REPORT

Christchurch City Council

Effects of Sea Level Rise for Christchurch City

Tonkin & Taylor

ENVIRONMENTAL AND ENGINEERING CONSULTANTS

REPORT

Christchurch City Council

Effects of Sea Level Rise for Christchurch City

Report prepared for:

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Tonkin & Taylor Ltd

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Executive summary

Christchurch City Council commissioned Tonkin & Taylor Ltd to undertake an assessment of sea level rise effects on the Christchurch City Council area. The purpose of the assessment is to update information contained in the 1999 T&T report titled: *Study of the effects of Sea Level rise for Christchurch* ("T&T original report"). The updated sea level rise assessment is intended to follow a similar methodology as the T&T original report for consistency and includes the following scope of works:

- undertake a sea level rise literature review
  - source relevant information from 1999 to 2012 focussed on sea level rise impacts and mitigation measures
  - review gaps in knowledge and uncertainties outlined in the original review and identify any additional items
  - produce an electronic database of the literature review references including metadata attributes for advanced searching
- provide an assessment of the effects of land movement due to earthquakes on coastal processes
- provide an assessment of impacts of sea level rise
  - undertake site visit to validate desk top assessments
  - identify possible shoreline retreat and inundation for open coast soft shore and dune areas based on a single 100 year sea level rise scenario to the year 2115
  - identify impacts on water level, salinity, sedimentation, bank stability, drainage and ecosystems for estuarine and river areas based on a single 100 year sea level rise scenario to the year 2115
- identify possible mitigation solutions for the potential impacts of sea level rise.

An electronic literature review database has been developed, which is based on the same structure as the Excel spreadsheet database provided as part of the T&T original report. A total of 324 references were reviewed and stored in the updated literature database, which is issued separately to this report.

The review of both global and national literature on sea level rise impacts and responses outlined in the T&T original report (T&T, 1999) remain valid. However, the advancement in our understanding of climate change suggests that sea level rise projections are likely to be higher than previous projections. For the purposes of this report, a future sea level projection of 1.0 m by 2015 is used, which is generally in line with the current state of knowledge presented in the MfE guidelines (2008).

Many of the uncertainties associated with sea level rise projections and climate change identified in the T&T original report remain valid today. The melting rate of the Greenland and West Antarctic ice sheets is probably the largest uncertainty in sea level rise projections at this time. Although we now understand the melting of the Greenland and West Antarctic ice sheets will become a dominant component of the sea level rise projections over the twenty first century, the rate of increase of movement and melting is still an unknown factor.

The Christchurch area has been affected by a large number of earthquakes following the initial Darfield Earthquake on 4 September, 2010. These events occurred in close proximity to the city causing extensive liquefaction, lateral spreading and vertical displacement of land surfaces. Comparison of pre and post earthquake ground levels show the northern part of the estuary where the Avon River discharges has subsided by 0.2 to 0.5 m and the southern part of the estuary including near the estuary mouth and the Heathcote River has risen by 0.3 to 0.5 m. These changes have resulted in an increase of dry estuary area at mid tide of approximately 50 hectares or 18% of the total dry estuary area. The reduction in the tidal prism has been estimated at approximately 1 million m^3 or 14%. We recommend monitoring changes to the South Brighton spit and Sumner Bar over time using aerial or oblique photographs, as changes to the tidal prism is likely to result in some change to the ebb-delta regime and surrounding beaches.

The greatest impact of sea level rise on Christchurch City will be the increased risk of storm inundation associated with the greater frequency of extreme tidal levels. The other main impact of sea level rise is the progressive shoreline retreat of low lying areas.

The Christchurch City Council has developed a number of planning responses within the Christchurch City District Plan to reduce the risk of sea level rise, including a policy to restrict development in Flood Management Areas (FMA). We recommend undertaking a review of both the FMA extent and the associated minimum floor levels once the IPCC Fifth Assessment Report is released. Based on the sea level rise projection adopted in this report, the minimum floor level would need to be increased by 0.5 m to 12.3 m (CCC datum) to allow for a sea level rise of 1.0 m to the year 2115. Furthermore, allowing for a sea level rise of 1.0 m within the existing 11.8 m minimum floor level, reduces the allowance for storm surge to approximately a 2% AEP event.

Protection responses to mitigate the impacts of sea level rise may be considered acceptable in some areas and could range from seawalls and flood walls to raising property and infrastructure. Many of the existing coastal protection structures will most likely require further upgrade works to ensure adequate protection from sea level rise.

We recommend the CCC develop a Christchurch City wide Sea Level Rise Adaptation Strategy. The Strategy should ideally be produced in close consultation with all stakeholders including the local community and provide specific local plans to increase the communities resilience to sea level rise.

1 Introduction

1.1 Background

Christchurch City Council (CCC) commissioned Tonkin & Taylor Ltd (T&T) to undertake an assessment of sea level rise effects on the Christchurch City Council area. The purpose of the assessment is to update information contained in the 1999 T&T report titled: *Study of the effects of Sea Level rise for Christchurch* ("T&T original report"). The three objectives of the T&T original report were to:

- gain a comprehensive overview, based on current knowledge of potential effects of sea level rise on the city of Christchurch, including an understanding of the likelihood and severity of these effects and their probable timing
- establish where gaps in the knowledge exist and to gain an understanding of the significance of these gaps
- provide a "best guess" of potential effects, their probability and significance, and suggestions for mitigation.

The T&T original report focussed on five locations within the CCC boundary for assessing the potential effects of sea level rise. Since 1999 the CCC boundary has been extended to include the Banks Peninsula area. Therefore, six additional areas are also included in this updated assessment (Table 1-1). Figure 1-1 displays a location plan of the original areas and Figure 1-2 displays a location plan of the additional areas.

Table 1-1 Areas included in assessment

Original areas	Additional areas	
• Waimakariri River & Brooklands Lagoon	• Akaroa	• Takamatua
• The Christchurch Dune System	• Wainui	• Port Levy
• The Avon-Heathcote Estuary	• Duvauchelle	• Okains Bay
• The Lower Avon & Heathcote Rivers		
• The Beaches South of the Estuary		

1.2 Work scope

The updated sea level rise assessment is intended to follow a similar methodology as the T&T original report for consistency and includes the following scope of works:

- undertake a sea level rise literature review
  - source relevant information from 1999 to 2012 focussed on sea level rise impacts and mitigation measures
  - review gaps in knowledge and uncertainties outlined in the original review and identify any additional items
  - produce an electronic database of the literature review references including metadata attributes for advanced searching
- provide an assessment of the effects of land movement due to earthquakes on coastal processes
- provide an assessment of impacts of sea level rise
  - undertake site visit to validate desk top assessments

- identify possible shoreline retreat and inundation for open coast soft shore and dune areas[1] based on a single 100 year sea level rise scenario[2] to the year 2115
- identify impacts on water level, salinity, sedimentation, bank stability, drainage and ecosystems for estuarine and river areas based on a single 100 year sea level rise scenario to the year 2115

- identify possible mitigation solutions for the potential impacts of sea level rise.

1.3 Report layout

Section 2 outlines the methodology and results of the sea level rise literature review. A key result of the literature review is identifying a suitable sea level rise projection to the year 2115. The literature review electronic database is also explained in this section.

Section 3 discusses the effects of land movement due to earthquakes on coastal processes and how these effects may influence the impact of sea level rise.

Section 4 identifies the potential impacts of sea level rise for the CCC area. The methodology and results are presented for each area separately. The possible mitigation solutions for these impacts are presented in Section 5. Section 6 outlines the conclusions of the report.

The majority of figures are presented in colour and therefore this report should be printed in colour to provide for optimum figure interpretation.

[1] Open coast soft shore and dune areas refers to all wave dominated sand and gravel beach shorelines located outside of estuary systems and excludes cliff shorelines.

[2] A single sea level rise scenario has been used to assess impacts for the purposes of this report as opposed to analysing a range of possible sea level rise scenarios.

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EFFECTS OF SEA LEVEL RISE
CHRISTCHURCH
Location Plan 1

FIG. No. Figure 1– 1

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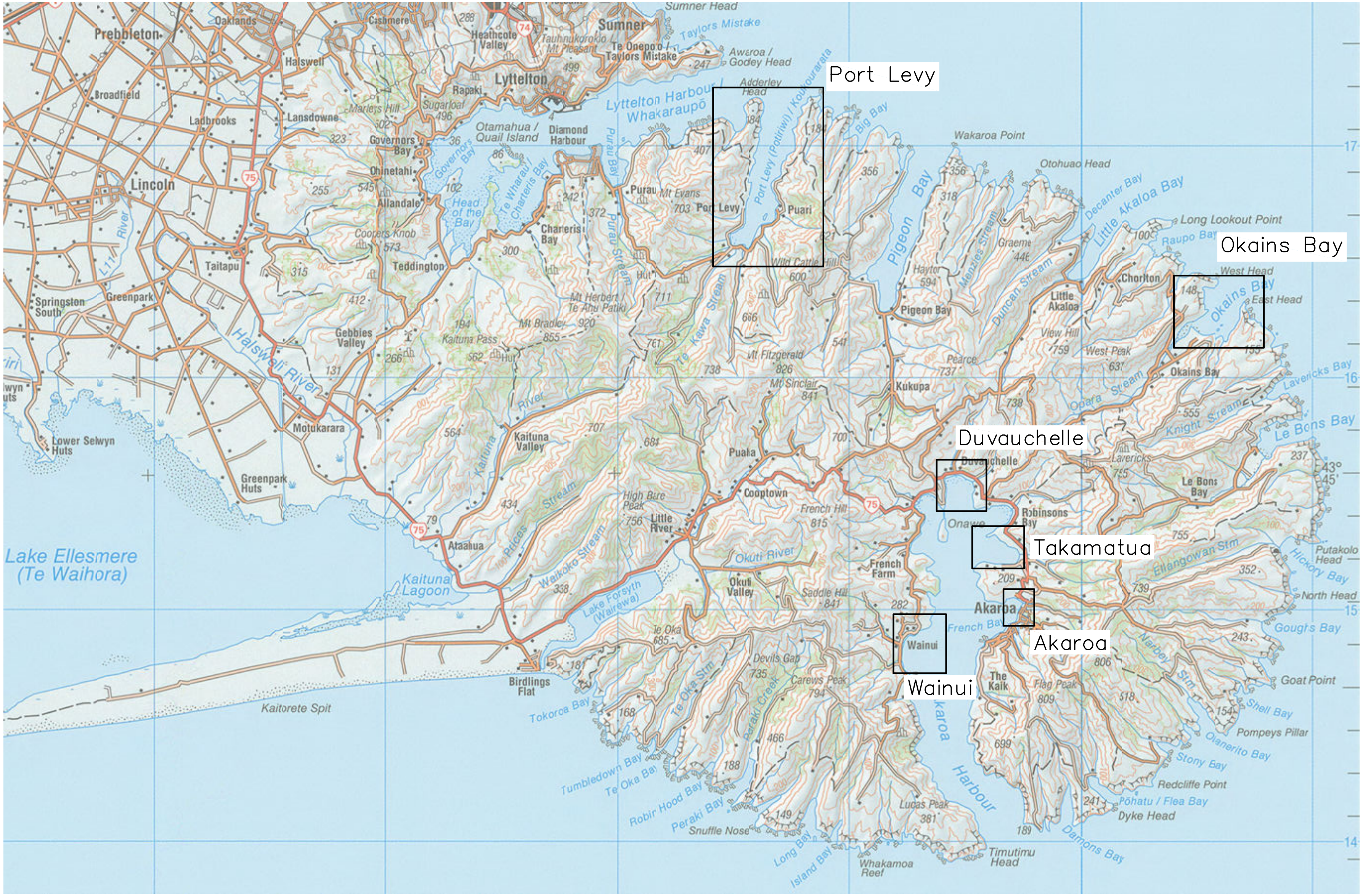

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CHRISTCHURCH CITY COUNCIL
EFFECTS OF SEA LEVEL RISE
BANKS PENINSULA
Location Plan 2

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2 Sea level rise literature review

2.1 Methodology

The literature review focused on the available information on sea level rise impacts and mitigation over the global, national and local context. Since the 1999 review, there have been various assessments and guidance documents produced which are applicable to the Christchurch area. Of note are guidance documents by the Intergovernmental Panel on Climate Change (IPCC), and the Ministry for the Environment (MfE). A summary of the literature review methodology is outlined below:

- The 2012 literature review sourced information from 1999 to October 2012 related to sea level rise and impact mitigation
- The literature review searched information related to changes in coastal process due to land movement from the 2010-2011 Canterbury earthquakes
- The literature review searched relevant available online information sources undertaken by T&T Library personal
- Literature Searches were also undertaken on existing databases from the University of Canterbury, Department of Conservation (DOC) and Environment Canterbury
- Create a literature review database.

2.2 Database

An electronic literature review database has been developed, which is based on the same structure as the Excel spreadsheet database provided as part of the T&T original report. Superseded information from the original database has been removed and all new references have been added. Each record has metadata attributes[3] selected that will allow advanced searches. Table 2-1 illustrates the metadata attributes and sub-attributes included in the updated database structure.

Table 2-1 Metadata attributes included in the sea level rise literature review database

Attribute Name	Number of sub-attributes
Marine Ecosystems and Habitats	12
Marine Species	9
Physical Data	14
Coastal and Marine Management	13
Climate Change	5
Tectonics	3

A total of 324 references were reviewed and stored in the updated literature database. The database was independently reviewed by the University of Canterbury (Dr Christopher Gomez – Natural Hazards Research Centre). The database is issued separately to this report and should be referenced as: *CCC Sea Level Rise Literature Review Database 2012.*

[3] Metadata attributes are additional information used to help describe and search data records, similar to library catalogues.

2.3 Literature review summary

The T&T original report summarised the literature review findings in two parts:

- The global perspective
- The New Zealand scene

The review of both global and national literature on sea level rise impacts and responses outlined in the T&T original report remain valid. The advancement in our understanding of both global and national climate change and sea level rise projections are detailed in this section below. The knowledge gaps and uncertainties identified in the review are presented in Section 2.4.

The Intergovernmental Panel on Climate Change (IPCC) is a leading international body for the assessment of climate change. The IPCC assess the most authoritative international science analysing global emission models in relation to future sea level projections. The IPCC produced major reports in 1990, 1996, 2001 and 2007 which outline their results including the most up to date future sea level rise projections. The T&T original report was based on the results of the Second Assessment Report (1996), which suggested a sea level rise projection of 0.49 m by the year 2100. The Fifth Assessment Report is due for publication in 2014.

The latest Fourth Assessment Report (AR4) released in 2007 did not provide a best estimate or upper bound for sea level rise because the understanding of some important effects driving sea level rise was considered to be too limited. However, the IPCC did report a range of projected global sea level rise of 0.18 to 0.59 m by the year 2100 relative to the average sea level over 1980–1999 (refer to Figure 2-1).

The IPCC (2007) range of projected sea level rise assumes that the contributions from ice flow from Greenland and Antarctica remain at the rates observed for 1993–2003. However, these rates are expected to increase in the future if global greenhouse gas emissions are not reduced (MfE, 2008). The MfE (2008) produced a summary document based on the Fourth Assessment Report to provide guidance on potential sea level rise for local government in New Zealand. The MfE (2008) guidelines suggest an extra 0.1 to 0.2 m rise in the upper ranges of the emission scenario projections would be expected if these ice sheet contributions were to grow in line with global temperature increases. This potential increase in the projected sea level range is shown in Figure 2-1 as the dark blue shaded range.

The MfE (2008) guidance report suggests using a risk management approach to responding to sea level rise and to consider a 0.5 m base value of sea level rise by 2090 relative to the 1980-1999 average sea level, with 0.1 m additional rise per decade thereafter. The MfE also recommends that the consequences of a sea level rise of 0.8 m by 2090 should be considered and recommends that scenarios above 0.8 m should also considered for planning beyond 2100 as well as for low probability / high consequence considerations. We note that the MfE guidance report may be updated to reflect the latest international science recommendations in the IPCC Fifth Assessment Report, which is due for final publication in 2014.

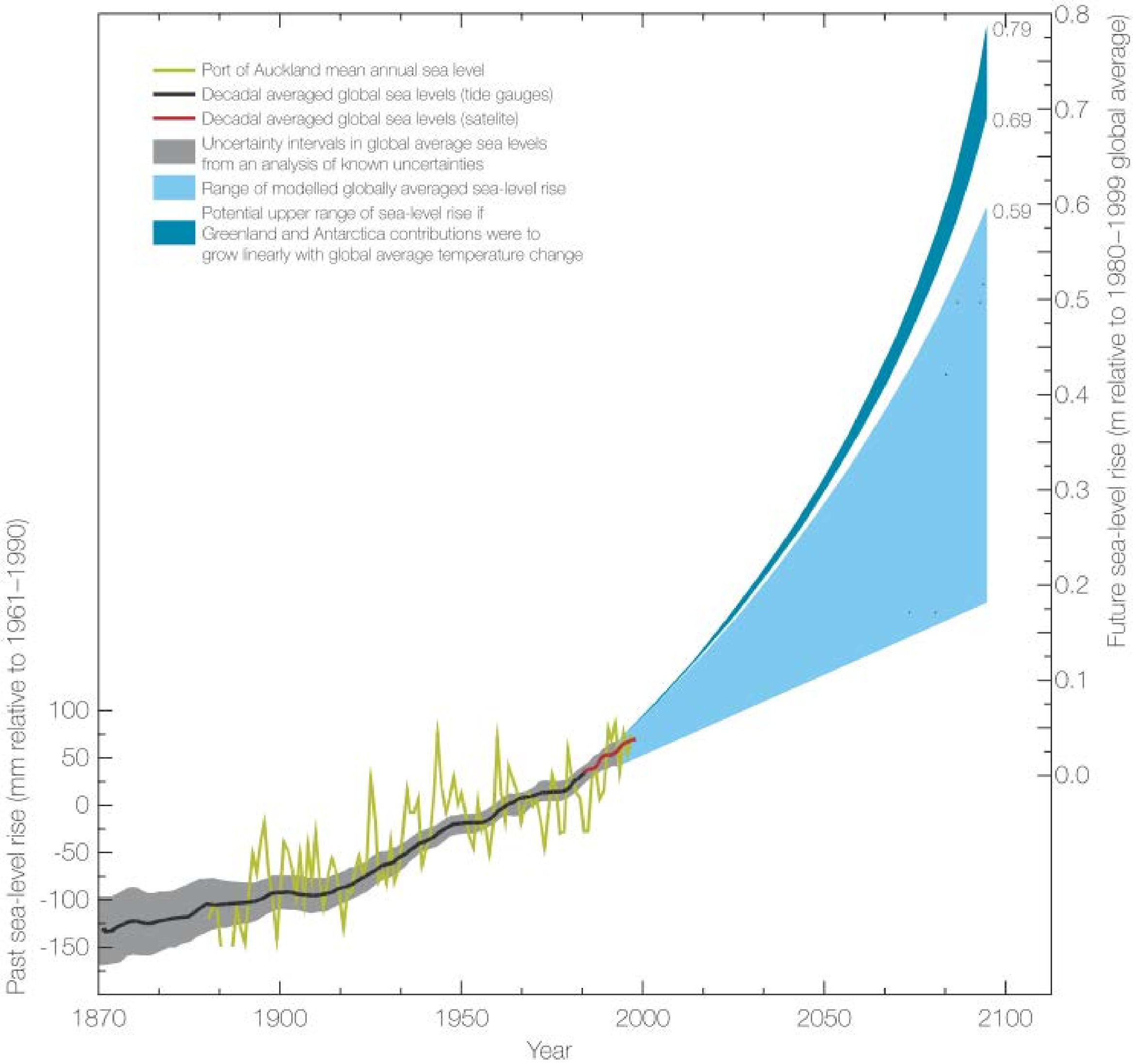

Figure 2-1 Projections of future global mean sea level rise and observations of past sea level rise (source: MfE, 2008)

The scientific understanding of how climate change will drive sea level rise has developed since the IPCC Fourth Assessment Report in 2007. The state of knowledge (up to mid 2010) about future sea level rise in New Zealand is summarised in a review of peer-reviewed papers presented by a Royal Society of NZ Emerging Issues paper (RSNZ, 2010). The key findings are outline below:

- Sea level rise is expected to be higher than previous IPCC recommendations. The upper limit on the rate of rise is poorly understood and a rise of 2 m by 2100 cannot be ruled out.
- Ice loss from Greenland and the West Antarctic ice sheets is predicted to become the dominant cause of sea level rise throughout the twenty first century and beyond. Therefore, the uncertainty in projections strongly depends upon how rapidly the movement and melting of polar ice sheets will accelerate.
- The majority of the New Zealand land mass is slowly sinking, by the order of 0.1 m per century (Hannah and Bell, 2012), increasing local sea level rise and associated local coastal hazards.
- Research since the last IPCC report (2007) suggests that a reasonable future sea level projection for New Zealand planning purposes is 1 m by 2100, with a plausible upper range

of 2 m. These sea level rise values are in agreement with international advice as summarised in Table 2-2.

Table 2-2 Summary of international sea level rise values for planning purposes (source: RSNZ, 2010)

Source	Report	Estimate of global mean rise by 2100
University of New South Wales Climate Change Research Centre	"The Copenhagen Diagnosis"	Up to 2 m
Department for Environment, Food and Rural Affairs (DEFRA)	"UK Climate Projections"	0.3-0.5 m, high scenario of 1.9 m
International Alliance of Research Universities (IARU)	"Synthesis Report from Climate Change, Global Risks, Challenges & Decisions" (2009)	0.5-1.5 m
California	"The Impacts of Sea-Level Rise on the California Coast"	1.0-1.4 m
United Nations Environment Programme (UNEP)	"Climate Change Science Compendium"	0.5-1.4 m
Deltacommissie, Denmark	"Working together with water"	0.65-1.3 m
Department of Climate Change, Australia	"Climate Change Risks to Australia's Coast"	1.1 m

The estimated sea level rise values presented in Table 2-2 are examples of the range in values that have been recently suggested for land use planning around the world.

Another uncertainty arises from possible differences in mean sea level when comparing the New Zealand region with global averages. Global sea levels have risen over the twentieth century with a global average rise of 1.8 ±0.3 mm/year estimated between 1950 and 2000 (IPCC, 2007). Relative sea level rise estimates in New Zealand appear largely consistent with this global average. Sea level recorded at Lyttelton Port increased at a rate of 1.9 ±0.1 mm/year between 1925 and 2010 (Hannah & Bell, 2012). Therefore, we consider it is reasonable to infer that global projections of sea level rise can be applied to obtain future projections of sea level rise in New Zealand.

The 2010 New Zealand Coastal Policy Statement (NZCPS) requires consideration of climate change effects covering at least a 100 year planning horizon. Therefore a planning timeframe of out to 2115 has been adopted for this report. For the purposes of this report, a future sea level projection of 1.0 m by 2115 (100 year planning time frame) is used, which is generally in line with the current state of knowledge presented in the MfE guidelines (2008) and the Royal Society of NZ Emerging Issues paper (RSNZ, 2010).

2.4 Knowledge gaps and uncertainties

There remain significant climate change uncertainties, in particular the estimates of a sea level rise projection over a 100 year time frame. The following uncertainties outlined in the T&T original report for determining sea level rise projections and potential impacts associated with climate change remain outstanding:

- Determining the change in track and frequency of tropical cyclones associated with warming of the South Pacific Ocean.
- Confirming the magnitude and change in the wind climate and the significance of these to the wave climate, beach orientation and sediment transport.

- Changes in rainfall patterns and the frequency of high intensity events, which will influence sediment supply to the coastal sediment budget.
- Confirming time lags between changes in global temperature and global sea level is still an unknown. However, we now understand that until about 2050 the sea levels will be relatively insensitive to changes in emissions because they are determined mostly by our past emissions. Future changes and trends in emissions become increasingly important in determining the extent of sea-level rise to expect beyond 2050.
- Determining the critical temperature rise required for the disintegration of the West Antarctic ice sheet. Although we now understand the melting of the Greenland and West Antarctic ice sheets will become a dominant component of the sea level rise projections over the twenty first century, the rate of increase of movement and melting is still an unknown factor. The melting rate of the Greenland and West Antarctic ice sheets is probably the largest uncertainty in sea level rise projections.
- Evaluating the response of shorelines to sea level rise. This has typically been done by equilibrium models such as the Bruun Rule (Bruun, 1962). Validation assessments of applying the Bruun Rule to New Zealand beaches have not been undertaken. Although this method is widely accepted to provide an order of magnitude result, the uncertainty of this method is still unknown. A quantitative method for predicting changes in gravel beach and estuarine morphology due to sea level rise is not presently available.

The following sea level rise uncertainties outlined in the T&T original report have been addressed:

- Historic sea level recorded at the Lyttelton Port has risen at a rate of 1.9 ± 0.1 mm/year between 1925 and 2010 (Hannah & Bell, 2012), which is in line with the global record. Therefore, we consider it is reasonable to imply that global projections of sea level rise can be applied to obtain future projections of sea level rise for Christchurch. Note, there is variance within the long term trend of sea level rise and the latest data from New Zealand port tide gauges shows the mean sea level has remained relatively constant for the last decade (Hannah & Bell, 2012).
- Natural sea level variation occurs from thermal expansion and contraction due to changes in sea surface temperatures and associated currents. This variation in sea level is related to climate cycles of varying time periods primarily dependant on the influence of the El Nino-Southern Oscillation (ENSO)[4] and the Inter-decadal Pacific Oscillation (IPO)[5]. The combined natural variation in sea level over climate cycles results in a total sea level fluctuation of +/- 0.25 m. Figure 2-2 summarises the components and values of natural sea level variation over three time scales (i.e. seasonal, ENSO and IPO).

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[4] The El Nino–Southern Oscillation (ENSO) refers to variations in both the water surface temperature and the air surface pressure between the eastern and western Pacific Ocean (El Nino and La Nina).

[5] The Inter-decadal Pacific Oscillation (IPO) refers to a long-term trend (20-30 years) in the ENSO cycle, of either periods of strong and frequent El Nino events, or periods of weak El Nino and stronger La Nina conditions on average.

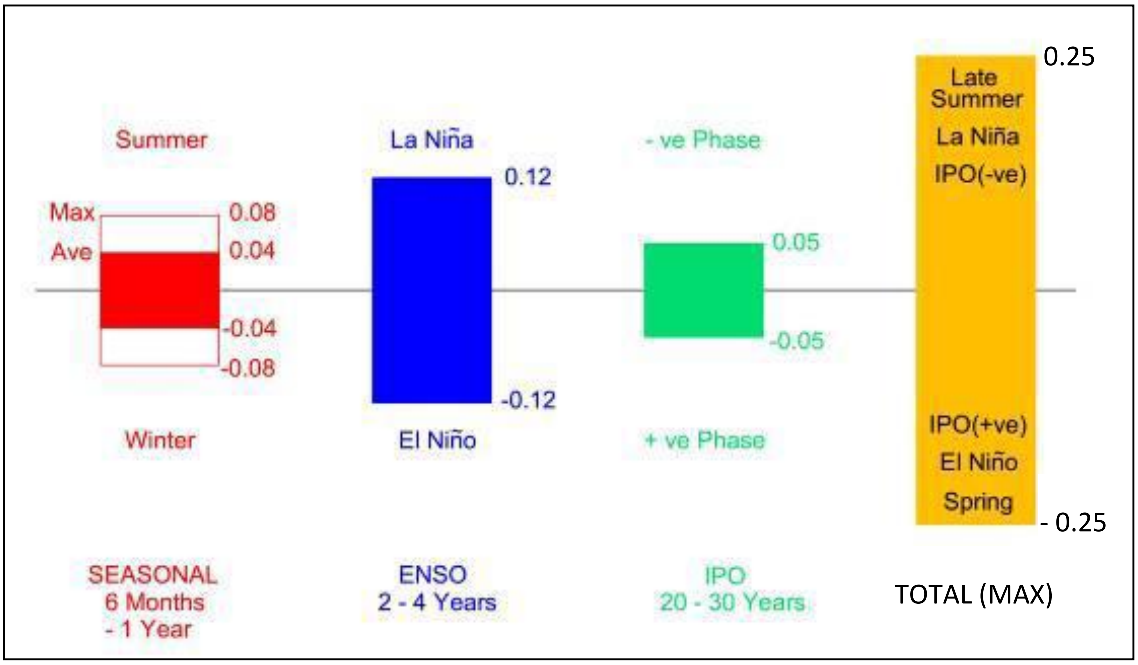

Figure 2-2 Components contributing to sea level variation over long term periods (source: Bell 2012)

The following knowledge gaps have not been addressed since the T&T original report:

- Although the Environment Canterbury wave buoy has been operational since 1999, no studies have assessed the variation in wave climate over this time. A 15 year wave climate would have been recorded in 2014, which could be analysed to assess any potential trends related to short term climate change.
- The cost of implementing various mitigation solutions has not been assessed across economic, social, cultural and environmental values. This assessment requires site specific studies that would provide important information to develop community based sea level rise adaption strategies.
- Relationships between discharge and sedimentation in the Avon-Heathcote Estuary and the role of ebb and flood tide bars on sediment volumes at Clifton and Sumner. Ebb and flood tide delta systems have some control on adjacent shoreline variation. Monitoring the sediment volume changes of both the delta systems and the adjacent beaches would provide information to assess the potential relationship.
- The sediment supply of the Waimakariri River to the coastal sediment budget has not been reassessed since the T&T original report. An updated analysis of the open coast beach profile dataset would provide information to assess whether the rate of historic shoreline accretion has changed over time.

3 Effects of land movement due to earthquakes

3.1 Geological setting and long-term tectonic movement

The geology of the Christchurch area is a result of tectonics, glacial and interglacial erosion and localised volcanism. The Canterbury plains lie east of the Australia-Pacific plate boundary where plate collision has caused the uplift of the Pacific plate to form the Southern Alps. Continued erosion of the uplifted materials and eastward transport in braided river systems has progressively formed the coarse-grained braidplain[6] upon which Christchurch is located.

Successive glacio-eustatic sea level fluctuations during the Quaternary have resulted in a stratified deposition comprising lowstand[7] fluvial gravels and sands and highstand[8] sand, silt, clay and peat deposits (Brown and Naish, 2003). The general form of this stratification in the Canterbury Plains near Christchurch is shown in Figure 3-1 with the Holocene[9] aged Christchurch formation comprising beach, estuarine, lagoonal, dune and coastal swamp deposits of gravel, sand, silt, clay, shell and peat overlaying previous deposits.

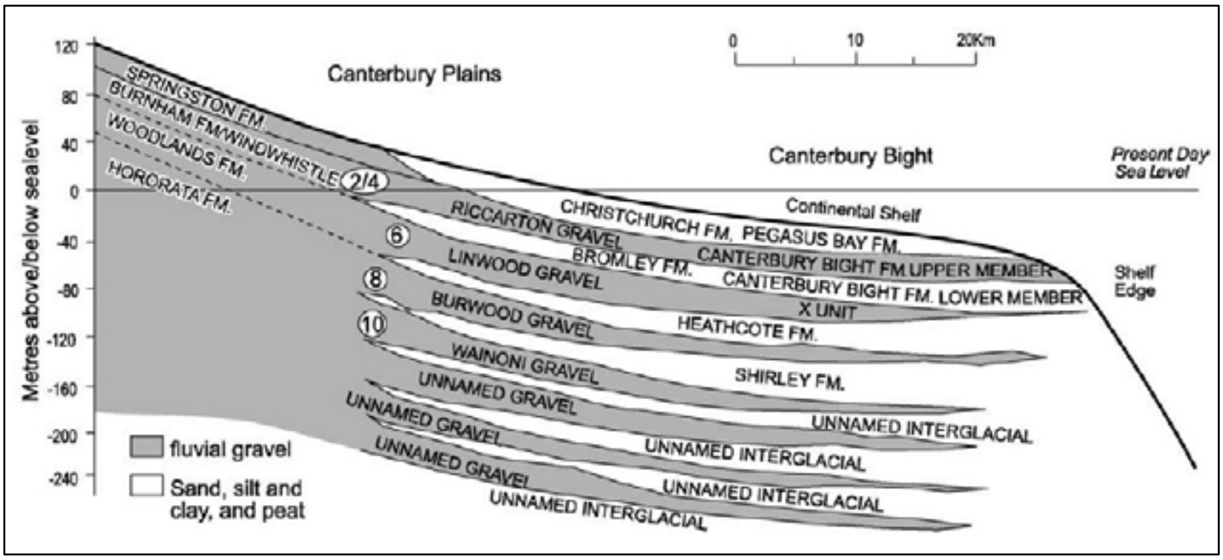

Figure 3-1 Stratigraphy near Christchurch showing lowstand fluvial gravels and sands overlain by highstand sand, silt, clay and peat (after Brown and Naish, 2003)

Sea level stabilised at its present interglacial highstand around 6000 years ago and inland transgression ceased (Figure 3-2). Since this time a succession of beach deposits, sand dunes, estuaries, lagoons and interdunal swamps accumulated resulting in shoreline advance (progradation) (Brown and Weeber, 1992) at an average rate of more than 2m/year (Wilson, 1976). Kirk (1987) suggests that this progradation material has been predominantly supplied by material from south of Banks Peninsula, which has moved northward around the peninsula and onto the Banner Bank before being reworked landward. Kirk considers that this reworking has now ceased and that the coastline has reached equilibrium with sand supplied by the Waimakariri River replacing sand removed by ongoing coastal erosion. Since European settlement in the

[6] A braidplain is defined as an area presently or formerly occupied by active river channels.
[7] A lowstand depositional unit forms when the rate of sedimentation outpaces the rate of sea level curve during the early stage of sea level rise.
[8] A highstand depositional unit forms during the late stage of base level rise when the rate of sea level rise drops below the sedimentation rate.
[9] The Holocene is a geological epoch which began approximately 12,000 years ago and continues to the present.

1850's extensive drainage and infilling of swamps with fill material has occurred, significantly changing the extents and hydraulic regimes of the Avon-Heathcoate estuarine system (MacPherson, 1978).

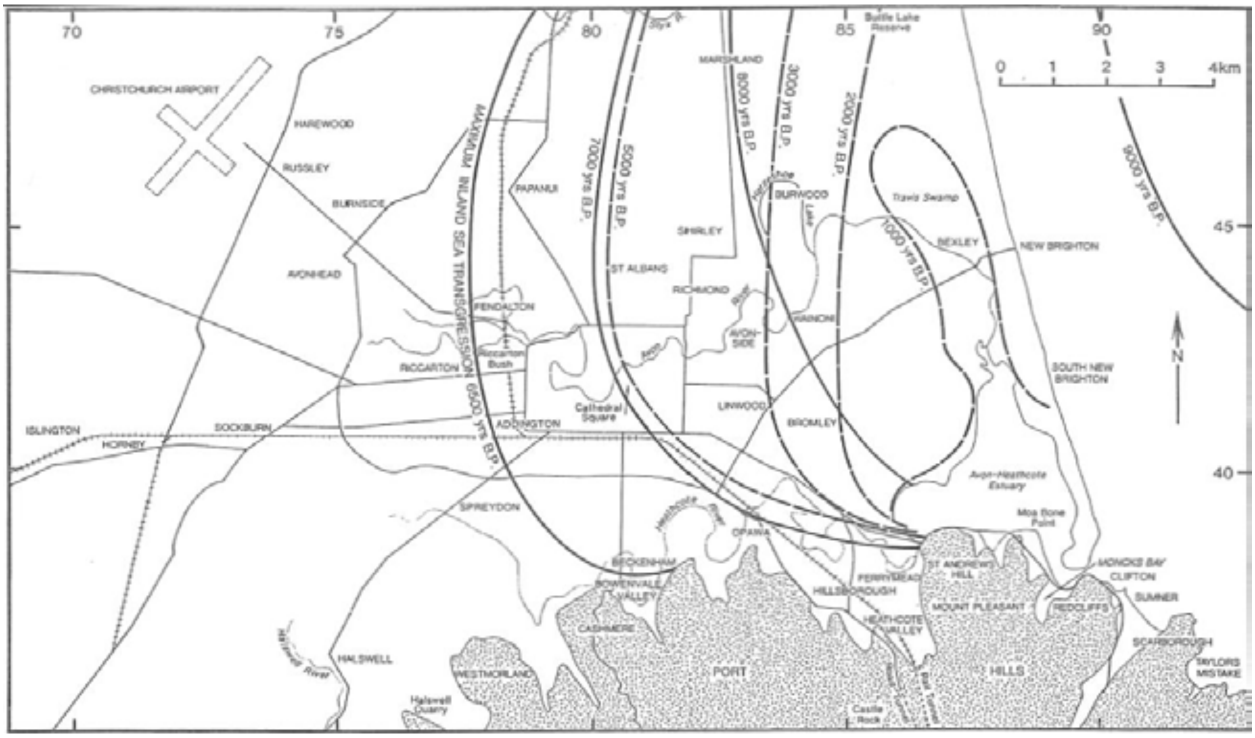

Figure 3-2 Postglacial marine transgression and progradation shorelines (after Brown and Weeber, 1992)

The Banks Peninsula comprises the deeply eroded and overlapping remnants of the Lyttelton and Akaroa Volcanoes with Basaltic deposits dipping gently towards the surrounding sea. These Miocene aged volcanoes had vents near the present-day harbours which are now drowned and their outer flanks have been deeply dissected resulting in a highly embayed coastline (Forsyth *et al.,* 2008).

Long term changes in land elevation may be caused by a number of processes including isostatic adjustment due to changes in mass loading on the Earth's-surface, long-term changes due to plate-tectonics, subsidence due to withdraw of fluids and subsidence due to the natural compaction of sediments (Beavan and Litchfield, 2012). Long-term tectonic movement in the Christchurch area includes tectonic uplift and strike-slip faulting producing the range and basin topography of northern and inland central Canterbury and subsidence of the braidplain (Forsyth *et al.,* 2008). Quaternary[10] subsidence rates for the Canterbury Plains have been estimated at up to 0.2 mm/year (Wellman, 1979) with higher rates of up to 0.55 mm/year found on the offshore shelf (Brown and Naish, 2003). In contrast, evidence of erosion-surfaces close to present sea level on the flanks of the Banks Peninsula suggests tectonic stability of this landform, at least during late Quaternary time (Lawrie, 1993; Bal, 1997).

[10] The Quaternary Period is the most recent of the three periods of the Cenozoic Era in the geological time scale, which began approximately 2.6 million years ago and continues to the present

3.2 Effect of the 2010-2011 Canterbury Earthquakes on land levels

The Christchurch area has been affected by a large number of earthquakes following the initial Darfield Earthquake on 4 September, 2010 (Figure 3-3), in particular, the earthquakes that occurred on 22 February, 13 June and 23 December 2011. These events occurred in close proximity to the city caused extensive liquefaction, slope instability, lateral spreading and vertical displacement of land surfaces resulting in damage to infrastructure and property and injury and loss of life.

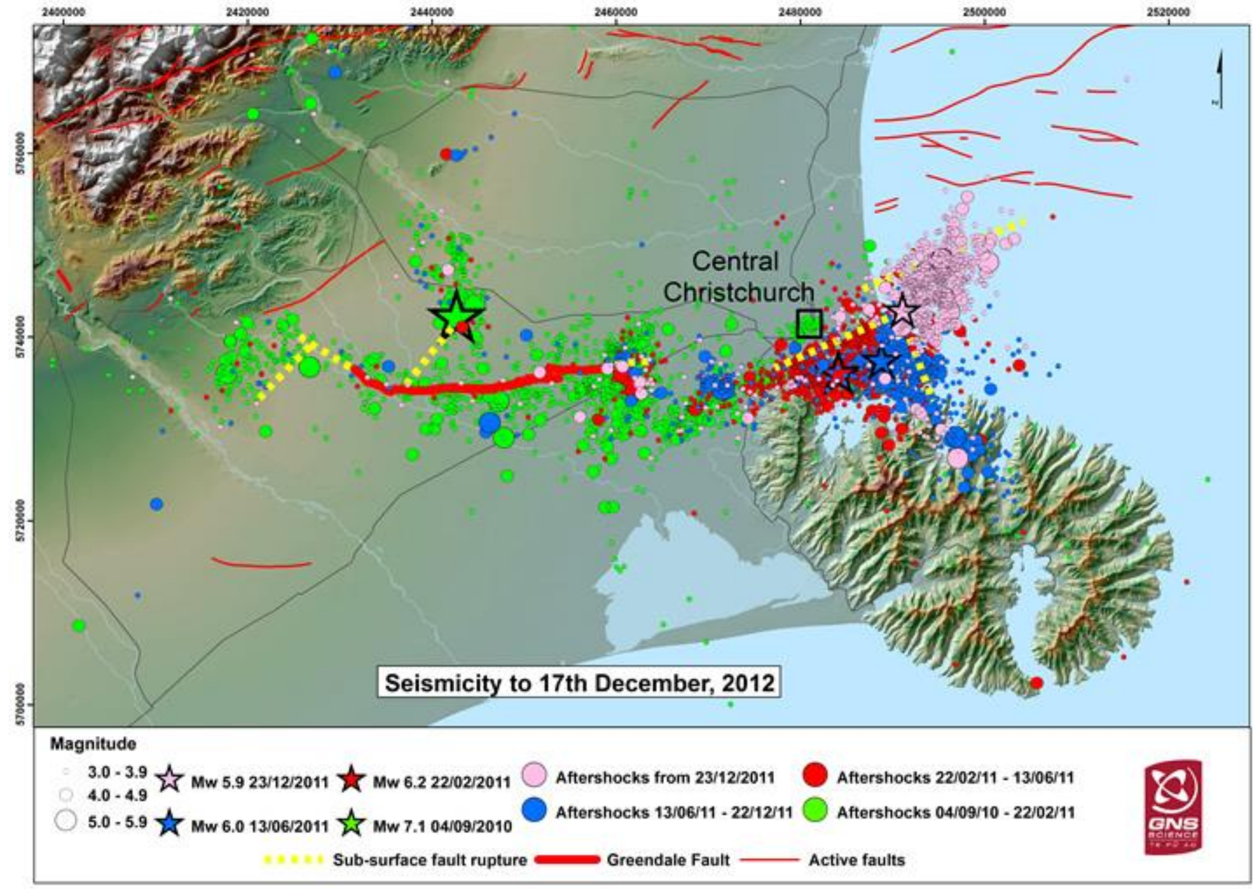

Figure 3-3 Seismicity of the Christchurch Area to 17 December 2012 (source: GNS 2012)

The ground around Canterbury has experienced regional scale tectonic movements caused by the earthquakes. These movements comprise both translation and elevation change which have deformed the ground surface. After each major aftershock, Land Information New Zealand (LINZ) re-surveyed a network of survey benchmarks around Canterbury (Donnelly et al., 2011). This survey re-established the location of the benchmarks relative to the rest of the physical survey network around New Zealand and allowed GNS to assess regional vertical tectonic deformation movements (Beaven *et al.,* 2012).

T&T working on behalf of the New Zealand Earthquake Commission (EQC) and Canterbury Earthquake Recovery Authority (CERA), analysed seven LiDAR datasets and ground based survey points collected between 6 July 2003 and 17 February 2012 (Table 3-1) to quantify vertical ground displacement throughout Christchurch City, parts of the Port Hills and Sumner. The LiDAR datasets were used to construct bare earth models which exclude vegetation and structures and are validated against survey control points. Further details are provided T&T (2013) but in general 90% of LiDAR points collected post-2010 are within ±0.1 m of the survey control points and within

±0.2 m in the 2003 LiDAR survey. Metadata supplied with the source LiDAR indicates the survey equipment had a vertical accuracy of ±0.15 m for the 2003 survey and ±0.07 m for the subsequent surveys.

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

Table 3-1 LiDAR source and commissioning agencies

DEM	Source LiDAR	Commissioning Agencies
Pre-earthquake	AAM, 6-9 Jul 2003	Christchurch City Council
	AAM, 21-24 Jul 2005	Environment Canterbury & Waimakariri District Council
	AAM, 6-11 Feb 2008	Environment Canterbury & Selwyn District Council
Post-Sept 2010	NZAM, 5 Sep 2010	Ministry of Civil Defence and Emergency Management
Post-Feb 2011	NZAM, 8-10 Mar 2011	Ministry of Civil Defence and Emergency Management
	AAM, 20-30 May 2011	Christchurch City Council
Post-June 2011	NZAM, 18 & 20 Jul, 11 Aug, 25-27 Aug, and 2-3 Sep 2011	Earthquake Commission
Post-Dec 2011	NZAM 17-18 Feb, 2012	Earthquake Commission

Results as presented within T&T (2013) are shown in Appendix A including LiDAR validation plots, cumulative change in ground surface elevation after each earthquake relative to pre-September 2010, cumulative tectonic movement over the same period and cumulative change in ground surface due to liquefaction (calculated by subtracting tectonic-induced movement from total elevation change).

Results show general subsidence across the city with subsidence from 0.1 m to more than 0.5 m (Figure 3-4) with the most pronounced subsidence occurring along the banks of the Avon River in the city's northeast. At the same time, the southeast of the city including the southern margins of the Avon-Heathcote Estuary and the Ferrymead area experienced uplift of up to 0.45 m, which can be attributed to tectonic related movement (Appendix A27). The analysis showed greater subsidence occurred after the 22 February 2011 earthquake compared to the September 2010 earthquake but subsequent earthquakes produced less additional subsidence. This is attributed to the majority of subsidence being due to densification of material rather than deep-seated movement.

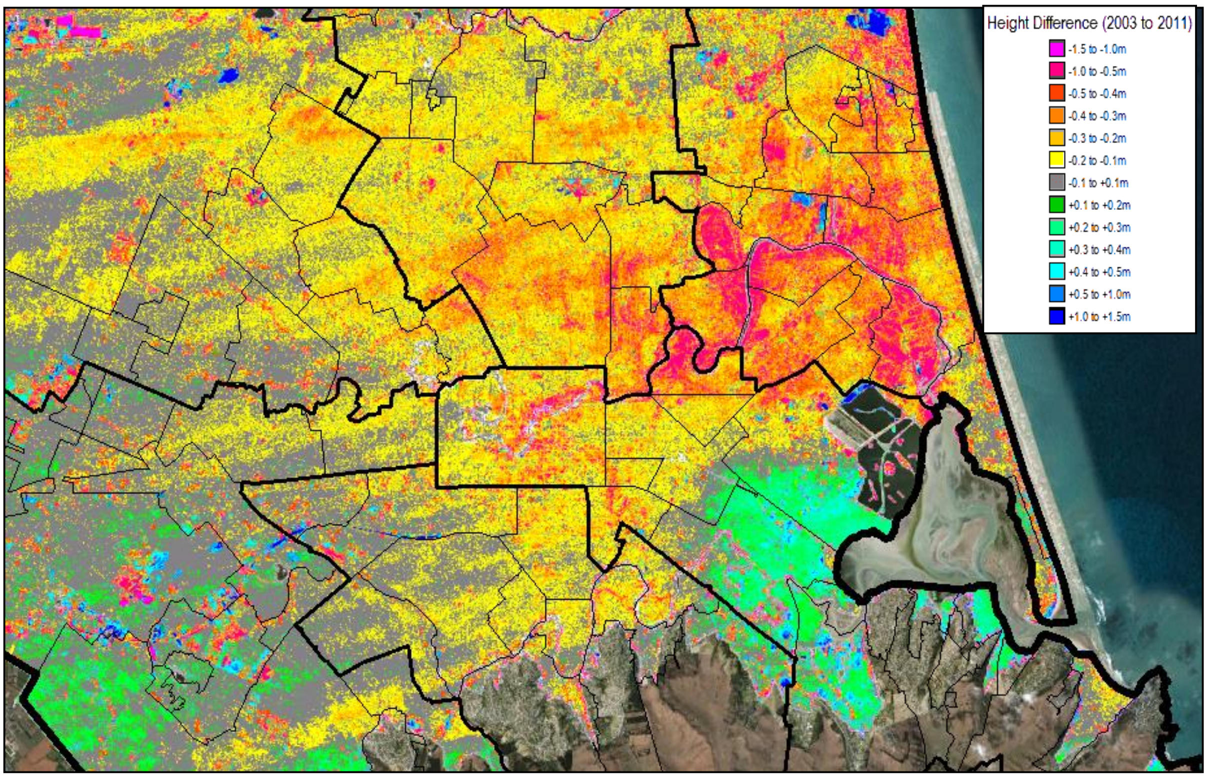

Figure 3-4 Summary of changes in ground elevation between 2003 and 2011 (source: T&T, 2013)

Measures *et al.,* (2011) assessed the physical changes to the Avon-Heathcote Estuary as a result of the September 2010 and February 2011 earthquakes using aerial photographs and topographic survey data. These included changes to the wetted area of the estuary at low, mid and high tide levels and the magnitude and spatial variation in elevation change across the estuary (Figure 3-5). Data collected included:

- Pre September 2010:
  - 27,000 RTK-GPS survey points collected within the Avon-Heathcote Estuary by University of Canterbury over the summer of 2009-2010
  - Airborne LiDAR data collected in July 2003 (limited coverage of estuary bed)
  - 28 point elevations collected by NIWA in 2007 using RTK-GPS as part of a study assessing the estuary response to the ocean outfall waste-water disposal regime.
- Post February 2011:
  - Hydrographic survey undertaken using Echo sounder and RTK-GPS by Paterson Pitts Partners in March 2011 and an RTK-GPS survey of the estuary perimeter
  - Airborne LiDAR data collected in March 2011
  - 28 point elevations collected by NIWA in June 2011 (same location as collected in 2007).

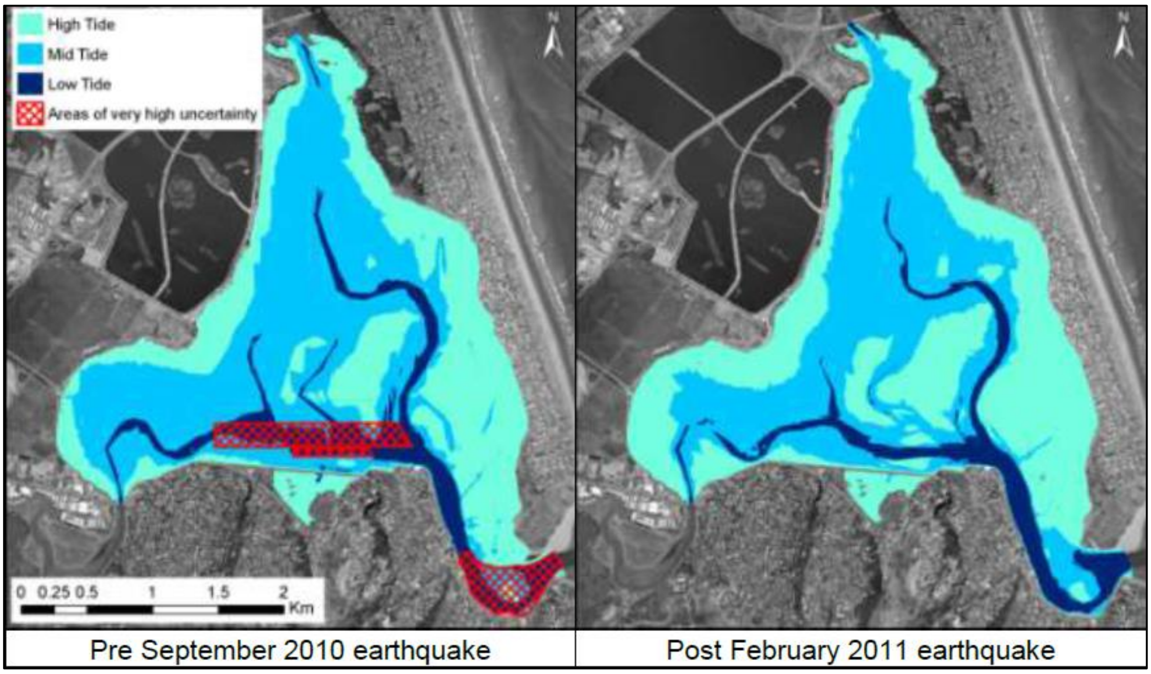

Figure 3-5 Tidal water surface extents pre- and post-earthquake (source: Measures et al., 2011)

Data was combined to create pre-September 2010 and post-February 2011 digital elevation models (DEMs) representing the estuary. Areas of insufficient data coverage or poor data quality were omitted. Results showed that the northern part of the estuary where the Avon River discharges has subsided by 0.2 to 0.5 m and the southern part of the estuary including near the estuary mouth and the Heathcote River has risen by 0.3 to 0.5 m (Figure 3-6). These results are consistent with analysis of the surrounding land (T&T, 2013). These changes have resulted in an increase of dry estuary area at mid tide of approximately 50 hectares or 18%. The change in the tidal prism[11] has been estimated by Measures et al. (2011) as approximately 1 million m^3 or a reduction of 14%.

[11] A tidal prism is the volume of water in an estuary between mean high tide and mean low tide levels.

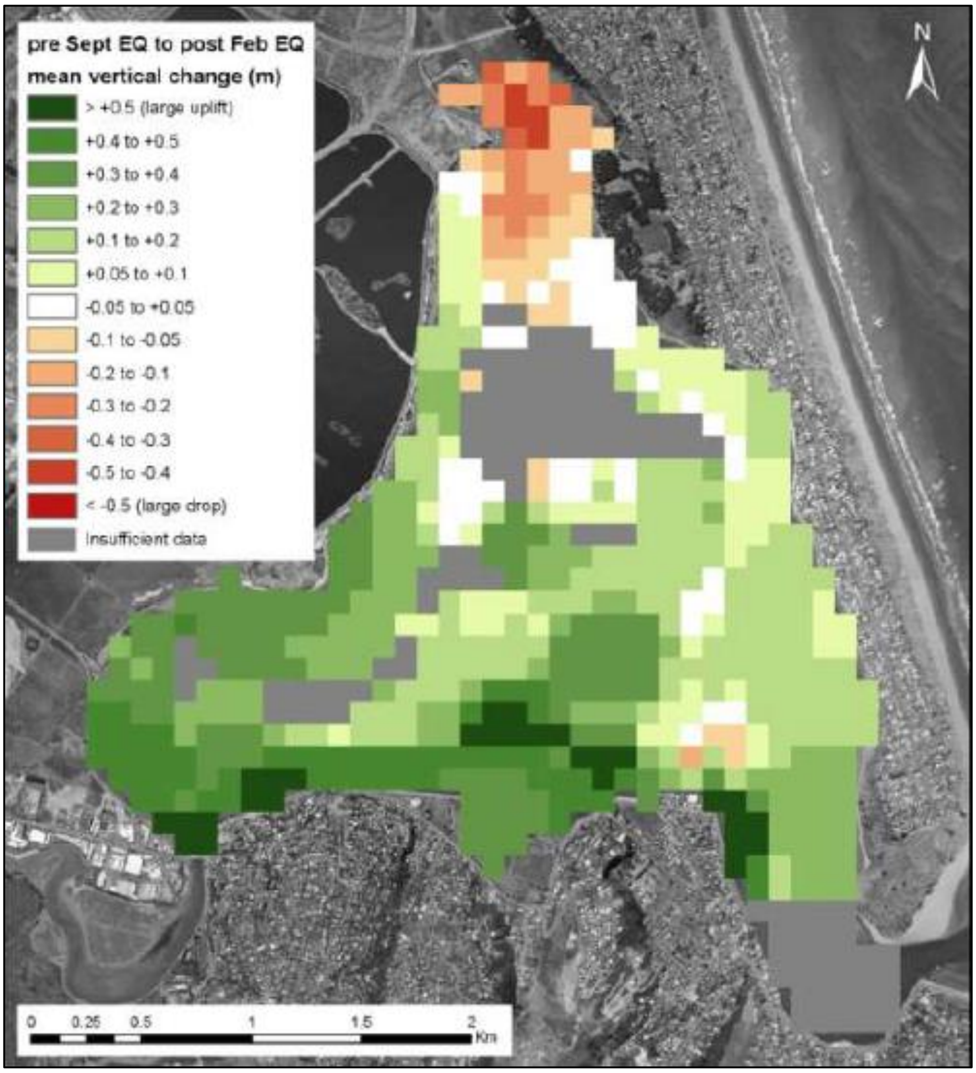

Figure 3-6 Vertical change pre September 2010 earthquake to post February 2011 earthquake (source: Measures et al., 2011)

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

3.3 Effect of land level change on coastal processes

Land elevation changes may occur both gradually or rapidly and on regional or local scales. Any change will result in a change in sea level relative to the adjacent land (relative sea level). The magnitude, temporal and spatial distribution of such changes will affect the observed response.

Hannah and Bell (2012) report long term relative sea level change at Lyttelton Harbour of 1.9 mm/year (±0.1 mm). On-going tectonic subsidence of 0.2 mm/year reported for the Canterbury Plains may mean this rate is slightly increased on the braidplain coast. As the Banks Peninsula is assumed tectonically stable (Bal, 1997) the long term relative sea level change would be appropriate for this area. The subsidence rate reported for the Canterbury Plains is roughly an order of magnitude below the eustatic (global) rate of sea level rise and may be near two orders of magnitude below the eustatic rate of rise at the end of the twenty-first century based on current prediction (IPCC, 2007). In this context the ongoing tectonic subsidence rate is a relatively small contribution and would likely result in only slight increases in ongoing sea level rise associated effects which are summarised below and discussed in detail with respect to Christchurch elsewhere in this report:

- Landward migration of the mean (tidal) water level by passive inundation
- Increase in the elevation and landward extent of extreme water levels
- Potential increase in depth-limited (nearshore) wave climate where seabed response does not keep up with sea level rise (i.e. hard bed with no sediment supply)
- Shoreline recession associated with equilibrium (Bruun) model response
- Increase in the tidal prism of estuaries resulting in greater throat currents and tidal deltas (possibly requiring additional sediment from adjacent beaches)
- Increased or decreased wetland areas depending on whether expansion is constrained by topographic or anthropogenic barriers
- Increased vulnerability to tsunami inundation
- Increased tailwater[12] levels of river/stream channels increasing terrestrial flooding
- Reduction in river gradient reducing fluvial sediment transport resulting in increased river aggradation[13] and decreased coastal sediment supply
- Increased relative groundwater level resulting in a thinning of the unsaturated surface crust and soils being more vulnerable to liquefaction damage
- Saline intrusion of groundwater.

Rapid and differential changes in land level as occurred during the 2010-2011 Canterbury earthquakes may affect both terrestrial and coastal processes. Specific changes may include:

- Subsidence along the northern New Brighton shoreline and uplift along the southern shoreline may modify littoral[14] transport processes potentially reducing the dominant southerly longshore drift rates.
- Decreases in the tidal prism of the Avon-Heathcote Estuary reported by Measures et al. (2011) may result in a decrease in both the outgoing tidal current velocities and the ebb tidal delta volume according to the relationships established by Hume and Herdendorf (1988). This could result in a landward movement of the ebb delta, with surplus sediment migrating to adjacent beaches or acting to block or reduce the size of the inlet.
- Rapid uplift of the southern Avon-Heathcote Estuary may have detrimental effects on flora and fauna which cannot adapt in time
- Uplift of the lower Heathcote River has decreased hydraulic gradient and may increase accumulation of sediment on the river bed.
- Subsidence of the northern Avon-Heathcote Estuary has increased relative groundwater levels (T&T, 2013) resulting in soils being more vulnerable to liquefaction damage
- Subsidence of land adjacent the lower Avon River and northern Estuary regions has increased the susceptibility of land to flooding.

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[12] Tailwater refers to the waters located immediately downstream of the mean high tide level. A rise in sea level will result in higher tailwater levels.
[13] Aggradation refers to the increase in land elevation due to the deposition of sediment.
[14] The littoral zone refers to the section of coast located between the high tide mark and the surf zone.

3.4 Gaps in knowledge

A significant amount of data describing land and estuary levels has been collected since the 2010-2011 Canterbury earthquakes. Analysis of this data has shown areas of the both subsidence and uplift and while some uncertainty in the specific values remain, general trends are likely to be correct.

Limited data has been collected, or analysis undertaken, on changes in the offshore seabed level or of the shore face. This is partially due to the difficultly and expense associated with collecting new offshore data and partially due to the continuous dynamic changes in the shoreface, rendering changes of 0.1 to 0.2 m as a result of the earthquake difficult to discern from background variations. Given the limited infrastructure or property located on or near the open coast shoreline, this lack of data and analysis is unlikely to be extremely important, however any change occurring as a response to rapid elevation change may provide insight as to possible long term response to larger eustatic sea level changes.

We recommend monitoring changes in the South Brighton spit and Sumner Bar over time using aerial or oblique photographs as changes to the tidal prism reported within the Avon-Heathcote Estuary is likely to result in some change to the ebb-delta regime and surrounding beaches.

Information on earthquake induced changes in land level outside of the Christchurch and the lower Port Hills area has not been presented to date, although based on existing information, any changes are likely to be small.

4 Assessment of impacts

Climate change is not expected to create any new coastal hazards that do not already exist, but at many locations it has the potential to increase the impact and consequence of existing hazards. Climate change may affect the:

- frequency and elevation of extreme sea levels
- height and dominant direction of waves
- frequency and intensity of rainfall and catchment flooding
- rate of mean sea level rise.

There remains considerable uncertainty on the effect of climate change on the first three items listed above. This report focuses on the impact of an increase in sea level rise on the following Christchurch City areas (refer to Figure 1-1 and Figure 1-2 for location plans):

- Banks Peninsula
- Waimakariri River & Brooklands Lagoon
- the Christchurch Dune System
- the Avon-Heathcote Estuary
- the Lower Avon & Heathcote Rivers
- the Beaches South of the Estuary.

Although this study focusses on the impacts of sea level rise, we note the CCC area is prone to multiple natural hazards (e.g. river flooding, landslides, liquefaction and tsunami).

4.1 Banks Peninsula

The Banks Peninsula area was not included in the extent of the original T&T report because the area was outside the CCC boundary at the time of reporting. The entire Banks Peninsula is now part of the Christchurch City local authority area. The following six settlements located on the northern shoreline of Banks Peninsula and within Akaroa Harbour are now included in this assessment:

- Northern Banks Peninsula settlements
  - Port Levy
  - Okains Bay
- Akaroa Harbour settlements
  - Wainui
  - Duvauchelle
  - Takamatua
  - Akaroa.

4.1.1 Site description

4.1.1.1 Northern Banks Peninsula

Port Levy and Okains Bay are located on the northern coast of Banks Peninsula (refer to Figure 1-2). Port Levy is a 6.5 km long rock walled inlet with an average width of 1 km. The water depth at the entrance to the inlet is approximately 14 m and the water depth reduces to 5 m half way up the inlet around Putaiti Point. The underlying volcanic base of Banks Peninsula is covered by thick

(~20 m) deposits of loess and loess colluvium from the Canterbury Plains (Forsyth *et al.*, 2008). The fine loess sediment is readily eroded from the hill slopes and transported to the coast.

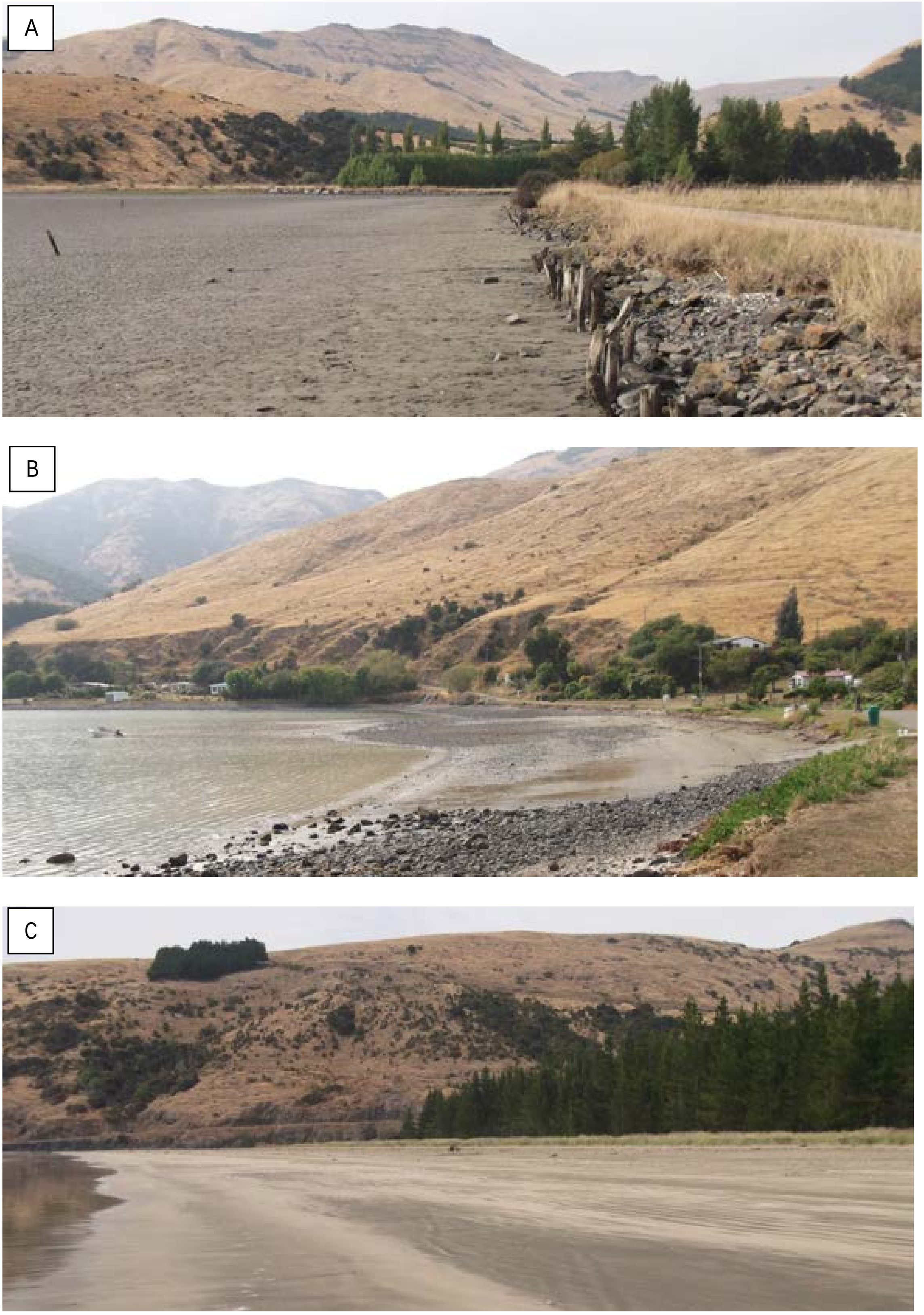

Figure 4-1 Photograph A-Port Levy southern-most bay, Photograph B-Port Levy (Puari), Photograph C-Okains Bay

Two bays have formed at the head of the Port Levy inlet. The southern-most bay is characterised by intertidal flats that are approximately 500 m wide. This bay is split by a central raised promontory (Fernlea Point) with streams running along either side of the raised ground supplying sediment into the bay. The backshore is low lying with an elevation of less than 1.0 m above high tide level (Figure 4-1 Photograph A). The second bay is located adjacent to Horomaka Island and is the location of the main Port Levy settlement (Puari). This bay also comprises intertidal flats and a relatively low lying backshore. The beach at Puari consists of silty sand and gravels (Figure 4-1 Photograph B).

Okains Bay is approximately 1.3 km wide and 2.3 km long. The bay head beach comprises fine sand material with a relatively flat intertidal zone that is approximately 150 m wide (Figure 4-1 Photograph C). The sandy beach is approximately 800 m long and is flanked to the west by the Opara Stream and to the east by Big Hill. The Opara Stream forms a tidal estuary over the lower 3 km section. The Okains Bay backshore is relatively low lying with an elevation of less than 1.0 m above high tide level. Landward of the beach is a sequence of dune and beach ridges extending approximately 3 km inland suggesting rapid progradation from marine sediment.

4.1.1.2 Akaroa Harbour

Akaroa Harbour is around 17 km long orientated north to south, with a relatively constant width of 2-3 km. The shoreline along the southern end of the harbour is dominated by steep cliffs of basalt and andesitic volcanic rock. The water depth at the harbour entrance is approximately 25 m and decreases to approximately 10 m half way up the harbour at around Wainui Bay. The upper section of the harbour has a number of bays interspersed between rocky headlands and wave shore platforms.

Wainui is located on the western shoreline of Akaroa Harbour and has a relatively steep gravel beach (Figure 4-2 Photograph A). The backshore elevation is approximately 3.5 m above mean high water springs (MHWS).

Duvauchelle comprises two bays with silty sand and gravel beaches. The bays are fronted by intertidal flats that are approximately 350 m wide and are protected with a vertical seawall along the majority of the length (Figure 4-2 Photograph B and C).

Takamatua Bay has a silty sand and gravel beach with intertidal flats that are approximately 730 m wide. The backshore elevation is approximately 1.0 m above MHWS (Figure 4-2 Photograph D).

Akaroa is located in French Bay and can be split into two shoreline types, with a natural shoreline located in the north of the bay and a modified shoreline located adjacent to the main settlement which is mostly protected by a vertical seawall (Figure 4-2 Photograph E). The northern bay has a silty sand beach and intertidal flats that are approximately 230 m wide.

Figure 4-2 Photograph A-Wainui, Photograph B-Duvauchelle north, Photograph C-Duvauchelle east, Photograph D-Takamatua, Photograph E-Akaroa

4.1.2 Previous assessments

4.1.2.1 Northern Banks Peninsula

Previous assessments have focussed on the coastal processes adjacent to the entrance of Port Levy in relation to the dredging of Lyttelton Harbour (Hart, 2004 and Mulgor, 2009). There are no known assessments at Port Levy relating to natural hazards including sea level rise.

The prograding[15] dune and beach ridge system at Okains Bay was investigated by Stephenson and Shulmeister (1999). Based on analysis of historical aerial photographs they calculated an average rate of shoreline progradation of 2.35 m/year. Stephenson and Shulmeister (1999) suggest the sediment source for this prograding strandplain[16] is most likely from the offshore Banners Bank located directly to the north of the site. A transect was surveyed through the ridge system which identified 48 beach berm and foredune ridges (Figure 4-3). The ridge crest elevations within the first 1.5 km inland from the beach are below 2.5 m above mean sea level (MSL), illustrating the flat low lying topography of the backshore.

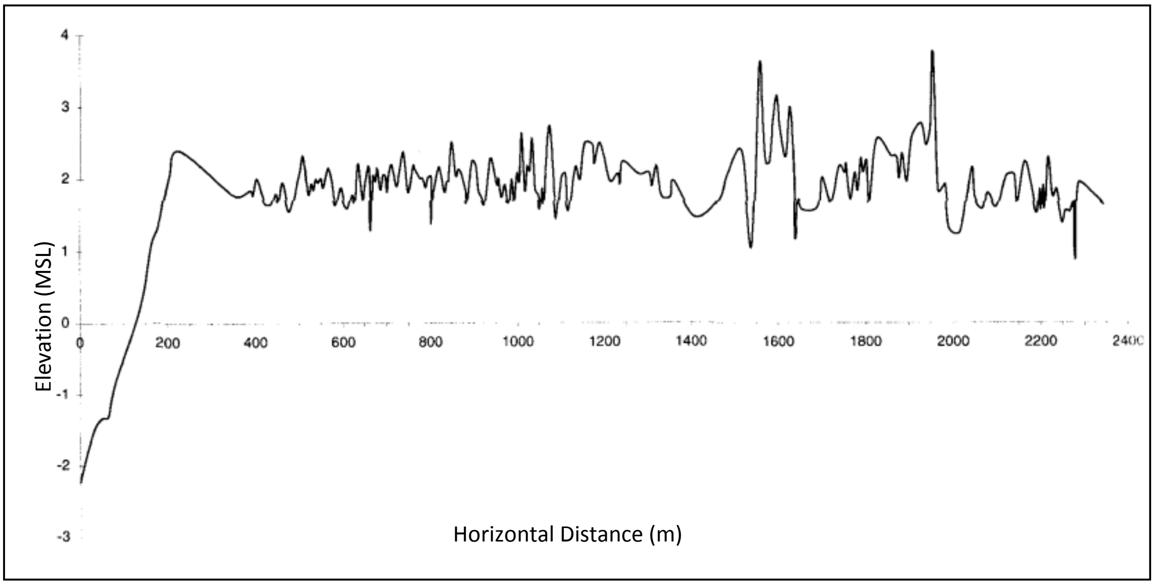

Figure 4-3 Transect through the prograding strandplain (source: Stephenson and Shulmeister, 1999)

4.1.2.2 Akaroa Harbour

Dtec (2008) undertook an assessment of coastal erosion and inundation for all Akaroa Harbour settlements including the potential impacts of sea level rise. The results of this report in relation to sea level rise are based on a future sea level projection of 0.2 m by 2050. Based on this sea level rise scenario the low lying beaches of Takamatua and Duvauchelle were calculated to retreat approximately 15 m by 2050. Akaroa and Wainui have steeper nearshore slopes and higher backshore elevations and were predicted to experience retreat of less than 10 m by 2050.

Dtec (2008) calculated a 50 year inundation level of 1.7 m above MSL, including tides, storm surge and sea level rise. Over 8 km of the 16 km shoreline within the Akaroa Harbour settlements has some form of erosion protection works. Approximately 50% of these structures are currently at risk from overtopping and inundation during storm surge conditions (Dtec, 2008). Sea level rise

[15] Prograding refers to the growth of the dune building out further towards the sea over time.
[16] A strandplain refers to a broad belt of sand along a shoreline with a surface exhibiting well defined parallel or semi-parallel sand ridges separated by shallow swales. Strand plains are typically created by the redistribution of river derived coarse sediment as part of a wave-dominated delta system.

will increase the frequency of overtopping along these structures potentially affecting main access roads to the Akaroa Harbour settlements and overtopping may also reduce the structural integrity of the protection structures.

LINZ conducted a detailed bathymetric survey of Akaroa Harbour in 2008 for the purpose of revising the New Zealand Hydrographic Chart NZ6324. The survey extent covered the upper harbour intertidal areas down to approximately the 20 m depth contour. The 2008 survey has the same depth contour and spot height intervals as the previous 1988 chart. UCAN (2009) undertook a baseline mapping study utilising this new survey data and analysed changes in bathymetry between 1988 and 2008. They found the levels along the central axis of the upper harbour have remained relatively constant over time with the following key changes:

- Takamatua Bay appears to have undergone sedimentation
- Akaroa inlet is in a slightly erosional phase
- Wainui Bay shows no significant change and appears to be a relatively high energy environment with sediment unable to infill the bay and shallow the profile
- silts and sands dominate much of the upper harbour sea bed with clays dominating the central area between Akaroa and Robinsons Bay (includes Takamatua Bay) indicating a possible sediment sink[17].

4.1.3 Effect of sea level rise on beach profiles

4.1.3.1 Methodology

The majority of the shoreline around Akaroa Harbour, Port Levy and Okains Bay are hard cliff shorelines which are not expected to undergo significant erosion from future potential sea level rise. However the settlements located at the head of the bays are located on soft shorelines with narrow beaches and relatively low lying backshores. The shorelines of Duvauchelle, Takamatua, Port Levy and Okains Bay consist of silty sand or fine sand beaches with wide, shallow intertidal nearshore zones. Akaroa and Wainui both have relatively steep nearshore zones with mixed sand and gravel beaches. These bay head beaches are affected by storm induced erosion.

Coastal erosion and shoreline retreat is likely to be exacerbated by climate change in all of the study areas within Banks Peninsula due to the following effects:

- rise in mean sea level
- possible increase in the frequency and intensity of coastal storms
- possible re-orientation of shorelines in response to changes in wave climate.

The scale and timing of these effects are uncertain and, apart from sea level rise, it is not presently possible to make any useful quantitative estimates of these effects on coastal erosion. Accordingly, this assessment of the potential impacts of climate change on coastal erosion is limited to consideration of a rise in mean sea level only.

There are many uncertainties associated with predicting the future impact of sea level rise on beach erosion. The most widely accepted method for assessing the impact of sea level rise on open coast sandy beaches is the Bruun Rule (Ramsay *et al.,* 2012). The Bruun Rule predicts that as sea level rises against a shore profile in equilibrium, beach erosion takes place to provide

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[17] Sediment sink refers to an area where sediment is lost from a coastal cell, such as an estuary, or a deep channel in the seabed.

sediments to the nearshore so that the seabed can elevate in direct proportion to the rate of sea level rise (refer to Section 4.2.3.1 for full description of the Bruun Rule).

The Banks Peninsula settlement beaches consist of either silty sand, fine sand or mixed sand and gravel and have no extensive dune system. Therefore they are expected to behave differently to sandy beaches in response to a rise in mean sea level. The silty sand and fine sand beaches are expected to behave similar to estuarine and harbour beaches which have a wide intertidal zone and no dune system. Gravel beach processes differ from sandy beaches in that run-up from storm waves push material higher on the profile, building the crest level up rather than moving sediment offshore. If run-up overtops the berm, material can be washed over the crest causing a loss of material from the beach face and building of a barrier back-berm. As sea level rises, an increasing volume of material is "overwashed" resulting in shoreline retreat.

The effect of sea level rise on estuarine type shorelines can be highly variable and complex and will depend on the interrelationship between:

- nearshore and backshore topography
- backshore geology
- sediment supply and storage.

Although sedimentation is apparent at some sites, it is expected that the acceleration in sea level rise is likely to exceed sedimentation rates (MfE, 2008). This may occur more quickly in developed areas where catchments are developed and restrict sediment supply.

The dynamics of coastal estuarine harbour processes and multi-year cycles of sand exchange between the intertidal flats, deltas and the adjacent coastline are complex. Thus any reliable statement about how individual inlet systems may respond to climate change effects is difficult to make. However, it is probable that there would be some shoreline retreat under accelerated sea level rise conditions.

Although the traditional Bruun Rule developed for open coast sandy beaches does not directly apply for estuarine and gravel type shores, one approach is to assume that the sediment supply and active beach width remains constant during a change in sea level. The beach profile is likely to respond to these conditions with an upward and landward translation over time (Komar, 1999). The landward translation of the beach profile (**X**) can be defined as a function of sea level rise (**Δs**) and the intertidal beach slope (**tanα**) out to Chart Datum. This relationship is given in Equation 1 and displayed in Figure 4-4 (equilibrium profile method).

$$\boldsymbol{X = \frac{\Delta s}{\tan \alpha}} \qquad (1)$$

Where:

X	=	the landward translation of the beach profile due to sea level rise (m)
Δs	=	increase in sea level rise (m)
tanα	=	average slope of the embayment.

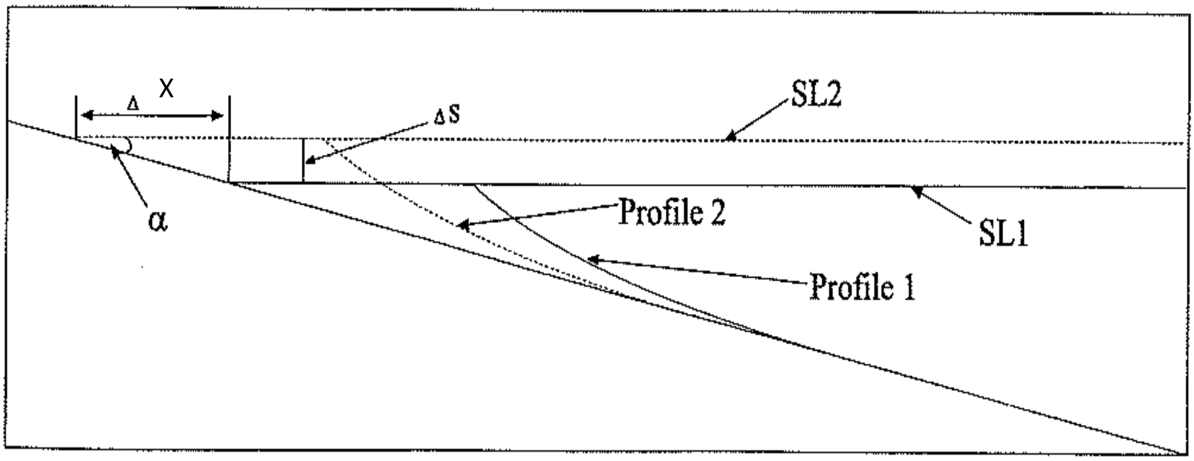


Figure 4-4 Horizontal translation distance of the beach profile under SLR (source: adopted from Hennecke and Cowell, 2000)

We consider that the equilibrium method is suitable to estimate the shoreline retreat due to sea level rise for the silty sand and mixed sand and gravel beaches of the Banks Peninsula settlements. Estimating the shoreline response to sea level rise using the equilibrium profile based method will depend on the existing backshore geology and topography, which varies considerably within each of the settlements. Therefore, the equilibrium profile method is expected to over predict the shoreline retreat in some areas and is considered to be suitable for identifying the likely maximum shoreline retreat distance.

A second method (passive inundation method) can also be applied to these beach types to identify the shoreline retreat due to sea level rise (EShorance, 2010). Passive inundation is simply the position of the high tide level (MHWS) in 2115 allowing for a sea level rise of 1.0 m. The landward extent of shoreline retreat through passive inundation is the intersect position between the sea level rise projection elevation above MHWS and the existing cross shore profile (Figure 4-5).

For the purposes of this study, we have used a pragmatic 10% MHWS level which is exceeded by 10% of the high water spring levels (MHWS). Based on a MWHS level of 1.15 m above Lyttelton Vertical Datum 1937 (LVD) and the sea level rise projection of 1.0 m, the passive inundation level is 2.15 m (LVD). Therefore, if the backshore profile remained constant over time the shoreline defined by the MHWS level in 2115 would be the existing 2.2 m contour (rounded to 1 decimal place). A digital terrain model is required to accurately calculate shoreline retreat using the passive inundation method.

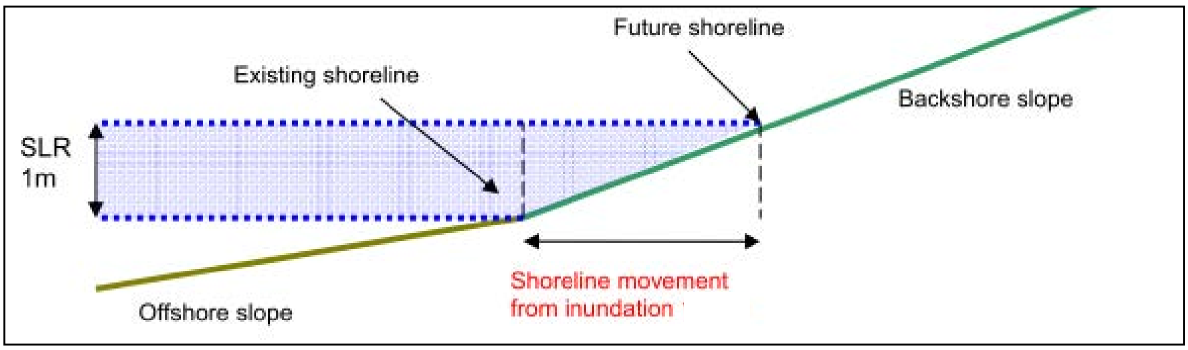


Figure 4-5 Example of calculating shoreline retreat based on passive inundation (source: EShorance, 2010)

4.1.3.2 Results

The effect of sea level rise on beach profiles has been estimated for the six Banks Peninsula settlements using both the equilibrium profile method and the passive inundation method (refer to Section 4.1.3.1 for the method descriptions). The passive inundation method requires a digital terrain model (DTM) of the backshore to accurately plot the contour of the sea level rise projection above MHWS. Therefore, this method was only applied to the Akaroa Harbour settlements, as no LiDAR data is currently available for the northern Banks Peninsula settlements. Refer to Section 4.1.4.1 for a description of the methodology used to create the DTM for this study.

Table 4-1 displays the estimated horizontal distance of shoreline retreat due to sea level rise to the year 2115 based on both the equilibrium profile method and passive inundation method. The geological properties landward of the beach often change along the shoreline which is likely to affect the potential shoreline retreat distance. Therefore the shoreline retreat distances presented in Table 4-1 can be considered to represent a maximum extent. The horizontal distance should be measured inland from the current MHWS level. Note the rate of shoreline retreat is not expected to be a linear trend, rather the rate is expected to increase in time in line with sea level rise predictions.

The shoreline retreat based on the passive inundation method is effectively the distance between the existing MHWS level and the 2.2 m contour (Figures 4-4 to 4-10). There are large variations in this distance within each settlement due to changes in the backshore topography along the shoreline. Therefore, the passive inundation method distance presented in Table 4-1 is calculated as the maximum horizontal distance between the 2.2 m contour and the existing MHWS level.

We note the shoreline retreat distances provided in Table 4-1 are an order of magnitude larger than the previous assessment undertaken in these areas by Dtec (2008). This mainly due to the differing planning time frames and selected sea level rise projection (0.2 m opposed to 1.0 m). The Dtec (2008) assessment was also based on the Bruun Rule, which we do not consider appropriate for these settlements due to the lack of a sandy dune system.

Table 4-1 Summary of the estimated shoreline retreat due to potential sea level rise

Settlement	Sea level rise (m)	Slope (Vertical:Horizontal)[1]	Equilibrium Profile Shoreline Retreat (m)[2]	Passive Inundation Shoreline Retreat (m)[2,3]
Port Levy	1.0	0.005	200	No data
Okains Bay	1.0	0.018	60	No data
Akaroa - North	1.0	0.015	70	20
Akaroa - South	1.0	0.050	20	170
Duvauchelle	1.0	0.010	100	60
Wainui	1.0	0.120	10	10
Takamatua	1.0	0.005	200	100

Note: [1]The vertical and horizontal distances were measured from LINZ Hydrographic Charts (6324 and 6321), LiDAR and site measurements.

[2]The shoreline retreat distance is rounded up to the nearest 10 m.

[3]Maximum horizontal distance between the 2.2 m contour and the existing MHWS level.

The results for the Akaroa settlement are split for the north and south areas. The north area is the 400 m long shoreline facing south west which is fronted by intertidal flats. The south area refers to the remainder of the shoreline to the south which has a steeper nearshore profile and is protected by a seawall along the majority of the length. Table 4-2 identifies the public assets located within the maximum extent of estimated shoreline retreat based on both the equilibrium profile and passive inundation methods.

Table 4-2 Public assets at within area potentially affected by shoreline retreat due to sea level rise

Settlement	Assets within area potentially affected by shoreline retreat
Duvauchelle	SH75 Onewa Flat Road Seafield Road School
Akaroa	Jubilee Park Beach Road
Takamatua	Takamatua Bay Road Old French Road
Wainui	Wainui Main Road
Port Levy	Fernlea Point Road Wharf Road
Okains Bay	Okains Bay Road

The public assets most at risk from shoreline retreat due to sea level rise are the low lying roads providing access to the settlements of Duvauchelle, Takamatua and Port Levy (Puari). These assets are considered to be at a higher risk due to the consequence of the loss of service resulting in these settlements being isolated from road access.

Some of the public road assets are currently protected by vertical seawalls. The seawalls have relatively low crests and are likely to be overtopped more frequently during future storm events. The crest elevations can only practically be raised to the existing backshore levels to avoid creating catchment drainage issues. Therefore, as sea level rises we would expect an increase in maintenance costs for seawall remedial works associated with overtopping scour in unpaved areas.

The foreshore levels fronting the seawalls are expected to lower over time as sea level rises and the shoreline attempts to retreat. Therefore many seawalls may experience an increase of scour at the foot of the structure resulting in undermining and slumping. Therefore, unless significant reconstruction or replacement works are undertaken the existing sea walls are likely to fail as sea level rises providing limited protection from future shoreline retreat.

4.1.4 Effect of sea level rise on inundation

4.1.4.1 Methodology

This section outlines the methodology used to assess the effect of sea level rise on inundation for harbour and estuary shorelines.

Storm surge[18] is a major component of coastal inundation and future changes to storm surge will depend on changes in the frequency and intensity of low pressure systems. There are significant uncertainties over changes to storm events in New Zealand due to climate change over the next 100 years. Since tidal characteristics are expected to remain unchanged by future sea level rise, storm tide characteristics are expected to remain similar (MfE, 2008). Therefore, to predict future extreme inundation levels, sea level rise can simply be added to the present day storm tide levels.

The current 1% annual exceedance probability (AEP) storm tide level for Sumner is 1.85 m above Lyttelton Vertical Datum 1937 (LVD) which includes tide, storm surge, and annual sea level fluctuations ("1% AEP inundation level") (Goring, 2011). This inundation level can be increased by 1.0 m to allow for sea level rise to 2115. A freeboard[19] allowance of 0.4 m should also be included to allow for some localised wave effects and other uncertainties. The freeboard allowance of 0.4 m was selected to be consistent with the existing freeboard set out in the Christchurch City District Plan for minimum floor levels in areas vulnerable to flooding. Therefore, the 1% AEP inundation level including sea level rise for Christchurch City is 3.3 m (LVD) (Table 4-4). This inundation level is considered appropriate to assess the impacts of sea level rise on inundation for the purposes of this study.

Table 4-3 Summary of 1% inundation level components

Component	Value (m)[1]
1% AEP inundation level	1.85
2115 sea level rise projection	1.0
Freeboard	0.4
Total	**3.3 m**
Note: [1]Vertical Datum taken as Lyttelton Vertical Datum 1937 (LVD).	

The 3.3 m level (LVD) was plotted on a DTM for each of the settlements to identify the areas expected to be flooded by a 1% AEP storm event including sea level rise to the year 2115. Three separate LiDAR surveys were used to create the DTM:

- February 2012 LiDAR survey (post 23 December 2011 earthquake levels) flown by NZAM
- September 2011 LiDAR survey (post 13 June 2011 earthquake levels) flown by NZAM
- 2003 LiDAR data supplied by CCC. Note that the CCC LiDAR data was thinned before supply making it less accurate than the other LiDAR data.

The vertical accuracy for the February 2012 and September 2011 surveys is ±0.1 m. Each LiDAR survey was converted into a 2 m resolution bare earth DTM using a point binning method for cells with no data and TIN (triangulated irregular network) interpolation to fill voids. The resulting grids were then combined (overlaid) in order of priority (most recent to oldest) with the February 2012 survey having highest priority and the 2003 survey having lowest priority. Therefore, the DTM incorporates the latest survey data available and can be considered to be an acceptable representation of the post earthquake ground level.

[18] Storm surge refers to an elevated water level due to the combined effects of low barometric pressure and wind set-up pressure pushing water up against the shoreline.
[19] Freeboard refers to a safety factor expressed as a vertical measurement above the predicted flood level. Freeboard should allow for unknown factors such as wave action, hydrological effects and errors in topographic survey. For comparison the Federal Emergency Management Agency (FEMA) recommend a freeboard allowance of 1 foot for the purposes of planning for flood management.

The inundation modelling was undertaken using GIS. A connected 'bathtub' process was used, where a uniform depth of water is applied to the existing land surface. The output produced is a polygon representing the land flooded to a given depth that is connected to the sea. There are limitations to this method, particularly that it does not consider any dynamic coastal processes, which could change the extent of inundation (e.g. wave set up attenuation). Therefore, the method does not allow for tidal dampening and may over predict inundation levels in the upper sections of the river areas. However, we consider this method is suitable to identify high level extents of sea level rise inundation hazard on a region wide basis.

4.1.4.2 Results

The 1% AEP inundation level of 3.3 m (LVD) is plotted in Figures 4-4 to 4-11 for the Akaroa settlements to represent the impact of sea level rise on inundation to the year 2115. LiDAR is not available for the northern Banks Peninsula settlements of Port Levy and Okains Bay, and therefore the 1%AEP inundation level has not been plotted in these areas.

Inundation risks for the Banks Peninsula settlements are significantly increased by a projected sea level rise of 1.0 m by the year 2115. The 2115 inundation level will potentially cut off the main Christchurch-Akaroa Road (SH75) that runs through the settlement of Duvauchelle. Onewa Flat Road, Seafield Road, Duvauchelle School and the local campground will also be significantly impacted at this inundation level. The total amount of land inundated at Duvauchelle by a 1% AEP extreme tide including sea level rise is approximately 10.5 ha. A summary of the potential impacts of 1% AEP inundation event including sea level rise is outlined in Table 4-4.

Table 4-4 Public assets at risk from 1% AEP inundation event including sea level rise

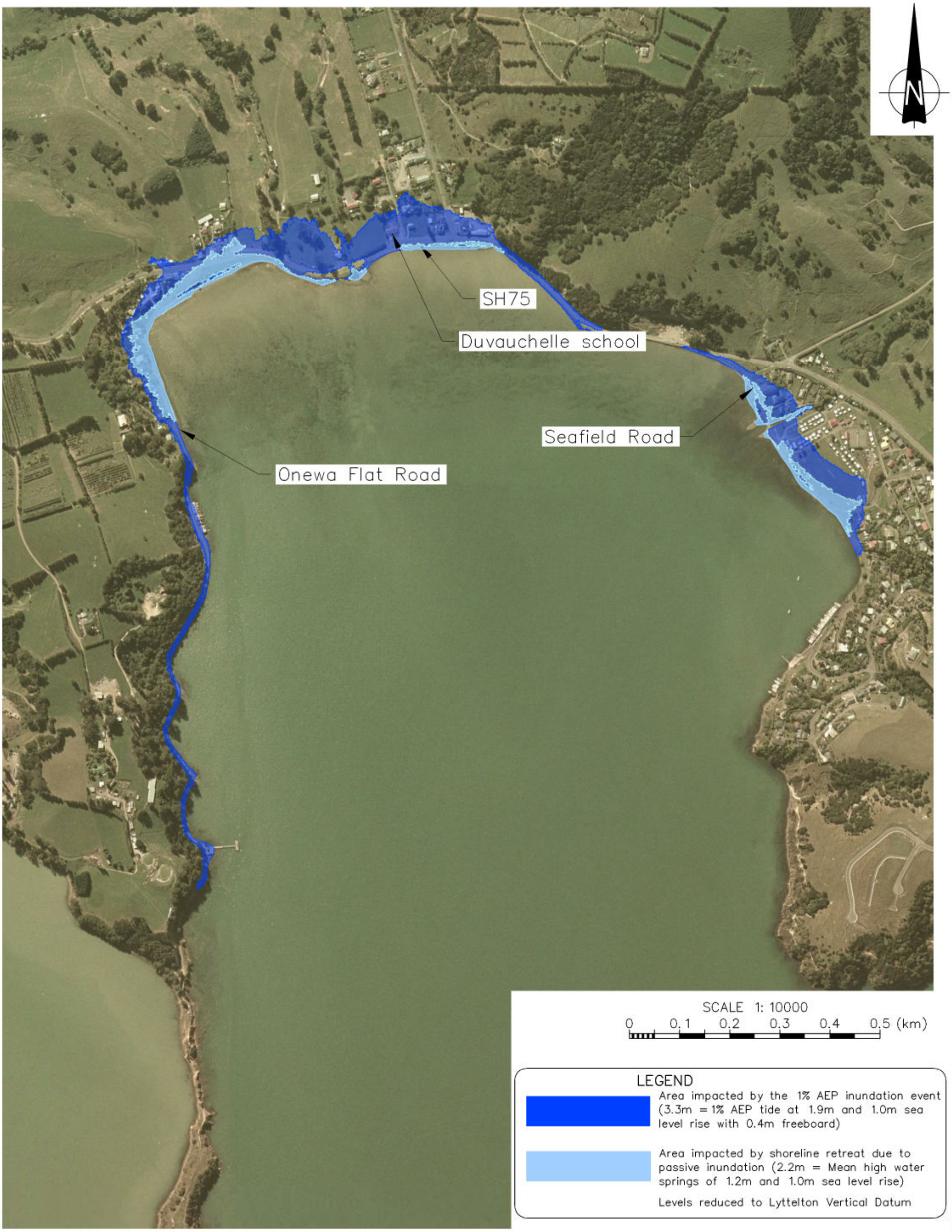
Settlement	Assets inundated	Area inundated (ha)[1]
Duvauchelle	SH75 Onewa Flat Road Seafield Road School	10.5
Akaroa	Jubilee Park Beach Road	13.3
Takamatua	Takamatua Bay Road Old French Road	7
Wainui	Wainui Main Road	3.4
Port Levy	Fernlea Point Road Wharf Road	No data
Okains Bay	Okains Bay Road	No data

Note: [1]Area above the current MHWS level

The central low lying area of Takamatua Bay is inundated, which impacts approximately 7 ha of land including significant sections of Takamatua Bay Road and Old French Road. Approximately 13.3 ha of the Akaroa settlement is flooded by the 1% AEP inundation event including Jubilee Park and a significant section of Beach Road. The settlement located in the Wainui Valley area situated near the centre of Wainui Bay will be flooded during the 1% AEP inundation event. The flooded area is approximately 3.4 ha which includes the Wainui Main Road. Due to the relatively steep foreshore, Wainui is not significantly affected by the permanent inundation level of 2.2 m by 2115.

Although the inundation impacts are unable to be plotted for the northern Banks Peninsula settlements, the 3.3 m inundation level is expected to flood a significant area of land. The access roads to the Port Levy settlement of Puari will be compromised during the 1% AEP inundation event.

Sea level rise is also likely to have an impact on the morphology of the Opara Stream located at Okains Bay. The increased tidal prism could result in greater currents at the outlet, which could alter the shoreline adjacent to the mouth of the Stream. The increased currents could also result in larger tidal deltas developing, which may result in wave refraction and a re-orientation of the shoreline position. The increased tail water level will also increase the terrestrial flooding area further up the valley. These impacts are also expected to occur at other smaller streams in the area.



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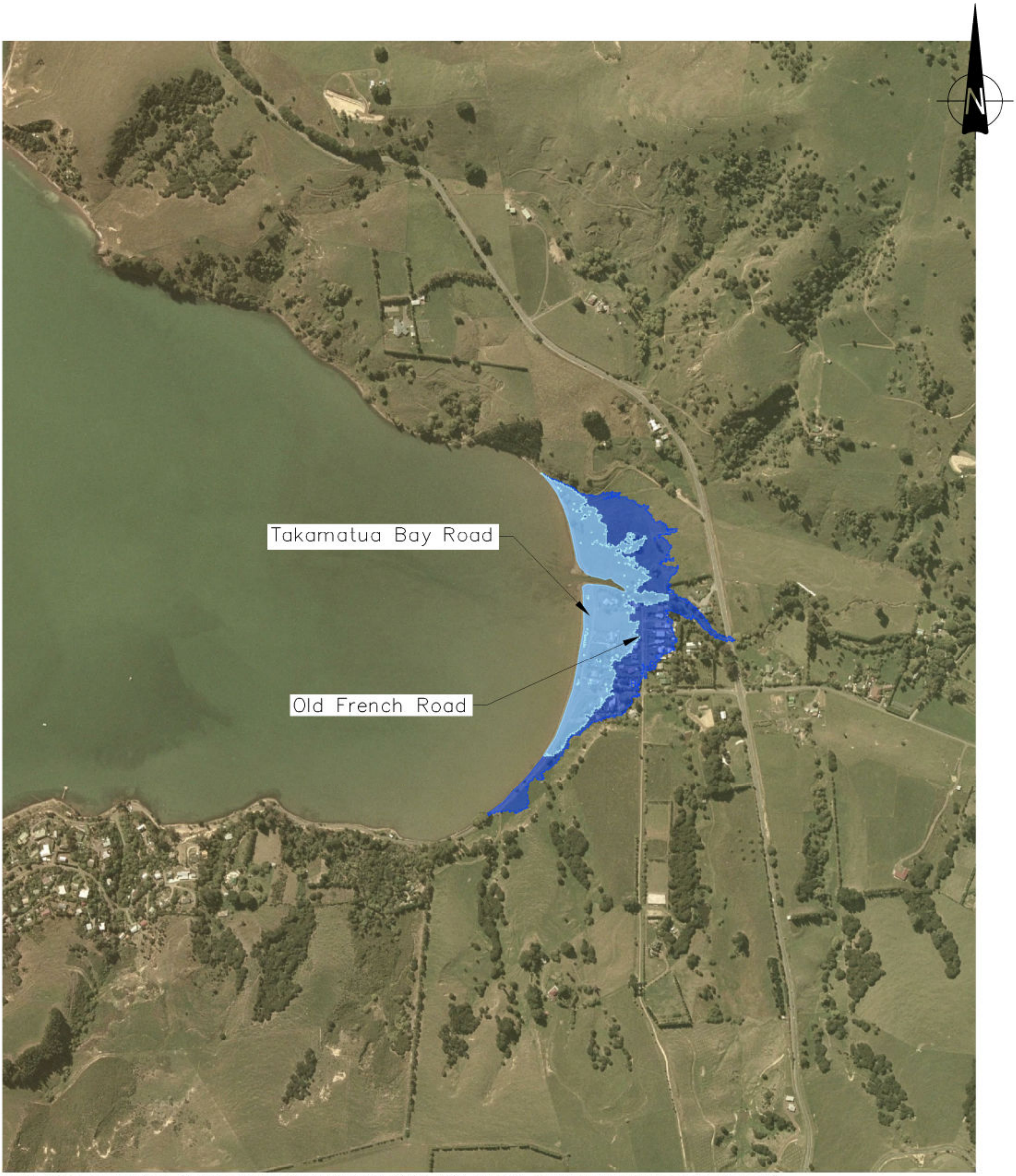
SCALES (AT A4 SIZE) 1:10,000

PROJECT No. 61707

CHRISTCHURCH CITY COUNCIL
EFFECTS OF SEA LEVEL RISE
DUVAUCHELLE
Site Plan

FIG. No. Figure 4–6

REV. 0



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LEGEND

- (dark blue) Area impacted by the 1% AEP inundation event (3.3m = 1% AEP tide at 1.9m and 1.0m sea level rise with 0.4m freeboard)
- (light blue) Area impacted by shoreline retreat due to passive inundation (2.2m = Mean high water springs of 1.2m and 1.0m sea level rise)

Levels reduced to Lyttelton Vertical Datum

SCALE 1: 10000

0 0.1 0.2 0.3 0.4 0.5 (km)

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SCALES (AT A4 SIZE) 1:10,000

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CHRISTCHURCH CITY COUNCIL
EFFECTS OF SEA LEVEL RISE
TAKAMATUA
Site Plan

FIG. No. Figure 4–7

REV. 0

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LEGEND

Dark blue	Area impacted by the 1% AEP inundation event (3.3m = 1% AEP tide at 1.9m and 1.0m sea level rise with 0.4m freeboard)
Light blue	Area impacted by shoreline retreat due to passive inundation (2.2m = Mean high water springs of 1.2m and 1.0m sea level rise)

Levels reduced to Lyttelton Vertical Datum

A3 SCALE 1: 5000

0 50 100 150 200 250 (m)

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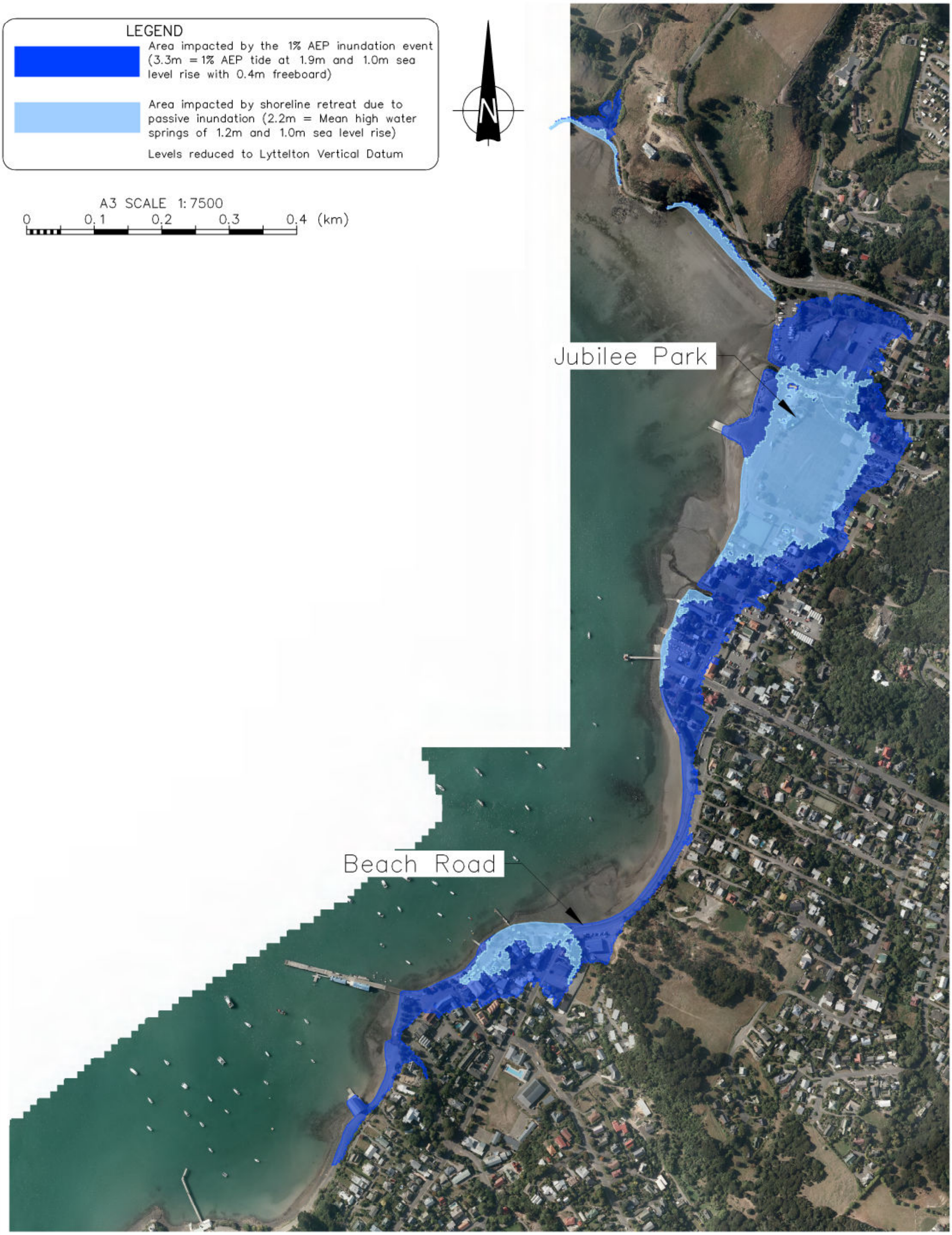
CHRISTCHURCH CITY COUNCIL
EFFECTS OF SEA LEVEL RISE
WAINUI
Site Plan

FIG. No. Figure 4–8

REV. 0



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Tonkin & Taylor Environmental and Engineering Consultants Level 1, 525 Cameron Road, Tauranga www.tonkin.co.nz	DRAWN	AMC	Jul.13	CHRISTCHURCH CITY COUNCIL EFFECTS OF SEA LEVEL RISE AKAROA Site Plan
	DRAFTING CHECKED	MCI	Nov. 13	
	APPROVED	MCI	Nov. 13	
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	SCALES (AT A4 SIZE) 1: 7,500			
	PROJECT No. 61707			FIG. No. Figure 4-9 — REV. 0

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Note: Site plan only. Areas impacted are not shown due to lack of LiDAR coverage

Tonkin & Taylor Environmental and Engineering Consultants Level 1, 525 Cameron Road, Tauranga www.tonkin.co.nz	DRAWN AMC Jul.13 DRAFTING CHECKED MCI Nov. 13 APPROVED MCI Nov. 13	CHRISTCHURCH CITY COUNCIL EFFECTS OF SEA LEVEL RISE OKAINS BAY Site Location Plan	
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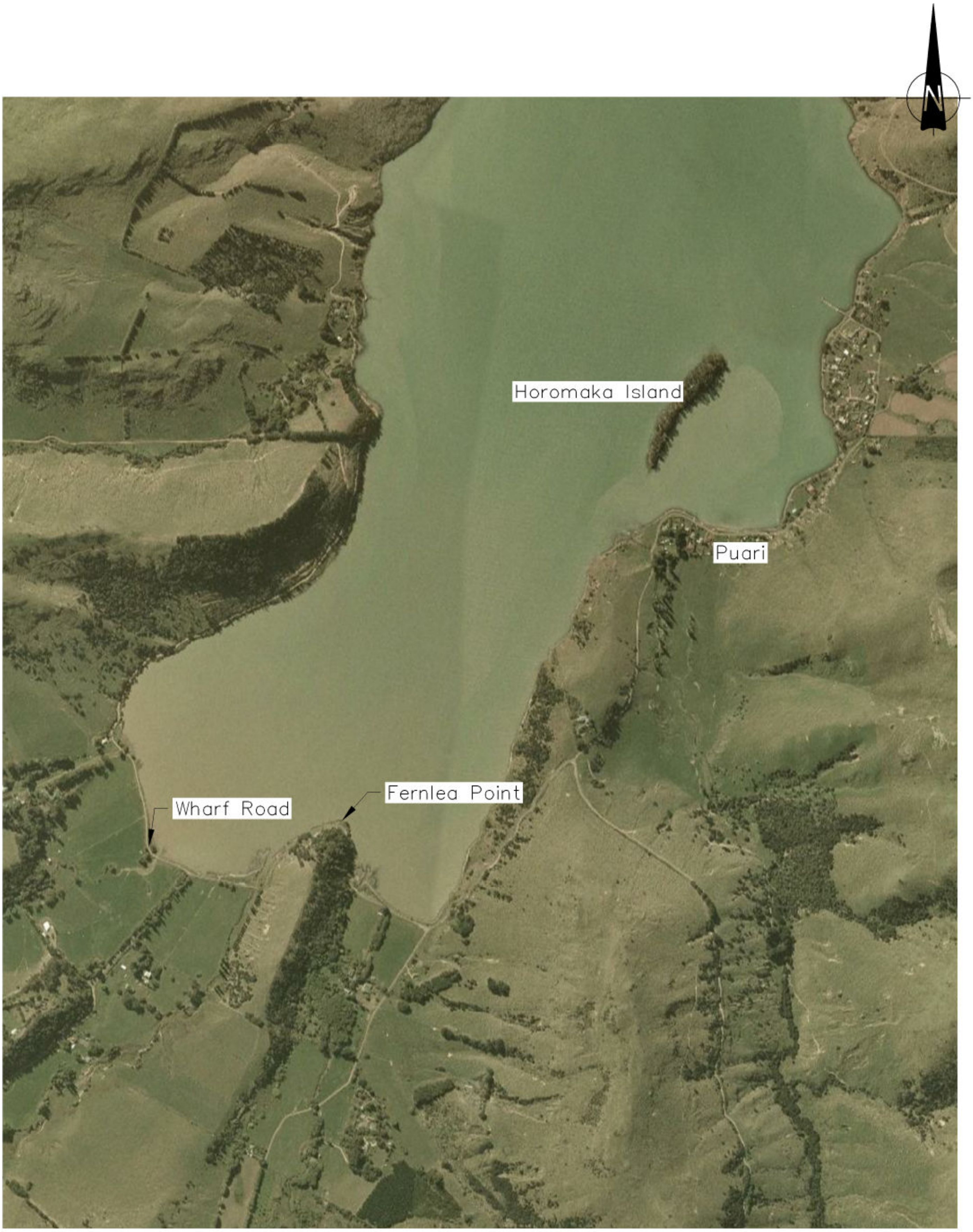
	SCALES (AT A4 SIZE) 1:15,000		
	PROJECT No. 61707	FIG. No. Figure 4– 10	REV. 0



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Note: Site plan only. Areas impacted are not shown due to lack of LiDAR coverage

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	PROJECT No. 61707	FIG. No. Figure 4–11	REV. 0

4.2 Christchurch Dunes

4.2.1 Site description

The Christchurch Dunes area described in this report is the open coast sandy beach located in southern Pegasus Bay between the Waimakariri River mouth in the north and the Avon Heathcote Estuary mouth to the south. The Christchurch Dunes area is approximately 20 km long and the sandy beach is backed by a vegetated dune system that ranges in height from 5 m to 9 m above MSL. The lower dune heights are located adjacent to Southshore at the southern end of the Brighton Spit.

4.2.2 Previous assessments

The supply of sand material to the Christchurch Dune area is almost exclusively from the suspended sediment load of the Waimakariri River (Hicks, 1993). Hicks (1993) estimated the net supply of sand material from the Waimakariri River to be approximately 360,000m^3/year. Approximately 50% of this volume is estimated to be transported south to the Christchurch Dune area (180,000m^3/year), and the remainder being transported to the northern Pegasus Bay beaches.

NIWA (2002) completed a wave refraction and longshore transport study for the Canterbury open coast based on modelling the nearshore wave environment. The study shows the sheltering effect of Banks Peninsula significantly reduces wave height along the Christchurch Dune area from the prevailing wave climate. The prevailing wave climate from the south to south east is expected to result in a net northward sediment transport along the majority of the Pegasus Bay coastline (Figure 4-12).

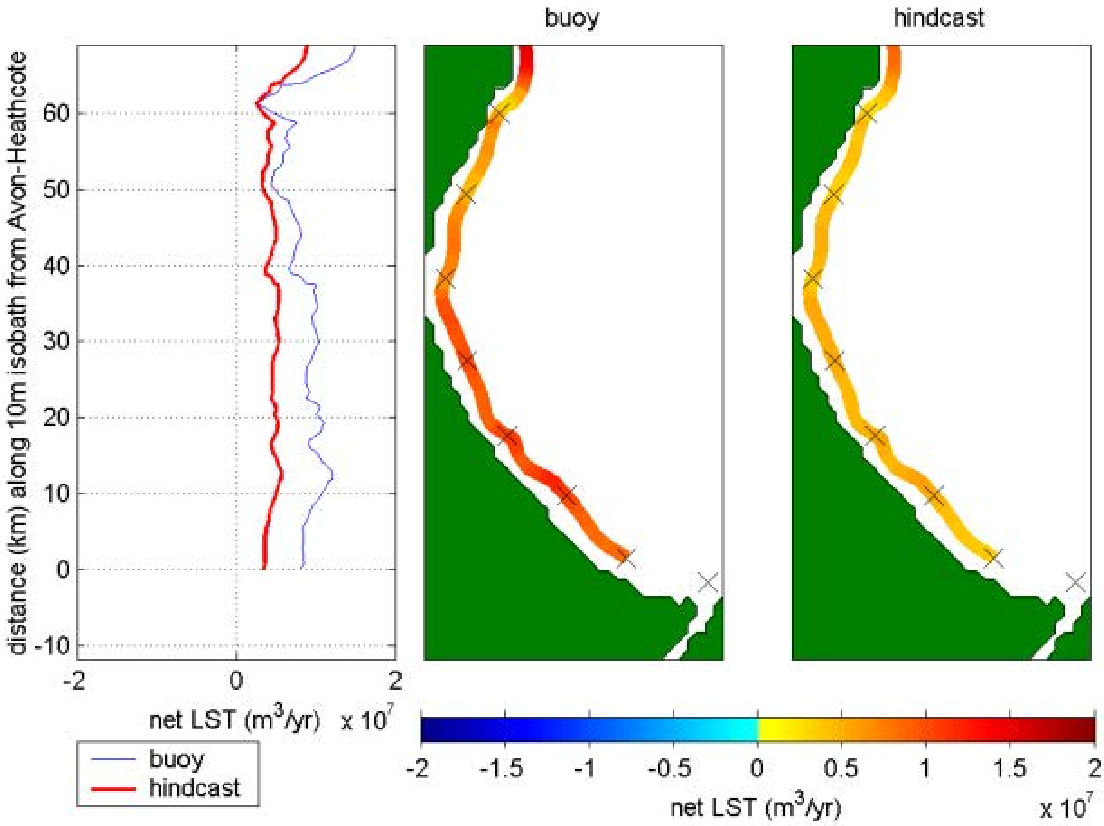


Figure 4-12 Mean net longshore sediment transport in Pegasus Bay, for wave climate derived from wavebuoy and hindcast data. Values are plotted in the left panel as a function of distance along the 10

m isobath from an origin off the Avon-Heathcote estuary. Positive values (red) denote northward transport (source: NIWA, 2002)

The model predicts a net northerly longshore sediment transport along the Christchurch Dunes area based on both the recorded wave buoy data and the 20 year hindcast wave data. NIWA (2002) state a key issue to resolve is the conflict between the model results and other indicators that suggest a net southerly longshore sediment transport along southern Pegasus Bay including the Christchurch Dunes area. The indicators include the existence of Brighton Spit and reported measurements of historical shoreline progradation. The NIWA (2002) study did not assess the effects of sea level rise on wave refraction or longshore sediment transport.

Hicks (1993) considered a mean sea level rise of 0.5 m would reduce wave refraction of southerly swell events with less wave re-orientation due to an increase in water depth. Due to less wave re-orientation, northerly longshore sediment transport would be increased with a corresponding reduction in southerly transport. For the Christchurch Dunes area this could result in a reduction in the longshore sediment transport south from the Waimakariri River, which is expected to be amplified with a sea level rise projection of 1.0 m by the year 2115.

4.2.3 Effect of sea level rise on beach profiles

4.2.3.1 Methodology

The effect of sea level rise on beach profiles is a relatively unexplored area of research in New Zealand. International research suggests sea level rise will alter the balance of sediment erosion and deposition in many coastal areas. The most widely accepted model for open coast beach profile response to sea level rise is that of Bruun (1962, 1988). The EnviroLink best practice guidelines for defining coastal hazard zones in New Zealand states the Bruun Rule is applicable to open coast sandy beaches (Ramsey *et, al*; 2012). The Bruun Rule has also been tested in the Environment Court and was accepted as a suitable precautionary approach to predict the beach response to sea level rise for the purposes of coastal hazard planning *(*Skinner v Tauranga District Council A 163/02).

The Bruun equilibrium model assumes that as sea level is raised, the equilibrium profile is moved upward and landward conserving mass and original shape according to the following assumptions:

- The upper beach is eroded due to the landward translation of the profile
- The volume of material eroded from the upper beach is balanced by equivalent deposition offshore
- The rise in the nearshore bottom as a result of this deposition is equal to the rise in sea level.

The Bruun equilibrium model (Bruun Rule) has remained the principal method for establishing shoreline response to sea-level rise. The Bruun Rule relationship essentially reduces to a translation of the profile up a regional slope and is defined by Equation 2 below:

$$R = \frac{L_*}{B + h_*} S \qquad (2)$$

Where:

R = the landward retreat

h_* = the typical depth of sediment exchange

L_* = the horizontal distance from the shoreline to the offshore position of h_*

B = the height of the dune crest within the eroded backshore

S = sea level rise.

The Bruun Rule is considered to provide an acceptable "order of magnitude" estimate of shoreline retreat distance due to a rise in sea level. However, it is governed by simple, two-dimensional conservation of mass principles and is limited in its application in the following aspects:

- The rule assumes that there is an offshore limit of sediment exchange or a 'closure depth' beyond which the seabed does not raise with sea level
- The rule assumes no offshore or onshore losses or gains
- The rule assumes instantaneous profile response following sea-level change
- The rule assumes an equilibrium beach profile where the beach may fluctuate under seasonal and storm influences but returns to a statistically average profile (i.e. the profile is not undergoing long term steepening or flattening)
- The rule does not accommodate variations in sediment properties across the profile or profile control by hard structures such as substrate geology or adjacent headlands.

The topographic components of the Bruun Rule where calculated from LiDAR (B – dune crest height) and digital LINZ bathymetry charts (L – offshore distance to h).

The major uncertainties that remain in using the Bruun Rule include the definition of a closure depth (h_*), the cross shore slope and the lack of any lag time between sea level change and profile response.

While some have questioned the actual existence of a closure depth (Cooper and Pilkey, 2004), the Bruun Rule is not necessarily reliant on its physical existence. While long term sediment exchange may occur to very deep water depths (i.e. the 'pinch-out' point), this "ultimate limit" profile adjustment extent is only valid if either the profile response is instantaneous or if sea-level changes and then stabilises with the profile 'catching up'. As sea level rise is expected to be ongoing and a lag in profile response is apparent, the outer limit of profile adjustment is likely to be left behind. The closure depth can therefore be more realistically defined as the point at which the profile adjustment can keep up with sea-level change and becomes a calibration parameter in lieu of an adequate depth dependent lag parameter.

Various definitions of closure depth have been presented in the literature including an 'ultimate limit' definition of closure of 3.5 x H_{sb} (Bruun, 1988) where H_{sb} is related to an extreme significant wave height (50 or 100 year ARI) or twice H_{sb} (USACE, 2006). However, as discussed above, these "ultimate limit" closure depths are likely to over predict retreat during ongoing sea level rise.

The method of Hallermeier (1983) is one of the most widely accepted for defining closure depths. Hallermeier summarised that the inner closure depth (**h_c**) is a function of sediment characteristics and local wave climate and for a sandy beach can be approximated as:

$$h_c = 2.28H_e - 68.5(H_e^2 / gT_e^2) \qquad (3)$$

Where:

h_c = is the closure depth below mean low water spring,

H_e = is non-breaking significant wave height exceeded for 12 hours in a defined time period, nominally one year, and T_e is the associated period.

Therefore, the d_l closure depth term is used to define both the typical depth of sediment exchange (h_*) and the horizontal offshore distance to this depth (L_*) as input terms to the Bruun Rule calculation (Equation 3).

For this study the wave climate parameters of H_e and T_e were based on the ECan wave buoy data recorded over a 14 year period between 1999 and 2013. The wave buoy is located in deep water east of Banks Peninsula. Waves from the south east to south west quadrants are expected to undergo refraction prior to reaching the site which is sheltered from this direction by Banks Peninsula. A reduction factor of 0.25 was applied to the ECan wave buoy data from the south east to south west quadrants based on nearshore modelling results presented by NIWA (2002). The resulting H_e and T_e parameters are 4.2 m and 10.8 s respectively. Based on these wave climate parameters the closure depth is calculated as 8.5 m below mean low water spring using the Hallermeier method defined in Equation 3.

4.2.3.2 Results

A rise in mean sea level is expected to result in shoreline recession over time. The Bruun Rule was used to estimate an "order of magnitude" distance of long term shoreline retreat due to sea level rise. The results outlined in Table 1 are a retreat distance measured horizontally from the current dune toe. The results are presented in both the calculated shoreline retreat due to a sea level rise of 1.0m expected over the 100 year planning timeframe, and also as a range to reflect the uncertainty in predicting sea level rise over the next 100 years (Table 4-5). The range is based on a lower and upper sea level rise projection of 0.5m and 1.5m respectively. Note the rate of shoreline retreat is not expected to be a linear trend, rather the rate is expected to increase in time in line with sea level rise predictions.

Table 4-5 Summary of estimated shoreline retreat due to sea level rise

Site	ECan Profile	Dune height (m)	Slope	Sea level rise (m)	Shoreline retreat (m)	Shoreline retreat range (m)
Spencer Park	C1755	5.0	0.01	1.0	70	30-100
Bottle Lake	C1400	9.0	0.01	1.0	50	30-80
Effingham Street, North New Brighton	C1065	5.1	0.01	1.0	70	30-100
Rawhiti Road, New Brighton	C0952	8.3	0.01	1.0	60	30-80
Rodney Street, New Brighton	C0815	8.6	0.01	1.0	60	30-80
Jellico Street, South New Brighton	C0600	8.7	0.01	1.0	60	30-80
Heron Street, Southshore	C0471	6.9	0.01	1.0	60	30-90

Due to the uncertainties in ongoing sediment supply from the Waimakariri River (Section 4.2.2) we have adopted a conservative approach of assuming the system is in dynamic equilibrium with no expected future long term trend of progradation. Therefore, the retreat rates provided in Table 4-5 have not been reduced by reported historic rates of progradation (as undertaken in the T&T original report) and can be considered to be a conservative estimate of shoreline position.

This is the main reason for the differences between the shoreline retreat results presented in the two reports.

The majority of the existing development within the Christchurch Dunes area is set back from the current dune toe by a distance of between 50 to 130 m. The main CCC asset at risk from shoreline retreat due to sea level rise is the northern section of Marine Parade located between Shackelton Road and Beach Road. This section of Marine Parade is approximately 3.2 km long and is located within 60 m of the current dune toe. The additional existing CCC assets located seaward of this section of Marine Parade are the New Brighton Community Library (Te Kete Wānanga o Karoro) and the North New Brighton Memorial and Community Centre including the associated car parking areas. The dune crest elevation is also lower in these areas which will most likely result in a greater distance of shoreline retreat than adjacent areas.

We do not expect a rise in sea level to increase wave height and storm cut significantly, because the nearshore water depth is predicted to remain constant assuming there is no time lag between the sea level rise and the profile response. A rise in mean sea level is not expected to have any effect on inundation risks from storm events due to the existing dune crest elevations being above predicted storm surge levels. However, a rise in mean sea level by 1.0 m could increase the impact of a tsunami event. Natural dune features are known to be effective in dissipating tsunami waves. A rise in mean sea level by 1.0 m may result in a tsunami wave overtopping the existing dune crests under some scenarios. We recommend that future studies assessing tsunami risk consider the effect of a sea level rise of 1.0 m to the year 2115.

4.3 Clifton, Scarborough and Taylor's Mistake

4.3.1 Site description

The three open coast beaches of Clifton, Scarborough and Taylor's Mistake are located south of the Avon Heathcote Estuary mouth. Clifton is a relatively flat estuary sandy beach, which is approximately 900 m long and has developed an incipient foredune at the eastern end. The western 400 m long section of Clifton Beach is backed by a rock revetment protecting Main Road and has no high tide beach. The eastern 500 m of Clifton Beach is a sandy beach which includes a vegetated dune system. Scarborough is the main sandy beach at Sumner which is approximately 1.2 km long and has no high tide beach or dune system. Scarborough Beach is backed by a rock revetment structure along the entire length. Taylor's Mistake is a sandy beach with a dune system that is approximately 500 m long.

4.3.2 Previous assessments

We are not aware of any prior assessments relating to the effect of sea level rise on the beaches south of the estuary.

4.3.3 Effect of sea level rise on beach profiles

Open coast beaches are expected to undergo shoreline retreat as a response to accelerated sea level rise. The shoreline retreat due to sea level rise at both Scarborough and Taylor's Mistake can be assessed using the Brunn Rule. Section 4.2.3.1 provides a full description of the Bruun Rule method used for this assessment. The results are presented for both the calculated shoreline retreat due to a sea level rise of 1.0m expected over the 100 year planning timeframe, and also as a range to reflect the uncertainty in predicting sea level rise over the next 100 years (Table 4-6). The range is based on a lower and upper sea level rise projection of 0.5m and 1.5m respectively.

Table 4-6 Summary of estimated shoreline retreat due to sea level rise

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

Clifton Beach is located adjacent to the Avon-Heathcote Estuary mouth and is connected to the estuary ebb tide delta sediment system. As the estuary tidal prism and tidal velocities increase with rising sea level, the entrance channel is likely to change. The higher tidal velocities are likely to cause scouring and channel widening. As the entrance channel widens the volume and area of both the flood and ebb tide deltas are expected to grow and adjacent beaches may experience some additional erosion in response to these changes (MfE, 2008).

Due to the large uncertainties associated with predicting shoreline response adjacent estuary mouths, we do not consider the Bruun Rule can be applied to estimate future shoreline retreat for Clifton Beach. We concur with the T&T original report conclusion that sea level rise is likely to result in a general lowering of the foreshore at Clifton causing scour at the base of the revetment and a retreat of the dune system. The western half of the Clifton Beach system may be squeezed out as Main Road restricts the accommodation space for the beach to retreat landward. Therefore, the beach is likely to lower over time and the Main Road erosion protection structure is likely to require upgrade works to prevent undermining over the 100 year planning time frame.

Scarborough Beach is backed by a rock revetment and there is no high tide beach or dune system. Therefore the potential shoreline retreat from sea level rise is expected to result in a general lowering of the foreshore causing scour at the base of the revetment. If regular maintenance and upgrade works are not undertaken we would expect the Scarborough Beach seawall to fail over the planning timeframe of 100 years. Under this scenario we would expect the shoreline to retreat a distance in the order of 60 m which would result in The Esplanade needing to be abandoned.

The Surf Clubs located at both Scaborough Beach and Taylor's Mistake are within the estimated shoreline retreat distance and are likely to require relocation at some time over the next 100 years.

4.3.4 Effect of sea level rise on inundation

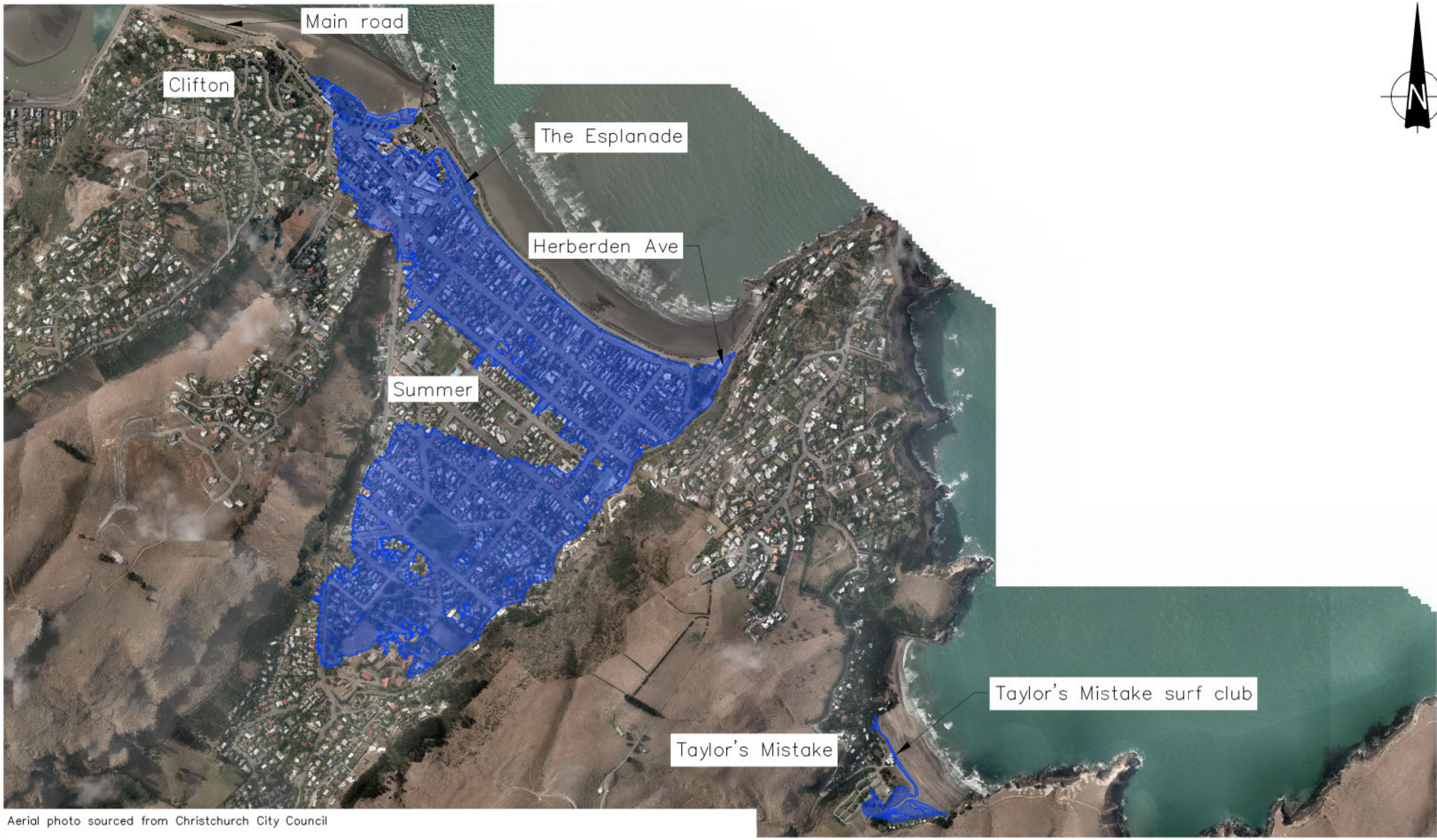
Sea level rise will increase the frequency of coastal inundation due to storm events. The 1% AEP inundation level including sea level rise of 1.0 m to the year 2115 is 3.3 m (LVD). Refer to Section 4.1.4.1 for a full description of the methodology used to calculate the 1% AEP inundation level. The 3.3 m contour has been plotted on a DTM of the three beaches including the inland catchment area to illustrate the impacts of sea level rise on inundation (refer to Figure 4-13). Refer to Section 4.1.4.1 for a full description of the methodology used to produce the DTM.

Although the majority of both public and council assets located at Taylor's Mistake are situated above the 1% AEP inundation level, the Surf Club is likely to experience some flooding during this event. The Sumner Surf Club is located on the active beach face and is also likely to be inundated during a 1% AEP storm event.

Scarborough Beach is characterised by a flat low tide beach backed by a sloped rock revetment, with no high tide beach or dune system. The revetment crest elevation is approximately 3.5 m to 4.0 m above LVD and provides a solid barrier to the 1% AEP inundation level along the majority of the structures length. However, there are low points at either end of the revetment structure at

Heberden Ave to the east and The Esplande to the west. These two low points will allow overflow of the 1% AEP inundation level into the low lying backshore area of both Sumner and Clifton. Raising the road elevations in these two areas may be required when the inundation risk is deemed intolerable.

Note the 3.3 m LVD 1% AEP inundation level is a “still water depth” and does not include wave setup and runup processes. The Scarborough revetment is likely to be overtopped by wave setup and runup during a 1% AEP event, resulting in seawater flowing over The Esplanade and potentially flooding at least the first row of houses in this area.



Aerial photo sourced from Christchurch City Council

LEGEND

Area impacted by the 1% AEP inundation event (3.3m = 1% AEP tide at 1.9m and 1.0m sea level rise with 0.4m freeboard)

Levels reduced to Lyttelton Vertical Datum

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FIG. No. Figure 4– 13

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4.4 Lower Waimakariri River and Brooklands Lagoon

4.4.1 Previous assessments

We are not aware of any previous assessments relating to the effect of sea level rise on either the lower Waimakariri River or Brooklands Lagoon (post-dating the T&T original report).

4.4.2 Lower Waimakariri River

4.4.2.1 Site description

The lower Waimakariri River is defined as the section within the tidal reach located at the northern boundary of CCC. Refer to Figure 1-1 for a location plan.

4.4.2.2 Sedimentation

The Waimakariri River is the main sediment supply source for Pegasus Bay. The lower river deposition zone begins some 2.5 km upstream of the mouth due to the change in river gradient at this location. The position of the deposition zone is unlikely to be notably affected by sea level rise.

Sediment movement in the lower Waimakariri River is influenced by the tidal range at the coast. A raised sea level will reduce the river gradient, which has the potential to increase sediment deposition (mostly sand and silt) in the lower river reach. However, scouring by flood events removes much of the deposited material and transports it to the coast, as currently occurs. If the magnitude and/or frequency of flood events changes as a result of climate change, then this is likely to have a larger effect on sedimentation than the change in sea level rise alone.

4.4.2.3 Water levels

As the mean sea level rises there will be an increase in predicted flood level in the tidally affected reach. The maximum water level change in the vicinity of the mouth is likely to be of similar magnitude to the predicted sea level rise (1.0 m), and will diminish with distance upstream. It would be considered conservative to apply the same increase in sea level to predicted flood levels upstream, which would potentially reduce the effectiveness of the existing flood scheme.

4.4.2.4 Salinity effects

The extent of tidal influence upstream will increase with sea level rise. As saline water has a greater density than fresh water, a saline ‘wedge’ usually undercuts the freshwater in its migration upstream. The extent of the saline migration is most pronounced during low flows and high tides. The effect of sea level rise on saline migration is the extension of the saline wedge further upstream from its current range. Other climate change effects may contribute to additional impacts. For example, if the frequency of low flows is increased from present, then there may be more regular saline migration to positions further upstream than at present.

As the saline extent during low flows is expanded with time, a gradual change in stream bank flora would be expected. This may result in some bank instability and could contribute to bank slumping, contained to low flow channels. Existing stopbanks and other flood control measures are mostly located back from the low flow channel, and are therefore unlikely to be notably affected by saline effects relating to sea level rise.

4.4.3 Brooklands Lagoon and Styx River

4.4.3.1 Site description

Brooklands Lagoon is located south of the Waimakariri River mouth. It extends through a historic entrance channel of the Waimakariri River, formed when the river mouth was situated approximately 6 km south of the current position. Brooklands Lagoon is approximately 4.5 km long and is approximately 800 m at its widest point. Refer to Figure 1-1 for a location plan.

4.4.3.2 Sedimentation

Increased sediment deposition in the tidally affected reach of the Lower Waimakariri River could have effects on the interface with Brooklands Lagoon. Similarly a change to the sediment carrying characteristics of the Lower Styx River could also have effects in this area. To some degree the likely effects could be opposite, with increased sediment deposition in the Lower Waimakariri River being countered by reduced sediment deposition in the Lower Styx River, downstream of the Harbour Road tide gates.

The tidal compartment within Brooklands lagoon will be subject to change in response to sea level rise, and this is likely to have effects on the mouth sediment equilibrium. Some changes to sandbank formation may be observed in this area, including the flood tide delta.

4.4.3.3 Water Level Changes

The Lower Styx Ponding Area is drained by tide gates at Harbour Road. The Lower Styx Ponding Area extent is defined in the Christchurch City District Plan City planning maps 1B, 4B and 11B. We understand that the critical rainfall event duration for this area is of the order of 18 hours (i.e. rainfall event duration that results in the highest peak water levels), which will span several tide cycles. Draining of the Lower Styx Ponding Area in the wake of a significant rainfall event occurs only when the pond water level exceeds the downstream tide level. If this downstream tide level is increased (i.e. sea level rise occurs), then the period over each tide cycle during which the tide gates are able to open will be reduced. This could affect the assessment of critical rainfall duration in this area, with longer duration events having less time over each tide cycle during which drainage may occur.

In addition, peak water level attained in the Lower Styx Ponding Area (in response to significant rainfall events) is likely to be increased as a result of sea level rise. The amount by which peak water level is increased is likely to be comparable to the magnitude of sea level rise for each rainfall duration considered. However, if critical rainfall duration is changed as a result of sea level rise, then the amount by which peak water level for an event of given Average Recurrence Interval (ARI) cannot be estimated without undertaking further flood modelling of the Styx River system.

In any such modelling, the critical factor is in the representation of the tide gates behaviour at Harbour Road. Typically models can be built to prevent negative flow, and allow for full flow through the cross sectional area as soon as a positive head difference exists across the gates. In reality the degree of gate opening is dependent on this head difference, with a small head difference leading to smaller gate opening and higher head losses (i.e. smaller flow area and higher velocity). Sea level rise will result in partial gate opening occurring more frequently than is currently the case. This could result in peak water levels in the Lower Styx Ponding Area being higher in the future, by an amount that exceeds the sea level rise prediction.

Examination of the available topographical information (i.e. LiDAR derived DTM) indicates that spill to the Brooklands Lagoon over Lower Styx Road may occur, and that this could effectively limit the water level able to be attained in the Lower Styx Ponding Area. Even though some lower-level hydraulic connections are potentially available, the level at which significant spill would occur would not be higher than the predicted 2115 MHWS level (2.2 m for sea level rise of 1.0 m). Therefore, flooding of the Lower Styx Ponding Area may occur via overflow from Brooklands Lagoon in extreme sea level events. Because of this, the peak flood level able to be attained in an extreme event may be able to be limited by allowing free spill to Brooklands Lagoon, rather than by ensuring that all outflow from the Lower Styx Ponding Area occurs via the tide gates at Harbour Road.

4.4.3.4 Erosion and Inundation

Water levels in Brooklands Lagoon will increase as sea level rise occurs, and the amount of any increase is likely to mirror the actual sea level rise. This is in accordance with the T&T original report, in which relative mouth widths of Brooklands Lagoon and the Waimakariri River were considered. Since the mouth widths are sufficient to allow the required volume of water to enter Brooklands Lagoon on a flood tide, there will be little tidal damping observable. Due to the flat terrain surrounding Brooklands Lagoon, sea level rise is likely to result in an enlarged lagoon footprint at high tide.

Sea level rise will increase the frequency of coastal inundation due to storm events. The 1% AEP inundation level including sea level rise of 1.0 m to the year 2115 is 3.3 m (LVD). Refer to Section 4.1.4.1 for a full description of the methodology used to calculate the 1% AEP inundation level. Approximately 1,640 ha is estimated to be inundated during a 1% AEP storm event (Figure 4-14). This extreme inundation level of 3.3 m is expected to reach the settlement of Kainga.

Bank erosion and shoreline retreat due to sea level rise can be estimated using the passive inundation method (EShorance, 2010). Passive inundation is simply the position of the high tide level (MHWS) in 2115 allowing for a sea level rise of 1.0 m. Refer to Section 4.1.3.1 for a full description of the passive inundation method. Approximately 700 ha of land is expected to be lost as the shoreline retreats inland to the 2.2 m contour by the year 2115 (Figure 4-14). This area includes the abandoned Brooklands Township, which is below the predicted 2115 MHWS level of 2.2 m.

4.4.3.5 Salinity

The tide gates at Harbour Road on the Lower Styx River will continue to inhibit saline progression upstream. Therefore, no changes to salinity within this system are anticipated, unless overflow from Brooklands Lagoon is able to occur. This could occur during the 1% AEP inundation event, where much of the Lower Styx Ponding Area would be inundated with saline water (Figure 4-14). Drainage of this event via the tide gates at Harbour Road would likely take several tide cycles and significant pasture vegetation die off is expected in this situation.

4.4.3.6 Ecology

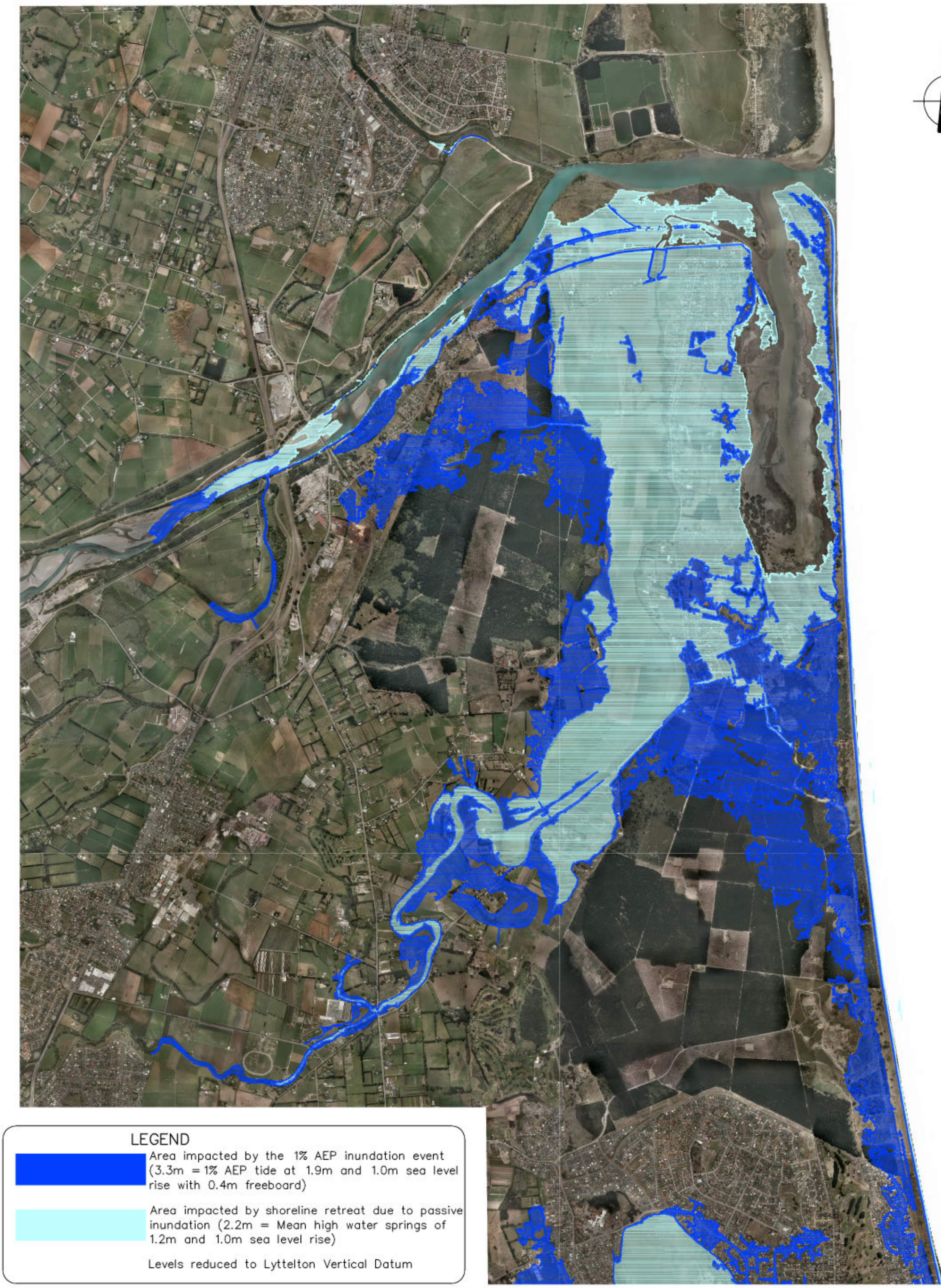
As sea levels rise under natural conditions vegetation communities are expected to migrate landward to maintain their position relative to the water level (EW, 2007). However, with accelerating rates of sea level rise and the impacts of human activity, there are a number of reasons why vegetation may not be able to survive (EShorance, 2010):

- The rate of change may be too fast for some vegetation communities. As water levels rise it will take time for the existing communities to adjust. If the water rises faster than the community can migrate, the community may disappear altogether.
- The geological and topographic conditions are not compatible with the vegetation. Vegetation communities generally occur only within a defined area. For example, a saltmarsh community is unlikely to migrate landward if the area behind is steep or rocky.

- Development landward of existing coastal vegetation communities may hinder inland migration as sea level rises. A plant species or community will only be able to migrate when there is adequate space and conditions are suitable. Modifications, such as roads, seawalls, or buildings, may block migration or alter the hydrological and soil conditions.

The summary of ecological effects outlined in the T&T original report remains valid. The key ecological effects of a 1.0 m rise in mean sea level on the Brooklands Lagoon ecology are:

- existing tidal mudflats will be permanently drowned and will migrate into existing salt marsh areas
- existing salt marsh environments will re-establish in higher elevations in areas where pasture and salt meadow currently exist
- fish and bird species are expected to transition to new environment locations and should not be adversely effected.



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BROOKLANDS LAGOON
Site Plan

FIG. No. Figure 4–14

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4.5 Lower Heathcote and Avon Rivers

4.5.1 Site description

The Avon River is a remnant flood channel of the Waimakariri River floodplain. It is spring fed and also receives quick flow runoff from the central city impervious areas in response to rainfall. The substrate in the Avon River channel ranges from gravels and cobbles in some reaches through the Central City area to sands and muds in lower reaches. The Avon River passes through developed suburbs and is constrained between stopbanks in lower reaches.

The Heathcote River also has origin as a flood channel, but is connected with the Cashmere Stream which drains the northern slopes of the Port Hills. The Heathcote River is spring fed and passes through the southern parts of Christchurch City. Therefore, this waterway receives runoff from largely undeveloped Port Hills catchments as well as from urbanised parts of Christchurch. A key feature is the upstream tributaries of Cashmere Stream and the Upper Heathcote River. These differ greatly in character with Cashmere Stream being of high water quality during low flow times, but receiving quick flow runoff from hills catchments in response to rainfall. The Upper Heathcote River catchment is significantly flatter with a slower rainfall runoff response.

4.5.2 Previous assessments

While the stopbanks on the Avon flood plain provide adequate flood protection for most properties, they are likely to be overtopped with greater frequency in the future due to the projected sea level rise. The CCC undertook a study in 2003 to examine the effects of sea level rise on the Avon River catchment and assess how the potential risks could be managed (MfE, 2003).

The study focused primarily on an economic analysis of likely damages, and the response options available to local government to mitigate the effects of a 1% AEP storm event including a sea level rise of 0.4 m. The total cost of this inundation scenario on the Avon River catchment with the current protection structures in place is $163,000,000. The study concludes that planning responses are likely to be the most cost efficient mitigation solution to reduce the risk over time. Upgrading the Hulverstone stopbank was the only protection response projected to show a positive cost benefit at the time of the study.

4.5.3 Waterway form

We acknowledge that sea level rise is one of several potential effects of climate change. Another potential effect of climate change is the change in rainfall intensity and depth for specific frequency events. These could have notable effects on channel capacity in being able to convey design flows. Similarly, sea level rise could have effects on channel capacity in that the available energy gradient will be reduced as sea level rises. In this report the effects of sea level rise on waterway form are examined in isolation of the effects of changes to rainfall intensity and frequency due to climate change.

Relationships representative of the waterway form of alluvial channels indicate that channel width ($\boldsymbol{w}$) is proportional to the product of energy gradient ($\boldsymbol{s_e}$) and dominant discharge ($\boldsymbol{Q}$). Richards (1982) indicates the following waterway form relationship:

$$\boldsymbol{w} \propto \boldsymbol{s_e}.\boldsymbol{Q} \qquad (4)$$

The dominant discharge is generally taken as the bank full discharge that is representative of peak flow events that contribute to sediment transport, and is a major variable that controls channel form.

If all other factors are kept constant, a rising sea level scenario will result in reduction in energy gradient in the Avon and Lower Heathcote Rivers. Two possibilities arise from this:

- assuming the dominant discharge remains constant, the waterway width will increase with sea level rise
- if the channel width is kept constant then dominant discharge (analogous to flood carrying capacity) will decrease with sea level rise.

Another likely scenario is that a rising sea level will result in gradual changes to the waterway form on a global scale. These changes will also be an effect of other changes in climatic conditions. Therefore, there is likely to be a continuous evolution of the waterway form both in localised cross sections and in long section along the entire length of the Lower Avon and Heathcote Rivers. The rate of these changes will be amplified by a (relatively) rapid rise in sea level. In areas where some evolution of channel form is restricted by structures, additional management and maintenance effort may be required into the future.

The following impacts emerge with regard to waterway form changes as a result of sea level rise:

- channel width is likely to increase by natural processes as sea level rise occurs
- flood carrying capacity is likely to be reduced where channel width increases are constrained, and additional erosion of banks in these areas of constraint is likely to occur
- recognition of ongoing channel evolution is required for long term maintenance and management.

The hydraulic conveyance is analogous to dominant discharge and in addition to the effects described above, the hydraulic conveyance is also affected by channel roughness or bed resistance. Different vegetation types offer differing degrees of hydraulic resistance, and if salinity changes result in notable changes in vegetation (in stream and on berms), then a corresponding change in hydraulic resistance (and hence conveyance) may also occur.

4.5.4 Low flow and flood levels

With sea level rise, flood management in the lower reaches will change to management of peak tide levels rather than peak flood levels. The effects of sea level rise on hydraulic level will be experienced every tide cycle.

Horseshoe Lake is drained via gates and flood relief pumps at Avonside Drive. We understand the critical rainfall event duration for this area (i.e. rainfall event duration that results in the highest peak water levels) is of the order of 9-18 hours, which would span several tide cycles. Draining of Horseshoe Lake by gravity in the wake of a significant rainfall event occurs only when upstream water level exceeds downstream river level. At other times, drainage is by pumping.

There are many other outfalls to the lower Avon and Heathcote Rivers that are flap-gated to prevent backflow or have installed flood relief pumps, as well as several that connect directly to the Avon-Heathcote Estuary.

If the downstream tide level is increased (i.e. sea level rise occurs), then the period over each tide cycle during which outflow by gravity is able to occur will be reduced. This could affect the assessment of critical rainfall duration in this area, with longer duration events having less time over each tide cycle during which drainage may occur.

In addition, peak water level attained in Horseshoe Lake and other similar areas is likely to be increased as a result of sea level rise. Under sea level rise conditions, greater demand is likely to be placed on the flood relief pumps at Horseshoe Lake (and at other sites). This is likely to have effects on operation and maintenance costs.

The amount by which peak water level is increased is likely to be comparable to the magnitude of sea level rise for each rainfall duration considered. However, if critical duration is changed as a result of sea level rise then the amount by which peak water level for an event of given Average Recurrence Interval (ARI) cannot be estimated without undertaking further flood modelling of the surface water systems.

4.5.5 Hydraulic structures

In some locations in both the Lower Avon and Heathcote river systems there are installed flood relief measures, including pumps, that provide a level of protection and reduction of flood probability. Flood relief pumps (for example those at Horseshoe Lake adjacent to the Lower Avon River) need to operate over high tide levels after significant rainfall. It is usual for flood relief pump stations to be comprised of duty and standby pumps. As sea level rises the period of time over each tide cycle when the receiving water level is higher than that which can be tolerated upstream is increased. Therefore, we would expect the duration over which pumping is required to also increase, leading to increased operating costs and increased maintenance requirements.

Figure 4-15 shows a sinusoidal time series which represents a tidal time series. For illustrative purposes a horizontal line has been drawn over the time series indicating an arbitrary threshold, either for a pump station 'on' level or flap gate closed level. Figure 4-15 illustrates a positive datum shift (vertical axis), as would occur with sea level rise, results in an increase in the period of time over which the threshold is exceeded.

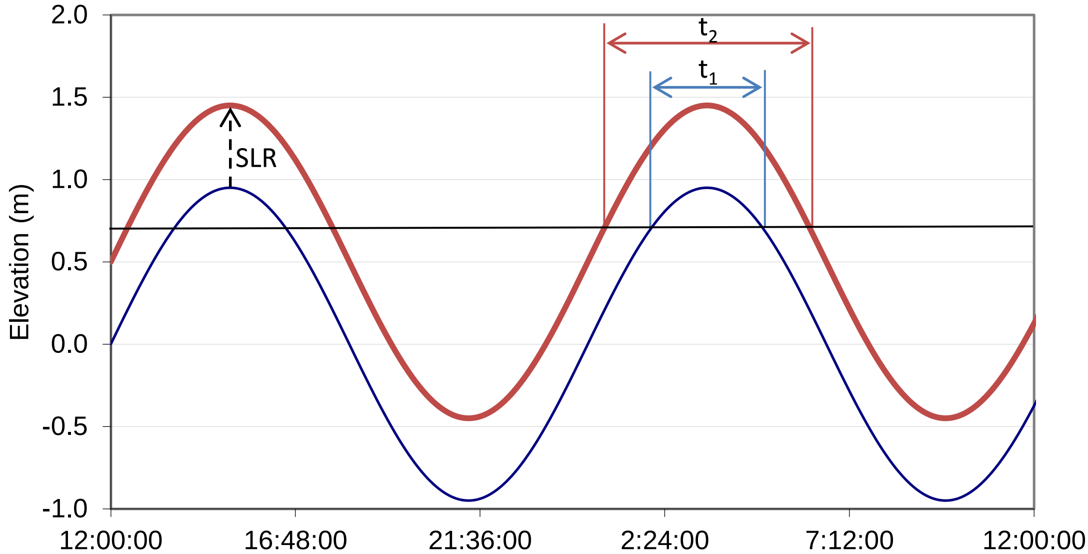


Figure 4-15 Sinusoidal time series, representing a tide curve and period of threshold exceedance

Another flood relief measure that is common in Christchurch City is flap gates (Figure 4-16). Flap gates prevent back flow and are often used to ensure that seawater does not flow upstream along surface waterways. The flap gates are opened by hydraulic head difference across them, where the gate will open when the upstream level is higher than downstream level. The degree of opening is mainly dependent on the head difference across the gate. The head difference is expected to be reduced with sea level rise, with a corresponding loss of opening cross sectional area. Therefore, ponding areas upstream of flap gates may take longer to drain against a raised sea level than they would under current conditions.

Figure 4-16 Flap gate examples

4.5.6 Salinity

As sea level rise occurs it would be expected that tidal saline effects would extend progressively further upstream. As a result of this, local ecological communities may face progressive change. For example, as a particular reach experiences increased salinity, the plant species on the banks will gradually change to being more salt-tolerant. Aquatic life will also gradually change, with introduction of salt-tolerant species.

These changes may result in adverse effects on bank integrity. If vegetation die-off as a result of a saline event occurs, then this could reduce the resilience of the stream banks to erosion.

4.5.7 Water levels and inundation

Sea level rise will increase the frequency of coastal inundation due to storm events. The 1% AEP inundation level including sea level rise of 1.0 m to the year 2115 is 3.3 m (LVD). Refer to Section 4.1.4.1 for a full description of the methodology used to calculate the 1% AEP inundation level. A summary of the land area impacted by inundation over the 100 year planning timeframe is presented in Table 4-7.

Table 4-7 Summary of inundation impacts for the Lower Avon and Heathcote Rivers

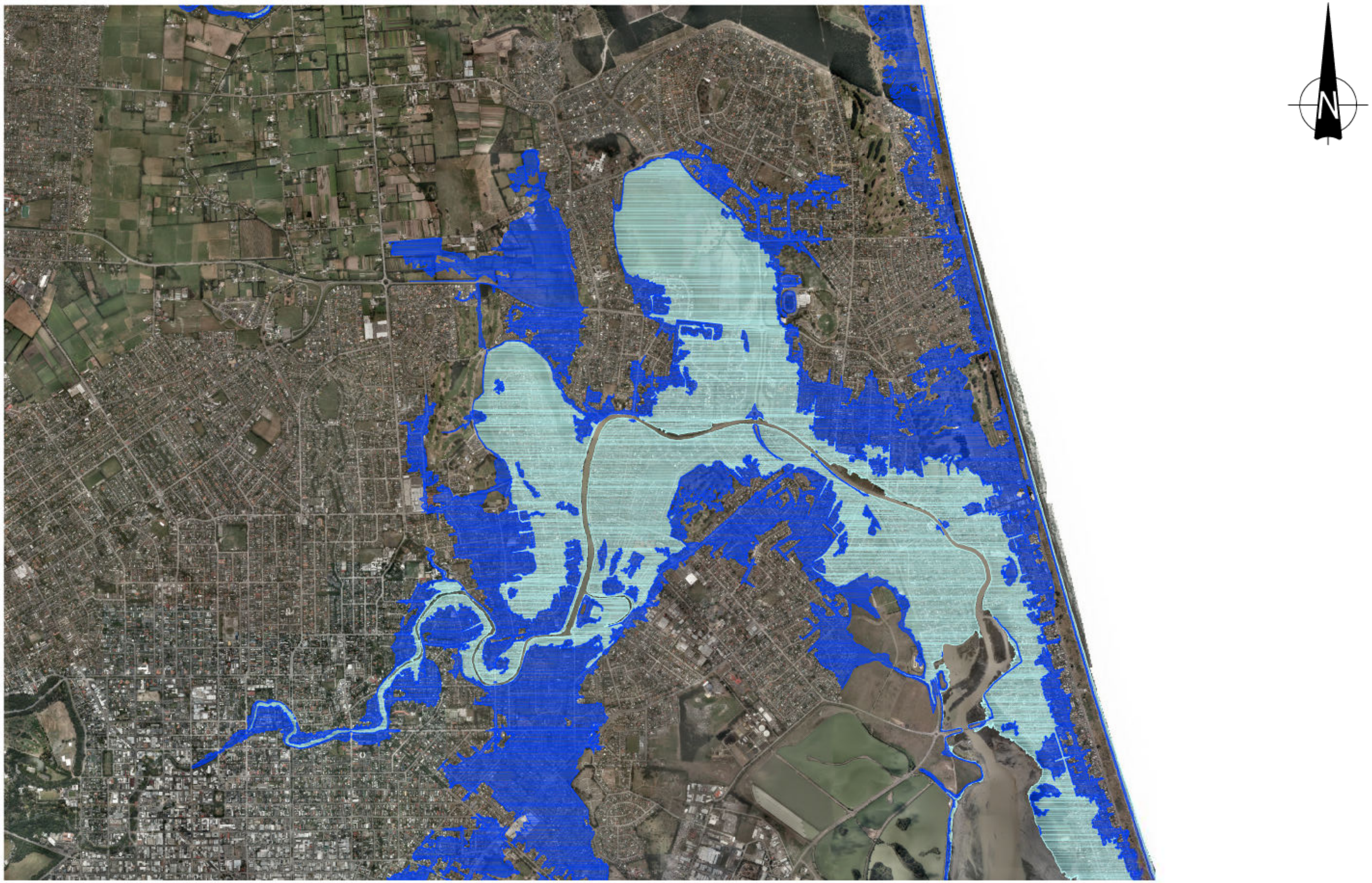
	Avon River	**Heathcote River**
Area of land inundated by 3.3 m level (1% AEP event)[1]	1,226 ha	1,171 ha
Suburbs affected by a 1% AEP event inundation level	Travis Wetland Avondale Wainoni Dallington Horseshoe Lake Bexley	Ferrymead Woolston Linwood Hillsborough
Notes: [1]Area calculated above the current MHWS level.		

There is approximately 1,226 ha of land connected to the Lower Avon River that is lower than the inundation level of 3.3 m (LVD). The existing stopbank crest level along the Lower Avon River does not appear to be suitable to hold back the predicted MHWS level by the year 2115. There is an area of approximately 1,171 ha connected to the Lower Heathcote River that is lower than the inundation level of 3.3 m (LVD). Refer to Figure 4-17 and Figure 4-18 for a graphical representation of the impacts of inundation on the Lower Avon and Heathcote Rivers.

4.5.8 Ecology

The summary of river ecological effects outlined in the T&T original report remains valid. The key ecological effects of a 1.0 m rise in mean sea level on the Lower Avon and Heathcote River ecology are:

- progressive die off of salt tolerant plant species at lower elevations as their habitats become flooded
- progressive up stream migration with an associated die off of non-salt tolerant species.



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- Area impacted by the 1% AEP inundation event (3.3m = 1% AEP tide at 1.9m and 1.0m sea level rise with 0.4m freeboard)
- Area impacted by shoreline retreat due to passive inundation (2.2m = Mean high water springs of 1.2m and 1.0m sea level rise)

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AVON RIVER
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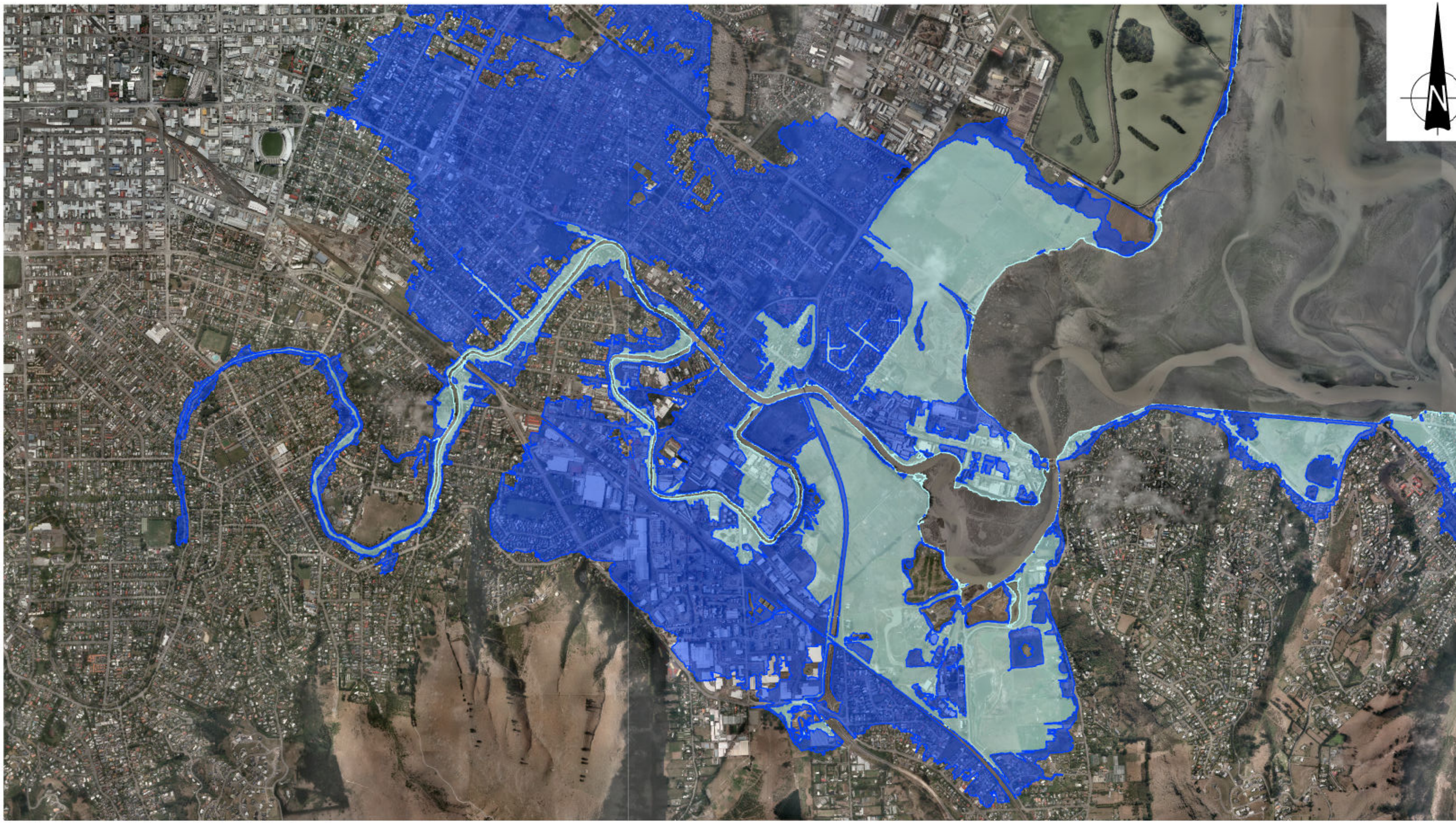

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LEGEND

Area impacted by the 1% AEP inundation event (3.3m = 1% AEP tide at 1.9m and 1.0m sea level rise with 0.4m freeboard)

Area impacted by shoreline retreat due to passive inundation (2.2m = Mean high water springs of 1.2m and 1.0m sea level rise)

Levels reduced to Lyttelton Vertical Datum

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HEATHCOTE RIVER
Site Plan

FIG. No. Figure 4 – 18

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4.6 Avon-Heathcote Estuary

4.6.1 Previous assessments

We are not aware of any previous assessments relating to the effect of sea level rise on Avon-Heathcote Estuary (post-dating the T&T original report).

4.6.2 Tidal compartment and mouth dynamics

The Avon-Heathcote Estuary channel is constantly adapting towards a state of dynamic equilibrium, accommodating the tidal prism, the flow area and the flow velocity. The tidal prism is the volume of seawater exchanged in and out of the estuary during an astronomical tidal cycle. The tidal prism will increase with rising sea level, causing coastal fringing land to progressively flood during high tides. The larger tidal prism will result in physical changes to the entrance channel through higher tidal velocities and scouring. The volume and height of sand shoals inside and outside the entrance will most likely grow (EShorance, 2010). These morphological changes have impacts on the estuary mouth dynamics and the adjacent open coast beaches.

With sea level rise of 1.0 m over the next 100 years, the increase in the estuary mouth cross sectional area due to greater water depth is likely to be around 135 m^2, based on empirical relationships (refer to Table 4-8). The T&T original report indicated estuary mouth cross sectional area increases of 27 m^2 and 67.5 m^2 for a sea level rise of 0.2 m and 0.5 m respectively. Based on the linear relationship method outlined in the T&T original report, the increase in tidal compartment for a 1.0 m SLR is some 5.0×10^6 m^3. The increase in tidal compartment is likely to result in a change in the estuary mouth channel width of between 40 to 50 m (Table 4-8). Note the 2010 – 2011 Canterbury Earthquakes resulted in a reduction in the tidal compartment of approximately 1.0×10^6 m^3 which we would expect to have reduced the mouth width by approximately 10 – 20 m.

The response of the mouth width to a rise in sea level is difficult to estimate and the distances presented below represent an expected order of magnitude change. We recommend monitoring changes in the estuary mouth, South Brighton spit and Sumner Bar over time using aerial or oblique photographs as changes to the tidal prism within the Avon-Heathcote Estuary is likely to result in some change to the ebb-delta regime and surrounding beaches.

Table 4-8 Summary of tidal compartment and mouth width changes with sea level rise

Sea Level Rise (m)	Increase in mouth cross sectional area (m^2)	Increase in tidal compartment (m^3)	Potential width of bank erosion at mouth (m)[1]
0.2	27	1.08×10^6	10 - 20
0.5	68	2.7×10^6	20 - 30
1.0	135	5.0×10^6	40 - 50
Notes: [1]Rounded up to the nearest 10 m.			

4.6.3 Sedimentation

Sedimentation in the Avon-Heathcote estuary is dependent on sediment supply to the estuary and the rate at which sediment is discharged from the estuary. Sea level rise on its own can only affect the rate of discharge from the estuary, but it is noted that more general climate change effects, such as changes to rainfall frequency and intensity, are likely to affect the rate of sediment supply.

Sea level rise is likely to result in increased sedimentation on tidal deltas within the estuary. It is reasonable to assume that the previously estimated estuary sedimentation rate in response to sea level rise of 1 mm/year will continue, giving a total accumulation of 100 mm over the next 100 years.

4.6.4 Erosion and inundation

We know that changes to individual storm conditions are likely, particularly in their intensity, as a result of climate change in general. It is less certain what these changes mean for the magnitude or frequency of storm surges, and how storm tide levels will change. Until further research and monitoring suggest otherwise, we have assumed that storm tide levels will rise only due to an increase in mean sea level rise. Therefore, rising sea level will decrease the inundation recurrence interval because the storm surge elevation is superimposed on an increasingly higher base level.

The 1% AEP inundation level including sea level rise of 1.0 m to the year 2115 is 3.3 m (LVD). Refer to Section 4.1.4.1 for a full description of the methodology used to calculate the 1% AEP inundation level. Approximately 522 ha is estimated to be inundated during a 1% AEP storm event (Figure 4-19).

Bank erosion and shoreline retreat due to sea level rise can be estimated using the passive inundation method (EShorance, 2010). Passive inundation is simply the position of the high tide level (MHWS) in 2115 allowing for a sea level rise of 1.0 m. Refer to Section 4.1.3.1 for a full description of the passive inundation method.

Approximately 233 ha of land is expected to be lost as the shoreline retreats inland to the 2.2 m contour by the year 2115 (Figure 4-14). This area includes significant sections of both South New Brighton and South Shore residential area, which is below the predicted 2115 MHWS level of 2.2 m. The maximum shoreline retreat distance due to passive inundation at South New Brighton and South Shore is estimated at 560 m and 370 m respectively. The low lying residential areas in Red Cliffs and Moncks Bay may are also expected to erode and may experience a maximum shoreline retreat, due to passive inundation, of 280 m and 180 m respectively.

4.6.5 Groundwater

Groundwater levels around the coastal fringe of the Avon-Heathcote Estuary may be controlled by the sea level. Therefore, as sea level rises, ground water levels are also expected to rise in some areas. A rise in groundwater level can result in a range of impacts, including:

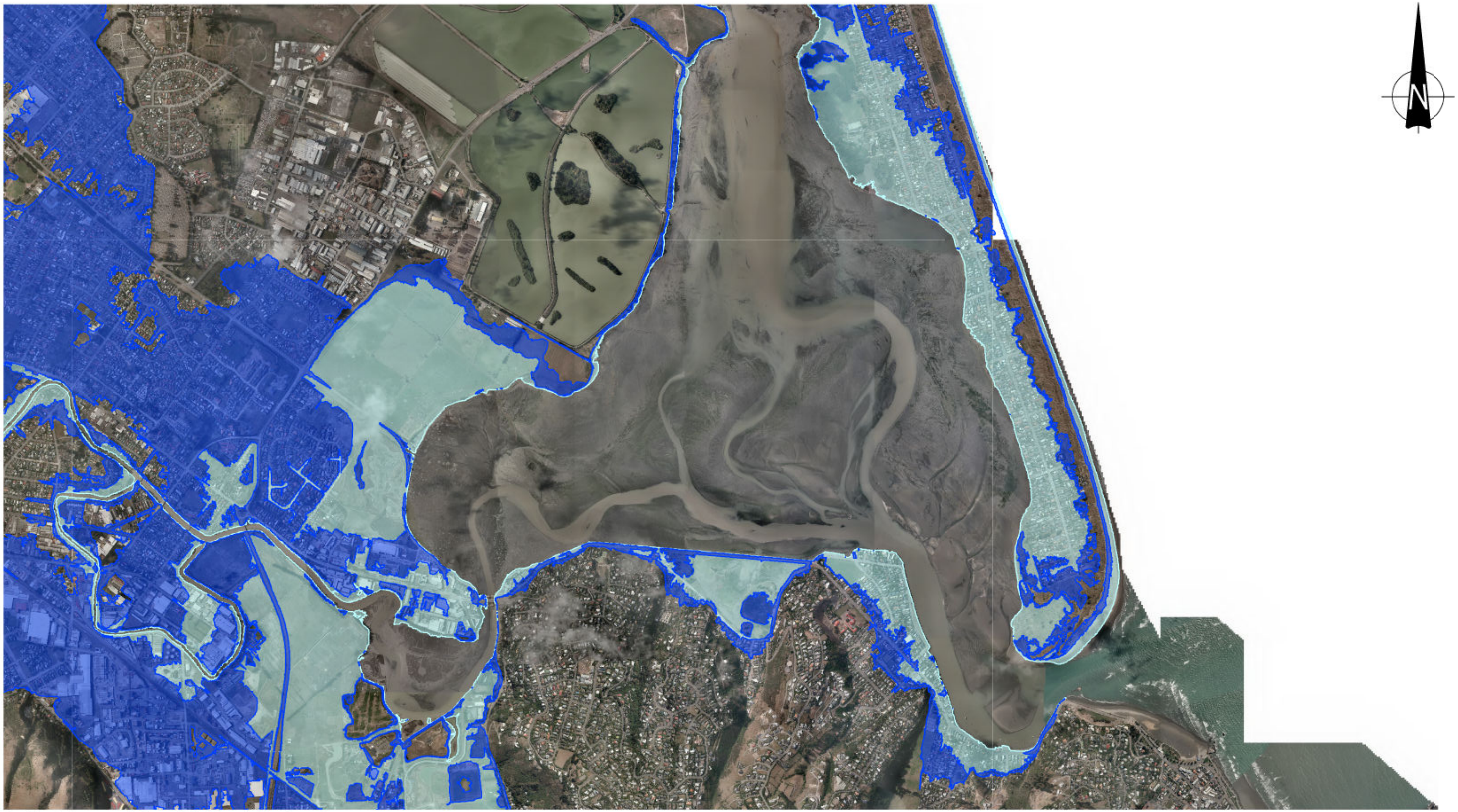
- increased uplift on buildings with sealed basements, possibly requiring strengthening of these structures
- underground tanks and services could start to ‘float’. This is particularly likely to impact large lightweight pipes (such as gas pipes) and fuel tanks
- possible water infiltration to basement structures, requiring waterproofing and pumping
- saline intrusion into the aquifer system and lateral migration of the fresh-saline interface
- increased risk of liquefaction
- changing discharge patterns that may impact on surface waters and groundwater dependant ecosystems
- near surface saline water could affect terrestrial vegetation on the coast and cause corrosion to underground assets.

4.6.6 Ecology

As sea levels rise under natural conditions, vegetation communities are expected to migrate landward to maintain their position relative to the water level. Refer to Section 4.4.3.6 for a further description of sea level rise effects on estuary ecology. The Avon-Heathcote Estuary has a significant amount of shoreline protected by hard structures, which will limit the landward transition of ecology. Therefore the key ecological effects of a 1.0 m rise in mean sea level on the ecology outlined in the T&T original report remains valid:

- eelgrass, sea rush and salt marsh species will be "squeezed out" as the intertidal zone reduces in area
- fish species expected to move with the transition in salinity, however eventually some species such as flounder, eels, and inanga (inaka) will lose their feeding grounds as water depths progressively increase
- wading birds will also be affected by a loss of habitat.

In areas where there is space for ecological migration, there will be a progressive die off of non-salt tolerant species with the rise in water levels and a succession to more salt tolerant species with the same vertical zonation as currently present.



Aerial photo sourced from Christchurch City Council

LEGEND

- Area impacted by the 1% AEP inundation event (3.3m = 1% AEP tide at 1.9m and 1.0m sea level rise with 0.4m freeboard)
- Area impacted by shoreline retreat due to passive inundation (2.2m = Mean high water springs of 1.2m and 1.0m sea level rise)

Levels reduced to Lyttelton Vertical Datum

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CHRISTCHURCH CITY COUNCIL
EFFECTS OF SEA LEVEL RISE
AVON–HEATHCOTE ESTUARY
Site Plan

FIG. No. Figure 4– 19

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5 Mitigation solutions

The 2010 New Zealand Coastal Policy Statement (NZCPS) requires consideration of climate change effects covering at least a 100 year planning horizon. Therefore a planning timeframe to the year 2115 has been adopted for assessing the impacts of future sea level rise and possible mitigation solutions.

Mitigation solutions for sea level rise and the associated effects on coastal hazards should provide for both undeveloped land (Greenfield areas) and existing developed areas. The potential impacts from sea level rise can be avoided for Greenfield areas through appropriate planning responses. Coastal areas that are already developed should manage the potential impacts from sea level rise by implementing an adaption strategy. An adaption strategy aims to reduce the impacts from sea level rise on existing development and could include both planning and protection responses (MfE, 2012). This section discusses both planning and protection responses as possible mitigation solutions to manage the impacts from sea level rise on Christchurch City.

5.1 Planning responses

The preferred planning response is to avoid development and redevelopment in areas vulnerable to natural hazards (MfE, 2012). Planning to avoid the potential impact from sea level rise over the intended lifetime of new development and infrastructure is the most sustainable long term solution. For example minimising infrastructure assets situated in areas that could be impacted, and creating zones where new development is prohibited. The impacts from sea level rise on existing development can also be reduced through managed retreat.

Managed retreat is defined as any strategic decision to withdraw, relocate or abandon private or public assets that are at risk of being impacted by coastal hazards (MfE, 2008). The process of managed retreat is central in the planning approach to sea level rise as it is unlikely to be affordable to provide protection to all areas of value vulnerable to sea level rise. Managed retreat is a difficult process to manage politically, but if communities cannot achieve a managed retreat, then the risk is likely to increase until a forced retreat is unavoidable (MfE, 2008). Existing use rights create a practical problem to managed retreat, in that existing buildings may remain unaltered (in terms of effects) and therefore uncontrolled for some time. This can create a patchwork of existing development with and without relocation controls (EW, 2006).

Managed retreat can occur at a range of spatial scales, from individual properties to whole communities and infrastructure links. It can also be implemented over a range of temporal scales and should be considered as a staged response, where assets are relocated or abandoned when the risks become intolerable (e.g. inundation from storm events becomes a frequent occurrence). Any managed retreat plan should also be monitored and reviewed on a regular basis to incorporate the latest knowledge of sea level rise projections and coastal hazard processes (Engineers Australia, 2012).

Managed retreat requires a range of planning responses to minimise the overall impact of sea level rise. Typical planning responses for areas at risk from sea level rise include:

- Changing the zoning of existing areas to prohibit any modifications or upgrades to existing buildings (expected to lead to a natural withdrawal from the area over time)
- Changing the zoning of existing areas to activities that result in a lower vulnerability to the impacts of sea level rise, such as recreational open space
- Requiring the construction of more resilient buildings in areas at risk, for example:
  - buildings on stilts
  - re-locatable buildings

  - designs that withstand storm events including suitable floor levels or flood proofing first floors
  - provision of access routes above expected future sea level rise.
- Make strategic decisions to locate assets in areas of lower risk or to adapt designs to accommodate changes due to sea level rise when carrying out major infrastructure upgrades or renewals, for example:
  - non-corrodible pipe types
  - additional storage or pumping in stormwater systems
  - provision of alternative road alignments, either elevated or following different routes or even tunnels.

Implementing these planning responses can result in Christchurch City being more resilient to the impacts of sea level rise. The CCC has implemented a number of these planning responses in the Christchurch City District Plan (CCDP). Table 5-1 outlines the planning policies developed in the CCDP that aim to avoid or mitigate the impact of sea level rise and the associated coastal hazards on Christchurch City.

Table 5-1 Summary of the CCDP policies relating to coastal hazards

Policy Number	Policy Name	Policy Description
2.5.2	Limitations on development	To avoid any increased risk of adverse effects on property, wellbeing and safety from natural hazards by limiting the scale and density of development.
2.5.4	Sea level rise	To avoid higher density forms of built development, and adverse effects from inundation, in areas that are projected to be subject to increased flood levels as a result of accelerated sea level rise.
2.5.5	Flooding	To impose standards in areas subject to flood hazard in order to ensure that the risk of adverse effects on property and people's wellbeing and safety from flooding and inundation is not increased.
2.5.9	Works	To undertake works to avoid or mitigate the adverse effects of natural hazards as a supplementary measure to regulation of activities, and the provision of information.
2.6.3	Coastal development	To avoid or mitigate the adverse effects of erosion and flooding in the coastal environment.
10.1.1	Inundation, flooding and sea level rise	To avoid any increased risk of adverse effects on property and the wellbeing and safety of the community from natural hazards by avoiding subdivision, or subjecting it to appropriate mitigation measures.

The CCDP policies outlined in Table 5-1 are implemented through the following methods:

- Plan zoning that limits development in areas vulnerable to natural hazards (e.g. South New Brighton Coastal Hazard Area, Flood Management Areas)
- General City rules relating to building, filling and excavation
- City rules for subdivision and development including rules for natural hazards
- Provision for information on the extent and location of natural hazards through the CCC Hazard Register.

CCC also administers the Banks Peninsula District Plan (BPDP). The BPDP includes natural hazard policy to avoid or mitigate the costs resulting from natural hazards in terms of loss of life and loss or damage to property and the environment (Chapter 38). There are no specific provisions in the BPDC for mitigating the effects of sea level rise.

Environment Canterbury has issued the draft Land Use Recovery Plan (LURP) for submissions which includes proposed amendments to the CCDP relating to natural hazards. The LURP recommends CCC amend the CCDP to protect people from “High Hazard Areas” and risks from natural hazards including sea level rise (LURP Action 38).

We understand CCC has developed a Hazards Notice Policy under s71-72 of the Building Act. A Hazards Notice must be attached to titles that are likely to be subject to hazards, where Council has granted building consent when it is demonstrated that adequate provision has been made to protect the land, building or property.

The CCC has responsibilities under the Resource Management Act 1991 (RMA) to identify areas subject to natural hazards and to control the use of land for the avoidance or mitigation of natural hazards. The key planning response CCC has developed to mitigate the risk of flooding within Christchurch City is the development of Flood Management Areas (FMA). The FMA include land identified as being subject to a greater risk of flooding than the City as a whole (Figure 5-1). The CCDP requires resource consent to be obtained for new buildings and additions within the FMA. This provides the CCC with the discretion over the finished floor level of new buildings within these areas.

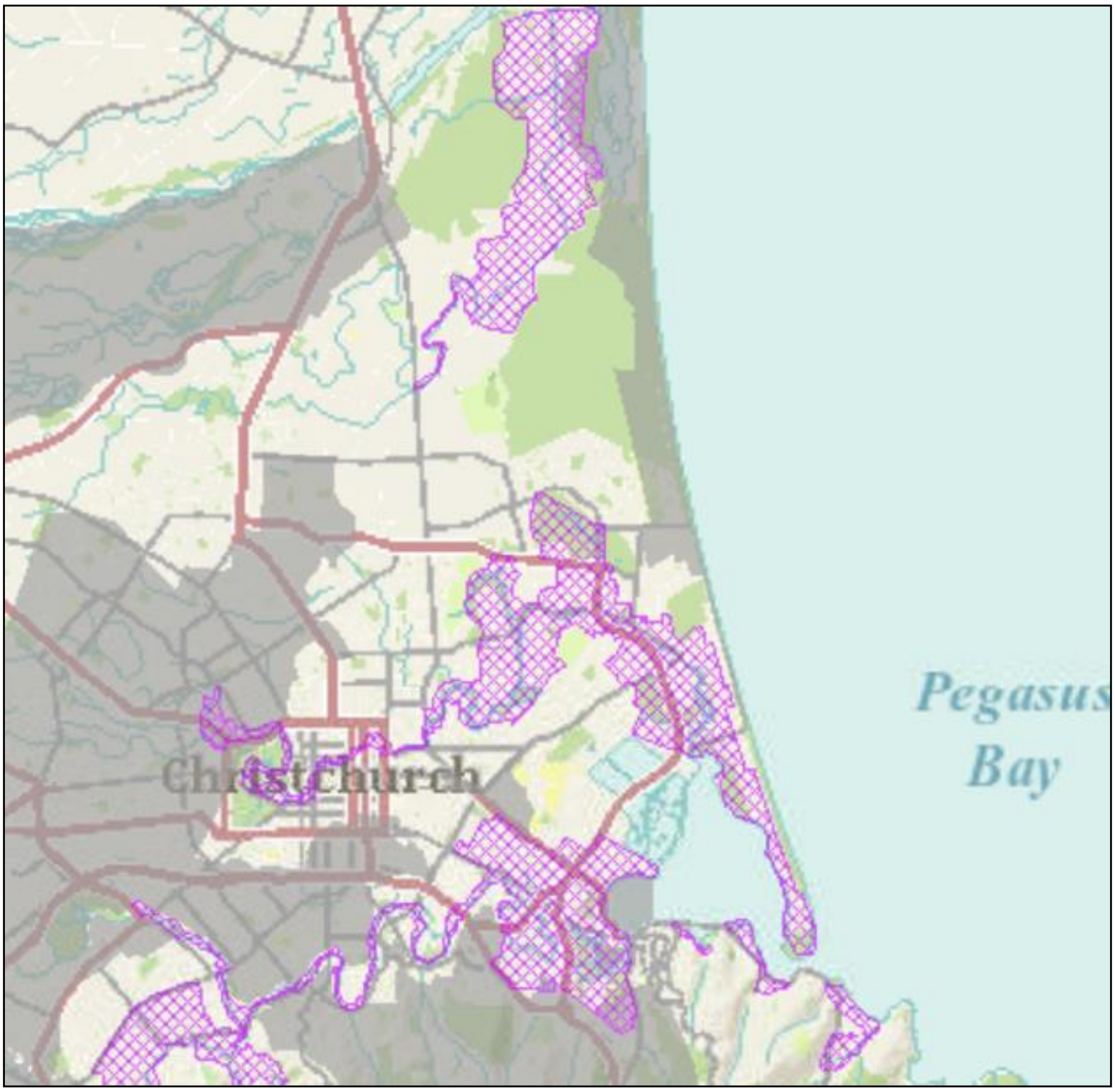

Figure 5-1 Flood Management Areas shown as pink hatch, and areas where the flooding modelling work is under development is shaded grey (source: http://maps.cera.govt.nz)

Two distinct floor levels have been identified as necessary in order to manage the effects of tidal and non-tidal flood risks. Tidal influenced flooding may result directly from seawater during extreme tide and storm events. A level of 11.8 m (CCC datum) has been set as the minimum floor level for tidal flooding, which includes (CCDP, 2005):

- 0.5 m allowance for sea level rise over the next 100 years
- 1% AEP storm event, once the sea level rise has occurred
- 0.4 m freeboard allowance.

We recommend undertaking a review of both the FMA extent and the tidal flooding level once the IPCC Fifth Assessment Report is released. Based on the literature review of sea level rise undertaken for this report, the tidal flood level would need to be increased by 0.5 m to 12.3 m (CCC datum) to allow for a sea level rise of 1.0 m to the year 2115. Furthermore, allowing for a sea level rise of 1.0 m within the existing 11.8 m level, the allowance for storm surge will be reduced to approximately a 2% AEP event.

5.2 Protection responses

Sea level rise will impact some existing developed areas on the low lying flood plains of Christchurch City, and avoiding all effects within vulnerable areas may not be possible. Protection responses to mitigate the impacts of sea level rise may be required in some areas and could range from seawalls and flood walls to raising property and infrastructure.

The traditional response to coastal hazards in Christchurch City has been to construct coastal protection structures to hold the shoreline position. MfE (2008) consider "hold the shoreline" coastal protection structures:

- lead to a false sense of future security and can often result in increased risk, with intensification of development in the landward area (e.g. Hurricane Katrina natural disaster)
- lead to other environmental damage and impacts on other coastal values
- lead to an expectation that defence will be maintained in perpetuity
- are reactive and rarely the most effective or sustainable long term option.

Many of the existing coastal protection structures will most likely require further upgrade works to ensure adequate protection from sea level rise. Where development exists in areas at risk from coastal erosion where no protection exists, there is likely to be pressure on local authorities to protect private properties from coastal hazards over time. Hard protection responses can negatively impact on other values such as amenity, public access, and natural character (MfE, 2012). However, hard protection responses may be justified for existing strategic long term assets (e.g. main access roads).

Soft protection responses such as dune and beach nourishment and the restoration of wetlands as energy dissipaters can provide an alternative to the "hold the shoreline" type of approach to managing the effects of erosion and inundation. These options require a good understanding of the coastal processes and may not be successful or cost effective at all locations, particularly in areas with deep water close to the shoreline. Soft protection solutions that are properly designed can assist in reducing natural hazards while protecting conservation values, public access and recreational use. They may also be combined with hard defences to provide areas of amenity along a raised shoreline.

There is also a range of possible innovative responses, including self-sufficient floating islands or large permanent cruise liners, and "water scrapers" where development occurs below the water. These futuristic solutions are not recommended at this stage as they are unlikely to be viable within the planning timeframe.

The CCDP identifies a key issue for Christchurch City is to determine what degree of risk is acceptable for property and people already located in areas vulnerable to the impacts of natural hazards (i.e. tolerable risk). Tolerable risk is defined as the level of risk individuals or the community are prepared to "tolerate" under certain circumstances in return for a specific benefit. The CCC needs to consider when the degree of risk becomes unacceptable, at what level of cost (economic, cultural, social and environmental) they are prepared to undertake protection responses. For this to happen there needs to be focussed discussion with the communities and stakeholders affected. There also needs to be an understanding of both the likelihood and consequence of the hazard to inform this discussion.

The CCC undertook a study in 2003 to examine the potential impacts of sea level rise on coastal inundation within the Avon catchment and to assess how these impacts could be mitigated (MfE, 2001). The assessment was based on a 1% AEP storm event and an allowance of 0.4 m for sea level rise. The study assessed the cost benefit of upgrades to the existing stopbank system and also construction of a tidal barrage across the estuary entrance as potential protection responses.

The study results show that only the Hulverstone stopbank would show an immediate benefit from improvements. Other stopbanks could be worth upgrading in the future but would not benefit under current conditions. Tidal barrages were considered unlikely to be feasible. They would not yield a net benefit and have considerable environmental and amenity issues. This option was not recommended for future consideration. Note this assessment was undertaken prior to the 2010 and 2011 earthquakes which caused ground settlement in this area. We understand the CCC has completed remedial works to the Hulverstone stopbank to reinstate the level of service prior to the 2011 earthquake. Significant amounts of low lying areas have also been red zoned within this catchment. Therefore the cost benefit analysis for these protection responses would need to be reassessed.

5.3 Sea Level Rise Adaption Strategy

We recommend the CCC develop a Christchurch City wide Sea Level Rise Adaptation Strategy (Strategy). This strategy should focus on adaptive management to prepare for the impacts of sea level rise in order to safeguard the community, environment and economy from likely risks. The Strategy should ideally be produced in close consultation with all stakeholders including the local community and provide specific local plans to increase the communities resilience to sea level rise. The key issues that should be included in the Strategy are:

- what do local communities consider to be a tolerable level of risk
- what do communities resilient to sea level rise look like
- how the risk of sea level rise should be communicated to existing land owners and potential property purchasers
- what protection should be provided to the environment and how can the environment help to protect the City.
- how future impacts can be avoided or mitigated including impacts on insurance
- what actions are required now for vulnerable areas, including appropriate planning and protective responses and changes to building codes or design requirements
- how emergency response can or should be strengthened to support proposed mitigation solutions.

Central to any adaption strategy is a phased and flexible approach to implementation. The benefits of phased implementation are illustrated in Figure 5-2. A decision not to adapt or respond to the pressures of sea level rise can result in the community being exposed to unacceptable levels of risk. A staged adaption strategy provides for appropriate responses at key points in time that reduce risk to tolerable levels. A flexible staged response is most often more cost effective than a precautionary response, where significant upfront investment is usually required to create long term benefits. There is also a risk that a less flexible or precautionary response will result in stranded assets or inappropriate investment (e.g. tidal barrier). However, a precautionary response may be appropriate when decisions are being made relating to long life strategic infrastructure or long term planning horizons.

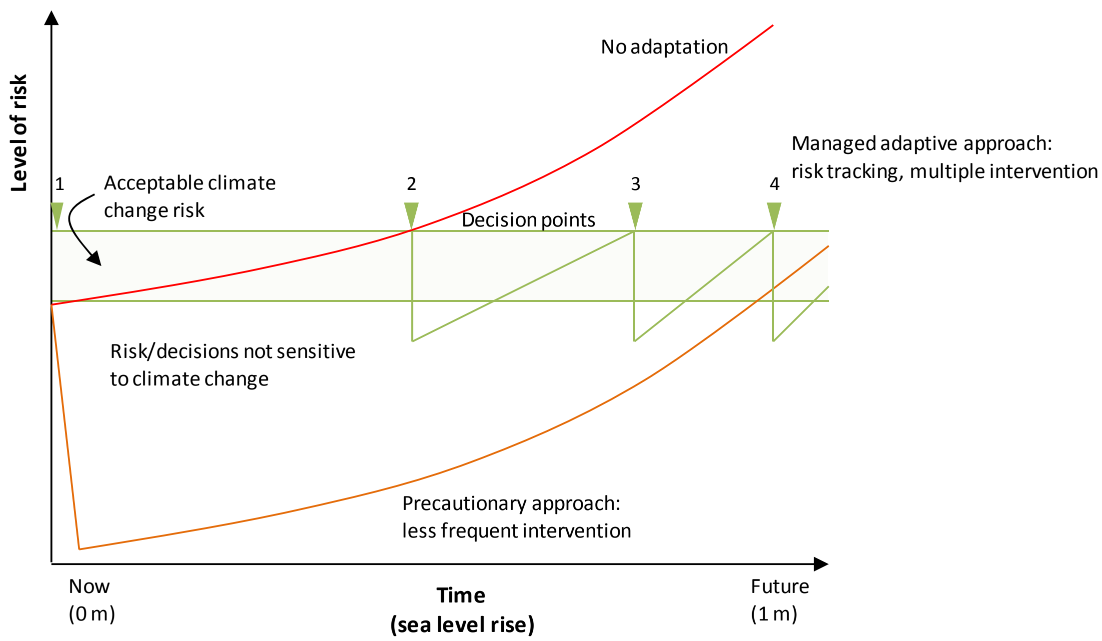

Figure 5-2 Approaches to adaptation to sea level rise and their effect on the level of risk over time (Source: Department of Sustainability and Environment, 2011)

The Strategy should aim to provide "no regrets" or "low regrets" responses, so the flexibility of each response is an important part of its likely future success. This concept also generally aligns with the decreasingly preferential hierarchy set out in the RMA to avoid, remedy or mitigate effects. A "low regrets" response costs little to prepare now, so proceeding with this type of response is justifiable, despite any uncertainties about future sea level rise. Examples of "low regrets" responses include (Titus and Newmann, 2009):

- planning for "set back" areas or land use changes in vulnerable locations
- requiring higher floor levels for development within areas that may be vulnerable to higher sea levels
- designing larger pipes for new or refurbished drainage systems in areas that could become prone to flooding as sea levels rises
- rebuilding roads to a higher elevation during routine reconstruction.

At the opposite end of the scale are responses that would cost a lot now and may not provide long term protection from sea level rise. Constructing a tidal barrier is an example of this, where costs would be very high and protection would be limited to a set sea level rise elevation which is bound by relatively large uncertainties. The investment in this high cost asset could become redundant before it reaches the end of its design life.

Short term decisions will influence longer term policies. Choosing to implement protection responses in vulnerable areas now is likely to result in increased development behind coastal defences. This will concentrate economic value and social vulnerability, resulting in a higher demand for protection in the long term. These options may not be sustainable either in terms of cost or technical feasibility.

Although the scope of this report was limited to analysing the impacts of one sea level rise scenario (i.e. 1.0m sea level rise by the year 2115), we recommend the Strategy considers a more flexible risk basked approach in areas of existing development. For example the local community may decide to accept a greater degree of risk for some assets that could be readily relocated or adapted (e.g. playgrounds, esplanade reserves, toilet blocks). In contrast, development of existing property and strategic long term assets with greater consequence (e.g. major infrastructure) should be assessed at the 1.0 m sea level rise projection to minimise the risk. The impacts from sea level rise on Greenfield areas could be assessed at a sea level rise projection greater than 1.0 m as mean sea level is expected to continue rising beyond 2115 (MfE, 2008).

6 Conclusions

For coastal margins the biggest climate change driver for both inundation and coastal erosion will most likely be sea level rise. Increases in wave and storm surge heights due to climate change in winds, storm frequency and intensity are likely to have a smaller effect relative to the projected rise in mean sea level.

The review of both global and national literature on sea level rise impacts and responses outlined in the T&T original report (T&T, 1999) remain valid. However, the advancement in our understanding of climate change suggests that sea level rise projections are likely to be higher than previous projections.

The 2010 New Zealand Coastal Policy Statement (NZCPS) requires consideration of climate change effects covering at least a 100 year planning horizon. Therefore a planning timeframe of 2115 has been adopted for this report. For the purposes of this report, a future sea level projection of 1.0 m by 2115 (100 year planning time frame) is used, which is generally in line with the current state of knowledge presented in the MfE guidelines (2008) and the Royal Society of NZ Emerging Issues paper (RSNZ, 2010). This sea level rise projection of 1.0 m by 2115 is double the value adopted in the Original T&T report.

Many of the uncertainties associated with sea level rise projections and climate change identified in the T&T original report remain valid today. The melting rate of the Greenland and West Antarctic ice sheets is probably the largest uncertainty in sea level rise projections at this time. Although we now understand the melting of the Greenland and West Antarctic ice sheets will become a dominant component of the sea level rise projections over the twenty-first century, the rate of increase of movement and melting is still an unknown factor.

The Christchurch area has been affected by a large number of earthquakes following the initial Darfield Earthquake on 4 September, 2010, in particular, the earthquakes that occurred on 22 February, 13 June and 23 December 2011. These events occurred in close proximity to the city causing extensive liquefaction, lateral spreading and vertical displacement of land surfaces.

Comparison of pre- and post-earthquake ground levels show the northern part of the estuary where the Avon River discharges has subsided by 0.2 to 0.5 m and the southern part of the estuary including near the estuary mouth and the Heathcote River has risen by 0.3 to 0.5 m. These changes have resulted in an increase of dry estuary area at mid tide of approximately 50 hectares or 18%. The reduction in the tidal prism has been estimated at approximately 1 million m^3 or 14%. We recommended monitoring changes in the South Brighton spit and Sumner Bar over time using aerial or oblique photographs as changes to the tidal prism reported within the Avon-Heathcote Estuary is likely to result in some change to the ebb-delta regime and surrounding beaches.

The greatest impact of sea level rise on Christchurch City will be the increased risk of storm inundation associated with the greater frequency of extreme tidal levels. The other main impact of sea level rise is the progressive shoreline retreat of low lying areas. A summary of the major impacts of sea level rise on Christchurch City are summarised in Table 6-1.

The CCC has developed a number of planning responses within the CCDP to reduce the risk of sea level rise, including policy to restrict development in Flood Management Areas (FMA). Based on the sea level rise projection adopted in this report, the minimum floor level would need to be increased by 0.5 m to 12.3 m (CCC datum) to allow for a sea level rise of 1.0 m to the year 2115. Furthermore, allowing for a sea level rise of 1.0 m within the existing 11.8 m minimum floor level, reduces the allowance for storm surge to approximately a 2% AEP event. We recommend undertaking a review of both the FMA extent and the associated minimum floor levels once the IPCC Fifth Assessment Report is released.

Protection responses to mitigate the impacts of sea level rise may be considered acceptable in some areas and could range from seawalls and flood walls to raising property and infrastructure. Many of the existing coastal protection structures will most likely require further upgrade works to ensure adequate protection from sea level rise.

We recommend the CCC develop a Christchurch City wide Sea Level Rise Adaptation Strategy (Strategy). This strategy should focus on adaptive management to prepare for the impacts of sea level rise in order to safeguard the community, environment and economy from likely risks. The Strategy should ideally be produced in close consultation with all stakeholders including the local community and provide specific local plans to increase the communities resilience to sea level rise.

The strategy should consider a flexible risk basked approach in areas of existing development. For example the local community may decide to accept a greater degree of risk for some assets that could be readily relocated or adapted (e.g. playgrounds, esplanade reserves, toilet blocks). In contrast, development of existing property and strategic long term assets with greater consequence (e.g. major infrastructure) should be assessed at the 1.0 m sea level rise projection to minimise the risk. The impacts from sea level rise on Greenfield areas could be assessed at a sea level rise projection greater than 1.0 m as mean sea level is expected to continue rising beyond 2115 (MfE, 2008).

In summary we provide the following recommendations:

- undertake review of both the FMA extent and the associated minimum floor levels once the IPCC Fifth Assessment Report is released
- develop a Christchurch City wide Sea Level Rise Adaptation Strategy
- monitor changes in the South Brighton spit and Sumner Bar over time using aerial photographs
- analyse the open coast ECan beach profile dataset to assess whether the trend of recorded shoreline movement has changed over time
- future studies involving tsunami, inundation and erosion hazards should consider the effect of a sea level rise of 1.0 m to the year 2115.

Table 6-1 Summary of impacts from sea level rise on Christchurch City

	Inundation	Morphological	Ecological	Uncertainty
Christchurch Dunes	• A rise in water level by 1.0 m will increase the risk of a tsunami event overtopping the dune crest	• Assume the dune system is in a dynamic equilibrium and historic rates of progradation will not continue under a SLR scenario. • This extent of shoreline retreat will impact the New Brighton Community Library (Te Kete Wānanga o Karoro) and the North New Brighton Memorial and Community Centre including the associated car parking areas.	• None	• SLR projection. • Sediment supply and historic progradation rates to continue under SLR scenario. • Equilibrium profile adjustment due to SLR. • Changes in wave climate.
Beaches South of estuary	• Increased inundation frequency for both Sumner and Taylors Mistake Surf Clubs. • Increased inundation frequency with approximately 70 ha expected to be flooded by a 1% AEP storm tide including SLR.	• Shoreline retreat of 40 m and 60 m at Taylor Mistake and Sumner respectively. • Foreshore lowering at Clifton and Sumner causing potential scour and undermining of existing seawall structures.	• None	• SLR projection. • Effect of ebb tide delta sediment system on Clifton beach. • Equilibrium profile adjustment due to SLR. • Changes in wave climate.
Avon-Heathcote Estuary	• Increased inundation frequency with approximately 532 ha expected to be flooded by a 1% AEP storm tide including SLR.	• Increases in mouth channel width by 40-50 m. • Increased sediment accumulation on the ebb and flood tide deltas. • Shoreline retreat at South Shore and South New Brighton of 370 m and 560 m respectively due to passive inundation.	• Migration and squeezing out of eel grass and salt marsh environments resulting in potential loss of feeding grounds for flounder, eels and inanga.	• SLR projection. • Response of tidal deltas and inside Brighton Spit. • Equilibrium profile adjustment due to SLR. • Changes in wave climate.

	Inundation	Morphological	Ecological	Uncertainty
Lower Avon and Heathcote Rivers	• Increased inundation frequency with approximately 1,226ha and 1,171 ha expected to be flooded by a 1% AEP storm tide including SLR for the Lower Avon and Heathcote Rivers respectively. • Increases in predicted flood levels in lower reaches.	• Channel width increase or reduced flood capacity, which could result in bank instability. • Saline boundaries extending further upstream resulting in vegetation die back and bank instability.	• Upstream migration of eel grass and salt marsh environments in the Lower Heathcote River with associated die off of non salt tolerant species • Squeezing of the above environments on the Lower Avon River due to stop banking.	• SLR projection. • Migration of saline boundary.
Brooklands Lagoon and Styx River	• Increased inundation frequency with approximately 1,640 ha expected to be flooded by a 1% AEP storm tide including SLR.	• Shoreline retreat resulting in an extension of Brooklands lagoon shoreline by 700 ha due to passive inundation.	• Migration of environments inland.	• SLR projection. • Effect of ebb tide delta sediment system on Brooklands Lagoon. • Changes in wave climate.
Port Levy	• Increased inundation frequency low lying backshore area. No topography data available to calculate area impacted.	• Shoreline retreat of 200 m impacting Fernlea Point Road and Wharf Road.	• Migration of ecological communities inland.	• SLR projection. • Equilibrium profile adjustment due to SLR. • Changes in wave climate.
Okains Bay	• Increased inundation frequency low lying backshore area. No topography data available to calculate area impacted.	• Shoreline retreat of 60 m impacting Okains Bay Road.	• Migration of ecological communities inland.	• SLR projection. • Effect of changes to the ebb tide delta sediment system on Okains Bay beach. • Equilibrium profile adjustment due to SLR. • Changes in wave climate.
Akaroa	• Increased inundation frequency with approximately 13.3 ha expected to be flooded by a 1% AEP storm tide including SLR.	• Shoreline retreat of 70 m for the northern area and 170 m for the southern area impacting Jubilee Park and Beach Road.	• Minimal impact as the shoreline is currently protected with little existing ecological value.	• SLR projection. • Equilibrium profile adjustment due to SLR. • Changes in wave climate.

	Inundation	**Morphological**	**Ecological**	**Uncertainty**
Takamatua	• Increased inundation frequency with approximately 7 ha expected to be flooded by a 1% AEP storm tide including SLR.	• Shoreline retreat of 200 m impacting Takamatua Bay Road, Old French Road.	• Migration of ecological communities inland.	• SLR projection. • Equilibrium profile adjustment due to SLR. • Changes in wave climate.
Duvauchelle	• Increased inundation frequency with approximately 10.5 ha expected to be flooded by a 1% AEP storm tide including SLR.	• Shoreline retreat of 100 m impacting SH75, Onewa Flat Road, Seafield Road and the School.	• Migration of ecological communities inland.	• SLR projection. • Equilibrium profile adjustment due to SLR. • Changes in wave climate.
Wainui	• Increased inundation frequency with approximately 3.4 ha expected to be flooded by a 1% AEP storm tide including SLR.	• Shoreline retreat of 10 m impacting Wainui Road.	• Minimal impact due to the steep foreshore resulting in insignificant shoreline retreat.	• SLR projection. • Equilibrium profile adjustment due to SLR. • Changes in wave climate.

7 Applicability

This report has been prepared for the benefit of Christchurch City Council with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose without our prior review and agreement.

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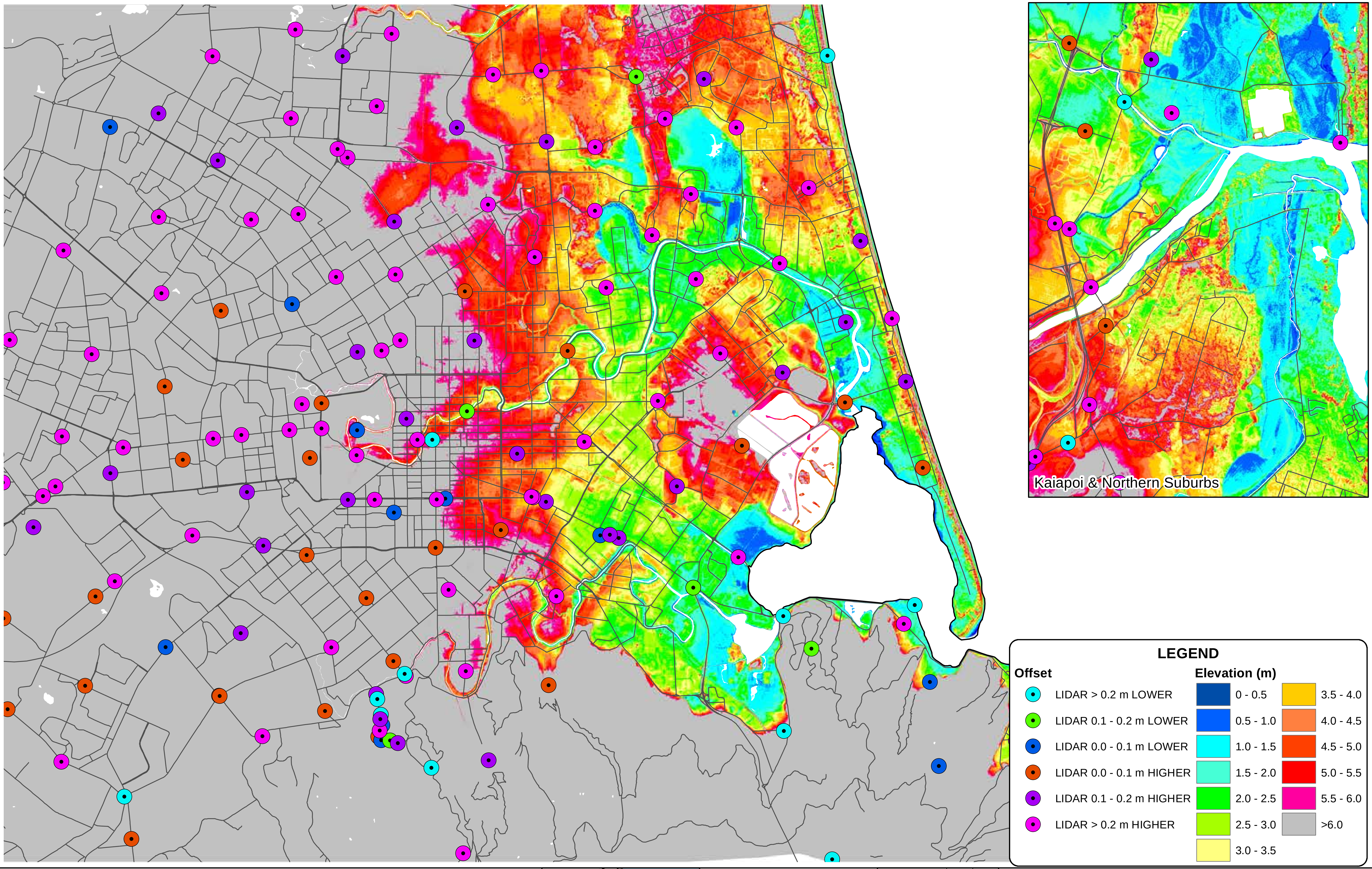
Appendix A: Land movement maps

- **Christchurch City & Kaiapoi LiDAR elevation and verification (Pre September 2010)**
- **A16 Christchurch City & Kaiapoi LiDAR elevation and verification (Post September 2010)**
- **A19 Christchurch City & Kaiapoi LiDAR elevation and verification (Post December2011)**
- **A20 Christchurch City & Kaiapoi earthquake related elevation change (pre September 2010 to Post September 2010)**
- **A23 Christchurch City & Kaiapoi earthquake related elevation change (pre September 2010 to Post December 2011)**
- **A24 Christchurch City & Kaiapoi tectonic related elevation change (pre September 2010 to Post September 2010)**
- **A27 Christchurch City & Kaiapoi tectonic related elevation change (pre September 2010 to Post December 2011)**
- **A28 Christchurch City & Kaiapoi liquefaction related elevation change (pre September 2010 to Post September 2010)**
- **A31 Christchurch City & Kaiapoi liquefaction related elevation change (pre September 2010 to Post December 2011)**



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0 1 2 3 4 (km)

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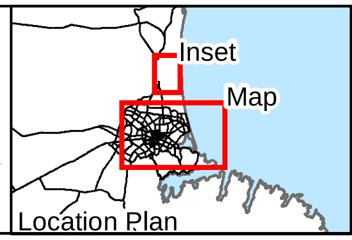

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DRAWN	CXP	Feb.13
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APPROVED		
ARCFILE 52020-0200-LSE02		
SCALE (AT A3 SIZE) 1:60,000		
PROJECT No. 52020.0200		

EARTHQUAKE COMMISSION
CHRISTCHURCH CITY & KAIAPOI
LiDAR Elevation and Verification
(Pre September 2010)

FIGURE No.

Rev. 0

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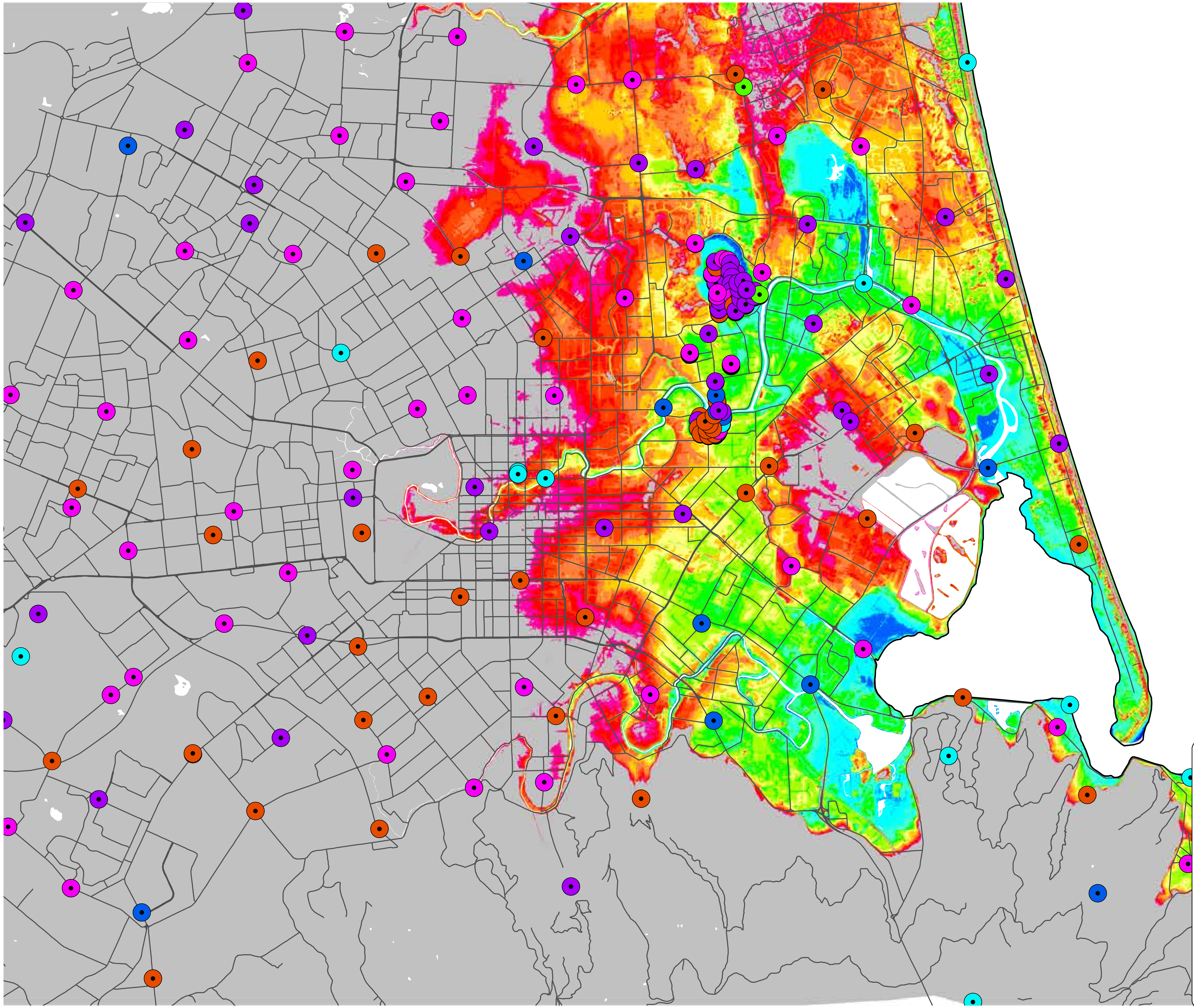

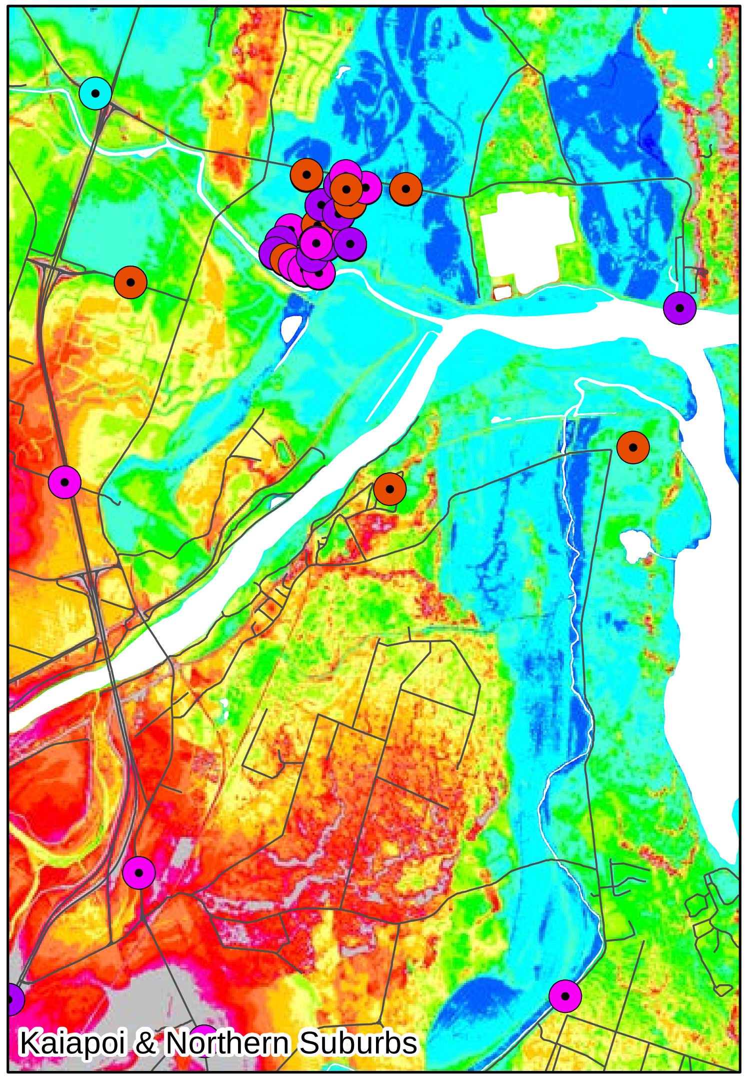

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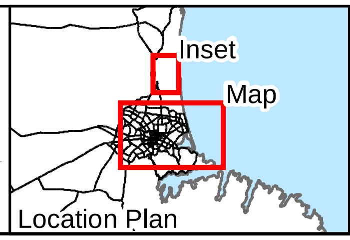

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Kōmihana Rūwhenua

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SCALE (AT A3 SIZE) 1:60,000		
PROJECT No. 52020.0200		

EARTHQUAKE COMMISSION
CHRISTCHURCH CITY & KAIAPOI
LiDAR Elevation and Verification
(Post September 2010)

FIGURE No.

Rev. 0

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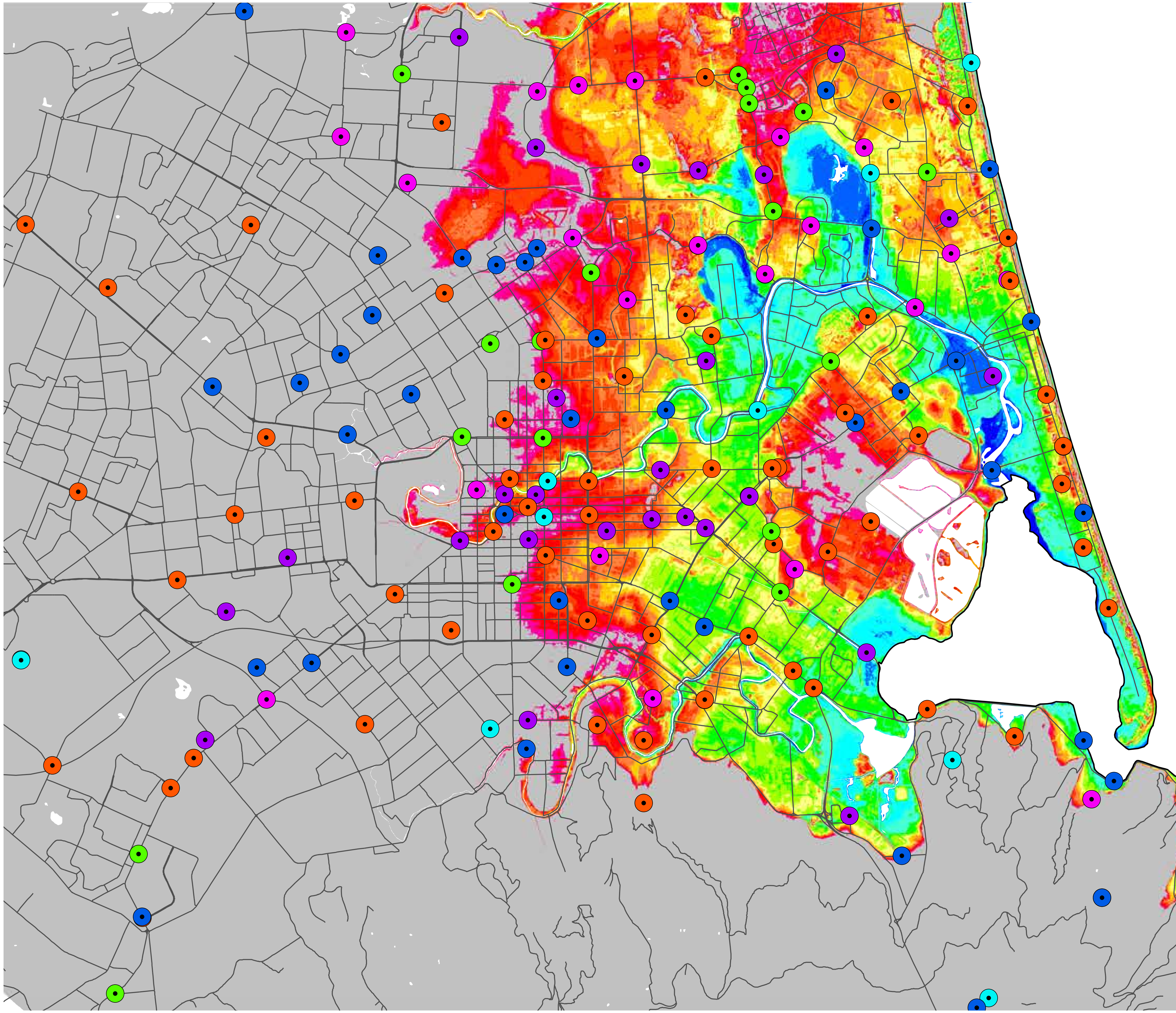

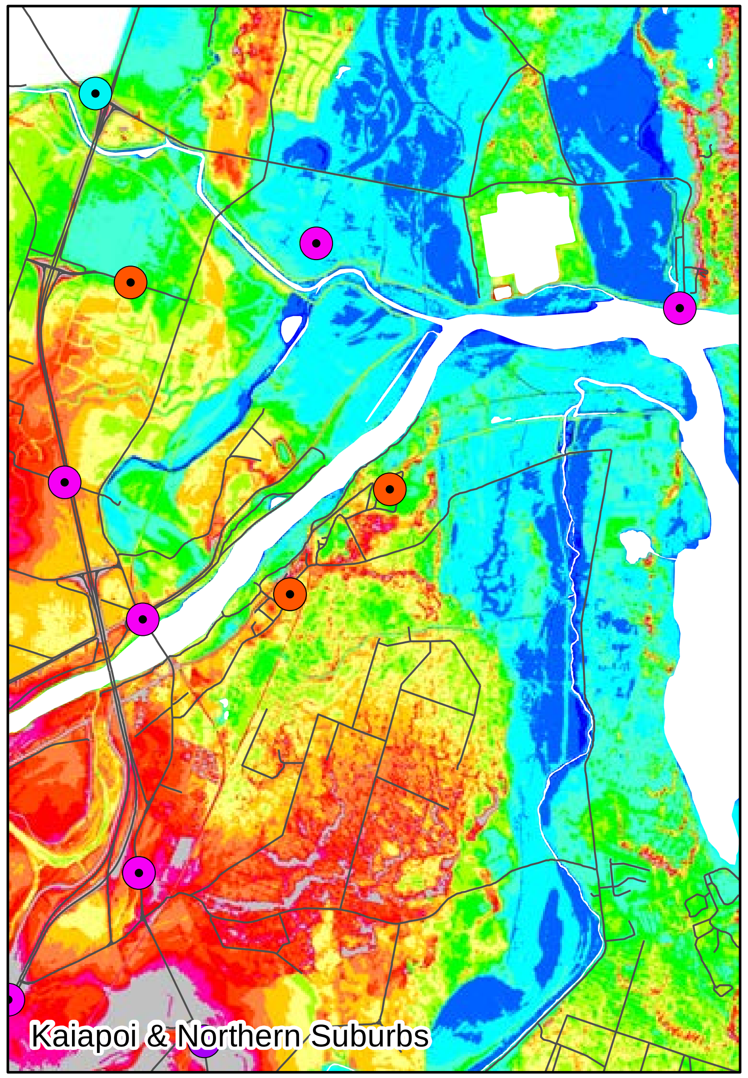

LEGEND

Offset	Elevation (m)	
LIDAR > 0.2 m LOWER	0 - 0.5	3.5 - 4.0
LIDAR 0.1 - 0.2 m LOWER	0.5 - 1.0	4.0 - 4.5
LIDAR 0.0 - 0.1 m LOWER	1.0 - 1.5	4.5 - 5.0
LIDAR 0.0 - 0.1 m HIGHER	1.5 - 2.0	5.0 - 5.5
LIDAR 0.1 - 0.2 m HIGHER	2.0 - 2.5	5.5 - 6.0
LIDAR > 0.2 m HIGHER	2.5 - 3.0	>6.0
	3.0 - 3.5	

Date: 22/02/2013 Time: 12:40:13 p.m.

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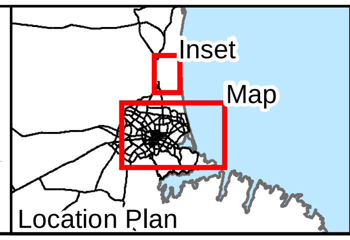
A3 SCALE 1:60,000

0 1 2 3 4 (km)

N



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DRAWN	CXP	Feb.13
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APPROVED		

ARCFILE 52020-0200-LSE15

SCALE (AT A3 SIZE) 1:60,000

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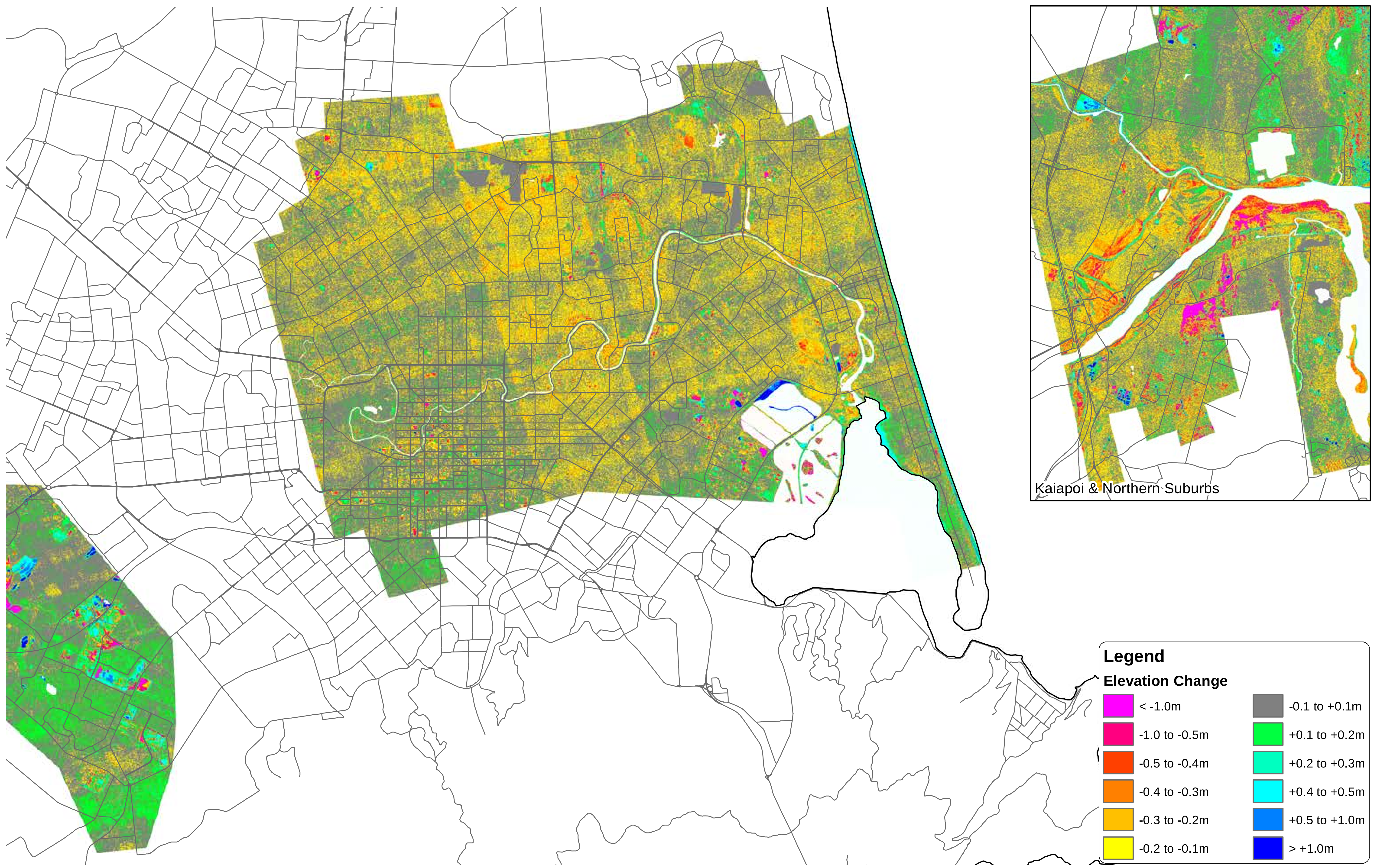
EARTHQUAKE COMMISSION
CHRISTCHURCH CITY & KAIAPOI
LiDAR Elevation and Verification
(Post December 2011)

FIGURE No.

Rev. 0



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A3 SCALE 1:60,000

0 1 2 3 4 (km)

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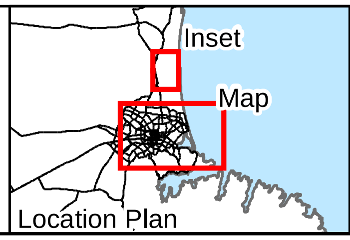

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DRAWN	JEL	Dec.12
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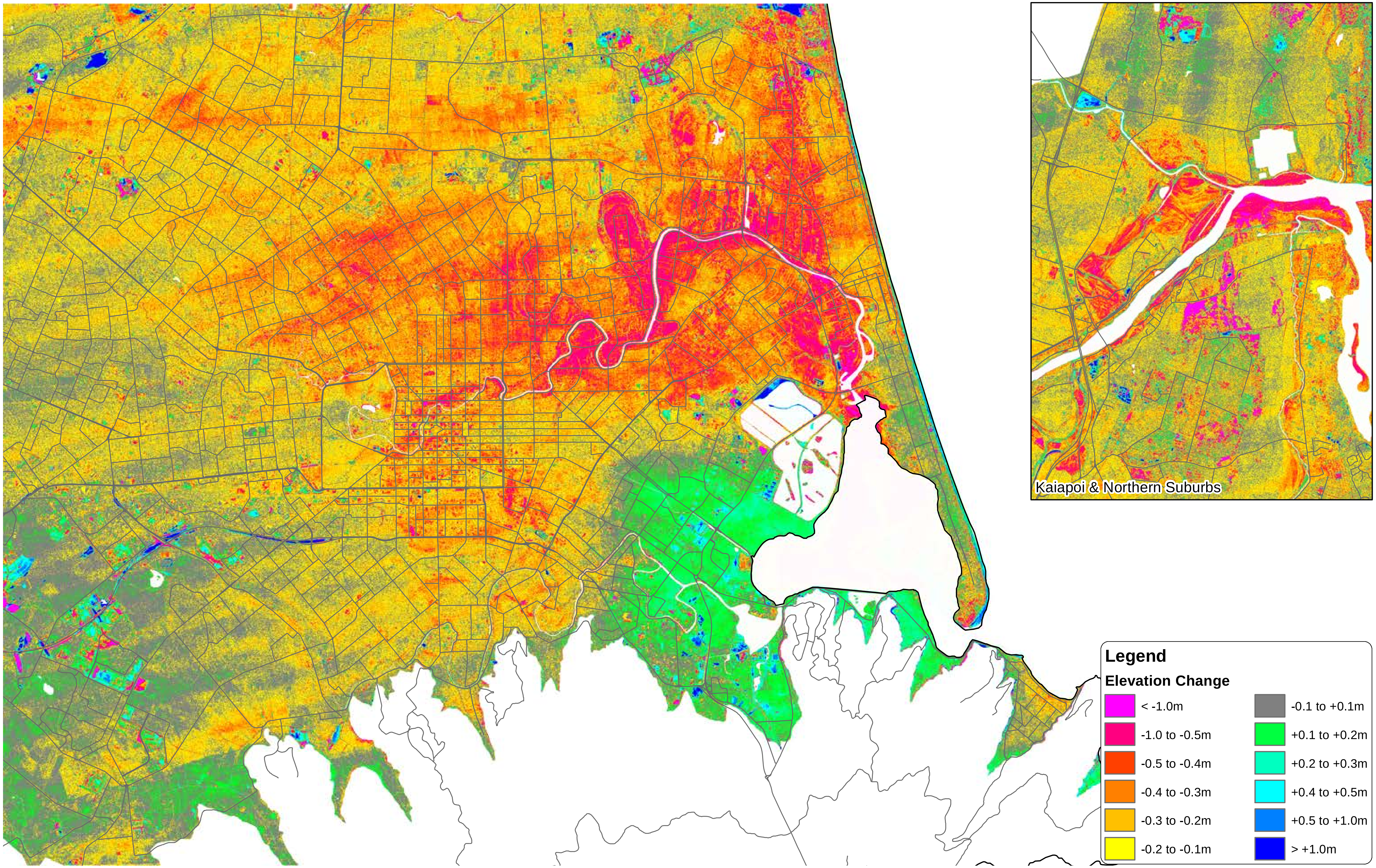
APPROVED		
ARCFILE 52020-0200-LEC32		
SCALE (AT A3 SIZE) 1:60,000		
Prepared By Tonkin & Taylor Ltd. Ref. 52020-0200		

EARTHQUAKE COMMISSION
CHRISTCHURCH CITY & KAIAPOI
Earthquake Related Elevation Change
(Pre September 2010 to Post September 2010)

FIGURE No.

Rev. 0

Date: 4/12/2012 Time: 2:01:23 p.m.



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A3 SCALE 1:60,000

0 1 2 3 4 (km)

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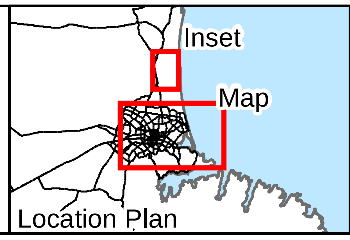

EARTHQUAKE COMMISSION
Kōmihana Rūwhenua

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SCALE (AT A3 SIZE) 1:60,000		
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EARTHQUAKE COMMISSION
CHRISTCHURCH CITY & KAIAPOI
Earthquake Related Elevation Change
(Pre September 2010 to Post June/December 2011)

FIGURE No.

Rev. 0

Date: 4/12/2012 Time: 2:00:17 p.m.

LEGEND

Elevation Difference

-1.5m to -1.0m	-0.1 to +0.1m
-1.0 to -0.5m	+0.1 to +0.2m
-0.5 to -0.4m	+0.2 to +0.3m
-0.4 to -0.3m	+0.4 to +0.5m
-0.3 to -0.2m	+0.5 to +1.0m
-0.2 to -0.1m	> +1.0m

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A3 SCALE 1:60,000

0 1 2 3 4 (km)

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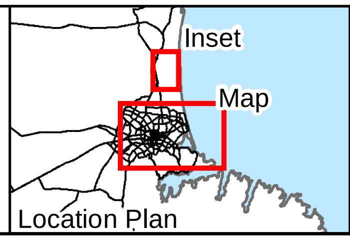

EARTHQUAKE COMMISSION
Kōmihana Rūwhenua

DRAWN	CXP	Feb.13
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ARCFILE 52020-0200-LEC04		
SCALE (AT A3 SIZE) 1:60,000		
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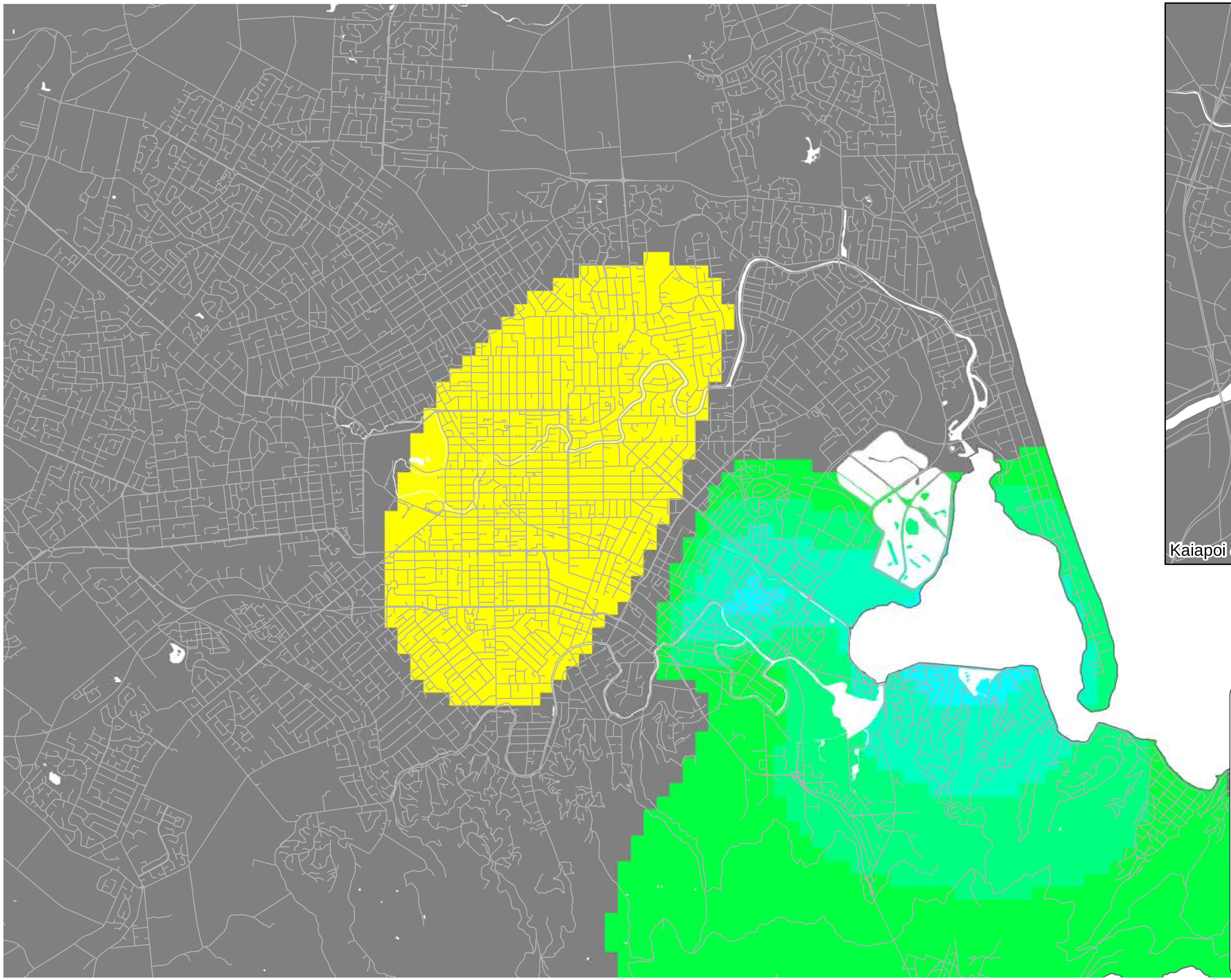
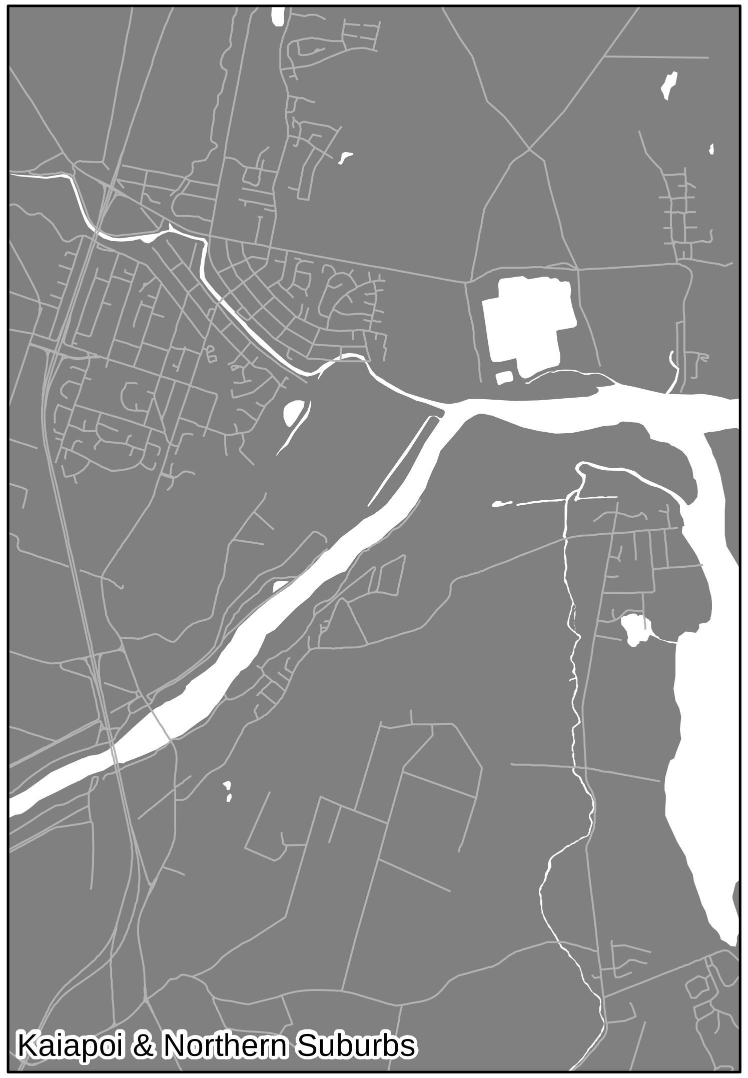
EARTHQUAKE COMMISSION
CHRISTCHURCH CITY
Tectonic Related Elevation Change
(Pre September 2010 to Post September 2010)

FIGURE No.

Rev. 0





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A3 SCALE 1:60,000

0 1 2 3 4 (km)

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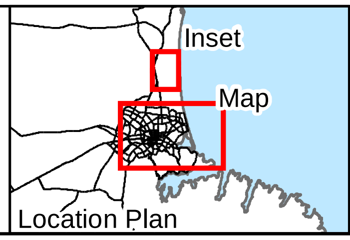

EARTHQUAKE COMMISSION
Kōmihana Rūwhenua

DRAWN	CXP	Feb.13
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ARCFILE 52020-0200-LEC29		
SCALE (AT A3 SIZE) 1:60,000		
PROJECT No. 52020.0200		

EARTHQUAKE COMMISSION
CHRISTCHURCH CITY
Tectonic Related Elevation Change
(Pre September 2010 to Post December 2011)

FIGURE No.

Rev. 0

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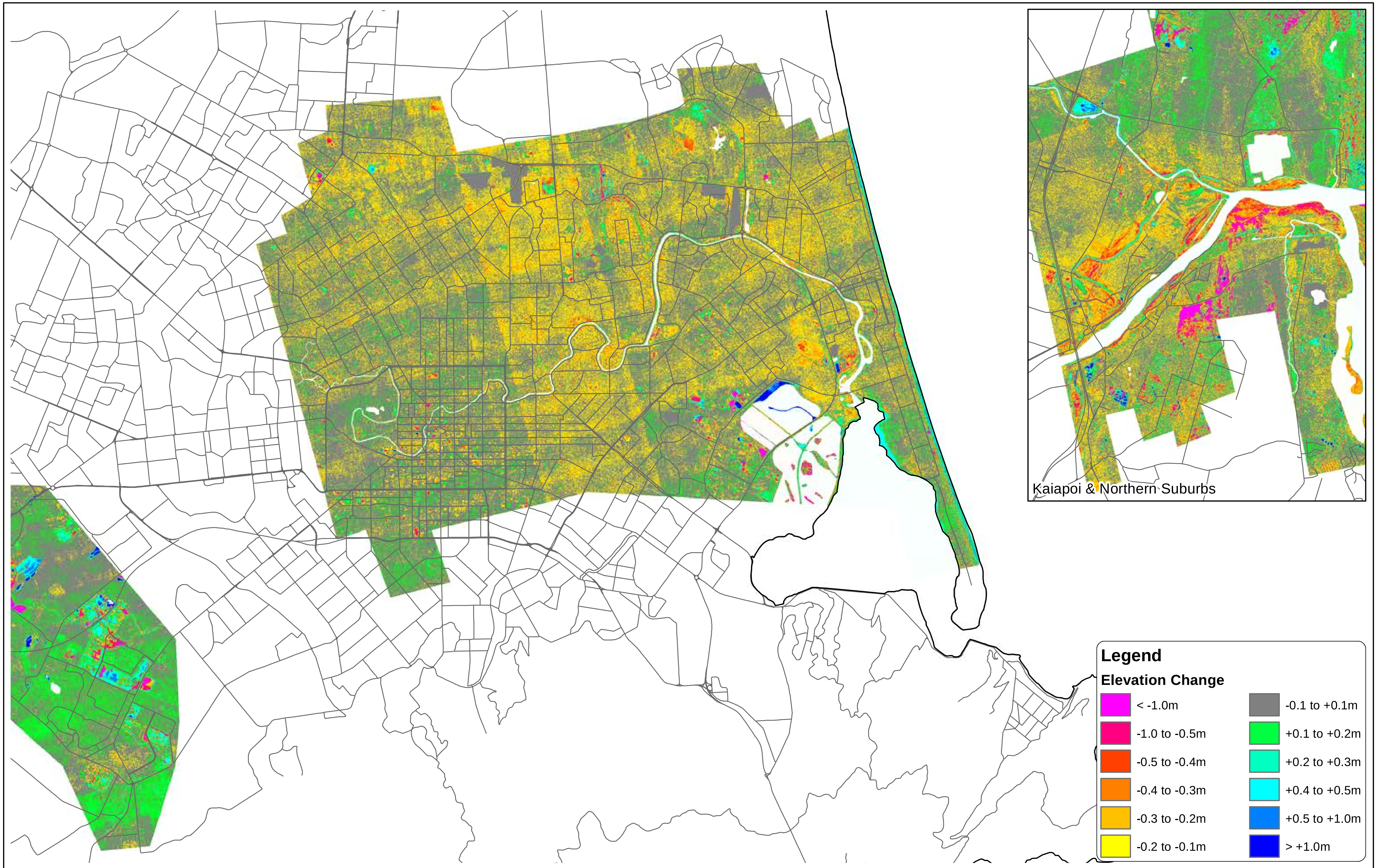

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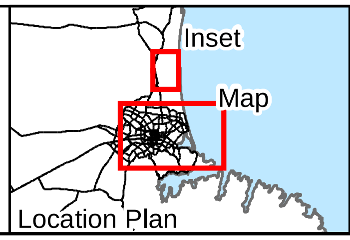

Location Plan

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ARCFILE 52020-0200-LEC36		
SCALE (AT A3 SIZE) 1:60,000		
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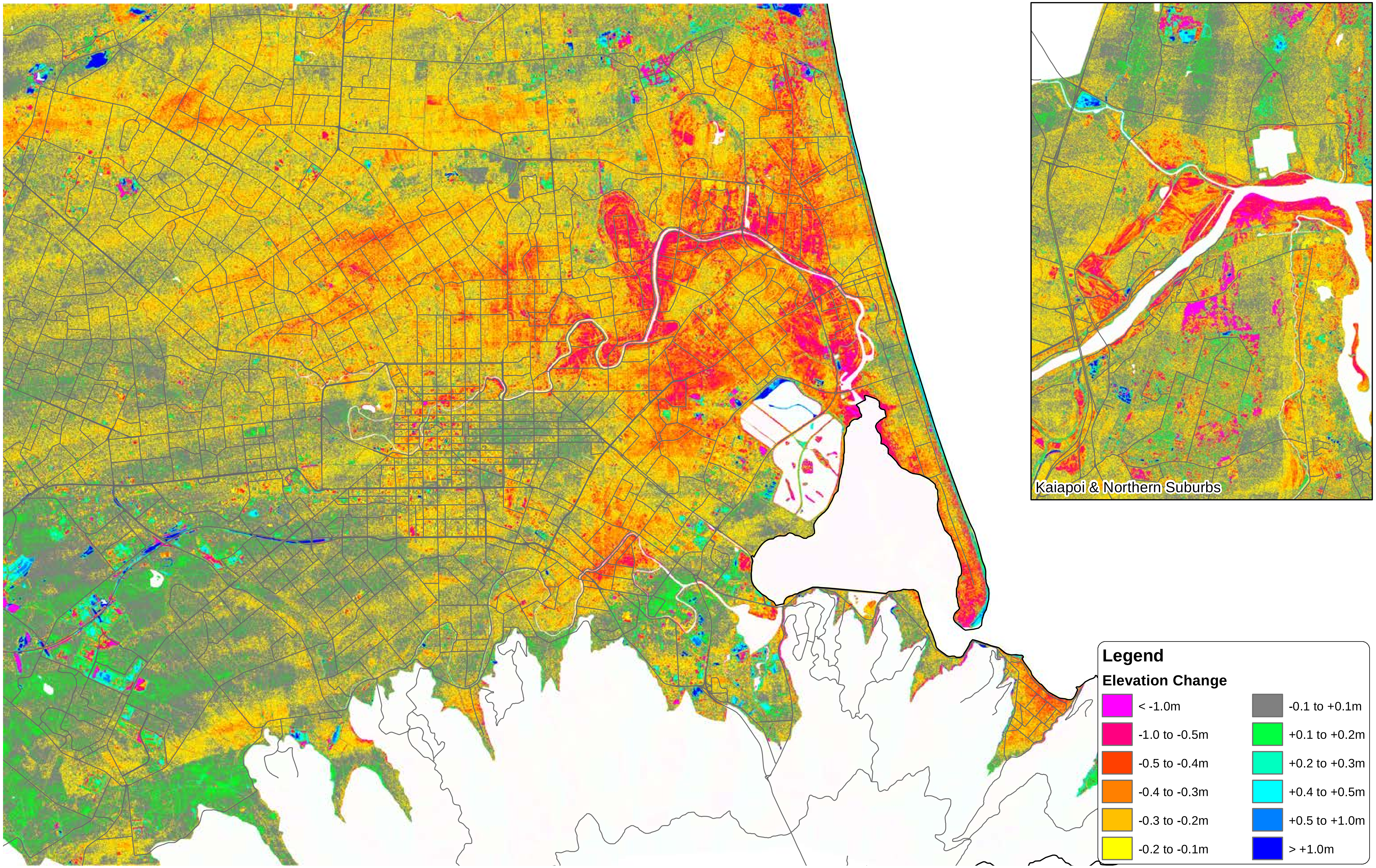
EARTHQUAKE COMMISSION
CHRISTCHURCH CITY & KAIAPOI
Liquefaction Related Elevation Change
(Pre September 2010 to Post September 2010)

FIGURE No.

Rev. 0

Date: 4/12/2012 Time: 2:36:06 p.m.



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A3 SCALE 1:60,000

0 1 2 3 4 (km)

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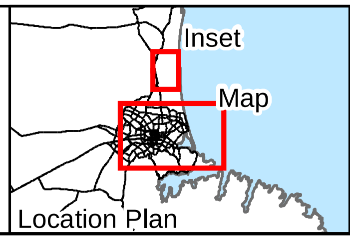

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ARCFILE 52020-0200-LEC39		
SCALE (AT A3 SIZE) 1:60,000		
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EARTHQUAKE COMMISSION
CHRISTCHURCH CITY & KAIAPOI
Liquefaction Related Elevation Change
(Pre September 2010 to Post June/December 2011)

FIGURE No.

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Date: 4/12/2012 Time: 3:11:50 p.m.

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