Environment Canterbury Regional Council
Kaunihera Taiao ki Waitaha

TECHNICAL REPORT Science Group

Kekerengu, Hāpuku and Oaro floodplain investigation

Report No. R19/04
ISBN 978-0-947511-49-4 (print)
ISBN 978-1-98-859300-5 (web)

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January 2019

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Summary

Background
The Kekerengu, Hāpuku and Oaro rivers, together with their floodplains, are located along the Kaikōura coastline. As part of the Kaikōura District Plan review, a better understanding of flooding from the larger local rivers was required. This modelling investigation has been undertaken to quantify the extent and depth of flooding for land adjacent to these rivers.

This modelling simulates flooding due to large, high-intensity rainfall events, rather than failure of any of the recent earthquake-induced landslide dams in the catchments (e.g. Hāpuku landslide dam).

What we did
This investigation used 2-dimensional (2D) hydraulic computer models to estimate flood extent, depths, and levels for 500 year Average Recurrence Interval (ARI) flood events. Climate change impacts were included, as well as sensitivity tests, to address the considerable uncertainty contained within the modelling results. Sources of uncertainty include, but are not limited to, inadequate hydrological data, no calibration data and the dynamic landscape.

What we found
For all three rivers modelled, 500 year ARI flood flows are largely contained within the river channel and land immediately adjacent to the rivers.

What does this mean?
Maps showing predicted 500 year ARI flood depths and extents, will assist land use planning within the area. The model results will allow appropriate floor levels for new buildings and extensions to be determined, and will assist in identifying high hazard flood areas The models developed as part of this investigation could also be used in the future to analyse existing or proposed flood protection works, and for emergency planning purposes.

15 November 2016 – Looking upstream along the Hāpuku River towards the railway bridge

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1 Introduction

As part of the Kaikōura District Plan review, a better understanding of flooding from larger local rivers, that drain mountainous coastal catchments, was required. This modelling investigation has been undertaken to quantify the extent and depth of flooding in the lower Kekerengu, Hāpuku and Oaro catchments (Figure 1-1).

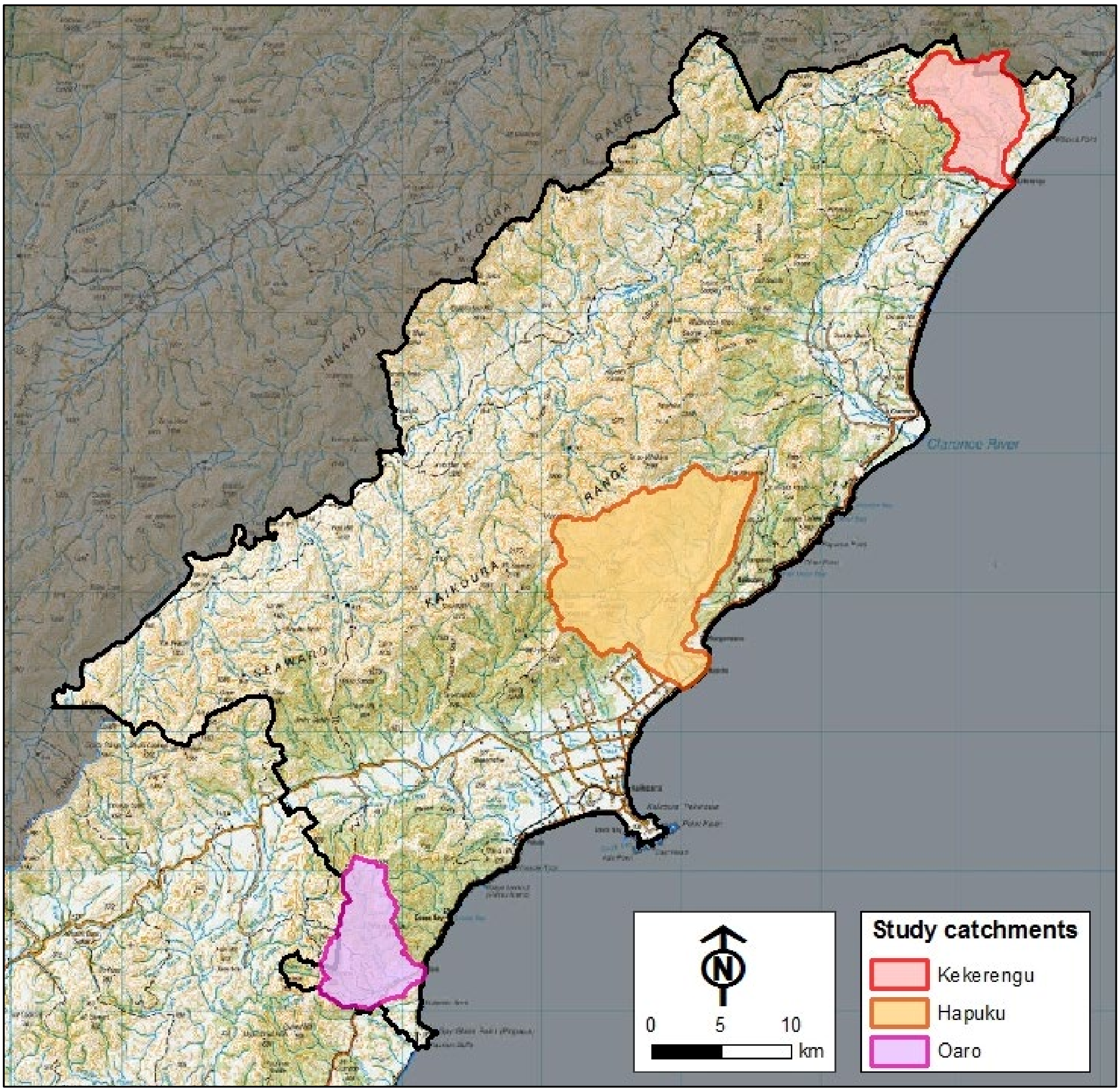


Figure 1-1: Location of the Kekerengu, Hāpuku and Oaro catchments

Detailed topographic data, and a 2D hydraulic computer model, were used to determine the likely extent and depth of flooding for 500 year ARI flood events.

This information will assist with land use planning (e.g. defining minimum floor levels and 'high hazard' areas) and emergency management planning (e.g. evacuation).

Chapter 11 of the Canterbury Regional Policy Statement (CRPS) includes policy which requires new buildings in areas subject to inundation to have floor levels above the 200 year ARI flood level. However, the current Kaikōura District Plan requires floor levels, in certain areas, to be above a 500 year ARI flood level. The CRPS also requires new development to be avoided in high hazard areas (see Glossary).

2 Background

2.1 Kekerengu River

The Kekerengu River flows into the sea ~50 km north-east of Kaikōura Township (Figure 1-1).

2.1.1 Kekerengu catchment

The Kekerengu River has a catchment area of around 48 km^2. This catchment extends upstream through hill country to Burnt Saddle, located immediately to the north of the Seaward Kaikoura Range (Figure 2-1). The main tributary is Ben More Stream, which enters the Kekerengu River ~300 m downstream of the Wiffens Road bridge. Near the coast, the river is incised into an older alluvial surface. Flood flows are contained by these elevated terraces that are adjacent to the floodplain.

Figure 2-1: Kekerengu catchment

The Kekerengu catchment has large areas of unstable weathered rock and surface material susceptible to slippage, when saturated during high-intensity rainfall events. Essenberg (2014) describes slips that occurred in April and June 2014, restricting road access within the valley. There was also speculation that the April 2014 slip may have temporarily blocked the river.

2.1.2 Flood protection works

Essenberg (2014) noted that local residents had observed considerable aggradation within the Kekerengu River (and Ben More Stream) over the last 50 years, with the river bed at the Wiffens Road bridges now around 3 m higher. Approximately 3 km further upstream, aggradation in the river bed was estimated to be around 6 m.

Following February 2008 flooding, Kaikōura District Council (KDC) carried out channel dishing in the river around the Wiffens Road bridges. Essenberg (2014) also noted that, at the time of the report, the council was undertaking significant works to raise the road immediately downstream of the Wiffens Road bridge, where the Kekerengu River was at approximately the same level as the road. Approximately 2800 m^3 of material was taken out of the Kekerengu River as part of this work (Figure 2-2).

Figure 2-2: The Kekerengu River – looking upstream toward the Wiffens Road bridge, 1 July 2014

The June 2014 work was completed under a 30 year resource consent (CRC100846) that was granted to KDC and local residents on 24 December 2009, to carry out river maintenance and erosion/flood control works.

The area of river bed covered by the resource consent extends along the Kekerengu River for ~550 m upstream and downstream of the Wiffens Road bridge. It also includes Ben More Stream from the Kekerengu River confluence to ~620 m upstream of the Wiffens Road bridge.

River works consist of:

a. The construction of bank protection structures.
b. The excavation of up to 3,000 m^3 of gravel, sand and other natural materials, in any consecutive 12 month period, for the purpose of maintaining flood carrying capacity.
c. The removal of vegetation from the active river bed to maintain the flood carrying capacity.
d. Planting vegetation, not including ‘Crack’ or ‘Grey’ willows, for flood and erosion control purposes.
e. The disturbance of the bed for the purposes of the works authorised by this consent.

2.2 Hāpuku River

The Hāpuku River and floodplain is located ~10 km north-east of Kaikōura township (Figure 1-1).

2.2.1 Hāpuku catchment

The Hāpuku River has a catchment area of 128 km^2 to SH1. The catchment extends upstream into the Seaward Kaikōura Range and includes the Puhi Puhi River (Figure 2-3). The Puhi Puhi River, with a catchment area approximately equal to half of the total Hāpuku catchment, enters the Hāpuku River ~2.7 km upstream from the coast.

Near the coast, the river is incised into an older Hāpuku alluvial fan surface. This has occurred as a result of continued uplift of the Seaward Kaikōura Range (CRC, 1999). Flood flows are expected to be contained by these elevated terraces that are adjacent to the floodplain. Figure 2-4 shows the Hāpuku River, looking downstream towards the SH1 road bridge.

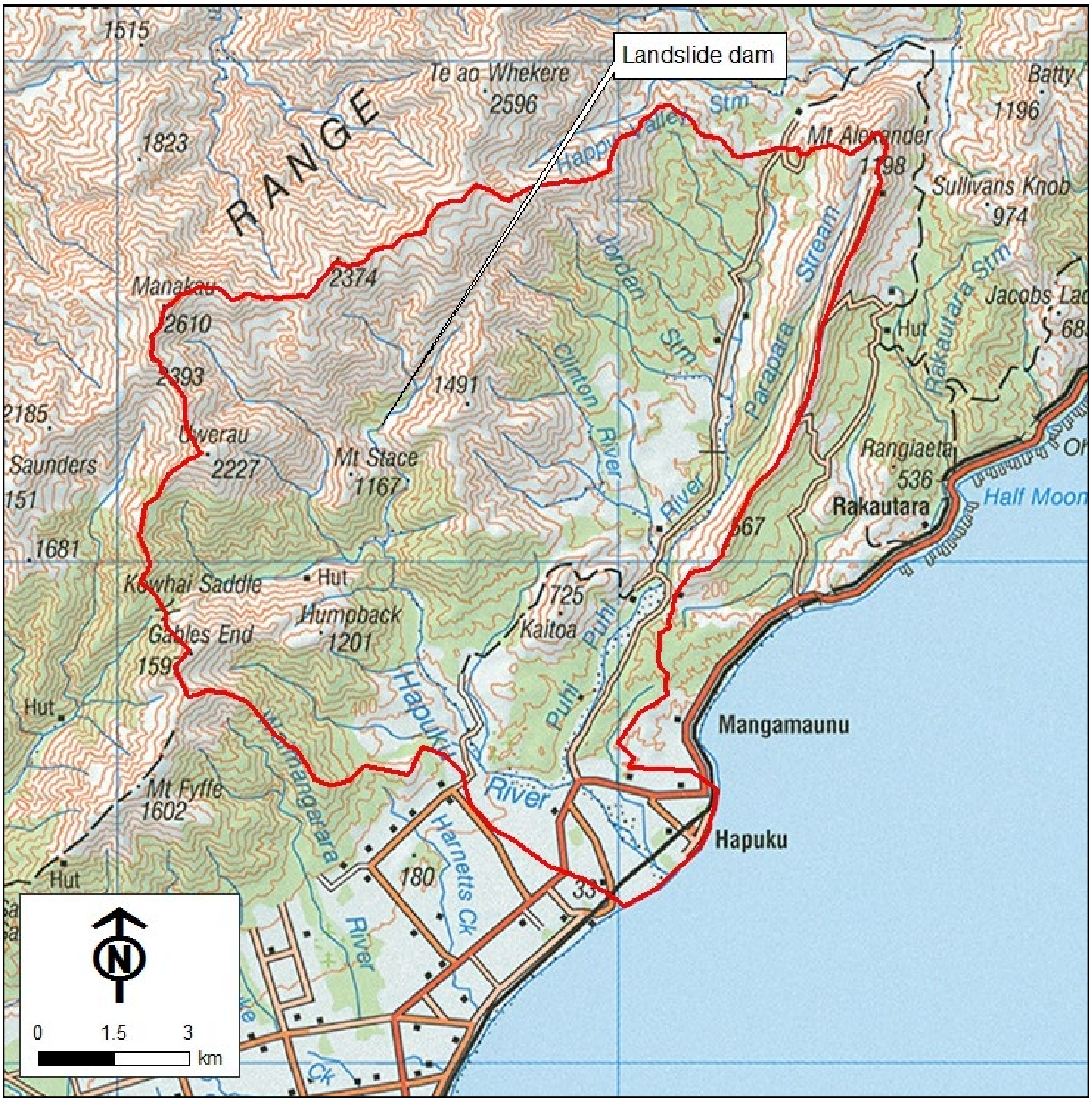


Figure 2-3: Hāpuku catchment

Figure 2-4: The Hāpuku River, looking downstream towards the SH1 road bridge (16 November 2016)

2.2.2 Hāpuku landslide dam

Soon after the 7.8 magnitude Kaikōura earthquake sequence, on 14 November 2016, a landslide dam was discovered on the Hāpuku River (Figure 2-3, Figure 2-5 to Figure 2-8). This dam (known as 'Hāpuku 740') formed when a landslide, from the north-western side of the valley, blocked the narrow river channel.

Because of the potential impact of the landslide dam breach on the downstream infrastructure, the New Zealand Transport Agency (NZTA) set up a water level site. This continuously monitored the landslide dam lake for sudden changes in water level.

Between 4 and 6 April 2017, rainfall associated with ex-Tropical Cyclone Debbie caused the Hāpuku landslide dam to overtop. This overtopping scoured a significant channel, which reduced the risk of major dam failure (Figure 2-9 and Figure 2-10).

On 19 September 2017, after a prolonged period of rain, the Hāpuku landslide dam overtopped again. This led to a rapid lowering of the lake level, by around 5 m. This caused downstream river levels to rise, although the surge of water travelling downstream was not observed.

Another significant drop in the lake level occurred between 7 November and 21 December 2018. At the time of this report, a smaller lake remained, and the outflow channel was expected to continue to degrade in a relatively controlled fashion.

2.2.3 Flood protection works

Following flood damage in May 1966, extensive river control works were put in place along the Hāpuku River. During a flood around 1983, some of the river control works on the northern bank of the Hāpuku River were washed out. Consequently, rock armouring is periodically replenished in this area (which includes small groyne structures).

Local river bed constrictions include the State Highway (SH1) Bridge and the downstream railway bridge. Upstream of the railway bridge, river control works reduce the width of the active river bed to protect adjacent farmland and the railway embankment. Boyds Echelon (a stopbank directing flows back towards the main channel and railway bridge) and the railway embankment also provide some protection for the river mouth settlement of Hāpuku (Figure 2-11). Figure 2-12 shows the constricted section of river at the SH1 road bridge.

Figure 2-5: Hāpuku landslide dam on 19 November 2016 – looking downstream along the lake

Figure 2-6: Hāpuku landslide dam on 21 November 2016 – looking north-west toward the dam

Figure 2-7: Hāpuku landslide dam on 12 December 2016 – looking at downstream face of dam

Figure 2-8: Hāpuku landslide dam on 24 January 2017 – looking downstream at the lake

Figure 2-9: Hāpuku landslide dam on 7 April 2017 – after significant scouring of channel

Figure 2-10: Hāpuku landslide dam on 7 April 2017 – looking at downstream face of landslide dam after significant scouring of channel

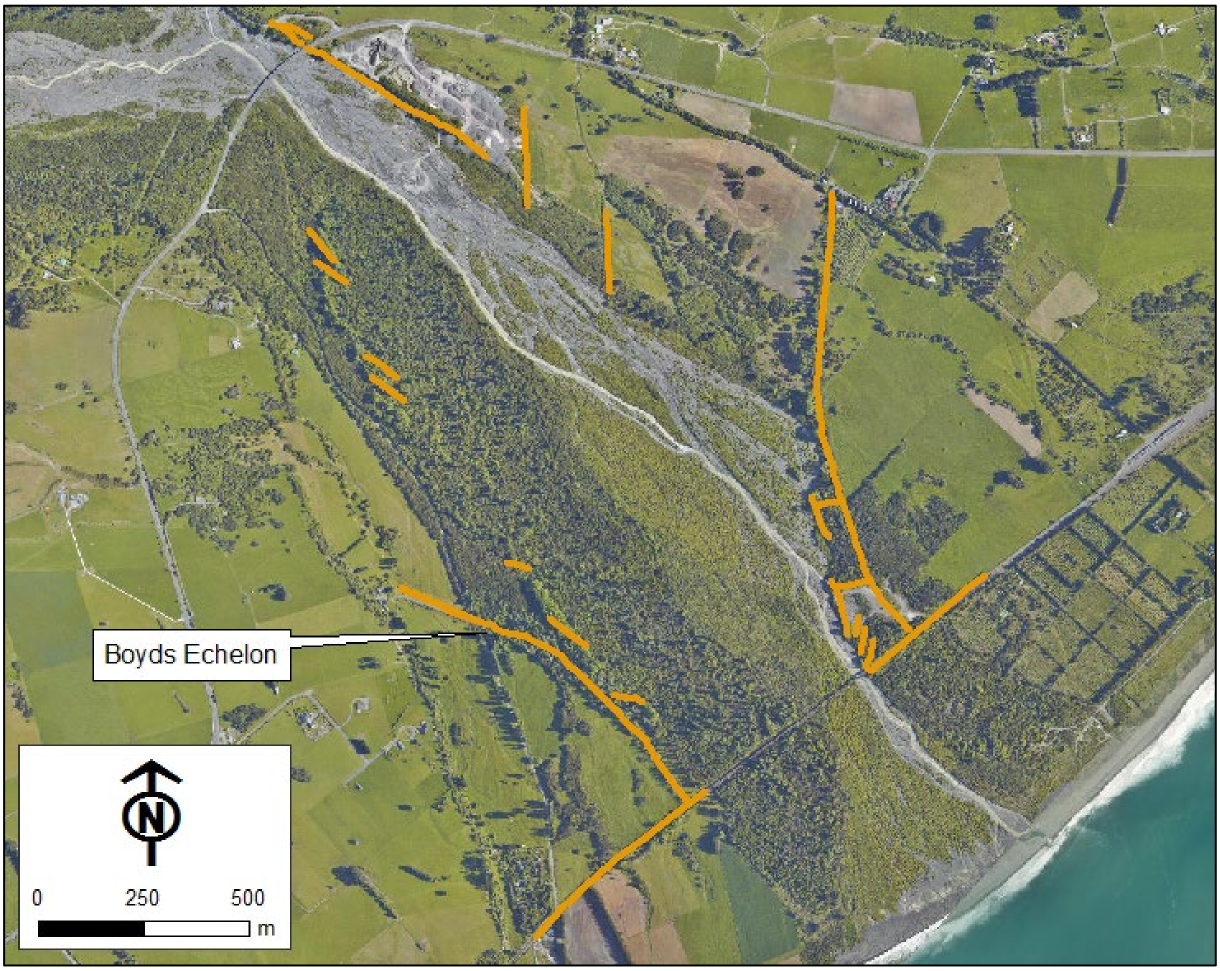


Figure 2-11: Hāpuku River flood protection works (SH1 to the sea)

Figure 2-12: Hāpuku River flood protection works, elevated terraces and SH1 road bridge (16 November 2016)

2.3 Oaro River

The Oaro River and floodplain is located ~19 km south-west of Kaikōura township (Figure 1-1).

2.3.1 Oaro catchment

The Oaro River has a catchment area of 46 km^2 at SH1. The catchment extends ~8 km inland, into the Hundalee Hills, with the main tributary, Te Moto Moto Stream, entering the Oaro River ~2 km upstream from the coast (Figure 2-13).

The small coastal settlement of Oaro is a Māori community where the land is overseen by Oaro M Incorporated.

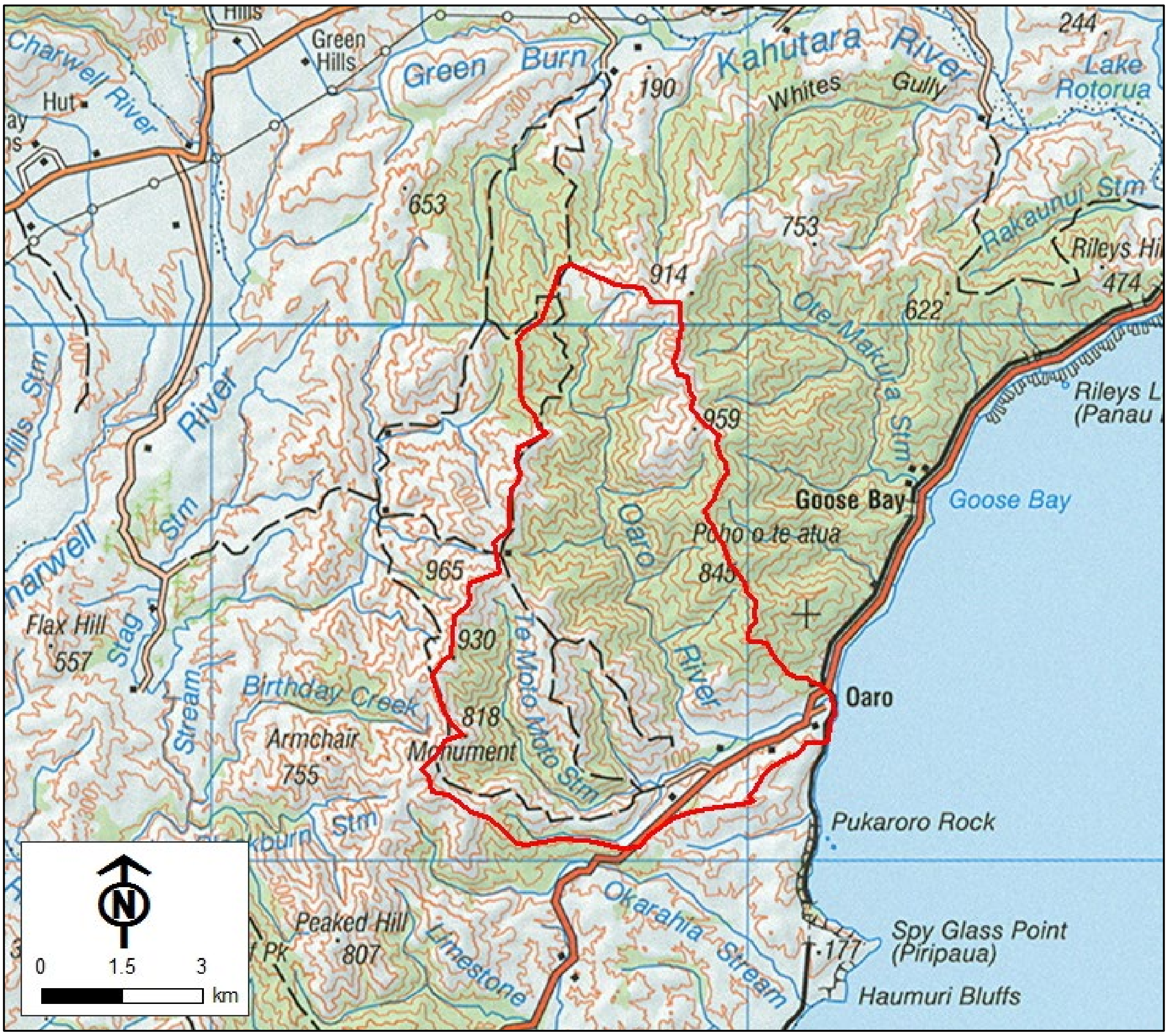


Figure 2-13: Oaro catchment

2.3.2 Flood protection works

Most of the properties in the Oaro settlement, are on elevated land. Figure 2-14 and Figure 2-15 show the Oaro River and upstream floodplain during a flood event in July 2008.

Erosion works were required after flooding in 2014, to protect properties closest to the river. Changes around the Oaro River mouth area in 2014 included:

- flood waters scoured out part of the railway access road which ran between the Oaro Settlement and the Oaro River;

- river engineering works were completed to place gravel and willows along the true right of the river to protect the Oaro Settlement from future floods;
- large areas of vegetation (native and exotic) were removed from within the river bed (either from flood flows or subsequent works by river engineers to keep the middle of the river bed clear of vegetation).

Figure 2-14: Oaro river mouth – 31 July 2008

Figure 2-15: Oaro River looking downstream towards SH1 Bridge – 31 July 2008

2.4 Historic flooding

High flows along the Kaikōura coastal rivers can occur when there is widespread, high-intensity, southerly tending rainfall events. Depressions formed from tropical cyclones can also produce extremely high-intensity rainfall along the Kaikōura coast. High flows can cause flooding (and sediment and landslide issues) for smaller streams and creeks that drain the steep range adjacent to the coastline.

Information regarding notable flood events along the Kaikōura coast are summarised below. A more detailed account of flooding in the Kaikōura area is provided in McPherson (1997).

Due to the dynamic nature of the heavily sediment-laden Kaikōura rivers and streams, there is limited information on flood flows. Measuring flood flows is a difficult process. Any flows quoted below (especially from older events), will be more indicative than precise measurements.

2.4.1 February 1868

This was the first documented flood event after European settlement in the area. It was described as '*the greatest flood ever recorded on the Marlborough coast'* by Sherrard (1966) in McPherson (1997, p 7). Mrs V Boyd described the flood event (as told by her mother) as several days of rain, followed by a cold southerly (with rain, hail and snow). On the 6th day a north-westerly rainfall event occurred. The snow and hail disappeared and the flooding described above occurred. She also was quoted in CRC (1999) as saying:

'Before the flood, the Waimangarara gorge was, for generations, built up with leaves, twigs and shingle, until the outlet was high up between the cliffs. When the flood started the shingle, it fanned out from Mt Fyffe Road till nearly across to Kincaid. The Hāpuku was doing its share there, and the waters met. As the flood waters increased, it tore everything out of the Gorge, down to the rocks. Then the shingle really "went to town". A bank, over thirty feet high on the Mt Fyffe side of the river, remains as proof to future generations of what the flood of 1868 did.'

2.4.2 May 1923

The May 1923 flood was a southerly rainfall event. Heavy rain also fell throughout the rest of Canterbury, and was torrential in North Canterbury (SCRCC, 1957). At the time, this was described as the worst flood since 1868. At Hāpuku approximately 610 mm of rain fell over 48 hours, and 690 mm over 5 days (SCRCC, 1957).

The Kahutara, Hāpuku, Kowhai and Clarence road and/or rail abutments washed out, and nearly every bridge in the County was damaged (McPherson, 1997).

2.4.3 November 1952

This was described as the worst southerly storm to hit the Kaikōura coast, and Marlborough, for many years. The Kowhai River broke its banks and flowed into Lyell Creek, flooding properties and part of the town (SCRCC, 1957).

2.4.4 January 1953

Prolonged, heavy rainfall along the east coast caused widespread flooding and closed the road along the Kaikōura coast. There was over 254 mm of rain recorded over 72 hours at Grange Road (McPherson, 1997). and in the Clarence Valley (SCRCC, 1957). The Hāpuku River rose 2 m at the railway bridge (SCRCC, 1957).

2.4.5 March 1975

High-intensity rainfall occurred along the Kaikōura coastal area due to the passage of Cyclone Alison. The Meteorological Office recorded 284 mm of rain and, in the Puhi Valley, a resident recorded 450 mm of rain (McPherson, 1997). The 6-hourly rainfall intensities exceeded 30 mm/hr in several locations (Bell, 1976). This caused widespread flooding and landslides – particularly along the Hāpuku River to Clarence River portion of the coastline.

As the high intensity rainfall was limited to the coastal area, the Clarence River did not flood. However, the Hāpuku River carried significant flows. Sediment accumulated in smaller coastal streams, and up to 5 m of sediment and debris was deposited where steep and confined smaller coastal streams flowed onto their 'flatter', and less confined, coastal floodplains (Bell, 1976).

2.4.6 March 1980

Like the Cyclone Alison storm, this event was caused by a depression that had formed from a tropical cyclone. Heavy rainfall was mainly confined to the coastal area, with 245 and 340 mm of rain recorded in Kaikōura and Luke Creek, respectively, over 24 hours (McPherson, 1997).

2.4.7 December 1993

This was an easterly rainfall event. A total of 147 mm of rain fell at Luke Creek in 10 hours, with hourly rainfall intensities of up to 20 mm/hour. In the Puhi Puhi River sub-catchment of the Hāpuku River, 300 mm of rain was recorded for this event (McPherson, 1997).

2.4.8 July 2008

Described as '*one of the worst storms in 30 years for North Canterbury*', there was extensive surface flooding in the Kaikōura District and Canterbury received more than twice the normal July rainfall. A farm in the Puhi Puhi Valley recorded 350 mm of rain in a 30-hour period during this event (https://hwe.niwa.co.nz/event/July_2008_New_Zealand_Severe_Storm, accessed April 2018).

Figure 2-14 and Figure 2-15 show the Oaro River during this flood event.

2.4.9 April 2014

Flooding was caused by the remnants of Cyclone Ita passing over the country. The worst affected area was the West Coast. In the Marlborough area heavy rain also caused flooding and landslips, with the worst damage in the Awatere Valley. Between Kaikōura and Picton, there were 24 slips and partial road blockages causing State Highway 1 to close.
(https://hwe.niwa.co.nz/event/April_2014_New_Zealand_Storm, accessed 5 April 2018).

2.4.10 February 2018

The remnants of Tropical Cyclone Gita passed across the Kaikōura area causing significant rainfall along parts of the Kaikōura coast. At Rosy Morn, 262 mm of rain fell in 12 hours.

2.5 Climate change

The impacts of future climate change on the Kaikōura rivers and floodplains are complex and, at present, not fully known. Some of the likely changes that are relevant to this flood modelling study include:

Air temperature
MfE (2016) presents projected changes in annual mean temperature for four scenarios of future radiative forcings, known as 'Representative Concentration Pathways (RCPs). These represent different pathways of human development and greenhouse gas emissions. For Canterbury, the average projected increases in annual mean temperature from a 1986-2005 baseline out to 2101-2120 range from 0.7 – 3.6 ºC.

Rainfall
In general, rainfall varies more significantly spatially and temporally than temperature. For the east coast of the South Island, summer is likely to become wetter, and winter and spring drier (MfE, 2016).

Rising air temperatures will also produce an increase in the intensity of extreme rainfalls since warmer air can contain up to ~8% more moisture for each 1ºC increase in temperature (Mullan *et al.,* 2008). On this basis, the projected increases to design rainfall events from a 1986-2005 baseline out to 2101-2120 under the four RCP scenarios range from 5.6 – 28.8%. A 2018 update (MfE, 2018) incorporates very extreme rainfall results from the "HIRDS" report (Carey-Smith *et al.,* 2018). This shows extreme rainfall increasing with climate change in all areas, with shorter duration events likely to have the more significant increases in rainfall.

In Kaikōura catchments, a mid-range increase in rainfall intensity would approximately double the frequency of the rainfall event. This means that, in 100 years from now, what is currently considered to be a 100 year ARI flood event may become a 50 year ARI flood event.

Sea level

MfE (2017) presents current sea level rise projections. For Canterbury, the projected increases in sea level from a 1986-2005 baseline out to 2120 range from 0.55 – 1.06 m (under the same RCP scenarios used for the temperature increase projections).

As the Kaikōura rivers have relatively steep gradients, any predicted increases in sea level will not have any impact on flood water levels upstream of the river mouths.

During the November 2016 earthquake sequence, ground levels along the Kaikōura coast generally uplifted relative to sea level. Any impacts on flooding due to sea level are therefore more likely to have decreased, rather than increased.

3 Methodology

Floodplain flows are often difficult to predict due to the multi-directional nature of the flows, the interaction between main river channel and floodplain flows, and the difficulty in identifying flow paths where ground levels vary gradually.

This floodplain modelling investigation used a combined 1-dimensional (1D) and 2-dimensional (2D) hydraulic modelling package (Mike Flood) to simulate flood events and determine river and floodplain water levels, depths, flood extent, flow patterns, and flow velocities. The methodology included:

- Compilation of historic flood event information (Section 2.4)
- Estimation of flood hydrology/design flows (Section 3.1)
- Estimation of Kaikoura sea levels and storm tides (Section 3.2)
- Construction of computational hydraulic models (Section 3.3)
- Calibration of the hydraulic models (Section 3.4)
- Modelling of design flood events (Section 3.5)
- Sensitivity analysis (Section 3.6)

3.1 Flood hydrology

The primary focus of this investigation was to determine the extent and depth of flooding on the Kekerengu, Hāpuku and Oaro floodplains for a 500 year ARI flood event.

As there are no flow records for these rivers, design flows derived from Tonkin and Taylor (2017) have been used. The methodology used to derive the design flows is described in detail in Tonkin and Taylor (2017), and the 500 year ARI design flood flows are summarised in Table 3-1.

Tonkin & Taylor (2017) did not calculate a mean annual flood factor (Q_{MAF}) or a 100 year ARI growth factor (q_{100}) for the Kekerengu River. Instead, the Hāpuku River values of 2.0 and 4.0, respectively, have been used to calculate the design flows. To account for climate change (to 2120), 25% of additional flow has been added to the 500 year ARI flows. This percentage increase is consistent with the higher range RCP air temperature projections presented in MfE (2016). A 2018 update (MfE, 2018) incorporates very extreme rainfall results from the "HIRDS" report (Carey-Smith *et al.,* 2018). This shows extreme rainfall increasing with climate change in all areas, with shorter duration events likely to have the more significant increases in rainfall. The 25% flow increase used in this study, to account for climate change to 2120, may therefore be closer to the mid-range RCP air temperature projections.

Table 3-1: 500 year design flows (derived using Tonkin and Taylor, 2017)

	Catchment area (km^2)	Flow (m^3/sec) - no climate change	Flow (m^3/sec) - with climate change
Kekerengu River			
Kekerengu River	34	250	313
Ben More Stream	14	110	138
Hapuku River			
Hapuku River	64	440	550
Puhi Puhi Stream	64	440	550
Oaro River			
Oaro River	30	170	213
Te Moto Moto	16	95	119

3.2 Kaikōura sea level and storm tides

Storm tides are a combination of tide, storm surge, seasonal cycles, and long-term fluctuations. These are outlined below.

3.2.1 Tide

Kaikōura sea level data are available on the Land Information New Zealand (LINZ) website (http://www.linz.govt.nz/sea/tides/sea-level-data/sea-level-data-downloads, accessed 14 February 2017). The 'data zero' value is approximately -2.95 m NZVD2016. From the LINZ website data, a relatively high perigean tide at Kaikōura (e.g. 11 January 2016) would be around +1.26 m NZVD2016.

3.2.2 Storm surge

Storm surge occurs when low barometric pressure (from low atmospheric weather systems) and strong winds temporarily elevate sea levels. Storm surge is limited to increases in sea level of less than 1 m for the New Zealand open coast (Bell, 2010). This does not include short lived localised wave run up effects.

3.2.3 Seasonal to long term fluctuations

Sea level can also fluctuate over longer periods of time due to seasonal cycles and El Niño-Southern Oscillation (ENSO) fluctuations, which can also increase sea level by 0.1 to 0.2 m (Bell *et al.,* 2000).

3.2.4 Storm tide

Analyses of existing sea level records around New Zealand has shown that the higher recorded storm tides tend to occur during a perigean tide combined with relatively small storm surges of 0.1 to 0.3 m (Bell, 2010).

For Kaikōura, a 500 year ARI flood event is likely to occur during a low pressure weather system. The high tide level of 1.26 m NZVD2016 is therefore likely to be combined with a storm surge. For this study, a storm surge of 0.4 m and a 0.1 m seasonal/ENSO water level fluctuation has been adopted to produce a maximum sea level of ~1.75 m NZVD2016.

This level has not been derived using a joint probability analysis of stream flows and sea level. However, it is considered appropriate for this study since overly conservative values have not been chosen for any of the components of the storm tide.

For all model runs, sea level is set to a constant level to simulate high tide occurring at the same time as the peak stream flow reaching the river mouth.

3.3 Hydraulic model construction

The Mike Flood modelling package combined 1-dimensional (1D) modelling for the coastal boundary, with 2-dimensional (2D) modelling for the Kekerengu, Hāpuku and Oaro river systems. The 1D and 2D models were linked along the coastal boundary, to allow flood water to move freely between the river/floodplain and the sea.

More detailed descriptions of the model are given below.

3.3.1 1D 'channel' boundary

A 1D model of the coastal boundary is included in each model to represent the sea as a large, wide channel. The northern end of each coastal 'channel' is closed, while the southern end has the specified water level. A Manning's n value of 0.06 has been used for the coastal 'channel' bed resistance.

3.3.2 2D floodplain model

The 2D component of the models included:

- Kekerengu River: Coast to ~600 m upstream of the Ben More Stream confluence.

- Hāpuku River: Coast to ~2.4 km upstream of the Puhi Puhi River confluence.
- Oaro River: Coast to ~1.2 km upstream of the Te Moto Moto Stream confluence.

The floodplain topography and roughness used in the models are described below.

Floodplain topography

To realistically model floodplain flows with any degree of accuracy, good topographic data (including features such as banks, terraces, overland flow channels, roads and railway embankments) are essential. For this study, high resolution topographic data were obtained from an airborne LiDAR survey (aerial laser scanning) flown between 3 December 2016 and 6 January 2017 by AAM NZ Limited. This work was commissioned by Land Information New Zealand (LINZ), after the 14 November Kaikōura earthquake sequence. The detail provided by LiDAR data can be seen in Figure 3-1.

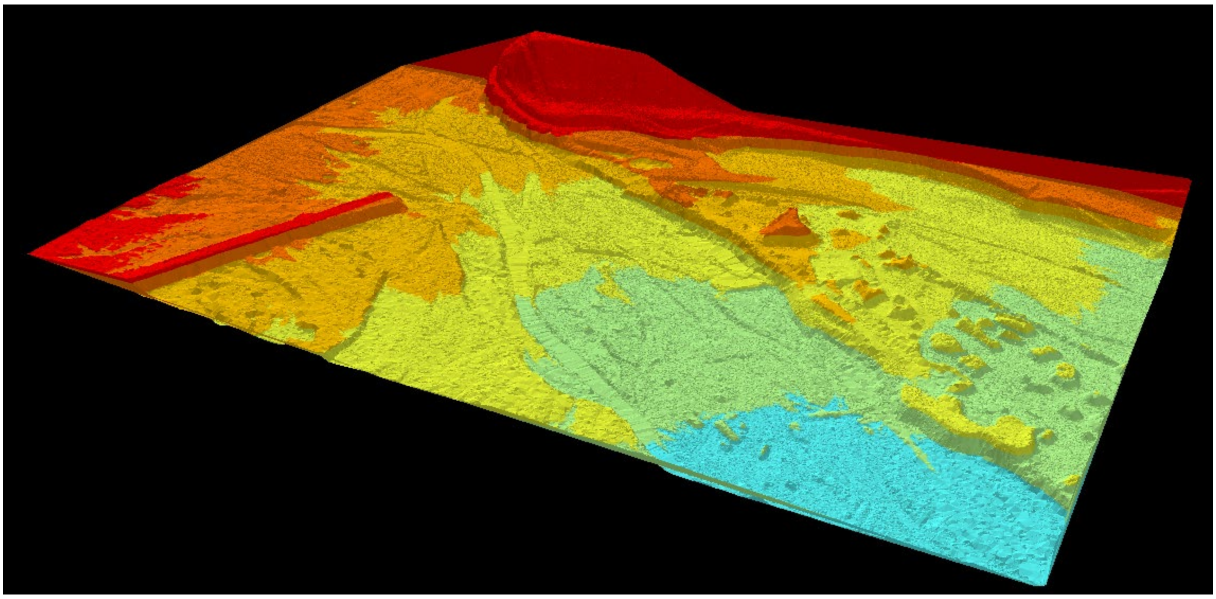


Figure 3-1: 3D image of the LiDAR data showing the Hāpuku River SH1 road bridge approach on the left (with vertical scale exaggerated by a factor of 2)

Water levels and flows on the floodplain are resolved on a rectangular grid. The size of the grid is based on the level of detail required, model stability, and computational efficiency (i.e. computer capacity and speed). For these models the 1 m digital elevation model (DEM), generated using the 2016/2017 LiDAR data, has been used to produce grids of 5 x 5 m cells to represent the floodplain topography.

A 5 m grid was chosen to allow for a reasonable degree of topographic detail while keeping the model run time reasonable. A 5 m grid can have some limitations when attempting to represent small features such as drains, but this is not an issue for this investigation.

The LiDAR data will also not penetrate water surfaces. This means any water in the rivers at the time of the survey will be recorded as the river bed level. As this investigation models large flood flows, the loss of channel capacity (due to the surveyed water level being represented as the bed level) is considered insignificant for the relatively low river flows present during the 2016/2017 LiDAR survey.

The LiDAR data were provided using the NZVD2016 vertical datum.

Floodplain roughness (surface resistance)

Floodplain flows, and depths, are influenced by the hydraulic resistance of the ground cover and other obstructions, such as structures and trees on the floodplain. Resistance values (i.e. Manning's n values) were assigned to the various surfaces of the floodplain by interpretation of aerial imagery.

A Manning's n value of 0.04 was used for the gravel river bed and floodplain, and 0.10 for more heavily vegetated berm areas. Figure 3-2 to Figure 3-4 show the floodplain roughness values for the Kekerengu, Hāpuku and Oaro rivers, respectively. Allowances have been made in some locations for river channel vegetation to be 'stripped' from the bed during flood flows. This has mainly been limited to scrub and small clusters of trees within the active gravel-bed river channel.

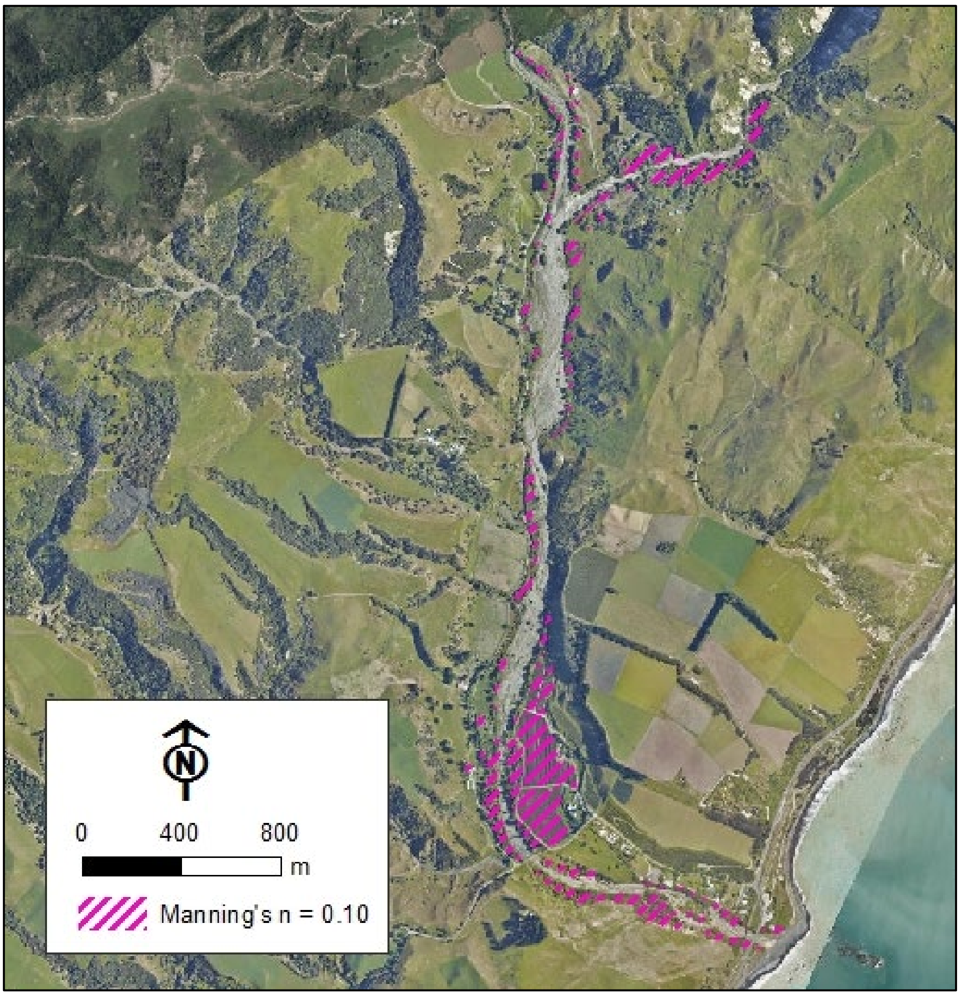


Figure 3-2: Kekerengu River floodplain roughness

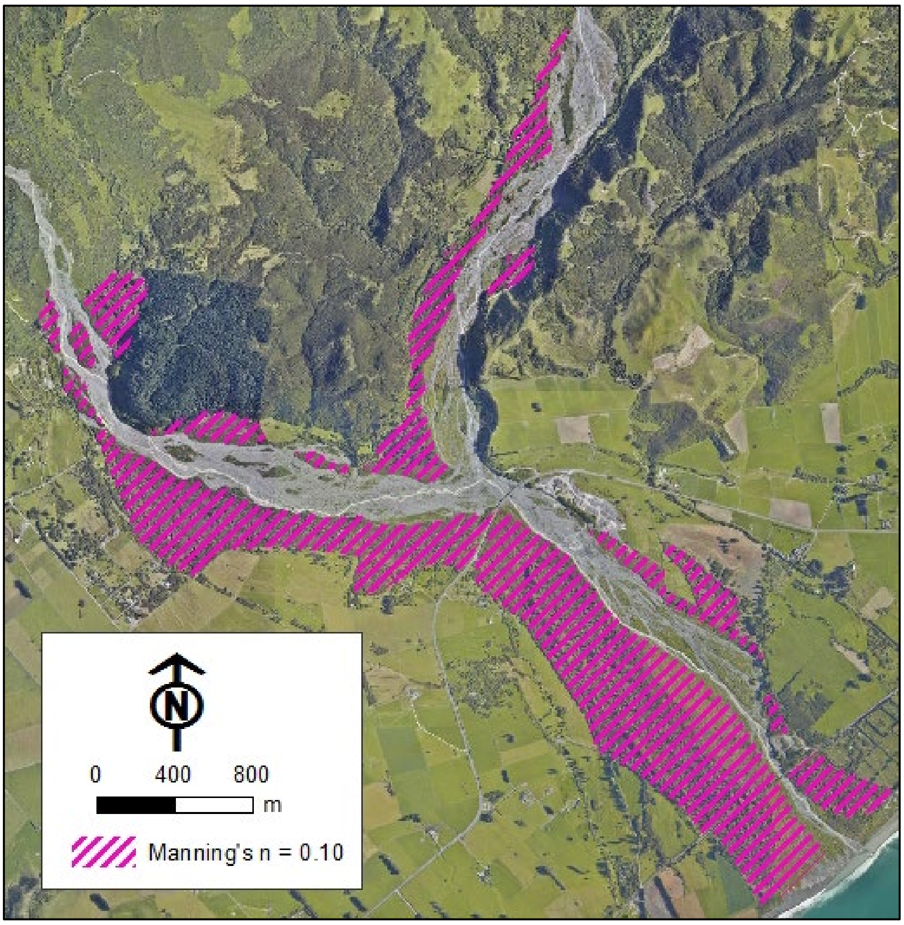


Figure 3-3: Hāpuku River floodplain roughness

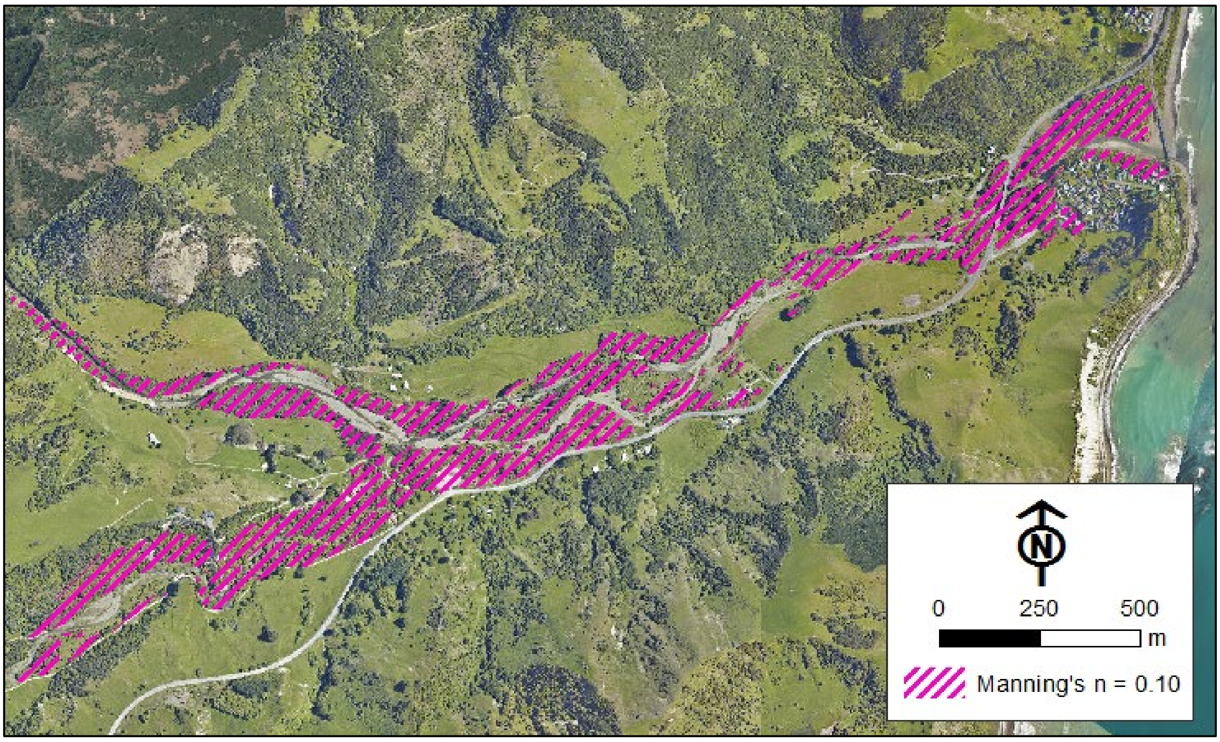


Figure 3-4: Oaro River floodplain roughness

Bridges

No bridges have been included in the rivers modelled for this investigation. The following assumptions have been made:

1. Railway and SH1 bridges generally have good clearance and are either close to the coast, or in an inland area where the river channel is wide. These bridges tend to have wide spans between piers, and significant blockages are considered less likely. For these bridges, only very localised increases in flood water levels would be expected immediately upstream of the bridge.

2. Where there are smaller upstream bridges (e.g. on the Kekerengu River at the Wiffens and Kekerengu Road bridges), the bridges usually have considerably less clearance. It is therefore more likely that the bridge will become blocked and/or considerable scour will occur around the bridge abutments. These smaller bridges often have a large portion of the river flow already bypassing the main river channel during more extreme, large flood events such as a 500 year ARI flood event. This investigation assumes that smaller bridges will either fail structurally, or localised increases in water level (due to blockages) will be relatively insignificant due to the large portion of the flood flow already being diverted around the bridge abutments either onto the floodplain or back into the main river channel. *It is difficult to predict exactly where river flows will be diverted by channel aggradation and scour.*

3.4 Model calibration

To provide confidence in model predictions, it is desirable to calibrate the model with historical flood events, to ensure that the models are behaving correctly.

For the Kekerengu, Hāpuku, and Oaro rivers, it has not been possible to obtain a sufficient number of flood photographs or measured flows/water levels. Changes in the stream and floodplain levels, post-2016 Kaikōura earthquake sequence, would also make any previous flood observations less helpful, as ground levels have changed. It has therefore not been possible to calibrate this model. Instead sensitivity model runs have been completed to quantify the sensitivity of the model to model parameters.

3.5 Modelling of design flood events

Flood events with an average recurrence interval (ARI) of 500 years have been modelled for land use planning and flood mitigation purposes.

The design events were run with a flow that ramped up linearly to the peak flow. All model simulations were based on either a 0.5 or 1 second time step to ensure stability, and results were saved every 15 minutes until water levels along the river system reached their maximums. Computer run times for each simulation were around 1 to 7 hours.

3.5.1 Design flows

Design flows, as specified in Table 3-1, were used to simulate 500 year ARI floods along the main branches of each river.

3.5.2 Downstream sea boundary water level

A constant water level of 1.75 m NZVD2016 was modelled to represent the ‘status quo’, for a relatively high tide, combined with storm surge and seasonal/ENSO fluctuations (see Section 3.2).

To account for climate change, in the design flood events (to 2120), the sea level has been increased to 2.75 m NZVD2016.

3.5.3 Design flood events

The 500 year ARI design flood events were modelled both with, and without, climate change (i.e. with and without 25% extra flow and 1 m of sea level rise). Maximum water depths are shown for the Kekerengu River (Figure 3-5 and Figure 3-6), Hāpuku River (Figure 3-7 and Figure 3-8) and Oaro River (Figure 3-9 and Figure 3-10).

Kekerengu River

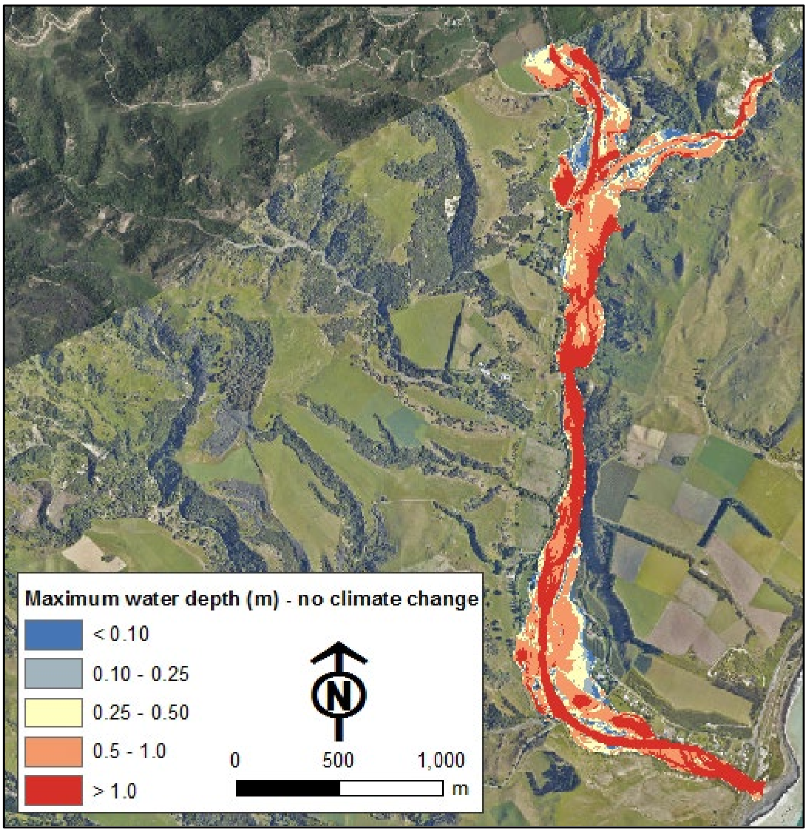


Figure 3-5: 500 year ARI Kekerengu floodplain maximum water depths (no climate change)

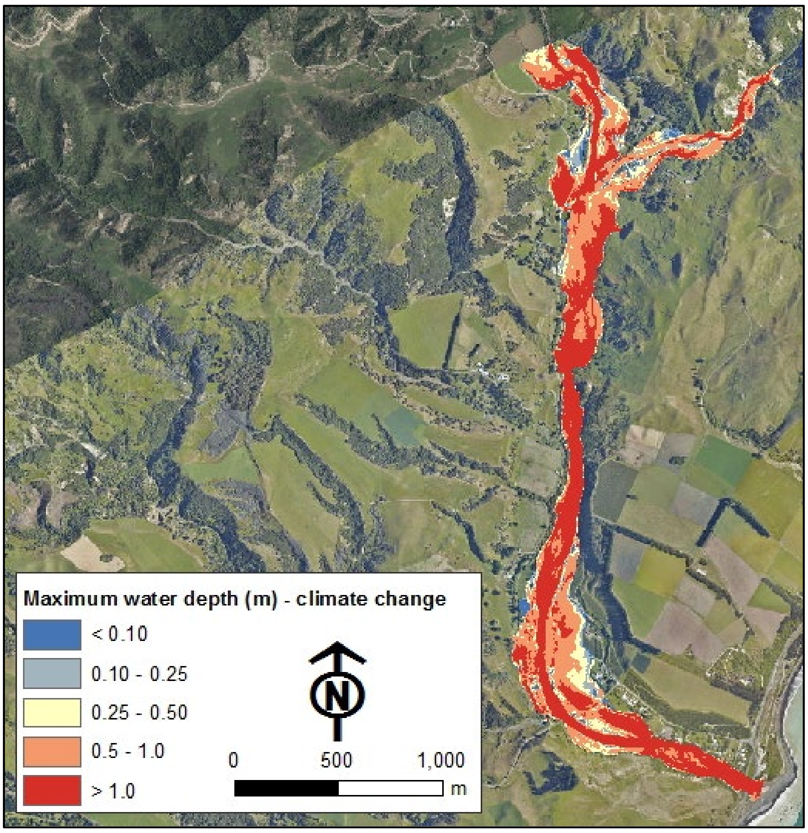


Figure 3-6: 500 year ARI Kekerengu floodplain maximum water depths (with climate change)

Hāpuku River

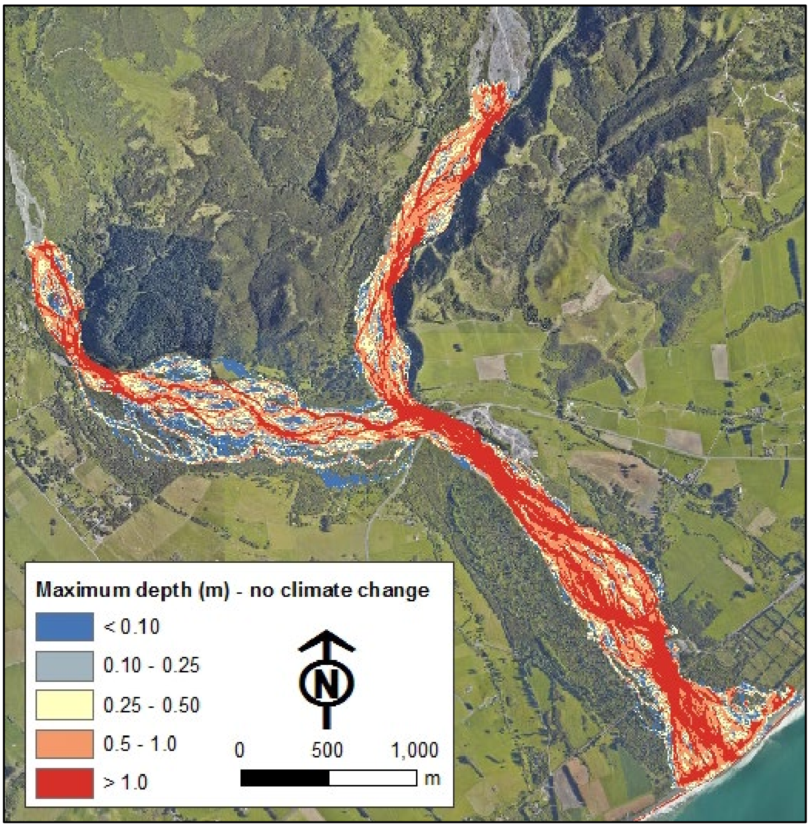


Figure 3-7: 500 year ARI Hāpuku floodplain maximum water depths (no climate change)

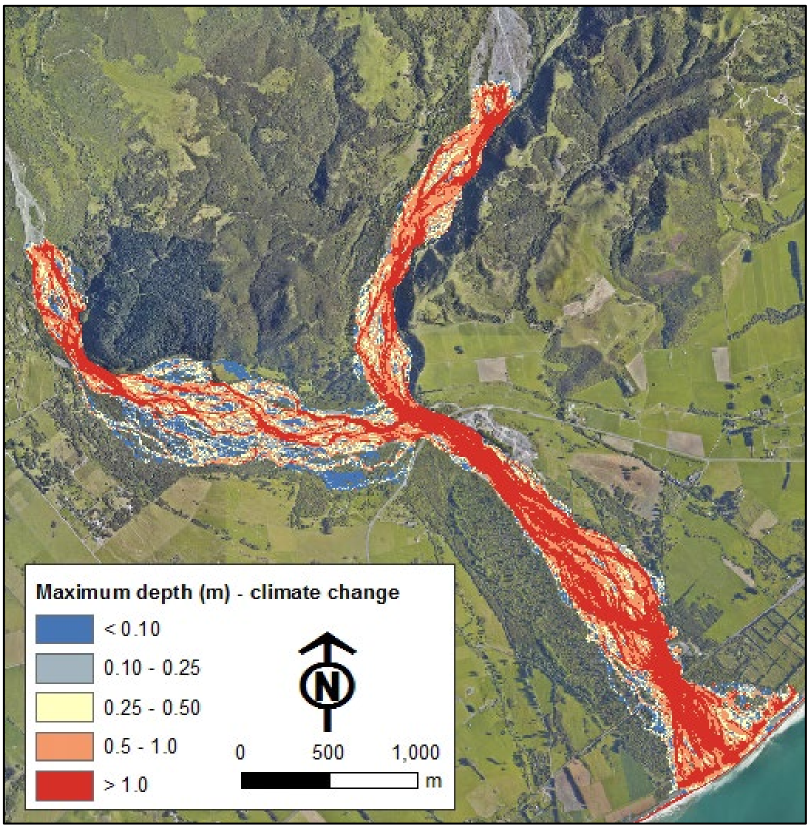


Figure 3-8: 500 year ARI Hāpuku floodplain maximum water depths (with climate change)

Oaro River

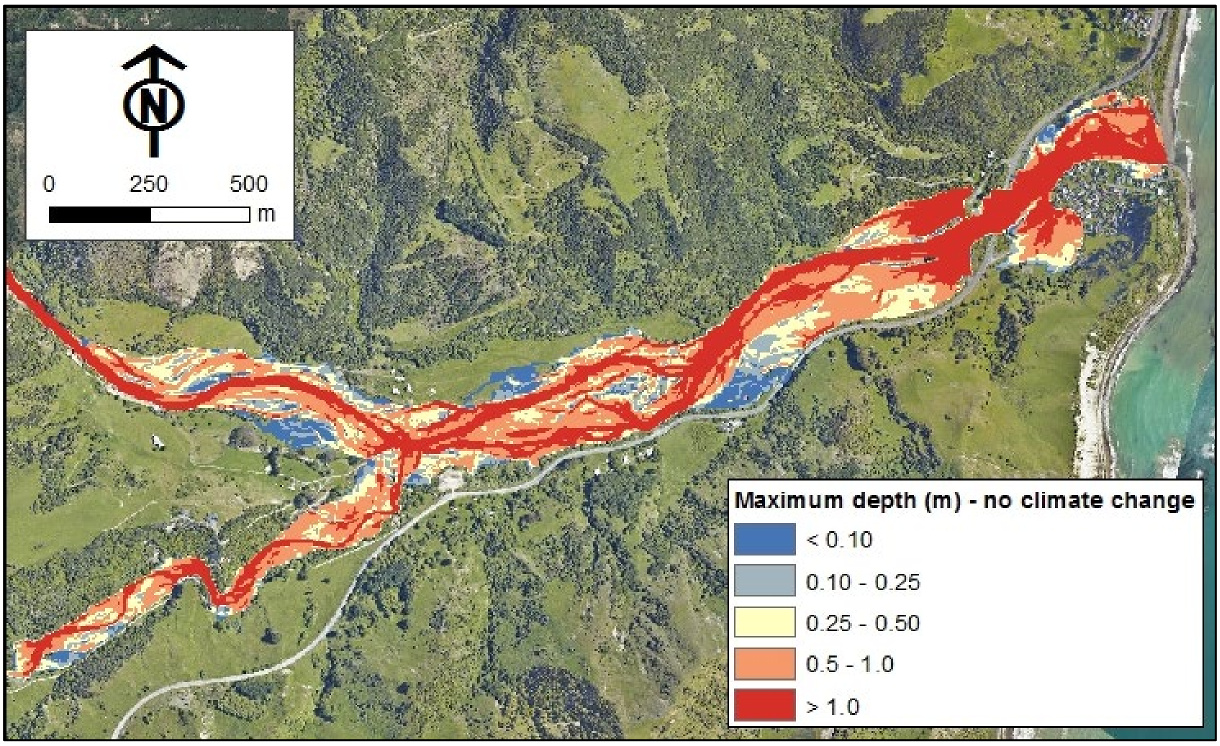


Figure 3-9: 500 year ARI Oaro floodplain maximum water depths (no climate change)

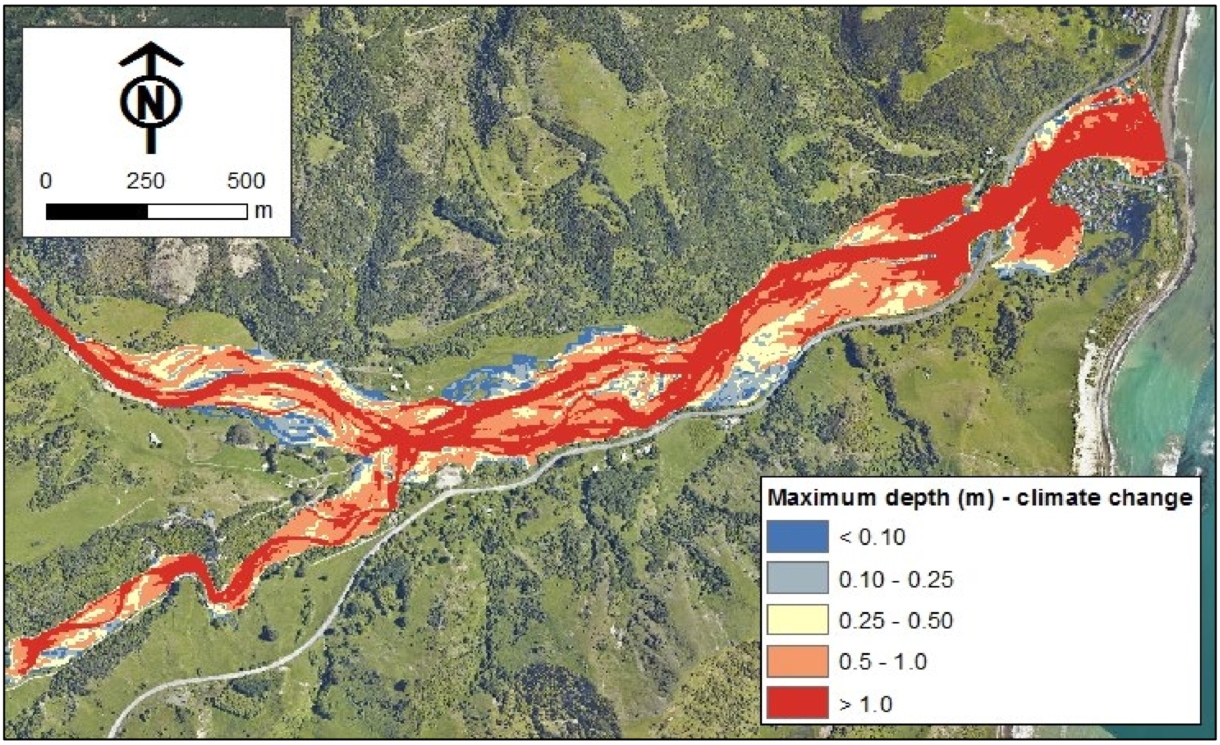


Figure 3-10: 500 year ARI Oaro floodplain maximum water depths (with climate change)

3.6 Model sensitivity analyses

As the models were not able to be calibrated, sensitivity tests were undertaken to determine how sensitive the model results were to the main model parameters and assumptions. The sensitivity tests are described below.

3.6.1 Floodplain and river roughness

Floodplain roughness values (Manning's n) used to represent the rivers and floodplains are described in Section 3.3.2. Manning's n values were increased for the 500 year ARI no climate change scenario, with the channel and berm Manning's n values increased from 0.04 to 0.045, and the heavily vegetated areas increased from 0.10 to 0.12. This enabled the impact of floodplain roughness on maximum floodplain water depths and extent to be examined.

Figure 3-11 shows the increases in maximum water level when Manning's n roughness is increased for the Kekerengu, Hāpuku and Oaro rivers. The increased areal extent of flooding for each river is summarised in Table 3-2.

Table 3-2: Increase in areal extent of flooding when channel and floodplain roughness is increased

	Increase in flooded area (hectares)	Increase in flooded area (%)
Kekerengu River	0.7	0.7
Hapuku River	4.2	1.9
Oaro River	1.4	2.1

3.6.2 No climate change

Climate change is generally expected to increase peak runoff, as described in Section 2.5. If peak flows do not increased by 25%, and sea levels do not rise by 1 m, Figure 3-12 illustrates that all three rivers would have maximum 500 year ARI flood levels up to ~0.3 m lower than the predicted water levels. Table 3-3 summarises the decrease in areal extent of flooding for each river.

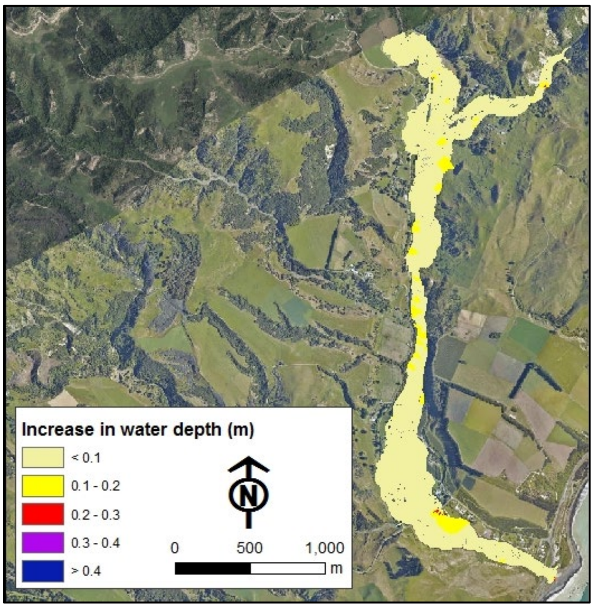
Table 3-3: Decrease in areal extent of flooding when climate change is excluded

	Decrease in flooded area (hectares)	Decrease in flooded area (%)
Kekerengu River	2.0	2.1
Hapuku River	16.3	6.7
Oaro River	3.3	4.7

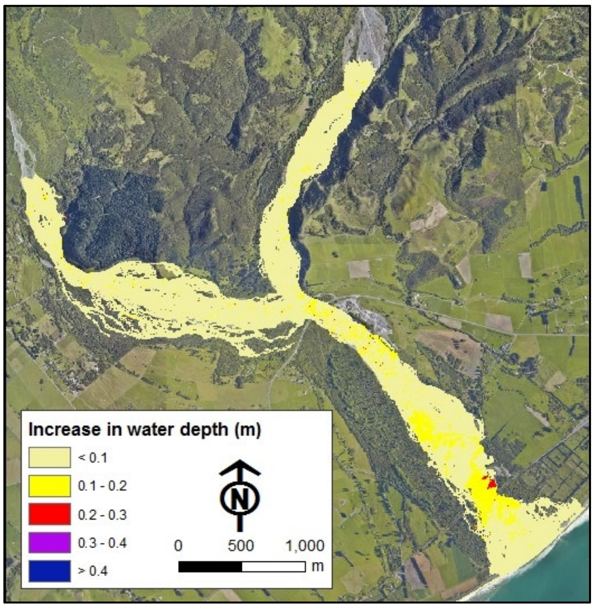
3.6.3 Summary

Within each of the rivers, changes in maximum water depths appear to be most significant where there are 'constrictions' in the river channel (i.e. where the river is most confined). For example, upstream of the Oaro SH1 road bridge, and in the Oaro M settlement ponding area. The Oaro river mouth is also sensitive to sea level rise.

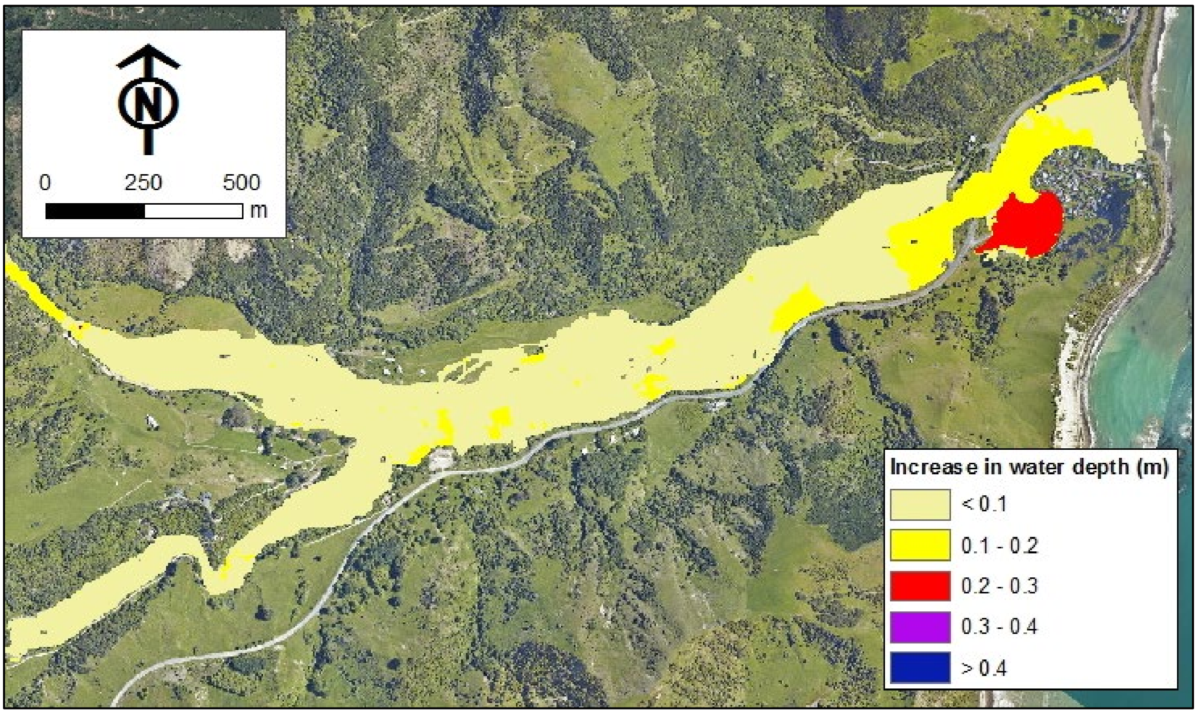
The Kekerengu River is bounded by high banks near the river mouth, as well as further upstream. Because the river is relatively confined, the extent of flooding is not particularly sensitive to changes in channel and floodplain roughness, and climate change.



(a) Kekerengu River

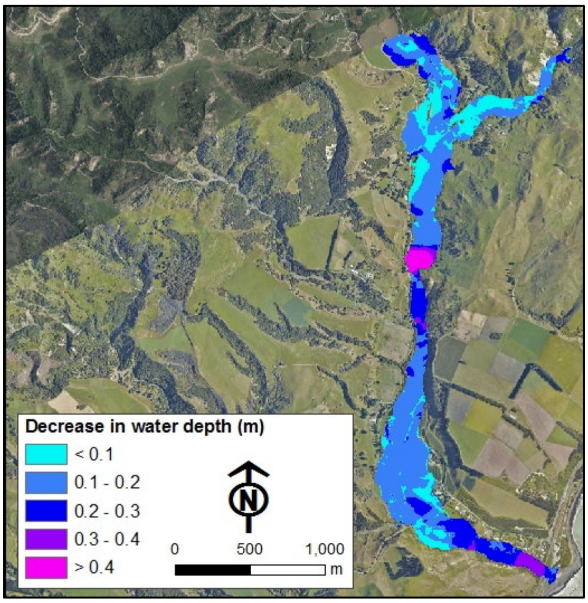


(b) Hāpuku River

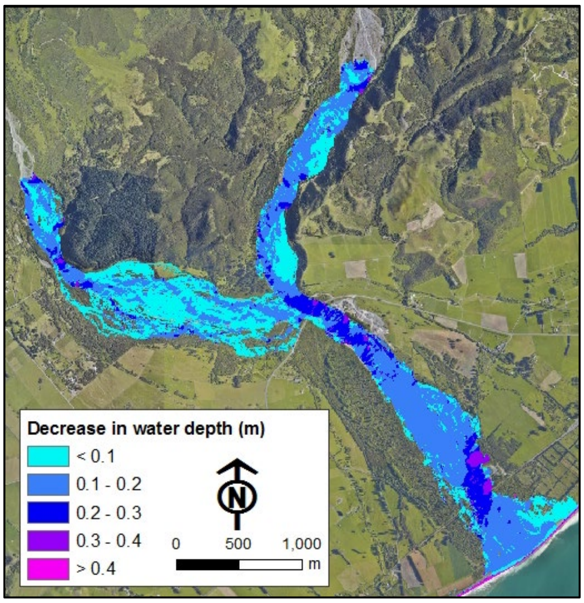


(c) Oaro River

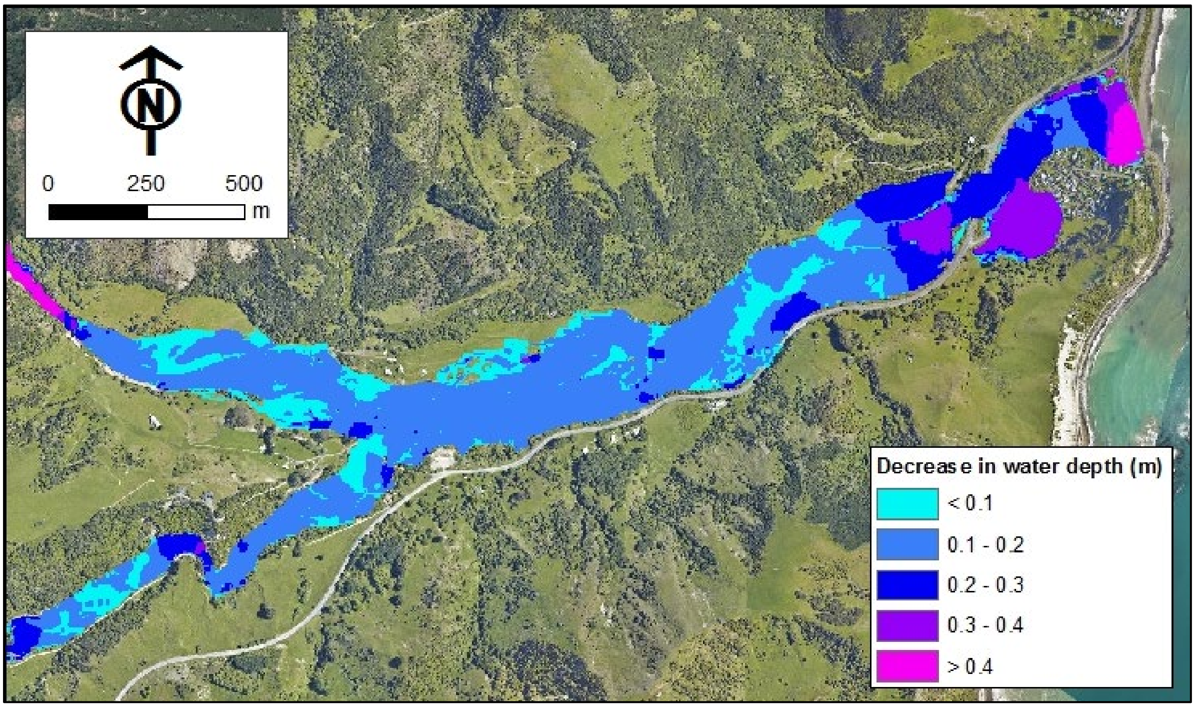
Figure 3-11: Change in maximum floodplain water depths when river and floodplain roughness is increased by 25% for the 500 year ARI flood event



(a) Kekerengu River



(b) Hāpuku River



(c) Oaro River

Figure 3-12: Change in maximum floodplain water depths if climate change is excluded

4 Discussion

Since it has not been possible to calibrate the models in this investigation against any historic flood events, there is considerable uncertainty in the predicted flood depths and extents. However, sensitivity tests demonstrate that the spatial extent of flooding is not hugely impacted by changes to flow, increases in sea level, and increases in Manning's n roughness. This is largely because the floodplains tend to be quite confined.

Historic aerial imagery shows that the amount of vegetation in all three watercourses has increased in recent times. For example, Figure 4-1 shows the increasing spatial extent of vegetation in the lower Oaro River from February 1969 to August 1995 to December 2016. Should the amount of vegetation on the floodplains increase further, it is likely to exacerbate the increases in water level expected for climate change.

As the catchments are sparsely populated, most buildings have historically been placed outside of the areas likely to flood, on more elevated land. However, there are a limited number of existing buildings potentially susceptible to flooding during a 500 year ARI flood event.

There is considerable uncertainty contained within the model results. The main model uncertainties, and the data required to calibrate the model, are summarised below.

4.1 Model uncertainty

Bales and Wagner (2009) outline some of the uncertainties associated with 1D hydraulic modelling using LiDAR data. These uncertainties are also relevant for this modelling study where uncertainties include:

- Model inputs (e.g. stopbank breach locations and sizes, flow magnitude and hydrograph shape, roughness values, energy loss parameters and climate change predictions).
- Topographic data (e.g. LiDAR data and any estimated submerged bed levels). Models also use a fixed bed level so don't account for scour and aggradation.
- Hydraulic model assumptions (e.g. simplification of equations by depth-averaging, as well as averaging topography and flow behaviour over a 5 m grid cell for computational efficiency).

Sensitivity tests can help address these uncertainties but modelling results should generally be interpreted, and used, by those who are familiar with all aspects of the modelling.

4.2 Data required to enable the model to be calibrated

To enable the model results to be used more confidently, measured flow records would be required to more accurately determine flood flows, ideally over a long period of time. However, this is not easy to do in steep gravel-bed rivers where, during flood events, there is considerable bed movement.

Flood information also needs to be gathered during and/or immediately after large flood events. This information should ideally include:

- Photographs of flood inundation, along with the time that the photographs were taken.
- Pegging, or marking with high-visibility paint, the peak water levels.
- Observations of any stopbank breaches (i.e. size, time).

Unfortunately, flood events often occur during the hours of darkness. Access to some areas may be compromised during a large flood event (e.g. road access may not be possible due to landslides, or damage to bridge structures), and helicopters may not be available, or able to fly, due to weather conditions. It would therefore be advantageous for local residents, who know the area well, to document as much as is practically possible (e.g. taking photographs and marking flood levels and times that they occurred).

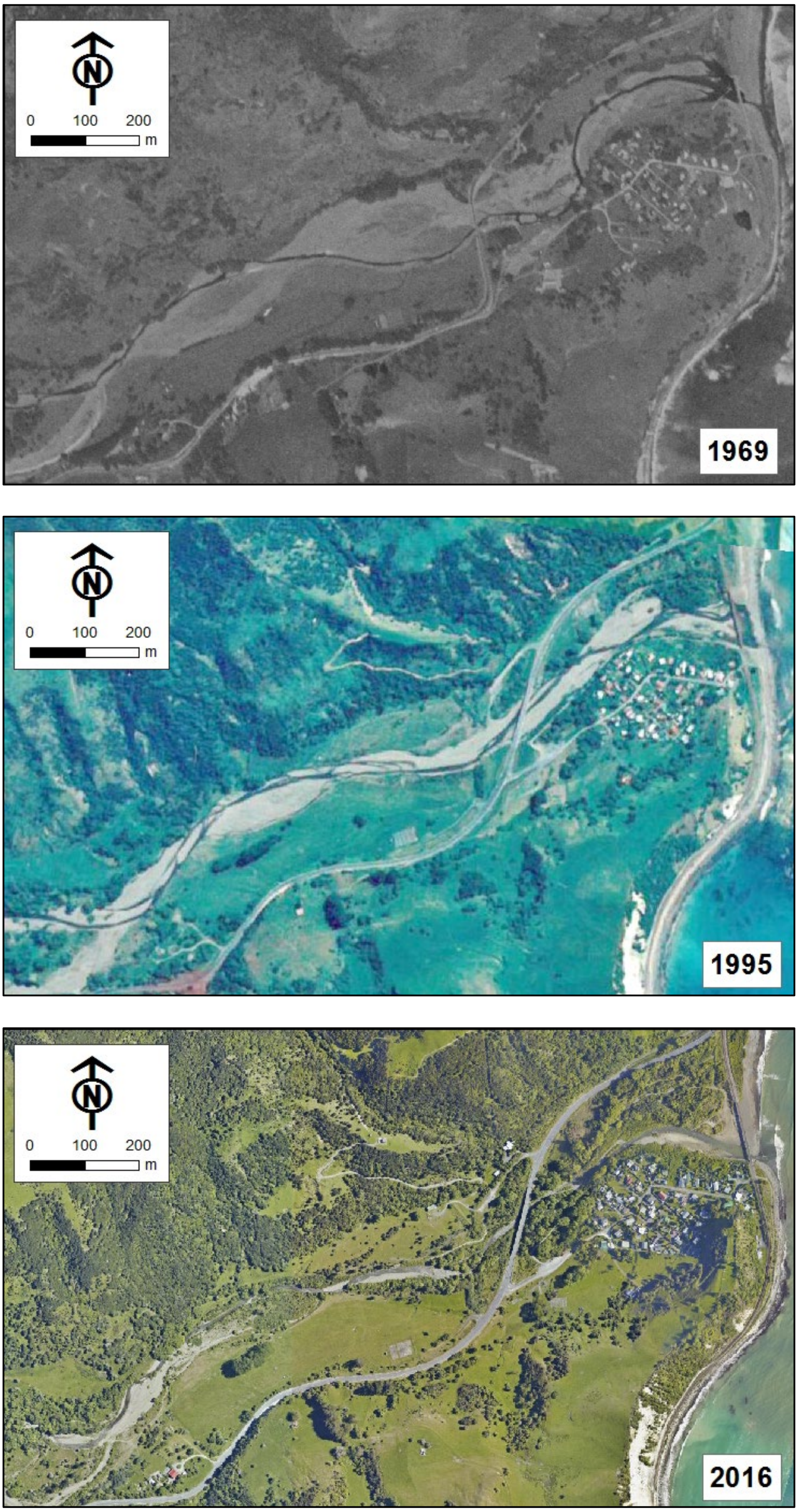


Figure 4-1: Aerial imagery of the Oaro River and Oaro settlement in 1969, 1995 and 2016

5 Conclusions

It is important to emphasise that the models used in this study have a fixed bed level and do not simulate changes in bed levels due to scour, aggradation, or channel avulsions - all processes that will be occurring during a large flood event in a steep, gravel-bed river. The model has also not been based on recorded flow data, nor calibrated against any historical flood events. Consequently, there is considerable uncertainty in the flood water levels produced. The model results produced in this study are therefore only able to provide guidance when determining 500 year ARI flood depths and extents, and high hazard areas.

Modelling indicates that 500 year ARI flood flows should be reasonably well contained by the existing Kekerengu, Hāpuku and Oaro River fairways, and their adjacent floodplains.

Further increases in vegetation in river channels, and on the floodplain, along with channel aggradation and any significant erosion and/or avulsions, may produce additional floodable areas. For example, the accumulative effect of vegetation and climate change is particularly of concern for part of the Oaro coastal settlement.

Given that the models used in this study have fixed beds, it is not possible to determine all possible 500 year ARI flood scenarios – particularly now that there is a considerable supply of additional sediment being stored in the upper catchment of these rivers due to the 2016 Kaikōura earthquake sequence. Climate change and sea level rise may also have an impact on rivers and their outlets to the sea. Care should therefore be taken when interpreting these model results.

6 Recommendations

It is recommended that:

1. Consideration be given to monitoring river bed levels for aggradation/degradation, particularly after flood events.

2. The 500 year ARI flood depths and extents be used to inform land use planning and emergency management.

3. Design flood depths and extents produced in this study are reassessed at a future date when additional climate change, hydrological and riverbed information becomes available. Bridge structures could also be included in the models if flood levels upstream or adjacent to these structures were of concern.

7 Acknowledgments

The 2016/2017 LiDAR data, along with the 1969 and 2016 aerial imagery, have been provided by Land Information New Zealand (LINZ). Ministry of Primary Industries (MPI) also own the 1995 aerial imagery.

The following Environment Canterbury staff have reviewed this report and provided valuable input to this study:

- Nick Griffiths (Team Leader, Natural Hazards)
- Tony Boyle (Principal Science Advisor)

8 External peer review

An external peer review of the Kekerengu, Hāpuku and Oaro computational hydraulic models was completed by Matthew Gardner of Land River Sea Consulting Ltd (Gardner, 2018). Recommendations made in the review are summarised in Table 8-1, and have been incorporated into the final model results.

Table 8-1: Model review recommendations

River	Recommendations (Gardner, 2018)	Actions
Kekerengu	Model rerun with a lower time step	Model time step reduced from 1 second to 0.5 second for all runs
Hāpuku	Model rerun with a lower time step	Model time step reduced from 1 second to 0.5 second for all runs
Oaro	Further sensitivity tests are carried out with increased Manning's n before the results are finalised. If the results are sensitive to higher Manning's n then the roughness should be more accurately represented.	Increasing Manning's n from 0.040 to 0.060 increased water depths in some areas by the order of 0.3 m, showing the model was reasonably sensitive to roughness. Manning's n roughness was therefore more accurately defined for all Oaro model runs.

9 Glossary

Aggradation: Deposition of shingle in a river, raising the river bed level.

Annual exceedance probability (AEP): The chance of a flood of a given, or larger, size occurring in any one year, usually expressed as a percentage. For example, if a peak flood discharge of 500 m^3/s has an AEP of 5%, it means there is a 5% chance (i.e. a one-in-twenty chance) of a peak flood discharge of 500 m^3/s occurring in any one year. AEP is the inverse of average recurrence interval (ARI), expressed as a percentage.

Average recurrence interval (ARI): The average time between floods of a given magnitude. For example, a 100 year ARI flood has a magnitude expected to be equal to, or exceeded, on average once every 100 years. Such a flood has a 1% chance of occurring in any given year, i.e. 1% AEP. ARI is often used interchangeably with 'return period' or 'flood frequency'.

Avulsion: The rapid movement of a river channel to form a new channel. This usually occurs when the channel finds an 'easier' flow route with a steeper slope (shorter channel length) than the existing channel.

Catchment: The land area draining through the main stream and tributaries to a particular site.

Degradation: Scouring of shingle or other sediment from a river bed, lowering the river bed level.

Discharge: The rate of flow of water measured in terms of volume per unit time, e.g. cubic metres per second (m^3/s).

Fairway: The open (ideally vegetation-free) area of the river bed that carries most of any flood flow. There is often a maintenance program in place for clearance of vegetation such as willows, gorse, and broom from fairways.

Floodplain: The area of relatively flat land, adjacent to the fairway, that is inundated by floodwaters from the upper catchment.

Floor level*:* The top surface of the ground floor of a building (prior to the installation of any covering).

High hazard areas: High hazard areas for this study are defined as '*flood hazard areas subject to inundation events where the water depth (m) x velocity (m/s) is greater than or equal to 1, or where depths are greater than 1 metre, in a 500 year ARI or 0.2% annual exceedance probability event*'.

Landslide dam: Occurs when a landslide blocks or 'dams' a river, forming a lake upstream of the landslide.

LiDAR (Light Detection and Ranging) data: Data acquired using a laser scanner mounted on an aircraft. The scanner measures the ground level at approximately one point every square metre. The point data are used to generate very accurate and high resolution digital elevation maps which enable topographic features to be identified.

NZVD2016: New Zealand Vertical Datum 2016 is the official vertical datum for New Zealand and its offshore islands.

Stopbank breach flow: Flow from the river onto the floodplain resulting from a stopbank failure (usually due to overtopping or lateral erosion/scour).

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Appendix A: Model run files

MikeFLOOD model: Release 2016, SP1

Kekerengu River 500 year ARI flood event runs

	No climate change	Roughness increased	With climate change
	500 year ARI flows and sea level of 1.75m NZVD2016	Manning's n of 0.040 and 0.10 increased to 0.045 and 0.12	Flows increased by 25% and sea level increased by 1 m

MikeFlood			
Couple file (*.mf)	Kekerengu_500yr_t_0_5sec	Kekerengu_500yr_n_045_t_0_5sec	Kekerengu_500yr_plus_25_perc_Q_1m_SL_t_0_5sec

Mike11			
Simulation file (*.sim11)	Keke_500yr_t_0_5sec	Keke_500yr_n_0_045_t_0_5sec	Keke_500yr_plus_25_perc_Q_1m_SL_t_0_5sec
Network file (*.nwk11)	Kekerengu_5m_sea_bdy		
Cross section file (*.xns11)	Sea_xsects		
Boundary file (*.bnd11)	Q500yr_ARI_Sea_1_75m	Q500yr_ARI_Sea_1_75m	Q500yr_ARI_Sea_2_75m
HD parameter (*.hd11)	Kekerengu_HD	Kekerengu_HD	Kekerengu_HD_SL_2_75m
Results file (*.res11)	Keke_500yr_t_0_5sec	Keke_500yr_n_0_045_t_0_5sec	Keke_500yr_plus_25_perc_Q_1m_SL_t_0_5sec

Mike21			
Simulation file (*.21)	Kekerengu_500_yr_t_0_5sec	Kekerengu_500_yr_n_0_045_t_0_5sec	Kekerengu_500_yr_plus_25_perc_Q_and_1m_SL_t_0_5sec
Bathymetry file (*.dfs2)	kekerengu_5m_2017		
Initial surface elevation (*.dfs2)	1.75	1.75	2.75
Resistance (*.dfs2)	kekerengu_5m_n_2017	kekerengu_5m_n_incr_2017	kekerengu_5m_n_2017
Results (*.dfs2)	Kekerengu_500_yr_t_0_5sec	Kekerengu_500_yr_n_0_045_t_0_5sec	Kekerengu_500_yr_plus_25_perc_Q_and_1m_SL_t_0_5sec
Sources	(103,750)→(112,750), (308,725)→(308,734)		
Drying depth (m)	0.01		
Wetting depth (m)	0.03		
Eddy viscosity	0.5		
Number of structures	0		
Simulation start time	1/1/2000 12:00am		
Simulation end time	1/1/2000 7:00am		
Time step (s)	0.5		
Length of run (# time steps)	50400		

Hāpuku River 500 year ARI flood event runs

	No climate change	Roughness increased	With climate change
	500 year ARI flows and sea level of 1.75m NZVD2016	Manning's n of 0.040 and 0.10 increased to 0.045 and 0.12	Flows increased by 25% and sea level increased by 1 m

MikeFlood			
Couple file (*.mf)	Hapuku_500yr_SL_1_75m_t_0_5sec_mf	Hapuku_500yr_SL_1_75m_n_0_045_t_0_5sec_mf	Hapuku_500yr_SL_1_75m_plus_25_perc_Q_1m_SL_t_0_5sec_mf

Mike11			
Simulation file (*.sim11)	Hapuku_500yr_ARI_SL_1_75m	Hapuku_500yr_ARI_SL_1_75m_n_0_045	Hapuku_500yr_ARI_SL_1_75m_plus_25_perc_Q_1m_SL
Network file (*.nwk11)		Hapuku_sea_bdy	
Cross section file (*.xns11)		Sea_bdy_xsects	
Boundary file (*.bnd11)	sea_lev_1_75m	sea_lev_1_75m	sea_lev_2_75m
HD parameter (*.hd11)	Sea_lev_bdy	Sea_lev_bdy	Sea_lev_bdy_2_75m
Results file (*.res11)	Hapuku_500yr_ARI_SL_1_75m_t_0_5sec	Hapuku_500yr_ARI_SL_1_75m_n_0_045_t_0_5sec	Hapuku_500yr_ARI_SL_1_75m_plus_25_perc_Q_1m_SL_t_0_5sec

Mike21			
Simulation file (*.21)	Hapuku_500yr_SL_1_75m_t_0_5sec	Hapuku_500yr_SL_1_75m_n_0_045_t_0_5sec	Hapuku_500yr_SL_1_75m_plus_25_perc_Q_1m_SL_t_0_5sec
Bathymetry file (*.dfs2)		hapuku_5m_crop	
Initial surface elevation (*.dfs2)	1.75	1.75	2.75
Resistance (*.dfs2)	hapuku_5m_n_crop	hapuku_5m_n_incr_crop	hapuku_5m_n_crop
Results (*.dfs2)	Hapuku_5m_500yr_SL_1_75m_t_0_5sec	Hapuku_5m_500yr_SL_1_75m_n_0_045_t_0_5sec	Hapuku_5m_500yr_SL_1_75m_plus_25_perc_Q_1m_SL_t_0_5sec
Sources		(50,717)→(69,717), (563,895)→(582,895)	
Drying depth (m)		0.01	
Wetting depth (m)		0.03	
Eddy viscosity		0.5	
Number of structures		0	
Simulation start time		1/1/2000 12:00am	
Simulation end time		1/1/2000 7:00am	
Time step (s)		0.5	
Length of run (# time steps)		50400	

Oaro River 500 year ARI flood event runs

	No climate change	Roughness increased	With climate change
	500 year ARI flows and sea level of 1.75m NZVD2016	Manning's n of 0.040 and 0.10 increased to 0.045 and 0.12	Flows increased by 25% and sea level increased by 1 m

MikeFlood			
Couple file (*.mf)	Oaro_500yr_v2	Oaro_500yr_n_045_v2	Oaro_500yr_plus_25_perc_Q_1m_SL_v2

Mike11			
Simulation file (*.sim11)	Oaro_500yr_v2	Oaro_500yr_n_0_045_v2	Oaro_500yr_plus_25_perc_Q_1m_SL_v2
Network file (*.nwk11)		Oaro_5m_sea_bdy	
Cross section file (*.xns11)		Sea_xsects	
Boundary file (*.bnd11)	Q500yr_ARI_Sea_1_75m	Q500yr_ARI_Sea_1_75m	Q500yr_ARI_Sea_2_75m
HD parameter (*.hd11)	Oaro_HD	Oaro_HD	Oaro_HD_SL_2_75m
Results file (*.res11)	Oaro_500yr_v2	Oaro_500yr_n_0_045_v2	Oaro_500yr_plus_25_perc_Q_1m_SL_v2

Mike21			
Simulation file (*.21)	Oaro_500_yr_v2	Oaro_500_yr_n_0_045_v2	Oaro_500_yr_plus_25_perc_Q_and_1m_SL_v2
Bathymetry file (*.dfs2)		oaro_5m_2017_mod	
Initial surface elevation (*.dfs2)	1.75	1.75	2.75
Resistance (*.dfs2)	oaro_5m_n_2017_mod_v2	oaro_5m_n_incr_2017_mod_v2	oaro_5m_n_2017_mod_v2
Results (*.dfs2)	Oaro_500yr_v2	Oaro_500yr_n_0_045_v2	Oaro_500yr_plus_25_perc_Q_and_1m_SL_v2
Sources		(24,240)→(25,232), (38,52)→(47,52)	
Drying depth (m)		0.01	
Wetting depth (m)		0.03	
Eddy viscosity		0.5	
Number of structures		0	
Simulation start time		1/1/2000 12:00am	
Simulation end time		1/1/2000 7:00am	
Time step (s)		1	
Length of run (# time steps)		25200	

Environment Canterbury Regional Council
Kaunihera Taiao ki Waitaha

Facilitating sustainable development in the Canterbury region

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