
Taranaki	439	381	0.05	11.6	1.3	0	0.5	0	2	28.1	431	0.4	6.9	7.5
Manawatu-Whanganui	901	1,459	0.29	43.1	2.9	1	10.1	13	0	61.8	1,186	2	65.2	26.1
Wellington	6,220	4,084	1.16	36.2	2.9	2	0.3	0	0	290.9	5,898	2.9	78.1	109.4
Canterbury	18,122	9,506	2.48	243.3	8.2	0	13.2	28	0	638.0	No Data**	14.7	104.3	86.4
Otago	10,802	5,506	1.56	166.3	25.1	1	7.7	9	0	416.4	11,318	4.4	133.1	52.3
Southland	3,103	1,711	0.73	42.3	8.8	0	0	0	0	157.0	2,512	2.8	5.3	7.1
Tasman	1,803	982	0.28	40.2	0	0	0	0	0	100.5	4,450	1.5	21.1	9.8
Nelson	1,118	907	0.27	7.3	0	1	0	0	0	99.0	3,037	0.9	0.7	1.2
Marlborough	318	334	0.15	24.2	0.6	0	20.5	28	0	0.8***	3***	0.5	37.6	13.4
NZ Total	**72,065**	**49,709**	**12.4**	**1,414**	**86**	**13**	**122**	**180**	**2**	**3,179**	**77,037**	**50**	**1,457**	**529**

* No LIDAR available for West Coast region.

** No three-waters infrastructure node data available for Canterbury region.

*** Limited three-waters infrastructure pipeline and node data available for Marlborough region.

Table 1-2: National and regional level exposure of elements at risk to ESL1 +0.3 m SLR above present-day MSL on land with available LIDAR DEM coverage.

Region*	Population (#)	Buildings		Transport			Electricity (National Grid)			Three-Waters		Land Cover (km²)		
		Building (#)	Replacement Value (2016 NZD$ Billion)	Roads (km)	Railway (km)	Airports (#)	Transmission Lines (km)	Structures (#)	Sites (#)	Pipelines (km)	Nodes (#)	Built	Production	Natural or Undeveloped
Northland	2,990	3,570	0.77	99.3	5.1	0	6.8	9	0	128.2	4,266	3.5	71.7	13.9
Auckland	4,151	2,719	1.21	70.6	12	1	25.4	31	0	198.7	7,863	3.3	97.1	25.1
Waikato	8,641	8,266	1.68	395	5.5	4	14.8	10	0	176.7	4,458	6.5	573.6	133.1
Bay of Plenty	13,115	10,822	2.57	281.5	16.6	2	38.2	92	0	657.1	19,365	6.7	273.6	34.9
Gisborne	145	247	0.05	17.8	9.8	1	0	0	0	29.7	711	0.6	26.3	6.9
Hawke's Bay	11,875	9,315	2.06	133.9	1.5	1	0.9	0	0	697.3	27,561	7	49.4	30.1
Taranaki	513	451	0.07	14	1.4	0	0.5	7	2	36.9	566	0.6	7.7	8
Manawatu-Whanganui	1,209	1,926	0.38	53.4	3.3	1	11.7	14	0	76.2	1,637	2.5	74.7	27.5
Wellington	9,838	6,421	1.97	68.7	4	2	0.8	0	0	490.0	10,124	4.5	89	111
Canterbury	25,809	14,338	3.96	320.8	10.1	0	15.6	34	1	831.4	No Data**	19	128.3	90
Otago	11,525	6,237	1.70	207	30.6	1	8.1	10	0	466.2	12,431	5.1	144.1	54.7
Southland	3,585	1,983	0.86	50.8	11.7	0	0	0	0	185.5	3,054	3.3	6.3	7.6
Tasman	3,058	1,654	0.48	62.5	0	0	0	0	0	147.9	5,650	2.3	26.1	10.9
Nelson	1,879	1,473	0.55	15.5	0	1	0	0	0	183.9	5,187	1.6	0.7	1.5
Marlborough	449	423	0.18	32.9	0.9	0	21.9	30	0	1.0***	5***	0.6	43.5	13.8
NZ Total	**98,782**	**69,845**	**18.49**	**1,823**	**112**	**14**	**144**	**237**	**3**	**4,307**	**102,878**	**67**	**1,612**	**569**

* No LIDAR available for West Coast region.
** No three-waters infrastructure node data available for Canterbury region.
*** Limited three-waters infrastructure pipeline and node data available for Marlborough region.

Table 1-3: National and regional level exposure of elements at risk to ESL1 +0.6 m SLR above present-day MSL on land with available LIDAR DEM coverage.

Region*	Population (#)	Buildings		Transport			Electricity (National Grid)			Three-Waters		Land Cover (km²)		
		Building (#)	Replacement Value (2016 NZD$ Billion)	Roads (km)	Railway (km)	Airports (#)	Transmission Lines (km)	Structures (#)	Sites (#)	Pipelines (km)	Nodes (#)	Built	Production	Natural or Undeveloped
Northland	3,550	4,419	1.06	126.1	8.1	0	7.3	11	0	176.4	5,833	4.4	79.1	15.1
Auckland	5,914	3,831	1.85	100.3	14.5	1	30.8	41	0	292.7	11,277	5.4	105.3	28.7
Waikato	9,598	9,387	1.93	449.5	7.4	4	15.8	13	0	216.8	5,416	7.6	602.6	148.5
Bay of Plenty	16,490	13,523	3.21	335.8	21.9	2	44.4	104	0	795.8	24,155	8.5	291.2	36.8
Gisborne	298	429	0.13	25.8	10.5	1	0	0	0	39.2	937	0.9	30.7	7.3
Hawke's Bay	18,008	14,302	3.19	178.5	2.9	1	1	0	0	904.9	33,716	9.8	60.7	32.8
Taranaki	600	564	0.09	17.3	1.8	0	0.5	7	2	46.7	742	0.7	8.5	8.3
Manawatu-Whanganui	1,556	2,454	0.49	61.6	3.9	1	13.2	15	0	93.4	2,290	2.9	88.9	28.7
Wellington	15,547	10,004	3.60	110.1	5.8	2	2.3	1	0	758.9	15,913	6.5	99.7	112.6
Canterbury	37,049	20,876	5.82	409.7	13.9	0	18	39	1	1,034.9	No Data**	24.3	156.4	93.6
Otago	12,035	6,639	1.98	244.7	37.9	1	9	11	0	531.6	14,023	5.9	154.4	56.9
Southland	4,103	2,277	1.04	59.5	12.2	0	0	0	0	209.9	3,492	3.8	7.2	8.1
Tasman	4,472	2,406	0.72	81.9	0	0	0	0	0	189.8	6,839	3.3	31.0	11.8
Nelson	2,623	2,171	0.85	29.2	0	1	0	0	0	278.9	7,794	2.6	0.8	1.9
Marlborough	807	609	0.22	43	1.3	0	23.6	33	0	2.1***	6***	0.7	49.3	14.1
NZ Total	**132,650**	**93,891**	**26.18**	**2,273**	**142**	**14**	**165**	**275**	**3**	**5,572**	**132,433**	**87**	**1,765**	**605**

* No LIDAR available for West Coast region.

** No three-waters infrastructure node data available for Canterbury region.

*** Limited three-waters infrastructure pipeline and node data available for Marlborough region.

Table 1-4: National and regional level exposure of elements at risk to ESL1 +0.9 m SLR above present-day MSL on land with available LIDAR DEM coverage.

Region*	Population (#)	Buildings		Transport			Electricity (National Grid)			Three-Waters		Land Cover (km²)		
		Building (#)	Replacement Value (2016 NZD$ Billion)	Roads (km)	Railway (km)	Airports (#)	Transmission Lines (km)	Structures (#)	Sites (#)	Pipelines (km)	Nodes (#)	Built	Production	Natural or Undeveloped
Northland	4,084	5,265	1.33	153.7	11.4	0	7.6	11	0	227.0	7,323	5.5	86.2	17.7
Auckland	8,890	5,371	3.22	136.6	16.2	1	35.4	45	0	424.3	16,140	6.9	112.0	32.3
Waikato	10,561	10,663	2.20	503.5	8.9	4	17.2	13	0	276.7	6,903	9	629.7	162.8
Bay of Plenty	19,549	15,828	3.81	379.9	28	2	49.8	116	0	910.9	27,844	10.3	307.7	38.6
Gisborne	505	649	0.18	34.9	11	1	0	0	0	50.3	1,200	1.2	36.2	7.9
Hawke's Bay	24,207	19,066	4.36	208.1	5	1	1.3	1	0	1,051.1	38,433	12.2	70.7	35.3
Taranaki	703	695	0.13	22.2	1.9	0	0.8	7	2	58.6	961	0.8	9.4	8.7
Manawatu-Whanganui	2,094	3,212	0.61	72.8	4.6	1	15	16	0	116.1	3,126	3.4	110.0	29.8
Wellington	20,775	13,330	5.59	157.1	7.7	2	4	3	0	1,009.7	22,210	8.2	110.8	114.5
Canterbury	47,777	27,224	7.68	497.2	19.1	0	19.4	39	1	1,226.9	No Data**	29.4	179.3	96.7
Otago	12,553	7,312	2.56	286.8	48.1	1	11.9	18	2	616.6	16,300	7.3	165.0	58.9
Southland	4,685	2,578	1.16	66.8	12.4	0	0	0	0	233.6	3,963	4.2	8.3	8.8
Tasman	5,512	2,979	0.87	102	0	0	0	0	0	224.6	7,840	4.1	35.7	12.8
Nelson	3,288	2,752	1.07	39.9	0	1	0	0	0	355.4	9,884	3.4	0.8	2.2
Marlborough	1,615	1,016	0.32	52.1	1.9	0	24.9	36	0	3.8***	6***	1.1	54.5	14.4
NZ Total	**166,789**	**117,940**	**35.1**	**2,713**	**176**	**14**	**187**	**305**	**5**	**6,786**	**162,130**	**107**	**1,916**	**641**

* No LIDAR available for West Coast region.
** No three-waters infrastructure node data available for Canterbury region.
*** Limited three-waters infrastructure pipeline and node data available for Marlborough region.

Table 1-5: National and regional level exposure of elements at risk to ESL1 +1.2 m SLR above present-day MSL on land with available LIDAR DEM coverage.

Region*	Population (#)	Buildings		Transport			Electricity (National Grid)			Three-Waters		Land Cover (km²)		
		Building (#)	Replacement Value (2016 NZD$ Billion)	Roads (km)	Railway (km)	Airports (#)	Transmission Lines (km)	Structures (#)	Sites (#)	Pipelines (km)	Nodes (#)	Built	Production	Natural or Undeveloped
Northland	4,755	6,133	1.58	175.6	13.5	0	7.9	12	0	272.2	8,654	6.6	93.4	19.1
Auckland	12,610	7,296	5.32	175.9	18.6	1	40.4	53	0	579.8	22,013	9.3	118.1	35.3
Waikato	11,972	12,486	2.58	555.7	9.8	4	20.8	15	0	356.9	8,771	10.8	655.5	183.8
Bay of Plenty	21,743	17,611	4.34	424.5	32.4	2	54.5	131	0	1,021.7	31,348	11.8	323.7	40.3
Gisborne	762	912	0.26	45.1	12.1	1	0	0	0	66.5	1,555	1.5	42.0	8.6
Hawke's Bay	29,100	22,619	5.31	234.8	9.6	1	1.7	1	0	1,191.6	43,262	14	80.0	38
Taranaki	802	798	0.17	26.7	2	0	1	8	2	68.9	1,149	1	10.4	9.2
Manawatu-Whanganui	2,586	3,918	0.73	85.6	5.2	1	16.9	18	0	138.5	3,974	3.9	130.8	31.2
Wellington	24,814	15,972	6.95	201.4	10.8	2	6.6	5	0	1,225.5	27,729	9.8	122.1	116.2
Canterbury	58,145	33,460	9.55	580.6	25.5	0	20.5	46	1	1,418.3	No Data**	34.3	198.6	100.4
Otago	13,054	7,827	2.96	323.8	54.7	1	13.6	22	2	677.8	17,758	8.4	175.2	60.7
Southland	5,400	2,942	1.30	74.5	12.7	0	0.2	0	0	259.0	4,415	4.7	9.5	9.6
Tasman	6,271	3,459	0.99	118.9	0	0	0	0	0	258.3	8,761	4.8	40.2	13.4
Nelson	4,058	3,376	1.30	49.6	0	1	0	0	0	424.2	11,745	4.1	0.8	2.5
Marlborough	2,504	1,435	0.43	61.5	5.3	0	27.1	38	0	5.9***	11***	1.5	59.2	14.8
NZ Total	**198,756**	**140,244**	**43.78**	**3,134**	**212**	**14**	**211**	**349**	**5**	**7,965**	**191,145**	**126**	**2,059**	**683**

* No LIDAR available for West Coast region.
** No three-waters infrastructure node data available for Canterbury region.
*** Limited three-waters infrastructure pipeline and node data available for Marlborough region.

Table 1-6: Combined national and regional level element exposure for ESL1 +3 m above present-day MSL (where SLR is calculated in meters above 1986-2005 baseline) on land with available LIDAR DEM and satellite DEM coverage.

Region*	Population (#)	Buildings		Transport			Electricity (National Grid)			Three-Waters		Land Cover (km²)		
		Building (#)	Replacement Value (2016 NZD$ Billion)	Roads (km)	Railway (km)	Airports (#)	Transmission Lines (km)	Structures (#)	Sites (#)	Pipelines (km)	Nodes (#)	Built	Production	Natural or Undeveloped
Northland	12,028	13,819	3.38	689	45	1	16.6	26	1	564	15,924	14	513	246
Auckland	37,185	18,092	14.13	354	32	2	63.2	89	0	1,298	45,253	24	155	52
Waikato	20,062	22,454	4.46	910	17	4	44	42	0	683	16,359	20	871	378
Bay of Plenty	51,211	34,962	9.4	740	59	2	87.7	244	2	2,102	68,674	26	411	48
Gisborne	6,739	5,733	1.24	153	21	1	0	0	0	259	5596	6	89	19
Hawke's Bay	48,856	37,976	10.01	451	51	1	6.6	4	1	1,867	70,065	24	134	47
Taranaki	1,690	1,660	0.36	56	4	0	1.2	8	2	128	2112	2	23	12
Manawatu-Whanganui	10,622	11,614	2.09	244	19	1	26.1	31	0	334	7,485	9	282	50
Wellington	44,304	28,288	12.12	450	22	2	31.8	36	3	2,235	53,011	19	180	126
West Coast*	11,610	7,428	2.07	398	47	4	22.1	59	3	517	13,937	10	151	373
Canterbury	118,761	70,702	21.53	1,276	73	1	58.7	172	2	2,588	No Data**	63	459	312
Otago	17,251	10,354	3.98	570	91	2	24.9	33	2	919	23,293	12	274	90
Southland	16,619	9,087	3.86	437	16	1	30.1	38	0	446	7,521	13	308	262
Tasman	9,703	5,517	1.53	193	0	0	0	0	0	393	12,607	7	76	43
Nelson	7,278	5,462	1.98	75	0	0	0	0	0	663	18,081	6	1	3
Marlborough	9,571	5,909	1.93	199	25	0	38.6	55	0	28***	236***	8	107	42
NZ Total	**423,490**	**289,057**	**94**	**7,195**	**520**	**22**	**451**	**837**	**16**	**15,024**	**360,154**	**263**	**4,031**	**2,102**

* No LIDAR available for West Coast region.
** No three-waters infrastructure node data available for Canterbury region.
*** Limited three-waters infrastructure pipeline and node data available for Marlborough region

1 Context for estimating coastal flooding exposure with rising seas

The mission[1] of the Deep South Science Challenge (DSC) is to enable New Zealanders to adapt, manage risk, and thrive in a changing climate.

Within the Impacts and Implications Programme, the DSC commissioned a 2-year research project "*Emergent exposure of flood inundation hazards under future climate change in New Zealand*"[2] to estimate population, building, infrastructure and land cover exposure to present and future coastal and river flooding. This report covers the national and regional exposure to coastal flooding from storm-driven extreme sea-levels and sea-level rise, building on the 2015 coastal risk assessment by the Parliamentary Commissioner for the Environment (Bell et al. 2015; PCE 2015).

This study differs from the 2015 study as follows:

- The 2015 study assessed national and regional exposure to population and assets for 0.5 m topographic elevation bands up to 3 m above mean high water springs (Bell et al. 2015; PCE 2015). The study used land elevations around New Zealand's coastal margin as a *proxy* for coastal flooding exposure. Land within each elevation band could not be linked to a specific coastal flood inundation probability combined with a specific SLR. The elevation bands were also too coarse for mapping the emergence of land exposure to SLR.

- In contrast, this study presents New Zealand's national and regional exposure to coastal flooding and SLR where coastal flood inundation is *directly* estimated by determining the 1% annual exceedance probability extreme sea level elevation (ESL1[3]) at present-day mean sea level (MSL), then applying +0.1 m SLR increments up to +3 m above ESL1. These ESL1 scenarios are mapped onto high-resolution topography data to identify low-lying land potentially at risk to present-day coastal flooding, and the emergence of land exposed to future SLR and coastal flooding.

1.1 Coastal flooding processes in a changing climate

Coastal flooding is a process that will threaten New Zealand's low-lying coastal land as sea-level continues to rise (PCE, 2015; MfE, 2017).

As sea levels rise, populations and assets occupying the coastal land will be exposed to flood inundation events arising from combinations of storm-tide, elevated groundwater, high river flows and intense rainfall superimposed above a higher baseline sea-level. In early 2018, coastal flood damage occurred in coastal settlements throughout New Zealand following extra-tropical cyclones *Fehi* and *Gita*, and an unnamed storm event on January 5th that flooded coastal areas around the Firth of Thames. Damage to buildings, roads, coastal protection structures and primary production land from coastal hazards contributed to the overall insured losses of $116 m from these three events (ICNZ, 2018). Ongoing sea-level rise will substantially increase the frequency of coastal flooding events (Stephens 2015).

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[1] https://www.deepsouthchallenge.co.nz/
[2] https://www.deepsouthchallenge.co.nz/projects/national-flood-risks-climate-change
[3] ESL1 refers to the estimated 1% AEP extreme sea level elevation at present-day mean sea level (MSL)

Several tidal, weather and/or climate processes can combine to generate an extreme sea-level which can flood low-lying coastal land (Figure 1-1). These processes are often combined into a 'storm-tide' event, and include elements of:

- The mean sea-level (MSL) elevation (which rises with SLR) relative to a local vertical datum,
- High tides (as part of normal tidal cycles),
- Storm-surge (caused by low barometric pressure and adverse winds),
- Wave setup inside the surf zone and wave run-up at the shoreline driven by offshore winds and swell waves, and,
- The monthly variability in sea-level anomaly (MSLA) caused by seasonal, interannual and inter-decadal climate variability such as the El Nino Southern Oscillation (ENSO) or Pacific Decadal Oscillation (PDO) (Stephens et al. 2014a).

Storm-tides occur as sea-level elevations peak at or close to high tide during a storm event. The 'extreme sea-level' elevation results from a combination of tide + MSLA + storm surge levels + wave setup and runup (e.g. Figure 1-1). Although wave runup can impact the immediate foreshore, it is not associated with widespread flooding further inland and so was omitted from this study. High-water 'peaks' are identifiable from sea-level records, which are analysed to estimate the magnitude and frequency of extreme storm-tide levels. Waves raise water levels along coastlines when energy is released upon breaking, causing a rise in average water level known as wave setup, which can be of similar height to the storm-tide. New Zealand has a long and wave exposed coastlines, so for flood modelling wave setup is an important component to include when estimating local extreme sea-level elevations on the open coast. In estuaries and harbours where wave processes are limited, the storm-tide (notwithstanding additional wave contributions) can be higher than on the open coast from amplified wind-induced setup in water level and higher tide ranges inside the estuaries.

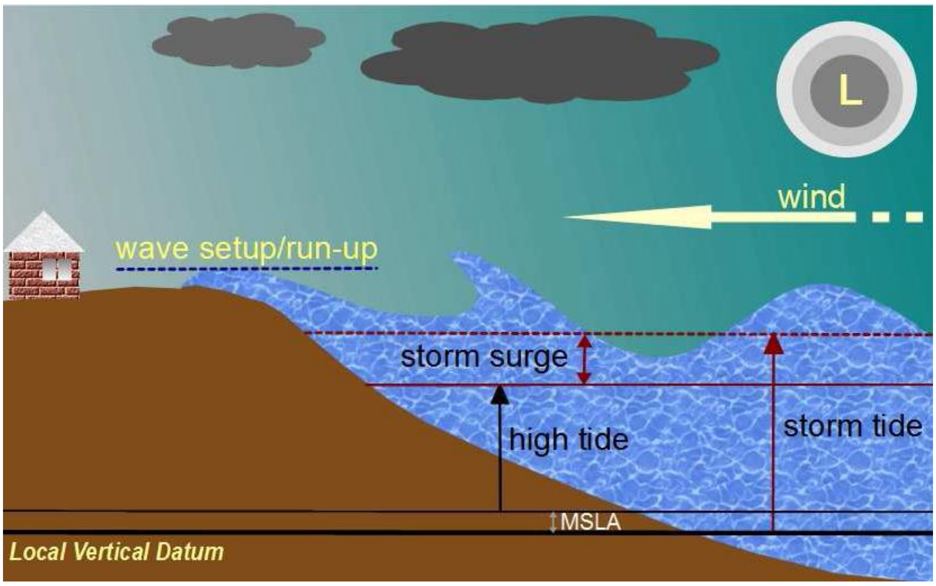

Figure 1-1: Schematic diagram of tidal, weather and climate components contributing to extreme sea-levels and storm-induced coastal flooding.

Climate change will also affect coastal flooding by changing these hazard drivers. Changes in wave/swell and storm surge characteristics, in response to future climate change, may exacerbate coastal flooding magnitude and frequency for low-lying coastal land (Stephens 2015), although the effects would be secondary to the dominant effect of SLR (MfE, 2017). This report focuses only on the effect of SLR. The potential effects of climate change on storm surge and wave regimes was not in the scope of this study.

1.2 National and regional coastal flooding exposure

National-scale land exposure to coastal flooding in New Zealand has not been assessed for extreme sea-levels. Bell et al. (2015) implemented a national assessment of land exposure to rising seas using increments of land elevation (PCE, 2015). High resolution LIDAR[4] digital elevation models (DEMs) were available, with vertical accuracies better than 0.1-0.15 m and a less-accurate national DEM at 25 m grid spacing with vertical accuracies of only 3-4 m, were used to spatially map land elevation around the coastal margin in New Zealand as a proxy for exposure to coastal flooding. Population and asset exposure for coastal land elevation increments up to 3 m above mean high water spring (MHWS) were expressed as counts of usually-resident population, land-cover area and built assets (e.g. buildings, roads, railways, airports, wharves).

The findings of Bell et al. (2015) provided valuable first-time national scale estimates of potential coastal flood risk exposure. However, these could not be linked to a specific inundation hazard exposure expressed as a coastal flooding probability combined with SLR.

This DSC commissioned assessment now provides a link to inundation hazard exposure from coastal flooding, by either direct overland flow of coastal water and indirect (e.g. residual risk exposure of low-lying land behind stopbanks, tide gates or from elevated groundwater levels).

This report presents New Zealand's national and regional exposure to coastal flooding and SLR. Coastal flood inundation is identified by calculating extreme storm-tide (ESL1) magnitudes around the New Zealand coast. These sea-levels are mapped onto LIDAR topography for present-day MSL, with additional +0.1 m SLR increments up to +3 m. Satellite derived topography was used to map land 0–3 m above ESL1 at present-day MSL for areas without LIDAR coverage. The combined LIDAR and satellite topography provided national coverage for mapping elements at risk (i.e. populations, built assets and land cover) to coastal flooding at national, regional council and territorial authority levels.

[4] Light Detection And Ranging – an aerial laser scanning technique to accurately measure land elevations

2 Methods

This study assesses New Zealand's exposure to coastal flood inundation from extreme sea-levels and SLR using a two-step process:

1. Mapping land exposed to coastal flood inundation from 1% annual exceedance probability (AEP) extreme sea-levels (ESL1) at present-day MSL, plus 0.1 m SLR increments up to +3 m SLR above the present-day (Section 2.1), and
2. At national, region and territory levels, enumerate the elements (e.g. populations, built assets and land cover) occupying the land exposed to coastal flood inundation in 1) at present-day MSL and future higher sea-levels (Section 2.2).

2.1 Coastal Flood Mapping

Mapping land exposed to coastal flood inundation from ESL1 involves four steps:

1. Estimate mean sea-level (MSL) and mean high water springs 10 (MHWS-10) elevations around the New Zealand coastline,
2. Estimate ESL1 elevations around the New Zealand coastline,
3. Create digital elevation models (DEM) of land topography, and
4. Spatial mapping of ESL1 elevations onto land to identify coastal flood inundation areas.

2.1.1 MSL and MHWS around the New Zealand coastline

Coastal flood inundation mapping requires accurate identification of the "zero baseline", which is used to define the land-sea boundary in the model so that flooding is mapped on land not usually submerged by water. This involves determining a mean high-water springs (MHWS) elevation relative to a MSL datum of 0 m, then applying an offset for average present-day MSL and the local vertical datum (LVD).

MHWS levels around New Zealand

MHWS-10 was used as a zero baseline for coastal flood inundation mapping. MHWS-10 is the water level exceeded only by the highest 10% of all high tides. The MHWS-10 zero baseline includes geographic tide variations, such as west coast spring-neap tides and east coast monthly perigean-apogean tides. MHWS-10 also applies in sheltered water bodies such as estuaries, where a maximum high-water level baseline may mean land with dunes, stopbanks, and vegetation could be partially below this level.

The MHWS-10 levels were estimated for 16 LINZ-defined standard ports and numerous secondary sites. The NIWA Exclusive Economic Zone (EEZ) tidal model (Walters et al. 2001) was also used to calculate MHWS-10 levels along coastlines with no tide gauges. 100 years of predicted high tides were used to calculate MHWS-10 levels at 290 locations covering New Zealand's main littoral cells.

The EEZ modelled MHWS-10 levels were compared to standard port levels and MHWS levels from secondary port sites with relatively long records (>30 years). Most EEZ levels were within a few centimetres of standard port MHWS-10 levels and within a decimetre of secondary port MHWS levels. EEZ model levels for sites with larger differences were adjusted to standard and secondary port levels. Model sites further from tide gauge sites that showed level offsets, were adjusted using linear interpolation. For example, if a gauge site needed no adjustment but the nearest subsequent gauge required a 0.04 m offset, then a model point equidistant from the gauges would need an adjustment of +0.02 m, or 50% of the difference between the two-gauge sites adjustment values. Most adjustments were less than 0.05 m. Adjusted MHWS-10 levels relative to present MSL=0 are provided in provided Appendix A.

An EEZ model limitation in this study is the exclusion of estuaries and upper harbour areas. For these locations, site specific tidal information was used for Waitemata, Manukau, and Kaipara Harbours (Stephens & Wadhwa 2012; Stephens et al. 2016), as well as Whitianga and Dargaville from NIWA gauge deployments. Where no harbour-specific data exist the nearest open-coast MHWS-10 levels to the harbour entrance were applied. To calculate MHWS-10 inside estuaries with no gauge, a scaling factor of 1.1 × MHWS-10 outside the estuary was used. This approximation accounts for the observation from gauged estuaries (Stephens et al. 2016) that the tide usually amplifies inside NZ estuaries. The amplification is caused by topographic constriction and frictional shoaling of the tidal wave inside the shallowing and narrowing estuary.

The national-scale methodology employed means complex tidal dynamics within estuaries are unlikely to be fully represented. Localised amplifications as tides travel up estuaries and the gradual tidal reduction in the river transitional area, requires detailed modelling of individual estuaries or harbours. Open-coast wave effects are also not considered when defining coastlines using MHWS-10. Incorporating these effects requires numerous calibrated site-specific models to estimate local wind-wave and swell effects. Resolving these limitations is outside the scope of this national-scale study.

MSL offsets around New Zealand

MSL offsets were required to convert storm-tide and wave setup elevations to LVDs used in LIDAR DEMs (see Appendix B). LVDs are derived from historic sea level data from early the last century. MSL has risen since these LVD's were defined, requiring a MSL offset value to accurately convert MHWS-10 levels to LVD. The MSL offsets were within 0.1–0.2 m and calculated using standard port levels for MSL (LINZ, 2015).

2.1.2 Extreme sea-level analysis around the New Zealand coastline

Extreme storm-tide and wave setup elevations from previous studies were used for some regions where available: Auckland (Stephens et al. 2016), Firth of Thames (Stephens 2018), Gisborne (Stephens et al. 2014b), Tasman-Nelson (Stephens et al. 2018b) and Canterbury (Stephens et al. 2015a). These studies used joint-probability modelling to determine the AEP of coincident extreme sea-levels from storm-tides + waves, and so use of these detailed modelling results give us high confidence in the ESL1 elevations within these regions.

Outside of the regions where detailed modelling studies are available, the wave setup allowance in steps 3 and 4 (Table 2-1) is approximate. Stephens and Wadhwa (2012) found that visual shoreline indicators corresponded to the MHWS-10 elevation + 0.7 m on Auckland's east-coast beaches, and + 1.5 m on Auckland's east-coast beaches. The detailed modelling studies indicated wave setup above 1% AEP storm-tide of median 0.5 and maximum 1 m on Auckland's east coast, approximately 2 m along the Canterbury coast except in the lee of Banks Peninsula where 0.5 m was appropriate, approximately 2 m in the Gisborne District and approximately 0.5 m in Tasman/Golden Bay. We have used +1.5 m wave setup above the 1% AEP storm-tide elevation in "exposed" wave locations, and

+0.5 m wave setup in more sheltered open-coast locations like Tasman Bay for example. Figure 2-1 shows the classification of exposed and sheltered open coast.

Table 2-1: Summary of methods used to calculate MHWS-10 and ESL1 levels.

Type of Site	MHWS-10	ESL1 Formula
1. Estuaries with gauge	Use MHWS-10 from gauge.	Use 1% AEP storm-tide previously calculated from gauge, add on local MSL offset.
2. Estuaries with no gauge	MHWS-10 = 1.1 x MHWS-10 (nearest open coast).	ESL1 = 1.28 (MHWS-10) + 0.34 + MSL offset
3. Open coast	Use MHWS-10 from NIWA tide model.	ESL1 = 1.28 (MHWS-10) + 0.34 + 1.5 m wave setup + MSL offset
4. Open coast sheltered	Use MHWS-10 from NIWA tide model.	ESL1 = 1.28 (MHWS-10) + 0.34 + 0.5 m wave setup + MSL offset

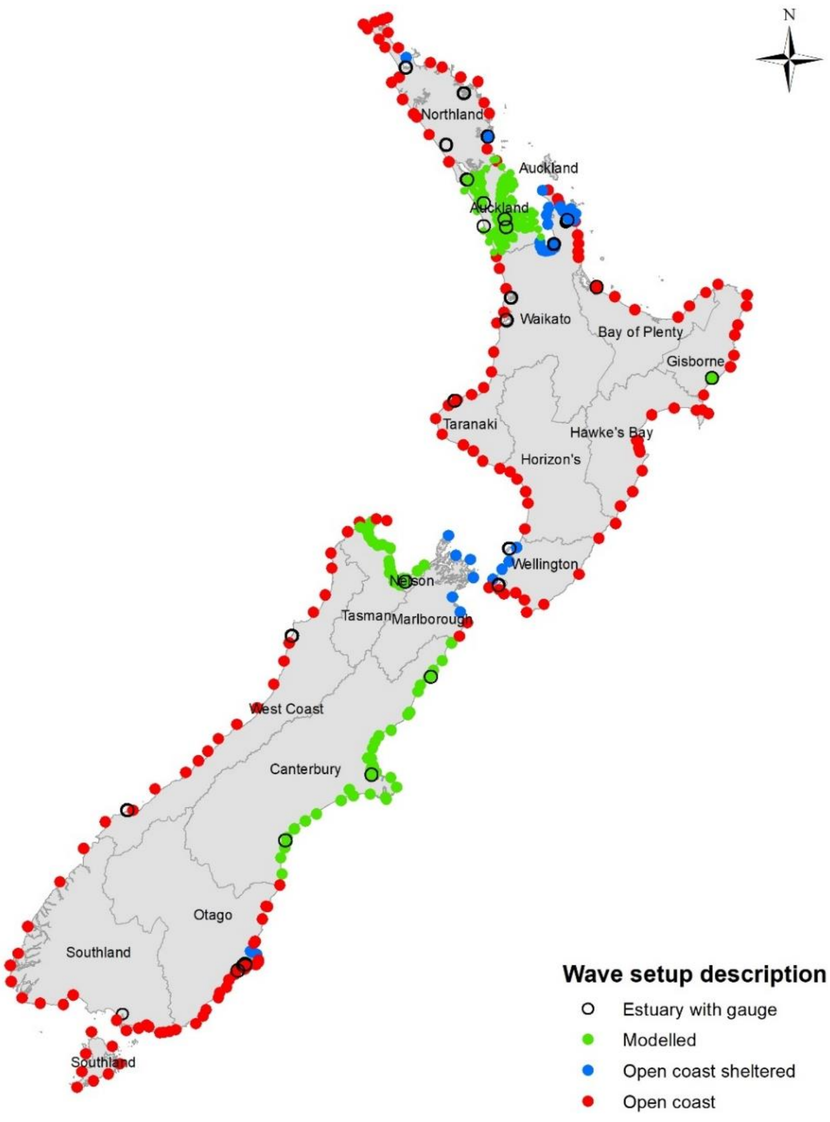

Figure 2-1: New Zealand coastline showing designated as estuarine or open (sheltered or exposed) coastlines for modelled wave setup elevations in extreme sea-level analysis.

Table 2-1 summarises the methods used to derive ESL1 and MHWS-10 around New Zealand, for regions where data did not already exist. One of four methods were used, depending on location and available sea-level information:

1. *Estuaries with sea level gauges*—The 1% AEP storm-tide levels were calculated from sea level records using methods from Batstone et al. (2013), with MSL offsets from Bell et al. (2015) and MHWS-10 from the gauge. No wave setup was added within the relatively wave-sheltered estuary environments.

2. *Estuaries with no sea-level gauge* - MHWS-10 elevation inside the estuary was calculated as 1.1 × MHWS-10 outside the estuary on the open coast—this approximately accounts for tidal amplification inside constricted estuaries as observed in other places (e.g. Stephens et al. 2016). The 1% AEP storm-tide elevation was then calculated using a linear relationship (Figure 2-2), derived from sea-level gauges around New Zealand being 1% AEP = 1.28 × MHWS-10 + 0.34, where the MHWS-10 from inside the estuary was used. Local MSL offsets were then added. No wave setup was added within the relatively wave-sheltered estuary environment.

3. *Open coast exposed* - MHWS-10 levels were estimated using the method described in Section 2.1.2. The 1% AEP storm-tide elevation was then calculated using the linear relationship described in step 2 above (Figure 2-2). An additional 1.5 m was added to account for wave set-up. Local MSL offsets were then added.

4. *Open coast sheltered* - MHWS-10 levels were estimated using the method described in Section 2.1.2. The 1% AEP storm-tide elevation was then calculated using the linear relationship described in step 2 above (Figure 2-2). An additional 0.5 m was added to account for wave set-up. Local MSL offsets were then added.

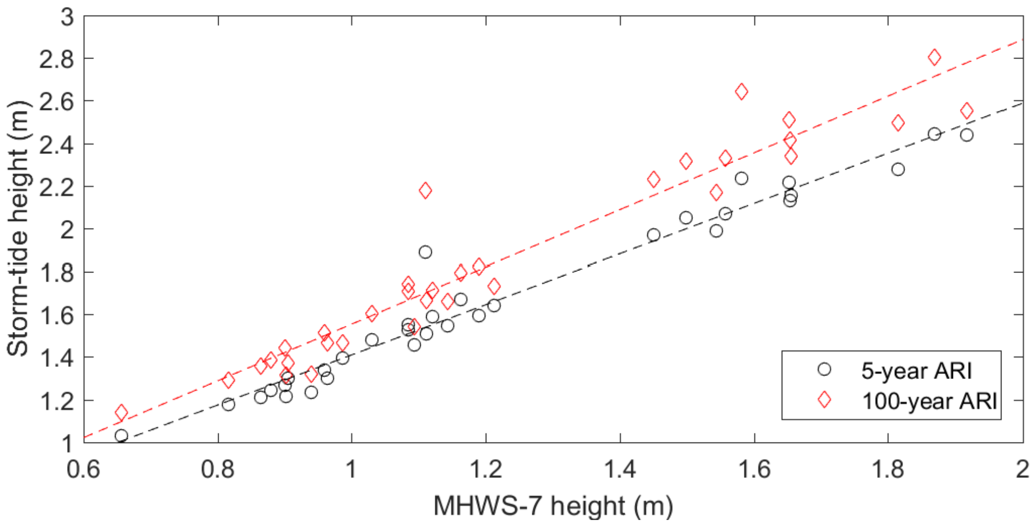

Figure 2-2: Linear relationship between MHWS and 1% AEP storm-tide derived from New Zealand sea-level gauges. Relationship shown between MHWS-7 (93rd % of all high tides) and the 5 and 100-year annual return interval (ARI) sea level.

The MHWS-10 and ESL1 elevations were output at 20 km intervals around the NZ coastline. At most sites, there were no sea level gauges, and the NIWA tide model was used to calculate MHWS-10 and the steps in Table 2-1 were followed to obtain ESL1. The following steps describe how the different locations were chosen:

- Along the open coast, a site was chosen at a depth of around 20 m offshore along each 20 km segment.
- A site was chosen inside each estuary. If there was more than one estuary inside a 20 km segment, then more than one location was analysed inside a single segment. If the estuary had a coastline longer than 20 km, then the estuary had one site for each 20 km segment.
- Elevations were produced inside and immediately outside estuaries near the estuarine mouth, to model the sea-level gradient from offshore into the estuary.
- Elevations derived from sea-level gauges were applied to the 20 km segment in which they were located.
- Figure 2-3 presents ESL1 estimates for the New Zealand coastline.

2.1.3 Digital elevation models

Airborne light detection and ranging (LIDAR) digital elevation models (DEM) were combined with a lower resolution satellite-derived DEM, to create a composite national (DEM) for mapping land exposed to coastal flood inundation.

Regional LIDAR Processing

Airborne LIDAR topography surveys provide greater accuracy than national DEMs (vertical elevation accuracy down to 0.10–0.15 m), so are more suitable for storm-tide + SLR inundation mapping. LIDAR DEMs are currently not available for all New Zealand coastlines (Figure 2-4), and notably, no LIDAR DEMs are available for the West Coast region.

Available LIDAR DEMs or raw point cloud data used in this study were provided by regional councils and territorial authorities or LINZ on behalf of these organisations. LIDAR DEM coverage extended from a 20 m inland height contour and out to a maximum of 1 km offshore. These datasets required quality checking and processing including the identification of shortcomings (e.g. buildings footprints visible in the Wellington region DEM), overlapping datasets, or incorrect water-land boundary locations. Hydraulic connectivity of land within LIDAR DEM coverage was not assessed due to time constraints. Land areas of lower elevations than extreme sea-levels are therefore mapped but could be disconnected from the sea and may not flood at the specified sea-level e.g. areas landward of stopbanks. National scale inclusion of these areas was assumed to have relatively small effect on potential overestimation of coastal flood inundation extents.

Coastal areas were divided into shoreline compartments corresponding to MHWS-10 elevation (see Section 2.1.2 for MHWS-10 definition). The MHWS-10 + regional MSL offsets to LVD were added as “zero baseline” level for each compartment.

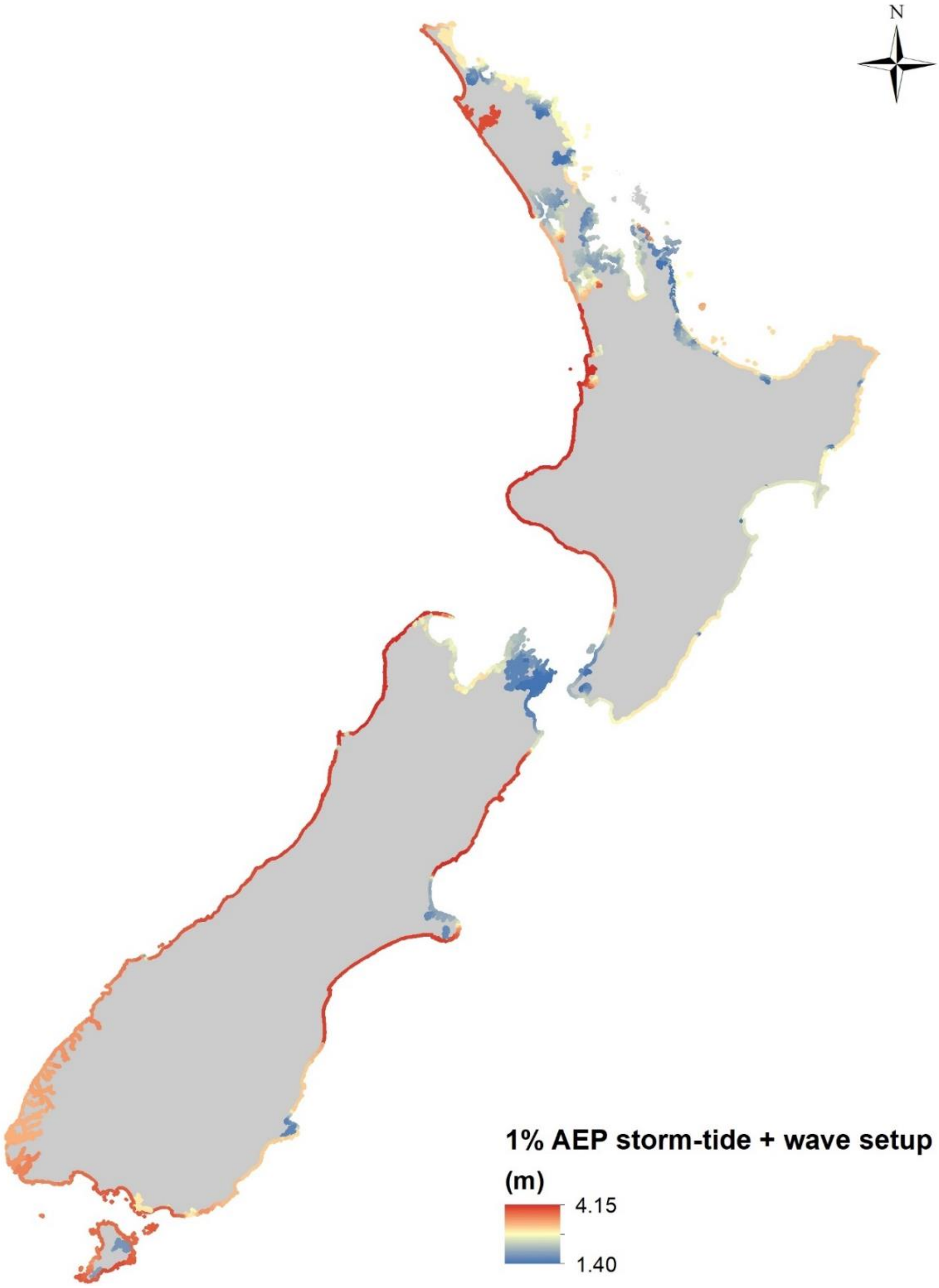

Figure 2-3: Estimated ESL1 levels around the New Zealand coastline.

Satellite DEM Processing

New Zealand's national DEMs were previously based on 10–20 m contours digitised from 1:50,000 series LINZ (Land Information New Zealand) mapping. This resolution is inadequate for coastal flood inundation mapping (Bell et al. 2015). In this study, a higher accuracy Multi-Error-Removed Improved-Terrain (MERIT) [5] DEM was used (Yamazaki et al. 2017).

[5] http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/

Figure 2-4: LIDAR DEM coverage for New Zealand's coastline (Note: Satellite DEM provides nationwide coverage).

The MERIT DEM was created using a combined NASA Shuttle Radar Topography Mission (SRTM) and AW3D DEM (Yamazaki et al. 2017). Vertical height error sources and corrections to improve accuracy include:

1. *Stripe noise* - transform filtering out stripe noise which is a regular height undulation sometimes caused by motion errors of the satellite equipment.
2. *Speckle noise* - using an adaptive smoothing filter (e.g. Gallant, 2011) to remove speckle noise where surface reflectance causes random short wavelength errors.
3. *Absolute bias* - using ICESat laser altimetry to reference ground elevation and estimate DEM absolute biases when there is a creep in average elevation over a large area that needs to be rectified with ground control-points where available.
4. *Tree height bias* - estimating tree height and density using forest data and ICESat, when there are issues caused by the inability to accurately measure beneath dense forest canopies.

The New Zealand MERIT DEM was applied to identify ESL1 +3 m SLR for the coastlines without LIDAR coverage. Identifying ESL1 for lower SLR increments was not feasible using the MERIT DEM due to potential for >2 m vertical error (Yamazaki et al. 2017). These vertical errors suggest that land unconnected to coastlines could remain within ESL1 +3 m SLR areas, particularly where barrier-forming topographic features (e.g. stopbanks) may not be identified at the DEM resolution.

2.1.4 Coastal flood inundation mapping of ESL1

Coastal flood inundation maps were created for ESL1 and ESL1 +0.1 m increments of SLR up to +3 m above ESL1. The levels were input to GIS at modelled points, then interpolated around the length of New Zealand's coastline. Extreme sea- levels were intersected with national and LIDAR DEMs, to create inundation area polygons. This static level or "bathtub" inundation mapping approach assumes all land below the mapped sea-level will be entirely inundated, irrespective of whether it is connected to the ocean.

2.1.5 Coastal flood inundation mapping limitations for extreme sea-levels

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 may however, 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 flow rates are restricted by a narrow connection to the sea e.g. drainage channels, culverts. Coastal flood inundation 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 coastal inundation from static sea-levels, or residual risk behind coastal defences such as stop banks.

Bathtub mapping of coastal flood inundation usually results in an over estimation of inundation extents from extreme sea-levels. This is demonstrated by the comparative inundation extents from 'bathtub' and 'dynamic' models in Figure 2-5 and Figure 2-6. The bathtub models show that more inundation (depth and extent) is indicated when the dynamics of the flooding process (e.g. depth, velocity, duration) are not included. This is illustrated in Figure 2-6 where the bathtub model overestimates inundation north of the main river feature where the topography is relatively lower with distance from the coast. Little difference in inundation extent occurs south of the river where topography is steeper. Despite its limitations, a bathtub method provides an approximation of coastal inundation extents for identifying key elements at risk e.g. populations, buildings, roads etc. Detailed dynamic modelling is likely to produce more accurate inundation scenario maps which could be required in areas with high potential population and asset exposure.

Figure 2-5: Comparison of coastal inundation in Tauranga Harbour estimated from dynamic (left) and bathtub models (right). The scenario modelled was a 1% AEP storm-tide + 1.25 m SLR in Tauranga Harbour Source: Stephens et al. (2018a).

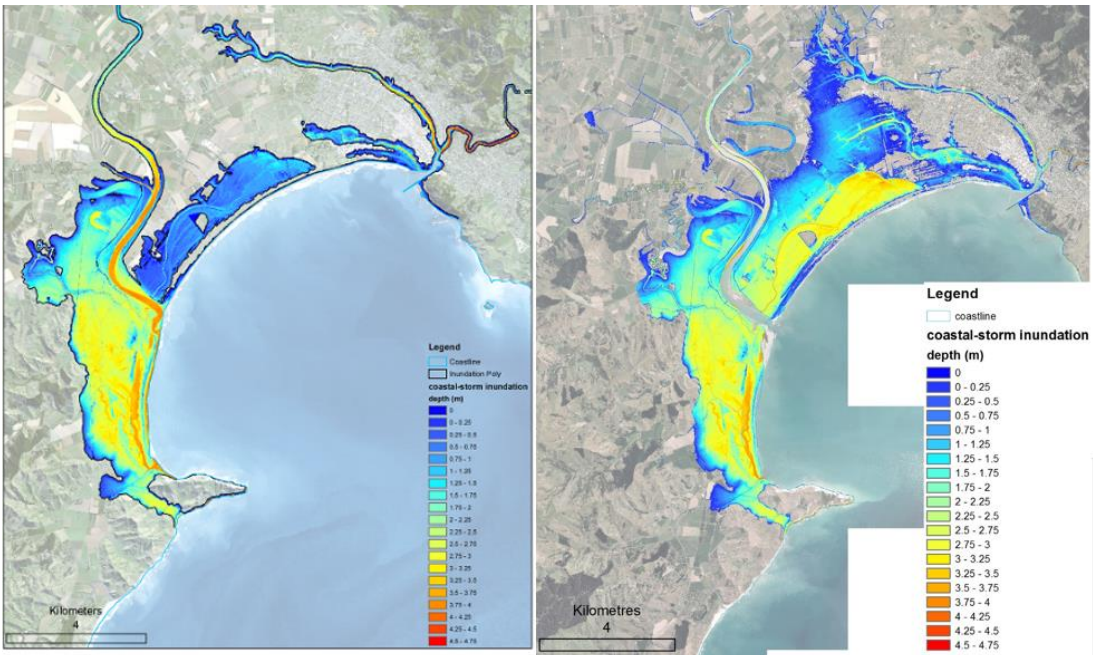

Figure 2-6: Comparison of coastal inundation in Poverty Bay (Gisborne District) estimated from dynamic (left) and bathtub models (right). Note the larger coastal inundation extent created by the bathtub model**.** Source: Stephens et al. (2015b).

2.2 Exposure mapping of elements at risk

In this New Zealand-wide study, elements at risk from coastal flood inundation exposure include population, built assets (e.g. buildings, transport, electricity and three-waters infrastructure) and land cover. Exposure of these elements occurs when they are located on land within mapped coastal flood inundation extents.

Elements at risk were assessed using available spatial datasets. This data was assumed to provide best available spatial representation of the current situation (October 2018) of the elements in New Zealand. In this study, only the coastal flood inundation exposure of present-day elements is enumerated. Short to long-term (i.e. next century) changes of elements from social and economic drivers or sea-level rise adaptation activities were beyond the scope of this assessment and were not considered.

2.2.1 Population

New Zealand's population was estimated using Census 2013 (5 March 2013) "usually-resident" population meshblock data[6] (Statistics New Zealand, 2017). Meshblock data is subdivided into two age groups, with 0–65 years old and >65 years old applicable for exposure analysis. These age groups were combined into a single total population per-meshblock. New Zealand residents who are away from their usual address for the 2013 census are allocated back to the area where they usually live and form part of the meshblock usually-resident population (Statistics New Zealand, 2017).

Residential building features from a New Zealand building database developed by NIWA and GNS Science for RiskScape (Bell and King, 2009) were assigned 'mean' occupancy values from corresponding meshblock population data. All residential buildings were spatially joined to 2013 meshblock areas in GIS to count meshblock residential building numbers. The usually-resident population total was divided by building count to estimate a 'mean' residential building occupancy rate. Over 1.7 million residential buildings with 'mean' building occupancy values were used for population exposure mapping.

The method to distribute usually-resident populations is dependent on available residential building features. While care was taken to develop an accurate New Zealand building dataset for RiskScape, residential buildings could be missing within individual meshblocks. Following the 2013 Census, occupation rates for individual residential buildings could have changed; increasing or decreasing population exposure within meshblocks. Despite these limitations and to compensate for the simple method of allocating population counts to geo-referenced buildings (and building-use categories and sizes), the method applied is considered appropriate for coastal inundation exposure mapping at national, regional and district levels.

2.2.2 Built assets

Buildings

Spatial information about New Zealand building assets is provided by a national dataset developed by RiskScape (Bell and King, 2009). The dataset contains structural and non-structural attributes for over 2.4 million buildings, sourced primarily from QV Property Valuation datasets with additional building attributes included from field surveys (Cousins, 2009). 'Use category' and 'replacement value' attributes were identified for exposed building features. Reported use categories (Table 2-2)

[6] Note: at the time of analysis for this report, the 2018 Census data was not available.

were summarised as; residential, commercial, industrial (includes primary production), critical facility, community and other (e.g. out-buildings, garages). Replacement values were derived for 2016 using the method described by Cousins (2009). Values are estimated using published New Zealand square metre (m^2) construction cost rates (QV, 2016), assigned to buildings based on use category, construction type, floor area and storeys.

Table 2-2: Use categories reported for New Zealand buildings.

RiskScape Building Use Categories	Reported Use Category
1: Residential Dwellings; 15: Resthome; 19: Lifestyle	Residential
2: Commercial – Business; 3: Commercial – Accommodation; 6: Fast Moving Consumer Goods Commercial	Commercial
4: Industrial - Manufacturing, Storage; 5: Industrial - Chemical, Energy, Hazardous; 17: Forestry, Mining; 18: Farm	Industrial
7: Government; 8: Territorial Authority/Civil Defence; 9: Lifeline Utilities; 10: Police; 11: Hospital, Clinic; 12: Fire Station; 14: Education	Critical Facility
13: Community; 16: Religious Community	Community
20: Parking; 21: Clear Site; 22: Other	Other

Transport

Transport infrastructure assets were limited to roads, railway, and airports available from public GIS databases. New Zealand Transport Agency (NZTA) national road data[7] was used to estimate road length (km) exposure. In addition, LINZ provides public data for railway and airport (also includes aerodromes) features at a national scale. Railway length (km) was estimated from representative line features while airport and aerodrome land exposed were identified from polygon features.

Electricity

Transpower provided electricity infrastructure components of the national grid. Transmission lines (e.g. cables), structures (e.g. pylons) and sites (e.g. substations, buildings) were used for this study[8]. Transmission line length (km) exposed to 1% AEP storm-tides is reported along with structures and sites counts.

Three-waters

Potable water, wastewater and stormwater (i.e. 'three-waters') infrastructure components are managed by New Zealand territorial and unitary authorities. Three-waters data for this study were either extracted directly from GIS RESTful services or provided from local government on request Three-waters components were categorised into 'nodes' or 'pipelines'. Inconsistent and unavailable attribute information meant only node counts and pipeline lengths (km) were reported for this study. Node and pipeline features were merged into single national datasets for three-waters types. Node features represented comprise many different component types (Table 2-3). Stormwater drains and channels were excluded as spatial data for these components were available for few territories.

[7] https://www.nzta.govt.nz/about-us/open-data/national-road-centreline-data-request
[8] https://data-transpower.opendata.arcgis.com/

Table 2-3: A summary of 'three-waters' node types included in this study.

Node Components	Reported Three-waters Category
Back Flow Prevention Device; Control Cabinet; Chamber; Connector; Filter; Fitting; Hydrant; Intake; Manhole; Meter; Pump Station; Reducer; Restrictor; Reservoir or Dam; Valve; Vent; Tank; Tap; Tee; Telemetry; Toby; Treatment Plant; Well	Potable Water
Access Point; Aeration pond; Aerator; Bio filter; Control cabinet; Chamber; Cleaning eye; Fitting; Flushing point; Generator; Inlet; Inlet structure; Inspection point; Intake; Manhole; Meter; Oxidation pond; Outlet; Outlet Structure; Pump; Pump Station; Reducer; Structure; Telemetry; Treatment Plant; Valve; Vent	Wastewater
Access Point; Chamber; Cleaning eye; Catchpit; Collection pond; Connector; Culvert; Detention dam; Floodgate; Inlet; Inlet structure; Intake; Manhole; Natural structure; Outfall; Outlet; Outlet Structure; Pump; Pump Station; Reducer; Septic Tank; Soak pit; Tank; Telemetry; Valve; Water Treatment; Device; Well; Water Treatment Facility	Stormwater

2.2.3 Land cover

New Zealand Land Cover Database Version 4.1 (LCDBv4.1) is a multi-temporal digital thematic map that describes the physical condition or state of the land surface. LCDBv4.1 is developed by Landcare Research[9] using satellite imagery and contain detailed information on land cover and land use boundaries change over time. LCDBv4.1 represents thirty-three land cover and land uses during the 2012–2013 period (Table 2-4). Land cover classes were categorised as built, production and natural for this study.

Table 2-4: Reported land cover categories from Land Cover Database Version 4.1.

Land Cover Database Version 4.1 Categories	Reported Land Cover Category
3: Built-up area; 33: Transport infrastructure Built-Environment	Built
7: Exotic forest; 10: Forest – harvested; 15: High producing exotic grassland; 20: Low producing exotic grassland; 25: Orchard vineyard and other perennial crops; 29: Short-rotation crop; 31: Surface mines and dumps	Production
1: Alpine grassland/herbfield; 2: Broadleaved indigenous hardwoods; 4: Deciduous hardwoods; 5: Depleted grassland; 6: Estuarine open water; 7: Exotic forest; 8: Fernland; 9: Flaxland; 11: Gorse and/or broom; 12: Gravel and rock; 13: Herbaceous freshwater vegetation; 14: Herbaceous saline vegetation; 16: Indigenous forest; 17: Lake or pond; 18: Land Cover; 19: Landslide; 21: Mangrove; 22: Manuka and/or Kanuka; 23: Matagouri or grey scrub; 24: Mixed exotic shrubland; 26: Permanent snow and ice; 27: River; 28: Sand and gravel; 30: Sub alpine shrubland; 32: Tall tussock grassland;	Natural or undeveloped

2.2.4 Mapping coastal flood inundation exposure for elements at risk

The exposure of elements to coastal flooding was calculated using geoprocessing functions in GIS.

[9] https://lris.scinfo.org.nz/layer/48423-lcdb-v41-land-cover-database-version-41-mainland-new-zealand/

Features represented as vector points (e.g. buildings, three-waters infrastructure nodes) were 'clipped' from each coastal flood scenario then 'spatially joined' with Statistics New Zealand 2016 regional council and territorial authority geographical boundary areas. Feature counts and relevant attributes were summed for each geographical area during the joining process.

Features represented as vector lines or polygons were 'clipped' from each coastal flood scenario then 'intersected' with 2016 regional council and territorial authority geographical boundary areas to segment features within each boundary. Feature geometries (e.g. 'LENGTH', 'AREA') were recalculated to update their extents within geographical boundary areas. Features were 'spatially joined' to regional council and territorial authority boundaries and geometries summed.

2.2.5 Exposure mapping limitations for elements at risk

National population, built assets and land cover datasets represented at an 'object-scale' (e.g. individual buildings, road segments etc.) experience spatial and temporal change in response to development or land use changes. At the time of analysis, assets and attribute data may represent the current asset state, whereas those in constant fluctuation (e.g. building replacement cost) can be under or overestimated. This study attempts to use the most relevant and recently available population, built asset and land cover spatial dataset to minimise the potential underestimation of coastal inundation exposure from ESL1.

New Zealand's usually-resident population is enumerated every few years on a national Census week-day in March. This can create issues for population counts in coastal inundation areas, as coastal settlements often experience temporal population changes during summer months and holiday periods. The 'Mean' population rates we assigned to residential buildings may offset some population change experienced by coastal settlements over a year's duration, particularly where populations are lower in March relative to summer months.

Population distributions for individual buildings are approximate, based on available population counts for meshblock area units. Meshblock averaged usually-resident populations assume each residential building is occupied on Census night and population counts are evenly distributed across these buildings within the meshblock. This approach is suitable for approximating population exposure to storm-tide inundation at national to district levels however, more detailed matching of meshblock usually-resident populations with buildings (e.g. individual buildings or clusters based on attributes such as use category, floor area, storeys) would improve population exposure counts.

Built asset and land cover spatial datasets are represented at an object-scale. Information about exposed assets at this scale can be enumerated within the inundation extents and reported for larger geographical boundaries. Estimating object-scale exposure is dependent however, on accurate information on asset feature location and attributes. In this study, counts or geometries (i.e. length or area) were estimated for built assets and land cover, though limited available attributes were reported.

3 Results

National, region and territory level exposure of elements at risk to ESL1 are reported in:

- Section 3.1: exposure to ESL1 at present-day MSL and with +0.1 m SLR increments up to +3 m SLR for land with LIDAR DEM coverage only. Element exposure is commonly reported for +0.3 m, +0.6 m, +0.9 m and +1.2 m SLR. These scenarios represent a range of New Zealand region SLR trajectories projected for median (M) and high (H) Representative Concentration Pathways (RCPs) out to 2120 (MfE, 2017).
- Section 3.2: exposure to ESL1 at present-day MSL with +3 m SLR (ESL1 0-3 m) for land with satellite 'National DEM' coverage only.
- Section 3.3: combined national exposure to ESL1 +3 m SLR and ESL1 0-3 m.

Tabulated results for 2016 regional council and territorial authority boundaries are provided in a digital appendix for this report (see Appendix C), in comma-separated value (.csv) and ESRI shapefile (.shp) formats.

3.1 LIDAR DEM

3.1.1 National exposure for coastlines with LIDAR DEM coverage

Coastal flooding exposure at present-day mean sea-level

National element exposure to ESL1 at present-day MSL is summarised in Table 3-1. An estimated 2,036 km^2 (0.8%) of New Zealand's land area is exposed to coastal flooding. This includes, 1,457 km^2 of production land along with 529 km^2 of natural or undeveloped land and 50 km^2 built land.

A usually-resident population of just over 72,000 occupies the exposed land. More than 49,000 buildings with a $NZD 12.5 B replacement value are also exposed, including 35,000 residential buildings ($NZD 8.5 B). Industrial buildings make up just under $NZD 1.5 B of the $NZD 3.9 B estimated replacement value for 14,000 exposed non-residential buildings. The replacement value for the other building categories (commercial, industrial, critical, community and other) sum to $NZD 2.4 B.

Land transport infrastructure network exposure includes 1,414 km of roads and 86 km of railway. Thirteen airports with a 3.5 km^2 land area are also exposed. National electricity grid includes 122 km of transmission lines with 204 support structures and two substation sites on or overlying exposed land. 'Three-waters' infrastructure network components also identified on this land includes 90,783 nodes and 3,766 km of pipelines.

Table 3-1: A summary of national level element exposure to ESL1 at present-day MSL and future SLR scenarios (where SLR is calculated in meters above 1986-2005 baseline) on land with available LIDAR DEM coverage.

Element at Risk	Sea-level Rise Scenario				
	Present-day	0.3 m	0.6 m	0.9 m	1.2 m
	Population				
Population (#)	72,065	98,782	132,650	166,798	198,576
	Built Assets				
Building (#)	49,709	69,845	93,891	117,940	140,244
Building Replacement Value (2016 $NZD Billion)	12.5	18.5	26.2	35.1	43.8
Roads (km)	1,414	1,824	2,273	2,714	3,134
Railway (km)	86.6	112.5	142.1	176.2	212.2
Airports (#)	13	14	14	14	14
Transmission Lines (km)	122.5	144.7	165.9	187.3	211.2
Structures (#)	180	237	275	305	349
Sites (#)	2	3	3	5	5
Three-waters Infrastructure Nodes (#)	77,037	102,878	132,433	162,130	191,145
Three-waters Infrastructure Pipelines (km)	3,179	4,307	5,572	6,786	7,965
	Land Cover				
Built (km^2)	50.3	67.1	87.3	107	126.5
Natural or undeveloped (km^2)	529	569	605	641	683
Production (km^2)	1,457	1,612	1,765	1,916	2,059

Coastal flood inundation exposure from sea-level rise

At a national level, element exposure to ESL1 shows a linear increase in response to sea-level rise. This trend is graphically illustrated in Figure 3-1 to Figure 3-14. Exposure at +0.3 m SLR increments is summarised in Table 3-1 and +0.1 m SLR increments up to +3 m are enumerated for selected elements in Table 3-2.

Relative to present-day sea level, an additional 422 km^2 land area and 60,585 more people (132,650 total) are exposed to coastal flooding at +0.6 m SLR. A further 44,314 buildings are exposed with an estimated $NZD 13.7 B replacement value. This raises total replacement value exposure to $NZD 26.1 B for 94,164 buildings. Road and railway exposure reaches 2,273 km and 142 km respectively, an increase of 859 km and 55 km relative to present-day exposure. Combined 'three-water' pipeline exposure increases by 2,392 km to 5,572 km, and node exposure nearly doubles from just over 77,000 at present-day to 132,433 at +0.6 m SLR.

Assessing the incremental exposure (i.e. per +0.1m SLR) of elements to ESL1 provides useful information about how quickly the magnitude of element exposure increases in response to SLR (Table 3-2). Several elements are sensitive to ESL1 exposure in response to a small SLR above present-day. Population, buildings, roads and three-waters infrastructure are elements that demonstrate relatively high incremental exposure as sea levels rise to +0.9 m. For example, incremental population exposure increases from 7,690 at +0.1 m SLR to 11,667 at +0.6 m SLR, while incremental building exposure increases by 2,517 between +0.1 m and +0.6 m SLR, and replacement values by $NZD 1.2 B, before a decreasing thereafter in response to rising sea levels. Horizontal infrastructure including roads, three-waters pipelines, experience their highest incremental exposure between +0.6 m to +0.8 m SLR.

Table 3-2: National level element exposure estimated for +0.1 m SLR increments. 'Greyed' values are above or equal to the mean increment exposure per +0.1 m SLR. Airports and sites are excluded due to their small datasets.

		Built Assets								Land Cover		
Sea-Level Rise (m)	Population (#)	Buildings (#)	Building Repalcement Value (2016 $NZD Billions)	Roads (km)	Railway (km)	Transmiss-ion Lines (km)	Structures (#)	Three-Waters Pipelines (km)	Three-Waters Nodes (#)	Built (km^2)	Product-ion (km^2)	Natural/ Undeveloped (km^2)
0	-	-	-	-	-	-	-	-	-	-	-	-
0.1	7,690	5,712	1.55	130.2	7.5	7.7	17	334.7	6,399	5	51	10.9
0.2	9,245	6,906	2.09	136.4	9.4	7.4	17	385.8	7,397	6	52.5	14.4
0.3	9,783	7,566	2.37	142.9	9.1	7.2	23	406.8	8,069	6.2	51.4	13.8
0.4	10,679	7,828	2.36	148.7	9.4	7	20	420.2	8,661	6.6	50.9	12.7
0.5	11,520	8,073	2.65	152.9	9.9	7	8	424.9	9,045	7.6	51.6	12.3
0.6	11,667	8,229	2.68	147.8	10	6.9	10	420.3	9,090	6.9	51.4	11.4
0.7	11,294	8,055	3	148.1	11.1	6.4	12	408.6	9,186	5.3	51	13
0.8	11,668	8,235	3.16	146.1	11	7.1	7	405	9,196	6.1	50	11.6
0.9	11,188	7,804	3.06	146.3	12.3	8.1	13	400	8,938	6.7	49.3	11.7
1	10,847	7,673	2.97	142.3	12	7.8	14	401.8	8,785	6.6	48.7	13.5
1.1	10,598	7,542	3.26	140.4	12.5	7.9	19	394.6	8,665	6.5	47.8	14.2
1.2	10,332	7,118	2.45	137.9	11.6	8.1	10	383.1	8,317	6.4	46.9	13.9
1.3	10,460	7,098	2.53	136.3	10.2	9.2	14	381	8,062	6.3	46	13.2
1.4	10,145	7,110	2.64	144.5	10.6	9.4	17	385.4	7,959	7.4	45.4	13.9
1.5	10,380	6,779	2.48	138.4	10.8	10.9	24	382	8,052	6.3	44.9	14.7
1.6	11,086	7,065	2.71	136.9	10	10.3	25	386.8	7,836	6.4	45	15.2
1.7	10,561	7,119	2.54	134.3	11.3	8.9	17	383.8	7,841	6.4	44.9	15.5
1.8	10,162	7,042	2.31	138	11.4	8.7	18	381.4	7,995	6.4	44.6	14.8
1.9	10,200	7,051	2.39	135.5	10.5	7.9	14	378.2	7,966	6.4	43.4	9
2	9,710	6,618	2.47	133.5	10.2	7.1	18	365.7	7,691	6.3	42.7	11.4
2.1	10,432	6,712	2.59	131.8	10.4	7.4	11	354	8,005	6	41.6	10.5
2.2	11,268	7,080	2	132.1	11	7.3	11	340.3	7,887	6.1	41.1	9.6
2.3	11,220	6,980	2.66	130.1	11	7	7	319.3	7,926	5.9	33.4	9.4
2.4	10,821	7,118	2.23	124.2	10.2	6.9	10	309.6	7,732	5.6	39.5	9.3
2.5	10,925	6,361	2.32	118.5	10.6	7.7	7	297.0	7,515	5.7	43	12.2
2.6	10,371	6,590	2.23	113.3	10.2	8	16	290.9	7,510	5.6	39	9.5
2.7	10,073	6,465	2.01	111.9	10.5	8.3	17	286	7,103	5.3	38.3	8.1
2.8	9,874	6,223	2.28	114.9	10.2	7.7	12	283.3	6,917	5.2	38	9.3
2.9	9,581	6,176	2.07	113.2	9.8	7.4	16	278.4	6,651	5.3	45	7.8
3	9,322	5,862	2.13	106.9	7.2	6.9	20	249.3	5,702	4.7	34.6	6.8
Mean	**10,437**	**7,073**	**2.48**	**133.8**	**10.4**	**7.9**	**14.8**	**361.3**	**7,937**	**6.1**	**45.1**	**11.8**
Max.	**11,668**	**8,235**	**3.26**	**152.9**	**12.5**	**10.9**	**25**	**424.9**	**9,196**	**7.6**	**52.5**	**15.5**
Min.	**7,690**	**5,712**	**1.55**	**106.9**	**7.2**	**6.4**	**7**	**249.3**	**5,702**	**4.7**	**33.4**	**6.8**
Range	**3,977**	**2,523**	**1.71**	**46.0**	**5.2**	**4.5**	**18**	**175.6**	**3,494**	**2.9**	**19**	**8.7**

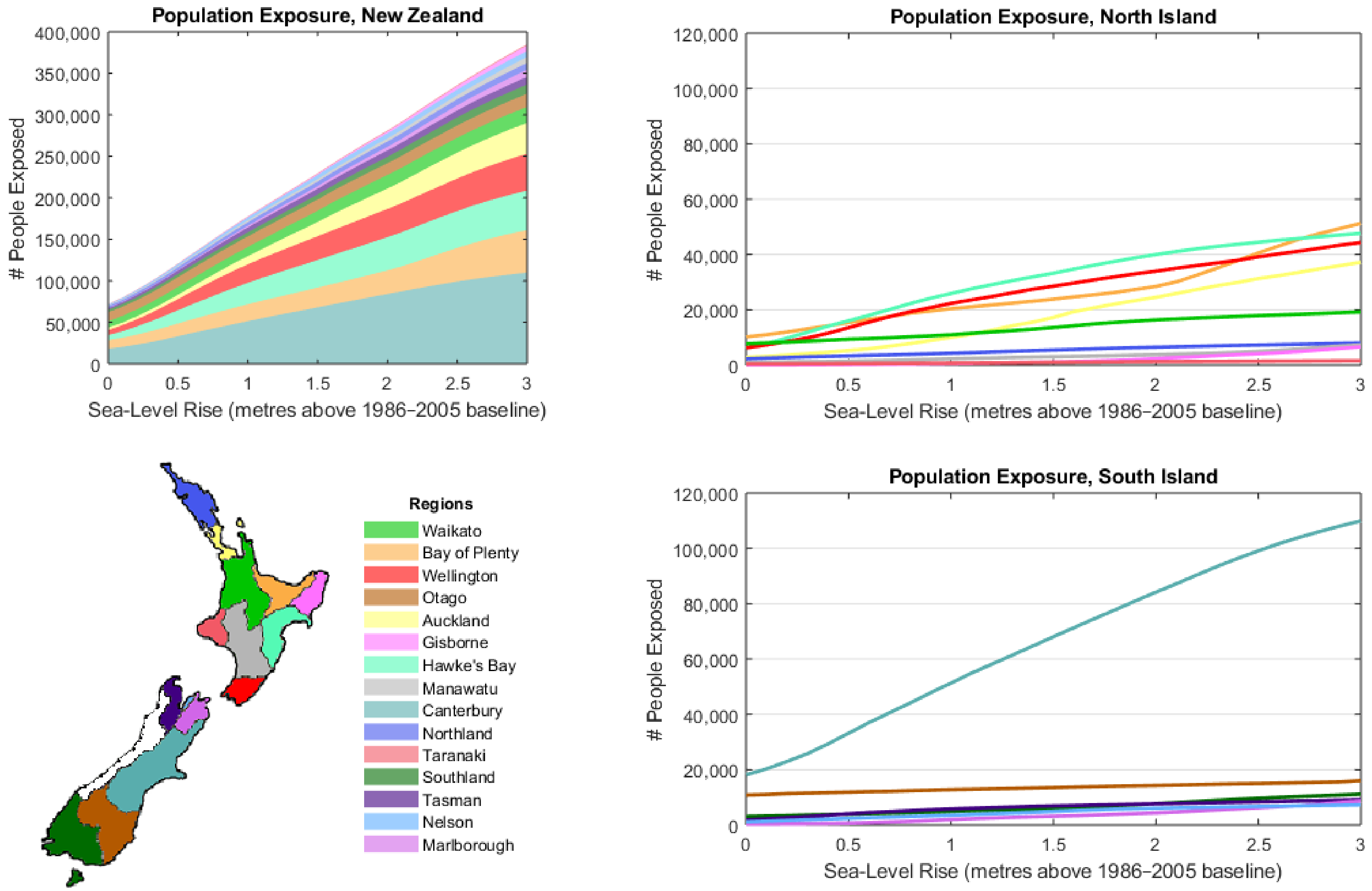

Figure 3-1: National and regional level population exposure for land areas with LIDAR DEM coverage (No data available for West Coast region).

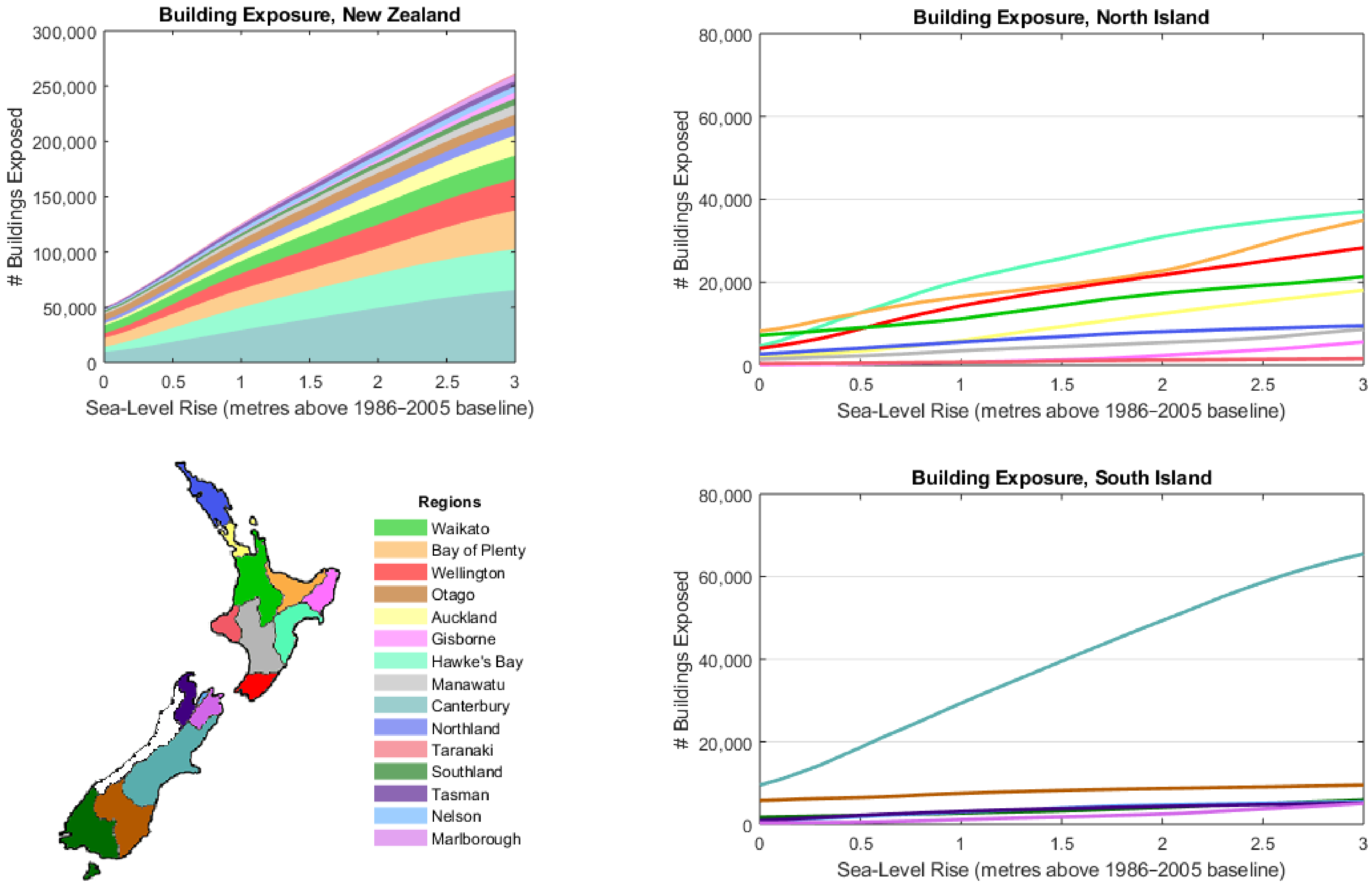

Figure 3-2: National and regional level building exposure for land areas with LIDAR DEM coverage (No data available for West Coast region).

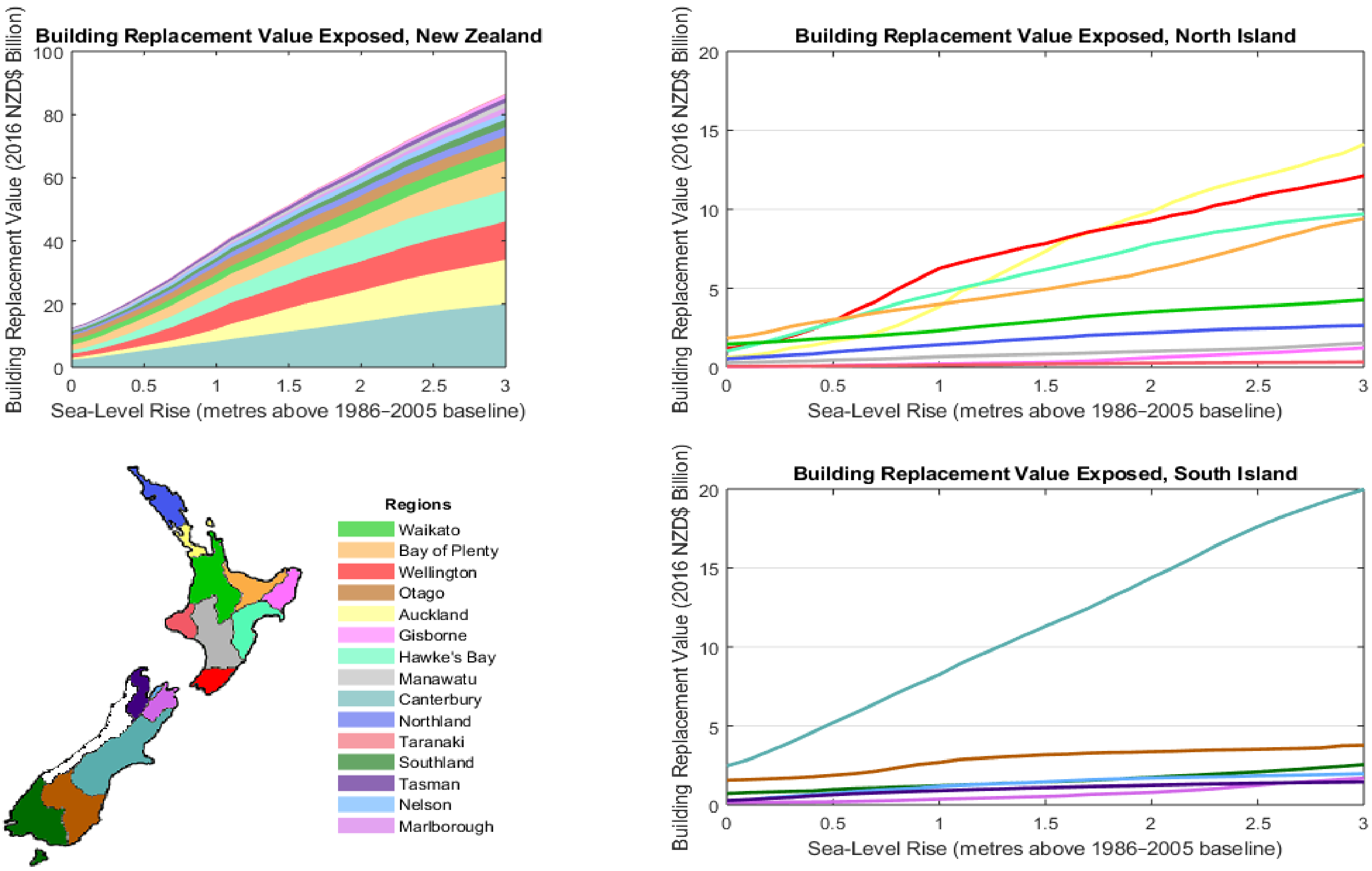

Figure 3-3: National and regional level building replacement value (2016 $NZD Billion) exposure for land areas with LIDAR DEM coverage (No data available for West Coast region).

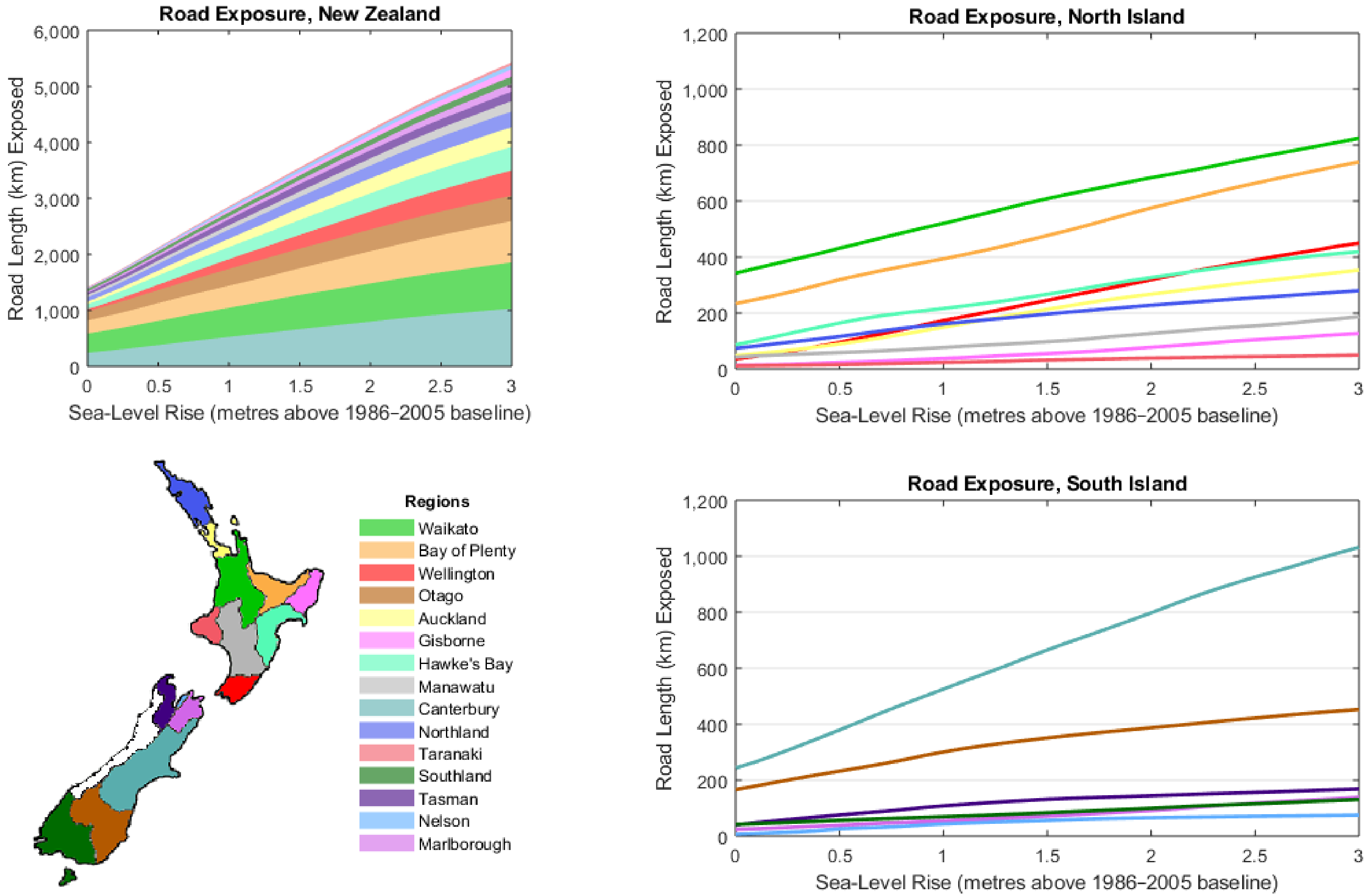

Figure 3-4: National and regional level road exposure for land areas with LIDAR DEM coverage (No data available for West Coast region).

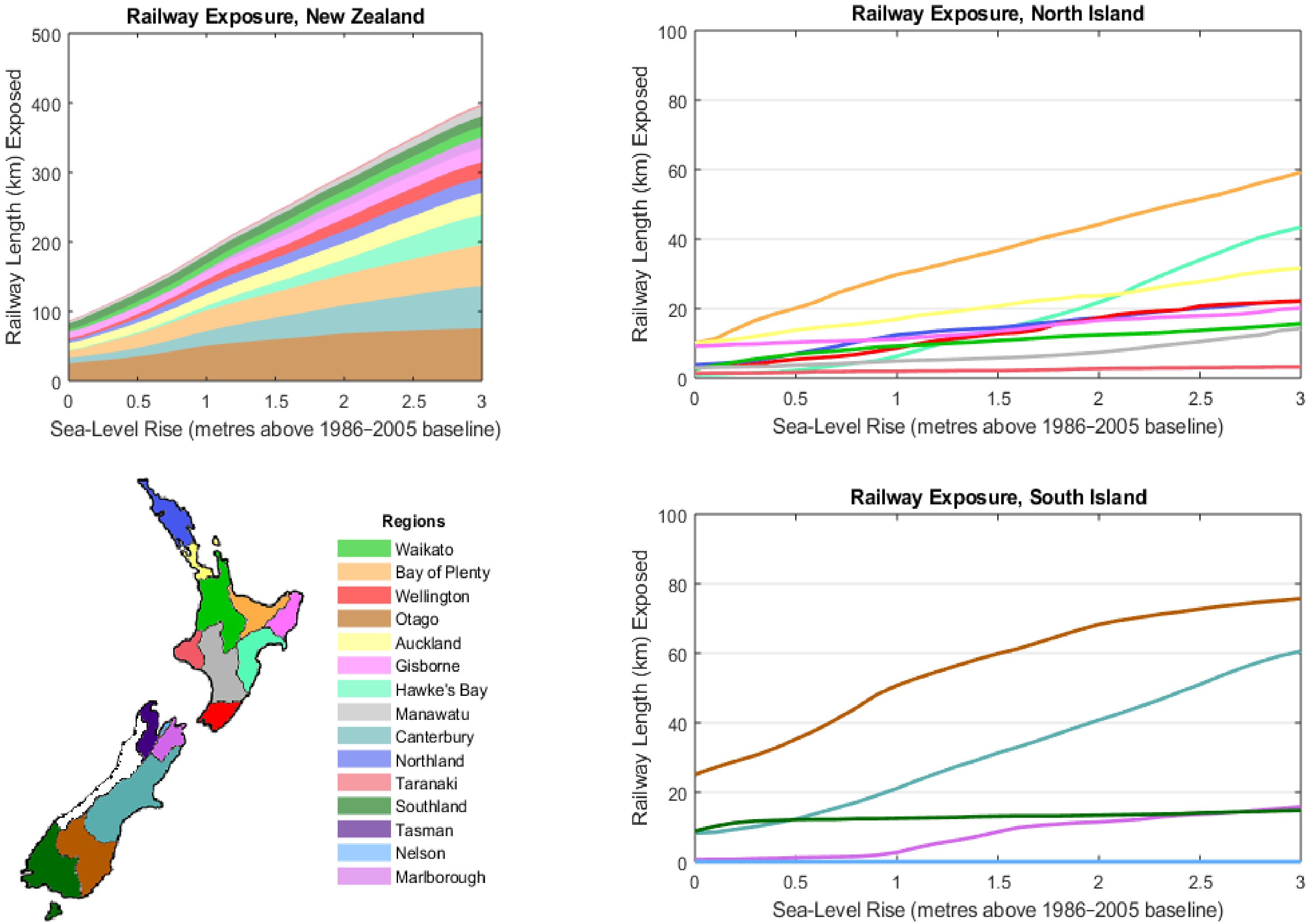

Figure 3-5: National and regional level railway exposure for land areas with LIDAR DEM coverage (No data available for West Coast region).

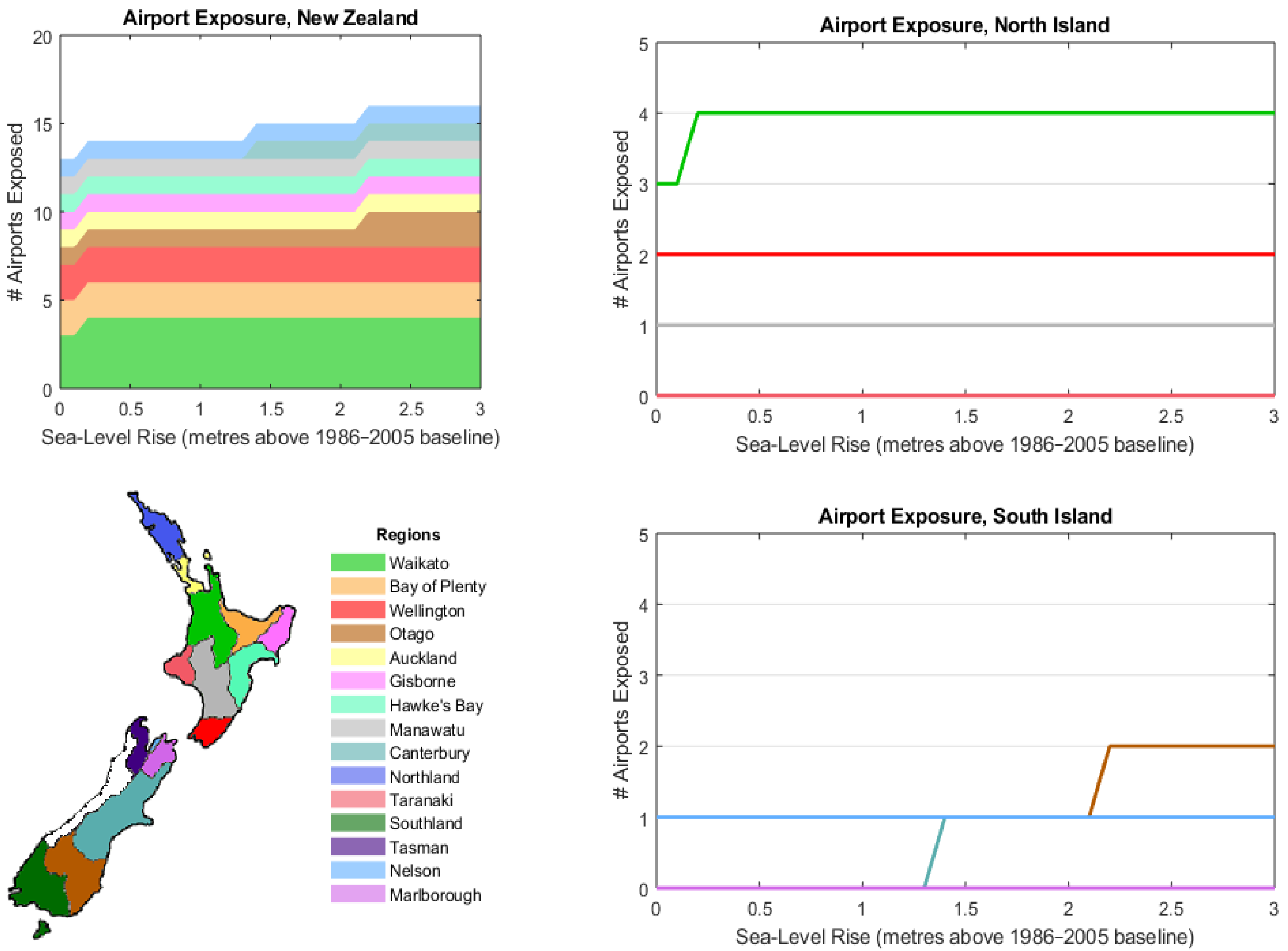

Figure 3-6: National and regional level airport exposure for land areas with LIDAR DEM coverage (No data available for West Coast region).

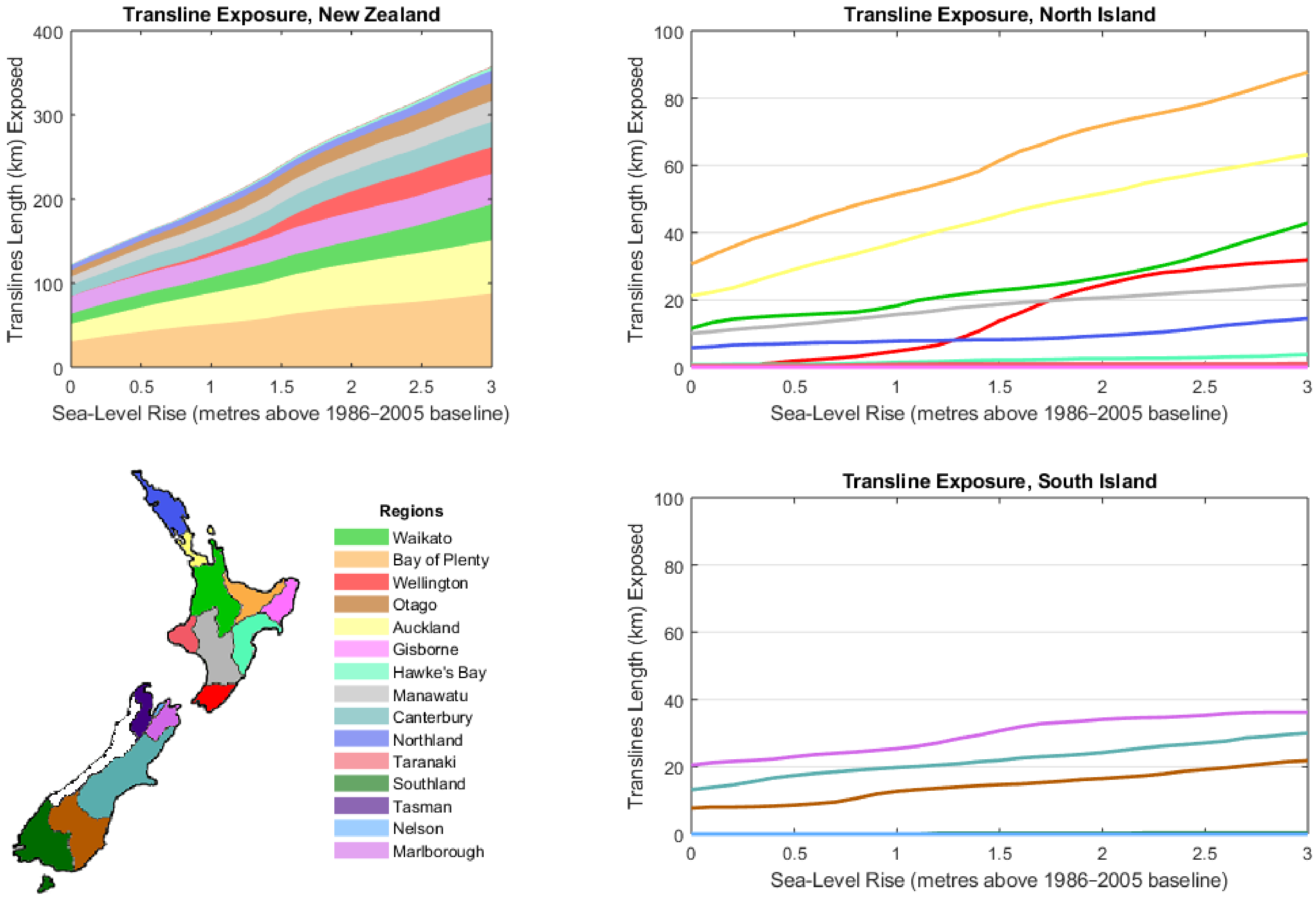

Figure 3-7: National and regional level electricity transmission line ('transline') exposure for land areas with LIDAR DEM coverage (No data available for West Coast region).

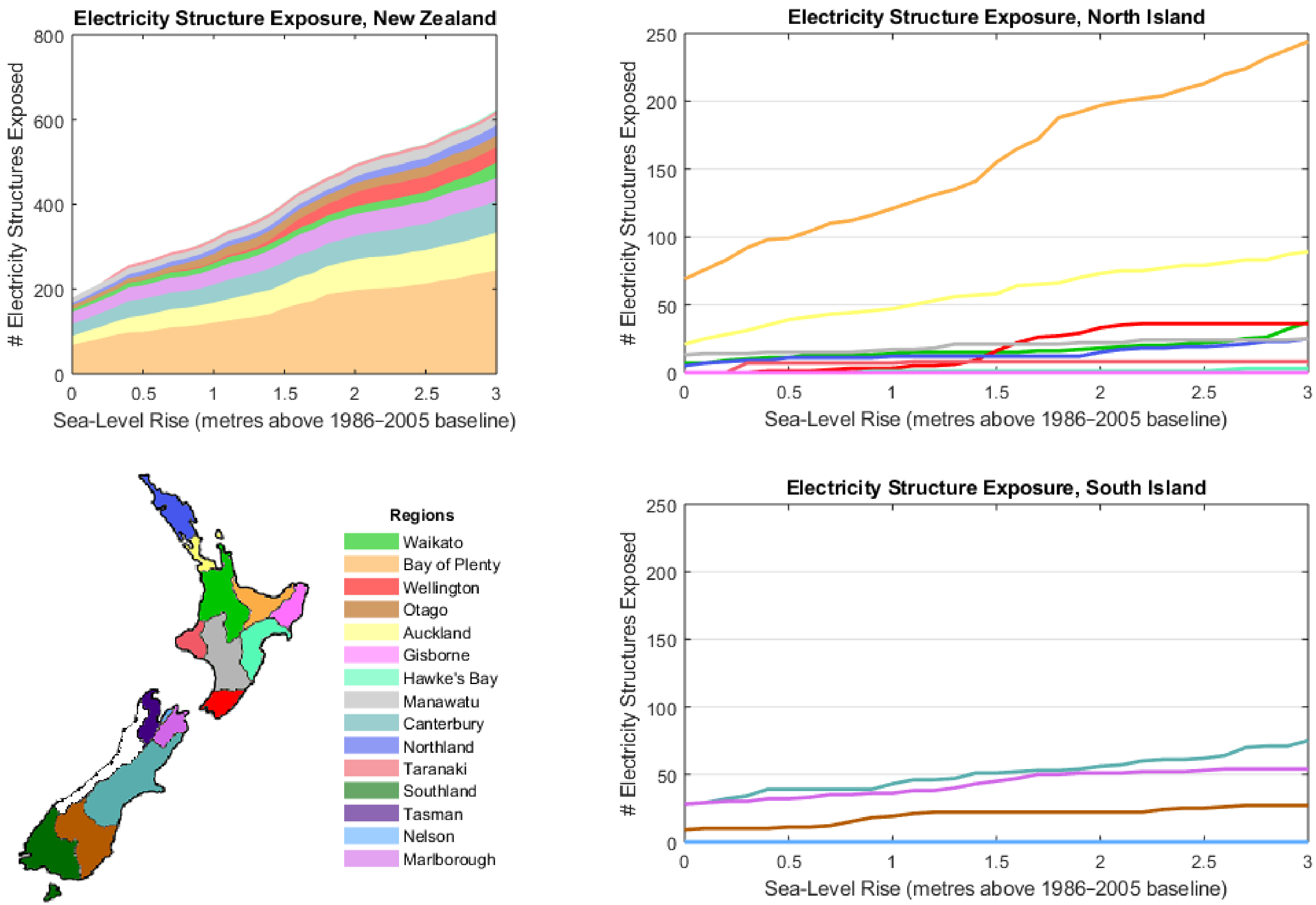

Figure 3-8: National and regional level electricity structure exposure for land areas with LIDAR DEM coverage (No data available for West Coast region).

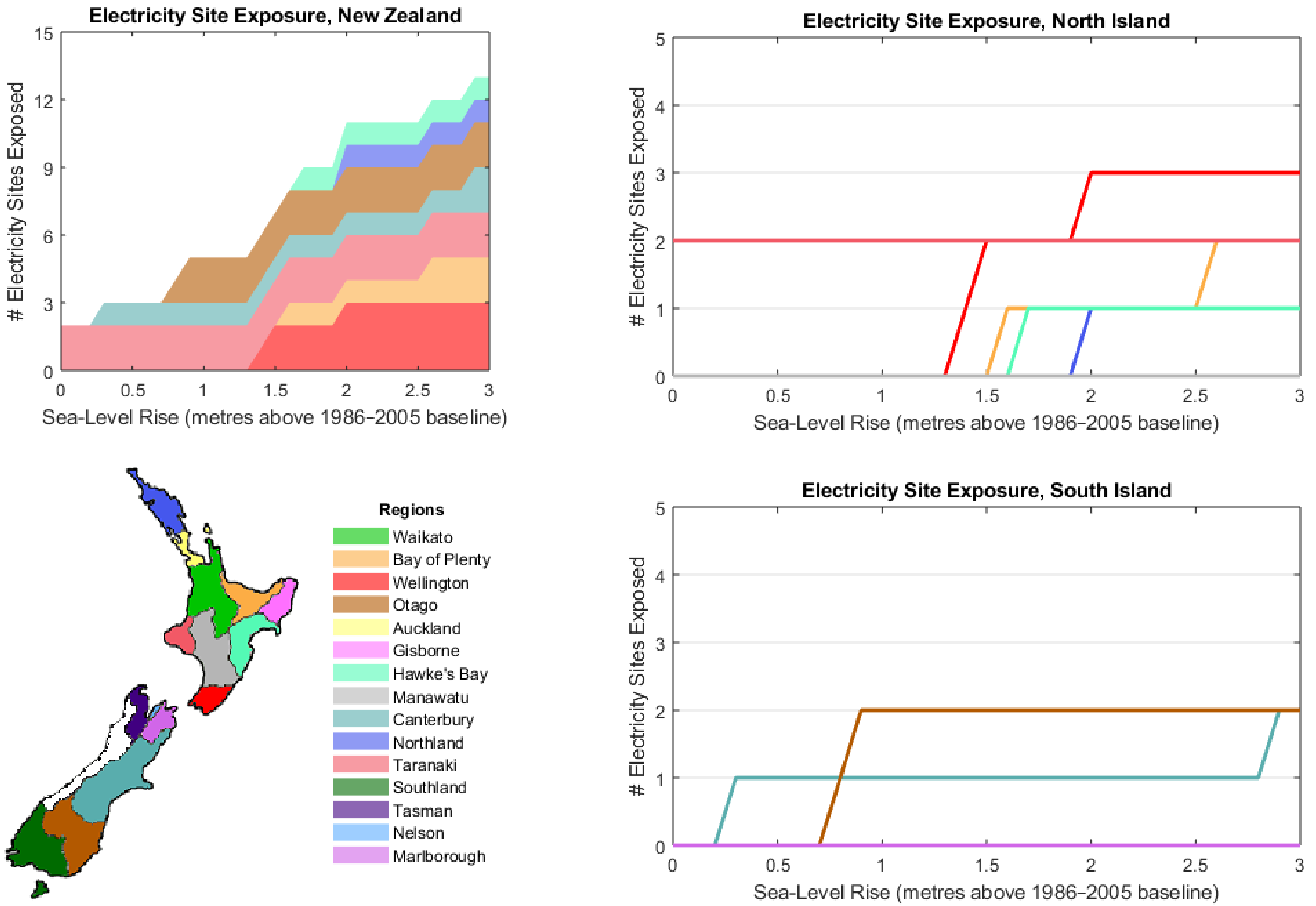

Figure 3-9: National and regional level electricity site exposure for land areas with LIDAR DEM coverage (No data available for West Coast region).

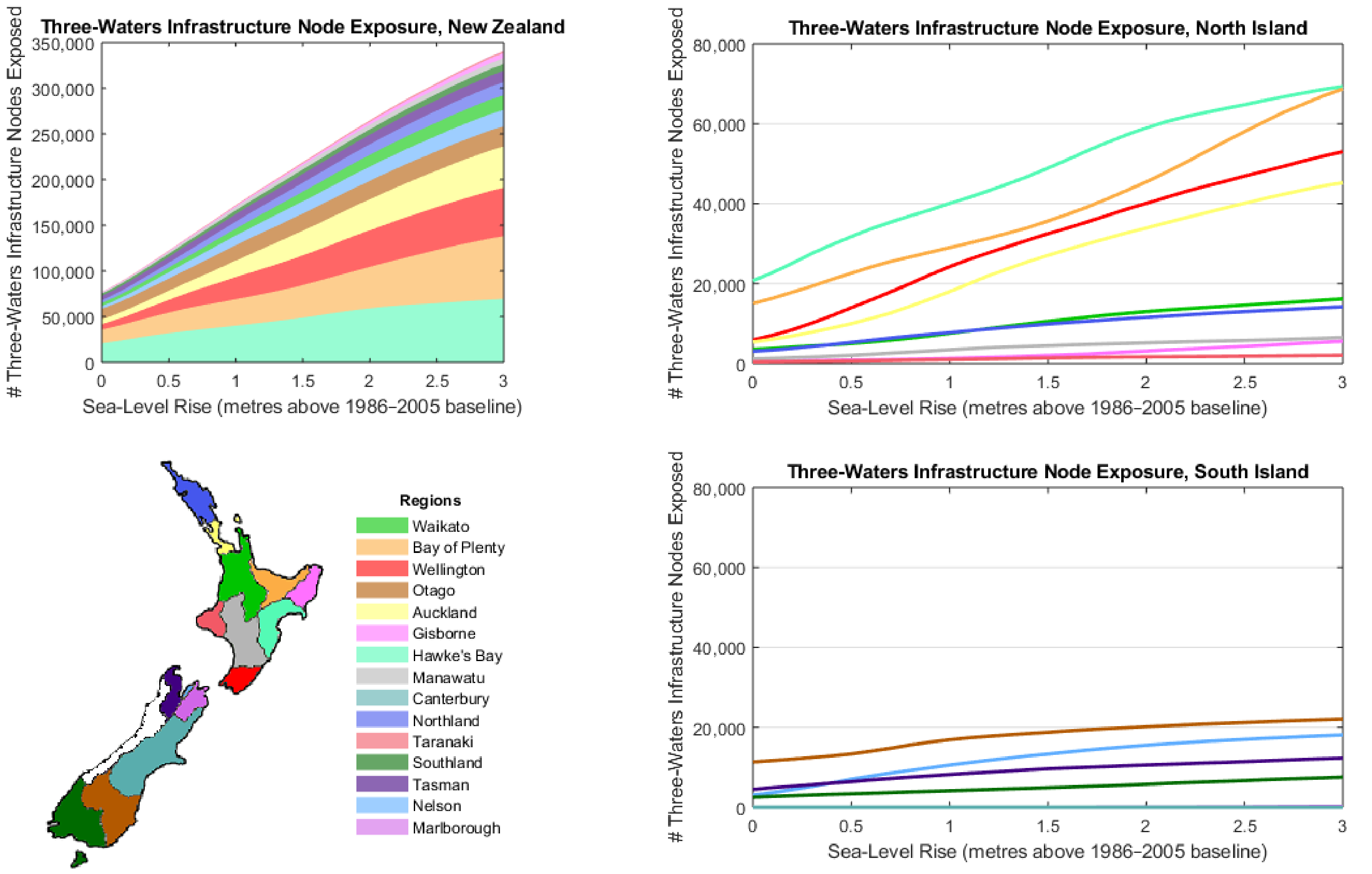

Figure 3-10: National and regional level three-waters infrastructure node exposure for land areas with LIDAR DEM coverage (No data available for West Coast and Canterbury regions).

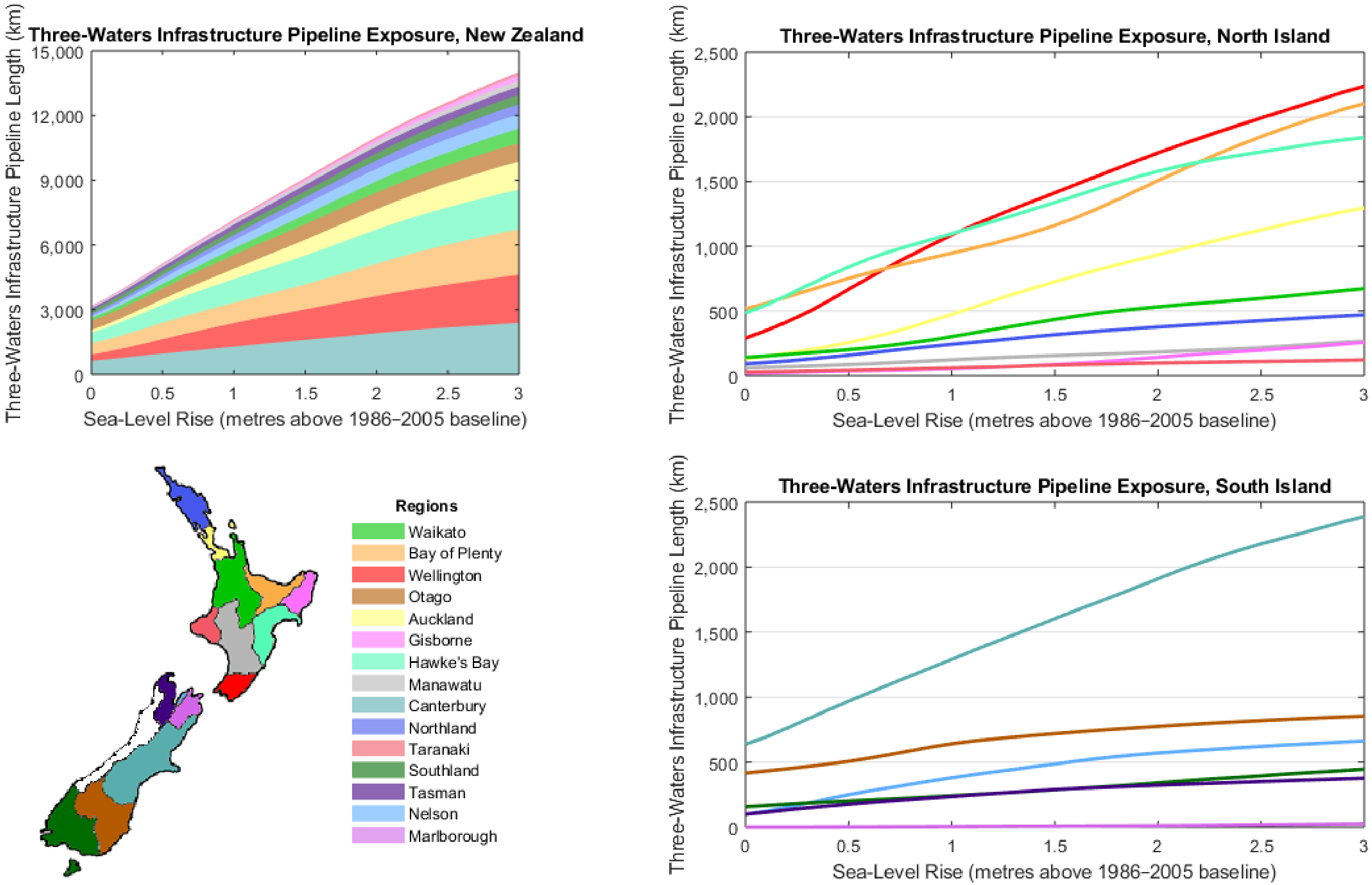

Figure 3-11: National and regional level three-waters infrastructure pipeline exposure for land areas with LIDAR DEM coverage (No data available for West Coast region).

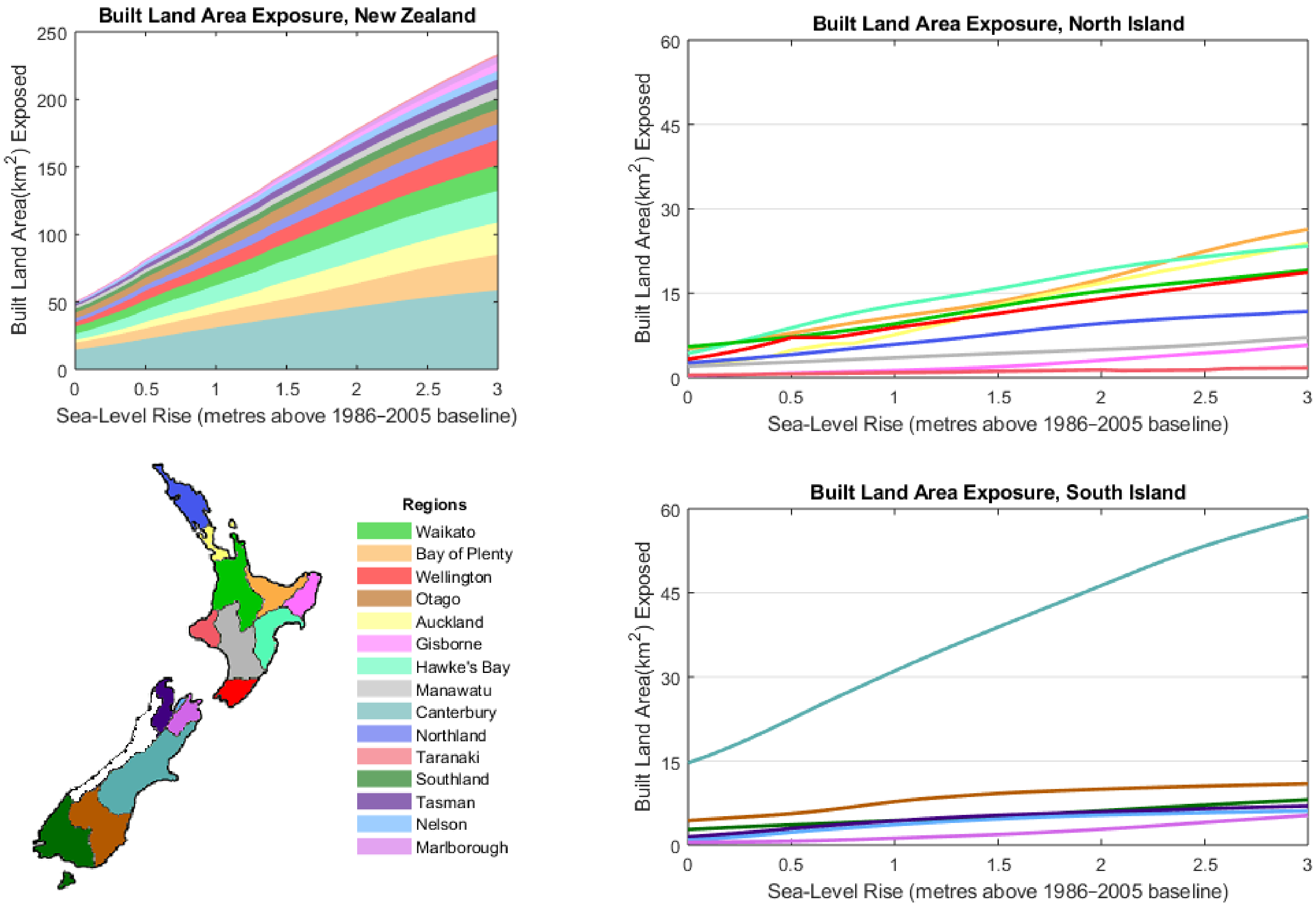

Figure 3-12: National and regional level built land exposure for land areas with LIDAR DEM coverage (No data available for West Coast region).

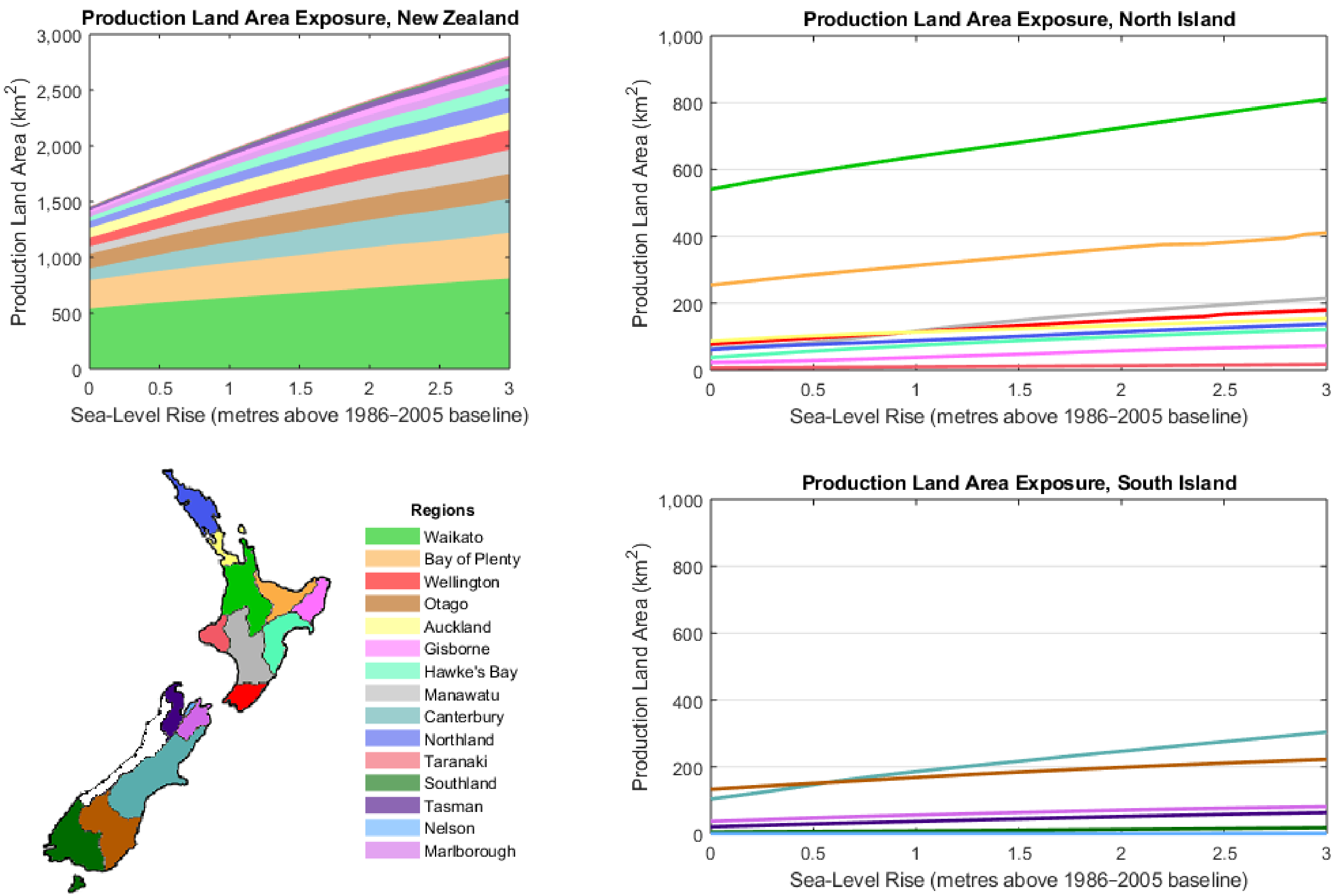

Figure 3-13: National and regional level production land exposure for land areas with LIDAR DEM coverage (No data available for West Coast region).

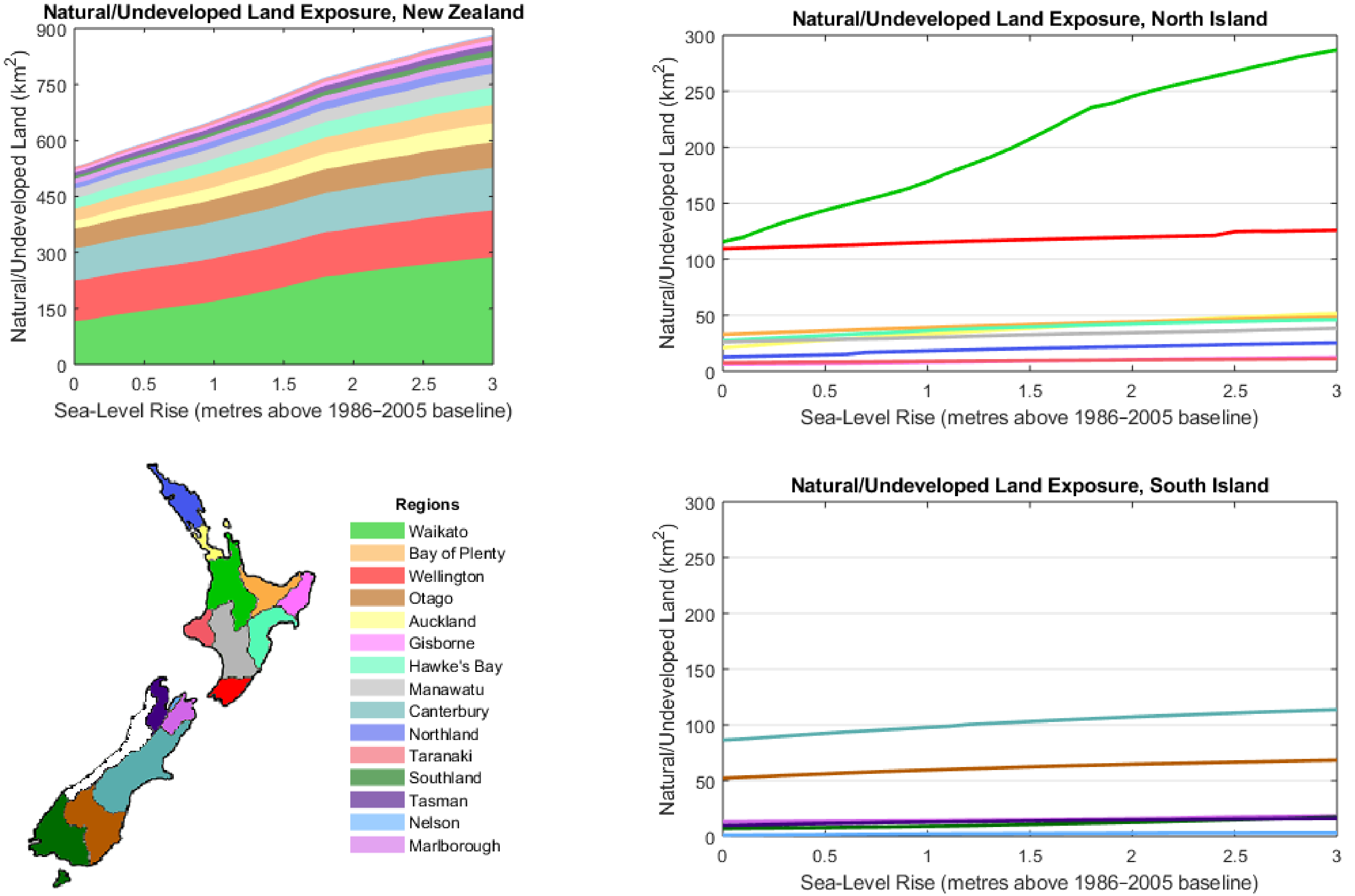

Figure 3-14: National and regional level natural or undeveloped land exposure for land areas with LIDAR DEM coverage (No data available for West Coast region).

3.1.2 Regions and territories for coastlines with LIDAR DEM coverage

Element exposure to ESL1 is estimated at region and territory levels present-day MSL and +0.1m SLR increments. Region[10] level exposure is presented in Figure 3-1 to Figure 3-14 for:

- Population
- Buildings (Count; Replacement Value)
- Roads
- Railway
- Airports
- Transmission Lines ('Translines')
- Structures
- Sites
- Three-waters infrastructure (Nodes; Pipelines)
- Land Cover (Built; Production; Natural).

Territory level exposure is tabulated provided in a digital appendix for this report (see Appendix C).

Coastal flooding exposure at present-day mean sea-level

Region and territory level exposure of elements at risk to ESL1 for present-day MSL is reported in the following sub-sections.

Land Cover

Waikato (662 km^2) has the largest regional land area exposed at present-day MSL. Production land accounts for 540 km^2 (81%) of Waikato's exposed land. Bay of Plenty has a similarly high proportion of production land (86%) for its 292 km^2 exposed land area. Otago (133 km^2) and Canterbury (104 km^2) also exceed 100 km^2 of production land. Natural or undeveloped land cover exposure at region level only exceeds 100 km^2 in Waikato. Canterbury region has the most extensive built land area exposure with just under 15 km^2, mostly located within Christchurch City (14.7 km^2).

Population

Canterbury has New Zealand's highest regional population (18,122) exposed to coastal flooding. Most of these people are in Christchurch City (11,941). Bay of Plenty and Otago regions exposed populations both exceed 10,000. Whakatane District contributes 7,184 of Bay of Plenty's exposed population, while 10,588 people of Otago's population are in Dunedin City.

Buildings

An estimated 9,506 buildings worth $NZD 2.4 B are exposed in Canterbury region. The regions buildings (6,653) and replacement value ($NZD 1.6 B) are in Christchurch City. Relatively high numbers of exposed buildings are identified in Bay of Plenty (8,241 worth $NZD 1.8 B) and Otago

[10] West Coast region is excluded due to no LiDAR DEM coverage.

(5,647 worth $NZD 1.5 B) regions. Most exposed buildings in these regions are respectively located in Whakatane District (5,322 worth $NZD 1.15 B) and Dunedin City (5,487 worth $NZD 1.5 B).

Residential building exposure is highest in Canterbury (8,847), with 6,575 located in Christchurch City. Over 4,500 residential buildings are exposed in Dunedin City, while Napier City has over 3,000 and Hauraki District, Lower Hutt City and Waimakariri District have over 2,000.

Commercial building exposure exceeds 100 in Whakatane District and Dunedin City. These territories each have more than 500 industrial buildings exposed. More than 200 industrial buildings are also exposed in Hauraki District (523), Tauranga City (219), Napier City (289), Lower Hutt (205) and Invercargill City (327).

Critical facilities are most highly exposed in Napier (60), Waimakariri District (41), Whakatane District (24) and Dunedin City (22). Forty-nine community buildings are exposed in Dunedin City while Auckland (28) and Waimakariri District (22) each have more than 20 exposed.

Transport

Over 200 km of roads in Waikato (342 km), Bay of Plenty (234 km) and Canterbury (243 km) are exposed to coastal flooding. Less than 20 km of road is exposed in Gisborne, Taranaki and Nelson regions. At territorial level, Hauraki District has more than 200 km of roads exposed, while over 100 km is exposed in Whakatane District, Christchurch City and Dunedin City. Combined, these territories account for 40% of New Zealand's road network exposure at present-day sea-level.

Otago's railway network (25.1 km) has the highest exposure at regional level, with 16 km located in Dunedin City. Networks providing high use commuter rail services are exposed to coastal flooding in Auckland (10.1 km) and Wellington region (2.9 km) across Porirua City, Lower Hutt City and Wellington City.

Thirteen airports have land exposed to coastal flooding. This includes international airports at Auckland and Wellington and major domestic airports in Tauranga City, Napier City, Nelson City and Dunedin City. Napier City's domestic airport has just over 1 km^2 of exposed land.

Electricity

New Zealand's national electricity grid is highly exposed in Bay of Plenty, with 30.7 km of transmission lines overlying exposed land. A further 20.5 km of lines are exposed in Marlborough District are exposed, where the South Island connection for the HVDC Inter-Island link (a.k.a. the 'Cook Strait cable') is located. Taranaki is the only region where substation 'sites' (2) are exposed to coastal inundation from ESL1.

Three-waters

Hawkes Bay has the highest three-waters nodes (20,711) exposure with over 19,000 located in Napier City. More than 10,000 nodes are also exposed in Bay of Plenty (15,051) and Otago (11,318) regions. Dunedin City accounts for 10,926 nodes in Otago. Territory wide node exposure exceeds 5,000 for Auckland, Whakatane District and Tasman District.

Potable water and wastewater nodes are most exposed in Napier City (10,003 and 1,674) and Dunedin City (8,010 and 1,351). Stormwater network node exposure is highest in Napier City (7,672) and Auckland (3,277). Node data was not available in this study for territories in Canterbury region. High levels of node exposure are expected on Christchurch City's 14.7km^2 of exposed built land.

Canterbury has the longest combined three-water network pipeline exposure with 638km. Hawkes Bay (282 km) and Otago (281 km) has similar potable water pipeline exposure to Canterbury region. Potable water pipeline exposure in Napier City (273 km) and Christchurch City (257 km) and Dunedin City (205 km) contribute over of all potable water pipeline exposure identified in New Zealand. Christchurch City has over 115 km of stormwater pipelines exposed while wastewater pipelines exposure exceeds 100 km in both Napier City (130 km) and Christchurch City (150 km).

Coastal flooding exposure from sea-level rise

Region and territory level element exposure to ESL1 in response to sea-level rise is reported in the following sub-sections.

At region and territory levels, element exposure demonstrates a non-linear ESL1 increase in response to rising sea-levels. This trend is graphically illustrated for exposed elements at regional levels in Figure 3-1 to Figure 3-14, but similarly occurs at territory levels. Detecting non-linear exposure dynamics is important for identifying where and when element exposure rates accelerate in response to SLR.

Land Cover

Regions and territories with major coastal urban areas (>50,000 pop.) on low-lying coastal land experience relatively higher rates of built land exposure as sea-levels rise. Christchurch City (15 km^2) has the largest built land area exposure increase between present-day MSL and +1.2 m SLR, while considerable exposure also emerges in Napier City (8.9 km^2) and Auckland (7.1 km^2) over this SLR. Territories with relatively small urban populations (i.e. <10,000 people) on low-lying coastal land, including Thames-Coromandel District and Hauraki District, have comparable built land area exposure to large urban areas between present-day MSL and +0.3 m SLR.

Production land exposure to ESL1 in Waikato and Canterbury regions increases by approximately 100 km^2 at +1.2 m SLR. Waikato (+114 km^2) has the highest increase in exposure at this sea-level, mostly in Hauraki District (+46 km^2) and Waikato District (+25 km^2). Auckland region also has 30 km^2 more production land exposed by +1.2 m SLR.

Waikato region also has the largest increase in natural or undeveloped land exposure to ESL1 under rising sea levels (Figure 3-14). Hauraki District (+20 km^2) and Waikato District (+34 km^2) have the largest increase in land exposure in response to sea-level rise by +1.2 m SLR.

Population

Regions and territories with major coastal urban areas have the highest population exposure in response to SLR. Canterbury, Hawkes Bay and Wellington's total population exposure doubles as sea-levels rise +0.6 m, and more than triples by +1.2 m SLR. This exposure represents high territory level population exposure increases in Christchurch City, Napier City and Lower Hutt City respectively.

Incremental population exposure rates are highly variable with several regions experiencing their highest rates for lower SLR scenarios. Northland and Otago's average rate is highest incremental exposure by +0.3 m SLR, lowering thereafter. Tasman and Nelson reach their highest incremental exposure at +0.6 m SLR while in Hawkes Bay, Wellington and Canterbury these occur at +0.8 m SLR. Other regions including Auckland, Bay of Plenty, Gisborne, Manawatu-Whanganui, Marlborough and Southland, observe a steady incremental exposure increase for every +0.1 m SLR above present-day MSL.

Canterbury region has the highest incremental regional population exposure of 3,060 per +0.1 m SLR. Auckland (1,145) and Wellington (1,074) are half this exposure, while less than 200 more people per +0.1 m SLR occurs in Taranaki (38), Northland (189) and Otago (175). Otago's population exposure at present-day MSL exceeds 10,000 however, at regional level it has the second lowest increment exposure increase per +0.1 m SLR. Most of Otago's population exposed to ESL1 occurs at relatively low SLR.

Buildings

Building exposure in Bay of Plenty, Hawkes Bay, Wellington and Canterbury increases to over 10,000 as sea-levels rise to ESL1 +0.6 m. Replacement values for buildings exposed in these regions increases in range from NZD$1 to 2 B to NZD$3 to 5 B over this SLR. In Canterbury and Hawkes Bay, building exposure in Christchurch City and Napier City increases to over 20,000 at ESL1 +1.2 m SLR. Replacement values for these buildings are estimated at NZD$7.8 B and NZD$4.8 B respectively. Auckland has less than 10,000 buildings exposed at ESL1 +1.2 m SLR, though replacement value exceeds NZD$5.3 B.

Canterbury has the highest total building ESL1 exposure as sea-levels rise. Over 24,000 more buildings in the region are exposed at +1.2 m SLR, at an incremental rate of 2,013 per +0.1 m SLR. Buildings are mostly residential (70% to 81%) and located in Christchurch City. Hawkes Bay and Wellington's incremental building exposure also exceed 1,000 per +0.1 m SLR as sea-levels rise +1.2 m. Wellington has fewer exposed buildings though replacement value increases at NZD$0.4 B per +0.1 m SLR, compared to NZD$0.35 B in Hawkes Bay. Wellington City's commercial building exposure is a major contributor, with total replacement values reaching NZD$1.9 B at +1.2 m SLR, 10 times more than Napier City.

The high proportion of residential buildings means incremental building exposure generally observe a non-linear trend similar to population exposure and region and territory levels. Several regions with major coastal urban areas including Bay of Plenty, Hawkes Bay, Wellington, Canterbury and Otago experience their highest incremental building exposure before +0.9 m SLR. Building replacement value exposure for Hawkes Bay, Wellington and Canterbury also shows a relatively high incremental increase of between NZD$0.35 B to NZD$0.53 B per +0.1 m SLR up to +0.9 m SLR. Auckland's building replacement value exposure increases steadily to a maximum of NZD$0.46 B per +0.1 m SLR, at +1.6 m SLR. At lower SLR, incremental replacement value exposure increase in Auckland is relatively low compared to other regions with major coastal urban areas however, at +1.6 m SLR more than 12 times Auckland's total replacement value exposed to ESL1 at present-day MSL is contributed from SLR.

Transport

Road exposure to ESL1 exceeds 400 km in Waikato, Bay of Plenty and Canterbury with +1.2 m SLR. These regions include seven of the highest ten territories for road exposure at present-day MSL. Canterbury's road network exposure increases by nearly 340 km at +1.2 m SLR, with 200 km located in Christchurch City. Over this SLR, incremental road exposure exceeds 10 km per +0.1 m SLR for most regions with major coastal urban areas, and maximum incremental exposure is often reached before +0.9 m SLR. Waikato's incremental road exposure over this sea-level rise increase by 18 km on average, predominantly on rural land in Hauraki District.

In the Bay of Plenty and Otago regions, railway exposure to ESL1 increases by over 20 km as sea-level rises to +1.2 m. Incremental regional railway exposure increases over this SLR only exceed 2 km per

+0.1 m SLR in Otago. Otago's railway exposure mostly occurs in Dunedin City where the network services Port of Otago. In other regions with major coastal urban areas, Auckland and Wellington commuter railway network ESL1 exposure increases by over 8 km and respectively in response to +1.2 m SLR.

One additional airport or aerodrome in Waikato region becomes exposed to ESL1 as sea-levels rise to +1.2 m.

Electricity

National electricity grid transmission line exposure to ESL1 in Bay of Plenty and Auckland nearly doubles in response to +1.2 m SLR. Territory level line exposure at this higher sea-level in Auckland and Whakatane District is approximately 40 km and supported 50 structures. Nationwide, three additional 'sites' located in Dunedin City (2) and Waimakariri District (1) are exposed to ESL1 +1.2 m SLR.

Three-waters

Three-waters infrastructure networks are most highly exposed in regions and territories with major coastal urban areas. Combined pipeline exposure exceeds 1,000 km in Hawkes Bay, Wellington and Canterbury by ESL1 +0.9 m, while node exposure in Bay of Plenty, Hawkes Bay, Wellington exceeds 20,000[11]. At territory level, more than 500 km of pipeline is exposed in Napier City, Lower Hutt City, Christchurch City and Dunedin City by ESL1 +1.2 m. In addition, more than 15,000 nodes are exposed in Auckland, Napier City and Dunedin City.

Pipeline components are rapidly exposed to ESL1 in Hawkes Bay, Wellington and Canterbury as sea-levels rise to +0.9 m. In response to this SLR, combined incremental pipeline exposure in these regions exceeds 50 km per +0.1 m SLR. Potable water pipelines are most frequently exposed in Hawkes Bay and Canterbury (31 km to 32 km per +0.1 m SLR), while wastewater pipelines are more exposed in Wellington (35 km per +0.1 m SLR). In Hawkes Bay and Canterbury regions, Napier City and Christchurch City potable water pipelines exposure exceeds 500 km at ESL1 +0.9 m, along >250 km wastewater and >100 km stormwater pipelines.

Incremental network node component exposure in the Bay of Plenty and Hawkes Bay increases by 1,451 and 2,199 respectively up to +0.6 m SLR. Over this SLR, nodes exposed to ESL1 are predominantly potable water with per +0.1 m SLR increases averaging 764 in Bay of Plenty and 1,246 in Hawkes Bay. At territory level, this reflects an increase in total potable water node component exposure to ESL1 in Tauranga City (2,500) and Napier City (6,870) over +0.6 m SLR. In other regions with coastal urban areas such as Wellington City and Otago, exposure of potable water nodes per SLR increment increases up to ESL1 +0.8 m SLR, while in Auckland this occurs up to ESL1 +1.7 m SLR. Although fewer node components are exposed relative to potable water, at region and territory levels both wastewater and stormwater nodes demonstrate a similar trajectory of increasing exposure in response to rising sea-levels.

3.2 National DEM

New Zealand has incomplete LIDAR DEM coverage for low-lying coastal land (Figure 2-4). National coastal flood mapping in this study required a lower resolution national DEM to provide coverage where a LIDAR DEM is not available. A 0-3 m elevation above ESL1 (ESL1 0-3 m) is used to identify

[11] Node data not available in this study for the Canterbury region.

land exposed to coastal flooding based on the DEM limitation to support mapping with +0.1 m SLR increments. Element exposure to ESL1 0-3 m at national and regional level is summarised in Table 3-3.

Exposure mapping for ESL1 0-3 m was not implemented in Auckland, Bay of Plenty, Wellington and Nelson due to regionwide LIDAR DEM coverage.

3.2.1 Land cover

Approximately 2,469 km^2 of low lying coastal land is exposed in addition to the LIDAR DEM. Similar area extents for production (1,221 km^2) and natural or undeveloped land (1,220 km^2) is exposed to ESL1 0-3 m. Production land exposure exceeds 150 km^2 in four regions. Northland (375 km^2) has the largest production land exposure with 223 km^2 located in Kaipara District. Additionally, over 160 km^2 is exposed in Southland District. The largest areas of natural or undeveloped (372 km^2) and built (9.7 km^2) land exposure occurs in the West Coast region. Natural or undeveloped land exposure in Westland District reaches 322 km^2, while more than 150 km^2 is also exposed in Far North District (152 km^2), Selwyn District (169 km^2) and Southland District (172 km^2).

3.2.2 Population

The total population identified within ESL1 0-3 m is 38,323. Seven regions exceed 1,000 people. West Coast (11,609) has the highest exposed population, with over half of this population in Buller District (6,457). In Canterbury, 5,806 of the regions 8,844 people exposed are in Christchurch City. Other territories where exposed populations exceed 2,000 are Kaipara District (2,284), Whanganui District (2,353) and Invercargill City (4,705).

3.2.3 Buildings

An estimated 27,533 buildings with $NZD 7.3 B replacement value are identified are exposed to ESL1 0-3 m. West Coast replacement values reach $NZD 2 B for 7,428 buildings. Replacement values in Canterbury and Southland regions also exceed $NZD 1 B, mostly for buildings in Christchurch City ($NZD 1.1 B) and Invercargill City ($NZD 1.08 B).

3.2.4 Transport

Road exposure to ESL1 0-3 m is 1,374 km, with over half located in Northland (408 km) and West Coast (398 km). Six territories, two each in Northland, West Coast in Southland exceed 100 km. Kaipara District (206 km) has the highest exposure of these territories.

Approximately 123 km of railway track is exposed to ESL1 0-3 m. Track exposure exceeds 10 km in West Coast (46 km), Northland (23 km), Otago (15 km) and Canterbury (12 km). In Buller District, 30 km of track is exposed while Kaipara District (19 km) also exceeds 10 km.

Eight airports or aerodromes are exposed to ESL1 0-3 m, including the West Coast domestic airports at Greymouth and Westport. Nationwide exposure of airport land is 4.5 km^2.

3.2.5 Electricity

Transmission lines exposure to ESL1 0-3 m is 93.6 km, with three regions (West Cost, Canterbury and Southland) exceeding 20 km. These lines are supported by 214 exposed structures, with 83 located in Waimate District. Buller District (2) and Westland (1) were the only territories with sites identified.

3.2.6 Three-waters

Three-waters infrastructure exposure to ESL1 0-3 m exceeds 19,000 nodes and 1,000 km of pipelines. Potable water nodes (9,850) and stormwater pipelines (521 km) are most exposed. West Coast region has 13,937 nodes and 516.8 km of pipelines exposed. In Buller District, a total of 238 km three-waters pipelines is exposed, including 65 km used for potable water.

Table 3-3: National level element exposure for ESL1 0-3 m above present-day MSL (where SLR is calculated in meters above 1986-2005 baseline) on land with Satellite DEM coverage (i.e. LIDAR DEM coverage unavailable).

Region*	Population (#)	Buildings		Transport			Electricity (National Grid)			Three-Waters		Land Cover (km^2)		
		Building (#)	Replacement Value (2016 NZD$ Billion)	Roads (km)	Railway (km)	Airports (#)	Transmission Lines (km)	Structures (#)	Sites (#)	Pipelines (km)	Nodes (#)	Built	Production	Natural or Undeveloped
Northland	4,069	4,301	0.75	409	23	1	2.1	1	0	94	1,754	2.1	375	220
Auckland	Not Included													
Waikato	851	1,088	0.2	86	1	0	1.1	5	0	10	168	0.8	61	91
Bay of Plenty	Not Included													
Gisborne	162	139	0.02	26	0	0	0	0	0	0.4	18	0.1	16	6
Hawke's Bay	1,231	931	0.31	32	7	0	2.8	1	0	28.6	775	0.7	12	1
Taranaki	101	99	0.03	6	1	0	0	0	0	5.4	58	0.1	6	1
Manawatu-Whanganui	3,285	2,963	0.57	57	5	0	1.5	6	0	67	977	2.0	67	12
Wellington	Not Included													
West Coast	11,610	7,428	2.07	398	47	4	22.1	59	3	516.8	13,937	9.7	151	373
Canterbury	8,844	5,204	1.54	245	12	0	28.7	97	0	185.8	No Data*	4.7	154	198
Otago	1,212	850	0.21	118	15	0	3.1	6	0	79.1	1,245	1.1	51	22
Southland	5,463	3,221	1.29	306	1	2	29.8	38	0		0	4.7	290	244
Tasman	618	351	0.08	24	0	0	0	0	0	17.2	332	0.3	13	27
Nelson	Not Included													
Marlborough	877	854	0.24	60	9	0	2.4	1	0	2**	0**	2.3	25	24
NZ Total	**38,323**	**27,429**	**7.32**	**1,766**	**122**	**7**	**93.6**	**214**	**3**	**1,007**	**19,264**	**29**	**1,221**	**1,220**

* No three-waters infrastructure node data available for Canterbury region.

** Limited three-waters infrastructure pipeline and node data available for Marlborough region.

3.3 Combined national Exposure to ESL1 + 3m Sea-Level Rise

New Zealand wide exposure of elements to coastal flood inundation from ESL1 is 'best estimated' for ESL1 +3m SLR. Consistent element exposure estimation is limited to ESL1 +3m SLR and ESL1 0-3m from LIDAR and satellite DEMs is respectively. This is due to the potential for >2 m vertical error in the satellite DEM. Element exposure to ESL1 +3m SLR at national and regional level is summarised in Table 3-4.

3.3.1 Land Cover

New Zealand's land area exposed to ESL1 +3m SLR is estimated to be 6,397 km^2. Production land has most extensively exposed area with 4,031 km^2, almost 100% greater than the natural or undeveloped land (2,102 km^2) area. Production land exposure exceeds 400 km^2 in four regions. Waikato (871 km^2) has both the largest production (871 km^2) and natural or undeveloped land area exposure (378 km^2). Canterbury's built land exposure is 63 km^2, with 48 km^2 located in Christchurch City.

3.3.2 Population

Total population exposure to ESL1 +3m SLR is 423,490. Five regions exceed 30,000 exposed people, with four located in the North Island (Table 3-4). Canterbury has the highest population exposure of 118,761 people, with 84% in Christchurch City. The lowest exposure population exposure occurs in Taranaki (1,660), while four other regions (1 North Island and 3 South Island) do not exceed 10,000.

3.3.3 Buildings

ESL1 +3 m SLR exposes 289,057 buildings with $NZD 94 B replacement value. In Canterbury, replacement values exceed $NZD 21 B for just over 70,000 exposed buildings. Replacement values in Auckland, Hawkes Bay and Wellington also exceed $NZD 10 B. Auckland has comparatively fewer buildings exposed than Hawkes Bay and Wellington, indicating the potential exposure of high value commercial buildings.

3.3.4 Transport

National road exposure to ESL1 +3 m SLR reaches 7,195 km, with nearly 20% of exposed roads located in Canterbury (1,276 km). Road exposure in three North Island regions exceeds 600 km (Northland, Waikato and Bay of Plenty) while one other South Island region (Otago) exceeds 500 km. Christchurch City has the highest exposure of all territories with 691 km.

Railway track exposure is 520 km at ESL1 +3 m SLR. Nearly 100 km of track is exposed in Otago, with 48 km located in Dunedin City. Auckland and Wellington regions, which both provide commuter services, respectively have 31 km and 22 km railway track exposed at ESL1 +3 m SLR.

Twenty-two airports or aerodromes are exposed ESL1 +3 m SLR ESL1 +3 m SLR, including the international airports at Auckland and Wellington.

3.3.5 Electricity

National electricity grid transmission line exposure to ESL1 +3 m is 451 km, with three regions (Auckland, Bay of Plenty and Canterbury) exceeding 50 km. These lines are supported by approximately 837 exposed structures, with over 240 located in Bay of Plenty, including 182 in Whakatane District. Sixteen sites are identified on land exposed to ESL1 +3 m, with two each exposed in New Plymouth District, Buller District and Dunedin City

Table 3-4: Combined national and regional level element exposure for ESL1 +3 m above present-day MSL (where SLR is calculated in meters above 1986-2005 baseline) on land with available LIDAR DEM and satellite DEM coverage.

Region*	Population (#)	Buildings		Transport			Electricity (National Grid)			Three-Waters		Land Cover (km²)		
		Building (#)	Replacement Value (2016 NZD$ Billion)	Roads (km)	Railway (km)	Airports (#)	Transmission Lines (km)	Structures (#)	Sites (#)	Pipelines (km)	Nodes (#)	Built	Production	Natural or Undeveloped
Northland	12,028	13,819	3.38	689	45	1	16.6	26	1	564	15,924	14	513	246
Auckland	37,185	18,092	14.13	354	32	2	63.2	89	0	1,298	45,253	24	155	52
Waikato	20,062	22,454	4.46	910	17	4	44	42	0	683	16,359	20	871	378
Bay of Plenty	51,211	34,962	9.4	740	59	2	87.7	244	2	2,102	68,674	26	411	48
Gisborne	6,739	5,733	1.24	153	21	1	0	0	0	259	5596	6	89	19
Hawke's Bay	48,856	37,976	10.01	451	51	1	6.6	4	1	1,867	70,065	24	134	47
Taranaki	1,690	1,660	0.36	56	4	0	1.2	8	2	128	2112	2	23	12
Manawatu-Whanganui	10,622	11,614	2.09	244	19	1	26.1	31	0	334	7,485	9	282	50
Wellington	44,304	28,288	12.12	450	22	2	31.8	36	3	2,235	53,011	19	180	126
West Coast*	11,610	7,428	2.07	398	47	4	22.1	59	3	517	13,937	10	151	373
Canterbury	118,761	70,702	21.53	1,276	73	1	58.7	172	2	2,588	No Data**	63	459	312
Otago	17,251	10,354	3.98	570	91	2	24.9	33	2	919	23,293	12	274	90
Southland	16,619	9,087	3.86	437	16	1	30.1	38	0	446	7,521	13	308	262
Tasman	9,703	5,517	1.53	193	0	0	0	0	0	393	12,607	7	76	43
Nelson	7,278	5,462	1.98	75	0	0	0	0	0	663	18,081	6	1	3
Marlborough	9,571	5,909	1.93	199	25	0	38.6	55	0	28***	236***	8	107	42
NZ Total	**423,490**	**289,057**	**94**	**7,195**	**520**	**22**	**451**	**837**	**16**	**15,024**	**360,154**	**263**	**4,031**	**2,102**

* No LIDAR available for West Coast region.

** No three-waters infrastructure node data available for Canterbury region.

*** Limited three-waters infrastructure pipeline and node data available for Marlborough region.

3.3.6 Three-waters

New Zealand's total three-waters infrastructure component exposure to ESL1 +3 m exceeds 360,000 nodes and 15,000 km of pipelines. Node exposure exceeds 50,000 components in at least three regions (no data available for Canterbury) while over 2,000 km of pipeline is exposed in Bay of Plenty, Wellington and Canterbury respectively, and more than 1,000 km is exposed in Auckland and Hawkes Bay. Potable water networks are most highly exposed with a national total of 170,773 nodes and 5,773 km of pipeline. At regional level, potable water node component exposure is highest in Bay of Plenty (40,949), while Hawkes Bay has the longest pipeline network exposed (909 km).

4 Discussion and conclusions

This study presents New Zealand's exposure to coastal flood inundation from 1% AEP extreme sea-levels (ESL1). Population, built assets (e.g. buildings, roads, railways, airports, electricity and 'three-waters' components) and land cover (e.g. built, production, natural) to ESL1 is estimated for present-day MSL and higher sea-levels. Exposure assessment at national, regional and territory levels spatially identifies the scale of potential coastal flooding effects from projected future sea-levels across New Zealand.

4.1 Applying Coastal Flood Exposure Information

4.1.1 Coastal flooding and element at risk exposure mapping

Mapping coastal flood inundation is reliant on high resolution topographical data. In this study, available LIDAR DEMs enabled accurate mapping of ESL1 for higher sea-level scenarios in +0.1 m increments up to 3 m above present-day. Region-wide LIDAR DEM coverage for coastlines was only available for Auckland, Bay of Plenty, Wellington and Nelson. No LIDAR DEM was available for the West Coast while coverage in other regions was often limited to coastal towns or cities. On low-lying coastal land without LIDAR coverage, a lower resolution satellite derived DEM limited coastal flood mapping within a 3 m elevation above ESL1. In future, complete national assessments will require LIDAR DEM coverage for the entire New Zealand coastline to accurately map coastal flood exposure in response to higher +0.1 m sea-level scenarios.

"Bathtub" mapping interpolates extreme sea-levels onto land until a corresponding land elevation is reached. Extreme sea-levels were estimated and mapped onto land for 20 km segments around the entire New Zealand coastline. Storm-tide and wave set-up constituents of storm driven extreme sea-levels can be highly variable along coastlines. Higher or lower levels than those estimated for this study may occur over shorter distance due to storm conditions or changing coastline morphology. The influence of these factors on local coastal flooding should be investigated through use of dynamic models, particularly for low-lying coastal towns and cities with high population and built asset exposure.

Coastal flooding maps in this study supported individual object identification on land at risk to inundation. Objects including built assets (e.g. buildings, roads, pipelines etc.), land cover types and population associated with residential building types were accurately mapped for each extreme sea-level scenario. Mapping at this scale is reliant on recent and available data on objects at risk. Attribute information for mapped objects was limited for this study, restricting reporting of exposure to object geometries e.g. road length, production land area. For highly exposed locations such as Christchurch City, Napier City and Dunedin City, accurate information on object attributes in combination with dynamic models will support the development of high resolution exposure or impact assessments for objects exposed to coastal flooding at present-day sea-levels or future higher sea levels.

4.1.2 Coastal flooding exposure under future sea-level rise

Policies 24 and 25 of the New Zealand Coastal Policy Statement (NZCPS) direct central and local government to identify coastal hazards and to avoid increasing risk from those hazards over at least the next 100 years.

Recent coastal hazard and climate change guidance (MfE 2017) provides four projected future SLR scenarios for New Zealand beyond 2120 (Figure 4-1). These scenarios represent three greenhouse gas concentration pathways (RCP2.6, RCP4.5 and RCP8.5). Three scenarios represent median projections of global SLR for regional climate projection (RCPs) presented by IPCC in their Fifth Assessment Report (Church et al. 2013). The fourth and highest projected SLR represents the upper-end of the "likely range" (i.e., 83rd-percentile) from an ensemble of SLR projections under emission scenario RCP8.5 (Kopp et al. (2014). MfE (2017) described this scenario as 'H^{+}'. In addition, MfE (2017) applied a New Zealand regional SLR adjustment to each global SLR projection and extrapolated each SLR scenario to 2150.

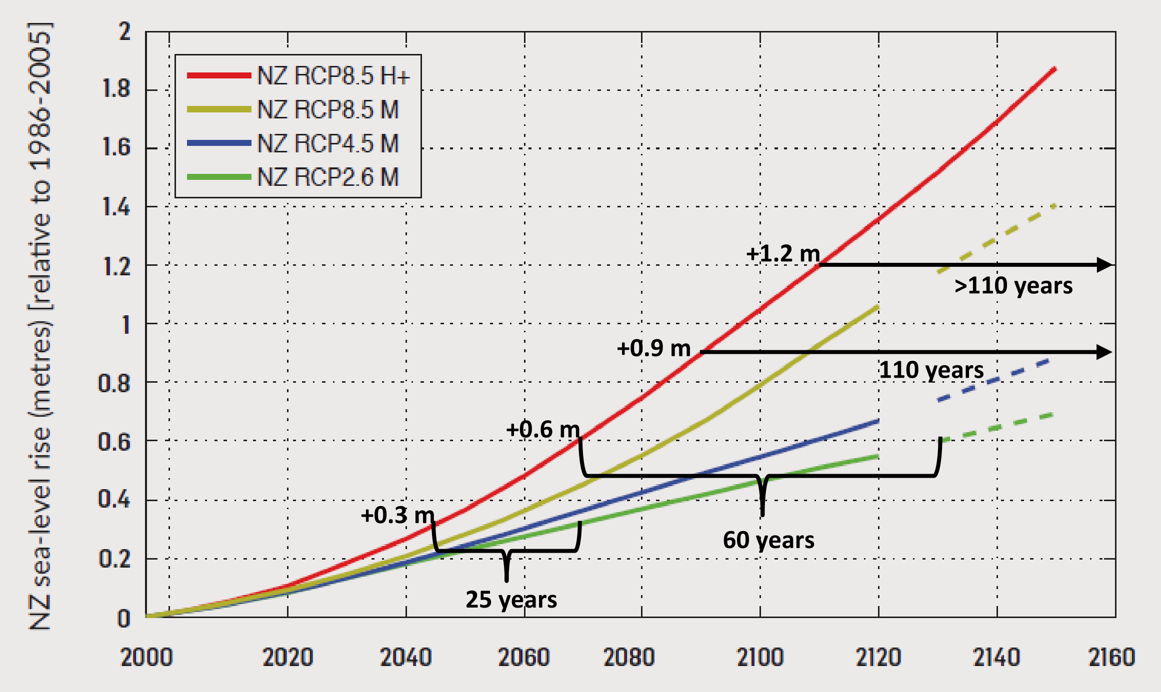

Figure 4-1: New Zealand median (M) scenario trajectories out to 2120, and high (H+) scenario trajectory out to 2150 (Kopp et al. 2014). Extrapolation of median projections is presented as dashed lines from 2130 to 2150. Projected sea level year ranges for +0.3 m, +0.6 m, +0.9 m and +1.2 m are presented for all four scenarios. Note: scenarios include a small SLR (SLR) offset from the global mean SLR for the regional sea around New Zealand (adapted from Figure 27 in MfE, 2017).

The four projected SLR scenarios for New Zealand region lie close together over the next 30 years (Figure 4-1). Beyond this timeframe, projected SLR rates for each scenario are variable, causing large uncertainty on the timing of when higher sea levels will occur over the next 100 years and beyond. MfE (2017) reports indicative timeframes for when higher sea levels could be reached for each SLR scenario (Table 4-1). Projected SLR for each RCP scenarios suggest a +0.3 m SLR (relative to 1986 to 2005 MSL), could be reached sometime within a 25-year period between 2045 and 2070. This period extends to 60 years (2070–2130) for a +0.6 m SLR. SLR over the next 100 years and beyond is deeply uncertain. In 2045, 0.2–0.3 m SLR is expected in response to RCP2.6 M and RCP8.5 H^{+} however, by 2120 the SLR difference between scenarios could vary by +0.8 m (0.55–1.36 m). Deep uncertainty in projection of SLR by 2120 and beyond, requires coastal flood assessments to map the inundation response to SLR for high resolution sea level increments (e.g. +0.1 m) to interpolate maps to higher future sea-level conditions.

ESL1 and SLR maps provide plausible scenarios of future coastal flooding exposure. Deep uncertainty of future SLR means these scenarios do not represent a specific future year but are indicative of a timeframe projected SLR in the New Zealand region may reach under four RCP scenarios (MfE, 2017). For instance, Christchurch City has 10,726 buildings and 192 km of roads exposed to coastal flooding at ESL1 +0.3 m SLR. This SLR as represented in all four RCP scenarios could be reached between 2045–2070 (MfE, 2017). Alternatively, in 2070 sea-levels could range between +0.3 m (2.6 M) and +0.6 m (8.5 H+) above present-day MSL. At ESL1 +0.6 m SLR under RCP 8.5 H+, 16,320 buildings and 245 km road could be exposed in Christchurch City. ESL1 and SLR coastal flooding maps help identify potential timeframes and uncertainty that elements at risk to higher sea levels projected in the New Zealand region under RCP scenarios (MfE, 2017).

Table 4-1: Approximate years, from possible earliest to latest, when specific SLR increments (metres above 1986–2005 baseline) could be reached for projected SLR scenarios in the New Zealand region (adapted from Table 11 from MfE, 2017).

SLR (m)	Year Achieved for RCP8.5H (83%ile)	Year Achieved for RCP8.5H (50%ile)	Year Achieved for RCP4.5 (50%ile)	Year Achieved for RCP2.6 (50%ile)
0.3	2045	2050	2060	2070
0.4	2055	2065	2075	2090
0.5	2060	2075	2090	2110
0.6	2070	2085	2110	2130
0.7	2075	2090	2125	2155
0.8	2085	2100	2140	2175
0.9	2090	2110	2155	2200
1	2100	2115	2170	>2200
1.2	2110	2130	2200	>2200
1.5	2130	2160	>2200	>2200

Extreme sea-levels and their frequency can be identified from sea-level records. Large and infrequent extreme sea-levels will become more frequent as sea-level rises. Stephens et al. (2014) demonstrate how SLR changes the frequency of present-day 1% AEP storm-tide levels in Auckland region. Expected annual exceedances for this storm-tide level increases from once every one-hundred years to once every two years with +0.3 m SLR. The level is then exceeded 9 times per-year with +0.6 m SLR and 292 times per-year with +1 m SLR (Figure 4-2). In Auckland, 1,790 buildings, including 1,349 residential, are exposed to present-day 1% AEP extreme sea-levels. An large increase to the number of extreme sea-level annual exceedances in response to SLR would imply many of these buildings would become uninhabitable, or require additional adaptation measures to remain serviceable. In other regions or territories, sea-level records can be similarly used to identify potential changes to extreme sea-level annual recurrence and subsequent exposure to coastal flooding.

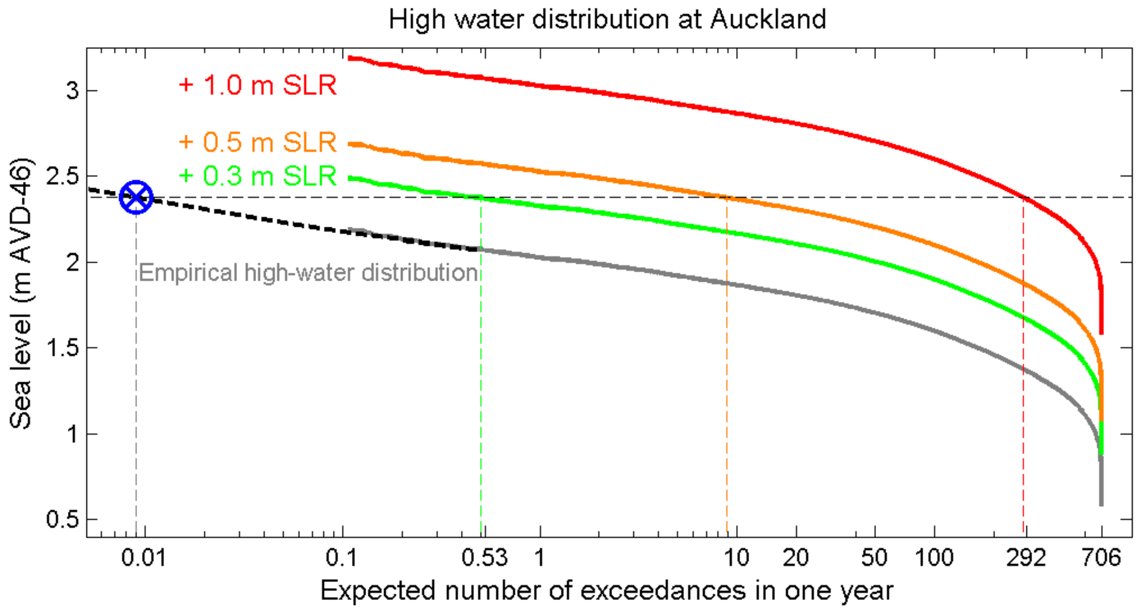

Figure 4-2: High-water distribution at Auckland plotted in terms of the expected number of exceedances in one year (Stephens et al. 2014). ⊗ marks the position of the 23 January 2011 storm tide (the highest on record) on the present-day extreme sea-level distribution curve plotted relative to AVD–46. The empirical curves have been truncated at AEP = 0.1 (10-year ARI). The lower curve corresponds to present-day sea level, while the upper curves have been raised to simulate 0.3, 0.5 and 1.0 m SLR. The bold black dashed line marks the extreme sea-level distribution. The horizontal dashed line shows the present-day 0.01 AEP sea level for SLR of 0.3, 0.5 and 1.0 m. High-tide exceedances are limited to the 706 high tides per-year.

4.2 Conclusions

This report presents New Zealand's exposure to 1% annual exceedance probability (AEP) coastal flooding events under present-day and future higher sea levels.

Coastal flooding was determined from the 1% AEP extreme sea-level elevation (ESL1) at present-day mean sea-level (MSL), resulting from combination of tide, storm-surge, mean sea-level anomaly and wave setup. Coastal flood inundation was mapped for low-lying coastal land by projecting ESL1 onto both high-resolution airborne LIDAR and a lower resolution satellite derived MERIT digital elevation models (DEM). On land with LIDAR DEM coverage, inundation from ESL1 is mapped for +0.1 m sea-level rise (SLR) increments up to +3 m above present-day MSL. On land without LIDAR DEM coverage, inundation is only mapped for +3 m SLR above present-day MSL using the satellite derived DEM. A composite LIDAR and satellite DEM with complete national coverage was used to map land exposed to ESL1 +3 m SLR around the entire New Zealand coastline.

Elements at risk identified on land exposed to each coastal flood inundation scenario included: population, buildings (count and 2016 NZD replacement value), transport infrastructure (roads, railways, airports), electricity infrastructure (transmission lines, structures, sites), three-waters infrastructure (nodes, pipelines), and land cover (built, production, natural or undeveloped). These elements only provided a representative sample of built assets and land cover types exposed within New Zealand's coastal floodplains.

At a national level, elements at risk are subject to a linear ESL1 exposure increase in response to rising sea levels. At region and territory levels, element exposure exhibits non-linear behaviours, with acceleration or deceleration in response to increasing SLR increments and the characteristics of elements at risk in these areas.

Population and built asset exposure in some regions and territories with major coastal urban areas, elements at risk experience an early (low SLR) acceleration of ESL1 exposure with SLR. Population and built asset exposure in Hawkes Bay (i.e. Napier City), Wellington (i.e. Lower Hutt City) and Canterbury (i.e. Christchurch City) accelerates rapidly to +0.9 m SLR above present-day MSL, before decelerating under higher SLR thereafter. In other populous regions (e.g. Auckland, Waikato, Bay of Plenty), population and built asset exposure increases at an approximately constant rate in response to SLR. These trends can signal both the spatial and temporal onset of increasing coastal flood inundation exposure in response to New Zealand region SLR scenarios projected for median and high greenhouse gas concentration pathways.

Coastal flood inundation mapping for +0.1 m SLR increments above present-day MSL enabled the magnitude of element exposure to ESL1 to be estimated at region and territory levels, and temporal onset of this exposure in response to projected New Zealand region SLR trajectories. Future rising sea-levels will increase the frequency of ESL1 at present-day MSL. Elements at risk to these extreme sea-levels in-turn could be more frequently exposed to coastal flood inundation. This information provides researchers and practitioners with locations to focus more detailed investigation on potential coastal flood impacts and management implications in response to future sea-level rise.

Finally, it is recommended that the coastal flood inundation maps and element at risk exposure information produced in this study should be updated as new LiDAR data is made available.

5 Acknowledgements

The study was funded by the Deep South Challenge (MBIE CONTRACT NUMBER: C01X1412). The provision of LIDAR datasets (point cloud files or DEMs and metadata) either through LINZ or directly from the relevant local authority is gratefully acknowledged as follows:

- Northland Regional Council
- Auckland Council
- Waikato Regional Council (elevation-band polygons provided directly)
- BOPLASS Ltd. (covering Bay of Plenty and Rotorua territorial authorities)
- Gisborne District Council
- Hawke's Bay Regional Council
- Greater Wellington Council (and Wellington City Council, Hutt City Council and Kāpiti Coast DC), with post-processing of the 2013 regional LIDAR survey by Landcare Research
- Environment Canterbury, Christchurch City Council and LINZ/CERA (post-earthquake surveys)
- Otago Regional Council and Dunedin City Council
- Nelson City Council
- Tasman District Council

The use of spatial datasets for elements at risk developed by the following agencies is gratefully acknowledged:

- Landcare Research: Land-Cover Database v4.1,
- LINZ: NZ Railways and NZ Airports,
- New Zealand Transport Agency: NZ Roads, and
- New Zealand Territorial and Unitary Authorities: NZ Three-waters;
  - Far North District
  - Whangarei District
  - Kaipara District
  - Thames-Coromandel District
  - Hauraki District
  - Waikato District
  - Matamata-Piako District
  - Otorohanga District

- Waitomo District
- Western Bay of Plenty District
- Tauranga City
- Whakatane District
- Opotiki District
- Gisborne District
- Wairoa District
- Hastings District
- Napier City
- Central Hawke's Bay District
- New Plymouth District
- South Taranaki District
- Whanganui District
- Rangitikei District
- Manawatu District
- Tararua District
- Horowhenua District
- Kapiti Coast District
- Porirua City
- Lower Hutt City
- Wellington City
- Masterton District
- Carterton District
- South Wairarapa District
- Tasman District
- Nelson City
- Marlborough District
- Kaikoura District
- Hurunui District

- Waimakariri District
- Christchurch City
- Selwyn District
- Ashburton District
- Timaru District
- Waimate District
- Waitaki District
- Dunedin City
- Clutha District
- Southland District
- Invercargill City
- Auckland

6 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.
Built Asset	Physical structures as part of the built environment e.g. buildings, infrastructure (e.g. roads, railways, electricity transmission lines etc.).
Coastal inundation	Coastal inundation occurs when normally dry, low-lying land is flooded by seawater.
Deep uncertainty	Deep uncertainty exists when parties to a decision do not know, or cannot agree on, the system model that relates action to consequences, the probability distributions to place over the inputs to these models, which consequences to consider and their relative importance.
DEM	Digital elevation model
ESL1	Estimated 1% AEP extreme sea-level elevation at present-day MSL, resulting from combination of tide, storm-surge, mean sea-level anomaly and wave setup
Exposure	Population, built asset and land cover features located within spatially mapped coastal inundation extents.
GIS	Geographic information system.
Land Cover	The physical condition or state of the land surface.
LIDAR	Airborne Light Detection and Ranging (LIDAR), is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth.
MERIT	Satellite derived Multi-Error-Removed Improved-Terrain DEM.
Meshblock	A meshblock is both a geographic unit and a classification. It is the smallest geographic unit for which statistical data is reported by Stats NZ. A meshblock is a defined geographic area, varying in size from part of a city block to large areas of rural land. Meshblocks are contiguous: each meshblock borders on another to form a network covering all of New Zealand, including coasts and inlets. The meshblock classification extends out to New Zealand's 200 mile exclusive economic zone (EEZ).
MHWS	Mean high-water springs.
MHWS-10	MHWS-10 is the level 10% of high waters 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 ENSO and IPO patterns on sea level, winds and sea temperatures, and seasonal effects.
Object-scale	Object-scale refers to the spatial location and attributes of individual elements such as buildings, infrastructure components (e.g. roads, railway etc.) etc.
Population	The census usually resident population count of an area in New Zealand is a count of all people enumerated by census, who usually live in that area, and were present in New Zealand on census night. For example, a Christchurch city resident visiting Wellington city on census night is included in the census usually resident population count of Christchurch city.
Present-day MSL	The best estimate of mean sea level for a region at time of writing, relative to local vertical datum.
RESTful	RESTful web service based on representational state transfer (REST) technology, an architectural style and approach to communications often used in web services development.
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 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 + tide + storm surge. In New Zealand this is generally reached around high tide.
Zero baseline	The minimum land elevation to include in the coastal flood hazard inundation mapping. MHWS was used as a zero baseline for inundation mapping, i.e. all land above the zero baseline (MHWS) level was included in the inundation and element at risk exposure mapping.

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Appendix A MHWS-10 heights around New Zealand

The following Figures show the MHWS-10 heights at nearly 290 coastal sites around New Zealand (some are omitted for clarity), where MHWS-10 values were used as the zero baseline coastal flood inundation mapping. These values are produced from the NIWA EEZ tide model and adjusted where required to match with local gauge measurements. Tide gauge data was used for large estuaries or harbours like Waitemata, Manukau and Kaipara Harbours. ın smaller ungauged estuaries a scaling factor of 1.1 × MHWS-10 outside the estuary was used. This approximation accounts for the observation from gauged estuaries (Stephens et al. 2016) that the tide usually amplifies inside NZ estuaries.

The MHWS-10 datum is set to local MSL=0, but a present-day MSL offset was applied for each region (Appendix B) to relate the MHWS-10 heights to the same datum used for corresponding LIDAR DEMs.

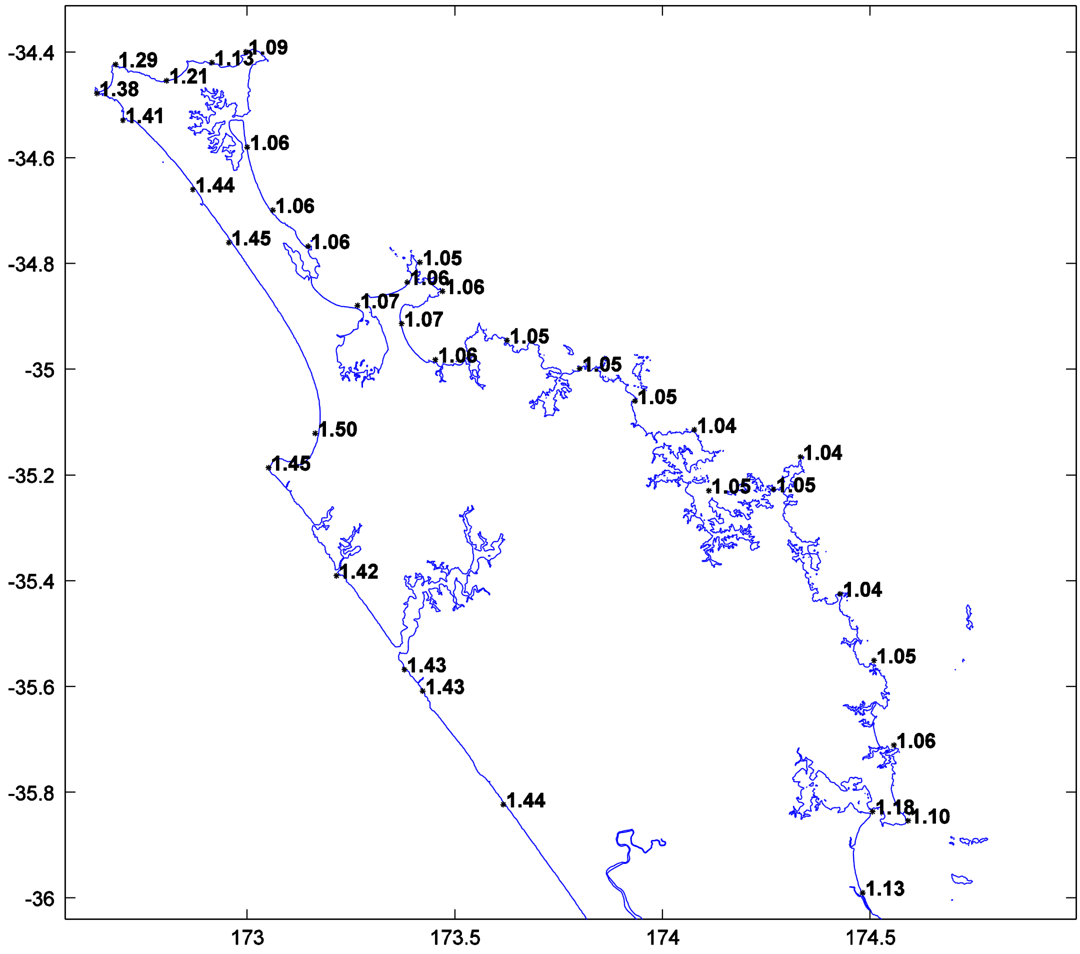

Figure A-1: MHWS-10 heights (relative to MSL=0) for Northland. Source: NIWA EEZ tide model, on latitude/longitude coordinate system.

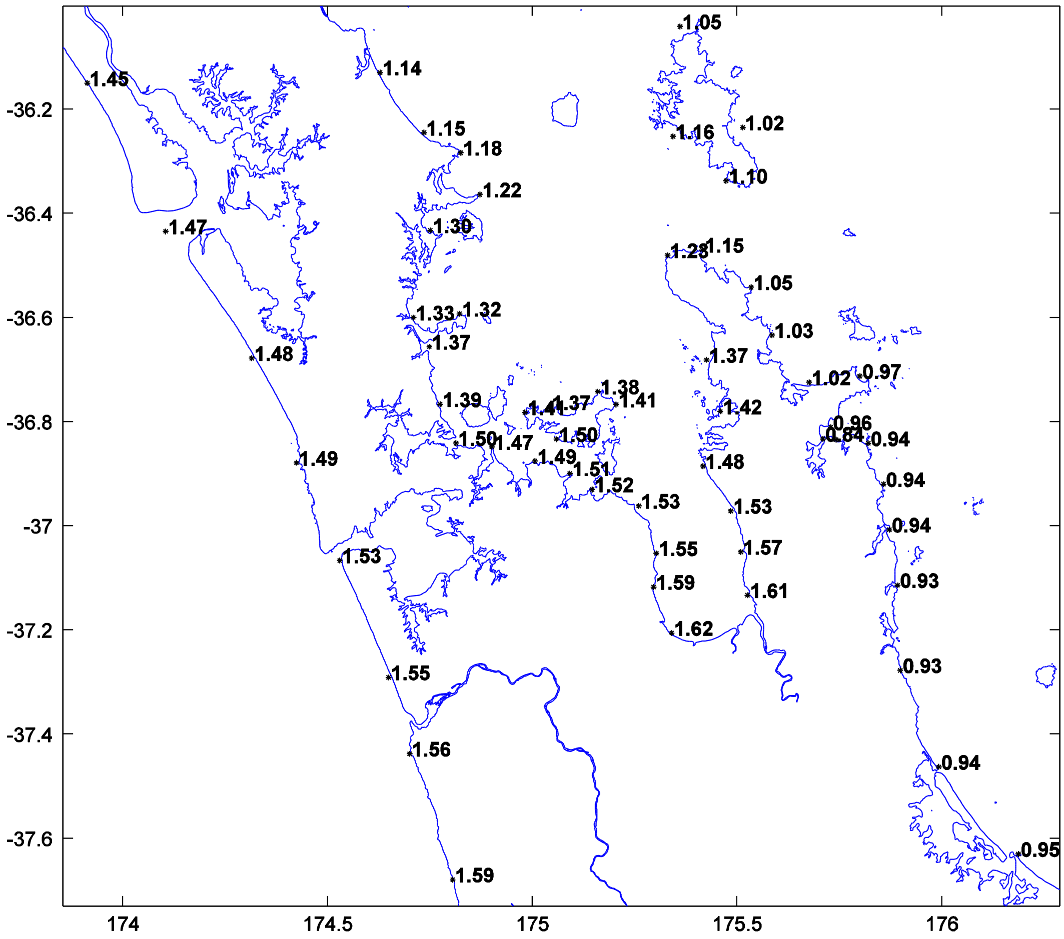

Figure A-2: MHWS-10 heights (relative to MSL=0) for Auckland and Waikato. Source: NIWA EEZ tide model, on latitude/longitude coordinate system.

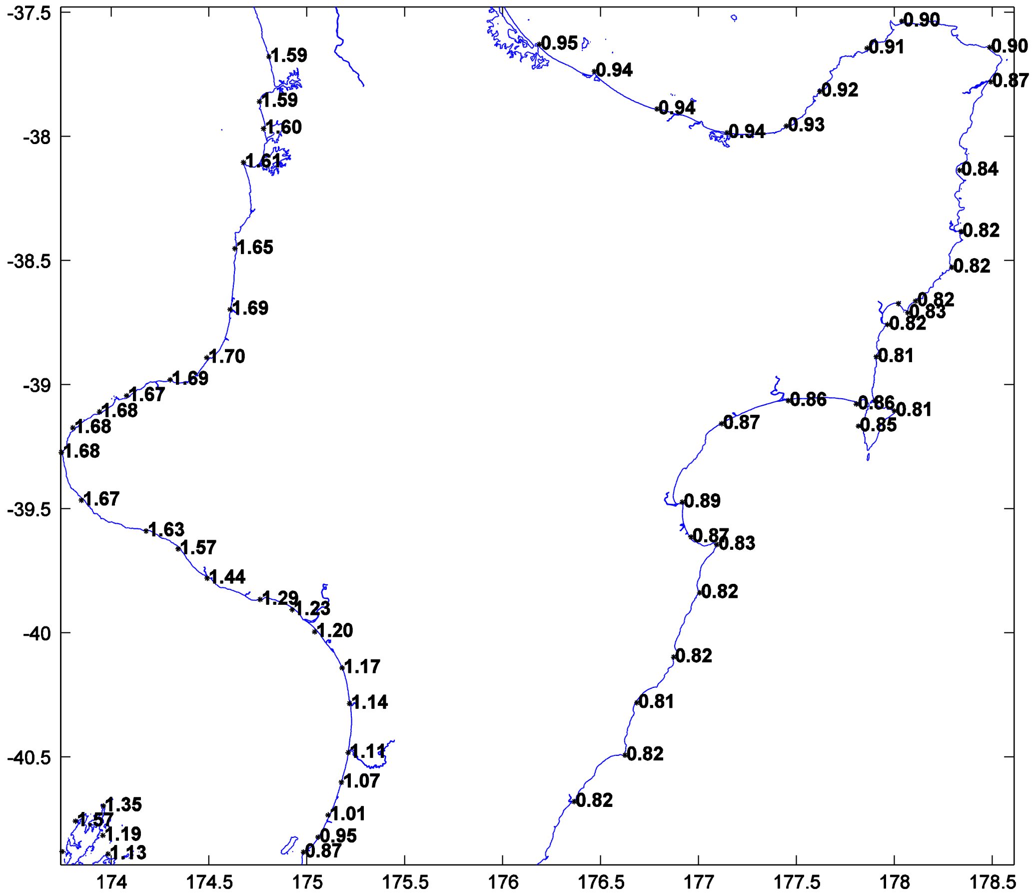

Figure A-3: MHWS-10 heights (relative to MSL=0) for Lower North Island. Source: NIWA EEZ tide model.

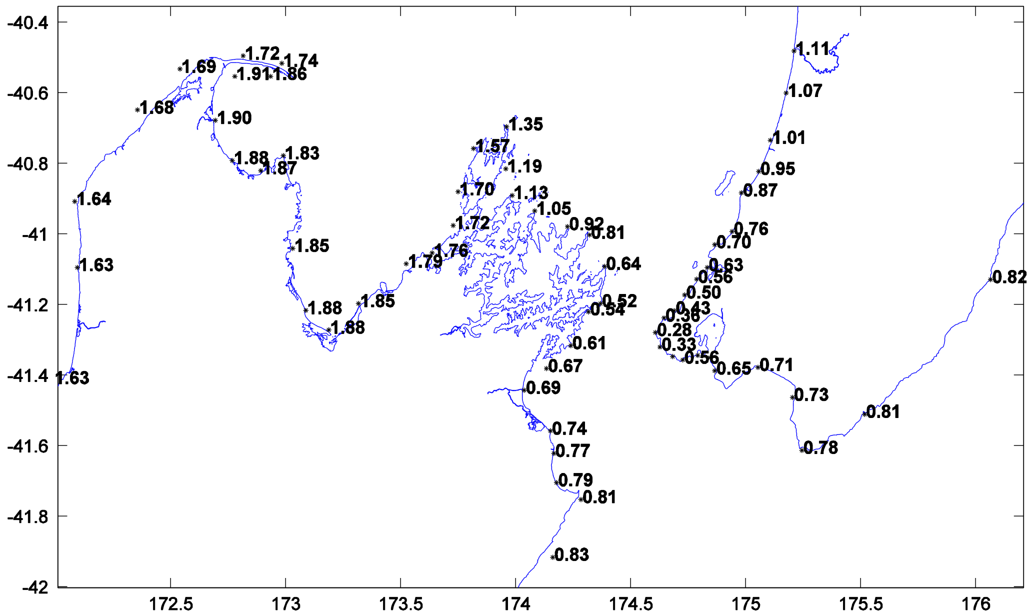

Figure A-4: MHWS-10 heights (relative to MSL=0) for Greater Cook Strait area. Source: NIWA EEZ tide model, on latitude/longitude coordinate system.

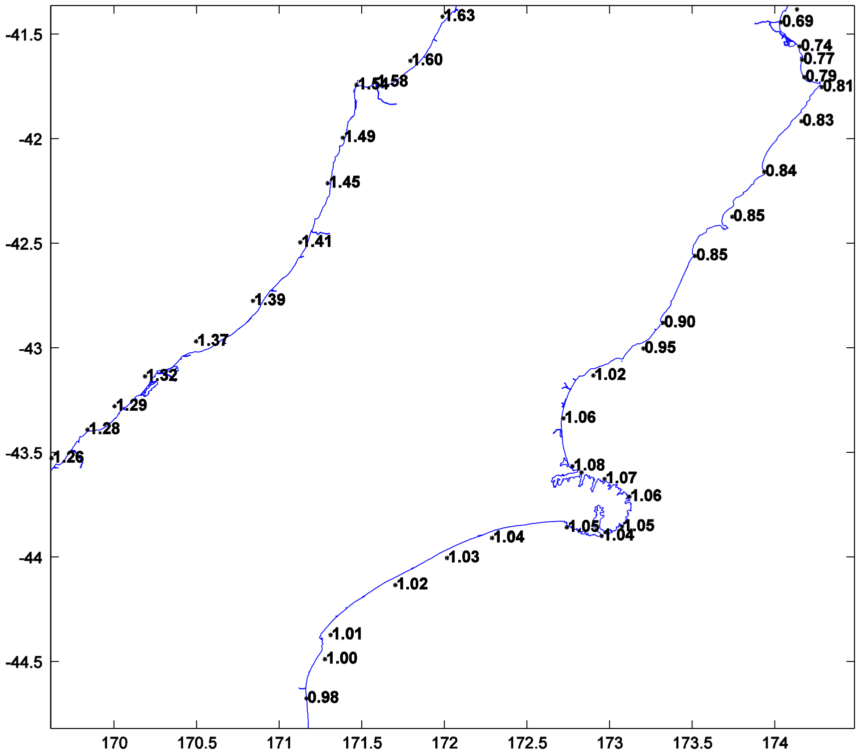

Figure A-5: MHWS-10 heights (relative to MSL=0) for Central South Island. Source: NIWA EEZ tide model, on latitude/longitude coordinate system.

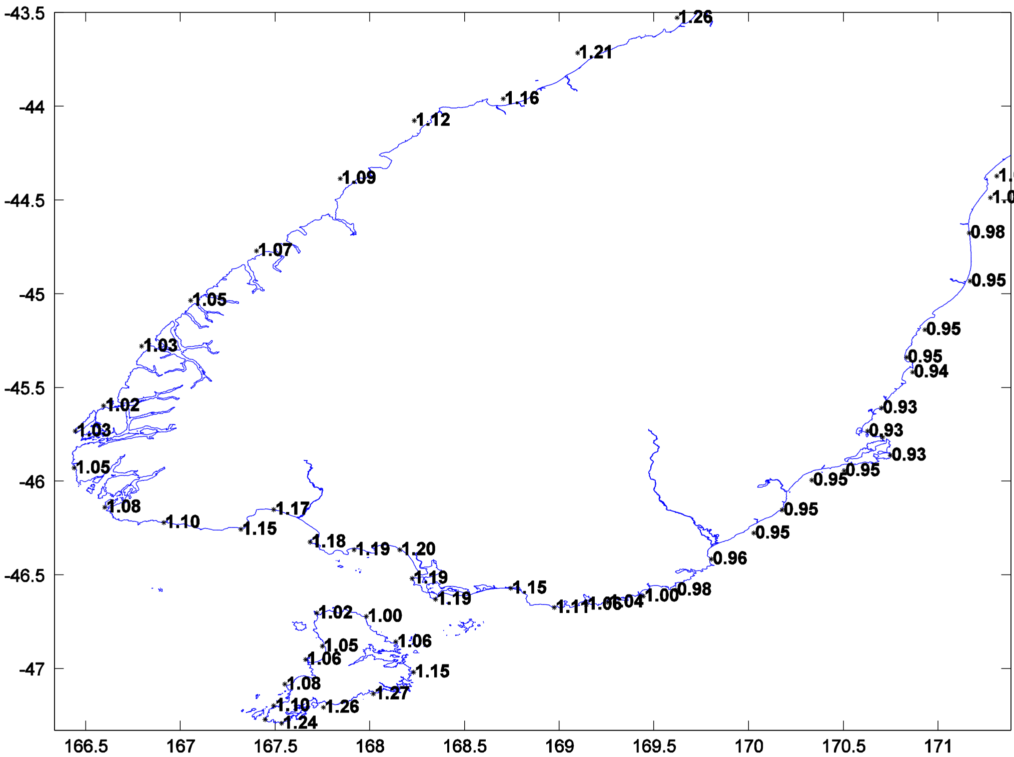

Figure A-6: MHWS-10 heights (relative to MSL=0) for Southland & Otago. Source: NIWA EEZ tide model, on latitude/longitude coordinate system.

Appendix B Local MSL offsets

Local MSL offsets were applied to the MHWS-10 heights to convert to the local vertical datum (LVD) used for the relevant LIDAR DEM supplied (Table B-1). These offsets are required as MSL has risen since the years for which data was used to derive the local vertical datum. The MSL offsets were calculated from recent epochs mostly covering between 7–8 years up to the 18-year nodal-tide cycle from available sea-level gauge records, derived from Standard Port levels for MSL in the Nautical Almanac (LINZ, 2015) or interpolated where needed (in absence of gauge data).

Table B-1: Estimated MSL offsets for various coastal regions relative to the relevant local vertical datum. Notes: i) these offsets are estimates at one location in the wider "coastal region" from a variety of gauge record lengths and LINZ Standard Port MSL values - *offsets not intended to be used locally for engineering design or cadastral purposes*; ii) offsets for Northland sites are mostly negative as One Tree Point datum is currently higher than present-day MSL.

Coastal region	Local Vertical Datum	MSL offset (m)	Notes (or epoch)
Dargaville (Northland)	One Tree Pt (1964)	0.27	Hoods Landing vs Anawhata
Open west coast (Northland)	One Tree Pt (1964)	-0.11	Assumed same as east coast
Northland- open east coast	One Tree Pt (1964)	-0.11	Marsden Pt (2004-12)
Whangarei - Northland	One Tree Pt (1964)	-0.08	Whangarei (1999-2006)
Marsden Pt - Northland	One Tree Pt (1964)	-0.11	Marsden Pt (2004-12)
Opua - Bay of Islands (Northland)	One Tree Pt (1964)	-0.09	0.01 m less than Whangarei
Auckland - east coast	Auckland (1946)	0.15	Auckland (1999-2008)
Auckland - west coast (Onehunga)	Auckland (1946)	0.22	Onehunga (2001-2013)
Auckland -west open coast	Auckland (1946)	0.16	Table 2.2 (Stephens et al. 2013)
Coromandel- east open coast	Moturiki (1953)	0.10	Based on Moturiki gauge
Whitianga Harbour	Moturiki (1953)	0.05	0.05 m lower (Wharf gauge)
Inner Firth of Thames - Tararu	Moturiki (1953)	0.22	Tararu gauge (1998-2014)
Outer Firth of Thames, Coromandel town	Moturiki (1953)	0.18	Interpolated: Moturiki-Auckland
Moturiki - all of Bay of Plenty	Moturiki (1953)	0.10	Moturiki gauge (1998-2014)
Waikato - west coast	Moturiki (1953)	0.06	MSL: Port Taranaki, Manukau Harbour Entrance
Waikato - Kawhia/Raglan Harbours	Moturiki (1953)	0.06	Same value as Taranaki, needs longer gauge record
New Plymouth - Taranaki	Taranaki (1970)	0.14	Port Taranaki (1995-2013)
Gisborne - East Cape	Gisborne (1926)	0.22	Gisborne (2004-2013)
Napier – Hawke's Bay	Napier (1962)	0.03	Napier (1999-2013)
Wairarapa Coast- Wellington region	Wellington 1953)	0.24	Interpolated: Napier-Wellington
Wellington	Wellington (1953)	0.19	Wellington (1995-2013)
Kāpiti Coast - Wellington region	Wellington (1953)	0.21	Interpolated: Taranaki-Wellington
Nelson-Tasman region	Nelson (1955)	0.08	Nelson (1999-2008)
Picton	Nelson (1955)	0.01	Picton (2005-2008)
Kaikoura - Canterbury region	Lyttleton (1937)	0.15	Same as Lyttleton
Lyttleton - Christchurch area	Lyttleton (1937)	0.15	Lyttleton (1999-2008)
Timaru	Lyttleton (1937)	0.15	Timaru (2002-2008)
Dunedin	Dunedin (1958)	0.11	Dunedin (1999-2013)
Port Chalmers	Dunedin (1958)	0.10	Port Chalmers (2000-2013)
Oamaru- North Otago	Dunedin (1958)	0.13	Interpolated: Timaru-Otago
Open Otago coast - Green Island	Dunedin (1958)	0.09	0.01 m lower than Port Chalmers
Bluff	Bluff (1955)	0.12	Bluff (1998-2013)

Appendix C Digital Appendix Contents

Coastal Flood Inundation Exposure for Elements at Risk

Please contact the report author or NIWA for any of the following files or information:

- Folder: 2016 Regional Council and Territorial Authority Boundaries
- Folder: Buildings
  - Buildings_COUNT_REGC2016.csv
  - Buildings_COUNT_TA2016.csv
  - Buildings_REPLACEMENT_REGC2016.csv
  - Buildings_REPLACEMENT_TA2016.csv
- Folder: Electricity
  - Translines_REGC2016.csv
  - Translines_TA2016.csv
  - Sites_REGC2016.csv
  - Sites_TA2016.csv
  - Structures_REGC2016.csv
  - Structures_TA2016.csv
- Folder: Land Cover
  - Built_REGC2016.csv
  - Built _TA2016.csv
  - Production_REGC2016.csv
  - Production _TA2016.csv
  - Natural_Undeveloped_REGC2016.csv
  - Natural_Undeveloped_TA2016.csv
- Folder: Population
  - Population_REGC2016.csv
  - Population_TA2016.csv
- Folder: Three-Waters
  - Nodes_REGC2016.csv

    - Nodes_TA2016.csv
    - Pipes_REGC2016.csv
    - Pipes_TA2016.csv
    - SWNodes_REGC2016.csv
    - SWNodes_TA2016.csv
    - SWPipes_REGC2016.csv
    - SWPipes_TA2016.csv
    - WNodes_REGC2016.csv
    - WNodes_TA2016.csv
    - WPipes_REGC2016.csv
    - WPipes_TA2016.csv
    - WWNodes_REGC2016.csv
    - WWNodes_TA2016.csv
    - WWPipes_REGC2016.csv
    - WWPipes_TA2016.csv
- Folder: Transport
    - Airports_REGC2016.csv
    - Airports_TA2016.csv
    - Railway_REGC2016.csv
    - Railway_TA2016.csv
    - Roads_REGC2016.csv
    - Roads_Undeveloped_TA2016.csv