Phase 2 Coastal Inundation Modelling

Final Study Report

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Waimakariri District Council

Contract 19/25

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Contents

Executive Summary

A hydrodynamic model suitable for examining the susceptibility of the coastal area of Waimakariri District to flooding through the Waimakariri and Ashley River mouths has been developed.

The model has been used to simulate flooding for:

- Separate storm tide and fluvial events of 1%, 0.5% and 0.2% annual exceedance probabilities (AEPs) with an allowance of 1m rise in mean sea level;
- A storm tide event of 1% AEP and rises in mean sea level of 0m, 0.5m, 1.0m and 1.88m.

The simulations include the effect of wave set-up on sea level at the river mouths and an allowance for initial depths of water in the floodplain due to breakout and ponding of groundwater. Groundwater ponding has been included for land where the median groundwater levels, estimated in a separate study, exceed local ground level and where the ground level is below mean sea level (including sea level rise) such that gravity drainage of ponding will be impeded by the water level in the rivers and sea.

The model takes account of the hydraulic connectivity of low-lying areas with the sea and the dynamic effects of storm tide propagation including the attenuation of flood waves in the river channels and overland flow areas.

Simple maps showing the maximum extent and depth of flooding in each model simulation have been produced.

Model results indicate that overtopping of stop banks or natural river banks occurs in all the scenarios considered. The flooded area in the simulations is relatively large, amounting to approximately 10km^2 within the study area (including the Ashley-Saltwater Creek Estuary) for the 1% AEP storm tide event with no sea level rise and an increased area for less frequent events and for scenarios including allowances for sea level rise.

- For the Waimakariri River, key flood flow routes are over the stop banks along Kairaki Creek and over the true left stop bank between Kairaki Creek and Kaiapoi Wastewater Treatment Plant. Overtopping occurs over the true left bank of the Kairaki Creek for all scenarios considered. The stop banks along the Kaiapoi River contain water in the river for all scenarios considered except for the 1% AEP event with 1.88m rise in mean sea level.
- For the Ashley River, the key flood flow route on the true right side of the river is over the lower parts of the stop bank and natural river bank at the car park on Beach Crescent and between the car park and the Taranaki Stream outfall. On the true left side of the river, the spread of water from the Ashley-Saltwater Creek Estuary is largely determined by the natural topography of the area. Water spreads up the Saltwater Creek and under the SH1 bridge crossing.

The results also indicate that:

- Flood levels in the lowest reaches of the Waimakariri River (including the Kaiapoi River) and Ashley River, within the area where overtopping of defences occurs, are strongly influenced by rise in mean sea level. However, the effect diminishes upstream and particularly rapidly in the Ashley River. For both rivers, flood levels at the SH1 bridge crossings and further upstream are not influenced by sea level rise.
- For the scenario of 1m rise in mean sea level, flooding occurs in both fluvial and storm tide events for a given AEP:

- In the Waimakariri River, flooding is more severe for a storm tide event of a given AEP than for a fluvial event of the same AEP, except for the smallest AEP considered (0.2%) for which flooding in the fluvial event is slightly more severe.

- In the Ashley River, flooding on the true right bank is marginally deeper and more extensive in fluvial events than in storm tide events for the all the AEPs considered. On the true left side of the river, in and around the Ashley-Saltwater Creek Estuary, the flood extents and depths are slightly greater for storm tide events.

An allowance for initial ponding of water in the floodplain due to elevated groundwater levels has been included in the simulations. Ponding is only included in areas of land which lie below mean sea level, on the basis that in these areas the drainage of any groundwater breakout via the existing gravity drainage systems will be impeded by the outfall water levels in the rivers. In areas of higher ground, i.e. above mean sea level, it is likely that surface and sub-surface drainage systems will tend to limit the depth of surface flooding originating from elevated groundwater levels and any flooding from this source will not be significantly influenced by coastal water level conditions, the focus of this study. However, such areas may still be vulnerable to surface flooding originating from groundwater. Assessment of this flooding mechanism is outside the scope of this study and further assessment of the risk from this source of flooding is recommended.

The accuracy of the modelling depends in part on the accuracy of the data used. Due to the lack of recent ground-based survey data, the model is largely based on aerial survey data (LiDAR, 2014). If new, ground based survey data becomes available, updating the models should be considered. In critical locations it could be worth considering collecting new survey data to refine the model.

Model calibration is outside the scope of this study and sensitivity testing to understand the uncertainty in the model results due to uncertainty in model parameters should be considered. Sensitivity tests to the model boundary conditions should also be considered, including the shape and duration of the storm surge component and wave setup allowance, given their significance to water levels in the rivers and floodplain.

Important note about your report

The sole purpose of this report and the associated services performed by Jacobs is to assess the extent of coastally driven flooding at the mouths of the Waimakariri and Ashley Rivers in accordance with the scope of services set out in the contract between Jacobs and Waimakariri District Council ('the Client'). That scope of services, as described in this report, was developed with the Client.

In preparing this report, Jacobs has relied upon, and presumed accurate, any information (or confirmation of the absence thereof) provided by the Client and/or from other sources, including the Environment Canterbury river models of the Waimakariri, Kaiapoi and Ashley Rivers. Except as otherwise stated in the report, Jacobs has not attempted to verify the accuracy or completeness of any such information. If the information is subsequently determined to be false, inaccurate or incomplete then it is possible that our observations and conclusions as expressed in this report may change.

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1. Introduction

1.1 Need for study

This study addresses the recommendations related to coastal flooding assessment of the "Coastal Erosion and Sea Water Inundation Assessment Technical Report" submitted to Waimakariri District Council (WDC) in June 2018 (part of the Natural Hazards Assessment for the Waimakariri District Plan Review). The assessment found that, using a "bathtub" mapping method, overtopping of the stopbanks at Waimakariri and Ashley River mouths in a 1% AEP coastal storm event combined with sea level rise could flood up to 4700 hectares around Kaiapoi, Kairaki-Pines and Waikuku in 50 years' time, and potentially up to 6500 hectares in 100 years' time.

Given the extensive areas identified as at risk of flooding by the bathtub mapping, the report recommended that further modelling with hydrodynamic models be undertaken to examine the susceptibility of those areas. The recommendation further noted that the additional modelling, termed as Phase 2 Coastal Inundation Modelling, should include a better definition of the role of set-up on river mouth water levels, the interaction of extreme sea levels with river flows (particularly backwater effects during catchment flood events), the hydraulic connectivity of low-lying areas with the sea and the dynamic effects of storm tide propagation including the attenuation of flood waves in estuaries and overland flow areas.

1.2 Study area and model extent

The extent of the area considered in the model for the simulation of flooding through the Waimakariri and Ashley River Mouths is shown in Figure 1. The area includes all land lying below the 5m (NZVD2016) contour within the Waimakariri District and extends beyond the expected tidal influence on water levels in the two rivers. The model includes a representation of the two river channels and the floodplain between the two rivers. This allows the contributions from both the rivers to flooding of the common floodplain between them to be included in a single model simulation.

1.3 Scenarios considered

WDC have specified nine scenarios to be simulated for each of the Waimakariri and Ashley River Mouths as detailed in Table 1. The scenarios cover a range of annual exceedance probabilities (AEP) of storm tide level and fluvial flow together with means sea level rise allowances of 0.5m, 1m[1] and 1.88m[2] – corresponding approximately to 50 years (RCP8.5 emissions scenario), 100 years (RCP8.5 emissions scenario) and 130 years (RCP8.5+ emissions scenario) of sea level rise (MfE[3], 2017).

Table 1: Scenarios specified by WDC for model simulations

Description	Scenario No.	Mean Sea Level Rise (m)	Storm Tide AEP	Fluvial Flow AEP
Current	1	0	1.0%	10.0%
Baseline	2	1	1.0%	10.0%
Varying Sea Level Rise	3	0.5	1.0%	10.0%
	4	1.88	1.0%	10.0%
Varying Coastal and Fluvial conditions	5	1	10.0%	1.0%
	6	1	0.5%	5.0%
	7	1	5.0%	0.5%
	8	1	0.2%	2.0%
	9	1	2.0%	0.2%

[1] Recommended by Ministry for Environment for controlling planning for existing coastal development and assets
[2] Recommended by Ministry for Environment for controlling planning for coastal sub-divisions, greenfield development and major new infrastructure
[3] Coastal Hazards and Climate Change. Guidance for Local Government land. Ministry for Environment 2017

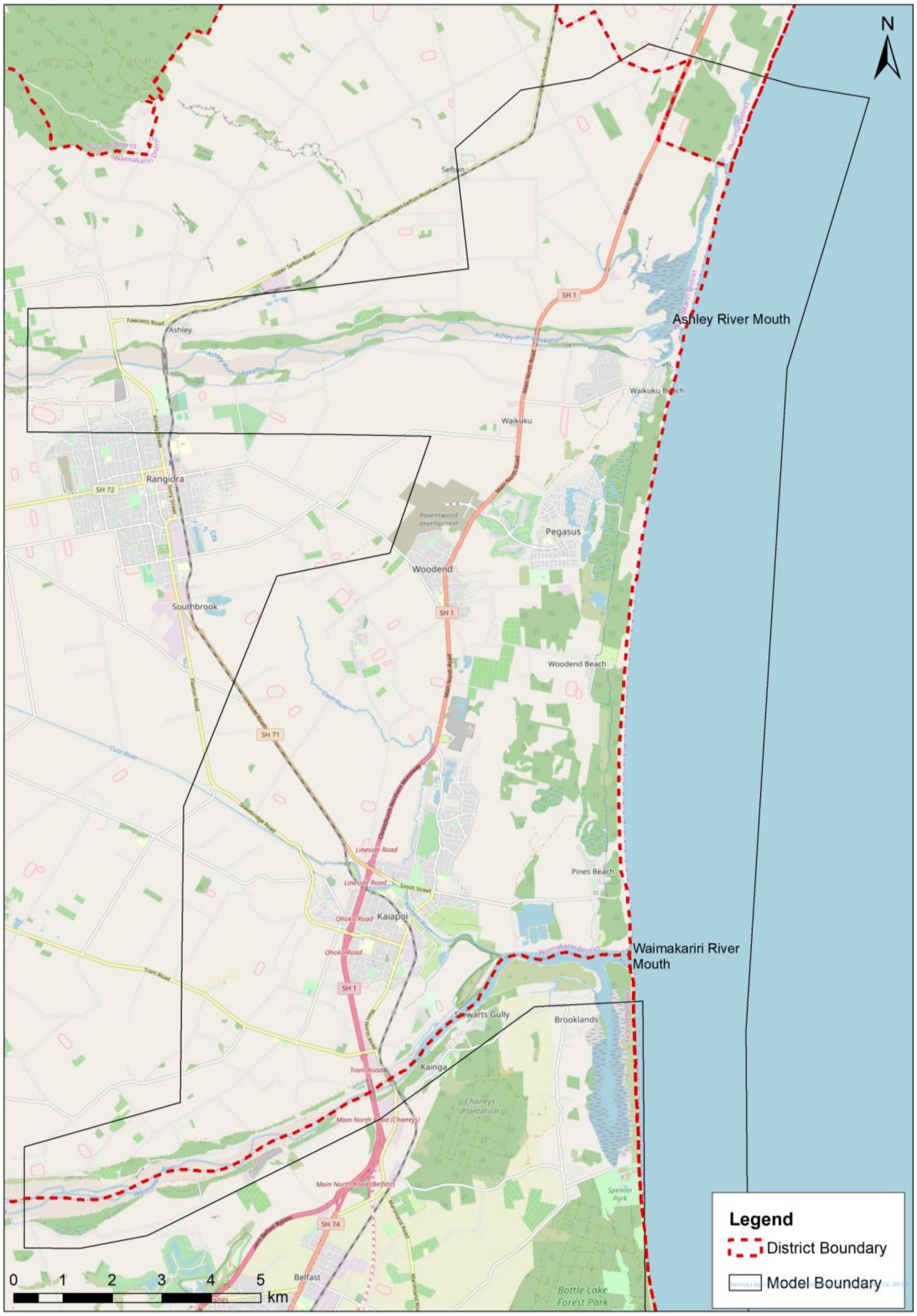


Figure 1: Model extent

1.4 Scope of model simulations

The model simulates flow across the existing stopbanks and natural banks of the Waimakariri and Ashley Rivers and across the floodplain for the purposes of identifying the extent and depth of flooding for the scenarios in Table 1.

Model outputs are only required within Waimakariri District boundary. However, flooding from both the Waimakariri River and Ashley River can extend beyond the District boundary. The model therefore extends beyond the District boundary in order to include the effects of more widespread flooding on water levels within the District. For the Ashley River, the detailed model extends north beyond the District boundary, up to the limit of the available detailed survey data, approximately 2km north of the boundary at the shoreline. For the Waimakariri River, the effect of storage of water within Brooklands Lagoon and the surrounding low-lying areas on river water levels is accounted for in the model by including a simplified representation of this area in the model.

The simulations include initial water levels in the floodplain derived from the estimated median groundwater level for the appropriate sea level rise allowance in each scenario (0m, 0.5m, 1.0m or 1.88m). Detailed groundwater modelling is excluded from scope of this study and groundwater levels have been derived from the results of a previous study (Groundwater Level Assessment, Waimakariri District Council, Groundwater Level Assessment Technical Report, IZ105900-0005-NC-RPT-0001, 25 May 2018).

Simulation of other inflows to the floodplain or of rainfall and runoff within the floodplain is outside the scope of this study. This includes rainfall in the model extent, and rainfall-runoff from the upstream minor catchments.

The effect of wave setup on water level at the mouth of the rivers has been estimated and has been added to the storm tide level for each scenario.

Values of storm tide levels and extreme fluvial flows have been obtained from available existing data. The duration of the model simulations corresponds to that of a representative coastal storm surge event, encompassing several tide cycles before and after the maximum design tide. In this way any potential accumulation of water in the floodplain resulting from overtopping by multiple successive high tides during a storm surge event is included in the simulations.

Assessment of the joint probability of river flows and storm tides is excluded from the scope of this work. River flows are modelled as fixed rate inflows for each scenario coincident with the maximum tide water level for the combinations of AEPs specified by WDC and listed in Table 1. The river flows correspond to the estimated peak flow for the specified AEP and are simulated as a fixed flow over the period of the highest tide in the simulation (12 hours). Outside this period the mean annual flood flow is adopted for the period of lower tides in the simulation.

The simulations consider the conditions where high fluvial flow in the Waimakariri or Ashley River does not occur at the same time as high fluvial flow in the other river. Simulations are performed with the specified high flow in one river and the mean annual flood flow in the other river and vice versa, resulting in a total of 18 scenario simulations. The storm tide water level condition specified in the sea at the mouth of each of the rivers is same for each scenario.

2. Methodology

2.1 Overview

Simulations of flooding from the Waimakariri and Ashley River Mouths have been performed using a DHI MIKE FLOOD hydrodynamic model of the rivers and the floodplain.

The principal tasks undertaken in the study to develop the model and perform the simulations are as follows:

i. Site visit
ii. Request and collate necessary data
iii. Develop model schematisation and build model
iv. Prepare boundary conditions for model simulations
v. Perform simulations and process results
vi. Prepare report

2.2 Site visit

A site visit was made to key locations on the Waimakariri and Ashley Rivers (Kaiapoi, Kairaki-Pines, Pegasus township and Waikuku) on 10 May 2019 to enable the modelling team to understand the physical characteristics of the site. Photographs showing selected features are presented in Figures 2 to 5.

Figure 2: Kairaki Creek, left bank at Sailing Club

Figure 3: Stop bank, Kaiapoi River left bank (Kaiapoi)

Figure 4: Stop bank, Ashley River right bank (Waikuku Beach)

Figure 5: Gated outfall to Ashley River (Taranaki Stream)

2.3 Data collection

The following information and data were obtained through requests to WDC and Environment Canterbury (ECan):

i. LINZ Canterbury-Rangiora 2014 LiDAR[4] 1m Digital Elevation Model (DEM) (provided by WDC under the Coastal Erosion and Sea Water Inundation Assessment project and resampled to 2m resolution DEM, NZGD2000 / New Zealand Transverse Mercator 2000 projection, NZVD2016 vertical datum).

ii. 1D MIKE 11 river models of the Waimakariri, Ashley and Kaiapoi Rivers (provided by ECan, 14 and 21 May 2019).

iii. Reports:

   a. Waimakariri River bed level investigation, Report No. R08/11, A J Boyle, M R Surman, January 2009, ECan;

   b. Flood frequency analysis pilot study: Orari, Temuka and Waimakariri Rivers, Report No. R15/129, K Steel, May 2016, ECan;

   c. Ashley River bed level investigation, Report No. R09/71, A J Boyle, M R Surman, September 2009, ECan;

   d. Kaiapoi River flood capacity investigation, Report No. R15/58, A J Boyle, April 2015, ECan.

iv. Information relating to the levels of stop banks and operation of drainage outfall structures (pers. comms. A J Boyle of ECan, various, May-June 2019; telephone call B McIndoe of ECan, 7 June 2019).

[4] Light Detection and Ranging (LiDAR): a surveying method used to measure ground levels by directing laser light at the ground surface from an aircraft and measuring the reflected light with a sensor. The ground level relative to the aircraft is calculated from the time of travel and differences in emitted and return wavelengths of the reflected light.

2.4 Model schematisation and build

2.4.1 Overview

The MIKE FLOOD model comprises two separate models. The main river channels are represented in a one-dimensional (“1D”) MIKE11 model and the floodplain and river mouths outside of the 1D model are represented in a more detailed two-dimensional (“2D”) MIKE21 model of the floodplain. The two models are dynamically linked during the simulations to allow water to pass from the river to the floodplain and vice versa, according to the relative values of river water level, floodplain water level and the level of the river bank or stop bank between the 1D river channel and 2D floodplain. Figure 6 shows the model schematisation.

The model is defined in terms of the NZGD2000 / New Zealand Transverse Mercator 2000 projection and NZVD2016 vertical datum, corresponding to the projection and level datum of the LiDAR data used to provide the ground elevation data for the model. The principal model outputs are maximum water depths which are independent of vertical datum system. Model maximum water levels, to NZVD2016 datum, are also available and can be converted to other vertical datum systems (e.g. Lyttelton 1937) through a simple transformation.

2.4.2 1D model

The 1D MIKE11 model is composed of four main branches: the Ashley River, the Waimakariri River, the Kaiapoi River and Brooklands Lagoon. In each branch the river channel shape is defined by a sequence of channel cross-sections, as shown in Figure 6.

For the three main river branches (Ashley River, Waimakariri River and Kaiapoi River) the models provided by ECan have been used. For the Brooklands Lagoon Branch, cross-sections of the lagoon have been extracted from LiDAR data. For the Waimakariri River Branch, two additional cross-sections have been created at the downstream, coastal end of the river in order to include a representation of the expansion in flow area downstream of the outlet of the river into the sea which forms the downstream limit of the ECan model (cross-section km-0.47).

The original model channel roughness values have been retained in the 1D channel cross-sections.

The ECan models are defined relative to Lyttelton 1937 local vertical datum. The cross-section data has adjusted to NZVD2016 vertical datum by specifying an offset of -0.356m. This corresponds to the average difference in datum surfaces over the project area, derived under a previous Jacobs study.[5] The difference in datums over the project area is not uniform but varies by less than +/-10mm from the average value adopted. The effect of local variations of this magnitude in the cross-section elevation data will have negligible effect on the model results.

Bank levels in the Kaiapoi River Branch have been adjusted (where necessary) to correspond to the design bank level of the recent (Summer 2018-2019) improvement works of 4m (Lyttelton 1937)[6].

In the Waimakariri River Branch, the position of the left levee bank markers (marker 1) for cross-sections downstream of 11929.02m (ECan cross-section 1.600) have been adjusted to correspond to the location of the lateral link which couples the 1D model to the 2D model. In this area the link lies within the Waimakariri stop bank to allow the entrance to the Kairaki Creek to be included in the 2D model. A 1D model is not available for this channel.

[5] Refer Table 3.1, Coastal Erosion and Sea Water Inundation Assessment Technical Report, IZ105900-005-NC-RPT-002, Jacobs, June 2018
[6] Email from A Boyle (ECan) 23 May 2019; Telcon B McIndoe (ECan) 7 June 2019

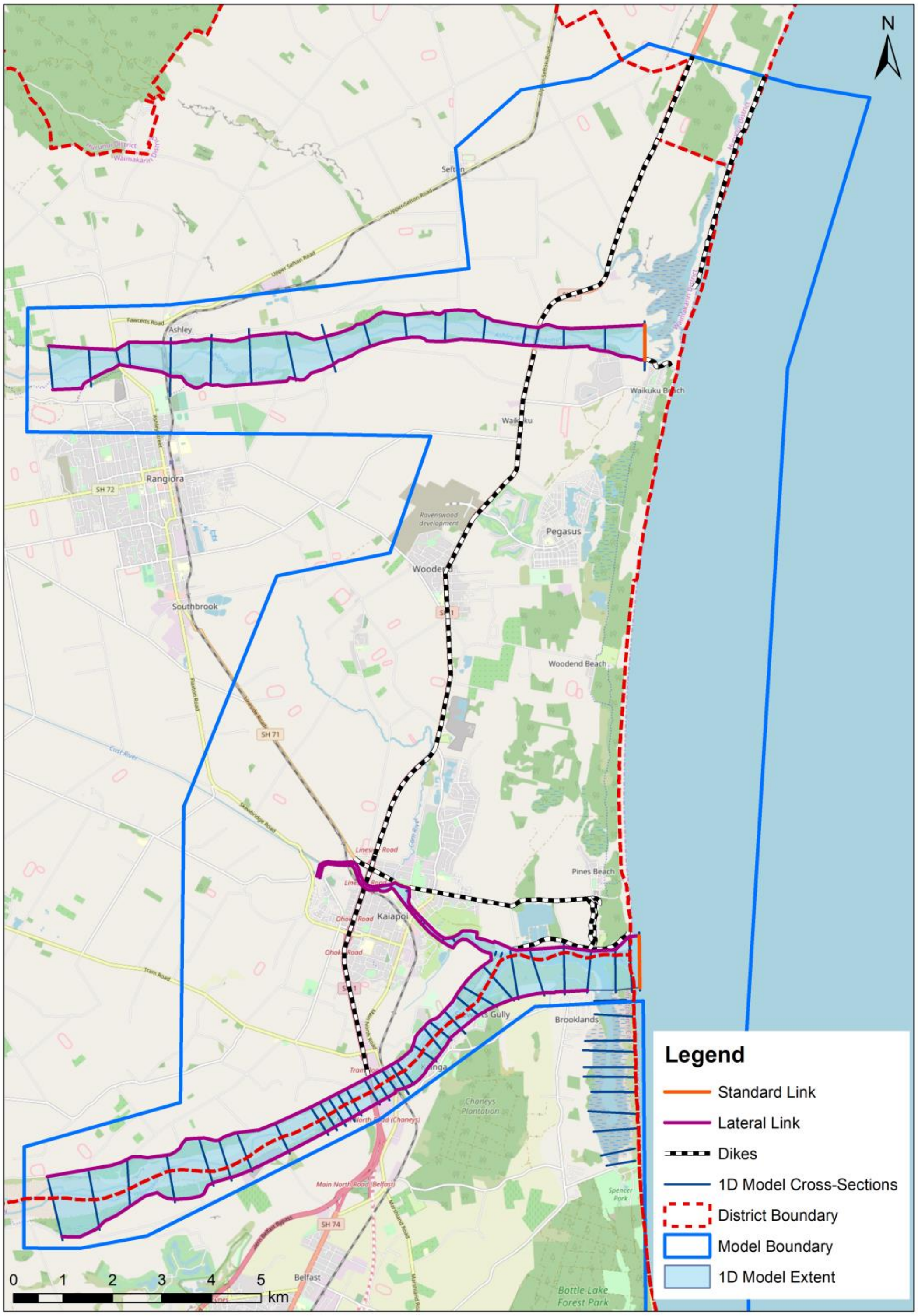


Figure 6: Model schematisation

2.4.3 2D model

The 2D MIKE21 model covers the area indicated by the overall boundary in Figure 6, excluding the 1D model domains. The model has been developed using the Flexible Mesh (FM) module of MIKE21. In this type of model, the ground surface is represented by a mesh of irregular triangular elements. The elevation of the mesh elements has been interpolated from the LiDAR data for the project. For the offshore part of the model, where bathymetry data is not available, a nominal low bed level has been applied.

A more detailed representation of key raised features which control the flow of water out of the river channels and across the floodplain has been included in the 2D model using the MIKE21 Dike Structure module. The crest levels of the features are defined as a series of points along the line of the “dike” structure. Computationally, the flow across the dike is calculated from the floodplain water levels either side of the line using a weir flow equation and the specified crest levels along the dike line as the weir crest level. Figure 6 shows the location of the dike structures in the model, representing the following features:

- Stop bank and natural river bank on the true right bank of the Ashley River downstream of the 1D model domain;
- Dune crest to the north of the Ashley River Mouth;
- State Highway 1 (SH1) road embankment;
- Smith Street/Beach Road from the intersection with SH1 to Pines Beach;
- Stop bank and natural river bank on the true left bank of the Waimakariri River between the confluence with the Kaiapoi River and the coast;
- Stop banks along both sides of Kairaki Creek.

Roughness values for the 2D model are specified according to the land cover types defined in the New Zealand Land Cover Database (LCDB) Version 4.1. Figure 7 shows the distribution of land cover types within the model boundary. The Manning’s roughness coefficients assigned to each land cover type are detailed in Table 2.

Table 2: 2D Model roughness coefficients according to LCDB land cover types

LCDB Class Name	Manning’s roughness coefficient “n”	LCDB Class Name	Manning’s roughness coefficient “n”
Road	0.014	Lake	0.020
Sand	0.025	Gravel	0.028
Open Space	0.033	River	0.035
Orchard	0.050	Surface Mine	0.060
Mixed Exotic Shrubland	0.080	Low Producing Grassland	0.090
Built-up Area	0.100	Deciduous Hardwoods	0.125
Exotic Forest	0.150	Transport Infrastructure	0.016

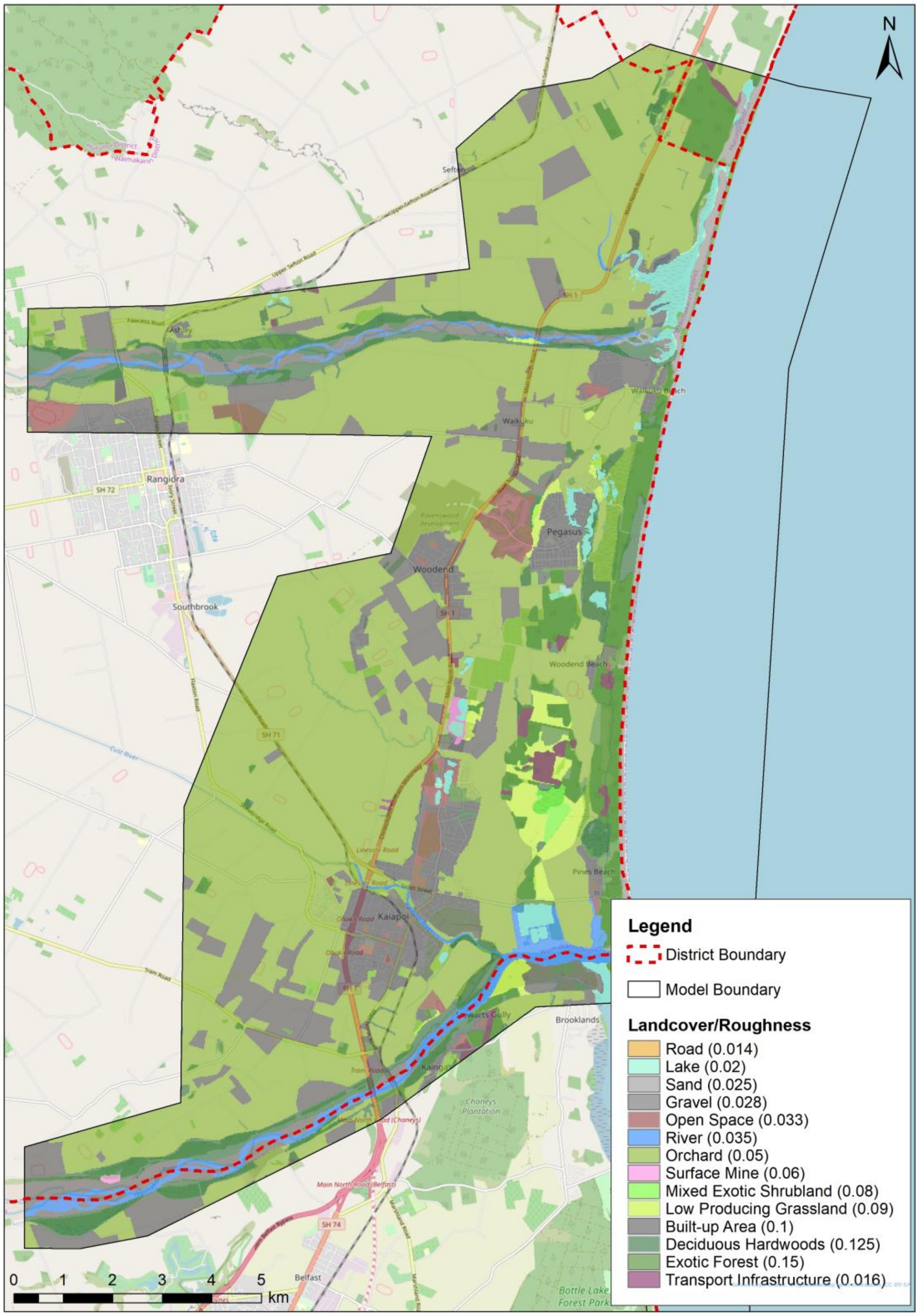


Figure 7: Land cover classes and roughness values for 2D Model

2.4.4 Coupling of 1D and 2D models

The 1D MIKE11 and 2D MIKE21 FM models are dynamically coupled in the MIKE FLOOD simulation using standard links and lateral links as shown in Figure 6.

The downstream boundaries of the Waimakariri and Ashley River branches are connected to the 2D model using standard links. The average water level along the link line in the 2D model is transferred as the water level at the downstream end of the 1D model branch. The flow at the downstream boundary of the 1D model branch is applied as a net inflow or outflow to the 2D model and is distributed along the link line according to depth in the 2D model.

Lateral links connect the left and right banks of the two rivers to the 2D model of the floodplain alongside the rivers. Flow over the lateral links from the 1D model to the 2D model (or vice versa) is calculated from the water levels in the 1D river branch and the 2D model using a weir flow equation and the bank level of the river.

For most of the lateral links the bank levels are specified by the “HGH” method – i.e. the maximum of the 1D model bank levels (as specified by the left and right levee markers in the channel cross-section data and interpolated between cross-sections) and the elevations in the 2D model mesh. For the lateral links along the banks of the Kaiapoi River, the bank levels are specified from the 1D model bank levels, which have been set at the design level of 4m (Lyttelton 1937).

2.5 Model boundary conditions

2.5.1 Model boundaries

A time varying water level boundary is applied along the eastern boundary of the 2D MIKE21 FM model. The boundary represents the tidal water level in the sea offshore of the river mouths. A single water level time series is applied along the entire length of the model boundary such that the storm tide water levels in the sea at each of the river mouths is the same.

Time varying flow boundary conditions are applied at the upstream boundaries of the Waimakariri and Ashley River branches in the 1D MIKE11 model. The boundaries represent the fluvial flow in each river. Fluvial flow contributions from the Kaiapoi River are not included in the scenarios simulated and a zero-flow boundary is applied at the upstream boundary of the Kaiapoi River Branch in the 1D MIKE11 model. Flows in other smaller streams are excluded from the model simulations.

2.5.2 Storm Tide water level boundary

The storm tide boundary for the scenarios comprises a series of tides to simulate the effects of storm surge and wave setup on the astronomical tidal water level at the coast adjacent to the river mouths for a representative storm event.

The extreme water levels derived by Goring[7] for Sumner Head are adopted for the maximum tidal water level in the boundary water level time series. Table 3 shows the values derived by Goring in terms of Christchurch Drainage Board (CDB) level datum and the equivalent values relative to Lyttelton 1937 datum and NZVD2016 datum (the model level datum). The table also shows the AEPs for the scenarios considered in this study, which are taken to be equivalent to the reciprocal of the return period for the purposes of the study.

[7] Extreme Sea Levels at Christchurch Sites: EV1 Analysis, Mulgor Consulting Limited, 24 July 2018

Table 3: Extreme sea level values (Goring, 2018[8])

Return period (years)	Scenario AEP	Storm tide level at Sumner Head (m above datum)		
		CDB datum	Lyttelton 1937 datum	NZVD 2016 datum
2		10.764	1.721	1.365
5		10.868	1.825	1.469
10	10%	10.937	1.894	1.538
20	5%	11.003	1.960	1.604
50	2%	11.089	2.046	1.690
100	1%	11.153	2.110	1.754
200	0.5%	11.217	2.174	1.818
500	0.2%	11.302	2.259	1.903
1000		11.365	2.322	1.966

The storm tide water level time series is constructed from:

i. a representative time varying astronomical tidal water level series;
ii. a representative time varying storm surge height series, scaled to achieve the required sea level;
iii. an allowance for wave setup on sea level;
iv. a constant mean sea level rise allowance.

Figure 8 shows how the model boundary water level series is developed for Scenario 2 (1% AEP sea level and 1m rise in mean sea level).

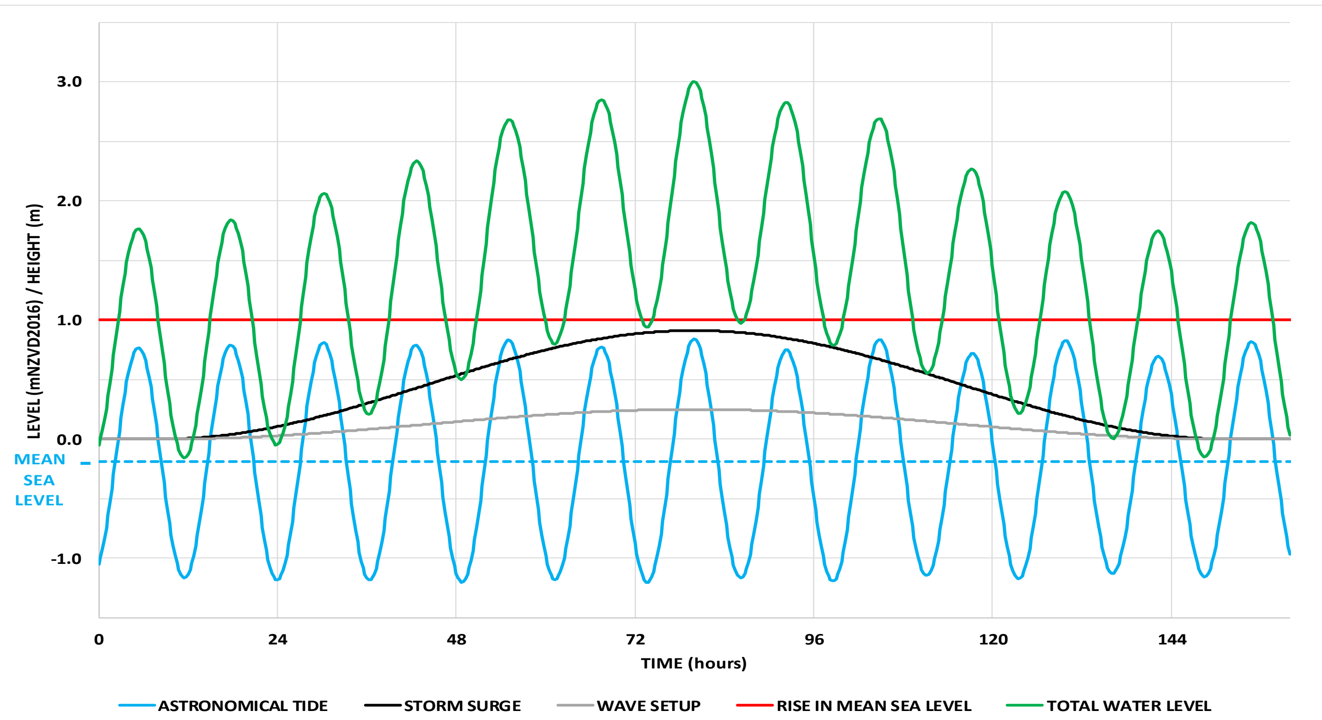


Figure 8: Development of model water level boundary for Scenario 2 (1% AEP sea level with 1m rise in mean sea level)

[8] Extreme Sea Levels at Christchurch Sites: EV1 Analysis, Mulgor Consulting Limited, 24 July 2018

- Astronomical water level

A representative water level series of the astronomical tide level in the study area has been derived using the DHI MIKE21FM Tide Generator software for a location close to Sumner Head (172.76E, 43.56S) at 15-minute intervals for the period 10/4/1999 to 26/4/1999. The period includes a high astronomical tide level. The calculated water level series is presented in Figure 9 together with the high and low water levels generated from the NIWA “Tide Forecaster” tool for the same period. The generated tide compares favourably with the NIWA predictions in terms of timing of the high and low waters. The generated values of high and low water levels are generally within 0.1-0.2m of the NIWA forecast values. This is considered acceptable for the purpose of this study given that the stated accuracy of the NIWA data is +/-0.1m[9] and the water level series is adopted as a representative underlying series, to which storm surge is added to achieve the required extreme water level, rather than for simulation of an actual event.

The highest astronomical water level in the generated time series is 1.03m above mean sea level. This is similar to the current Mean High Water Perigean Spring Tide (MHWPS) height of 1.06m[10] above mean sea level. This tide has been selected as the central tide for the model simulation time period, to which the storm surge height is added to achieve the required extreme sea level.

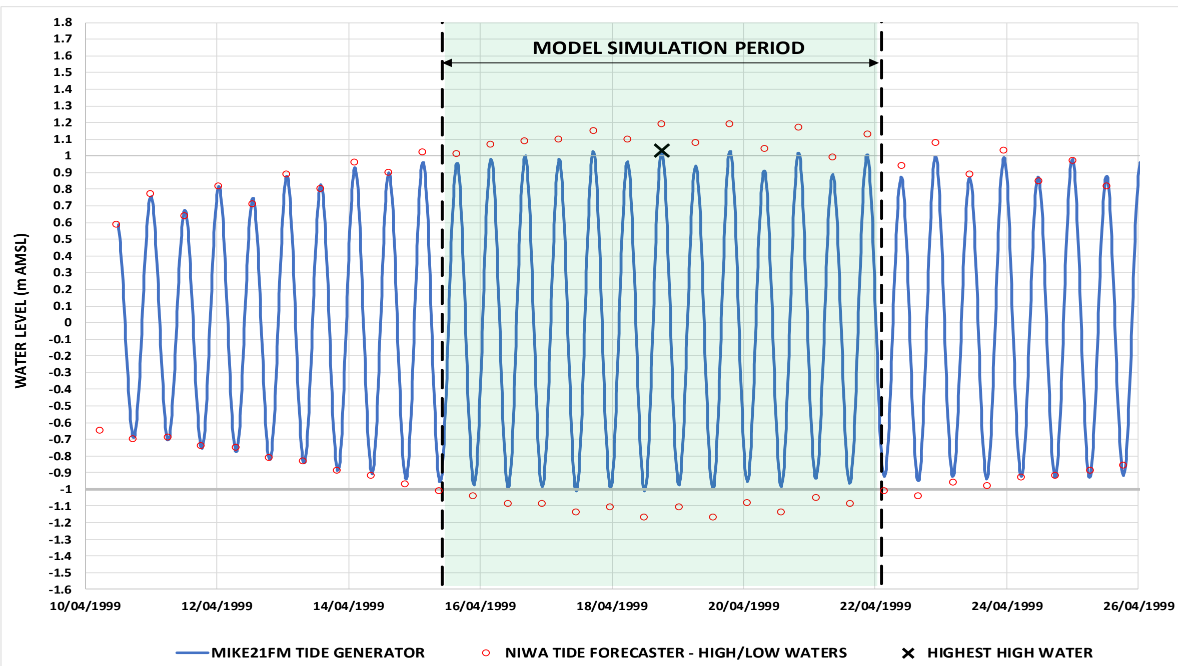


Figure 9: Astronomical water level time series generated for model water level boundary

- Storm surge height

A representative storm surge time series has been developed by fitting a simple sinusoidal time series to the actual surge height for the event of 24 July 2017 as shown in Figure 10. The fitted surge series is scaled as required to achieve the specified extreme high-water level for each simulation scenario when added to the astronomical tide series. The surge is centered coincident with the highest astronomical high water in the series, as indicated in Figure 8.

9 https://tides.niwa.co.nz/

10 Refer Table 3.1, Waimakariri District Plan Review - Natural Hazards, Coastal Erosion and Sea Water Inundation Assessment Technical Report, June 2018

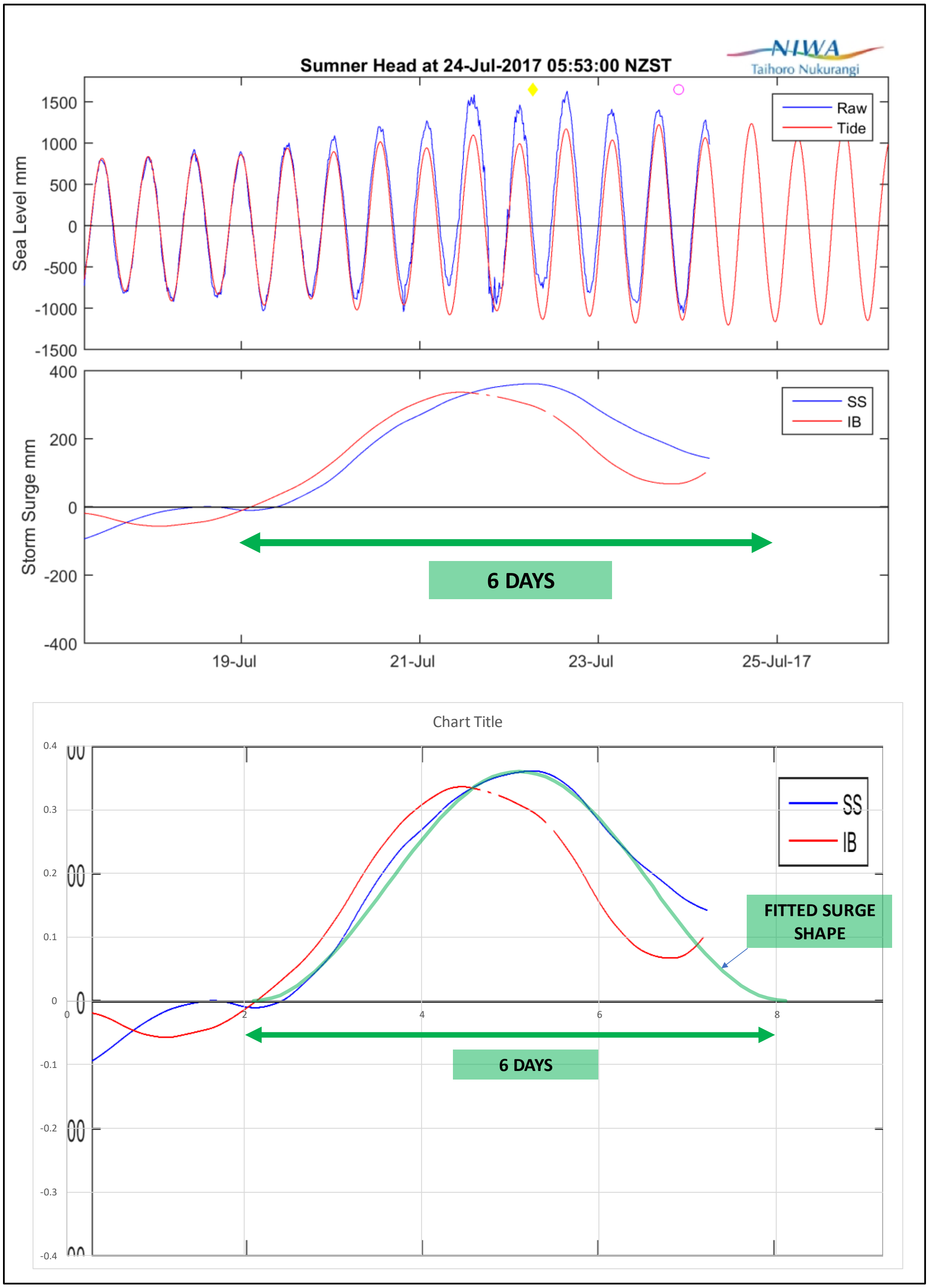


Figure 10: Development of fitted surge height time series from actual surge of 24/7/2017 (SS=Storm Surge, IB=Inverse Barometric sea level rise)

- Wave setup

  An allowance of 0.25m for the maximum effect of wave setup on sea level at the mouths of the rivers is included in the model boundary water level. The basis for this value is described in Appendix A of this report. The wave setup is included as a time varying height, using the same sinusoidal variation in time as the storm surge on the basis that wave heights and wave setup are likely to be greatest at the time of highest storm intensity (corresponding to time of maximum surge height).

- Mean sea level rise

  The sea level rise allowance specified for each scenario in Table 1 is added as a constant value to the entire boundary water level series for the scenario.

2.5.3 River flow boundaries

High fluvial flows in the Waimakariri River and Ashley River not simulated simultaneously. Different weather systems are usually responsible for high flows in each river – typically north-westerly systems for the Waimakariri River and south-westerly or south-easterly systems for the Ashley River. Simulations are performed with the specified high flow in one river and the mean annual flood flow in the other river and vice versa. For each river, the period of high fluvial flow is combined coincidentally with the period of the highest tide cycle.

Extreme fluvial flows derived by ECan for the Waimakariri[11] and Ashley[12] Rivers at the SH1 bridges are adopted for the flows in the model boundary time series. Table 4 shows the values provided by ECan together with the AEPs for the scenarios considered in this study, taken to be equivalent to the reciprocal of the return period for the purposes of the study. The value of flow for the 20-year return period for the Waimakariri River is not included in the data provided by ECan and has been estimated through simple interpolation of the data provided.

River	Flow (m^3/s)									
	Mean annual flood	5 year	10 year	20 year	25 year	50 year	100 year	200 year	500 year	1000 year
			10% AEP	5% AEP		2% AEP	1% AEP	0.5% AEP	0.2% AEP	
Waimakariri	1405	1800	2200	*2600*#	2800	3400	4000	4700	5800	6700
Ashley	783	1070	1340	1620	n/a	2020	2360	2730	3280	3740

value not provided by ECan, value estimated from data provided

Table 4: Extreme fluvial flows for the Waimakariri and Ashley rivers at SH1 (source: ECan)

Two sets of upstream flow boundaries have been developed for each of the rivers:

i. constant flow corresponding to the mean annual flood flow;
ii. constant flow corresponding to the required extreme value for the scenario over the duration of the highest tide (12 hours) and constant flow corresponding to the mean annual flood flow for the remainder of the simulation period.

[11] Flood frequency analysis pilot study: Orari, Temuka, and Waimakariri Rivers, Report No. R15/129, ECan, May 2016
[12] Email, A Boyle, ECan, 10 May 2019

Figure 11 illustrates the flow boundaries and tidal water level boundary developed for Scenario 2 for the Waimakariri River (1% AEP sea level,1m rise in mean sea level, 10% AEP flow in Waimakariri River, mean annual flood in Ashley River).

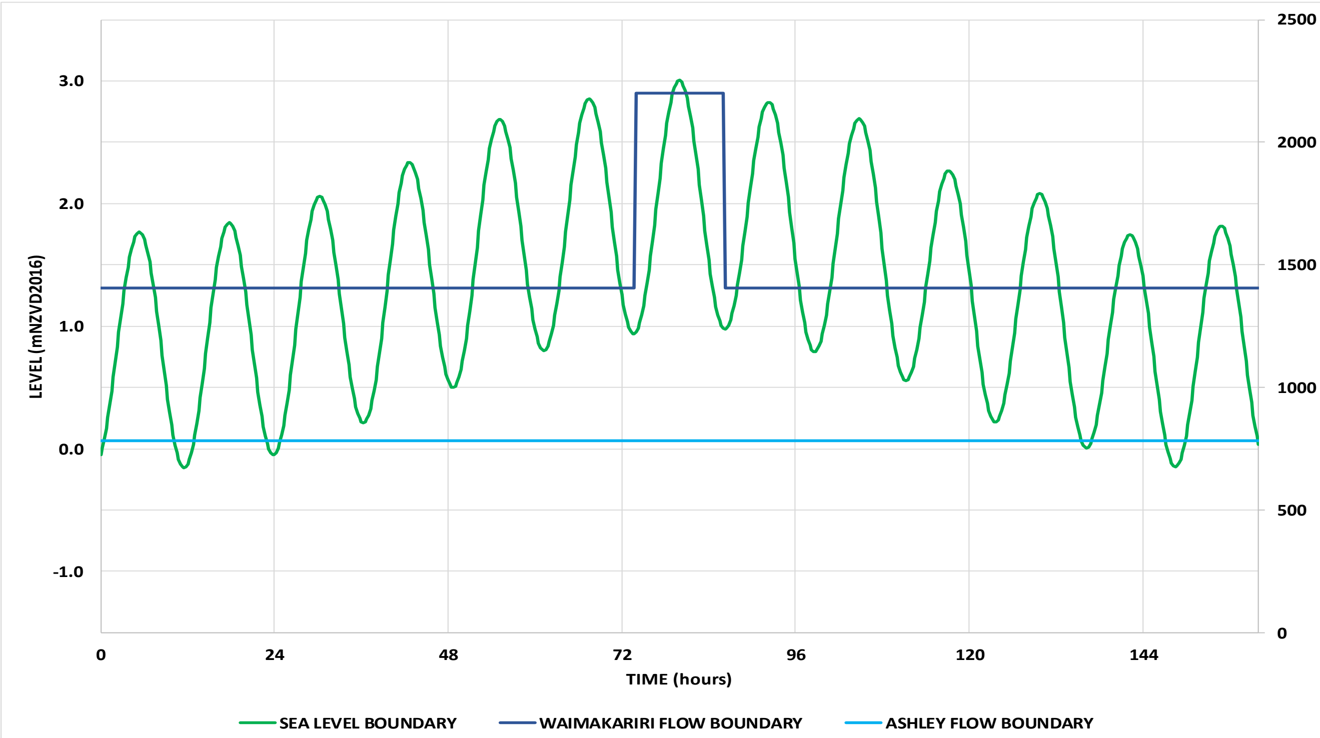


Figure 11: Sea level and river flow boundaries for Scenario 2 for the Waimakariri River (1% AEP sea level,1m rise in mean sea level, 10% AEP flow in Waimakariri River, mean annual flood in Ashley River)

2.6 Model initial conditions

The scope for the scenarios to be simulated with the model requires inclusion of initial water levels in the land outside the Waimakariri and Ashley River corridors corresponding to the median groundwater level where this level exceeds ground level.

The groundwater level varies within this area and is influenced by the mean sea level. The median groundwater levels for present-day mean sea level and the estimated increase in groundwater levels for rises in mean sea level of 1.06m and 1.88m have been estimated in a previous study[13] and have been used to develop the initial water levels for the model simulations. The groundwater levels estimated in the study represent the piezometric surface – the level to which water would rise in a well at any given point and a measure of the water pressure in the ground.

The purpose of the previous study was to better understand the risk of flooding solely from groundwater, i.e. to identify locations at risk from groundwater breaking out at the ground surface and ponding or flowing overland. The analysis provides estimate the values of more extreme (85th-percentile) groundwater levels within the shallow unconfined aquifer in this area. These were derived by uplifting the median groundwater levels in the aquifer by the average difference in median and 85th-percentile levels at individual boreholes. If groundwater

[13] Groundwater Level Assessment Technical Report, WDC, IZ105900-0005-NC-RPT-0001, May 2018, DDS-06-10-02-05-06/171129129688

pressure exceeds the ground surface level in these unconfined aquifers, then water will break out onto the ground and pond or flow. Data from boreholes which measure the pressure in deeper, confined aquifers were excluded from the analysis. Such data represents “artesian” pressures, which would not normally result in flooding when higher than the ground surface level due to the confined nature of the aquifer.

2.6.1 Groundwater levels

For the purposes of this study, median values of groundwater levels have been considered for each sea level rise scenario and have been determined as follows:

- For Scenario 1 (no rise in mean sea level) the previously derived present-day median groundwater levels have been adopted.
- For Scenarios 2, 5, 6, 7, 8 and 9 (1m rise in mean sea level), the increases in groundwater level previously derived for a rise in mean sea level of 1.06m have been added to the previously derived present-day median groundwater levels.
- For Scenario 4 (1.88m rise in mean sea level), the increases in groundwater level previously derived for a rise in mean sea level of 1.88m have been added to the previously derived present-day median groundwater levels.
- For Scenario 3 (0.5m rise in mean sea level), the increases in groundwater level due to a sea level rise of 0.5m have been interpolated from those previously derived for a rise in mean sea level of 1.06m, and added to the previously derived present-day median groundwater levels

Figure 12 shows the areas where the estimated present-day median groundwater level exceeds ground level and the resulting potential water depths above the ground for Scenario 1. Groundwater levels are lowest for this scenario.

Figure 13 shows the estimated increases in groundwater level previously derived for a rise in mean sea level of 1.88m. Figure 14 shows the resulting areas where the resulting groundwater level exceeds the ground level and the resulting potential water depths for Scenario 4. Groundwater levels are highest for this scenario.

2.6.2 Preliminary simulations

Simulations of the nine flood scenarios for each river were initially performed using the median groundwater levels derived for each scenario as the initial water levels throughout the entire 2D model extent.

Figure 15 shows the resulting maximum flood extent and depth for the simulation of Scenario 1 (1% AEP tide and present-day sea level) for the Waimakariri River using the initial groundwater depths shown in Figure 12. Figure 16 shows the results for the same model simulation but with no initial water levels specified in the 2D model – i.e. “dry ground” at the start of the simulation. Comparison of Figures 15 and 16 shows that most of the flooding in the preliminary scenario originates from the initial water depths in the model, representing groundwater ponding. Comparison of Figure 12 and Figure 15 also shows spreading of the initial water volume due to the gradient of the ground surface such that the maximum flood extent is significantly greater than the initial groundwater depths.

The results in Figure 15 for the preliminary simulation of Scenario 1 (1% AEP tide and present-day sea level) for the Waimakariri River are not considered realistic compared to the evidence for the depths and extent of present day surface flooding originating from high groundwater levels in the Waimakariri District, which is much less extensive. One reason for this is that the model simulation does not take account of surface and sub-surface drainage networks which tend to limit the extent and depths of surface flooding originating from elevated groundwater levels.

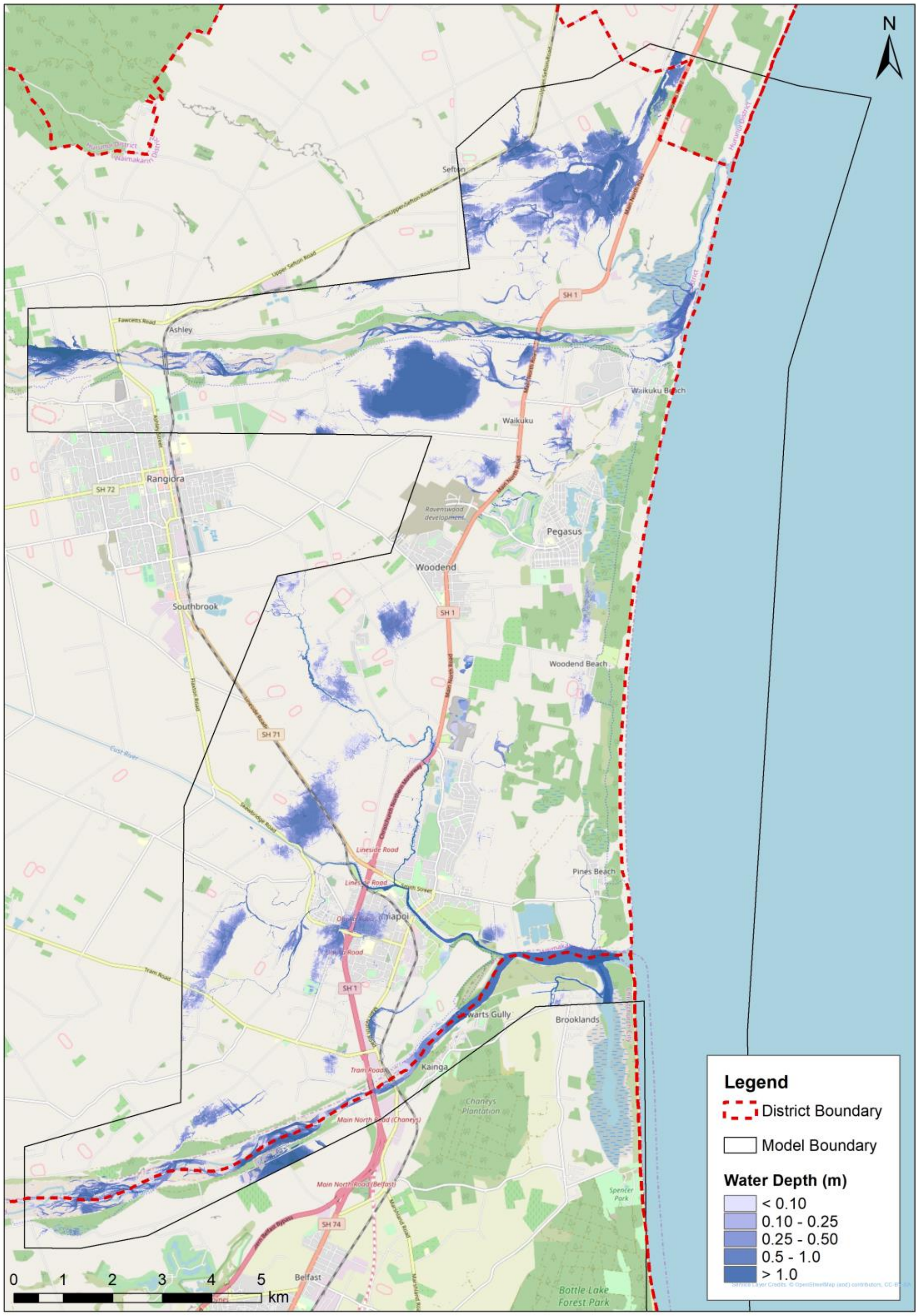


Figure 12: Potential water depth above ground level for median groundwater levels in Scenario 1 (present-day mean sea level)

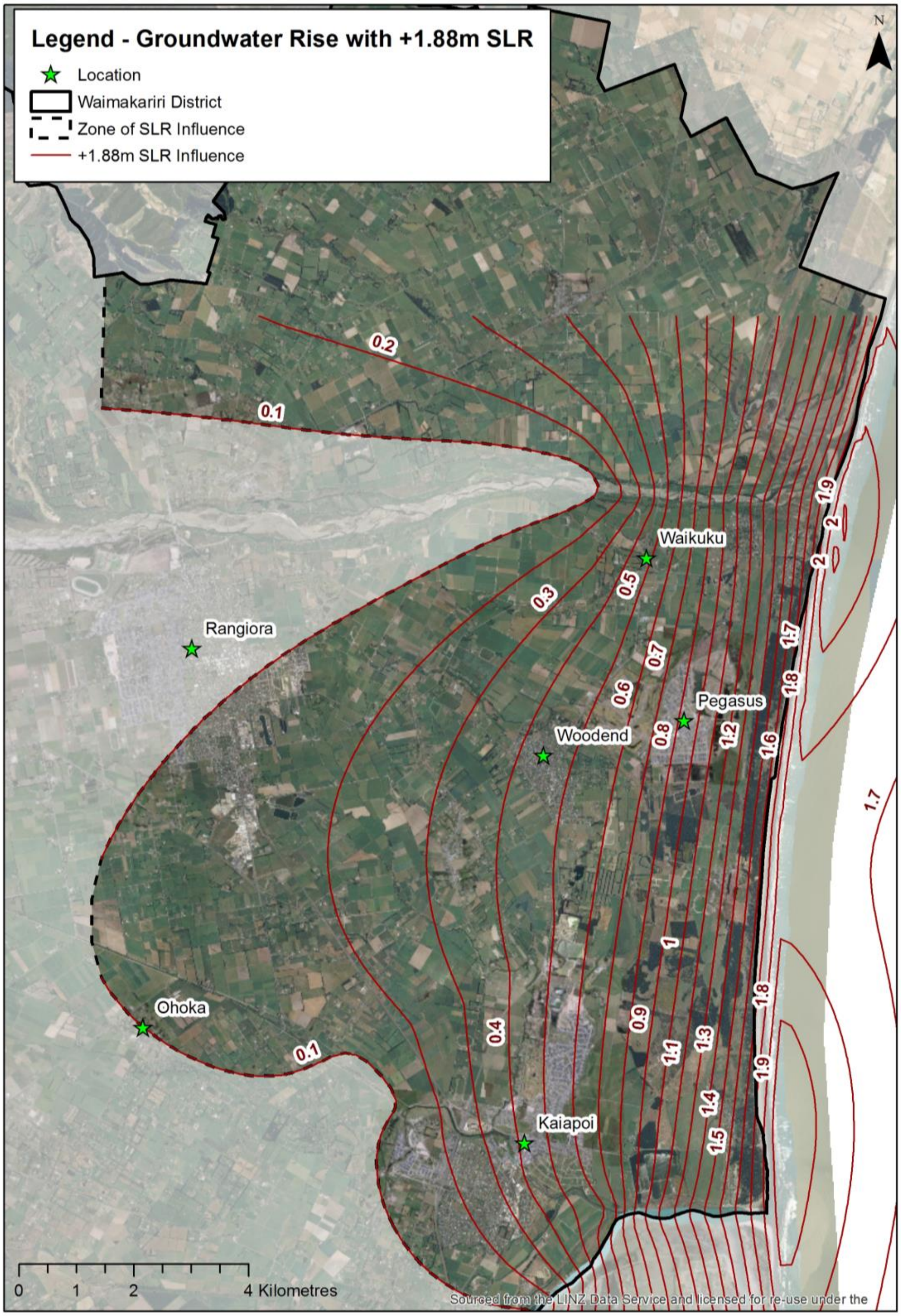


Figure 13: Groundwater level rise contours driven by 1.88m rise in mean sea level (Figure 3.4 from Groundwater Level Assessment Technical Report, WDC, IZ105900-0005-NC-RPT-0001, May 2018)

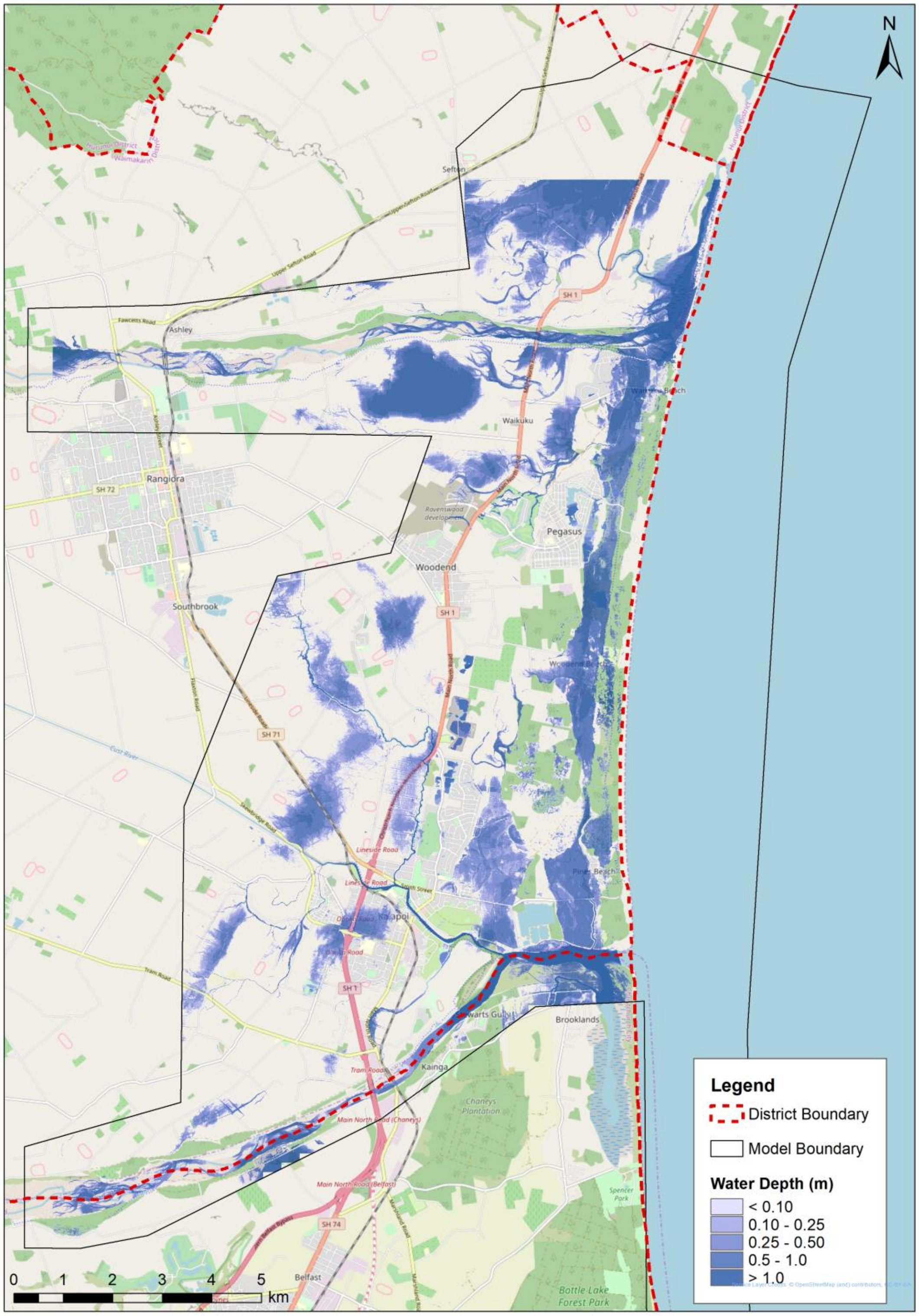


Figure 14: Potential water depth above ground level for median groundwater levels in Scenario 4 (1.88m rise in mean sea level)

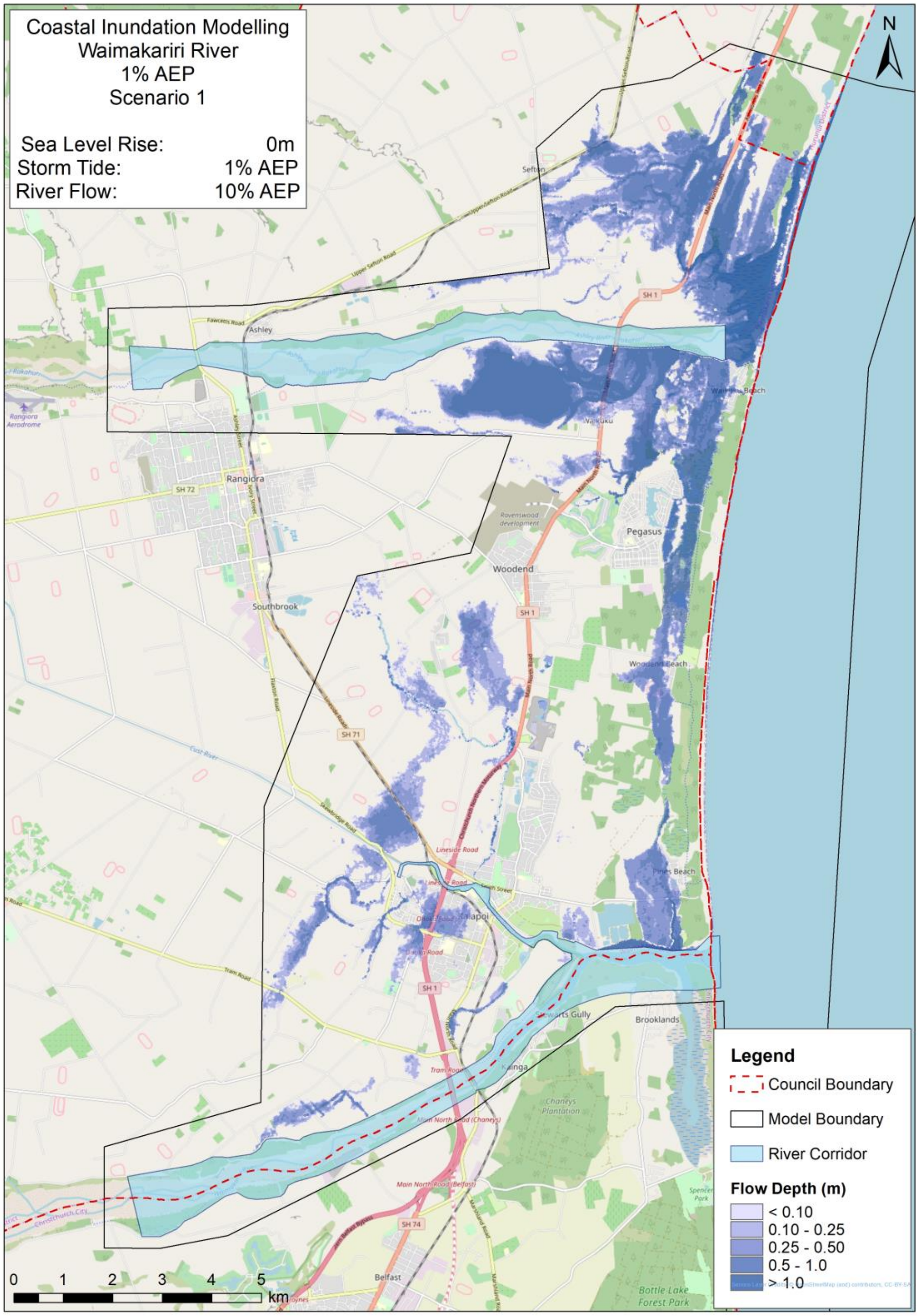


Figure 15: Maximum flood extent and depth for preliminary simulation of Scenario 1 for Waimakariri River (present day sea level) using the initial groundwater depths shown in Figure 12.

Figure 16: Maximum flood extent and depth for simulation of Scenario 1 for Waimakariri River (present day sea level) with no initial groundwater ponding ("dry ground")

2.6.3 Revised methodology

Given the results of the preliminary simulations, a revised method for including a more realistic allowance for ponding in the floodplain due to elevated ground water levels has therefore been developed as follows:

i. Ponding (initial depths of water in the model) is only included in areas of land which lie below the mean sea level in each scenario. In these areas the drainage of groundwater breakout via the existing gravity drainage systems will be impeded by the outfall water levels in the rivers and sea. In areas of higher ground, i.e. above mean sea level, drainage systems will tend to limit the depth of surface flooding from groundwater and any flooding from this source will not be significantly influenced by coastal water level conditions, which is the focus of this study.

ii. Initial water levels specified in the model are the lower of the groundwater level and mean sea level. Existing gravity drainage systems will generally control typical water levels in the floodplain to mean sea level or lower levels.

The method for including initial water levels in the model is illustrated diagrammatically in Figure 17, a schematic cross-section of the study area, showing the relationship between ground level, mean sea level, groundwater piezometric level and the resulting initial water level specified in the model simulation. Maps showing the areas of land below mean sea level and areas of land below the median groundwater level for Scenario 1 (0m sea level rise) and Scenario 4 (1.88m sea level rise) are presented in Figures 18 and 19 respectively. Initial water depths for ponding in the model are specified in the area of overlap of the two conditions, as indicated on the figures.

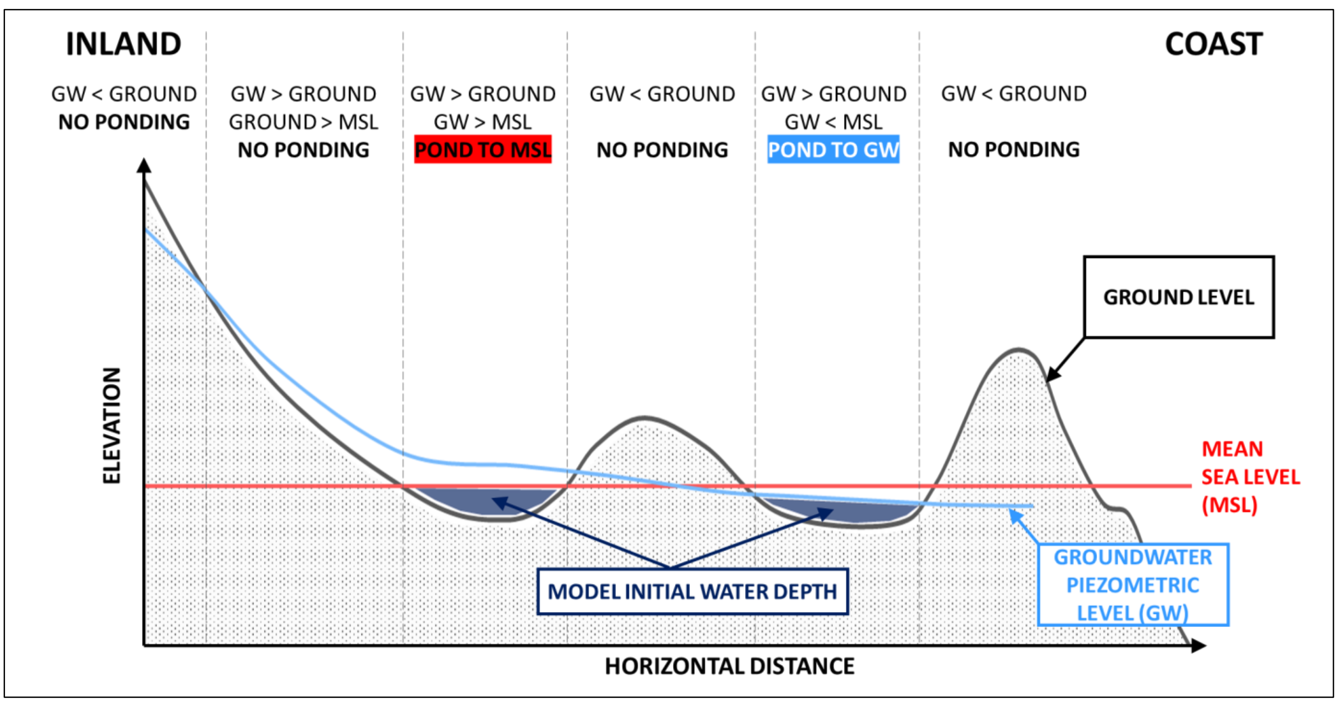


Figure 17: Schematic cross-section through study area indicating criteria for inclusion of initial water depth from groundwater in model simulations

Maps showing the initial model water depths based on the revised methodology for the simulations of each of the four mean sea level rise scenarios (0m, 0.5m, 1.0m and 1.88m), representing the initial ponding from groundwater prior to overtopping from the rivers, are provided in Appendix D.

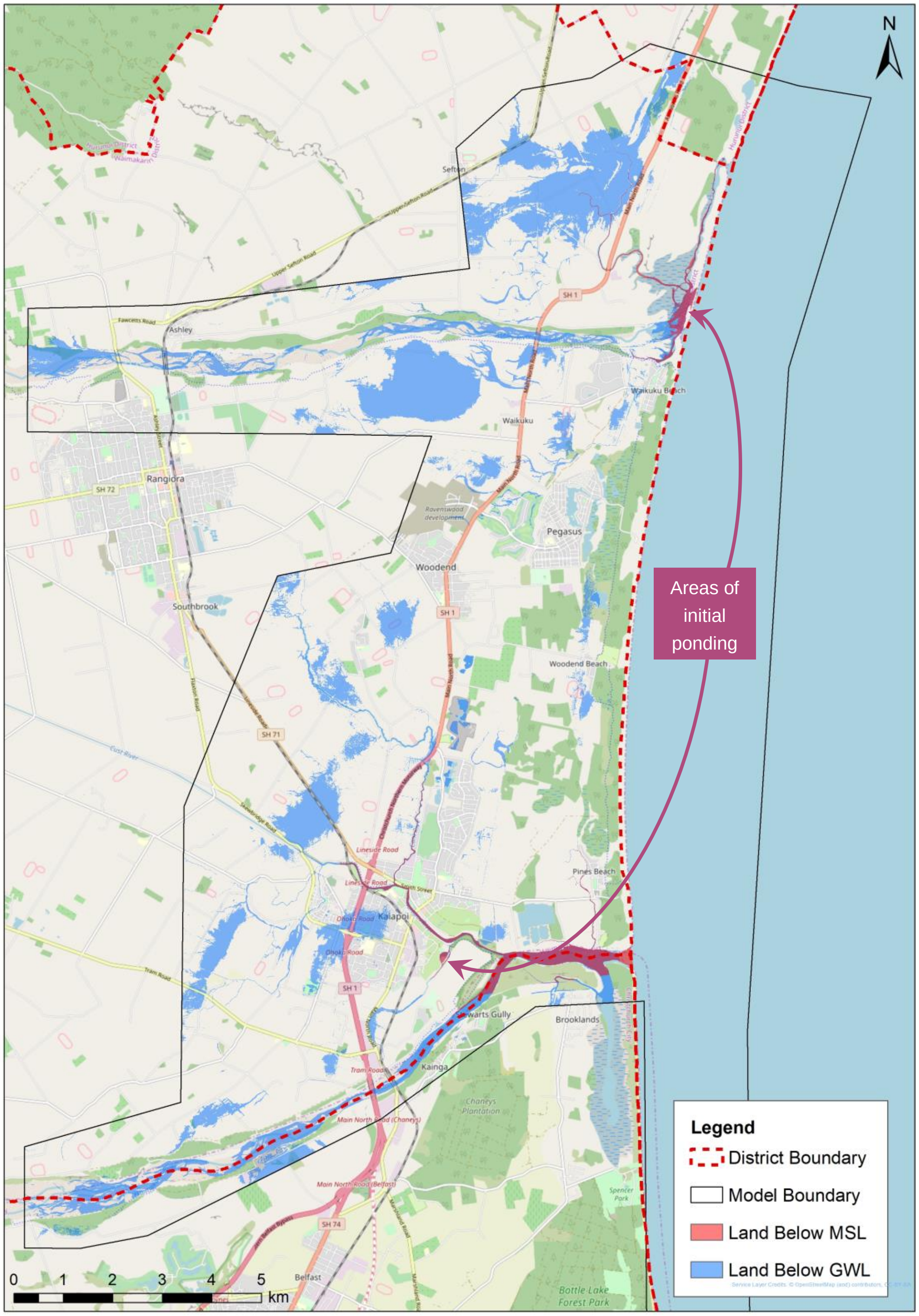


Figure 18: Areas of land below mean sea level (MSL), areas of land below the median groundwater level (GWL) and overlapping areas where initial ponding is specified in the model simulation for Scenario 1 (0m sea level rise)

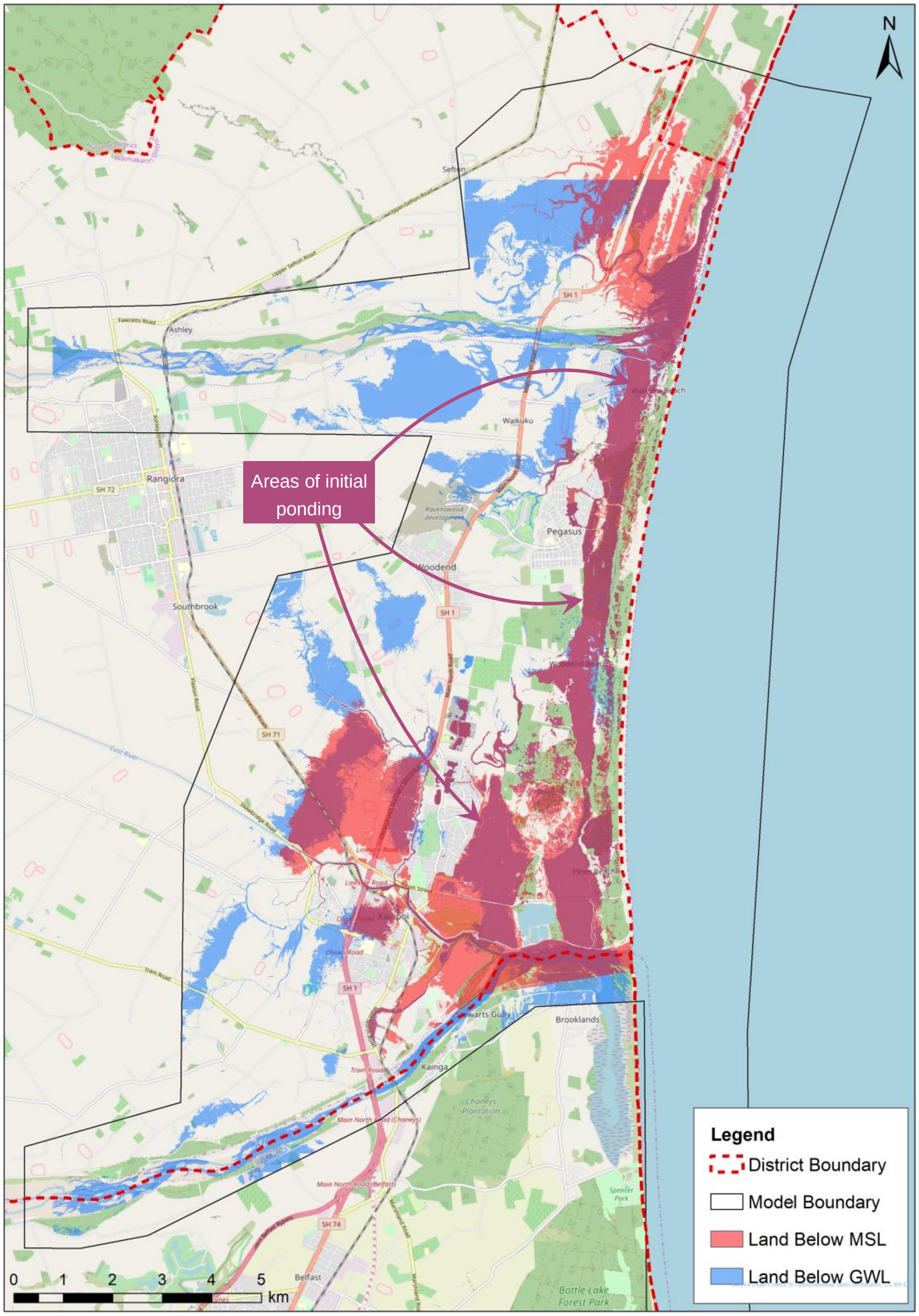


Figure 19: Areas of land below mean sea level (MSL), areas of land below the median groundwater level (GWL) and overlapping areas where initial ponding is specified in the model simulation for Scenario 4 (1.88m sea level rise)

2.7 Limitations and exclusions

In the model developed for simulating flooding from the Waimakariri and Ashley River Mouths in accordance with the project scope, the representation of some aspects of the flooding mechanisms is simplified and the effects of some features of the real system are excluded from the simulations. This can limit the accuracy and level of detail in the model results. The data available for developing the model has certain limitations which also limit the accuracy of the model outputs.

1. Variations in sea level along the coast are not considered in defining the model boundary. Extreme sea level estimates at Sumner Head and a representative astronomical tidal series and storm surge height series at the same location have been used to develop a sea level boundary. The same boundary is applied along the entire coastal boundary of the model between the Ashley and Waimakariri River Mouths. The resulting water level time series at the river mouths corresponds closely to the tidal water level boundaries developed for the study.

2. The effects of longshore currents, differences in water density due to differences in salinity in the sea water and river and Coriolis effects are excluded from the simulations.

3. The geometry of the river channels and mouths and the topography of the land outside the rivers are as defined in the survey data used to develop the model. The morphology of the Ashley River Mouth is particularly dynamic, and the position of the main river outlet to the sea can move considerably in relatively short periods of time. Water levels in the downstream section of the Ashley River may be sensitive to the morphology of the Ashley-Saltwater Creek Estuary and the outlet to the sea.

4. The scope for this study does not include calibration or validation of the model developed in the study against actual events. However, it is understood that the 1D MIKE11 models of the Waimakariri, Kaiapoi and Ashley Rivers developed by ECan and incorporated within the study model have previously been calibrated.

5. Up to date ground-based surveys of the current stop bank crest levels were not available at the time of developing the model. Crest levels for calculating overtopping flow in the model are generally taken from the bank levels in the 1D models or the LiDAR data available to the project. Spot checks indicate that the 1D bank levels are generally consistent with the LiDAR data. However, the 1D data is relatively sparse. It is understood that, apart from the Kaiapoi stop banks (for which a uniform design level has been adopted), no works have been undertaken to the stop banks since the LiDAR data was collected in 2014. However, the accuracy of LiDAR data is not as high as that of ground-based survey and introduces some uncertainty in the model results.

6. The crests of key features (e.g. stop banks) which control the volume of water leaving the rivers have been defined explicitly in the model. Elsewhere levels are interpolated to the model mesh from the LiDAR data. This can mean that the some smaller more local features, such as walls, and their effect on the spreading of the flood water are less accurately represented in the model due to the size of the model mesh elements relative to the size of the features.

7. Apart from the main channels of the Waimakariri, Kaiapoi and Ashley Rivers, all other channels are represented in the 2D model. Most of these channels are small drainage ditches within the floodplain and their capacity is not significant in terms of determining the extent of coastally driven flooding. The Kairaki Creek on the true left bank of the Waimakariri River is an important inlet for flooding since the stop banks along both sides of the creek (which are each around 1km in length from the Waimakariri River to the tide gate at the Beach Road crossing) are lower than those along the Waimakariri River upstream of the creek and water can overtop Beach Road at a relatively low level. The channel is defined in the 2D model mesh using a break line along the bed of the creek and dike structures to control overtopping of the stop banks on each side of the creek. For lower tidal events, the flow along

the creek and volume of overtopping may be sensitive to the capacity of the creek as represented in the model. If necessary, this could be improved by representing the creek within the 1D model domain but this would require a channel survey.

8. Drainage outfall structures are not included in the model. All the main outfalls to the rivers are fitted with tide gates which close mechanically on water level difference between the river and the drain to prevent reverse flow from the river into the drains (as shown in Figure 5, for example). It is understood that the gates on the Cam River are closed manually in response to high flow in the Waimakariri River (when the river level at Waimakariri Gorge gauge exceeds 3.5m)[14] to protect against flooding due to the backwater from the Waimakariri River in the Kaiapoi River. Based on ECan historic gauge records[15], the closure trigger level corresponds to flows lower than the 10-year return period flow provided by ECan. Therefore, these gates would be closed for all fluvial flows defined in the model scenarios. In practice, during the low water period between tides the outfalls could allow some drainage of any water which has overtopped the stopbanks. The volume that could be drained is expected to be small relative to the volume of water in the floodplain due to the limited capacity of the outfall and drainage network and the short time periods between closures of the outfall gates. Therefore, exclusion of outfalls in the model is not expected to significantly influence the maximum flood depths outside the stopbanks. It is understood that for one of the outfalls, McIntosh Drain on the true left bank of the Kaiapoi River, drainage under normal tides has been so restricted by the relative levels in the drain and river that on occasions water needs to be pumped over the stop bank to increase the drainage rate[16].

9. Simulations of future sea level rise scenarios are based on present-day land levels and stop bank levels. Future changes to either land levels or defence levels, due to subsidence or seismic events, or through raising of stop banks or managed realignment of defences, could result in changes to the extents and depths of flooding simulated in the model.

10. The simulations do not allow for the additional volume of flooding that may occur from breaching or other failures of the stop banks. The simulated storm tide water levels exceed the current stop bank crest levels in some locations by 0.5m or more for most of the scenarios considered. The flow of water over the stop banks under these conditions could result in erosion and failure of the structures and additional flow into the floodplain. The simulations also do not allow for any breaching of the coastal dune field under the effects of sea level rise and storm events. The location and elevation of the dunes are assumed to remain at the surveyed positions.

11. Water levels representing the estimated median groundwater levels in each scenario are included as the initial water levels in the 2D model. The initial water levels are only applied to land where the ground level is below mean sea level and where the groundwater level exceeds the ground level. In these areas the drainage of any groundwater breakout via the existing gravity drainage systems will be impeded by the outfall water levels in the rivers. The effect of providing pumped drainage in the future in these areas has not been considered in the simulations. In areas of higher ground, i.e. above mean sea level, it is likely that surface and sub-surface drainage systems will tend to limit the depth of surface flooding originating from elevated groundwater levels and any flooding from this source will not be significantly influenced by coastal water level conditions. Although ponding in these areas is not included in the simulations and result of this study, such areas may still be vulnerable to surface flooding originating from groundwater.

[14] Telcon B McIndoe (ECan) 7 June 2019
[15] Flood frequency analysis pilot study: Orari, Temuka, and Waimakariri Rivers, Report No. R15/129, ECan, May 2016
[16] Telcon B McIndoe (ECan) 7 June 2019

3. Results

To illustrate the predicted extent and depth of inundation in each scenario, the model results have been processed to produce GIS depth grids of the maximum water depth achieved in the 2D model over the entire period of each model simulation. This includes the initial water depths specified in the model due to groundwater ponding which, in some scenarios, are locally slightly higher than the maximum depth attained over the remainder of the run due to equalising of water levels over the ponding area. The flood depth grids are illustrated in a simple map template in Appendix B for the Waimakariri River scenarios and Appendix C for the Ashley River scenarios.

For comparison purposes, maps showing the initial model water depths in the simulations for each of the four mean sea level rise scenarios (0m, 0.5m, 1.0m and 1.88m), representing the initial ponding from groundwater prior to overtopping from the rivers, are provided in Appendix D.

3.1 Waimakariri River

3.1.1 Flooding mechanisms

Table 5 presents typical defence levels at key points on the Waimakariri River and the maximum water level in each of the model simulations at these points, indicating in which scenarios overtopping occurs and at which points. The water level point locations are shown in Figure 20.

Table 5: Maximum model water levels and typical defence levels at key points for the Waimakariri River

Location	Typical Defence level#		Maximum model water levels#								
		Scenario No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
		Sea level rise	*0*	*1m*	*0.5m*	*1.88m*	*1m*				
		Tide AEP	*1%*				*10%*	*0.5%*	*5%*	*0.2%*	*2%*
		Flow AEP	*10%*				*1%*	*5%*	*0.5%*	*2%*	*0.2%*
Tidal water level boundary			**2.00**	**3.00**	**2.50**	**3.88**	**2.79**	**3.07**	**2.85**	**3.15**	**2.94**
A – Kairaki Creek	1.50 (left)		2.09	3.03	2.56	3.90	2.95	3.10	3.08	3.20	3.28
	2.40 (right)		2.09	3.03	2.56	3.90	2.95	3.10	3.08	3.20	3.28
B - Kaiapoi Confluence	3.64		2.16	3.05	2.61	3.88	3.06	3.12	3.20	3.24	3.40
C - Kaiapoi SH1	3.64		2.17	3.05	2.62	3.81	3.09	3.14	3.25	3.26	3.45
D - Waimakariri SH1	7.40 (left)		4.23	4.39	4.29	4.69	5.54	4.69	5.95	5.21	6.52

m NZVD2016

Indicates overtopping

The lowest defence levels relative to river water level are along the stop banks on either side of Kairaki Creek. The true left (eastern) bank is lower than the true right (western) bank. The left bank level varies between 1.5m and 2.0m NZVD2016 (see Figure 2) and the right bank level is between 2.4m and 2.5m. At the Beach Road crossing a tide gate prevents water passing further up the creek. However, the stop bank levels grade down to just above the road level (around 1.2m NZVD2016) and are not tied into the low flood wall on the bridge – the crest level is estimated to be around 1.6m NZVD2016 (no survey available) – see Figure 21. Overtopping of the left bank of the creek occurs in all scenarios and flow passes northwards, over Beach Road and then west and south into the area protected by the higher stop bank on the true right bank of the creek. Overtopping of the right bank of the creek occurs in all scenarios except Scenario 1 (present day 1% AEP tide).

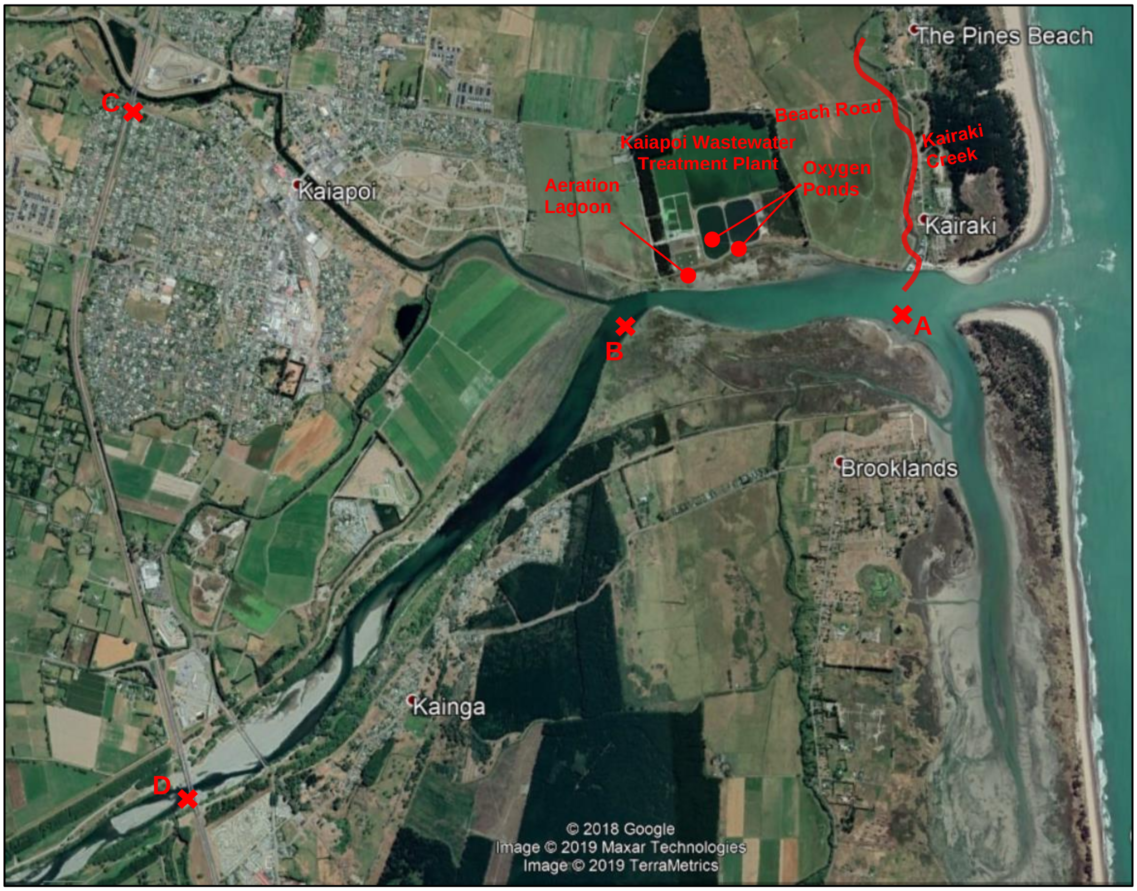


Figure 20: Location of reported water level points and key features – Waimakariri River

Figure 21: Beach Road bridge crossing on Kairaki Creek, looking downstream (10 May 2019)

Overtopping of the true left bank of the Waimakariri River between Kairaki Creek and the Kaiapoi Wastewater Treatment Plant occurs in all scenarios except Scenario 1 (present day 1% AEP tide) – bank levels vary from around 2.4m NZVD2016 at Kairaki Creek to 3.0m NZVD2016 at the Plant.

Levels along the section of the bund around the Oxidation Ponds at the Plant which faces the river are higher (typically around 3.8m NZVD2016) and the bund is only overtopped in Scenario 4 (1.88m rise in mean sea level and 1% AEP tide). Levels along the bund around the ponds inland of the river bank are somewhat lower and more variable and some overtopping occurs in the model simulation for Scenario 9 (1m rise in mean sea level, 2% AEP tide, 0.2% AEP flow). More accurate ground survey of the bund crest levels around the ponds would be needed to confirm the flood risk at this location in this scenario.

The crest level of the bund around the Aeration Lagoon is substantially higher (over 5m NZVD2016) and is not flooded in any of the scenarios simulated.

Part of the flow overtopping the stop banks along Kairaki Creek and the stop bank between Kairaki Creek and the Wastewater Treatment Plant flows northwards through Pines Beach and Woodend Beach towards Pegasus. These areas also receive flow which overtops the true right bank of the Ashley River at Waikuku Beach and flows southwards.

Some of the flow overtopping the Waimakariri stop banks flows westwards into the area between Kaiapoi and the Wastewater Treatment Plant reaching just west of Williams Street in the most extreme event (Scenario 4). There is potential for untreated wastewater to escape from the wastewater network and to be transported into residential areas by the flood water. Further assessment of this risk, which could include contaminant tracing and modelling, should be considered by WDC.

Overtopping of the stop banks along the Kaiapoi River (understood to have been improved to a level of 4.0m Lyttelton 1937) only occurs in Scenario 4 (1.88m rise in mean sea level and 1% AEP tide).

In all scenarios, maximum water levels along the Waimakariri River between the confluence with the Kaiapoi River and the SH1 bridge are below the stop bank crest level on the true left bank of the river, as defined by the river cross-section data and LiDAR data.

3.1.2 Effect of sea level rise and fluvial flow

- Sea level rise

  Figure 22 compares the maximum model water levels in Table 5 for Scenarios 1 to 4 – these scenarios simulate the 1% AEP tide and 10% AEP river flow for four values of mean sea level rise: no sea level rise, 0.5m, 1.0m and 1.88m sea level rise.

  Within the lower Waimakariri River (downstream of the Kaiapoi confluence) and within the Kaiapoi River, maximum water levels increase approximately in line with the rise in mean sea level. Water levels increase slightly inland except for Scenario 4 (1.88m rise) where there is small fall in maximum water level along the Kaiapoi. This is due to overtopping of the stop banks along the river in this scenario and the relatively greater ratio of overtopping volume to channel volume and flow compared to the Waimakariri River.

  At the SH1 bridge, the influence of sea level rise on maximum water levels in the Waimakariri River is relatively small for the river flow simulated (10% AEP). The effect of sea level rise on flows large enough to cause flooding at this location is likely to be negligible.

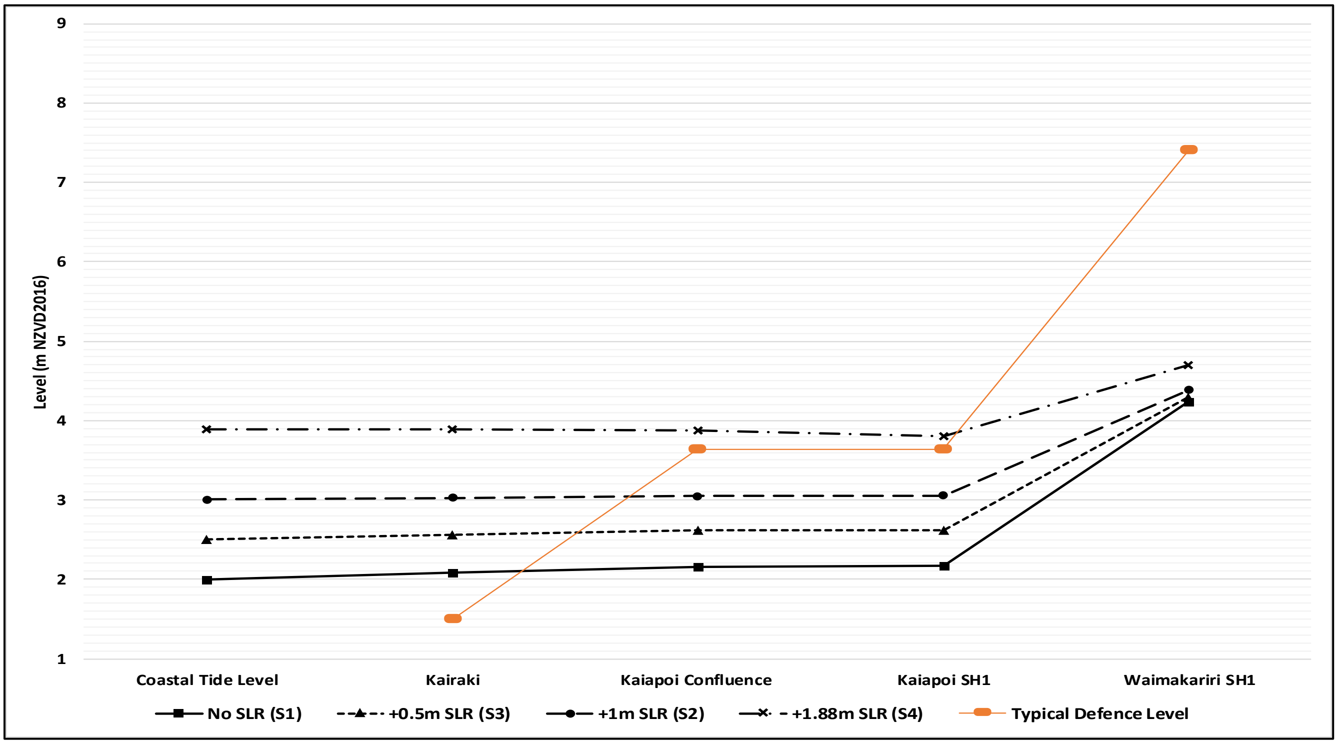


Figure 22: Maximum model water levels at key locations for Scenarios 1 to 4 (1% AEP tide, 10% AEP flow) – Waimakariri River

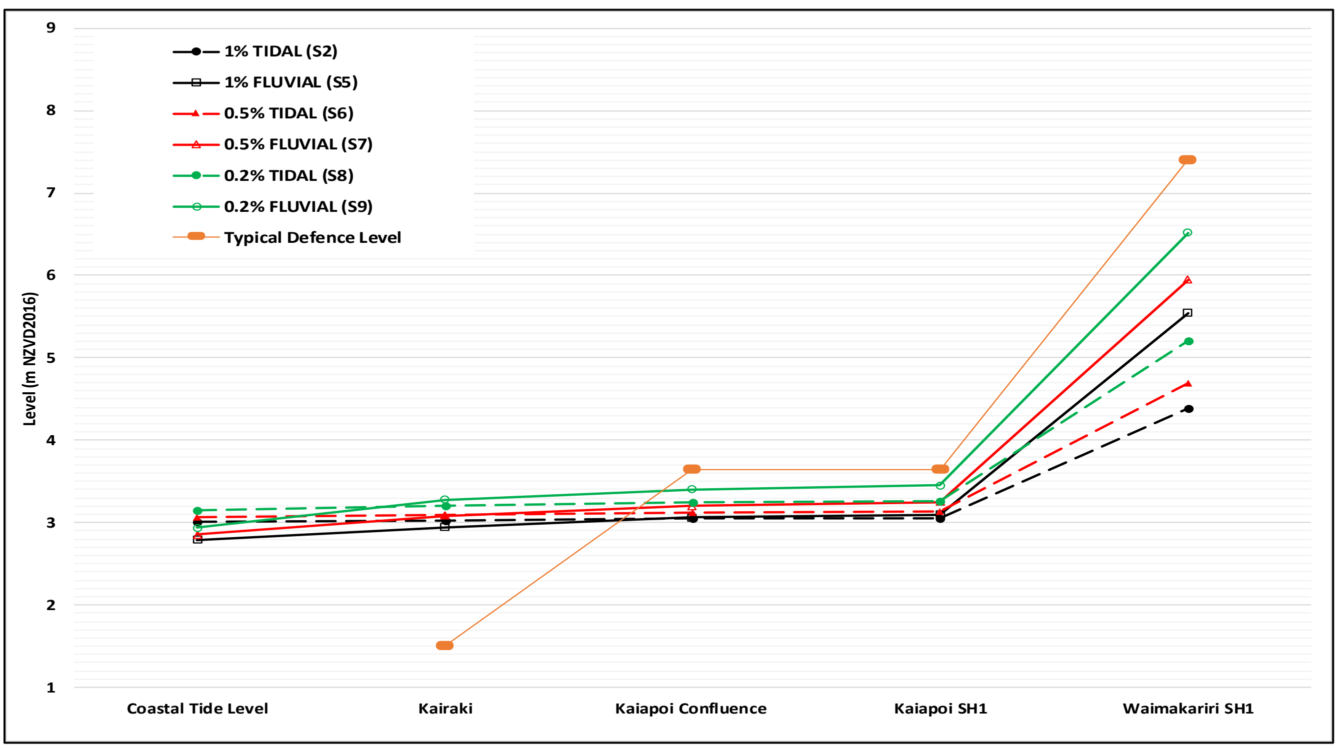


Figure 23: Maximum model water levels at key locations for Scenarios 2 and 5 to 9 (1m sea level rise for 1%, 0.5% and 0.2% AEP tides and 1%, 0.5% and 0.2% AEP river flows) – Waimakariri River

- Fluvial flow

Figure 23 compares the maximum model water levels in Table 5 for Scenario 2 and Scenarios 5 to 9. The scenarios simulate the 1%, 0.5% and 0.2% AEP storm tides (with 10%, 5% and 2% AEP river flows respectively) and the 1%, 0.5% and 0.2% AEP river flows (with 10%, 5% and 2% AEP tides respectively). The rise in mean sea level is the same in all scenarios (1m).

The results show that for the 1% AEP (Scenarios 2 and 5), storm tide event water levels are higher than fluvial event water levels for the entire length of river in which levels are high enough to result in overtopping (i.e. lower Waimakariri). The flood extent maps (Appendix B) show more flooding for the storm tide 1% AEP event (Scenario 2) than for the 1% AEP river flow event (Scenario 5).

For the 0.5% AEP (Scenarios 6 and 7), maximum levels upstream of Kairaki are slightly higher for the fluvial event than the tidal event. However, the flood maps show that the extent of flooding is still greater for the storm tide event because there is accumulation of water in the floodplain from several successive tides in this event for which the tidal water levels are higher than for the fluvial event (fluvial flow only affects the largest tide in the period simulated).

For the 0.2% AEP (Scenarios 8 and 9), maximum levels are higher along the whole river for the fluvial event and the flood maps show that flooding in this event is also slightly more extensive and deeper due to the substantially greater volume of overtopping during the highest tide of the period.

3.2 Ashley River

3.2.1 Flooding mechanisms

Table 6 presents typical defence levels at key points on the Ashley River and the maximum water level in each of the model simulations at these points, indicating in which scenarios overtopping occurs and at which points. The water level point locations are shown in Figure 24.

Table 6: Maximum model water levels and typical defence levels at key points for the Ashley River

Location	Typical Defence level[#]		Maximum model water levels[#]								
		Scenario No.	1	2	3	4	5	6	7	8	9
		Sea level rise	*0*	*1m*	*0.5m*	*1.88m*	*1m*				
		Tide AEP	*1%*				*10%*	*0.5%*	*5%*	*0.2%*	*2%*
		Flow AEP	*10%*				*1%*	*5%*	*0.5%*	*2%*	*0.2%*
Tidal water level boundary			**2.00**	**3.00**	**2.50**	**3.88**	**2.79**	**3.07**	**2.85**	**3.15**	**2.94**
A - Waikuku Beach (Beach Crescent car park)	2.30		2.44	3.1	2.71	3.89	3.13	3.19	3.24	3.31	3.38
B- Taranaki Stream Outfall	4.20 (right)		3.21	3.47	3.29	4.03	3.87	3.63	4.03	3.83	4.21
	4.50 (left)		3.21	3.47	3.29	4.03	3.87	3.63	4.03	3.83	4.21
C - Waikuku Stream Outfall	6.10 (right)		4.90	4.92	4.91	5.01	5.78	5.18	6.04	5.52	6.39
	6.30 (left)		4.90	4.92	4.91	5.01	5.78	5.18	6.04	5.52	6.39
D - Ashley SH1	8.70 (right)		7.39	7.39	7.39	7.39	8.24	7.64	8.51	7.97	8.88
	8.70 (left)		7.39	7.39	7.39	7.39	8.24	7.64	8.51	7.97	8.88

[#] m NZVD2016

Indicates overtopping

Figure 24: Location of reported water level points and key features – Ashley River

The lowest defence levels relative to river water level are along the stop bank and dunes on the true right bank of the river at Waikuku Beach, between the car park on Beach Crescent and opposite the downstream end of the stop bank on the true left bank (River Road). Minimum defence levels are in the range of 2.3m to 2.7m NZVD2016 rising to around 3.7m NZVD2016 opposite the end of River Road. Overtopping occurs in all scenarios, however the extent of flooding from overtopping is very localised in Scenario 1 (present day 1% AEP tide) due to the small depth of overtopping and higher ground levels in the dunes around the car park.

Between the downstream end of River Road and the SH1 bridge, defence levels are generally above the maximum model water levels for the scenarios simulated, with only small amounts of overtopping occurring in Scenario 9 (1m rise in mean sea level, 2% AEP tide, 0.2% AEP flow).

The Ashley River flows north into the Ashley-Saltwater Creek Estuary before discharging to the sea. In general there are no flood defences around the estuary and the spread of water from the Ashley River or incoming water from the sea is limited primarily by the natural topography of the area. The SH1 road embankment restricts flow inland somewhat. However, water can pass up Saltwater Creek under the road bridge crossing.

The flow overtopping the stop bank and natural bank on the true right bank of the river at Waikuku Beach flows southwards through Waikuku Beach and Pegasus towards Woodend Beach. These areas also receive flow which overtops the true left bank of the Waimakariri River at Kairaki.

3.2.2 Effect of sea level rise and fluvial flow

- Sea level rise

Figure 25 compares the maximum model water levels in Table 6 for Scenarios 1 to 4 – these scenarios simulate the 1% AEP tide and 10% AEP river flow for four values of mean sea level rise: no rise, 0.5m, 1.0m and 1.88m sea level rise.

Within the lower Ashley River, below the downstream end of the River Road stop bank, maximum water levels increase largely in line with the rise in mean sea level for this fluvial flow (10% AEP). Further upstream water levels increase and the effect of sea level rise rapidly diminishes. At the Waikuku Stream outfall (Point C on Figure 24) the maximum water level rises by 0.11m for a sea level rise of 1.88m and for lower values of sea level rise the effect is negligible. Further upstream, at the SH1 bridge, the effect of sea level rise is negligible in all scenarios.

- Fluvial flow

Figure 26 compares the maximum model water levels in Table 6 for Scenario 2 and Scenarios 5 to 9. The scenarios simulate the 1%, 0.5% and 0.2% AEP tides (with 10%, 5% and 2% AEP river flows respectively) and the 1%, 0.5% and 0.2% AEP river flows (with 10%, 5% and 2% AEP tides respectively). The rise in mean sea level is the same in all scenarios (1m).

The results show that for each AEP simulated, the difference in maximum water levels at the Beach Crescent car park at Waikuku Beach (Point A on Figure 24) for the fluvial and storm tide events is small. In each case the fluvial levels are slightly higher (0.03m to 0.07m) than the tidal levels. Further upstream the fluvial event levels are significantly higher (0.4m to 0.9m depending on the AEP) than the corresponding tidal levels. However, with the exception of the 0.2% AEP river flow event, maximum levels are below the typical defence levels.

For each AEP simulated, the flood extent maps show marginally more flooding for the fluvial events on the true right bank, in and around Waikuku Beach. The difference in flooding is small due to the limited length of bank which overtops and the small difference in water levels between the fluvial and storm tide events. On the true left side of the river, in and around the Ashley-Saltwater Creek Estuary where flooding is not controlled by elevated banks, the flood extents and depths are slightly greater for the storm tide events due to residual accumulations of water from successive high tides before and after the highest tide. These tides are higher than the corresponding ones for the fluvial event due to the higher storm surge component.

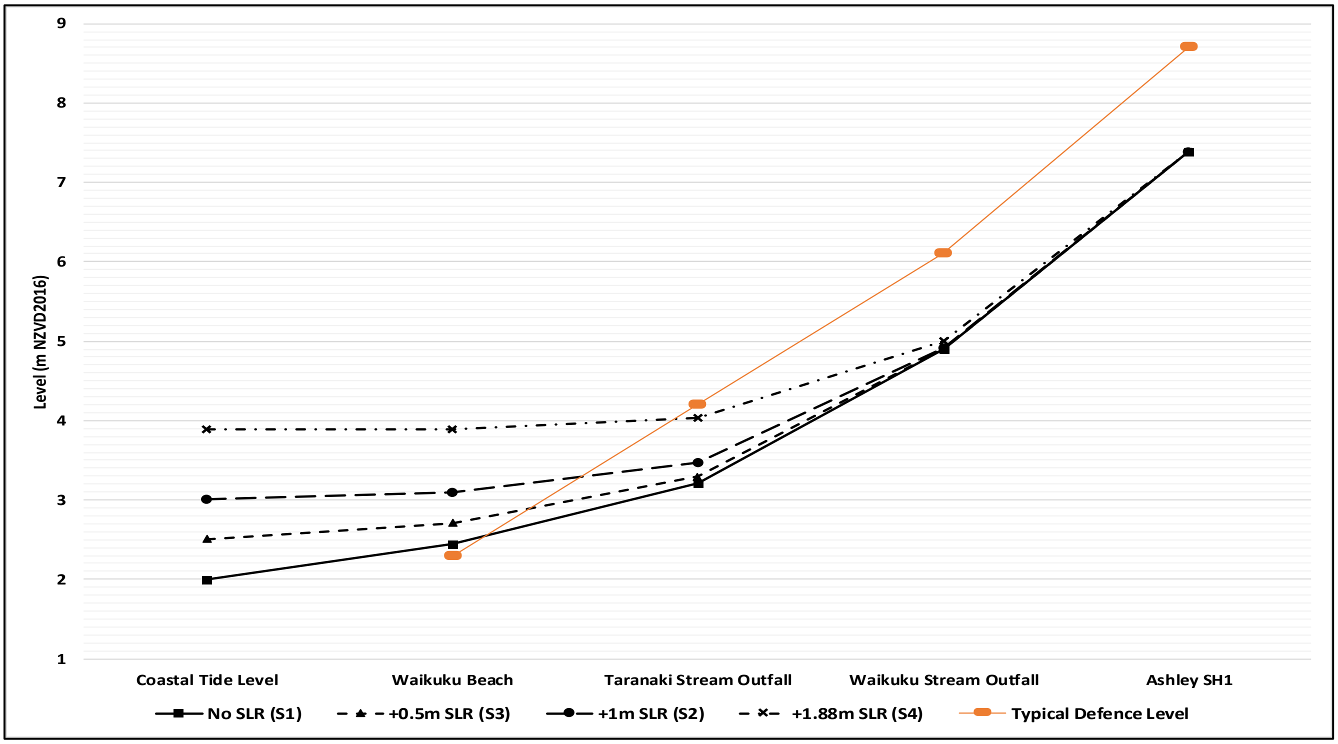


Figure 25: Maximum model water levels at key locations for Scenarios 1 to 4 (1% AEP tide, 10% AEP flow) – Ashley River

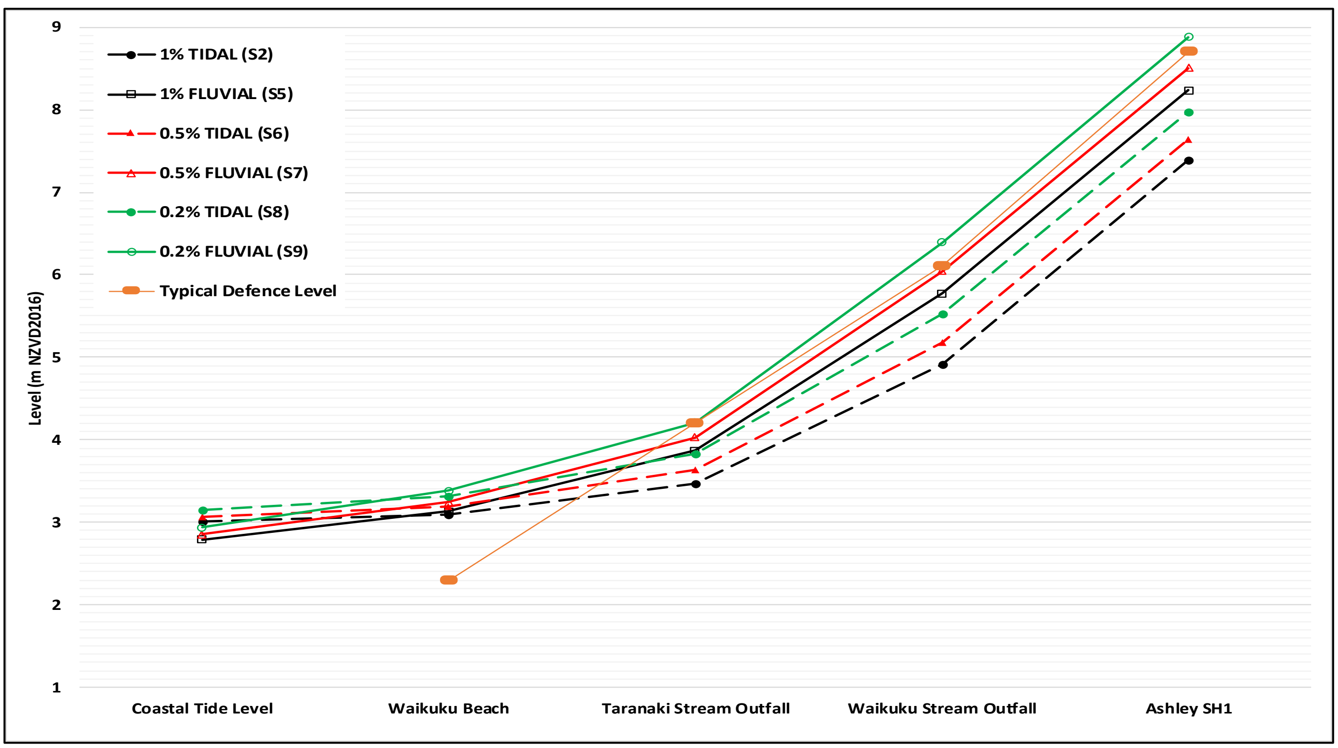


Figure 26: Maximum model water levels at key locations for Scenarios 2 and 5 to 9 (1m sea level rise for 1%, 0.5% and 0.2% AEP tides and 1%, 0.5% and 0.2% river flows) – Ashley River

4. Conclusions and recommendations

4.1 Conclusions

A hydrodynamic model suitable for examining the susceptibility of the coastal area of Waimakariri District to coastally driven flooding from the Waimakariri and Ashley River Mouths has been developed.

Simulations have been performed for a range of storm tide and fluvial events and a range of mean sea level rise allowances. The simulations include the effect of wave set-up, the interaction of extreme sea levels with river flows (backwater effects during catchment flood events). The model takes account of the hydraulic connectivity of low-lying areas with the sea and the dynamic effects of storm tide propagation including the attenuation of flood waves in the river channels and overland flow areas.

The simulations include an allowance for initial depths of water in the floodplain due to breakout of groundwater in areas where the estimated median groundwater levels (including an allowance for effect of mean sea level rise) exceed ground level and the ground level is below mean sea level.

Model results indicate areas at risk of flooding in all the scenarios considered. Flooding is a combination of initial ponding from elevated groundwater levels and overtopping of stop banks. The contribution to flooding from groundwater breakout that is influenced by coastal conditions is small for present day sea level but increases with sea level rise.

Flooding through overtopping of stop banks or natural river banks occurs in all the scenarios simulated:

- For the Waimakariri River, key flow routes are over the stop banks along Kairaki Creek and over the true left stop bank between Kairaki Creek and Kaiapoi Wastewater Treatment Plant. The stop banks along the Kaiapoi River contain water in the river for all scenarios considered except for the 1% AEP storm tide event with 1.88m rise in mean sea level.

- For the Ashley River, the key flow route on the true right side of the river is over the lower parts of the stop bank and natural river bank at the car park on Beach Crescent and between the car park and the Taranaki Stream outfall. On the true left side of the river, the spread of water from the Ashley-Saltwater Creek Estuary is largely determined by the natural topography of the area. Water spreads up the Saltwater Creek and under the SH1 bridge crossing.

Simulations of different sea level rise allowances with a 10% AEP fluvial flow show that:

- Water levels in the lower Waimakariri River (downstream of the Kaiapoi confluence) and within the Kaiapoi River are strongly influenced by sea level rise and maximum water levels increase approximately in line with the rise in mean sea level. The effect of sea level rise on water levels in the Waimakariri River diminishes upstream of the confluence with the Kaiapoi and at the SH1 bridge crossing the effect of sea level rise on flows large enough to cause flooding at this location is likely to be very small.

- At the downstream end of Ashley River, below the downstream end of the River Road stop bank, maximum water levels increase largely in line with the rise in mean sea level. Further upstream the effect of sea level rise rapidly diminishes. At the Waikuku Stream outfall the maximum water level rises by 0.11m for a sea level rise of 1.88m and for lower values of sea level rise the effect is negligible. Further upstream, at the SH1 bridge, the effect of sea level rise is negligible in all scenarios considered.

Simulations of separate fluvial events and tidal events of the same AEP with a sea level rise allowance of 1m show that flooding occurs for both fluvial and tidal events for a given AEP:

- For the Waimakariri River, flooding is more severe in storm tide events than in fluvial events for the 1% and 0.5% AEPs. For the smallest AEP considered (0.2%), flooding from the fluvial event is slightly greater than the storm tide event.
- For the Ashley River, flooding on the true right bank is marginally deeper and more extensive in fluvial events than in storm tide events for the all the AEPs considered. On the true left side of the river, in and around the Ashley-Saltwater Creek Estuary where flooding is not controlled by elevated banks, the flood extents and depths are slightly greater for the storm tide events due to residual accumulations of water from successive high tides before and after the highest tide.

4.2 Recommendations

- The accuracy of the modelling depends in part on the accuracy of the data used, in particular the level of key features, such as stop banks, which control the volume of overtopping and the spread of water. Due to the lack of recent ground-based survey data, the model is largely based on LiDAR data. If new survey data becomes available, updating the models should be considered.

  In certain key locations it would be worth considering collecting new survey data:

  - the stop banks along Kairaki Creek and the Beach Road crossing
  - the stop bank and ground levels around the Beach Crescent car park at Waikuku Beach

- The model has not been calibrated against actual flood events. While there may be no suitable recent events for calibrating flow in the floodplain, it should be possible to review the calibration of the river reaches if data is available.

- In the absence of calibration, sensitivity tests to quantify the uncertainty in the model results due to the uncertainty in model parameters should be considered. These could include:

  - Channel and floodplain roughness values
  - Model mesh size
  - Numerical solution parameters

  Sensitivity tests to the model boundary conditions could also be considered, primarily to the shape and duration of the storm surge component and wave setup allowance.

- Given the extensive areas identified as at risk from high groundwater levels and the potential for surface flooding from groundwater breakout, further assessment of the risk from this source of flooding is recommended. In particular, for areas of higher ground, above the mean sea levels simulated, in which drainage is less likely to be affected by coastal conditions and have therefore not been considered in this study.

- There is potential for untreated wastewater to escape from the wastewater network and to be transported into residential areas by the flood water. Further assessment of this risk, which could include contaminant tracing and modelling, should be considered by WDC.

Appendix A. Wave set-up assessment

Purpose

The purpose of this assessment is to better define the value of the wave set-up contribution to water levels in the Waimakariri and Ashley River Mouths for input into the Phase 2 Coastal Inundation modelling for these river mouths.

Background

Wave set-up is a process that can elevate water levels at entrances to inlets. As noted by Tonkin & Taylor (2017), *"the research on wave set up at estuary and river entrances is still developing and there are knowledge gaps on all the relevant physical processes and interactions. However, research by Irish and Canizares, (2009) indicate that wave induced gradient flow contributes an additional 15 to 35% to the total storm tide level. The wave-breaking process is capable of raising the mean sea level and this includes wave breaking and set-up on the ebb-tide delta as well as a contribution to water levels from the gradient between the wave set-up on the adjacent coast and at the inlet".*

For the Avon-Heathcote Estuary, Tonkin & Taylor (2017) used the Unibest-LT model to calculate the maximum set-up from wave breaking on the ebb tide delta as being 0.3 m, which was 0.39 m less that set-up on the adjacent beach, hence applied a 0.1 m addition to the set-up for wave induced gradient flow (being between the 15-35% from Irish and Canizares, (2009) of the 0.39 m difference) to get a total wave set -up value of 0.4 m entering the estuary.

Other additional international literature on wave set-up effects on water levels in river entrances and estuaries suggests that the magnitude of set-up is up to 2-14% of the offshore wave height (Tanaka & Tinh, 2008; Zaki *et al*, 2015) for untrained river mouths. The literature also indicates that the wave set-up is lower for deeper estuaries, and reduces with increased magnitudes of flood flow.

Values used in the Waimakariri Stage 1 bathtub modelling

For the stage 1 coastal hazards report involving bathtub coastal inundation modelling, a wave set-up value of 14% of the offshore wave height was used. It was noted that from the components of the joint probability 1% AEP storm tide and wave set-up water levels presented by Stephens *et al* (2015) via the Canterbury coastal calculator, the percentage of wave set-up to offshore wave height was 14%, therefore it was considered that this was an appropriate conservative value of extreme coastal water level entering the river mouths that is suitable for use in the first pass bathtub approach.

Applying the joint probability 1% AEP storm tide and wave set-up from Stephens et al (2015) for Pines Beach give a wave set up contribution of 0.26 m (From wave height of 1.82 m) to a total water level of 1.93 m (LVD) which was used for the bathtub inundation modelling inside both the Waimakariri and Ashley River Mouths. The report noted that further consideration of these input levels should be undertaken should hydrodynamic modelling be undertaken, particularly for the Waimakariri River mouth area due to the deeper bed levels and larger flood flows.

Values in proposal for stage 2 hydrodynamic inundation modelling

In the proposal for the stage 2 hydrodynamic inundation modelling the range of possible wave set-up values were given as 0.07 -0.48 m, covering the range of 2-14% of the independent 1% AEP wave heights at Pines Beach from Stephens et al (2015) of 3.43 m with a storm beach slope of 1:17.

Literature review

The following is a brief of the relevant literature referenced above to determine which of the approaches are most appropriate for the Waimakariri District.

Irish & Canizares (2009)

- Paper describes wave-driven flow process at tidal inlets and demonstrates its impact on bay flooding on 3 tidal inlets at Long Island, New York. The inlets have similar or smaller widths and similar depths to the Waimakariri Mouth but, as tidal inlets rather than rivers have up to 10 times the bay area and tidal prism that given by Hume et al (2016) for the Waimakariri. All three inlets are an order of magnitude larger than the Ashley River Mouth.

- Numerical simulations using a coupled hydrodynamic (Delft3D-FLOW) and wave model (Delft3D_WAVE) were used to estimate contributions to bay water level by wave-driven gradient flow in two major historical coastal storms and a smaller storm during which the model was validated using field measurements of water level.

- The findings indicated that wave-induced flow contributions make up 15–35% of the total inlet water level, or 8-23% of the storm tide (astronomical tide + storm surge). Contributions were higher for smaller storm events, and smaller bays. The degree to which the wave induced flow contributes to bay storm water level was found to be a function of inlet efficiency, storm duration, and bay response time.

Tanaka & Tinh (2008)

- Objectives of the study was to investigate the influence of wave setup height to sand spit evolution at the Yoneshiro River Mouth, and the effect of regularly extreme wind to wave setup height at the Yoneshiro and Iwaki River Mouths. Both rivers discharge into the Japan Sea which is exposed to extreme winds, and Iwaki River has mouth training structures. Water depths in the river mouths are 2.3m (Yoneshiro) and 4.5m (Iwaki), compared to depth at Waimakariri River Mouth estimated at around 6m and Ashley River Mouth estimated at 2-3m (both estimated from most down-stream river cross section). The study output includes a relationship between wave setup height with offshore wave height and average water depth at the river mouth.

- The study included storm events with wave heights up to 5.5 m.

- Results agreed with earlier findings of Nguyen et al (2007) for 7 river mouths discharging into Pacific Ocean in a typhoon during Oct 2006, with wave set-up height at the entrance being between 2-14% of offshore wave height. Set-up height was found to be inversely proportional to water depth at the entrance, such that shallower depths had greater wave set-up.

Zaki et al (2015)

- Motivated by the differences in the field study findings of Hanslow & Neilsen (1992) and Tanaka & Tinh (2008), the purpose of this laboratory study was to quantify wave setup in estuaries by considering both the offshore wave characteristics and the effect of freshwater flood flows.

- Findings were:
  1) With no river outflow, wave set-up is approximately ten percent of offshore wave height.
  2) In terms of wave steepness, wave set-up is significant when breaking occurs for wave steepness exceeding 0.01.
  3) Deeper estuaries contribute to lower wave set-up.

4) In the presence of freshwater subcritical flood-outflow, the wave setup reduces with the magnitude of the flow. Critical flow in the entrance will lead to no setup.

Resulting appropriate set-up levels to apply to Waimakariri District river mouths

Applying the joint probability 1% AEP storm tide from Stephens et al (2015) for Pines Beach of 1.50 m (LVD), and wave height of 1.82 m, the following would be the range of wave set-ups:

- From Irish & Canizares (2009) (8-23% of storm tide): 0.12 m to 0.35 m.
- From Tanaka & Tinh (2008) and Zaki et al (2015) (2-14% of storm wave): 0.04 m to 0.25 m.

The actual likely set-up contribution is difficult to determine and could lie anywhere within the above ranges. However, based on the characteristics of the inlets in the above studies and it is considered that the relationships in the Tanaka & Tinh (2008) and Zaki et al (2015) are more appropriate as are for river mouth environments. These relationships also fit more with our understanding of wave set-up, being a function of wave height and bed slope from ocean into the mouth.

Therefore, we propose an upper contribution of 0.25 m to the joint 1% AEP sea water levels entering the river mouth environments. Based on the relationships between set-up and wave heights presented in Tanaka & Tinh (2008), for the wave heights being considered, this would be a conservative estimate of set-up. The deeper water in the Waimakariri River Mouth is likely to result in lower maximum set-up, possibility as low as 0.1 m from relationship given in Tanaka & Tinh (2008). For the Ashley River, the set-up contribution to water levels is assumed to occur regardless of whether the mouth is perpendicular to the coast or off set.

It is considered that the set-up contribution will vary temporally with the onset of the coastal storm that drives storm surge. It is considered that the temporal increase and decay of the set-up values within the modelling should mirror the temporal increase and decay of the storm surge.

Although it is recognised that set-up will decease with increase in the river hydrograph towards flood peak, we have no information on which to base this decay or what the critical flow would be to reduce the set-up to zero. Assumptions in this could be made in the modelling, or leave the base level, which would have to be recognised as an overly conservative estimate.

References

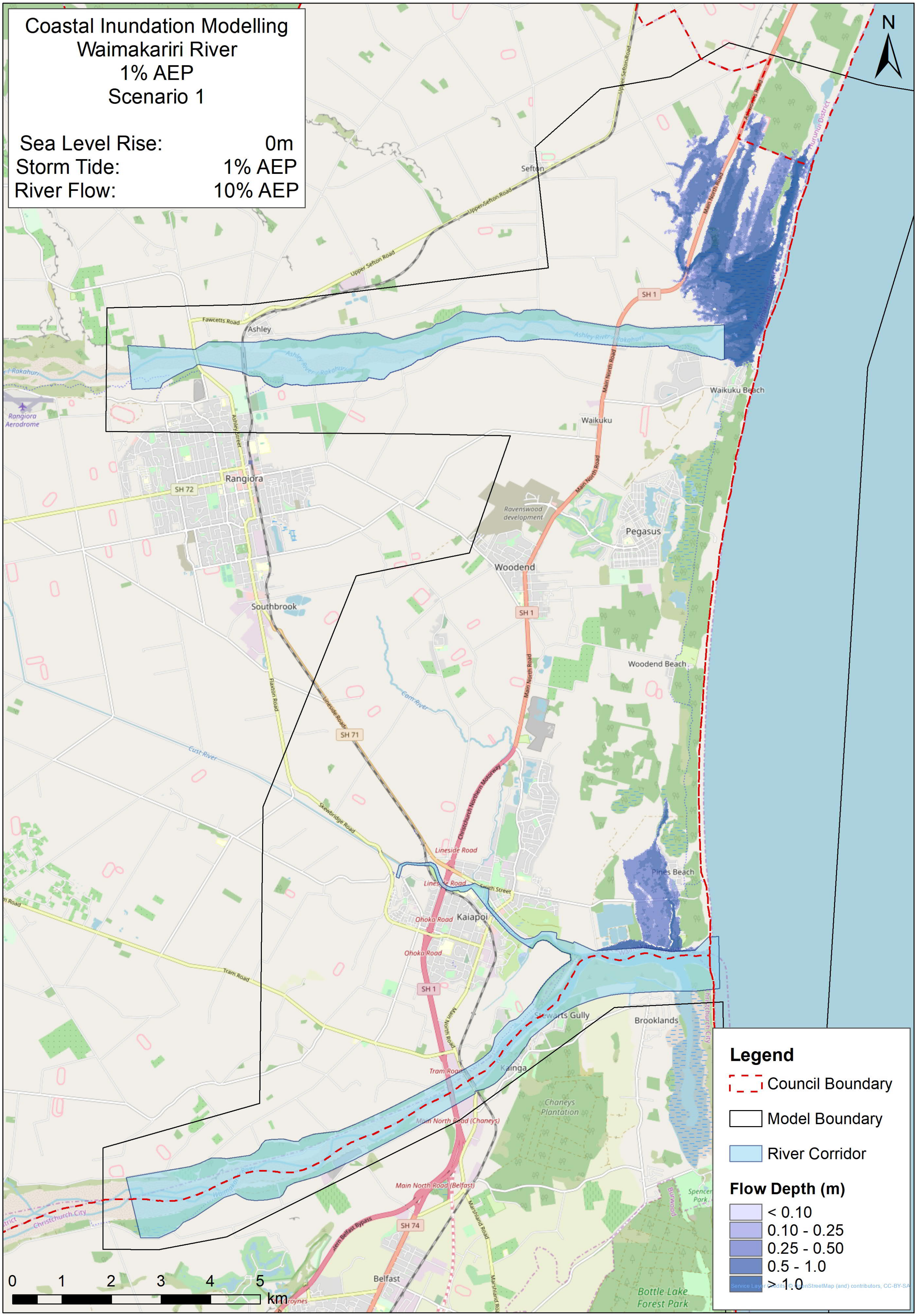
Irish, J.L. and R. Canizares (2009). Storm-wave flow through tidal inlets and its influence on bay flooding, Journal of Waterway, port, coastal and ocean engineering, pp 52-60, ASCE, March/April 2009

Nguyen, X. T., Tanaka, H. and Nagabayashi, H. (2007). Wave setup at river and inlet entrances due to an extreme event. International Conference on Violent Flows, Organized by RIAM, Kyushu University, Fukuoka, Japan, 2007.

Tanaka H. & Tinh N.X. (2008) Wave setup at river mouths in Japan. Journal of water Resources and environmental Engineering; 23: 5-12.

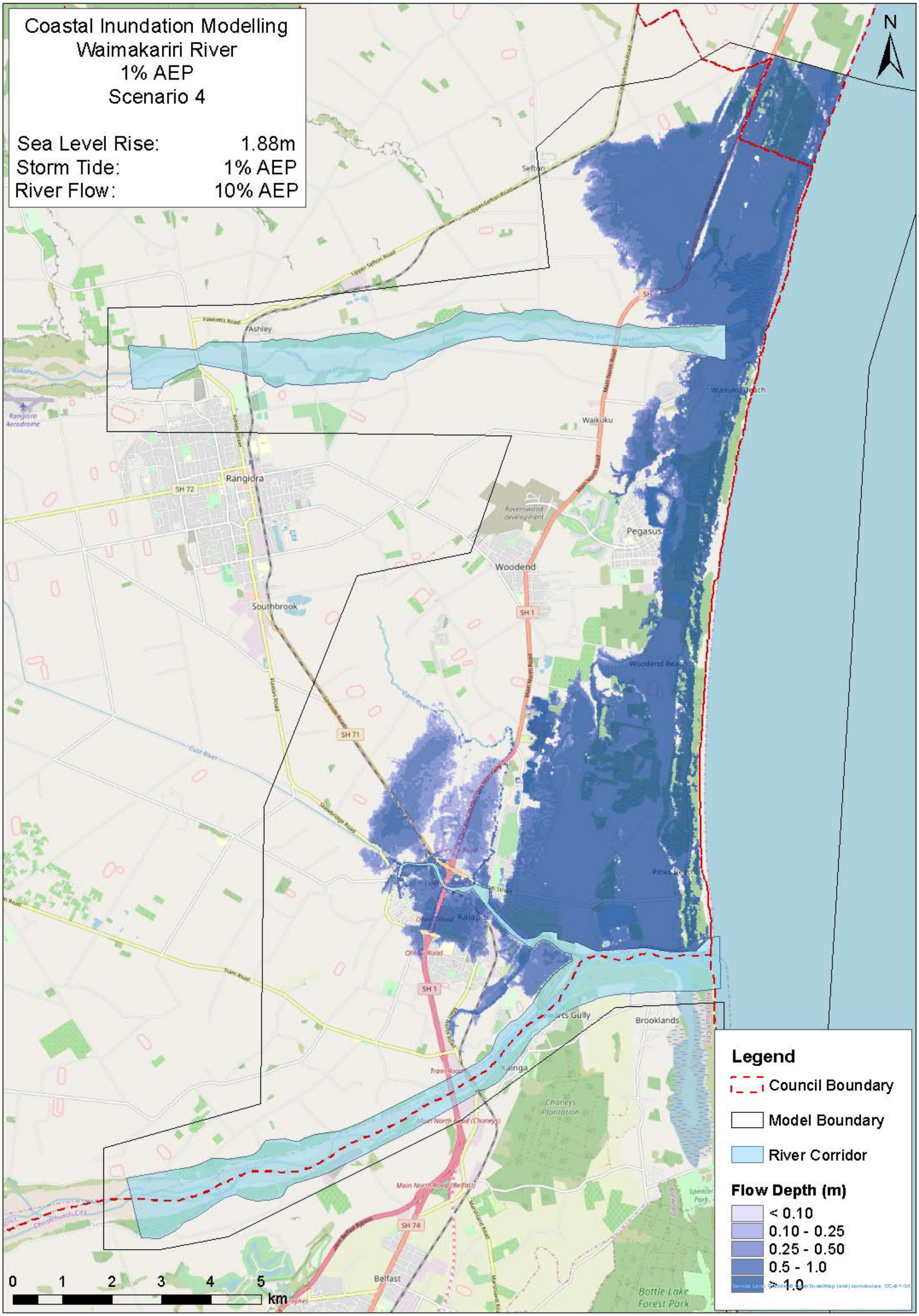
Zaki *et al* (2015) 2_D investigation of river flow on wave setup in estuaries. 22nd Australasian Coastal and Ocean Engineering Conference, Sydney, 2015 p578-581.

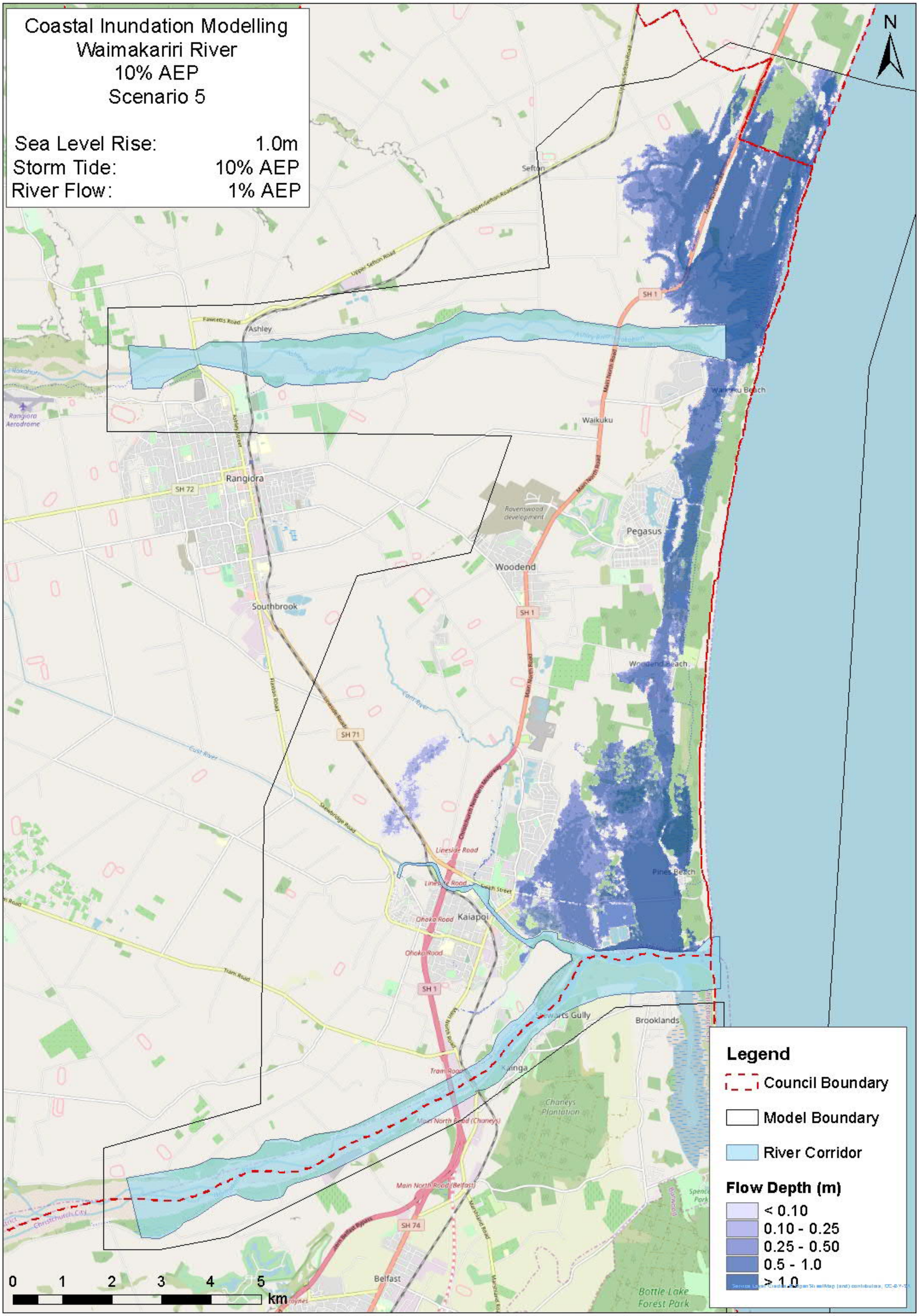
Appendix B. Waimakariri River scenario maps

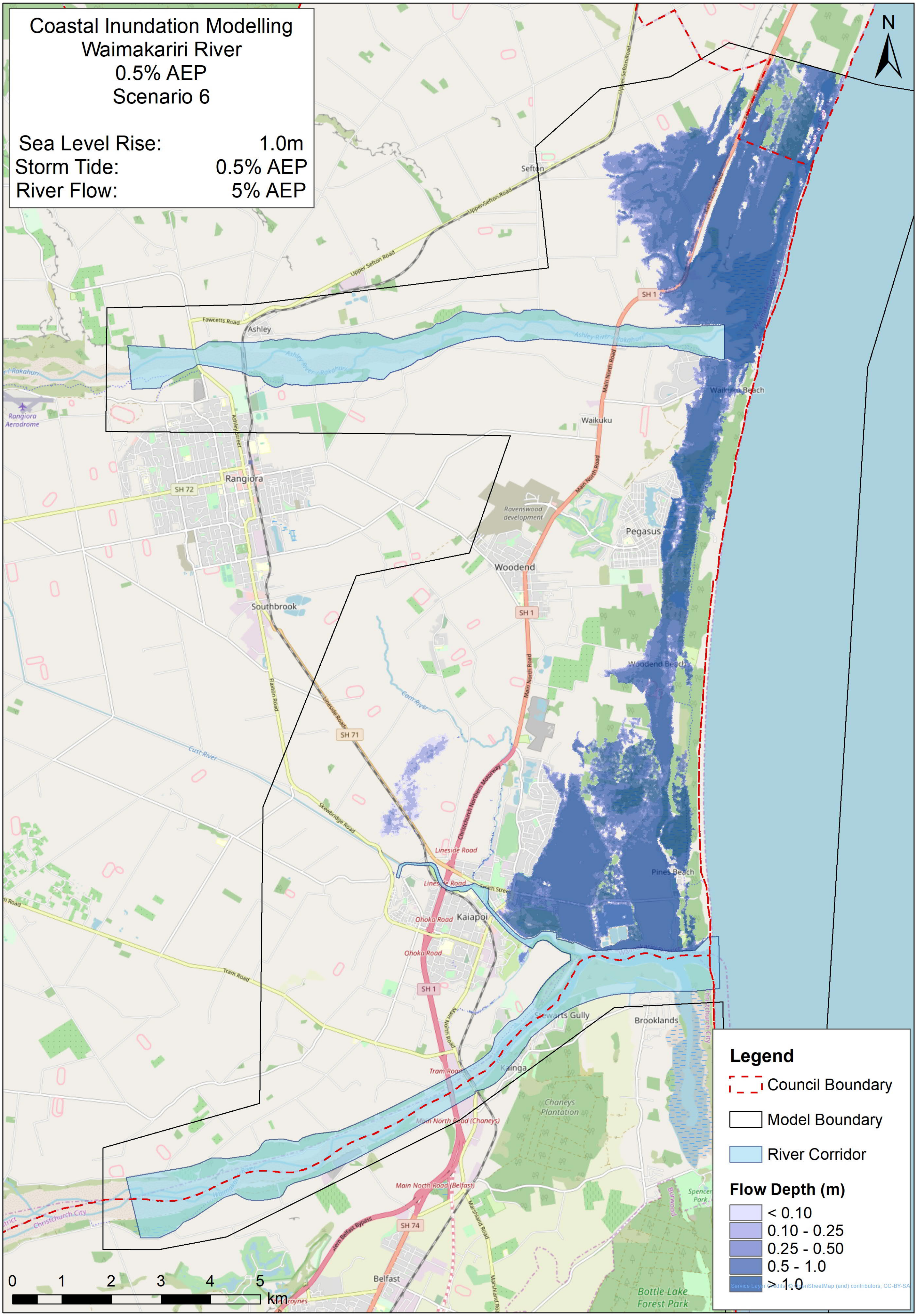

Coastal Inundation Modelling
Waimakariri River
1% AEP
Scenario 1
Sea Level Rise: 0m
Storm Tide: 1% AEP
River Flow: 10% AEP
N
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5
km
Sefton
Ashley
Rangiora
Southbrook
Woodend
Pegasus
Waikuku
Waikuku Beach
Woodend Beach
Pines Beach
Kaiapoi
Stewarts Gully
Brooklands
Kainga
Belfast
Chaneys Plantation
Bottle Lake Forest Park
Ravenswood development
SH 1
SH 72
SH 71
SH 74
Main North Road
Lineside Road
Ohoka Road
Tram Road
Flaxton Road
Ashley Street
Fawcetts Road
Upper Sefton Road
Skewbridge Road
Smith Street
Christchurch Northern Motorway
Main North Road (Chaneys)
Main North Road (Belfast)
Marshland Road
Cust River
Cam River
Ashley River / Rakahuri
Rangiora Aerodrome
Christchurch City
Hurunui District

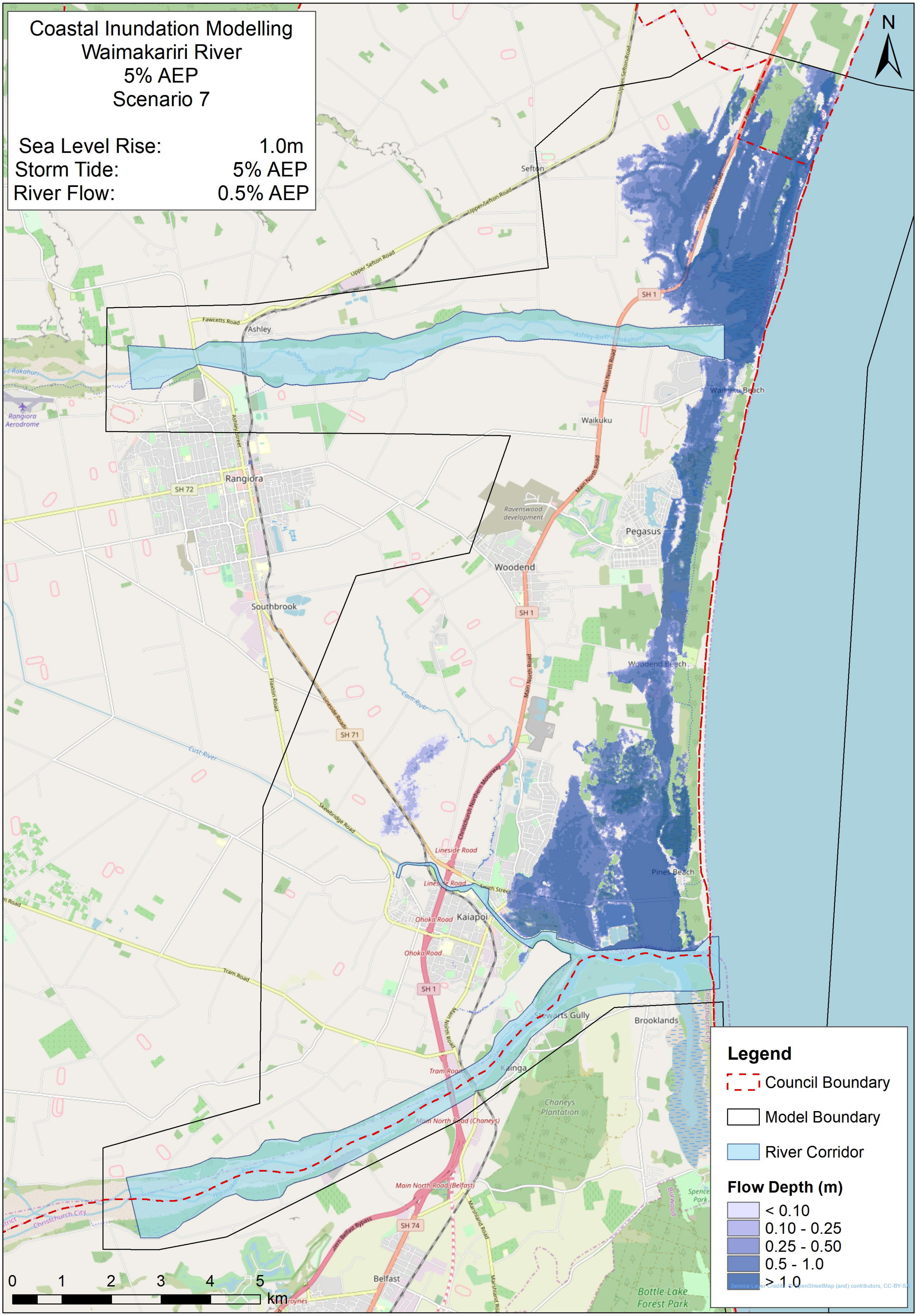

Coastal Inundation Modelling
Waimakariri River
1% AEP
Scenario 2
Sea Level Rise: 1m
Storm Tide: 1% AEP
River Flow: 10% AEP
N
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5
km
Sefton
Ashley
Rangiora
Southbrook
Woodend
Pegasus
Waikuku
Waikuku Beach
Woodend Beach
Pines Beach
Kaiapoi
Stewarts Gully
Brooklands
Kainga
Belfast
Chaneys Plantation
Bottle Lake Forest Park
Spencer Park
Ravenswood development
Rangiora Aerodrome
Cust River
Cam River
Ashley River / Rakahuri
SH 1
SH 71
SH 72
SH 74
Main North Road
Lineside Road
Ohoka Road
Tram Road
Flaxton Road
Skewbridge Road
Ashley Street
Fawcetts Road
Upper Sefton Road
Marshland Road
Christchurch Northern Motorway
Christchurch City
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA

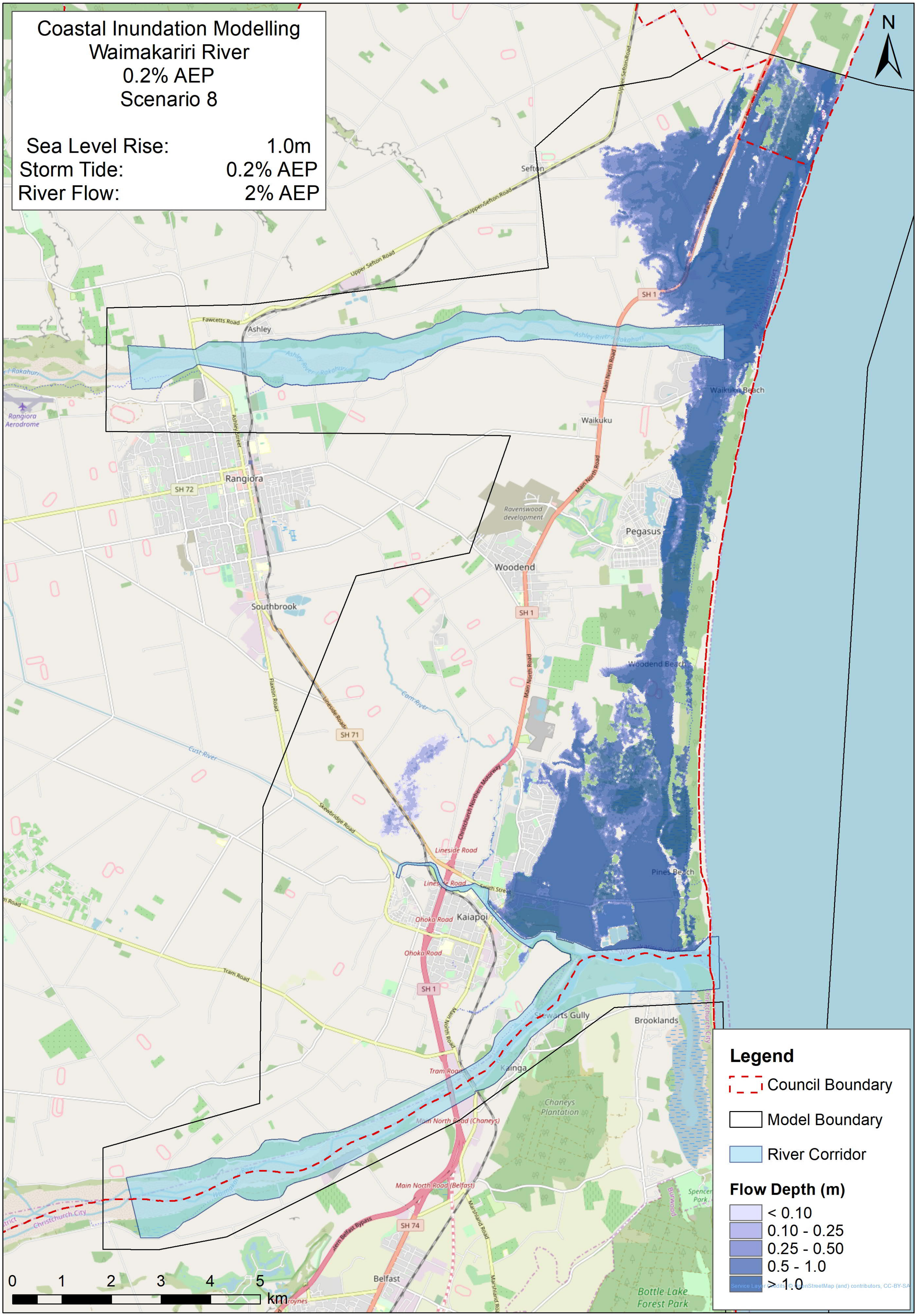

Coastal Inundation Modelling
Waimakariri River
1% AEP
Scenario 3
Sea Level Rise: 0.5m
Storm Tide: 1% AEP
River Flow: 10% AEP
N
Sefton
Ashley
Rangiora
Waikuku
Waikuku Beach
Pegasus
Woodend
Southbrook
Woodend Beach
Pines Beach
Kaiapoi
Brooklands
Kainga
Belfast
SH 1
SH 71
SH 72
SH 74
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5 km

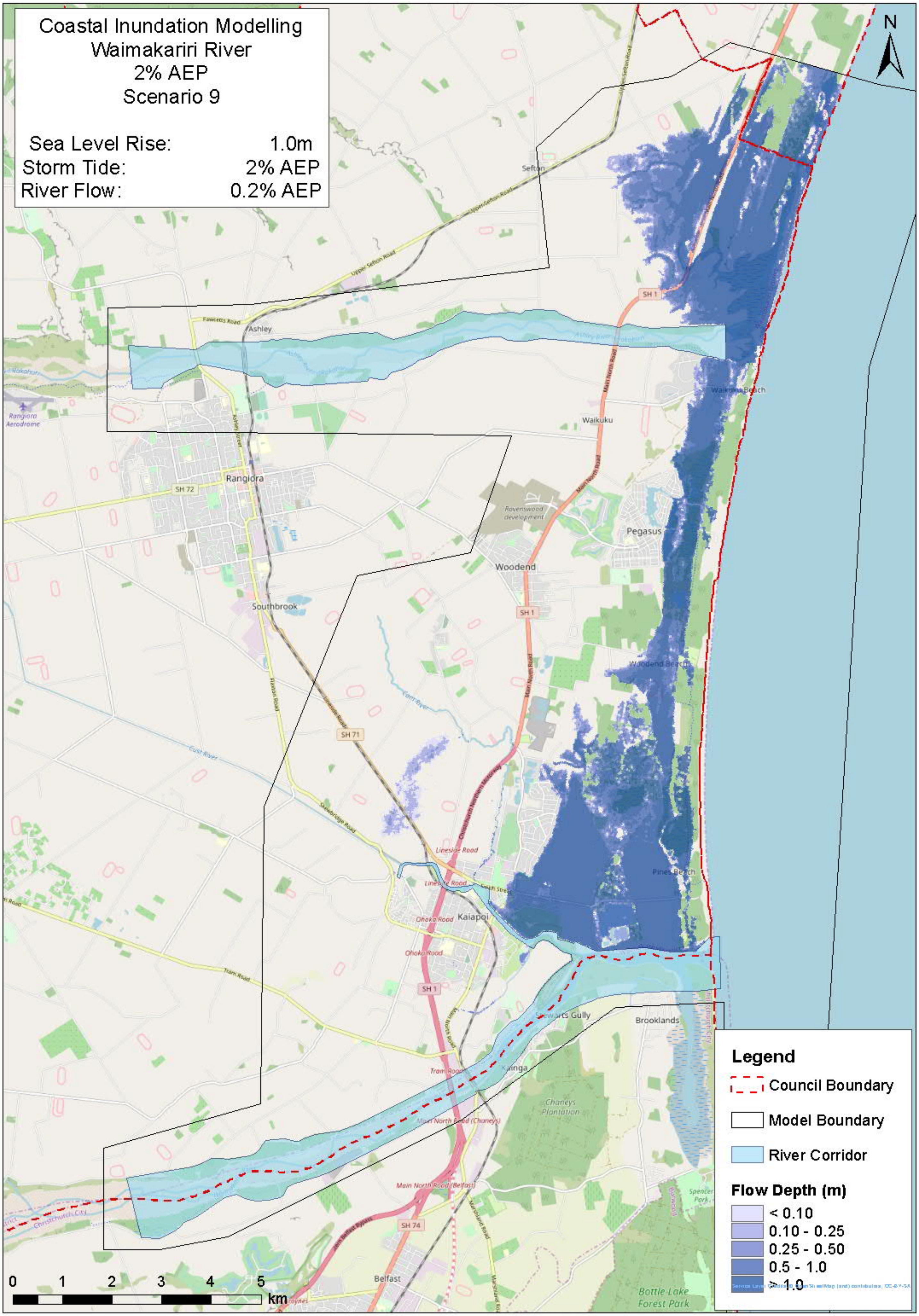

Coastal Inundation Modelling
Waimakariri River
1% AEP
Scenario 4
Sea Level Rise: 1.88m
Storm Tide: 1% AEP
River Flow: 10% AEP
N
Sefton
Ashley
Rangiora
Waikuku
Waikuku Beach
Pegasus
Woodend
Southbrook
Woodend Beach
Pines Beach
Kaiapoi
Brooklands
Kainga
Belfast
SH 1
SH 71
SH 72
SH 74
0 1 2 3 4 5 km
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0


Coastal Inundation Modelling
Waimakariri River
10% AEP
Scenario 5
Sea Level Rise: 1.0m
Storm Tide: 10% AEP
River Flow: 1% AEP
N
Sefton
Ashley
Rangiora
Southbrook
Woodend
Pegasus
Waikuku
Waikuku Beach
Woodend Beach
Pines Beach
Kaiapoi
Stewarts Gully
Brooklands
Kainga
Belfast
Chaneys Plantation
Bottle Lake Forest Park
SH 1
SH 71
SH 72
SH 74
Main North Road
Upper Sefton Road
Fawcetts Road
Lineside Road
Ohoka Road
Tram Road
Cust River
Rangiora Aerodrome
Ravenswood development
Christchurch City
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5
km


Coastal Inundation Modelling
Waimakariri River
0.5% AEP
Scenario 6
Sea Level Rise: 1.0m
Storm Tide: 0.5% AEP
River Flow: 5% AEP
N
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5
km
Sefton
Ashley
Rangiora
Southbrook
Woodend
Pegasus
Waikuku
Waikuku Beach
Woodend Beach
Pines Beach
Kaiapoi
Stewarts Gully
Brooklands
Kainga
Belfast
Chaneys Plantation
Bottle Lake Forest Park
Ravenswood development
Rangiora Aerodrome
SH 1
SH 71
SH 72
SH 74
Main North Road
Lineside Road
Flaxton Road
Tram Road
Ohoka Road
Skewbridge Road
Upper Sefton Road
Fawcetts Road
Cam River
Cust River
Ashley River / Rakahuri

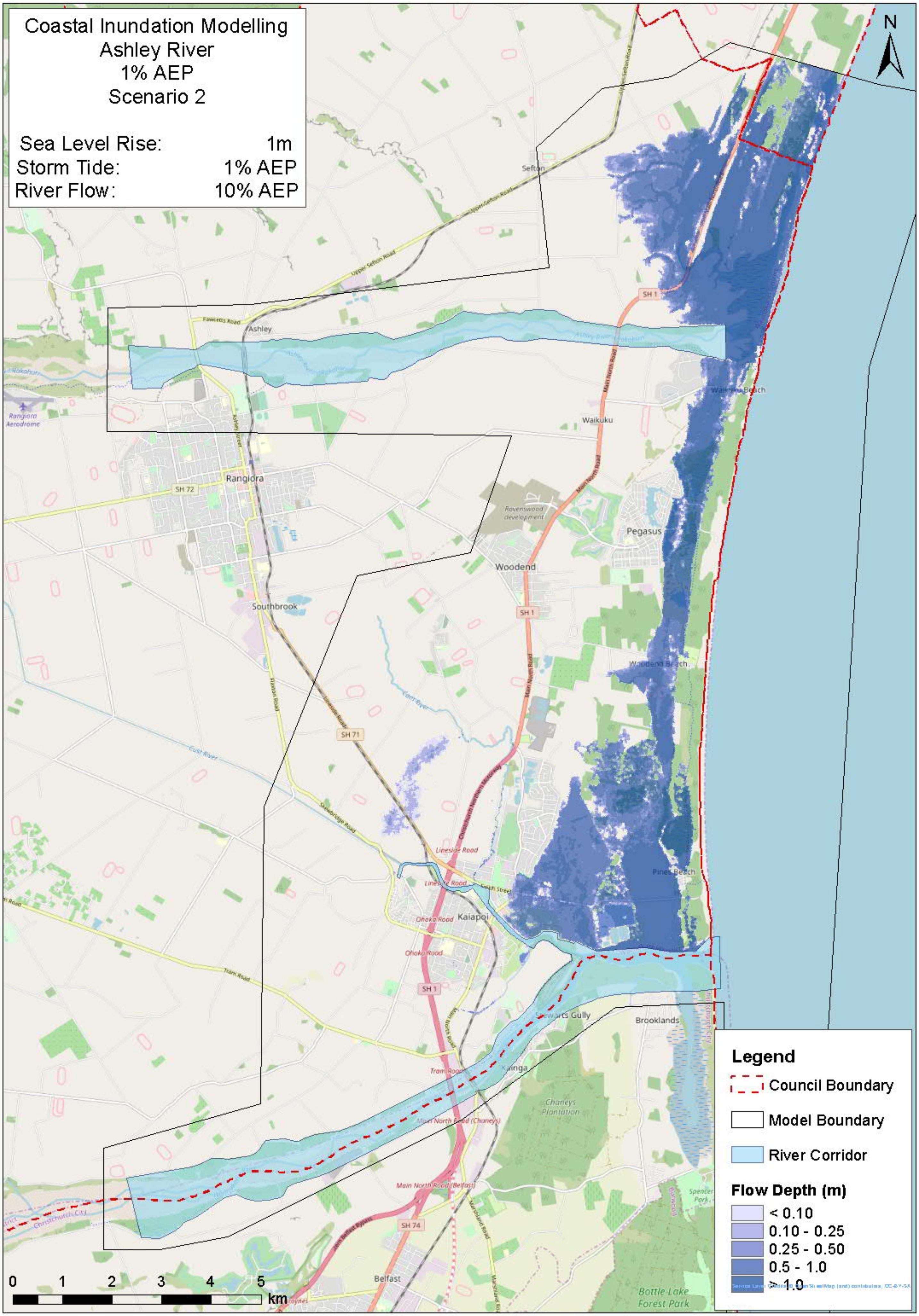

Coastal Inundation Modelling
Waimakariri River
5% AEP
Scenario 7
Sea Level Rise: 1.0m
Storm Tide: 5% AEP
River Flow: 0.5% AEP
N
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5 km
Rangiora
Kaiapoi
Woodend
Pegasus
Southbrook
Ashley
Sefton
Waikuku
Waikuku Beach
Woodend Beach
Pines Beach
Brooklands
Kainga
Stewarts Gully
Belfast
Chaneys Plantation
Bottle Lake Forest Park
Ravenswood development
Rangiora Aerodrome
SH 1
SH 71
SH 72
SH 74
Main North Road
Lineside Road
Tram Road
Ohoka Road
Flaxton Road
Skewbridge Road
Upper Sefton Road
Fawcetts Road
Ashley River / Rakahuri
Cust River
Cam River
Christchurch Northern Motorway
Christchurch City
Main North Road (Chaneys)
Main North Road (Belfast)
Marshland Road
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA


Coastal Inundation Modelling
Waimakariri River
0.2% AEP
Scenario 8
Sea Level Rise: 1.0m
Storm Tide: 0.2% AEP
River Flow: 2% AEP
N
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5 km
Sefton
Ashley
Rangiora
Southbrook
Woodend
Pegasus
Waikuku
Waikuku Beach
Woodend Beach
Pines Beach
Kaiapoi
Stewarts Gully
Brooklands
Kainga
Belfast
Chaneys Plantation
Bottle Lake Forest Park
Ravenswood development
Rangiora Aerodrome
SH 1
SH 72
SH 71
SH 74
Main North Road
Flaxton Road
Lineside Road
Tram Road
Ohoka Road
Skewbridge Road
Upper Sefton Road
Fawcetts Road
Ashley Street
Christchurch Northern Motorway
Ashley River
Cust River
Cam River
Christchurch City


Coastal Inundation Modelling
Waimakariri River
2% AEP
Scenario 9
Sea Level Rise: 1.0m
Storm Tide: 2% AEP
River Flow: 0.2% AEP
N
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5 km
Sefton
Ashley
Rangiora
Waikuku
Waikuku Beach
Pegasus
Woodend
Southbrook
Woodend Beach
Pines Beach
Kaiapoi
Brooklands
Kainga
Belfast
Chaneys Plantation
Bottle Lake Forest Park

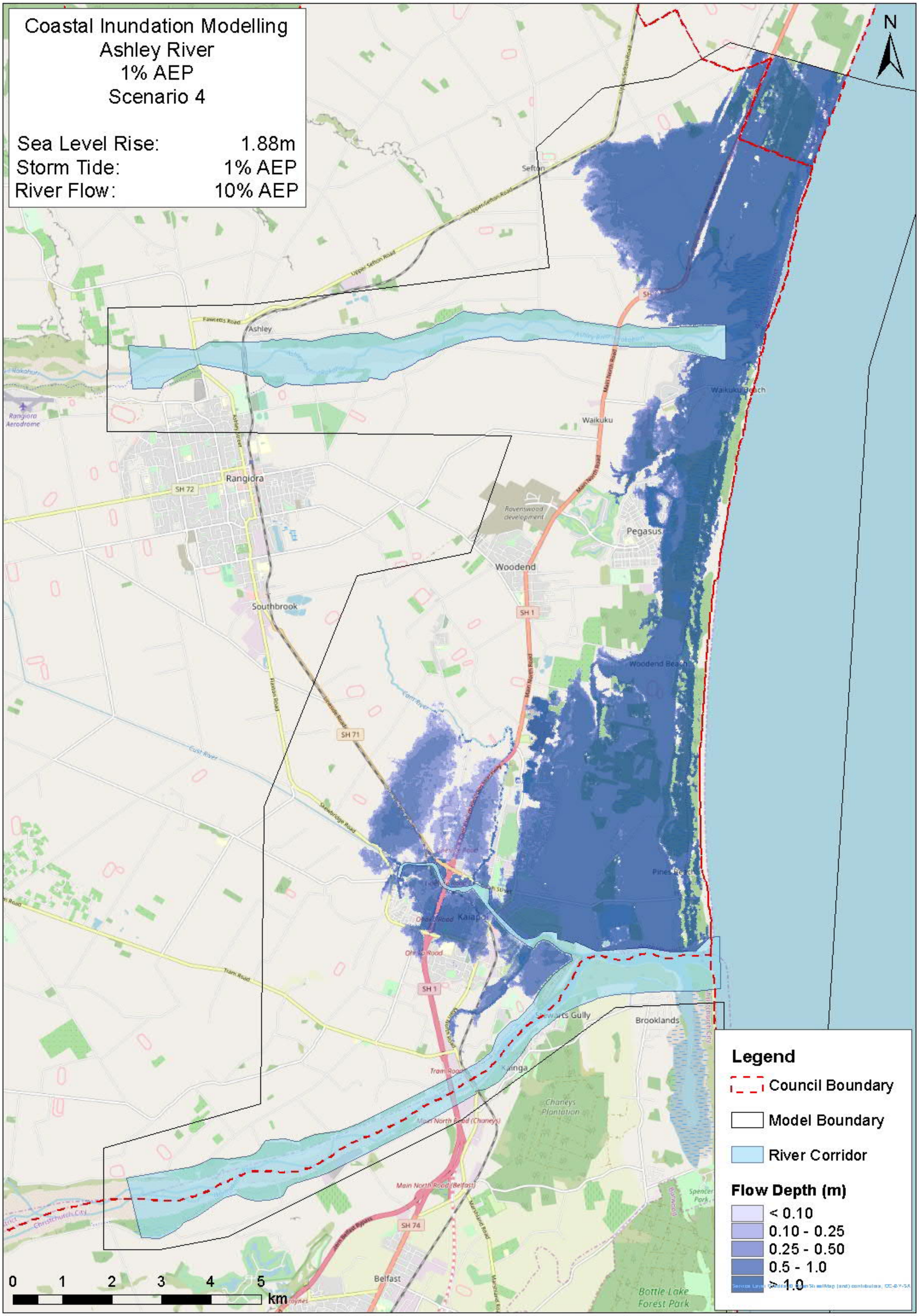
Appendix C. Ashley River scenario maps

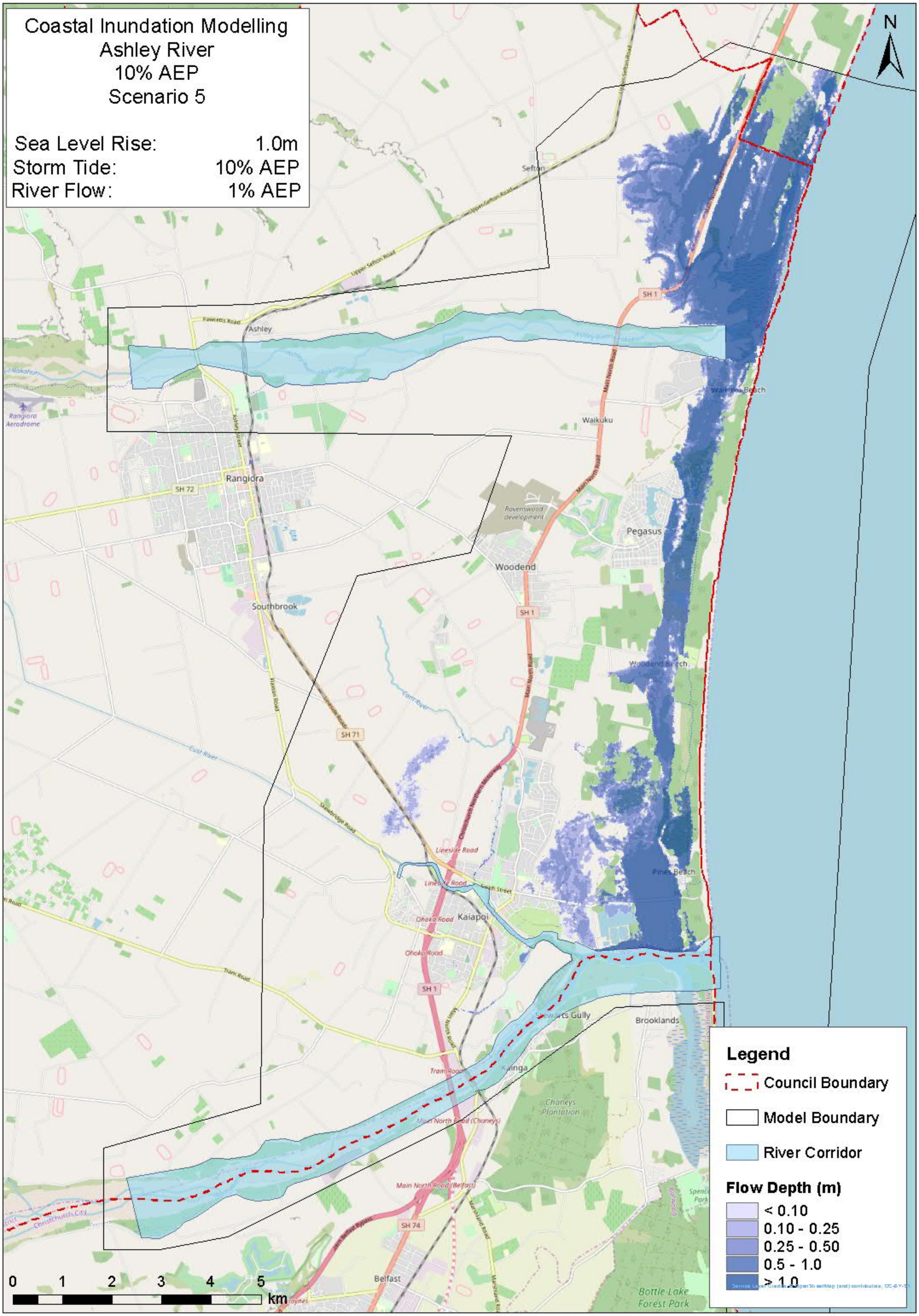

Coastal Inundation Modelling
Ashley River
1% AEP
Scenario 1
Sea Level Rise: 0m
Storm Tide: 1% AEP
River Flow: 10% AEP
N
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5
km
Sefton
Ashley
Rangiora
Southbrook
Woodend
Pegasus
Waikuku
Waikuku Beach
Woodend Beach
Pines Beach
Kaiapoi
Stewarts Gully
Brooklands
Kainga
Belfast
Chaneys Plantation
Bottle Lake Forest Park
SH 1
SH 71
SH 72
SH 74
Main North Road
Lineside Road
Ohoka Road
Tram Road



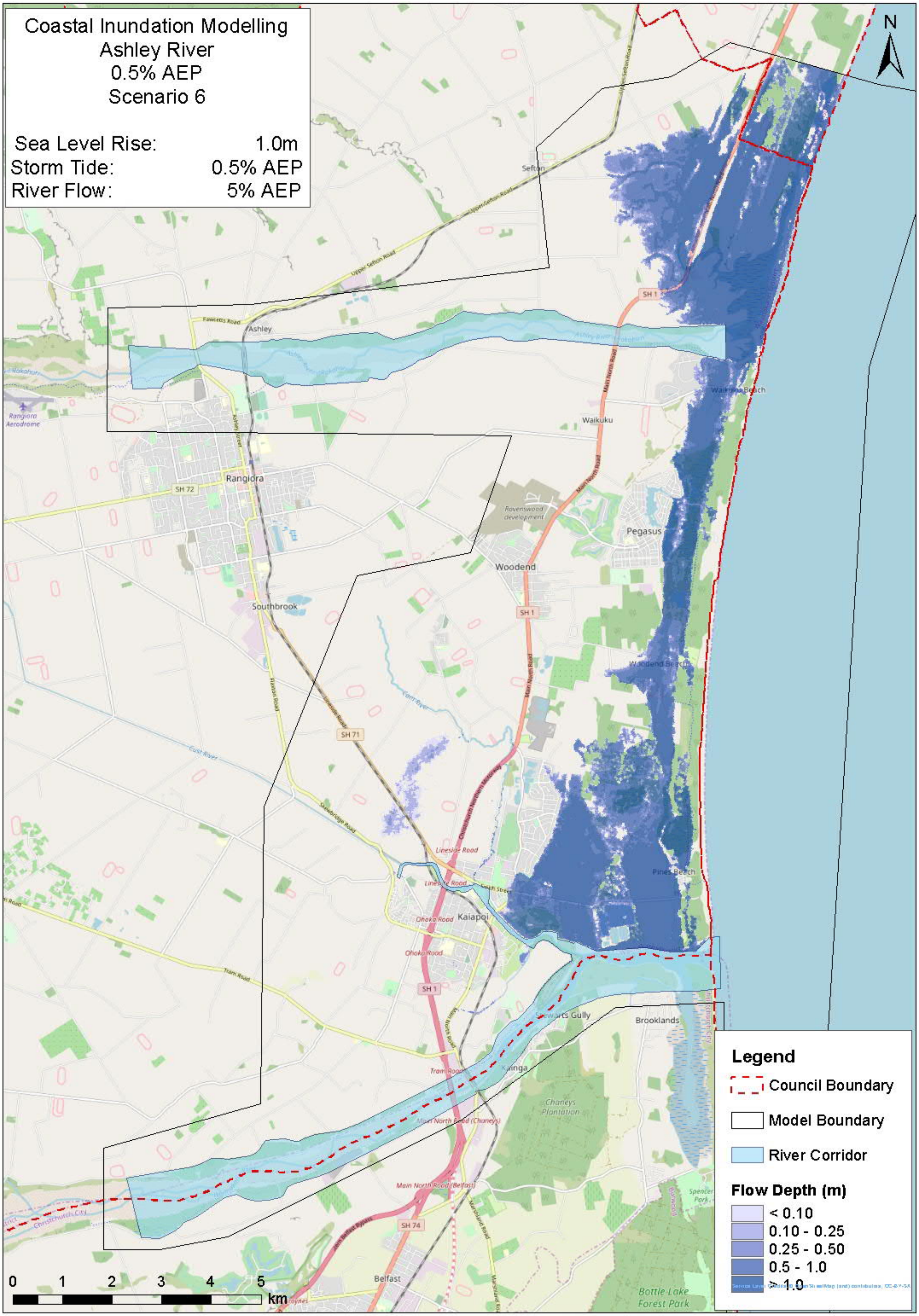
Coastal Inundation Modelling
Ashley River
1% AEP
Scenario 2
Sea Level Rise: 1m
Storm Tide: 1% AEP
River Flow: 10% AEP
N
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5 km
Sefton
Ashley
Rangiora
Southbrook
Waikuku
Pegasus
Woodend
Woodend Beach
Pines Beach
Kaiapoi
Brooklands
Kainga
Belfast
Chaneys Plantation
Bottle Lake Forest Park
Ravenswood development
SH 1
SH 71
SH 72
SH 74
Main North Road
Upper Sefton Road
Fawcetts Road
Lineside Road
Ohoka Road
Tram Road
Cust River
Rangiora Aerodrome

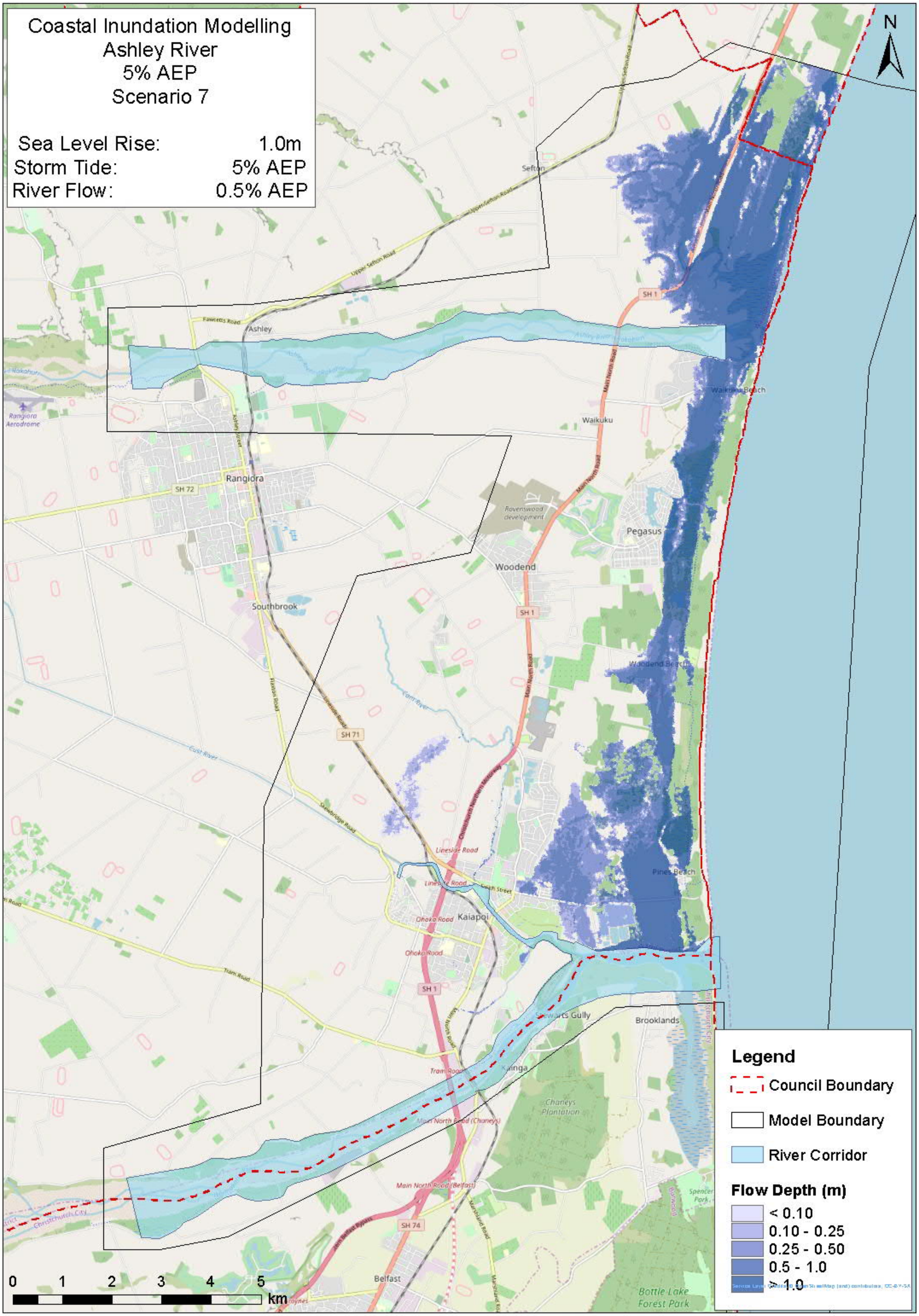

Coastal Inundation Modelling
Ashley River
1% AEP
Scenario 3
Sea Level Rise: 0.5m
Storm Tide: 1% AEP
River Flow: 10% AEP
N
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5 km
Sefton
Ashley
Rangiora
Southbrook
Waikuku
Waikuku Beach
Pegasus
Woodend
Woodend Beach
Pines Beach
Kaiapoi
Brooklands
Kainga
Belfast
Ravenswood development
Chaneys Plantation
Bottle Lake Forest Park
SH 1
SH 72
SH 71
SH 74

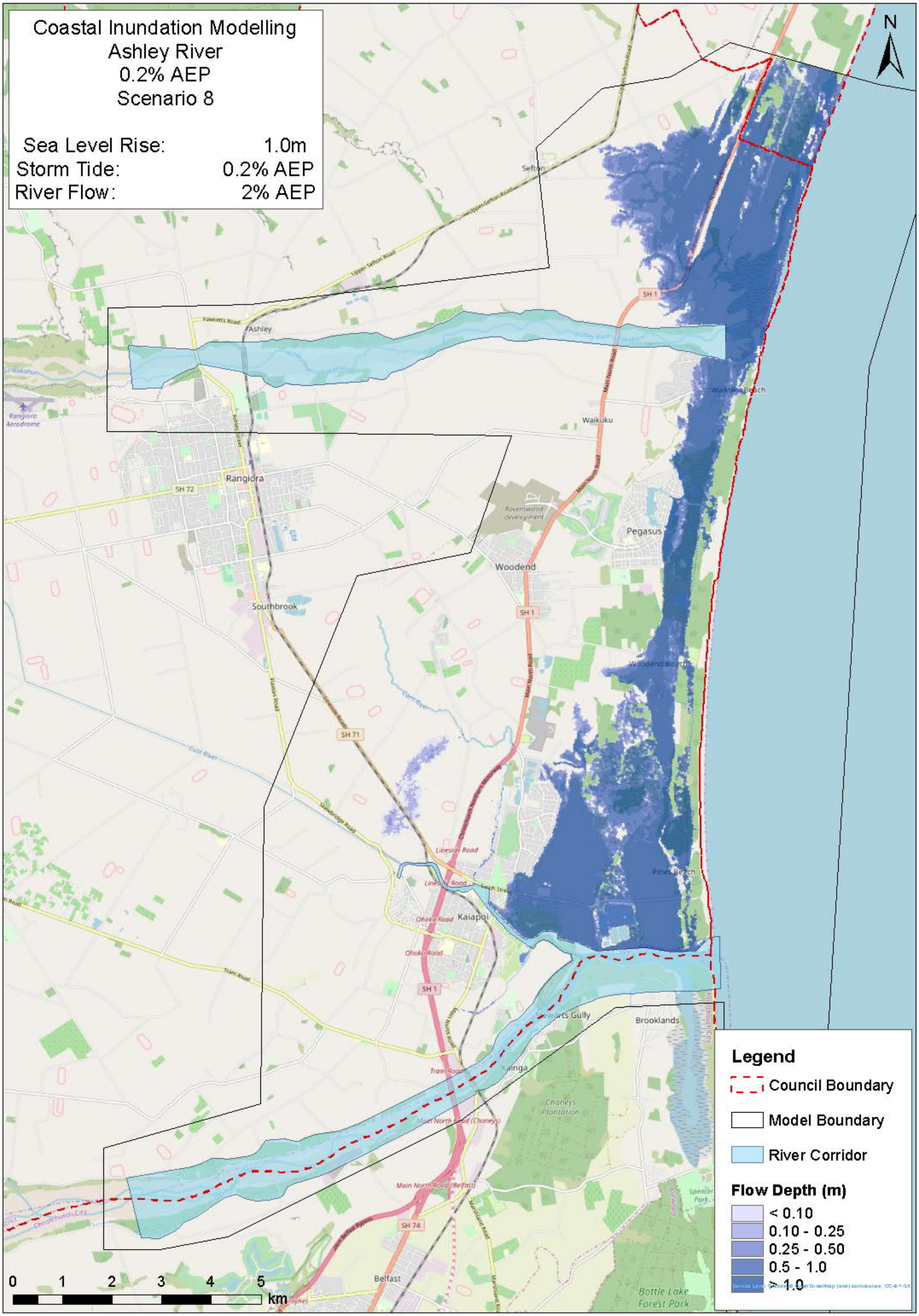

Coastal Inundation Modelling
Ashley River
1% AEP
Scenario 4
Sea Level Rise: 1.88m
Storm Tide: 1% AEP
River Flow: 10% AEP
N
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5 km
Sefton
Ashley
Rangiora
Waikuku
Waikuku Beach
Pegasus
Woodend
Southbrook
Woodend Beach
Pines Beach
Kaiapoi
Brooklands
Kainga
Belfast
SH 72
SH 1
SH 71
SH 74
Chaneys Plantation
Bottle Lake Forest Park



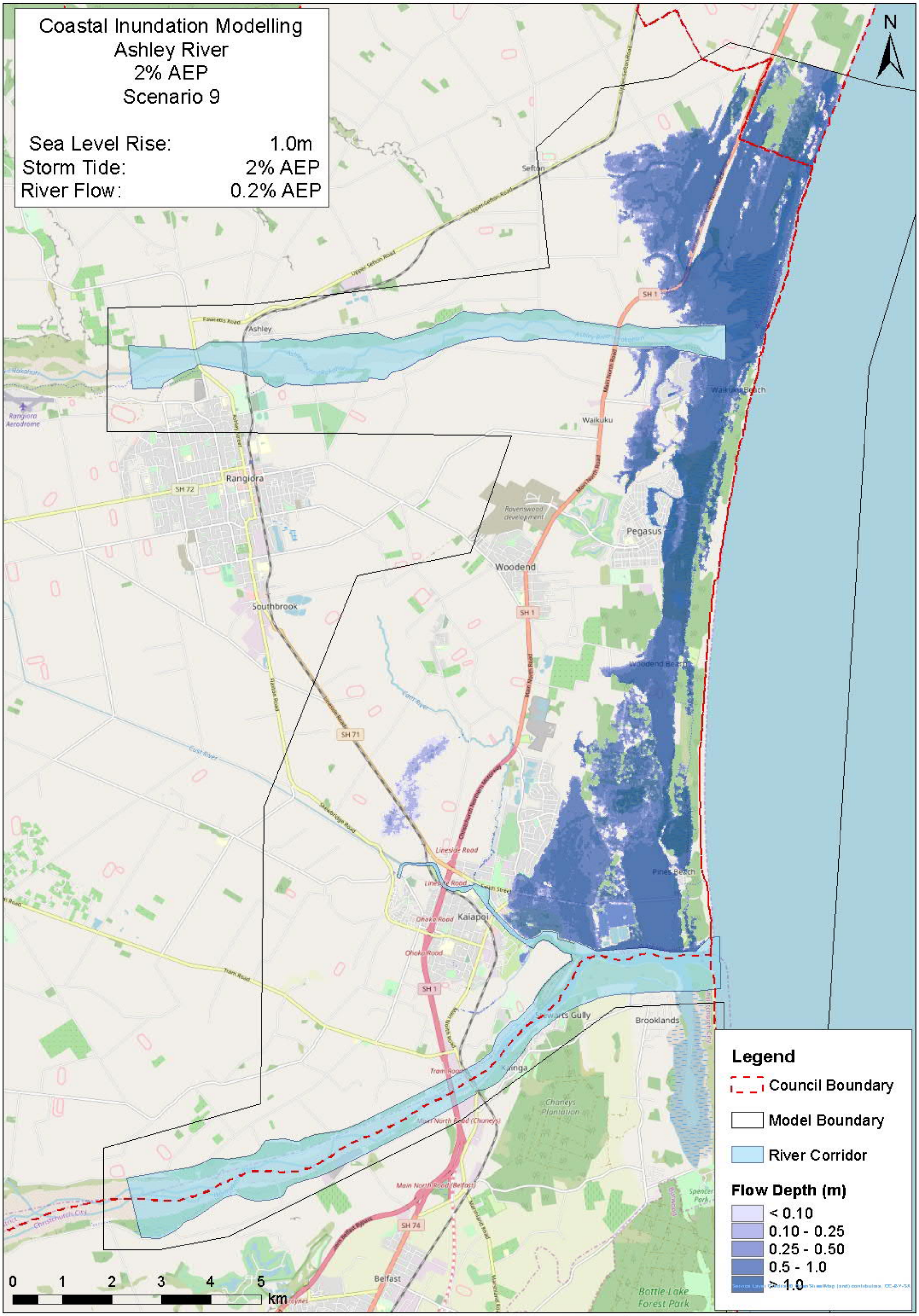
Coastal Inundation Modelling
Ashley River
10% AEP
Scenario 5
Sea Level Rise: 1.0m
Storm Tide: 10% AEP
River Flow: 1% AEP
N
Sefton
Ashley
Waikuku
Rangiora
Pegasus
Woodend
Southbrook
Woodend Beach
Pines Beach
Kaiapoi
Brooklands
Kainga
Belfast
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5
km


Coastal Inundation Modelling
Ashley River
0.5% AEP
Scenario 6
Sea Level Rise: 1.0m
Storm Tide: 0.5% AEP
River Flow: 5% AEP
N
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5
km
Sefton
Ashley
Rangiora
Southbrook
Waikuku
Pegasus
Woodend
Kaiapoi
Brooklands
Kainga
Belfast
SH 1
SH 72
SH 71
SH 74
Rangiora Aerodrome
Ravenswood development
Chaneys Plantation
Bottle Lake Forest Park
Main North Road
Lineside Road
Ohoka Road
Tram Road
Cust River


Coastal Inundation Modelling
Ashley River
5% AEP
Scenario 7
Sea Level Rise: 1.0m
Storm Tide: 5% AEP
River Flow: 0.5% AEP
N
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5 km
Sefton
Ashley
Rangiora
Southbrook
Waikuku
Waikuku Beach
Pegasus
Woodend
Woodend Beach
Pines Beach
Kaiapoi
Brooklands
Kainga
Belfast
SH 1
SH 71
SH 72
SH 74
Main North Road
Upper Sefton Road
Fawcetts Road
Lineside Road
Ohoka Road
Tram Road
Cust River
Chaneys Plantation
Bottle Lake Forest Park
Christchurch City



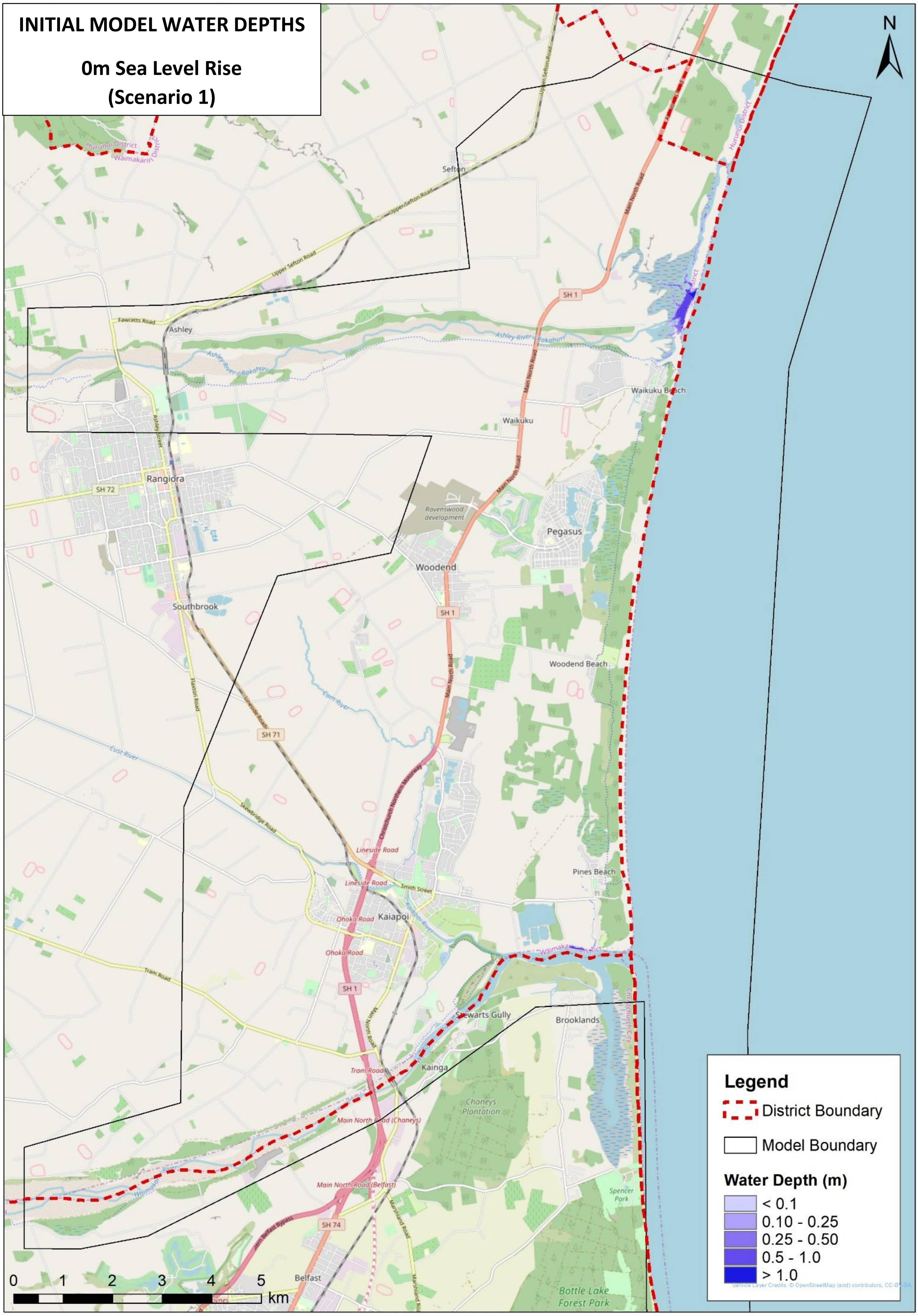
Coastal Inundation Modelling
Ashley River
0.2% AEP
Scenario 8
Sea Level Rise: 1.0m
Storm Tide: 0.2% AEP
River Flow: 2% AEP
N
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5 km
Sefton
Ashley
Waikuku Beach
Waikuku
Rangiora
Rangiora Aerodrome
Ravenswood development
Pegasus
Woodend
Southbrook
Woodend Beach
Pines Beach
Kaiapoi
Brooklands
Kainga
Chaneys Plantation
Belfast
Bottle Lake Forest Park
Spencer Park
SH 1
SH 72
SH 71
SH 74
Main North Road
Lineside Road
Ohoka Road
Tram Road
Skewbridge Road
Fawcetts Road
Upper Sefton Road
Ashley Street
Flaxton Road
Cust River
Christchurch City

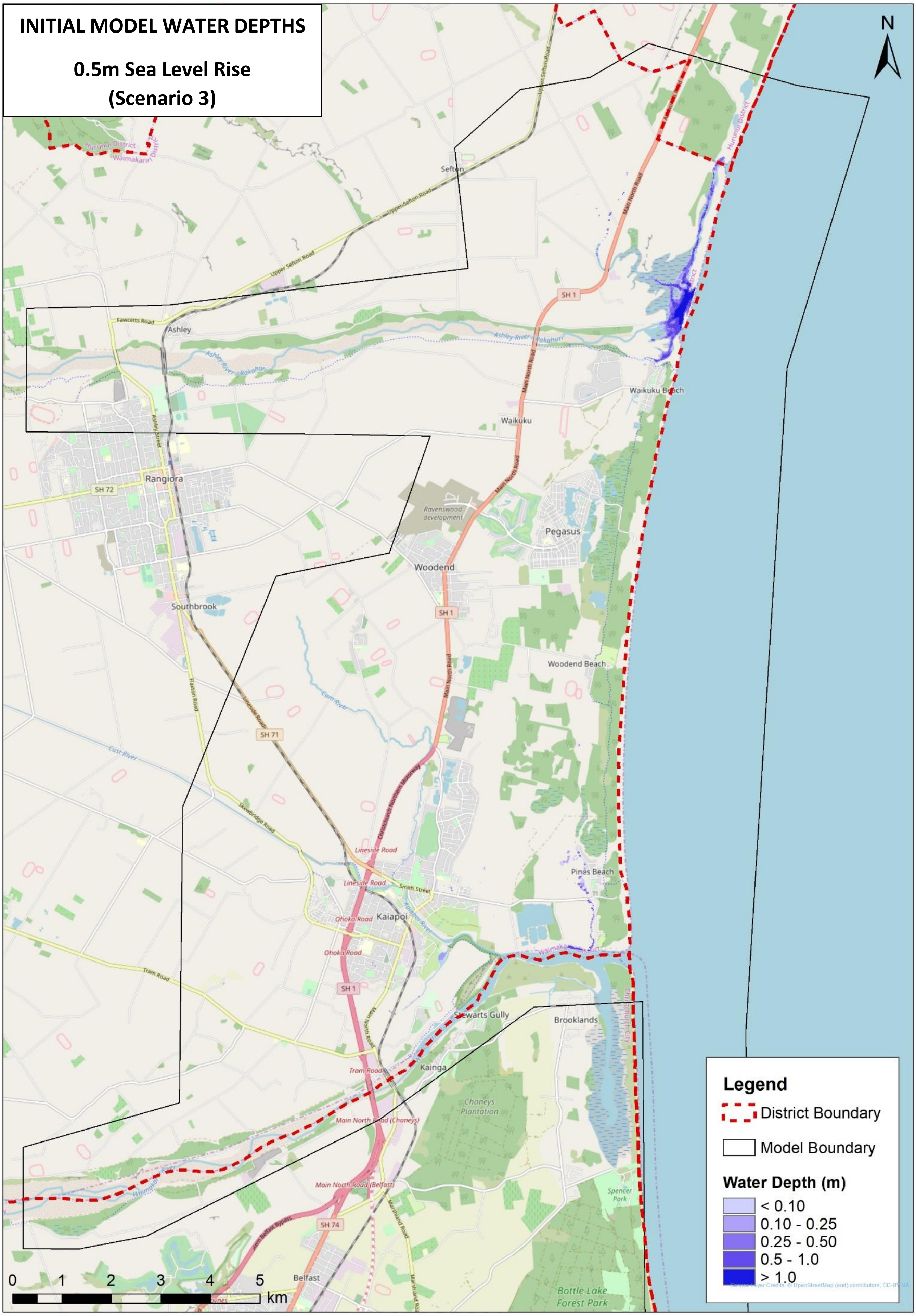

Coastal Inundation Modelling
Ashley River
2% AEP
Scenario 9
Sea Level Rise: 1.0m
Storm Tide: 2% AEP
River Flow: 0.2% AEP
N
Legend
Council Boundary
Model Boundary
River Corridor
Flow Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5 km
Sefton
Ashley
Rangiora
Southbrook
Waikuku
Waikuku Beach
Pegasus
Woodend
Woodend Beach
Pines Beach
Kaiapoi
Stewarts Gully
Brooklands
Kainga
Belfast
Chaneys Plantation
Bottle Lake Forest Park
Ravenswood development
SH 1
SH 71
SH 72
SH 74

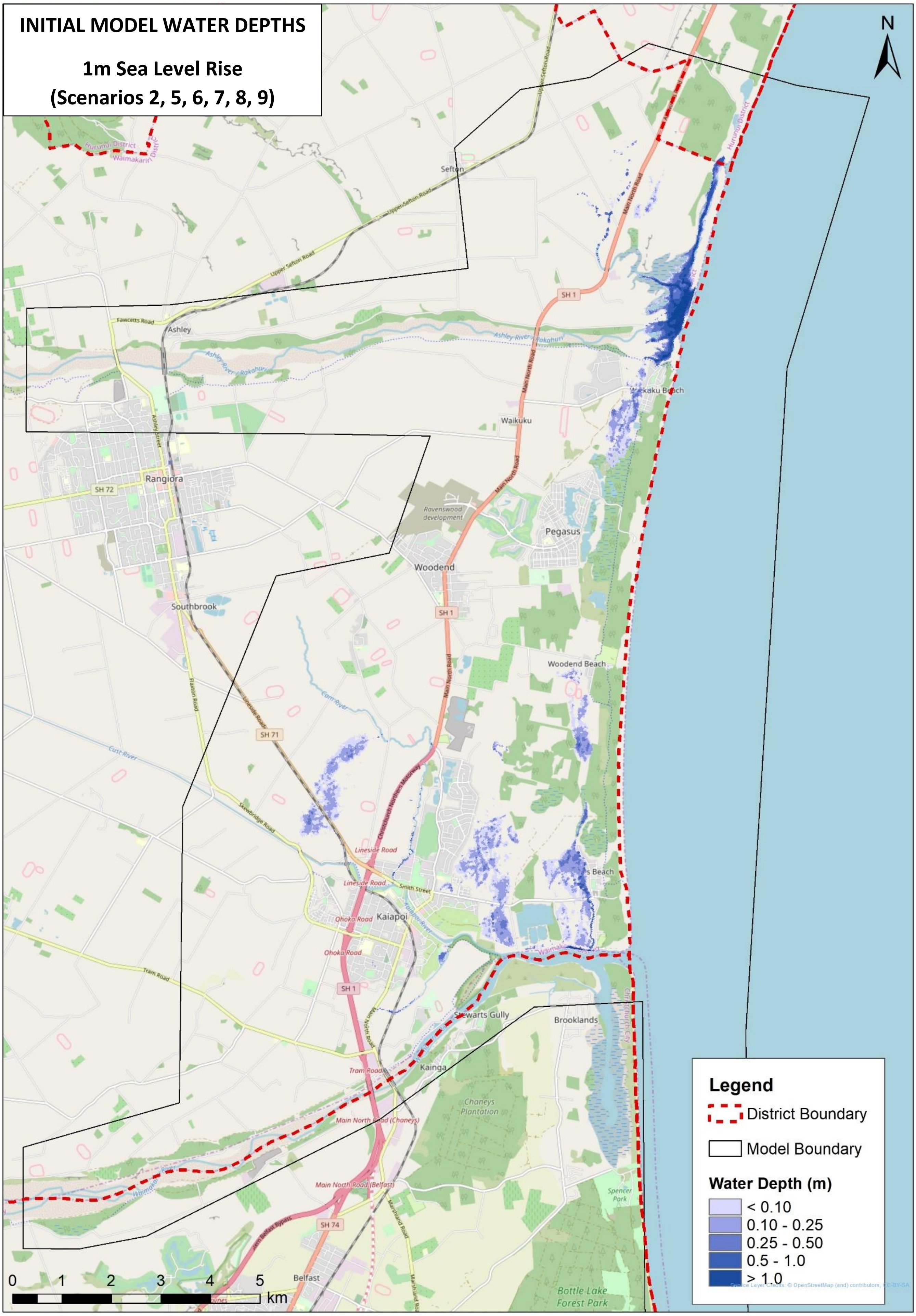
Appendix D. Initial model water depth maps

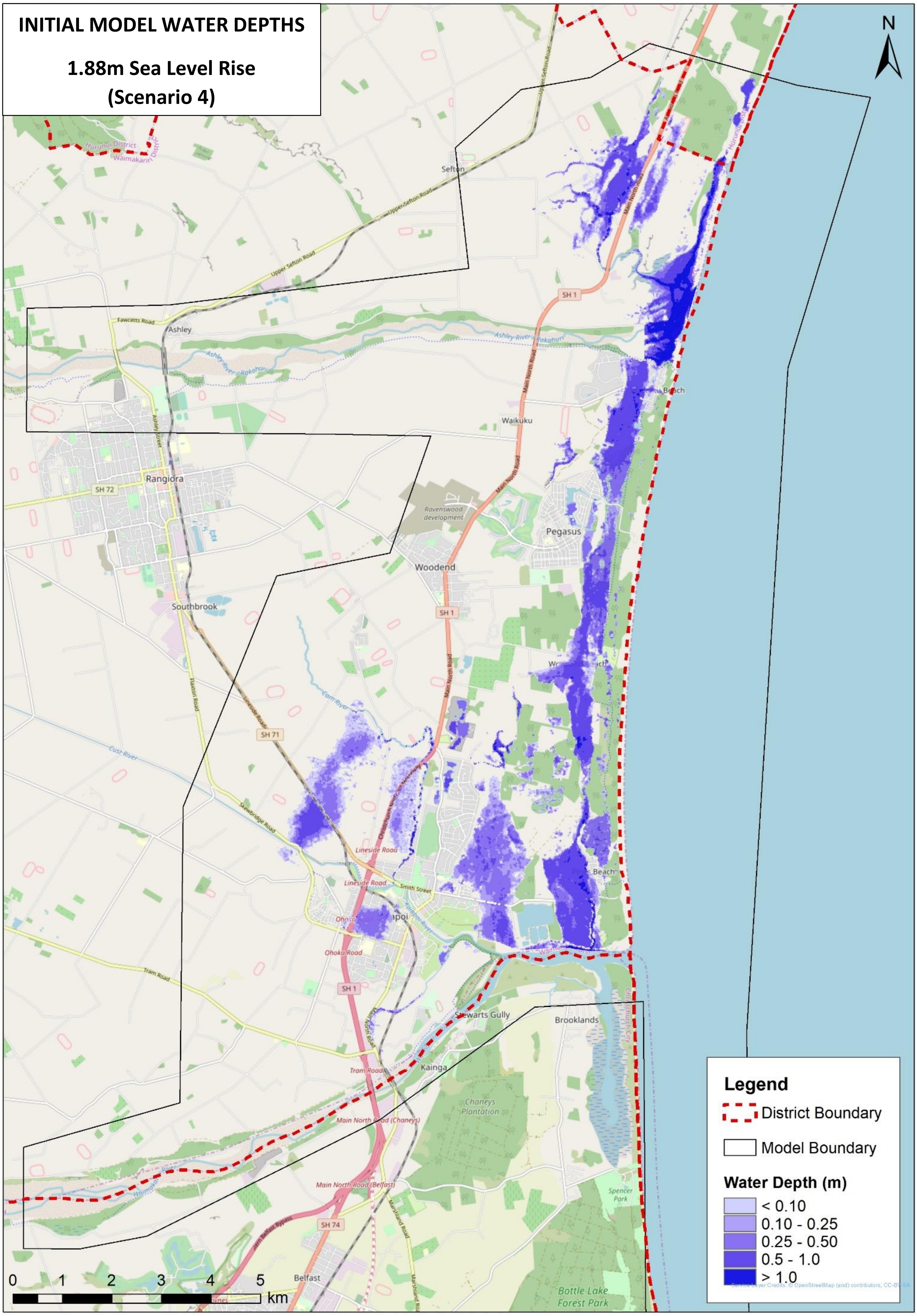
INITIAL MODEL WATER DEPTHS

0m Sea Level Rise (Scenario 1)




INITIAL MODEL WATER DEPTHS
0.5m Sea Level Rise
(Scenario 3)
N
Legend
District Boundary
Model Boundary
Water Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5 km
Sefton
Ashley
Rangiora
Southbrook
Waikuku
Waikuku Beach
Pegasus
Woodend
Woodend Beach
Pines Beach
Kaiapoi
Stewarts Gully
Brooklands
Kainga
Belfast
Ravenswood development
Chaneys Plantation
Bottle Lake Forest Park
Spencer Park
SH 1
SH 71
SH 72
SH 74
Fawcetts Road
Upper Sefton Road
Main North Road
Lineside Road
Smith Street
Ohoka Road
Tram Road
Flaxton Road
Skewbridge Road
Cust River
Cam River
Ashley River / Rakahuri
Main North Road (Chaneys)
Main North Road (Belfast)
Marshland Road


INITIAL MODEL WATER DEPTHS
1m Sea Level Rise
(Scenarios 2, 5, 6, 7, 8, 9)
Legend
District Boundary
Model Boundary
Water Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0
1
2
3
4
5
km
N
Sefton
Ashley
Rangiora
Southbrook
Waikuku
Pegasus
Woodend
Woodend Beach
Kaiapoi
Stewarts Gully
Brooklands
Kainga
Belfast
Chaneys Plantation
Bottle Lake Forest Park
Spencer Park
Ravenswood development
SH 1
SH 71
SH 72
SH 74
Main North Road
Lineside Road
Ohoka Road
Tram Road
Smith Street
Flaxton Road
Skewbridge Road
Upper Sefton Road
Fawcetts Road
Ashley River / Rakahuri
Cust River
Cam River
Main North Road (Chaneys)
Main North Road (Belfast)
Marshland Road


INITIAL MODEL WATER DEPTHS
1.88m Sea Level Rise
(Scenario 4)
N
Sefton
Ashley
Rangiora
Southbrook
Waikuku
Pegasus
Woodend
Ravenswood development
Stewarts Gully
Brooklands
Kainga
Chaneys Plantation
Belfast
Bottle Lake Forest Park
Spencer Park
SH 1
SH 71
SH 72
SH 74
Fawcetts Road
Upper Sefton Road
Main North Road
Lineside Road
Smith Street
Ohoka Road
Tram Road
Skewbridge Road
Flaxton Road
Main North Road (Chaneys)
Main North Road (Belfast)
Ashley River / Rakahuri
Cust River
Cam River
Legend
District Boundary
Model Boundary
Water Depth (m)
< 0.10
0.10 - 0.25
0.25 - 0.50
0.5 - 1.0
> 1.0
0 1 2 3 4 5 km