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Kaunihera Taiao ki Waitaha

TECHNICAL REPORT Science Group

Waiau Toa/Clarence River floodplain investigation

Report No. R19/34
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Michelle Wild

April 2019

	Name	Date
Prepared by:	*Michelle Wild* *Hazards Analyst (Flooding)*	*8 February 2019*
Reviewed by:	*Brodie Young* *Environmental Science & Hazards Manager*	*25 March 2019*
Model externally reviewed by:	*Matthew Gardner* *Land River Sea Consulting Ltd*	*6 November 2018*
Approved by:	*Tim Davie* *Chief Scientist*	*1 April 2019*

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200 Tuam Street
PO Box 345
Christchurch 8140
Phone (03) 365 3828
Fax (03) 365 3194

75 Church Street
PO Box 550
Timaru 7940
Phone (03) 687 7800
Fax (03) 687 7808

Website: www.ecan.govt.nz
Customer Services Phone 0800 324 636

Summary

Background
The Waiau Toa/Clarence River is approximately 33 km northeast of Kaikōura Township. During the November 2016 Kaikōura Earthquake Sequence, ground movement caused significant changes to the Waiau Toa/Clarence River and adjacent floodplain. This included the loss of a bridge and significant uplift of the riverbed.

As part of the Kaikōura District Plan review, a better understanding of flooding from the larger local rivers was required. This modelling investigation has therefore been undertaken to quantify the extent and depth of flooding for land adjacent to the Waiau Toa/Clarence River. Modelling simulates flooding due to large, high-intensity rainfall events, rather than failure of any of the recent earthquake-induced landslide dams.

What we did
This study used a combined 1-dimensional and 2-dimensional hydraulic computer model to estimate the extent of flooding likely for small (5 to 10), 50, and 500 year Average Recurrence Interval (ARI) flood events. Sensitivity runs were also completed to address the considerable uncertainty 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
Significant changes to the Waiau Toa/Clarence River and floodplain occurred due to the 2016 Kaikōura Earthquake Sequence. Areas that are now more susceptible to flooding include the Clarence Valley Road bridge area, and the northern bank of the Waiau Toa/Clarence River, downstream of Corner Hill. More flooding is also expected on the northern floodplain between the railway and SH1.

In the future, climate change is likely to exacerbate flooding in these areas further, due to the increased peak flood flows predicted to accompany higher air temperatures (and higher precipitation). Conversely, increases in sea level are likely to only have a small, localised impact on maximum flood levels in the riverbed areas immediately adjacent to the sea.

For a 500 year ARI flood event, a north-westerly storm is likely to cause more flooding upstream of the Wharekiri & Miller confluence, while a southerly or easterly storm is likely to cause more flooding downstream of the confluence. The reason being that coastal tributary inflows for a 500 year ARI flood (mainly from Wharekiri and Miller Streams) push the total Waiau Toa/Clarence River flows up to a higher combined flow.

What does this mean?
Modelled flood levels, depths and velocities for 500 year ARI flood events will assist land use planning within the area. As the Waiau Toa/Clarence River is continuing to respond to the changes caused by the November 2016 Kaikōura Earthquake Sequence, the results presented in this report have been determined for the river and floodplain as at January 2018. The river will continue to respond to earthquake and flood induced changes into the future, as will the flood hazard landscape of the surrounding area.

The model developed as part of this study has been made available for other studies assessing flood risk and road access within the Waiau Toa/Clarence River valley. However, the model will need to be updated as the river system changes with future flood events, together with any further earthquake activity.

15 November 2016 - Looking downstream along the Papatea Fault towards the Clarence Valley Road bridge site and Woodbank Station overflow, showing the new river channel forming (left side of photo).

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1 Introduction

The Waiau Toa/Clarence River mouth and floodplain are located ~33 km northeast of Kaikōura Township. Figure 1-1 shows the Waiau Toa/Clarence floodplain area included in this modelling investigation.

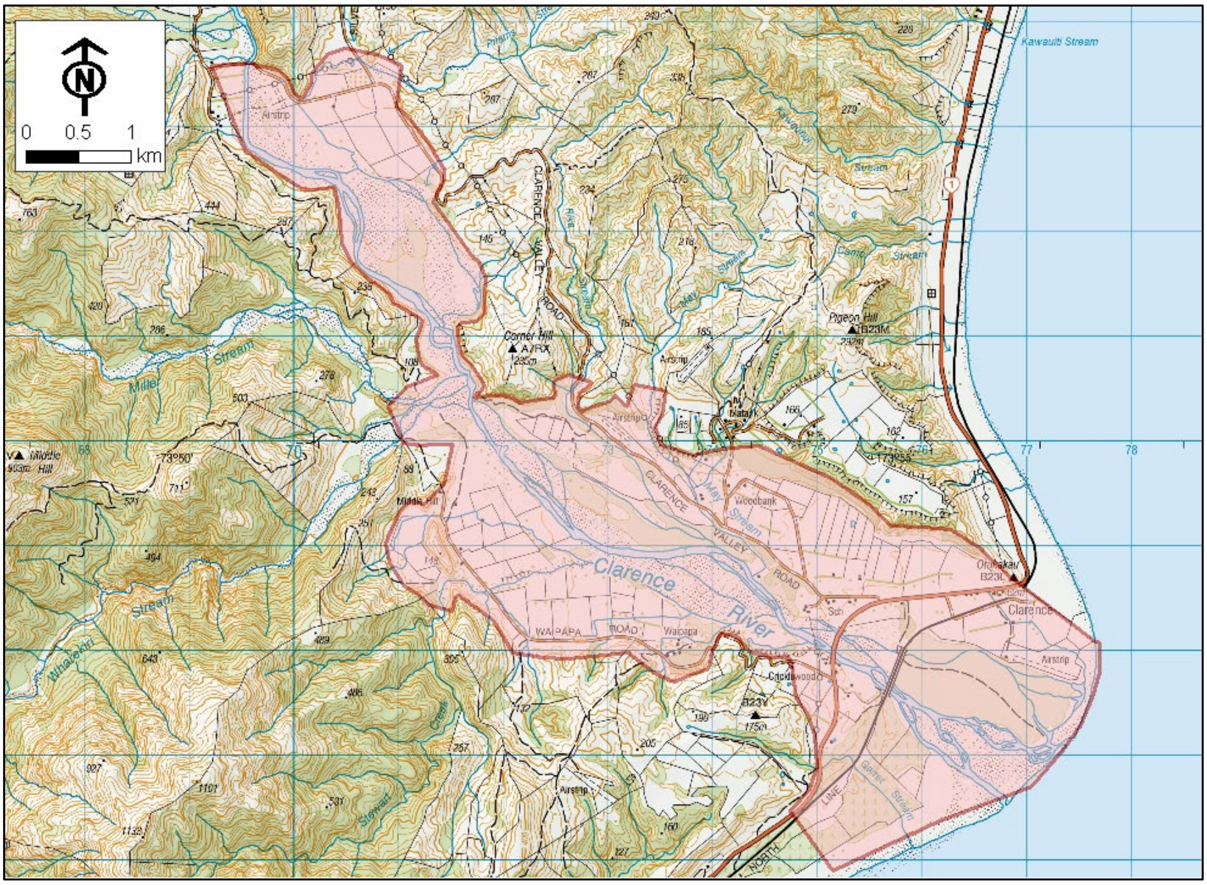


Figure 1-1: Location of Waiau Toa/Clarence River floodplain study area

As part of the Kaikōura District Plan review, a better understanding of flooding from the larger local rivers was required. This modelling investigation has therefore been undertaken to quantify the extent and depth of flooding for land adjacent to the Waiau Toa/Clarence River.

During the 2016 Kaikōura earthquake sequence, part of the Waiau Toa/Clarence River was uplifted, changing the riverbed and floodplain. The Waiau Toa/Clarence River altered its course downstream of the Clarence Valley Road bridge site, forming a new channel through farmland. The flood hazard in this area has consequently changed.

Detailed topographic data, and a combined 1-dimensional (1D) and 2-dimensional (2D) hydraulic computer model, were used to determine the likely extent and depth of flooding on the Waiau Toa/Clarence River floodplain for small (5 to10), 50, and 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. flood warning and 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 floors 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 (as defined in the Glossary).

The model has also been used to assist in the assessment of post-earthquake access to the Clarence Valley (Beca, 2018). However, the modelled cross sections and floodplain topography used in these reports will continue to change in the future with each new flood event. The rate of change is likely to be very high because the earthquake has left significant changes in gradient along the riverbed and the river is expected to adjust substantially over time. The model will therefore need to be updated with new cross section and ground level data after significant flood events to remain pertinent.

2 Background

The primary focus of this investigation is to quantify the extent and depth of flooding on the Waiau Toa/Clarence River floodplain following the 2016 Kaikōura Earthquake Sequence.

2.1 Study area

The Waiau Toa/Clarence River and floodplain study area extends from the coast to approximately 11 km upstream, near the site of the Clarence Valley Road bridge that was destroyed in the 2016 Kaikōura Earthquake Sequence (Figure 1-1).

The Waiau Toa/Clarence River has a catchment area of over 3300 km^2, with the upper catchment originating to the north of Hanmer Springs, upstream of Lake Tennyson (Figure 2-1). The river traverses over 200 km of remote landscape before reaching the coast, making the Waiau Toa/Clarence River one of the longer rivers in New Zealand.

Figure 2-1: Waiau Toa/Clarence River catchment location map

A large portion of land within the catchment is located within the Molesworth, St James, Hossack, Cloudy Range, Muzzle, and Middle Hill Stations, with conservation, farming, and recreation being the main land uses. Ground cover in these areas is a mixture of tussock grasslands, shrublands, forest, loose scree material, and bare rock. As most of the land is managed as Crown Pastural Land, through the Department of Conservation, there is limited development in the catchment.

Approximately 6.5 km upstream of the sea, the Miller and Wharekiri Streams flow into the Waiau Toa/Clarence River (Figure 2-2). The large sediment supply from these sub-catchments creates an alluvial fan that constricts Waiau Toa/Clarence River flows. Upstream of this constriction, the Waiau

Toa/Clarence River has a more gradual channel slope, and finer riverbed material (Thomson, 1966). Downstream of the constriction, the channel slope is greater, and the larger bed material is likely to be due to reworking of old terrace gravels (Thomson, 1966).

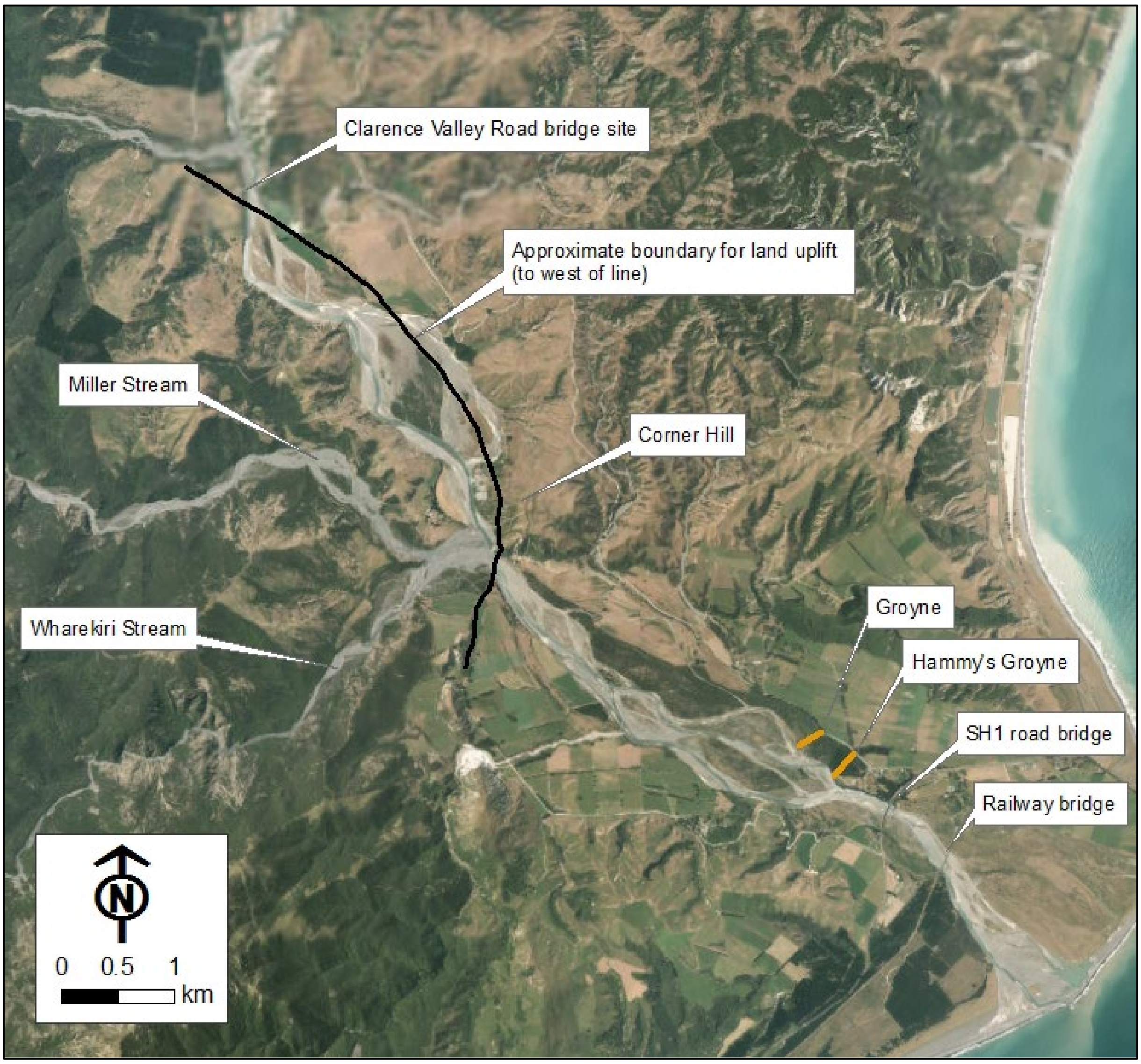


Figure 2-2: Lower Waiau Toa/Clarence River location map

2.2 Timeline for 2016 Kaikōura Earthquake Sequence

Land uplift, during the 14 November 2016 Kaikōura Earthquake Sequence (Figure 2-2), has made significant changes to the Waiau Toa/Clarence River floodplain. Large additional volumes of sediment have also entered the river system in the form of rock falls and landslides, with one landslide temporarily damming the river. Further information on the 2016 Kaikōura Earthquake Sequence is summarised below.

2.2.1 Landslide dam

A large landslide, originating on Haycock Range, blocked the Waiau Toa/Clarence River upstream of the Dart Stream confluence. Due to the remote location, approximately 44 km upstream of the Waiau Toa/Clarence River mouth, it was not initially observed – although a passing helicopter did observe the breach around 4:20pm on 14 November 2016; (http://www.stuff.co.nz/national/86436608/warning-as-large-clarence-river-dammed-by-landslide, accessed 16 May 2017). Figure 2-3 and Figure 2-4 show the landslide dam.

Figure 2-3: 14 November 2016 - Looking downstream towards the Waiau Toa/Clarence River landslide dam before it breached around 4:20pm

Figure 2-4: 15 November 2016 at 12:15pm - Looking downstream at the Waiau Toa/Clarence River landslide dam after it breached

As the *Waiau Toa/Clarence @ Clarence Valley Road Bridge* water level/flow recorder was destroyed in the earthquakes, it was not possible to measure the landslide dam breach flows. However, the rail and SH1 road bridges were not damaged, and flows appear to have remained within the riverbanks.

2.2.2 Waiau Toa/Clarence River floodplain

November 2016

The 14 November 2016 Kaikōura Earthquake Sequence caused the Papatea Fault, between Corner Hill and the Clarence Valley Road Bridge site, to uplift the Waiau Toa/Clarence riverbed by over 5 m relative to the floodplain area on the north-eastern side (Figure 2-2, Figure 2-5 and Figure 2-6). This destroyed the Clarence Valley Road Bridge, and significantly increased the likelihood of flooding, with a river course change through the portion of Woodbank Station upstream of Corner Hill (Heslop, 2016).

Figure 2-5: 15 November 2016 - Looking downstream along the Waiau Toa/Clarence River towards the Clarence Valley Road bridge site and Woodbank Station overflows

After the main earthquake, overflows occurred immediately downstream of the Clarence Valley Road bridge site at near normal river flows (Figure 2-5). Gully head erosion migrated from the downstream end of the overflow channel in an upstream direction. At Woodbank Station they reacted quickly, constructing a stopbank to prevent further overflows and a significant shift in the main channel (Figure 2-7 and Figure 2-8).

At Corner Hill, the earthquakes also caused the Wharekiri and Millers stream confluence to be uplifted by over 4 m (Figure 2-9), producing a new waterfall/rapid in the Waiau Toa/Clarence River reach upstream of Corner Hill.

<u>April 2017</u>
High river flows destroyed part of the newly constructed stopbank at Woodbank Station (Figure 2-10). This allowed the Waiau Toa/Clarence River to further establish the new channel through farmland, along the boundary of the uplifted fault (Figure 2-11). Additional farmland became riverbed and the Clarence Valley Road bridge approaches were washed out.

<u>September 2017</u>
During September 2017 there were two relatively small flood events around the 19th and 27th September. These high flows continued to scour and enlarge the new Waiau Toa/Clarence River channel, now flowing through farmland downstream of the Clarence Valley Road Bridge site (Figure 2-12 and Figure 2-13). The 4 m deep layer of gravel stored at the Wharekiri and Miller Stream confluence was also down-cut to the underlying rock shelf, raised during earthquake uplift (Figure 2-14). This down-cutting continued upstream along the Wharekiri and Miller Streams, to beyond the ford crossing, which now provides the only road access to the upper valley on this side of the river.

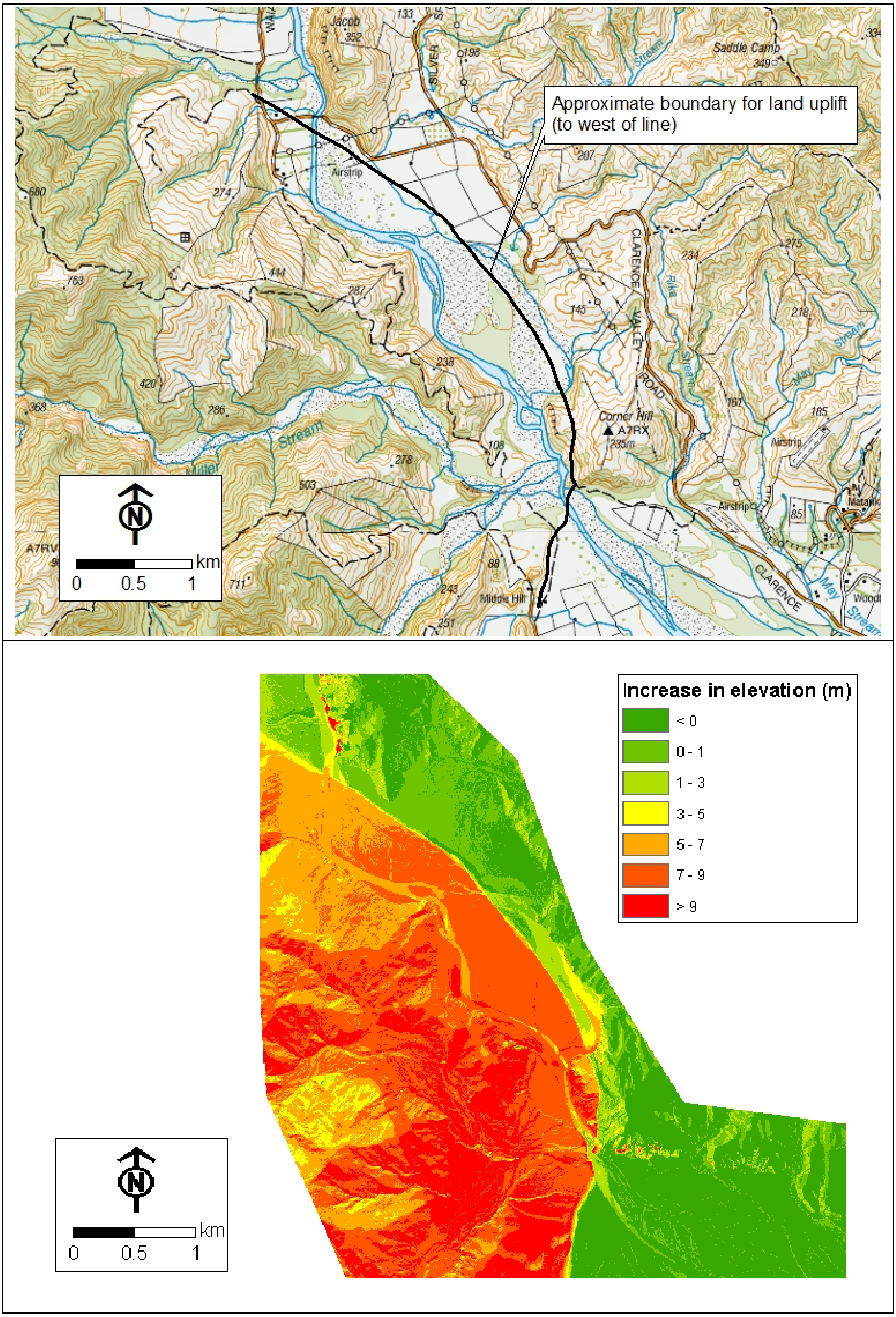


Figure 2-6: Change in ground level post-2016 Kaikōura Earthquake Sequence

Figure 2-7: 25 November 2016 - Woodbank Station stopbank constructed in the area immediately downstream of the Clarence Valley Road bridge site

Figure 2-8: 25 November 2016 - Clarence Valley Road bridge site with Woodbank Station stopbank constructed post-2016 Kaikōura Earthquake Sequence

Figure 2-9: 25 November 2016 - Looking upstream at the elevated Wharekiri and Miller Stream confluence where it meets the Waiau Toa/Clarence River

Figure 2-10: 18 July 2017 - Looking upstream along the new Waiau Toa/Clarence River channel to the destroyed section of Woodbank Station stopbank and Clarence Valley Road Bridge

Figure 2-11: 18 July 2017 - Looking downstream from near the Clarence Valley Road Bridge to the new Waiau Toa/Clarence River channel running along the fault through farmland

Figure 2-12: 27 September 2017 - Looking downstream at the destroyed Clarence Valley Road Bridge and new main Waiau Toa/Clarence River channel along the fault (left channel)

Figure 2-13: 27 September 2017 - Looking downstream from near the Clarence Valley Road Bridge at the new main Waiau Toa/Clarence River channel along the fault

Figure 2-14: 27 September 2017 - Looking downstream across the downcut Wharekiri and Miller stream confluence at Corner Hill

Downstream of Corner Hill, much of the bed material from the Waiau Toa/Clarence River and the Wharekiri and Miller Streams was deposited in the Waiau Toa/Clarence River channel. This formed a central island that split the flow, directing flow towards both river banks (Figure 2-15). Vegetation was washed away and river banks were eroded. As the river flows receded, further deposition occurred in the channel, along with significant bank erosion (Figure 2-16).

The combination of lower bank levels, and considerable aggradation in the river channel, encouraged further overflows into remnant river channels (through farmland) on the northern floodplain during subsequent high flows (Figure 2-17). The only residents located on this floodplain self-evacuated before access was compromised by the flows. Clarence Valley Road runs alongside one of the overflow channels, making it also susceptible to these overland flows.

Figure 2-15: 22 September 2017 - Looking downstream from Corner Hill at the large island that formed in the Waiau Toa/Clarence River

Figure 2-16: 19 September 2017 - Looking downstream along the true right (south) bank of the Waiau Toa/Clarence River, downstream of Corner Hill

Figure 2-17: 27 September 2017 - Looking upstream towards Corner Hill at overflows over the northern (true left) bank

Since the September 2017 flood events, gravel has been extracted from the beach below Corner Hill. A channel was also cut through the gravel island to direct flows back into the centre of the river, rather than toward the banks. Rock protection works, mainly in the form of small rock groynes, have also been placed along both banks downstream of Corner Hill (Figure 2-18). As there is no River Management Scheme in place, rock protection works have been funded by land owners. These rock protection works performed well in early July 2018, when flows around a mean annual flood passed along the river from the upper catchment.

(a) **(b)**

Figure 2-18: Rock protection work downstream of Corner Hill on (a) true left bank in February 2018 and (b) true right bank in April 2018

Currently, one of the biggest issues in the Clarence Valley is returning road access to the upper Clarence Valley, and maintaining access along the section of Clarence Valley Road that remains along the northern side of the river. The newly formed Waiau Toa/Clarence River channel, located downstream of the Clarence Valley Road bridge site, has continued to erode along the true left (northern) bank. It is likely that this erosion will continue until, at some time in the future, the road is compromised. Emergency river protection works funded by the NZ Transport Agency are currently underway to prevent, or at least delay, this erosion. Beca (2018) also provides further information on morphological changes with regards to Clarence Valley access.

2.3 Historic flooding

Because of the remote location of this catchment, there is little available information on historic flooding. Flooding will generally result from three different weather patterns, as outlined below:

1. Southerly and easterly rainfall events in the lower catchment (i.e. Kaikōura Seaward Ranges). These flood events tend to produce relatively short-duration high flows, as occurred in 1923 and 1966 (Thomson, 1966).
2. North-westerly rainfall spilling into the upper catchment in the Lake Tennyson area. Lengthy periods of high flow may occur after these flood events, but they do not usually produce the more extreme flood events.
3. Prolonged heavy rainfall over the entire catchment. This can lead to the most severe, longer-duration, high flow, flood events at the Waiau Toa/Clarence River mouth, as occurred in 1953 (Thomson, 1966).

Historically, the rail and road bridges have been washed out on several occasions. After the 1953 flood event, two new spans were added to the Waiau Toa/Clarence River road bridge, effectively lengthening it by 75%. There has also been erosion of farmland in the area adjacent to the bridges (Thomson, 1966).

Further information, regarding notable flood events in the Waiau Toa/Clarence River, is summarised below. A more detailed account of flooding in the Kaikōura area is also provided in McPherson (1997). Measuring flood flows in steep and sediment-laden braided rivers is a difficult process. Therefore, any flows quoted below (especially from older events) may be more indicative than precise.

2.3.1 February 1868

This was the first documented flood event after European settlement in the area, and was described as '*the greatest flood ever recorded on the Marlborough coast'* by Sherrard (1966) in McPherson (1997, p7). Mrs V Boyd described the flood event 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. The Waiau Toa/Clarence River was higher than ever known before, with flood waters washing away many acres of valuable land (https://hwe.niwa.co.nz/event/February_1868_New_Zealand_Storm, accessed 1 October 2018).

2.3.2 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).

In this event, there was considerable flow in a flood overflow channel to the north of the Waiau Toa/Clarence River road bridge, where the lower end is behind the present school (Thomson, 1966). The bridge abutments were washed out, as well as two spans of the bridge (Thomson, 1967). From the northern end of the bridge, the river took a new course 180 metres to the north (SCRCC, 1957). Nearly every bridge in the County was damaged (McPherson, 1997). In the Upper Awatere River, two bridges were also washed away (SCRCC, 1957).

2.3.3 March 1941

Heavy rain on 17 and 18 March caused the Waiau Toa/Clarence River to become 'a raging torrent', overflowing its banks (McPherson, 1997). The Waiau Toa/Clarence River flooded low-lying land towards Waipapa Point and washed away the new northern abutment for the railway bridge which collapsed the first bridge span.
(https://hwe.niwa.co.nz/event/March_1941_Upper_South_Island_and_Manawatu-Wanganui_Flooding, accessed 1 October 2018).

2.3.4 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). The peak flow at the Waiau Toa/Clarence River road and rail bridges was estimated as being 2500 m^3/s. The river was running bank to bank, and it was considered the heaviest flooding in the Waiau Toa/Clarence River since 1923 (McPherson, 1997).

2.3.5 January 1953

Prolonged, heavy rainfall along the east coast caused widespread flooding with 127 mm of rain in the Clarence Valley in 8 hours, and 254 mm over 72 hours (SCRCC, 1957). There was widespread rainfall over the entire Waiau Toa/Clarence River catchment (Thomson, 1966).

The Acheron River at Pudding Hill (catchment area 738 km^2) peaked at 127 m^3/s at the lime works (SCRCC, 1957). Meanwhile, the peak flow in the Waiau Toa/Clarence River, at the road and rail bridges, was estimated as being 2400 m^3/s, and the northern approach to the road bridge was washed out (Thomson, 1966). SCRCC (1957) also gave a peak flow of 2300 m^3/s for the Waiau Toa/Clarence River at the Waiau Toa Bridge, with a level 127 mm lower than November 1952. Although the peak flow was estimated to be less than the 1952 flood, there was more flood damage, due to prolonged rainfall over the entire catchment.

2.3.6 May 1966

A depression moved south-easterly from Lord Howe Island towards the centre of New Zealand. It was accompanied by a cloud front and resulted in gale force southerly winds in the Cook Strait area. The depression moved away south from Northland on the morning of the 23rd, with heavy and persistent rain causing severe flooding in Marlborough on the 23rd and 24th May.
(https://hwe.niwa.co.nz/event/May_1966_New_Zealand_Storm, accessed April 2018).

This southerly rainfall event produced 457 mm of rain in 24 hours at Coverham Station. Heavy rain also fell in the Awatere Valley and along the coastal Kaikōuras. (https://hwe.niwa.co.nz/event/May_1966_New_Zealand_Storm, accessed April 2018).

The south abutment of the Waiau Toa/Clarence River railway bridge was washed out (Figure 2-19). It was the fourth time in 43 years that one of the bridge abutments had been washed out (Thomson, 1966).

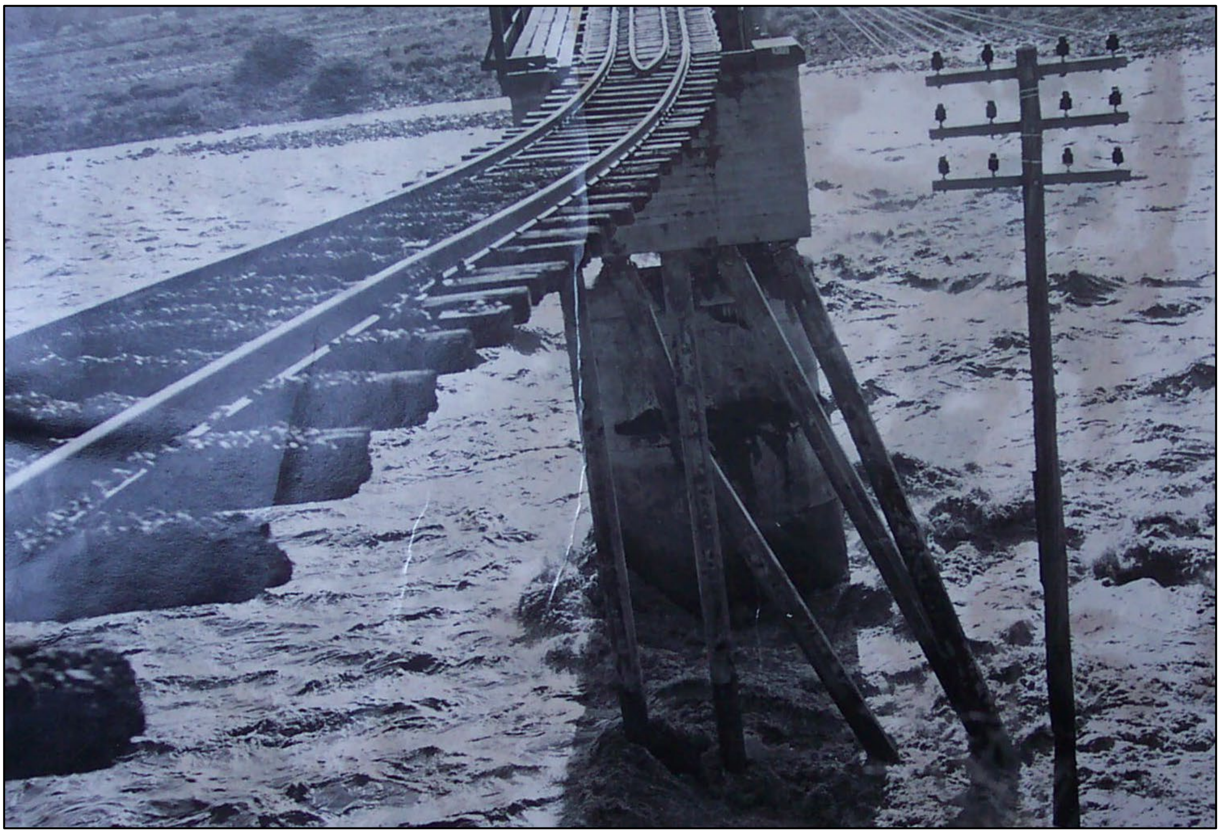


Figure 2-19: Washout of Waiau Toa/Clarence River south abutment of main trunk railway line in May 1966

2.3.7 March 1975 – Cyclone Alison

The Meteorological Office recorded 284 mm of rain and, in the Puhi Puhi Valley, a resident recorded 450 mm of rain (McPherson, 1997). The 6-hourly rainfall intensities also exceeded 30 mm/hr in several locations (Bell, 1976). This caused widespread flooding and landslides – particularly along the Hāpuku River to Waiau Toa/Clarence River portion of the coastline.

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

2.3.8 April 1975

In Marlborough, '*heavy rain was associated with a depression which developed in the North Tasman Sea and moved south-eastwards towards Fiordland. The significant contributing factor to the large rainfalls was the strong north-westerly surface wind. Heavy rain began at 8:30am on the 1st of April and a 15 hour period of heavy rain followed*' (https://hwe.niwa.co.nz/event/April_1975_Tasman-Nelson_and_Marlborough_Flooding, accessed April 2018).

2.3.9 August 1979

Marlborough Catchment Board documents refer to flood damage on the Kowhai River from storms around this time (McPherson, 1997). A maximum stage of 6.82 m (1520 m^3/s) was recorded at the Glen Alton water level recorder (the maximum recorded at the site between 18/6/79 and 27/6/1985).

2.3.10 March 1980

Like the Cyclone Alison storm in March 1975, this event was caused by a depression, formed from a tropical cyclone that travelled south into the Tasman Sea. 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).

2.3.11 April 1980

This storm affected the whole east coast of Marlborough, with heaviest rainfall around the inland areas of Kaikōura (McPherson, 1997).

2.3.12 July 1983

'*An eastward moving depression with its band of rain was reinforced by a moist northerly airstream, which brought torrential rain to the high country of the Nelson-Marlborough provinces'* (https://hwe.niwa.co.nz/event/July_1983_Upper_South_Island_Flooding, accessed 5 April 2018).

From 8 to 10 July the moist tropical northerly flow of air caused widespread and prolonged rainfall and flooding in the Tasman-Nelson, Marlborough and West Coast areas. This was the result of a slow-moving depression located in the Tasman Sea, coinciding with a slow-moving anti-cyclone to the east of New Zealand (https://hwe.niwa.co.nz/event/July_1983_Upper_South_Island_Flooding, accessed 5 April 2018). The Awatere River was in flood and a flow of 957 m^3/s was recorded in the Waiau Toa/Clarence River at Glen Alton.

2.3.13 October 1983

Between 21 to 23 October heavy rain caused flooding in the Tasman-Nelson and Marlborough regions. Flooding washed out the one-way bridge over the Awatere River.
(https://hwe.niwa.co.nz/event/October_1983_Marlborough_and_Tasman-Nelson_Flooding, accessed April 2018).

2.3.14 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 rainfall was recorded for this event (McPherson, 1997).

2.3.15 November 1994

'*Heavy rain, flooding, high winds and thunderstorms occurred around the lower North Island and upper South Island*' and '*Marlborough rivers burst their banks, bringing flooding*'.
(https://hwe.niwa.co.nz/event/November_1994_Lower_North_Island_and_Upper_South_Island_Storm, accessed April 2018)

2.3.16 October 2007

'*A frontal system approached the South Island from the west in the early hours of the 7th, rapidly increasing the north-westerly flow preceding it. There was heavy rain about, and on, the west of the mountains in northern South Island the rivers were pushed to flood levels*' (https://hwe.niwa.co.nz/event/October_2007_Lower_North_Island_and_South_Island_Storm, accessed April 2018)

2.3.17 July 2008

A deepening low to the north-west of New Zealand travelled in a southerly direction across the central part of the country, bringing heavy rain to Marlborough and Canterbury late on 30 July and 31 July 2008. This event brought the greatest volumes of rain to North Canterbury, and the Kaikōura Coast. Although there is no information specifically relating to this river during the 31 July 2008 flood event, photographs show the Waiau Toa/Clarence River at high flows (Figure 2-20 and Figure 2-21).

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 also recorded 350 mm of rainfall in a 30-hour period during this event (https://hwe.niwa.co.nz/event/July_2008_New_Zealand_Severe_Storm, accessed April 2018).

Figure 2-20: Looking upstream from the Waiau Toa/Clarence River road bridge during the July 2008 flood event

Figure 2-21: View looking south from the true left bank of the Waiau Toa/Clarence River, downstream of the road bridge, during the July 2008 flood event

2.3.18 August 2008

'*A succession of low pressure systems moved out to the east, dragging in blustery south-easterlies and driving a succession of wet patches into Marlborough and beyond. On the 24th, a deepening low that had developed in the western Tasman Sea was close enough to bring stormy weather to New Zealand. On the 25th, the low remained slow moving over the North Island, while a stationary front combined with a moist east to south-east flow to bring rain to North Canterbury and Marlborough;* (https://hwe.niwa.co.nz/event/August_2008_Canterbury_Flooding_and_North_Island_Landslides, accessed April 2018).

In the 24 hours from 9am 25 August to 9am 26 August, Kaikōura received 126 mm of rain, with 200 mm of rain recorded over 2 days. Inland from Kaikōura more than 400 mm of rain fell over a few days (https://hwe.niwa.co.nz/event/August_2008_Canterbury_Flooding_and_North_Island_Landslides, accessed April 2018). Heavy rain was also noted in the Awatere Valley.

2.3.19 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). The peak flow in the Waiau Toa/Clarence River at Clarence Valley Road Bridge was approximately 1300 m^3/s.

2.4 Flood protection works

Over the years, river protection works have been constructed to protect both the road and rail bridges, as well as private property, with varying degrees of success.

After the 1923 flood, two stone and netting groynes were constructed to protect the old highway bridge approach (Figure 2-2). However, maintenance was minimal for many years and over 7 m of silt had reportedly built up behind the upstream (Hammy's) groyne by 2003 (CRC Flood Hazard Assessment, Ref: AD5C-0018), compromising the effectiveness of this structure. There are also concrete block and steel bank protection works (sputniks) between the downstream groyne and the SH1 road bridge, although some of the blocks have been undermined and dislodged.

3 Methodology

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

This floodplain investigation used a combined 1-dimensional (1D) and 2-dimensional (2D) hydrodynamic computer model (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 historical flood event information (Section 2.3)
- Estimation of flood hydrology/design flows (Section 3.1)
- Estimation of Kaikōura sea levels and storm tides (Section 3.2)
- Construction of computational hydraulic models (Section 3.3)
- Calibration of the models (Section 3.4)
- Modelling of present-day design flood events (Section 3.5)
- Model sensitivity analysis (Section 3.6)
- Present-day comparison with pre-earthquake flooding (Section 3.7)
- Modelling design flood events including climate change to 2120 (Section 3.8)

3.1 Flood hydrology

The only long-term water level recorder sites along the Waiau Toa/Clarence River system are located in the upper reaches of the river, with two shorter periods of water level record near the mouth. Table 3-1 summarises the available water level (and flow) data.

Table 3-1: Water level (and flow) recorders in the Waiau Toa/Clarence River catchment

Site no.	Site name	Catchment area km^2	Record length	Max recorded flow m^3/s
62103	Acheron @ Clarence	973	2/4/1958 - present	1008
62105	Waiau Toa/Clarence @ Jollies	440	30/4/1958 - present	437
62106	Waiau Toa/Clarence @ Glen Alton	3154	18/6/1979 - 27/6/1985	1520
62107	Waiau Toa/Clarence @ Clarence Valley Rd	~3154	28/2/2014 - 14/11/2016	1278

3.1.1 Waiau Toa/Clarence River coastal tributary design flows

Downstream of the Clarence Valley Road bridge (Sites 62106 and 62107), there are several tributaries that contribute significant inflows to the Waiau Toa/Clarence River during high-intensity rainfall along the Seaward Kaikōura Range. They include Miller and Wharekiri Streams, as well as the smaller Stewart Creek, Priams Creek, Rika Stream and May Stream tributaries (Figure 3-1).

At present, there are no available flow data to derive design flows for these tributaries. Instead, the methodology described in Tonkin and Taylor (2017) for the Hāpuku River was used to derive the tributary mean annual flows (Q_{maf}). The Hāpuku River mean annual flood factor ($Q_{mf} = Q_{maf}/A^{0.9}$) is 2.0, and the dimensionless flood peak flow for a 100 year ARI flood ($q_{100} = Q_{100}/Q_{maf}$) is 4.0. Flood frequency growth factors from Griffiths *et al.* (2011) were used to convert the mean annual flood flows to the various design flows. These growth factors have been chosen to match a q_{100} of 4 (Table 3-2). Design tributary flows are summarised in Table 3-3.

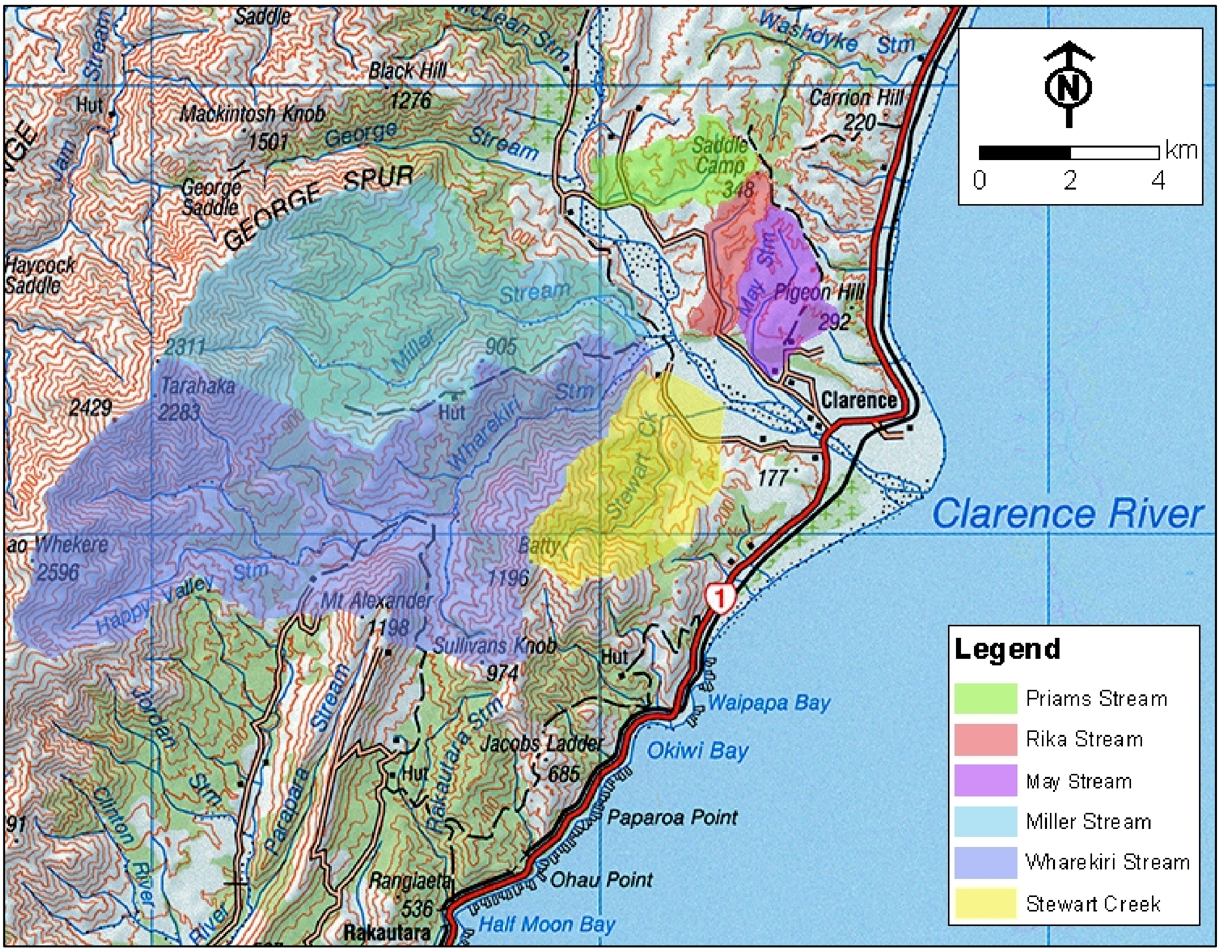


Figure 3-1: Location of Waiau Toa/Clarence River coastal tributary catchments downstream of the Clarence Valley Road bridge site

Table 3-2: Q/Q_{maf} values for a q_{100} value of 4.0 (Griffiths *et al.*, 2011)

Average recurrence interval (ARI)	Q/Q_{maf}
5	1.69
10	2.25
20	2.78
50	3.48
100	4.00
200	4.52
500	5.20

Table 3-3: Design flows for Waiau Toa/Clarence River coastal tributaries

Watercourse	Catchment Area (km^2)	Q_{maf} (m^3/s)	Q_{10} (m^3/s)	Q_{50} (m^3/s)	Q_{500} (m^3/s)
Priams Stream	5	10	20	30	45
Rika Stream	3	6	15	20	30
May Stream	5	10	20	30	45
Miller Stream	40	50	110	170	260
Wharekiri Stream	60	80	180	280	410
Stewart Creek	15	20	50	70	110
TOTAL	120	170	390	560	890

Note: Q_{maf} = Mean annual flood peak flow, Q_{10} = 10 year ARI peak flow, etc

3.1.2 Waiau Toa/Clarence River flows

Waiau Toa/Clarence River flows have been measured over the two short time periods shown in Table 3-1. To extend the available annual peak flow time series, historic records were examined. However, the only additional flow estimates found were for the 1952 and 1953 floods at the SH1 road and rail bridges (i.e. downstream of the local coastal tributaries described in Section 3.1.1). Table B-1 (Appendix B) summarises peak flows for various high flow events that have been documented for the Waiau Toa/Clarence River.

To determine Clarence Valley Road bridge design flows, the sparse collection of annual flows for this site have been pieced together. The annual flow series data were plotted using the Gringorten plotting position. The plotting positions included rough estimates of where additional unmeasured flood flows may have been ranked in terms of largest to smallest flood events (i.e. it has been assumed that the recorded floods are not necessarily the only big floods).

To estimate the larger design flood events, the six largest events from 1952 to 2016 have been plotted. This series assumed that there was likely to have been one unrecorded flood event with a magnitude between 1520 and 1800 m^3/s, and another between 1280 and 1520 m^3/s, during this 65 year time period (Table 3-4). Possible flood events with magnitudes in this range may include May 1966, October 1968, November 1994 or July/August 2008, although we have no data able to confirm this.

Table 3-4: Annual exceedance probability (AEP) for the Waiau Toa/Clarence River at Clarence Valley Road site based on the largest annual estimated flows (1952 to 2016)

Event rank	Event year	Flow (m^3/s)	Gringorten Plotting position (return period, years)	Annual Exceedance Probability (AEP)
1	1953	1900	114.5	0.009
2	1952	1800	41.10	0.024
3	?	?	25.05	0.040
4	1979	1520	18.01	0.056
5	?	?	14.06	0.071
6	2014	1280	11.53	0.087

To estimate the smaller design flood events, the two periods of recorded flows for the Clarence Valley Road bridge (sites 62106 and 62107) have been used. Rough assumptions have been made regarding the size of flood events occurring between July 1985 and February 2014, when only flows in the upper catchment were measured. This series assumed that there was likely to have been other flood events with magnitudes between 1280 and 1520 m^3/s, 960 and 1150 m^3/s, and 700 and 960 m^3/s, during this 38 year time period (Table 3-5). Possible flood events with magnitudes in these ranges include November 1994, October 2007, July/August 2008 and December 1993.

Table 3-5: Annual exceedance probability (AEP) for the Waiau Toa/Clarence River at Clarence Valley Road site based on the largest annual recorded flows (1979 to 2016)

Event rank	Event year	Flow (m^3/s)	Gringorten Plotting position (return period, years)	Annual Exceedance Probability (AEP)
1	1979	1520	68.1	0.015
2	?	?	24.4	0.041
3	2014	1280	14.9	0.067
4	1980	1150	10.7	0.093
5	?	?	8.4	0.12
6	1983	960	6.9	0.15
7	?	?	5.8	0.17
8	1981	700	5.0	0.20
9	1982	680	4.5	0.23

The data in Table 3-4 and Table 3-5 are plotted in Figure 3-2, along with estimates of design flows. The design flows are also summarised in Table 3-6. These design flow estimates are based on limited information and contain considerable uncertainty. For example, if no other flood events were large enough to fill the gaps in Table 3-4 or Table 3-5, the design flows would most likely be smaller. As further data becomes available, these design flows should therefore be updated.

Table 3-6: Waiau Toa/Clarence River (at Clarence Valley Road) estimated design flows

Average recurrence interval (ARI)	Annual Exceedance Probability (AEP)	Flow (m^3/s)
5	0.20	700
10	0.10	1300
50	0.02	1800
100	0.01	1950
200	0.005	2100
500	0.002	2300

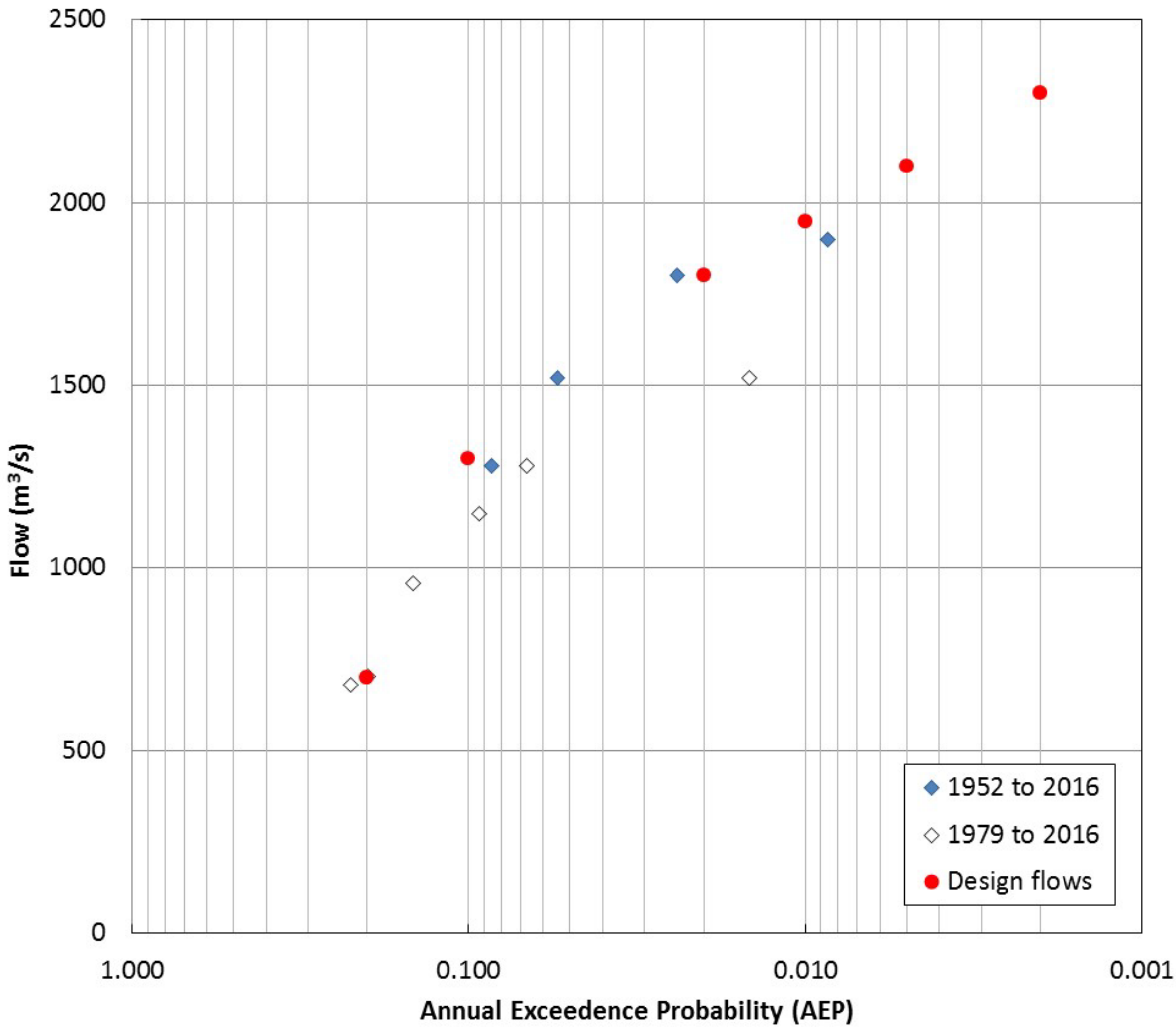


Figure 3-2: Estimated annual exceedance probability (AEP) for the Waiau Toa/Clarence River at Clarence Valley Road bridge

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 seasonal/ENSO water level fluctuation of 0.1 m has been assumed 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.

All model runs had a constant sea level to simulate high tide occurring at the same time as the peak river flow reached the river mouth. For this study, the area of interest was upstream of the river mouth where maximum flood levels are not affected by sea level.

3.3 Hydraulic model construction

The Mike Flood modelling package was used, combining 1D modelling for the Waiau Toa/Clarence River channel and coastal boundary, with 2D modelling for the Waiau Toa/Clarence River floodplain. The 1D and 2D models were linked to the floodplain, along the river and coastal boundaries, to allow flood waters to move freely between the river, floodplain and sea. As the post-2016 Kaikōura Earthquake Sequence river channel migrated to a completely different location, the pre- and post-earthquake models were configured differently. The pre- and post-earthquake model schematics are shown in Figure 3-3 and Figure 3-4, respectively. A detailed description of the models is given below.

3.3.1 1D river channel model

The Waiau Toa/Clarence River and coastal boundary are included in the 1D model. The Waiau Toa/Clarence River channel extends upstream from the coast for ~11 km, and the coastal boundary extends north along the river mouth for ~1.6 km. The northern end of the coastal 'channel' has a specified sea level and the southern end is closed.

The post-earthquake model includes a second 1D channel to represent the new Waiau Toa/Clarence River channel formed over farmland between the Clarence Valley Road Bridge site and Corner Hill (Figure 3-4).

Cross sections

Initial cross sections for the Waiau Toa/Clarence River models were extracted from high resolution topographic data, obtained from airborne LiDAR surveys (see Section 3.3.2). After the November 2016 Kaikōura Earthquake Sequence, further cross section details were provided by two surveyed cross sections. A drone survey, specifically targeting two of the areas with greatest flood-induced changes since November 2016, was also undertaken in January 2018 (see Section 3.3.2).

One problem with the available LiDAR data is that it does not distinguish between a water surface and a ground level. At the time of the survey, flows in the lower Waiau Toa/Clarence River were low. This made the reduction in cross sectional area relatively insignificant, when compared to extreme flood events such as a 500 year ARI flood.

At the time of the 2016/17 LiDAR survey, changes due to uplifting of the riverbed resulted in several areas along the Waiau Toa/Clarence River being inundated with significant volumes of water, hiding large portions of the riverbed. The areas most affected were upstream of the Clarence Valley Road bridge site, and in the lake formed upstream of Corner Hill. Where the more recent drone data was not available, cross section profiles were estimated for the ponding areas using 2012 LiDAR, with adjustments for uplift. Downstream of the Clarence Valley Road bridge, the newly formed channel cross sections were roughly based on the two cross sections measured on 24 January 2018 (around the time of the drone survey). A summary of the cross section data sources is given in Table B-1.

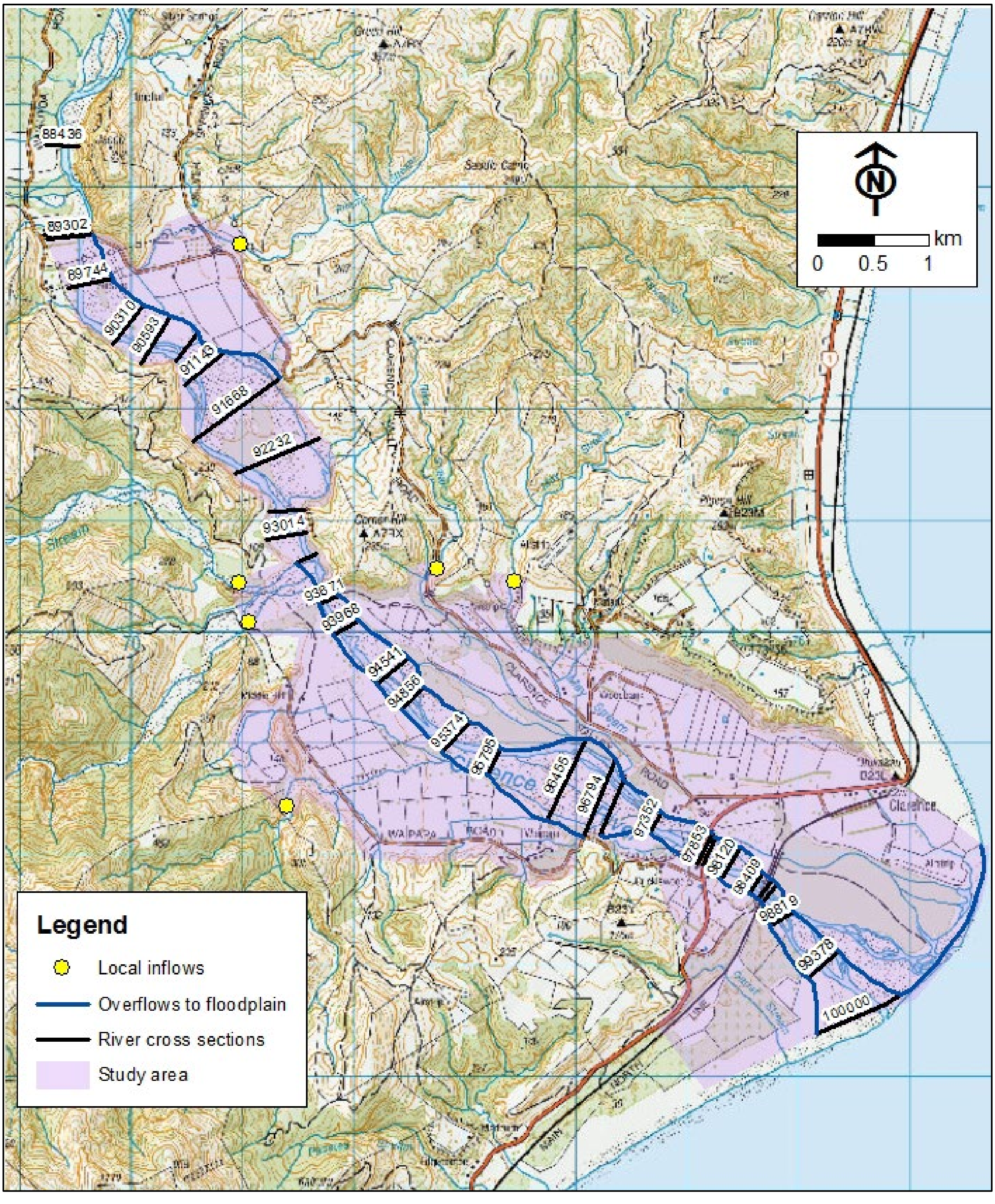


Figure 3-3: Pre-earthquake Waiau Toa/Clarence River model schematic

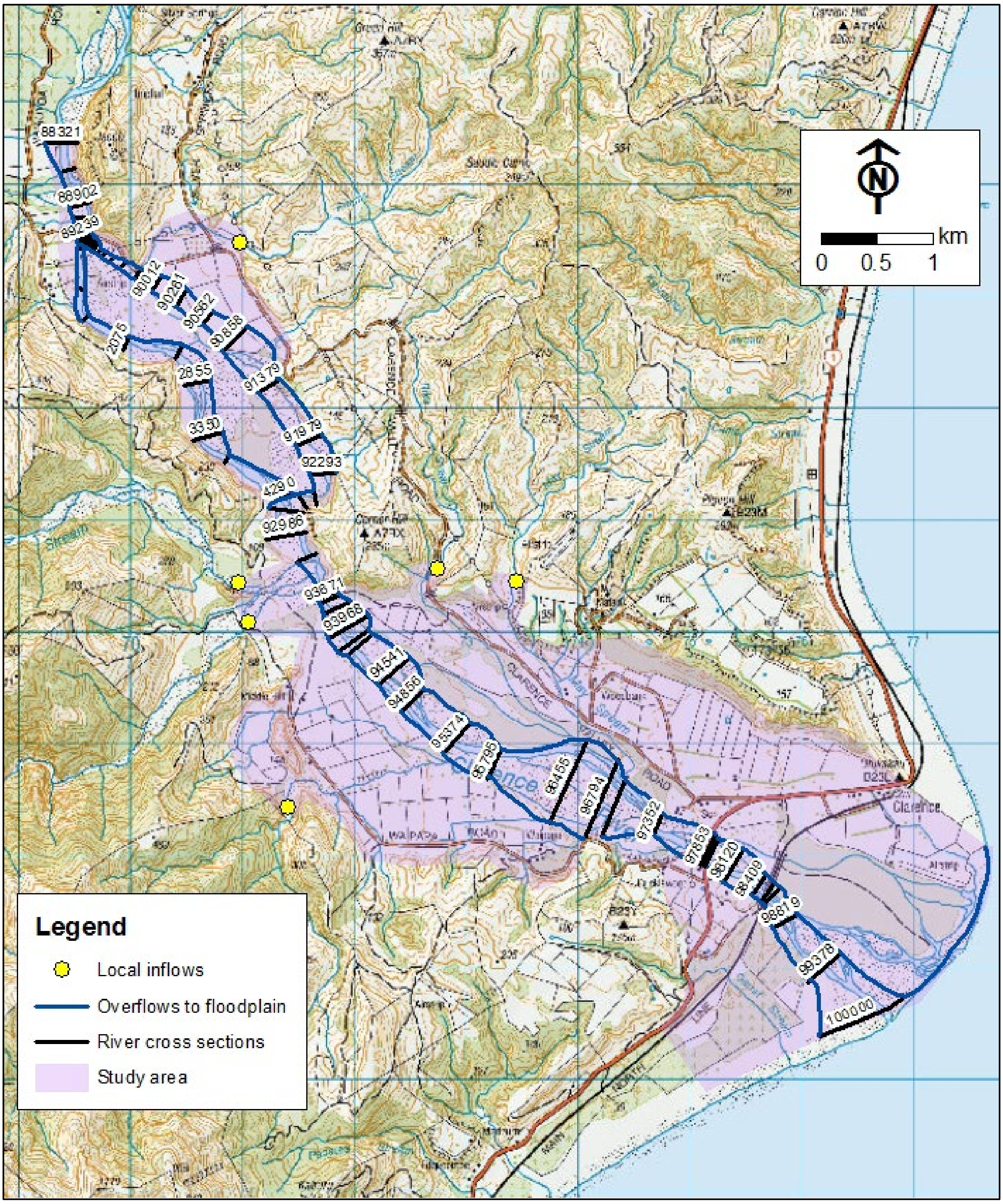


Figure 3-4: Post-earthquake Waiau Toa/Clarence River model schematic

Channel roughness
A Manning's n value of 0.045 has been used for the bed resistance along the Waiau Toa/Clarence River. This is a relatively high value of 'n' for a braided gravel-bed river, but it was considered necessary to take into consideration any channel vegetation and the relatively large boulder sizes. As the model is not able to be calibrated, a relatively conservative approach was taken.

Structures
The 1D model does not include the SH1 road bridge or the railway bridge (Figure 3-5). Under normal circumstances, these bridges have good clearance, and only produce local increases in water level (e.g. around the piers). The model assumes no significant blockage of either bridge.

Figure 3-5: Looking downstream along the Waiau Toa/Clarence River to the SH1 road bridge and the railway bridge

3.3.2 2D floodplain model

The 2D component of the model covers the Waiau Toa/Clarence floodplain from the river mouth to ~10.5 km upstream. To ensure that additional runoff from the 6 main tributaries near the coast were properly represented, local tributary inflows were added to the model grid for some model scenarios. Figure 3-3 and Figure 3-4 show the inflow locations. The floodplain topography and roughness used in the model 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 the Waiau Toa/Clarence River and floodplain, high resolution topographic data was obtained from two LiDAR (aerial laser scanning) surveys. The latest survey was flown between 3 December 2016 and 6 January 2017 by AAM NZ Limited. This work was commissioned by Land Information New Zealand (LINZ), immediately after the 2016 Kaikōura Earthquake Sequence. The detail provided by LiDAR data can be seen in Figure 3-6.

LiDAR data collected on 10 and 17 July 2012 was also used in this study to model the likely extent of flooding before the 2016 Kaikōura Earthquake Sequence. Both sets of LiDAR data provided give elevations in New Zealand Vertical Datum 2016 (NZVD2016).

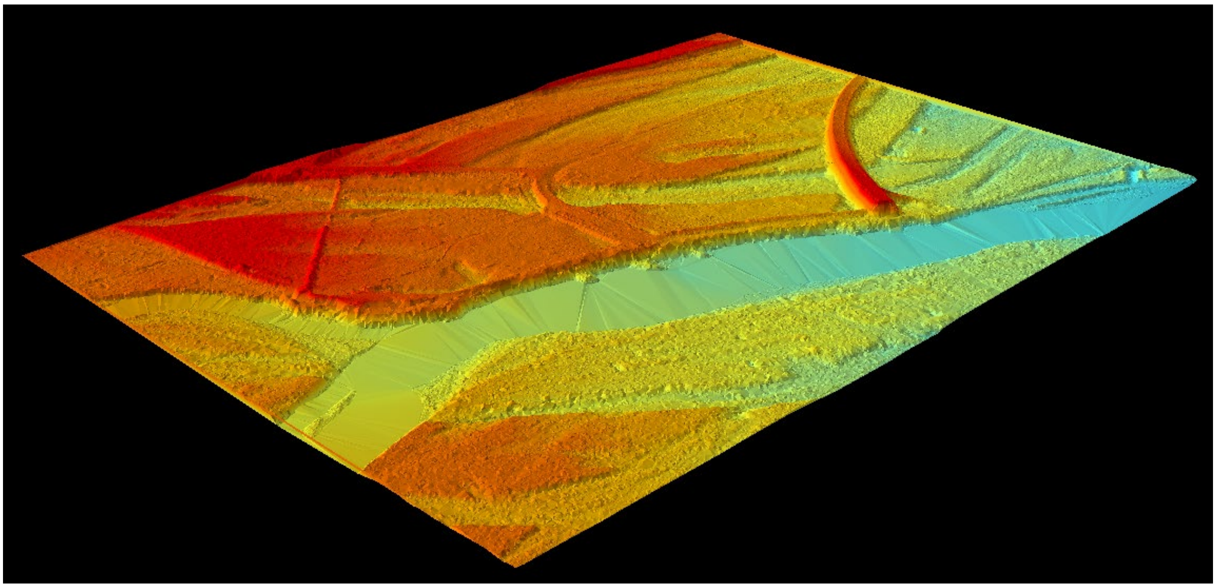


Figure 3-6: 3D image of LiDAR data for the Waiau Toa/Clarence River and floodplain with elevated embankment for SH1 road bridge shown in upper right (with vertical scale exaggerated by a factor of 2)

Water levels and flows on the floodplain were resolved on a rectangular grid. The size of the grid was based on the level of detail required, model stability, and computational efficiency (i.e. computer capacity and speed). For this model the 1 m digital elevation model (DEM), generated using the LiDAR data, has been used to produce a grid 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.

To take into consideration some of the rapid changes occurring along the Waiau Toa/Clarence River, a drone was used in January 2018 to obtain additional ground level information and aerial photography at two key locations:

- downstream of the Clarence Valley Road Bridge
- at the Wharekiri/Miller Stream confluence and downstream of Corner Hill

This data, shown in Figure 3-7, replaced 2016/17 LiDAR data, where it was available.

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

Where vegetation was thick, or there were significant restrictions to the flow path (e.g. hedges, houses, etc.), the Manning's n value can be increased, to increase the surface resistance. Likewise, where there were smoother surfaces (e.g. roads) the Manning's n value can be decreased to reduce surface resistance. For this study, a constant Manning's n value of 0.05 has been used to represent most of the floodplain, which is predominantly land used for grazing/pasture. Where there are significant 'barriers' to the flow (i.e. dense bush and/or trees or houses) a Manning's n value of 0.12 has been used. Figure 3-8 shows the roughness grids for the pre-, and post-, earthquake scenarios

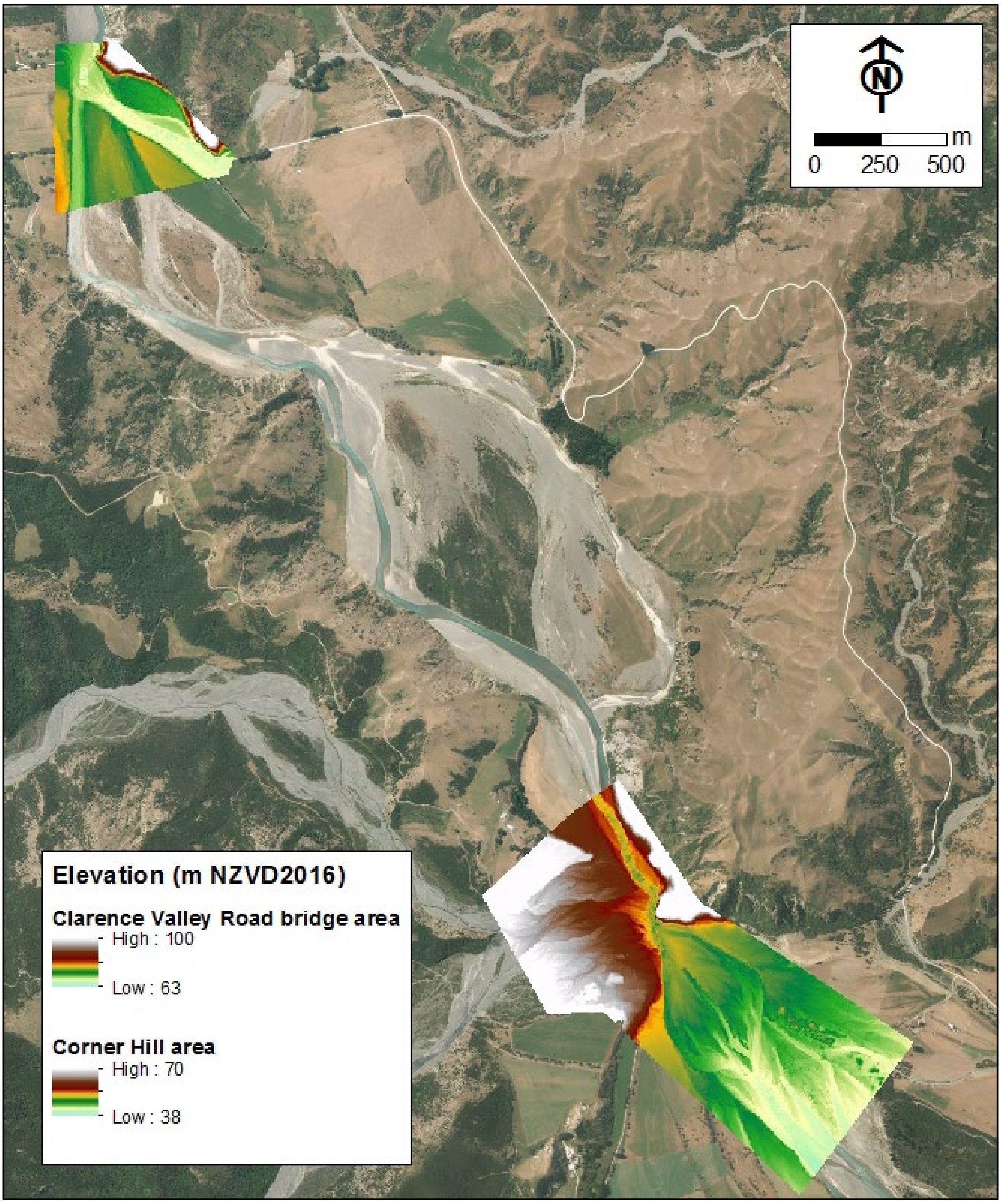


Figure 3-7: January 2018 drone data

3.4 Model calibration

To provide confidence in model predictions, models should be calibrated using historical flood events to ensure they are realistic. For the Waiau Toa/Clarence River, there are very limited flood photographs or measured water levels available. Historic flow records are also limited to short time periods. Changes in the river and floodplain levels post-2016 Kaikōura earthquakes also make any previous flood observations invalid. It has therefore not been possible to calibrate this model.

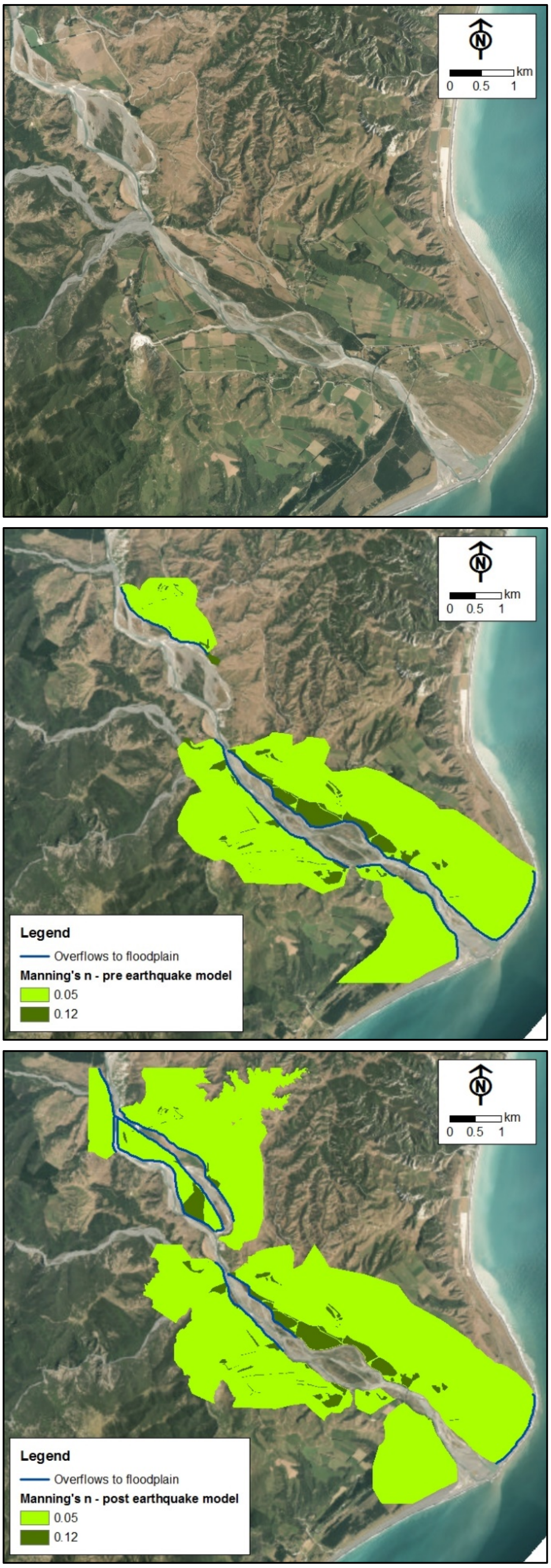


Figure 3-8: 2D model Manning's n roughness maps (compared to aerial photography)

3.5 Present-day design flood events

Present-day design flood events, with small (5 to 10), 50, and 500 year average recurrence intervals (ARIs), have been modelled to provide an indication of how the extent of flooding has changed since the 2016 Kaikōura Earthquake Sequence. In this case, modelling of the smaller events is also of interest as it will provide an indication of areas that may now be subject to flooding during smaller and more frequent flood events (i.e. do we now need to be more concerned during smaller flood events?).

As the Waiau Toa/Clarence River catchment is large, both north-westerly flood events (i.e. high flows originating in the upper catchment) and widespread southerly or easterly flood events (i.e. high flows over the whole catchment, focussing more on the coastal catchment area) have been considered. The design flood events were simulated over a 37-hour period with all model simulations based on a 0.5 second time step, to ensure stability. Results were saved every 15 minutes, and computer run times (for each simulation) were around 1 to 1.5 days.

The final elevation of the new stopbank, located on the true left (northern bank) on the Foster's property, is currently not known. For these design flood events, it was assumed that the new Foster's stopbank was not overtopped and did not fail due to lateral erosion (i.e. an arbitrarily high bank was placed along the true left bank in the model grid). This scenario is largely 'hypothetical' as it is unrealistic to expect this stopbank to withstand a 500 year ARI flood event. This scenario is, however, less complicated when examining the sensitivity of the model to the various model parameters in Section 3.6, and provides additional information regarding the susceptibility of the bank opposite Foster's stopbank to flooding, when the river protection works are place. The derivation of the design flow hydrographs, and design flood events, is outlined below.

3.5.1 Waiau Toa/Clarence River at Clarence Valley Road design flows

To determine design flow hydrographs for the Waiau Toa/Clarence River (upstream of the Clarence Valley Road bridge site), flow records for Glen Alton (Site 62106) and Clarence Valley Bridge (Site 62107) were analysed. Flow hydrographs from both sites were divided by flood event peak flows to produce non-dimensional hydrograph profiles (Figure 3-9). The 1983 hydrograph profile was considered a 'typical' flood hydrograph and was scaled by the design flows to produce design flow hydrographs (Figure 3-10).

3.5.2 Waiau Toa/Clarence River coastal tributary design flows

To determine design hydrograph profiles for the Waiau Toa/Clarence River coastal tributaries, the flow records for Rosy Morn (Site 63501), Kowhai River at below Orange Grove (Site 63201) and Charwell at Gorge (Site 64305) were analysed. Flow hydrographs for each site were divided by the peak flow (for each specific flood event) to produce a non-dimensional hydrograph profile for Rosy Morn (Site 63501), Kowhai River (Site 63201) and Charwell River (Site 64305) for periods of high flow. An 'average' hydrograph shape was then produced by fitting a hydrograph through the hydrographs (Figure 3-11). The non-dimensional hydrograph was then scaled by the peak design flows for each tributary to produce the design flow hydrographs. Figure 3-12 shows the design flow hydrographs for a 500 year ARI flood event.

3.5.3 Downstream sea boundary water level

Model runs were completed using a constant water level of 1.75 m NZVD2016. This level represents a relatively high tide combined with storm surge, and seasonal/ENSO fluctuations (see Section 3.2).

3.5.4 North-westerly flood event

During north-westerly flood events, spill over rainfall into the upper Waiau Toa/Clarence River catchment usually causes the Waiau Toa/Clarence and Acheron rivers to rise. During these flood events, there is often little or no rainfall in the Waiau Toa/Clarence River coastal catchments. The north-westerly flood event scenarios modelled are summarised in Table 3-7.

For the north-westerly events it was assumed that all flood inflows are from upstream of the Clarence Valley Road bridge site. A 5 year ARI flood event has been modelled, as well as the 50 and 500 year ARI flood events, for flood warning purposes (i.e. to determine whether the extent of flooding has increased post-earthquakes, for smaller, more frequent flood events).

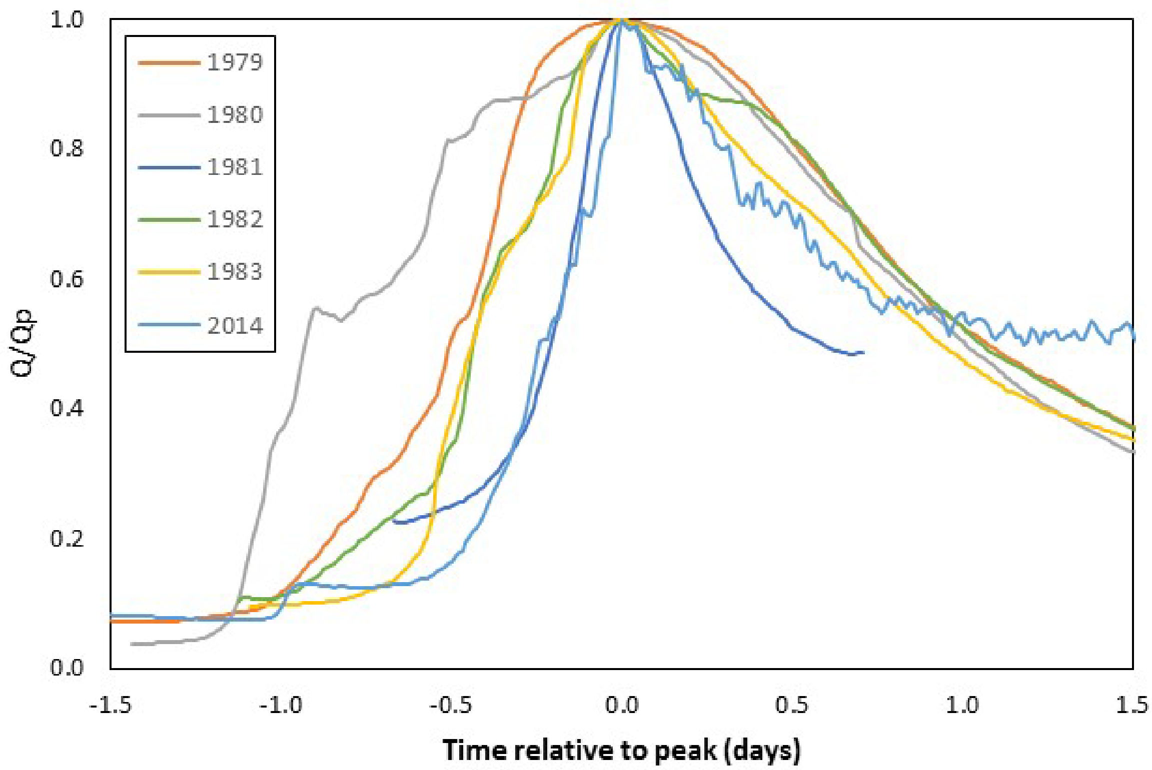


Figure 3-9: Non-dimensional hydrographs for the upper Waiau Toa/Clarence River catchment inflows

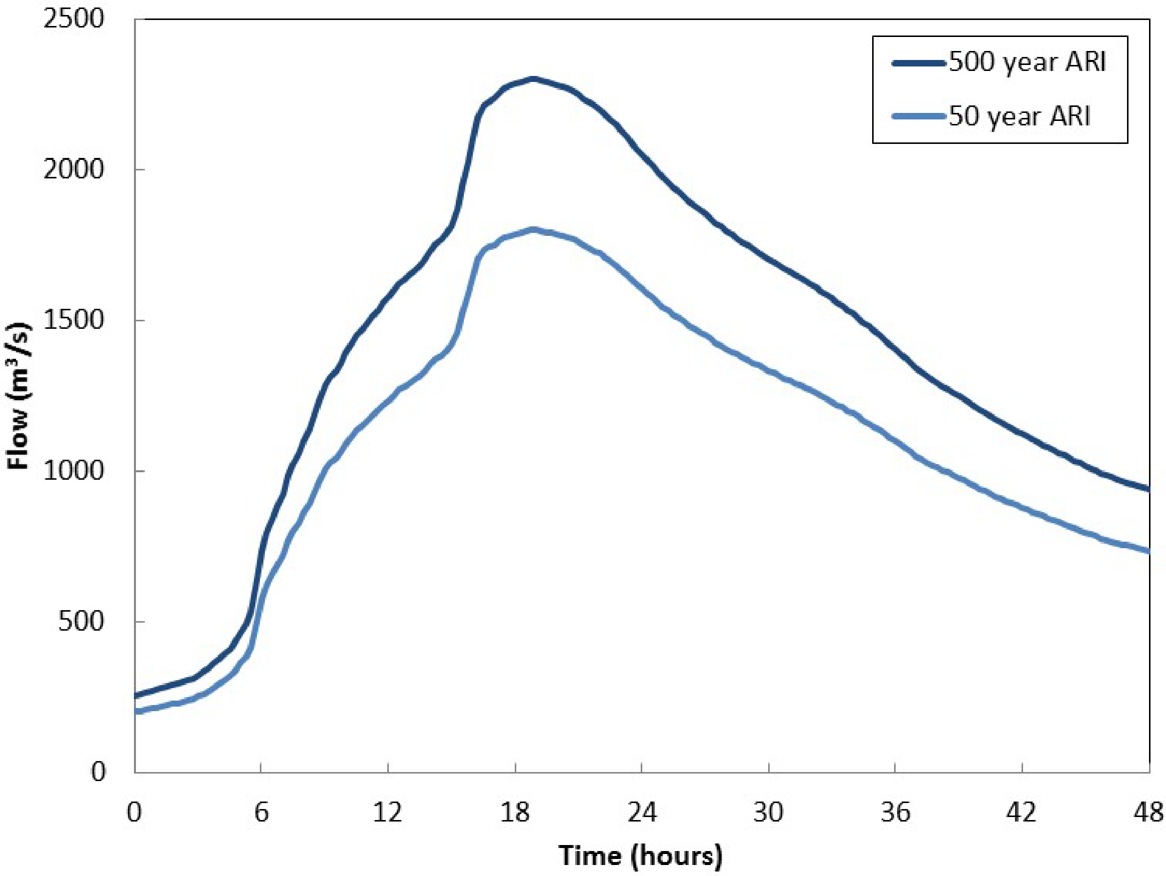


Figure 3-10: Design flows for the upper Waiau Toa/Clarence River catchment inflows at Clarence Valley Road bridge site

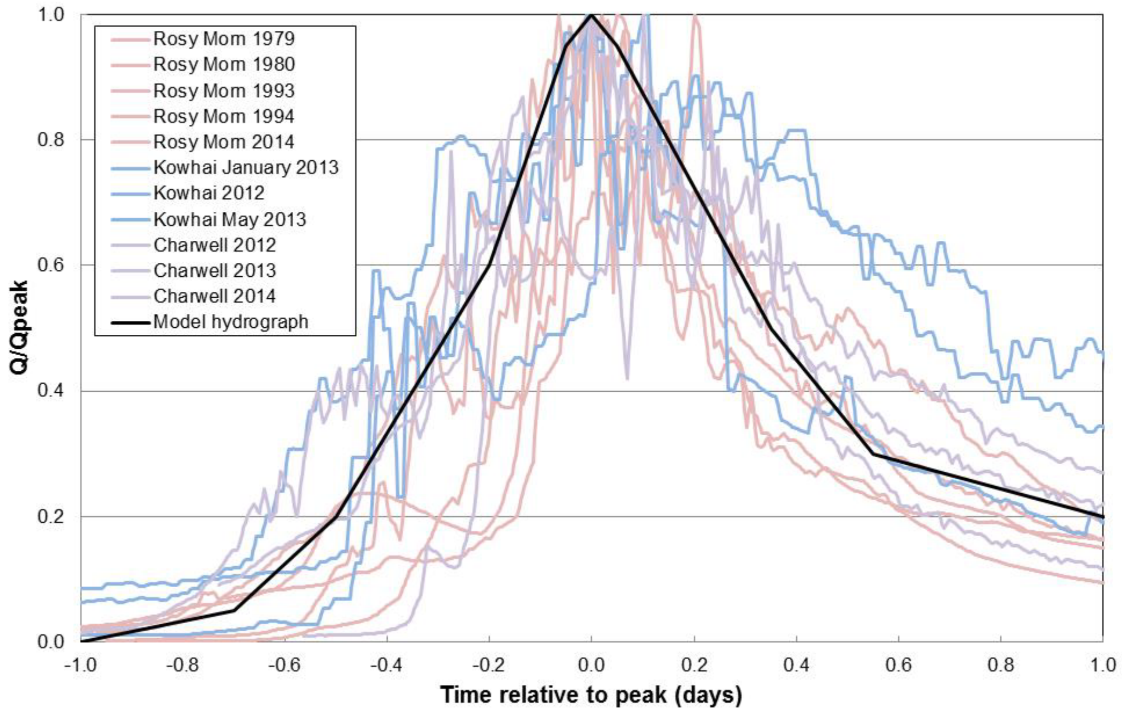


Figure 3-11: Non-dimensional hydrographs for the coastal tributaries of the Waiau Toa/Clarence River

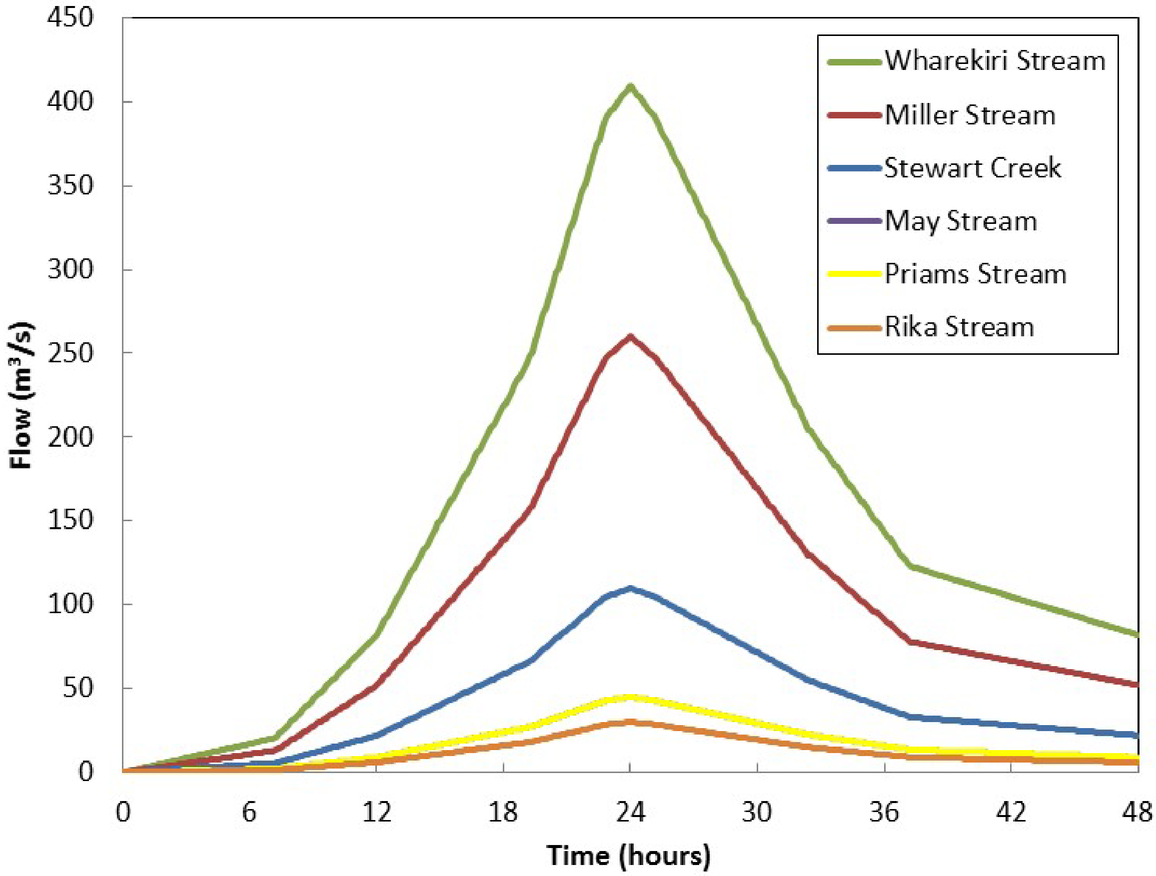


Figure 3-12: 500 year ARI design flows for the coastal tributaries of the Waiau Toa/Clarence River

3.5.5 Southerly or easterly flood event

During a southerly or easterly flood event, high-intensity rainfall can occur in all the coastal tributary catchments of the Waiau Toa/Clarence River, causing all tributaries to have high flows. For large, widespread flood events, rainfall may also be high over the middle and upper Waiau Toa/Clarence River catchments. This is likely to produce a hydrograph with a longer period of high flows, but the flow peak is likely to be attenuated as it travels along the river system to reach the Waiau Toa/Clarence River at Clarence Valley Road bridge site. The flow peak is also likely to occur after the peak flow in the smaller (and closer) coastal tributaries. Design flows from the middle and upper catchment have therefore been modelled as a constant flow for this flood scenario. The southerly or easterly flood event scenarios modelled are summarised in Table 3-7.

Table 3-7: Waiau Toa/Clarence River design flood events

Design flood event (ARI)	Waiau Toa/Clarence River at Valley Road bridge ARI	Peak flow (m^3/s)	Coastal tributary ARI	Combined tributary peak flow (m^3/s)
<u>North-westerly</u>				
5 year	5 year	700	-	-
50 year	50 year	1800	-	-
500 year	500 year	2300	-	-
<u>Southerly or easterly</u>				
10 year	~mean annual flood	400	10 year	390
50 year	5 year	700	50 year	560
500 year	50 year	1800	500 year	890

3.5.6 Model results

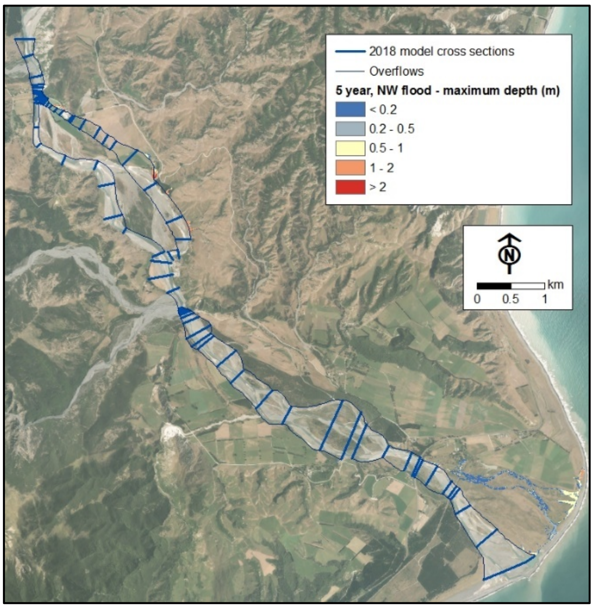
Maximum flood depths for the present-day north-westerly, and southerly or easterly, flood events are shown in Figure 3-13 and Figure 3-14, respectively. These model results do not take into consideration any changes to the river system beyond January 2018 (i.e. the model does not include any further scour, erosion, and channel aggradation).

3.6 Model sensitivity analysis

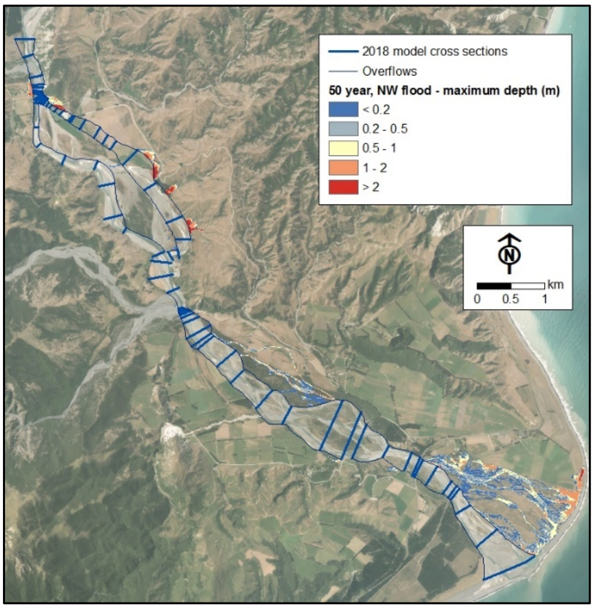
As the model was not able to be calibrated, sensitivity tests were undertaken to determine the sensitivity of flood inundation to various model parameters and assumptions for the present-day model. These are described below.

<u>River channel roughness</u>
The volume of flood water entering the floodplain is somewhat reliant on the correct roughness values being used to represent the river system (i.e. if Manning's n roughness increases, water levels in the river will increase and additional flow may pass onto the floodplain).

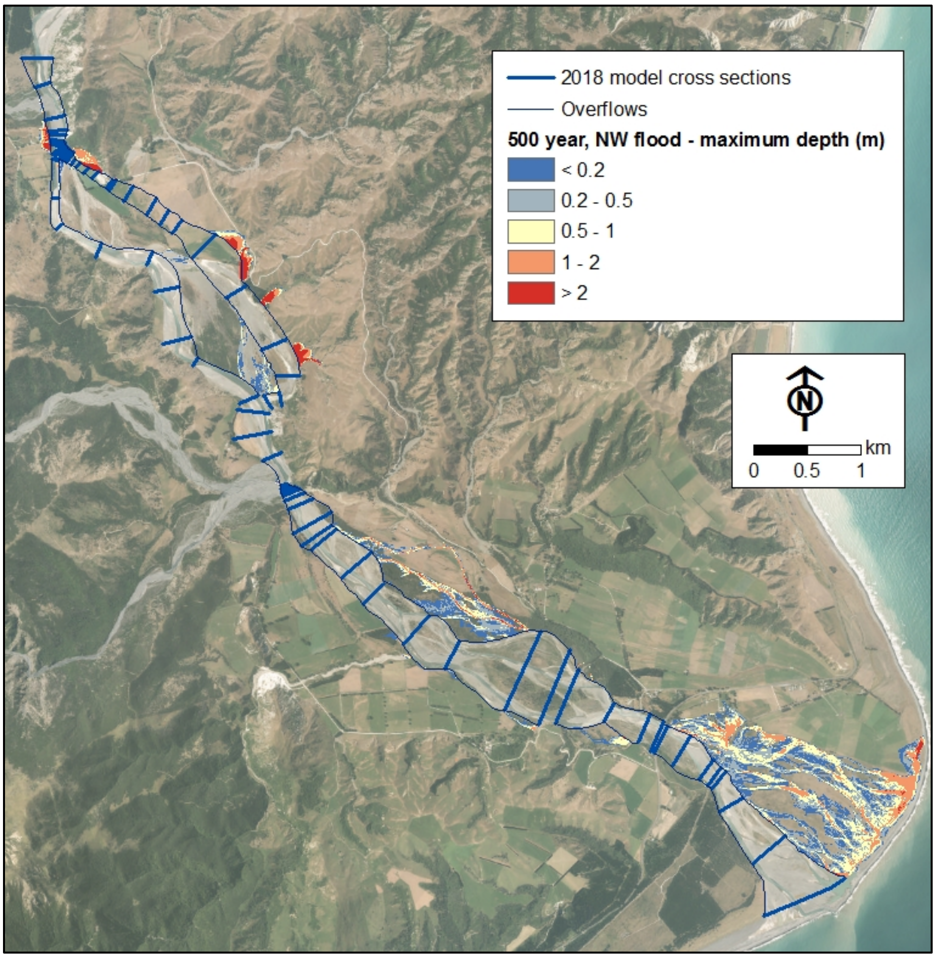
Manning's n roughness values along the river channel were increased by 25% (i.e. the 'base' roughness was increased from 'n' = 0.045 to 0.056) for the 500 year ARI north-westerly flood event. This is a relatively high roughness value for this gravel-bed channel and would only be expected to be valid if there was significant vegetation present. The increase in maximum water depths from increased river channel roughness (for a 500 year ARI north-westerly flood event) is shown in Figure 3-15. This figure shows that the higher channel roughness produces maximum water levels over 0.3 m higher in many areas.



5 year ARI

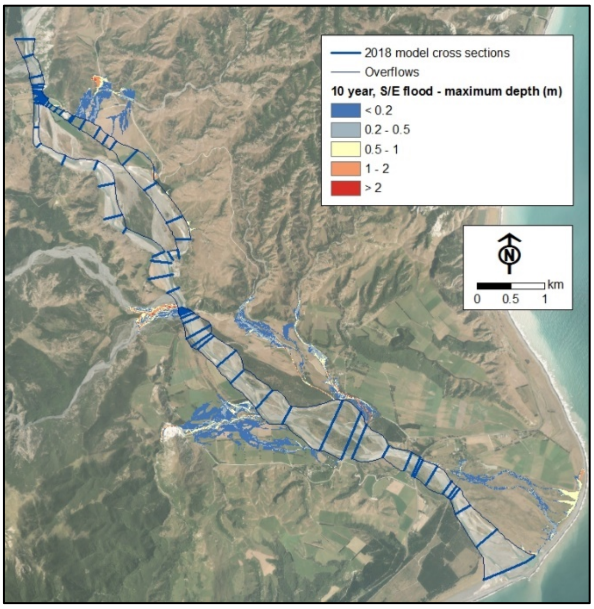


50 year ARI

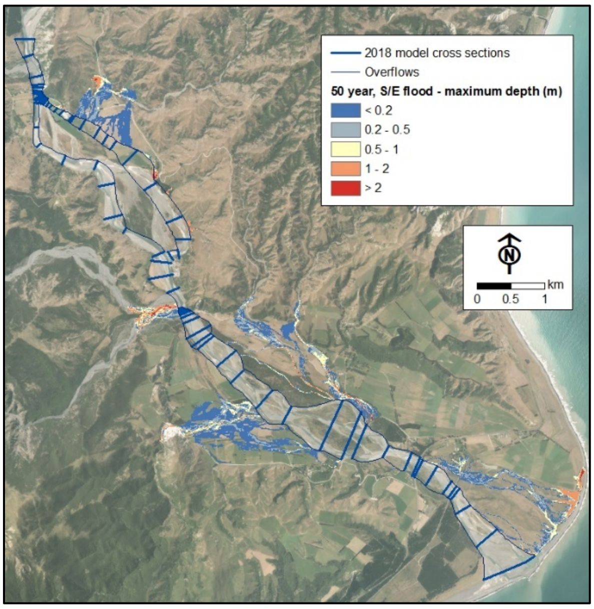


500 year ARI

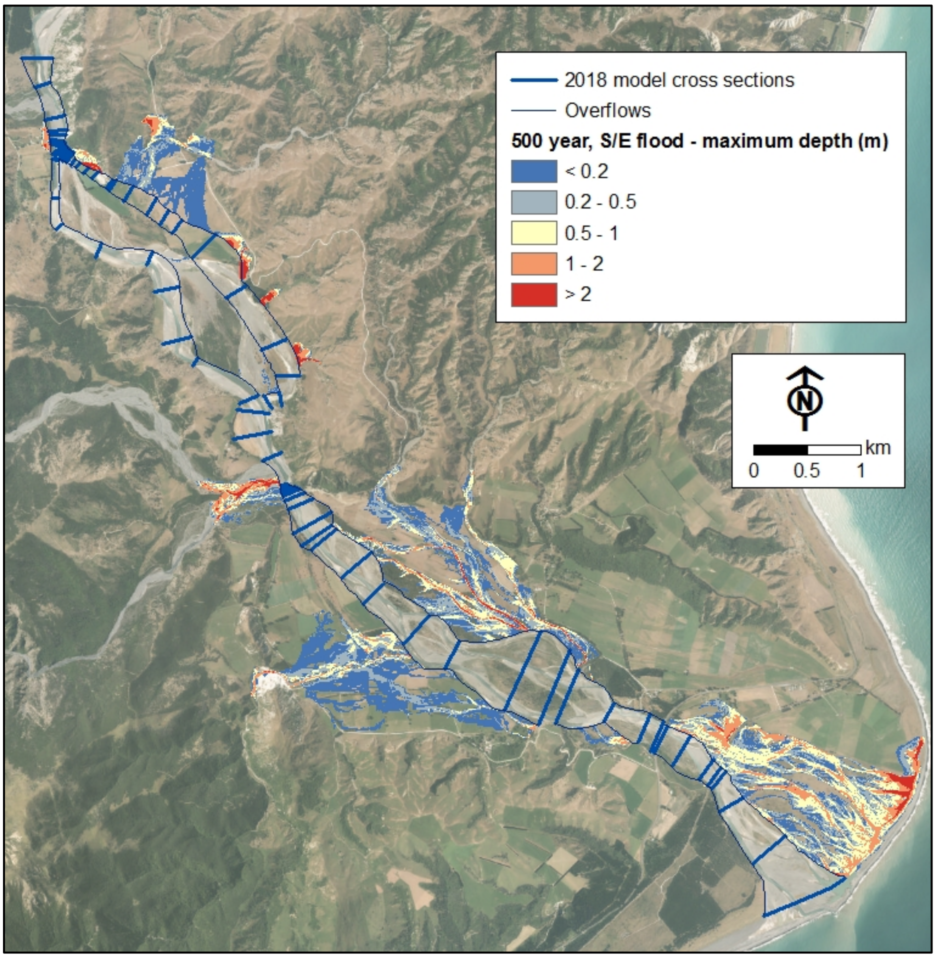
Figure 3-13: Present-day north-westerly design flood events - maximum water depths



10 year ARI



50 year ARI



500 year ARI

Figure 3-14: Present-day southerly or easterly design flood events - maximum water depths

Floodplain roughness

Floodplain roughness values used to represent the Waiau Toa/Clarence River floodplain are described in Section 3.3.2. The Manning's n floodplain roughness value was increased by 25% for the 500 year ARI southerly or easterly flood event.

The increase in maximum water depths from increased floodplain roughness (for a 500 year ARI southerly or easterly flood event) is shown in Figure 3-16. Maximum floodplain water depths generally increase by less than 0.1 m when floodplain roughness is increased by 25%; the exception being where there are higher flow velocities and depths. For example, along the Wharekiri and Miller watercourses water depths increase by more than 0.3 m.

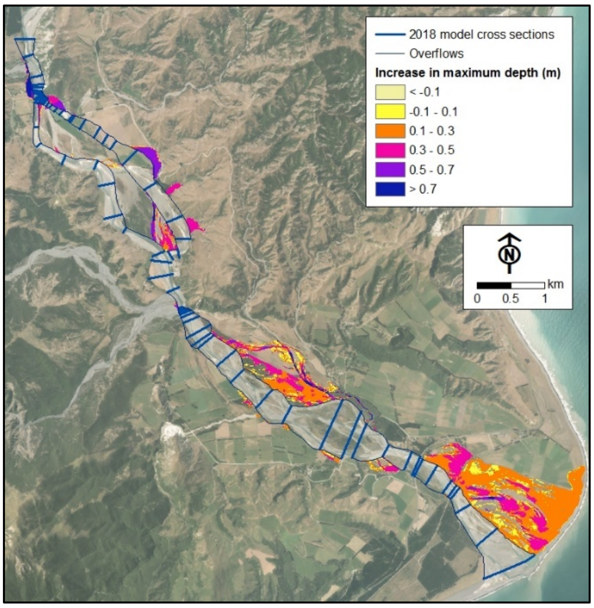


Figure 3-15: River channel 'n' increased by 20% for present-day 500 year ARI north-westerly flood event - increase in maximum water depths

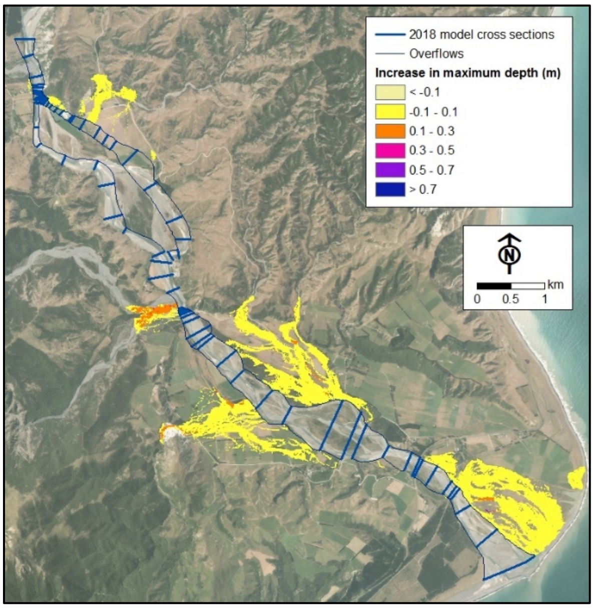
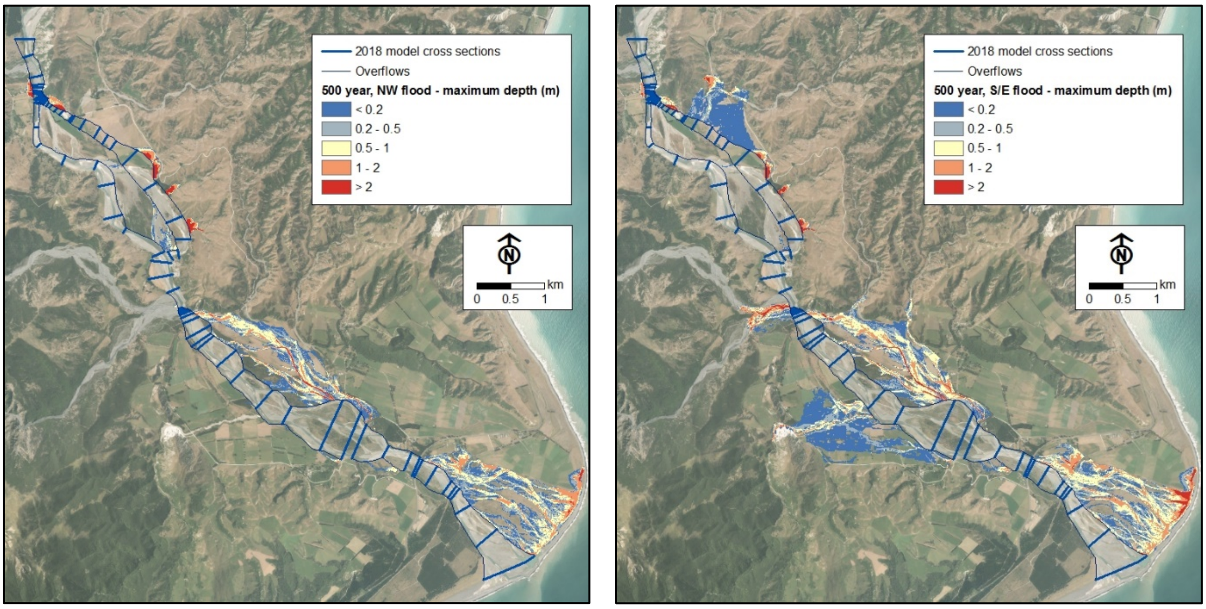


Figure 3-16: Floodplain 'n' increased by 25% for present-day 500 year ARI southerly or easterly flood event – increase in maximum water depths

Stopbank breach (Foster's stopbank removed)

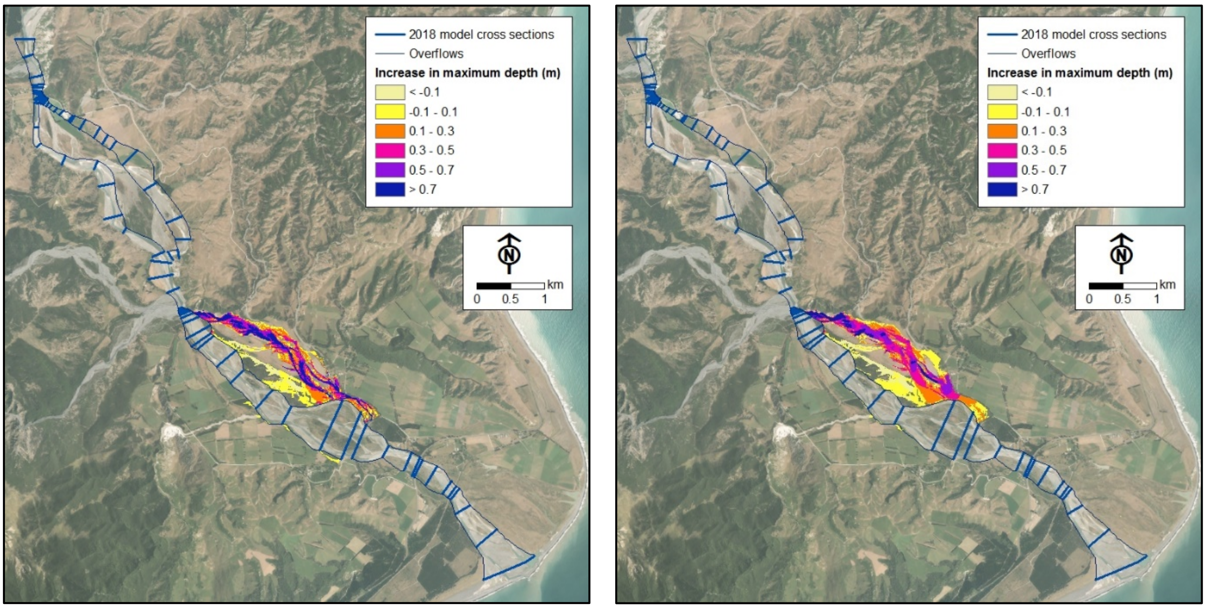
For the present-day design flood events modelled in Section 3.5, it was assumed that the new Foster's stopbank was not overtopped and did not fail due to lateral erosion. In reality, the highly erosive nature of the braided river is likely to lead to failure of the stopbank by either overtopping or lateral erosion during a 500 year ARI flood. For these sensitivity tests, the 500 year ARI north-westerly and southerly or easterly flood events have been modelled with the Foster's stopbank (located on the true left/northern bank) removed. Figure 3-17 and Figure 3-18 show an increase in the amount of flood water on the floodplain downstream of the Foster's stopbank.

Water depths increase by up to 1 m deep on the Clarence Valley Road for the southerly or easterly flood event with the Foster's stopbank removed. Further downstream, on the berm/floodplain area upstream of Hammy's Groyne (see Figure 2-2 for location), additional flood water is also directed towards Hammy's Groyne when the Foster's stopbank is not present. There are no significant changes to water depths adjacent to the Clarence settlement, or downstream of SH1 (i.e. flood water depths are not dependent on the integrity of the Foster's stopbank in these areas). The Clarence Settlement does, however, rely on both Hammy's Groyne, and a stopbank running along the riverbank from Hammy's Groyne to the SH1 Bridge, for flood protection. These structures need to be monitored, and maintained, to minimise flood risk within the settlement.



North-westerly flood event **Southerly or easterly flood event**

Figure 3-17: Present-day 500 year ARI (Foster's stopbank removed) - maximum water depths

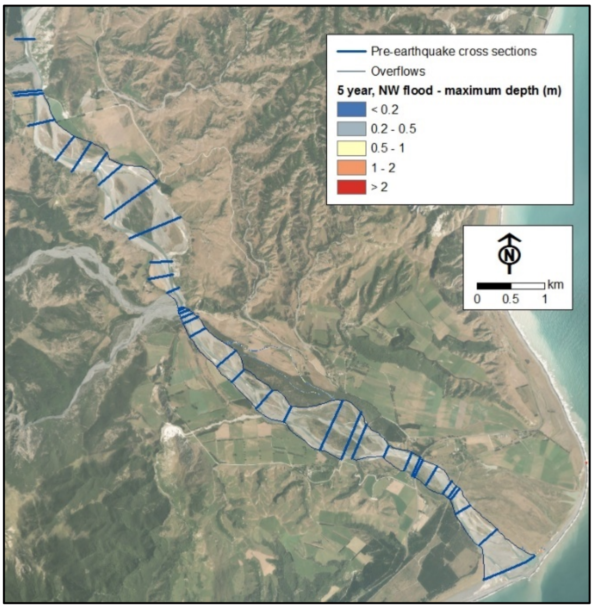


North-westerly flood event **Southerly/easterly flood event**

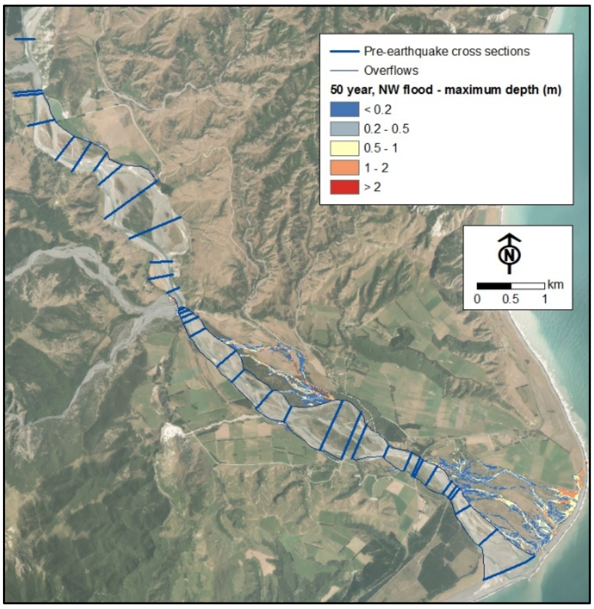
Figure 3-18: Present-day 500 year ARI (Foster's stopbank removed) - increase in maximum water depths

3.7 Present-day comparison with pre-2016 Kaikōura Earthquake Sequence

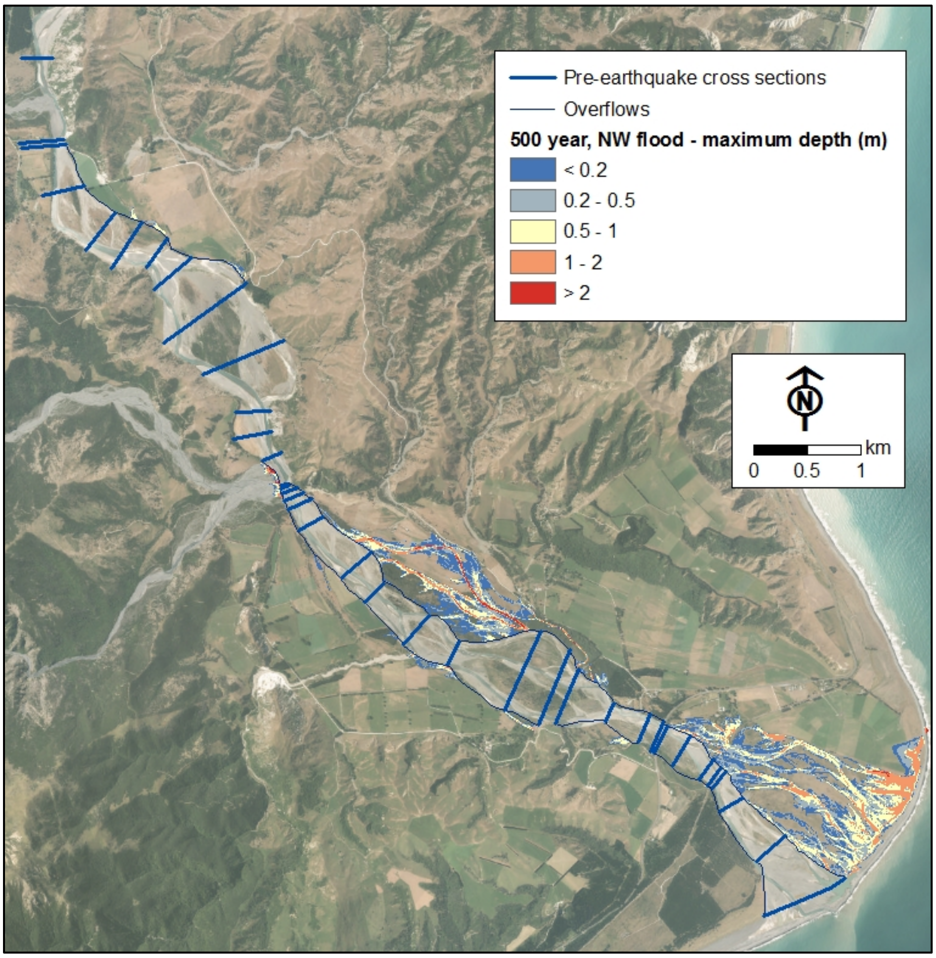
To compare the present-day flood hazard, to that prior to the 2016 Kaikōura Earthquake Sequence, the pre-earthquake model was used to model north-westerly design flood events. The maximum modelled water depths for 5, 50, and 500 year ARI flood events are shown in Figure 3-19.



5 year ARI



50 year ARI



500 year ARI

Figure 3-19: Pre-2016 Kaikōura Earthquake Sequence north-westerly design flood events - maximum water depths

The model results indicate that the 2016 Kaikōura Earthquake Sequence has increased the potential extent and depth of flooding for large flood events, particularly if the Foster's river protection and stopbank fails. The following areas appear to be more susceptible to flooding post-2016 Kaikōura Earthquake Sequence:

- Clarence Valley Road bridge area
  - immediately upstream and downstream of the bridge site on the true right bank
  - downstream of the bridge site on the true left bank.
  - Clarence Valley Road, approximately 1.8 km downstream of the bridge site.

- True left bank downstream of Corner Hill (assuming Foster's river protection and stopbank are compromised)
  - floodplain on Foster's property and ~1 km length of Clarence Valley Road, along with two smaller sections of the road further downstream.
  - berm/floodplain upstream of Hammy's Groyne.

- Downstream of SH1 bridge
  - more flow on northern floodplain between railway and SH1.

3.8 Design flood events (including climate change to 2120)

For land use planning and flood mitigation, the impacts of future climate change on the Waiau Toa/Clarence River and floodplain need to be taken into consideration. Flood modelling in this section incorporates climate change to 2120, with expected climate change impacts described below. For these design flood events, it was assumed that the Foster's stopbank fails (i.e. the arbitrarily high bank was replaced with ground elevations along the true left bank in the model grid). This is a more realistic scenario for land use planning and flood mitigation purposes.

3.8.1 Climate change

Climate change impacts are complex and, at present, not fully known. Some of the likely changes are:

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 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 Waiau Toa/Clarence River has a relatively steep gradient, any predicted increases in sea level will not have any impact on flood water levels upstream of the river mouth.

3.8.2 Design flows

To account for climate change to 2120, the present-day design flows were increased by 25%, for both north-westerly and southerly or easterly flood events. 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 could, therefore, be more representative of a mid-range RCP air temperature projection for the Clarence / Waiau Toa River.

3.8.3 Downstream sea boundary water level

The present-day sea level of 1.75 m NZVD2016 was increased by 1 m, to 2.75 m NZVD2016, to account for sea level rise.

3.8.4 Model results

Modelled maximum flood depths for the north-westerly, and southerly or easterly, flood events are shown in Figure 3-20 and Figure 3-21, respectively. These model results do not take into consideration any changes to the river system beyond January 2018 (i.e. the model does not include any further scour, erosion, and channel aggradation).

The increase in maximum water depths for the 500 year ARI flood events, with Foster's stopbank removed and climate change taken into consideration, are shown on Figure 3-22. This shows that, as well as additional water passing onto the floodplain downstream of Foster's stopbank, all other floodplain areas with overflows have increased maximum water depths.

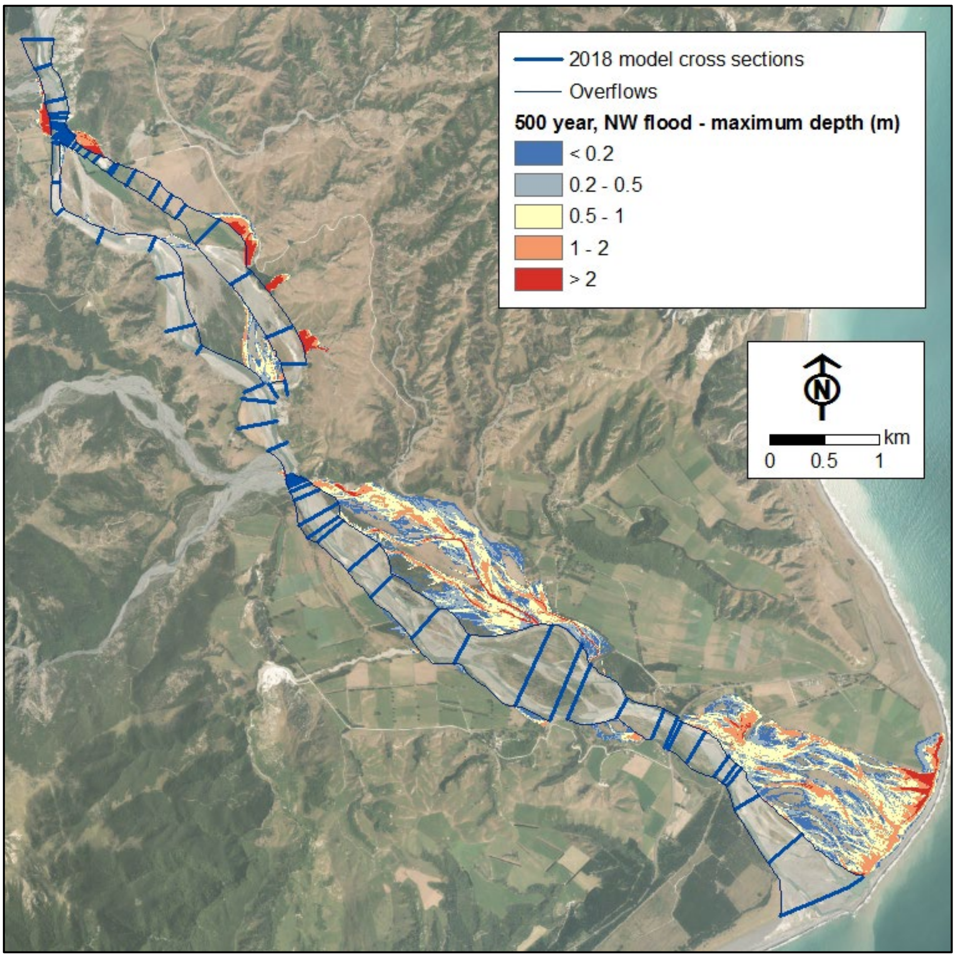


Figure 3-20: Design 500 year ARI north-westerly flood (with climate change to 2120) – maximum depths

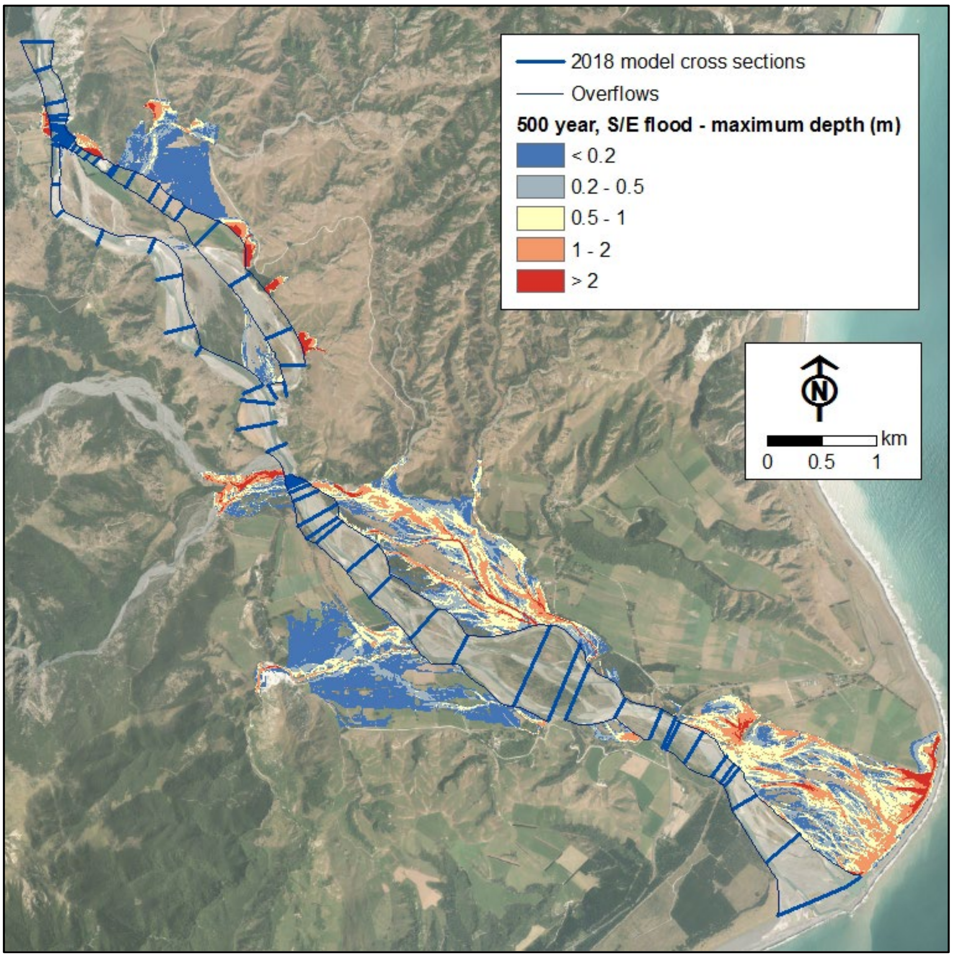
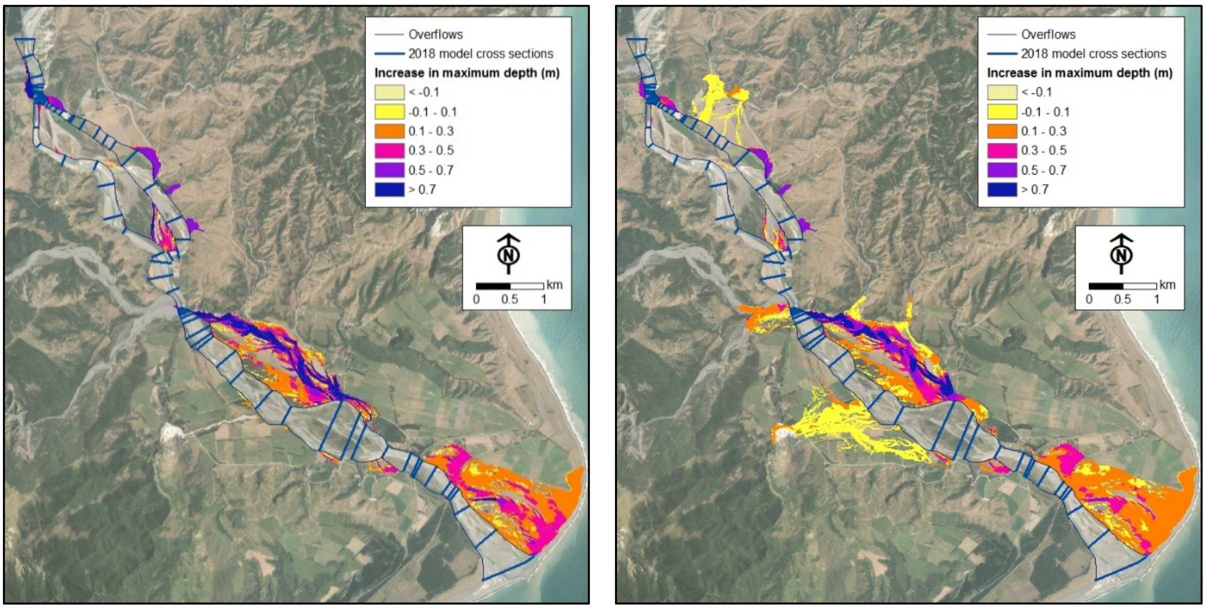


Figure 3-21: Design 500 year ARI southerly / easterly flood (with climate change to 2120) – maximum depths



North-westerly flood event **Southerly / easterly flood event**

Figure 3-22: Design 500 year ARI flood (no Foster's stopbank and climate change to 2120) compared to present-day (with Foster's stopbank) - increase in water depths

Increases in water depths tend to be greater where floodplain flows are confined by natural barriers. For example, upstream of the Clarence Valley Road bridge site maximum water depths increase, by over 1.3 m, with climate change (i.e. flow increase of 25%). Maximum water depths also increase by around 0.5 to 0.7 m along the true left bank of the new channels formed upstream of Corner Hill. Where the flow can spread out over a wide area of floodplain, increases in maximum water depths tend to be less. Downstream of Corner Hill, increases in water depths are generally less than 0.5 m. This includes along the overflow channel downstream of Foster's stopbank, where the more significant increase in water depth is due to the stopbank being removed (rather than climate change which only increases water depths by approximately 0.2 m).

3.9 Derivation of high hazard areas

High hazard areas are defined in the Canterbury Regional Policy Statement (CRPS) 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 flood event.***

During a 500 year ARI flood event in the Waiau Toa/Clarence River, it is highly likely that the new bank protection works downstream of Corner Hill will fail. Significant scour, erosion, and aggradation is also likely to occur throughout the river system. Therefore, to allow for climate change to 2120 and realistic extreme flood conditions, the modelled high hazard area for the Waiau Toa/Clarence river and floodplain includes:

- a 25% increase in the peak present-day 500 year ARI flows,
- a 1 m increase in present-day sea levels,
- failure of the Foster's bank protection works downstream of Corner Hill.

Both the north-westerly, and southerly or easterly, 500 year ARI flood scenarios were modelled in Section 3.8, with maximum water depths shown in Figure 3-20 and Figure 3-21, respectively. High hazard areas were determined for both scenarios and then combined into one dataset. Figure 3-23 identifies these areas on the Waiau Toa/Clarence floodplain that meet the CRPS definition of high hazard, based on the above assumptions and both north-westerly, and southerly or easterly, 500 year ARI flood events.

As the computer model used in this investigation has a fixed bed, it does not take into consideration scour, erosion, and lateral movement (including channel avulsions) of the gravel river channels. Additional areas of the floodplain are, therefore, likely to meet the high hazard classification as the river channels continue to migrate across the floodplain.

3.10 Flood warning

For flood events originating in the upper catchment, a relationship between measured water levels and flow has been estimated for the Clarence Valley Road water level site (cross section 89161). This was based on the post-earthquake Waiau Toa/Clarence River model and included drone data (ground levels) collected in January 2018.

Figure 3-24 details the estimated water level versus flow relationship (i.e. rating curve) for the water level site for January 2018. This rating will continue to change with each flood event, although it may be able to provide an indication of the relative size of any flood event.

As a guide, if the water level at the Clarence Valley Road bridge site increases above a base flow by:

- 3 m ~5 year ARI north-westerly flood event of around 700 m^3/s.
- 4 to 5 m ~50 year ARI north-westerly flood event of around 1800 m^3/s.
- > 5 to 5.5 m ~500 year ARI north-westerly flood event of around 2300 m^3/s.

Note: At the time of the drone survey in January 2018, the water level recorder reduced level at zero stage was approximately 69.4 m (NZVD 2016).

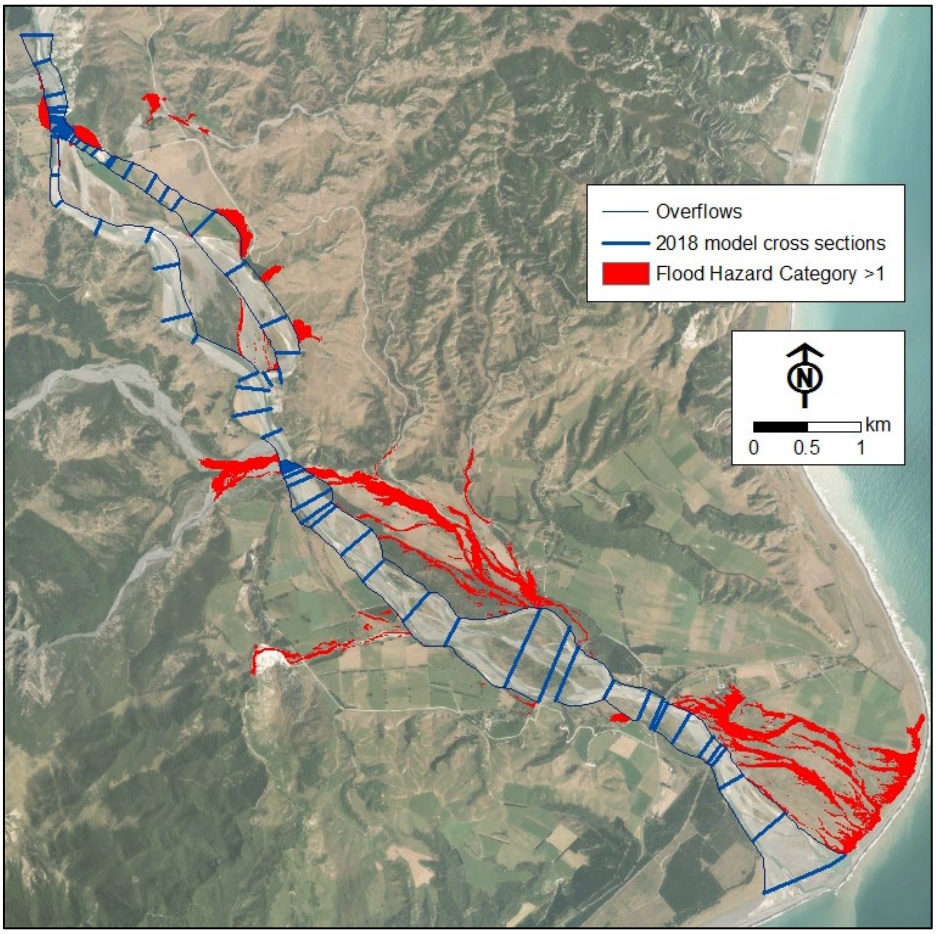


Figure 3-23: High hazard flood areas for the Waiau Toa/Clarence floodplain (fixed bed model)

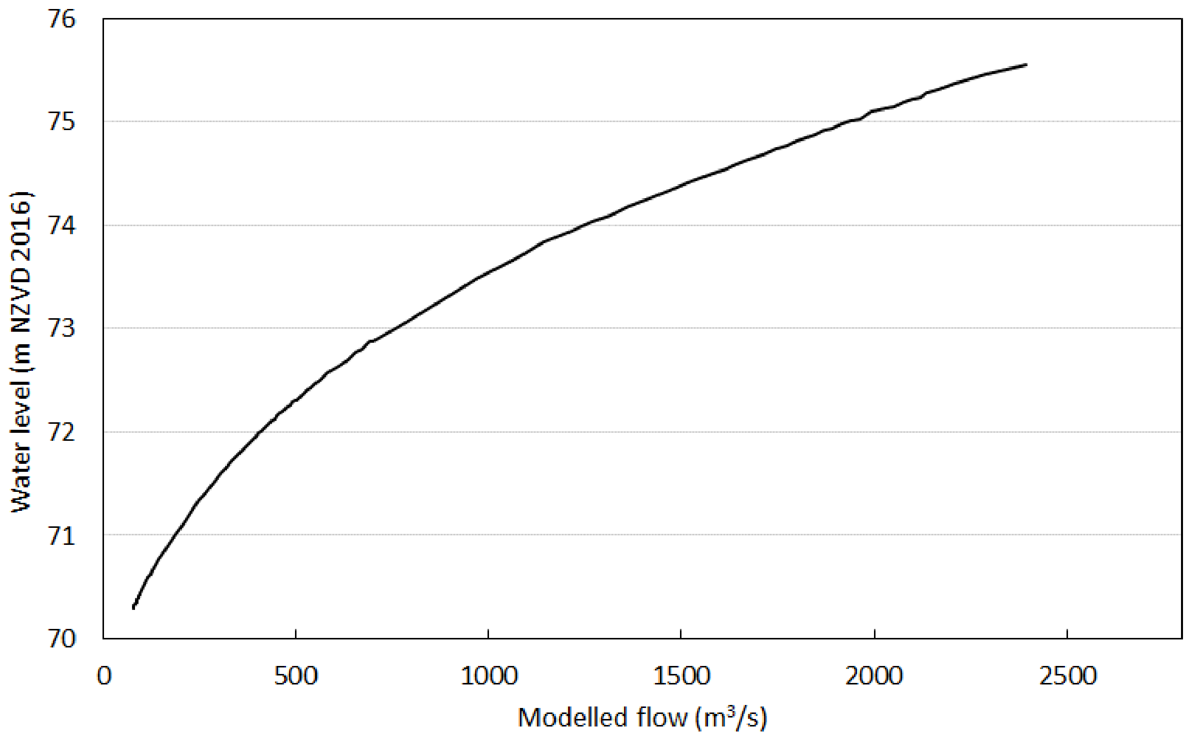


Figure 3-24: Estimated rating curve for the Clarence Valley Road water level recorder (January 2018)

4 Discussion

The model used in this investigation has a fixed bed level and does not simulate changes in bed levels due to scour, aggradation or channel avulsions – all processes that are likely to be occurring during a large flood event in a steep, gravel-bed river. The model has also not been calibrated against any historical flood events, so there is considerable uncertainty in the flood water levels, depths and extents produced. The main model uncertainties, and the data that would be required to calibrate the model, are summarised below. The model output should only be used to provide guidance, in conjunction with other available information.

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 hydrographs, roughness values and energy loss parameters).
- Topographic data (e.g. LiDAR data, estimated submerged bed levels, continuously changing river system with bank and channel erosion post-earthquakes).
- 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 only 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 better calibrated

To enable the model results to be used more confidently, monitored water level/flow recorders would be required to more accurately determine flood flows, ideally over a long period of time. Flood information would also need to be gathered during and/or immediately after large flood events. This information should ideally include:

- Photographs of flood inundation, including when and where the photographs were taken.
- Pegging or marking the peak water levels.
- Observations of any stopbank breaches (i.e. size, time).

Unfortunately, flood events often occur during the hours of darkness. For the Waiau Toa/Clarence River, access to the area may also be compromised during a large flood event. For example, road access may not be possible due to landslides, flooding in the tributaries that the access roads cross, and/or damage to bridge structures. Helicopters may also not be available, or they may not be able to fly due to weather conditions. It would therefore be advantageous for locals, who know the area well, to document as much as is practically possible (e.g. taking photos and marking flood levels and times that they occurred).

5 Conclusions

When using the modelling results from this study, it is important to note that the model used in this study has a fixed bed level and does not simulate changes in bed levels due to scour, aggradation or channel avulsions. The model has also not been based on reliable flow data, nor calibrated against any historical flood events. Consequently, there is considerable uncertainty in the flood water levels produced. The model results should therefore only be used to provide guidance, in conjunction with other available information, when determining 500 year ARI flood levels and high hazard areas.

Significant changes to the Waiau Toa/Clarence River and floodplain occurred due to the 2016 Kaikōura Earthquake Sequence. The modelling showed the following areas became more susceptible to flooding:

1. <u>Clarence Valley Road bridge area</u>
    - o immediately upstream and downstream of the bridge site on the true right bank
    - o downstream of the bridge site on the true left bank.
    - o Clarence Valley Road, approximately 1.8 km downstream of the bridge site.

2. True left bank downstream of Corner Hill (assuming Foster's river protection and stopbank are compromised)
    - floodplain on Foster's property and ~1 km length of Clarence Valley Road, along with two smaller sections of the road further downstream.
    - berm/floodplain upstream of Hammy's Groyne.

3. Downstream of SH1 bridge
    - more flow on northern floodplain between railway and SH1.

In the future, climate change is also likely to exacerbate flooding in these areas further due to the increased peak flood flows predicted to accompany higher air temperatures (and higher precipitation). These increases in flooding are likely to be most noticeable immediately upstream of the Clarence Valley Road bridge site, for large flood events such as a 500 year ARI north-westerly flood event. For this scenario, the narrow channel at the bridge site, combined with the reduced channel capacity caused by the Papatea Fault uplift, mean that at high flows this area of channel will act as a constriction to flows. This may cause the water to back up, increasing water depths upstream of the bridge site further, unless the erosive nature of the braided river flows continues to erode the river channels further, increasing the channel capacity. At present it is not known how much additional channel erosion will occur (i.e. how much erosion can occur before bedrock is reached in the gravel riverbed). Conversely, increases in sea level (due to climate change) are likely to only have a small, localised, impact on maximum flood water levels in the riverbed that is immediately adjacent to the sea.

For the same design flood event (e.g. a 500 year ARI), a north-westerly storm is likely to cause more flooding upstream of the Wharekiri and Miller confluence, while a southerly or easterly storm is likely to cause more flooding downstream of the confluence. The reason for this is that coastal tributary inflows for a 500 year ARI flood (mainly from Wharekiri and Miller Streams) push the total Waiau Toa/Clarence River flows up to a higher combined flow.

Areas considered as high hazard in this study, are generally limited to the active braided riverbed and adjacent floodplain areas. These floodplain areas are mainly undeveloped pastureland, although it does also include several buildings on one farm, and several stretches of Clarence Valley Road.

6 Recommendations

At present there is very little flood information for the Waiau Toa/Clarence River area. It is recommended that:

1. Consideration be given to monitoring Waiau Toa/Clarence riverbed levels for aggradation/degradation and bank erosion, particularly after significant flood events.

2. The modelled 500 year ARI maximum water levels and high hazard areas be used in the interim to inform land use planning.

3. The Clarence Valley Road bridge site rating curve, derived from this modelling study, be used as a guide for estimating river flood flows and event magnitude, and for emergency management purposes (e.g. evacuation).

4. Consideration be given to monitoring and maintaining Hammy's Groyne, and the stopbank extending downstream to SH1, to minimise ongoing flood risk to the Clarence Settlement.

5. Climate change estimates, design flood flows and levels, high hazard areas, and the rating curve produced in this study be reassessed (and the model calibrated) once additional climate change, flood hydrology and riverbed/floodplain information are available.

7 Acknowledgments

The 2016/2017 LiDAR data have been provided by Land Information New Zealand (LINZ).

The National Institute of Water and Atmospheric Research (NIWA) provided Environment Canterbury with permission to use the flow records at Rosy Morn (Site 63501), Acheron at Clarence (Site 62103) and Waiau Toa/Clarence at Jollies (Site 62105).

Ian Heslop, Principal River Engineer at Environment Canterbury, has been heavily involved in all aspects of the post-2016 Kaikōura Earthquake Sequence, monitoring of geomorphic changes, and river engineering works within the Clarence Valley. He provided valuable technical advice, and background information for this study.

The following Environment Canterbury staff have reviewed this report:

- Ian Heslop (Principal River Engineer)
- Tony Boyle (Principal Science Advisor)
- Nick Griffiths (Team Leader, Natural Hazards)

8 External peer review

An external peer review of the computational hydraulic model was completed by Matthew Gardner of Land River Sea Consulting Ltd (Gardner, 2018). This review concluded "*Overall the model is well built and is considered to be fit for the purpose outlined in the modelling report.*"

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: Waiau Toa/Clarence River flood summary

Table A-1: Waiau Toa/Clarence River peak flow summary for flood events

	Peak flow (m^3/s)			
Date	Clarence at Valley Rd Bridge	Acheron at Clarence	Clarence at Jollies	Description
Feb 1868	?	?	?	*Higher than ever known before*
May 1923	?	?	?	*Worst flood since 1868.* Heavy rain throughout Provence, southerly gale.
Mar 1941	?	?	?	
Nov 1952	2500[a] (est. 1900)	?	?	*Heaviest flooding since 1923.* Southerly storm
Jan 1953	2400[a] (est. 1800)	?	?	Extensive flooding in all parts of the County
24 May 1966	?	339	315	*4th time in 43 years a bridge abutment was washed out.* Southerly rainfall event.
30 Oct 1968	?	717	312	
c.13 Mar 1975	?	127	53	Tropical Cyclone Alison
2 Apr 1975	?	750	128	Depression in north Tasman, moved SE towards Fiordland with strong NW winds
27 Aug 1979	1520	257	437	
3 Mar 1980	941	57	102	Remnants of tropical cyclone
10 Apr 1980	1149	135	170	Remnants of tropical cyclone?
15 Jun 1981	704	?	40	
26 Jun 1982	679	?	220	
10 Jul 1983	957	1009	247	Northerly tropical flow
21 Oct 1983	?	585	172	
17 Dec 1984	333	432	67	
6 Jun 1985	309	232	81	
23 Dec 1993	?	321	370	
8 Nov 1994	?	680	281	
8 Oct 2007	?	547	245	
31 Jul 2008	?	?	?	
26 Aug 2008	?	297	323	Low in west Tasman & stationary front to east led to strong SE/S flow.
18 Apr 2014	1278	212	127	Remnants of Tropical Cyclone Ita
23 Sep 2015	415	10	63	
13 Nov 2016	338	132	43	
13 April 2017	?	179	91	Remnants of Tropical Cyclone Cook
19 Sep 2017	?	180	290	Coastal rainfall event
27 Sep 2017	?	250	330	Heavy rain in headwaters.
July 2018	?	200	460	Gale NW and heavy rain.

[a] Peak flow measured downstream at road and rail bridges (i.e. below local tributary inflows).

Appendix B: Cross section details

Table B-2: Waiau Toa/Clarence River cross section data summary

Location	2018 model chainage (m)	2018 source data	2012 model chainage (m)	2012 source data
Top of model	88321	2016/17 LiDAR - channel cut	88438	2012 LiDAR
	88563	Lake in 2016/17 LiDAR - mainly stitched in 2012 LiDAR & channel cut	88680	2012 LiDAR
	88902	Lake in 2016/17 LiDAR - mainly stitched in 2012 LiDAR & channel cut	89019	2012 LiDAR
	89063	Lake in 2016/17 LiDAR - mainly stitched in 2012 LiDAR & channel cut	89180	2012 LiDAR
	89117	January 2018 drone data with channel cut		
	89141	January 2018 drone data with channel cut		
Upstream of Clarence Valley Road bridge	89157	January 2018 drone data with channel cut	89258	2012 LiDAR
Upstream of Clarence Valley Road bridge	89167	January 2018 drone data with channel cut		
	89185	January 2018 drone data with channel cut	89302	2012 LiDAR
	89239	January 2018 drone data with channel cut		
|	89304	January 2018 drone data with channel cut		
|	89309	January 2018 drone data with channel cut		
|	89314	January 2018 drone data with channel cut		
|	89324	January 2018 drone data with channel cut		
New channel	89339	January 2018 drone data with channel cut		
|	89368	January 2018 drone data with channel cut		
|	89418	January 2018 drone data with channel cut		
|	89472	January 2018 drone data with channel cut		
|	89563	January 2018 drone data with channel cut		
|	89664	January 2018 drone data with channel cut	89744	2012 LiDAR

<table>
<tr><th>Location</th><th>2018 model chainage (m)</th><th>2018 source data</th><th>2012 model chainage (m)</th><th>2012 source data</th></tr>
<tr><td>|
|</td><td>89819</td><td>January 2018 drone data with channel cut</td><td></td><td></td></tr>
<tr><td>|
|</td><td>89849</td><td>January 2018 ground survey with centre of channel levels estimated</td><td></td><td></td></tr>
<tr><td>|
|
|
|</td><td>90012</td><td>Estimated basd on survey of bank edge, upstream and downstream surveyed cross sections and 2016/17 LiDAR</td><td>90310</td><td>2012 LiDAR</td></tr>
<tr><td>New channel
|
|
|</td><td>90261</td><td>Estimated basd on survey of bank edge, upstream and downstream surveyed cross sections and 2016/17 LiDAR</td><td>90593</td><td>2012 LiDAR</td></tr>
<tr><td>|
|</td><td>90420</td><td>January 2018 ground survey with centre of channel levels estimated</td><td></td><td></td></tr>
<tr><td>|
|
|
|</td><td>90562</td><td>Estimated basd on survey of bank edge, upstream and downstream surveyed cross sections and 2016/17 LiDAR</td><td>90890</td><td>2012 LiDAR</td></tr>
<tr><td>|</td><td>90858</td><td>Estimated basd on survey of bank edge, upstream and downstream surveyed cross sections and 2016/17 LiDAR</td><td>91143</td><td>2012 LiDAR</td></tr>
<tr><td></td><td>91379</td><td>Lake in 2016/17 LiDAR - mainly stitched in 2012 LiDAR</td><td></td><td></td></tr>
<tr><td></td><td>91979</td><td>Lake in 2016/17 LiDAR - mainly stitched in 2012 LiDAR</td><td>92232</td><td>2012 LiDAR</td></tr>
<tr><td></td><td>92293</td><td>Lake in 2016/17 LiDAR - mainly stitched in 2012 LiDAR</td><td></td><td></td></tr>
<tr><td></td><td>92474</td><td>2016/17 LiDAR - channel cut</td><td></td><td></td></tr>
<tr><td></td><td>92624</td><td>2016/17 LiDAR - channel cut</td><td></td><td></td></tr>
<tr><td></td><td>92772</td><td>2016/17 LiDAR - channel cut</td><td>92807</td><td>2012 LiDAR</td></tr>
<tr><td></td><td>92986</td><td>2016/17 LiDAR - channel cut</td><td>93014</td><td>2012 LiDAR</td></tr>
<tr><td>|</td><td>93244</td><td>January 2018 drone data</td><td>93244</td><td>2012 LiDAR</td></tr>
<tr><td>|</td><td>93533</td><td>January 2018 drone data</td><td>93533</td><td>2012 LiDAR</td></tr>
<tr><td>|</td><td>93557</td><td>January 2018 drone data</td><td>93557</td><td>2012 LiDAR</td></tr>
<tr><td>Wharekiri delta</td><td>93582</td><td>January 2018 drone data</td><td></td><td></td></tr>
<tr><td>|</td><td>93606</td><td>January 2018 drone data</td><td>93606</td><td>2012 LiDAR</td></tr>
<tr><td>|</td><td>93626</td><td>January 2018 drone data</td><td></td><td></td></tr>
<tr><td>|</td><td>93671</td><td>January 2018 drone data</td><td>93671</td><td>2012 LiDAR</td></tr>
<tr><td></td><td>93760</td><td>January 2018 drone data</td><td>93760</td><td>2012 LiDAR</td></tr>
<tr><td></td><td>93968</td><td>January 2018 drone data</td><td>93968</td><td>2012 LiDAR</td></tr>
<tr><td></td><td>94115</td><td>January 2018 drone data</td><td></td><td></td></tr>
<tr><td></td><td>94178</td><td>January 2018 drone data</td><td></td><td></td></tr>
<tr><td></td><td>94541</td><td>January 2018 drone data</td><td>94541</td><td>2012 LiDAR</td></tr>
</table>

Location	2018 model chainage (m)	2018 source data	2012 model chainage (m)	2012 source data
	94856	2016/17 LiDAR	94856	2012 LiDAR
	95374	2016/17 LiDAR	95374	2012 LiDAR
	95795	2016/17 LiDAR	95795	2012 LiDAR
	96455	2016/17 LiDAR	96455	2012 LiDAR
	96794	2016/17 LiDAR	96794	2012 LiDAR
	96930	2016/17 LiDAR	96930	2012 LiDAR
	97352	2016/17 LiDAR	97352	2012 LiDAR
	97712	2016/17 LiDAR	97712	2012 LiDAR
Upstream of the SH1 bridge	97853	2016/17 LiDAR	97853	2012 LiDAR
Downstream of the SH1 bridge	97896	2016/17 LiDAR	97896	2012 LiDAR
	98120	2016/17 LiDAR	98120	2012 LiDAR
	98409	2016/17 LiDAR	98409	2012 LiDAR
Upstream of the railway bridge	98506	2016/17 LiDAR	98506	2012 LiDAR
Downstream of the railway bridge	98562	2016/17 LiDAR	98562	2012 LiDAR
	98819	2016/17 LiDAR	98819	2012 LiDAR
	99378	2016/17 LiDAR	99378	2012 LiDAR
	100000	2016/17 LiDAR	100000	2012 LiDAR
Original channel				
Confluence with new channel	1000	January 2018 drone data with channel cut		
	1005	January 2018 drone data		
	1010	January 2018 drone data		
	1373	January 2018 drone data	~89744	
	1650	2016/17 LiDAR with channel cut		
	2075	2016/17 LiDAR with channel cut		
	2550	2016/17 LiDAR with channel cut	~90890	
	2855	2016/17 LiDAR with channel cut	~91143	
	3350	2016/17 LiDAR with channel cut	~91668	
	3650	2016/17 LiDAR with channel cut		
	4290	2016/17 LiDAR with channel cut		

Appendix C: Model run files

MikeFLOOD model: Release 2016, SP1

Present-day North-westerly design flood event files

	5 year ARI	50 year ARI	500 year ARI
	Peak flow of 700 m^3/s at bridge, no tributary inflows	Peak flow of 1800 m^3/s at bridge, no tributary inflows	Peak flow of 2300 m^3/s at bridge, no tributary inflows

MikeFlood			
Couple file (*.mf)	Clar_2018_NW_5yr_ARI_mf	Clar_2018_NW_50yr_ARI_mf	Clar_2018_NW_500yr_ARI_mf

Mike11			
Simulation file (*.sim11)	Clar_2018_NW_5yr_ARI	Clar_2018_NW_50yr_ARI	Clar_2018_NW_500yr_ARI
Network file (*.nwk11)	Clarence_2018_NZVD_v2		
Cross section file (*.xns11)	Clarence_XS_2018_v2		
Boundary file (*.bnd11)	Clar_2018_NW_5yr_ARI_ SL_1_75m	Clar_2018_NW_50yr_ARI_SL_1_75m	Clar_2018_NW_500yr_ARI_SL_1_75m
HD parameter (*.hd11)	Clar_2018_n_0_45_HD		
Results file (*.res11)	Clar_2018_NW_5yr_ARI	Clar_2018_NW_50yr_ARI	Clar_2018_NW_500yr_ARI

Mike21			
Simulation file (*.21)	Clar_2018_NW_5yr_ARI	Clar_2018_NW_50yr_ARI	Clar_2018_NW_500yr_ARI
Bathymetry file (*.dfs2)	Clar_2_branches_2018_5m_dem_Foster_SB		
Initial surface elevation (*.dfs2)	1.75		
Resistance (*.dfs2)	2018_Clar_n		
Results (*.dfs2)	Clar_2018_NW_5yr_ARI	Clar_2018_NW_50yr_ARI	Clar_2018_NW_500yr_ARI
Sources/Sinks	-		
Drying depth (m)	0.01		
Wetting depth (m)	0.04		
Eddy viscosity	1		
Number of structures	-		
Simulation start time	1/1/2000 12:00am		
Simulation end time	2/1/2000 1:00pm		
Time step (s)	0.5		
Length of run (# time steps)	266400		

Present-day Southerly or easterly design flood event files

	10 year ARI	50 year ARI	500 year ARI
	Flow increasing to 400 m^3/s at bridge, 10 year ARI tributary inflows	Flow increasing to 700 m^3/s at bridge, 50 year ARI tributary inflows	Flow increasing to 1800 m^3/s at bridge, 500 year ARI tributary inflows

MikeFlood			
Couple file (*.mf)	Clar_2018_S_E_10yr_ARI_mf	Clar_2018_S_E_50yr_ARI_mf	Clar_2018_S_E_500yr_ARI_mf

Mike11			
Simulation file (*.sim11)	Clar_2018_S_E_10yr_ARI	Clar_2018_S_E_50yr_ARI	Clar_2018_S_E_500yr_ARI
Network file (*.nwk11)	Clarence_2018_NZVD_v2		
Cross section file (*.xns11)	Clarence_XS_2018_v2		
Boundary file (*.bnd11)	Clar_2018_S_E_10yr_ARI_SL_1_75m	Clar_2018_S_E_50yr_ARI_SL_1_75m	Clar_2018_S_E_500yr_ARI_SL_1_75m
HD parameter (*.hd11)	Clar_2018_n_0_45_HD		
Results file (*.res11)	Clar_2018_S_E_10yr_ARI	Clar_2018_S_E_50yr_ARI	Clar_2018_S_E_500yr_ARI

Mike21			
Simulation file (*.21)	Clar_2018_S_E_10yr_ARI	Clar_2018_S_E_50yr_ARI	Clar_2018_S_E_500yr_ARI
Bathymetry file (*.dfs2)	Clar_2_branches_2018_5m_dem_Foster_SB		
Initial surface elevation (*.dfs2)	1.75		
Resistance (*.dfs2)	2018_Clar_n		
Results (*.dfs2)	Clar_2018_S_E_10yr_ARI	Clar_2018_S_E_50yr_ARI	Clar_2018_S_E_500yr_ARI
Sources	Miller (390,896)→(390,900), Wharekiri (409,854)→(413,854) & (413,840)→(417,840), Stewart (475,509)→(476,509), Priams (394,1514) →(394,1515), Rika (746,928) →(746,929), May (887,918) →(888,918)		
Drying depth (m)	0.01		
Wetting depth (m)	0.04		
Eddy viscosity	1		
Number of structures	-		
Simulation start time	1/1/2000 12:00am		
Simulation end time	2/1/2000 1:00pm		
Time step (s)	0.5		
Length of run (# time steps)	266400		

Present-day sensitivity tests – 500 year ARI design flood event files

	North-westerly, channel roughness increased	Southerly or easterly, floodplain roughness increased
	500 year ARI north-westerly event with channel roughness, 'n', increased from 0.045 to 0.056	500 year ARI southerly or easterly event with floodplain roughness increased by 25%
MikeFlood		
Couple file (*.mf)	Clar_2018_NW_500yr_ARI_n_chan_0_056_mf	Clar_2018_S_E_500yr_ARI_fp_n_plus_25_perc_mf
Mike11		
Simulation file (*.sim11)	Clar_2018_NW_500yr_ARI_n_chan_0_056	Clar_2018_S_E_500yr_ARI_fp_n_plus_25_perc
Network file (*.nwk11)	Clarence_2018_NZVD_v2	
Cross section file (*.xns11)	Clarence_XS_2018_v2	
Boundary file (*.bnd11)	Clar_2018_NW_500yr_ARI_SL_1_75m	Clar_2018_S_E_500yr_ARI_SL_1_75m
HD parameter (*.hd11)	Clar_2018_n_0_56_HD	Clar_2018_n_0_45_HD
Results file (*.res11)	Clar_2018_NW_500yr_ARI_n_chan_0_056	Clar_2018_S_E_500yr_ARI_fp_n_plus_25_perc
Mike21		
Simulation file (*.21)	Clar_2018_NW_500yr_ARI_n_chan_0_056	Clar_2018_S_E_500yr_ARI_fp_n_plus_25_perc
Bathymetry file (*.dfs2)	Clar_2_branches_2018_5m_dem_Foster_SB	
Initial surface elevation (*.dfs2)	1.75	
Resistance (*.dfs2)	2018_Clar_n	2018_Clar_n_plus_25_perc
Results (*.dfs2)	Clar_2018_NW_500yr_ARI_n_chan_0_056	Clar_2018_S_E_500yr_ARI_fp_n_plus_25_perc
Sources	-	Miller (390,896)→(390,900), Wharekiri (409,854)→(413,854) & (413,840)→(417,840), Stewart (475,509)→(476,509), Priams (394,1514) →(394,1515), Rika (746,928) →(746,929), May (887,918) →(888,918)
Drying depth (m)	0.01	
Wetting depth (m)	0.04	
Eddy viscosity	1	
Number of structures	-	
Simulation start time	1/1/2000 12:00am	
Simulation end time	2/1/2000 1:00pm	
Time step (s)	0.5	
Length of run (# time steps)	266400	

Present-day sensitivity tests – 500 year ARI design flood event files (no Foster's stopbank)

	North-westerly	Southerly or easterly
	500 year ARI north-westerly event, no stopbank	500 year ARI southerly or easterly event, no stopbank

MikeFlood		
Couple file (*.mf)	Clar_2018_NW_500yr_ARI_no_Fosters_SB_mf	Clar_2018_S_E_500yr_ARI_no_Fosters_SB__mf

Mike11		
Simulation file (*.sim11)	Clar_2018_NW_500yr_ARI_no_Fosters_SB	Clar_2018_S_E_500yr_ARI_no_Fosters_SB_
Network file (*.nwk11)	Clarence_2018_NZVD_v2	
Cross section file (*.xns11)	Clarence_XS_2018_v2	
Boundary file (*.bnd11)	Clar_2018_NW_500yr_ARI_SL_1_75m	Clar_2018_S_E_500yr_ARI_SL_1_75m
HD parameter (*.hd11)	Clar_2018_n_0_45_HD	
Results file (*.res11)	Clar_2018_NW_500yr_ARI_no_Fosters_SB_	Clar_2018_S_E_500yr_ARI_no_Fosters_SB_

Mike21		
Simulation file (*.21)	Clar_2018_NW_500yr_ARI_no_Fosters_SB	Clar_2018_S_E_500yr_ARI_no_Fosters_SB
Bathymetry file (*.dfs2)	Clar_2_branches_2018_5m_dem_NO_Foster_SB	
Initial surface elevation (*.dfs2)	1.75	
Resistance (*.dfs2)	2018_Clar_n	
Results (*.dfs2)	Clar_2018_NW_500yr_ARI_no_Fosters_SB	Clar_2018_S_E_500yr_ARI_no_Fosters_SB
Sources	-	Miller (390,896)→(390,900), Wharekiri (409,854)→(413,854) & (413,840)→(417,840), Stewart (475,509)→(476,509), Priams (394,1514) →(394,1515), Rika (746,928) →(746,929), May (887,918) →(888,918)
Drying depth (m)	0.01	
Wetting depth (m)	0.04	
Eddy viscosity	1	
Number of structures	-	
Simulation start time	1/1/2000 12:00am	
Simulation end time	2/1/2000 1:00pm	
Time step (s)	0.5	
Length of run (# time steps)	266400	

Pre-earthquake north-westerly design flood event files

	5 year ARI	50 year ARI	500 year ARI
	Peak flow of 700 m^3/s at bridge, no tributary inflows	Peak flow of 1800 m^3/s at bridge, no tributary inflows	Peak flow of 2300 m^3/s at bridge, no tributary inflows
MikeFlood			
Couple file (*.mf)	Clar_2012_NZVD_NW_5yr_ARI_mf	Clar_2012_NZVD_NW_50yr_ARI_mf	Clar_2012_NZVD_NW_500yr_ARI_mf
Mike11			
Simulation file (*.sim11)	Clar_2012_NZVD_NW_5yr_ARI	Clar_2012_NZVD_NW_50yr_ARI	Clar_2018_NW_500yr_ARI
Network file (*.nwk11)		Clarence_2012_NZVD	
Cross section file (*.xns11)		Clarence_XS	
Boundary file (*.bnd11)	Clar_2012_NW_5yr_ARI_SL_1_75m	Clar_2012_NW_50yr_ARI_SL_1_75m	Clar_2012_NW_500yr_ARI_SL_1_75m
HD parameter (*.hd11)		Clar_2012_n_0_45_HD	
Results file (*.res11)	Clar_2012_NZVD_NW_5yr_ARI	Clar_2012_NZVD_NW_50yr_ARI	Clar_2012_NZVD_NW_500yr_ARI
Mike21			
Simulation file (*.21)	Clar_2012_NZVD_NW_5yr_ARI	Clar_2012_NZVD_NW_50yr_ARI	Clar_2012_NZVD_NW_500yr_ARI
Bathymetry file (*.dfs2)		2012_5m_nzvd	
Initial surface elevation (*.dfs2)		1.75	
Resistance (*.dfs2)		2012_Clar_n	
Results (*.dfs2)	Clar_2012_NZVD_NW_5yr_ARI	Clar_2012_NZVD_NW_50yr_ARI	Clar_2012_NZVD_NW_500yr_ARI
Sources/Sinks		-	
Drying depth (m)		0.01	
Wetting depth (m)		0.04	
Eddy viscosity		1	
Number of structures		-	
Simulation start time		1/1/2000 12:00am	
Simulation end time		2/1/2000 1:00pm	
Time step (s)		0.5	
Length of run (# time steps)		266400	

500 year ARI design flood event files (with climate change to 2120, no Fosters stopbank)

	North-westerly	Southerly or easterly
	Peak flow of 2875 m^3/s at Clarence Valley Road bridge, sea level +1m	Q= 2250 m^3/s at Clarence Valley Road bridge, tributary inflows + 25%, sea level +1m

MikeFlood		
Couple file (*.mf)	Clar_2018_NW_500yr_ARI_no_Fosters_SB_with_climate_change_mf	Clar_2018_S_E_500yr_ARI_no_Fosters_SB_with_climate_change_mf

Mike11		
Simulation file (*.sim11)	Clar_2018_NW_500yr_ARI_no_Fosters_SB_with_climate_change	Clar_2018_S_E_500yr_ARI_no_Fosters_SB_with_climate_change
Network file (*.nwk11)	Clarence_2018_NZVD_v2	
Cross section file (*.xns11)	Clarence_XS_2018_v2	
Boundary file (*.bnd11)	Clar_2018_NW_500yr_ARI_with_climate_change_SL_2_75m	Clar_2018_S_E_500yr_ARI_with_climate_change_SL_2_75m
HD parameter (*.hd11)	Clar_2018_n_0_45_HD	
Results file (*.res11)	Clar_2018_NW_500yr_ARI_no_Fosters_SB_with_climate_change	Clar_2018_S_E_500yr_ARI_no_Fosters_SB_with_climate_change

Mike21		
Simulation file (*.21)	Clar_2018_NW_500yr_ARI_no_Fosters_SB_with_climate_change	Clar_2018_S_E_500yr_ARI_no_Fosters_SB_with_climate_change
Bathymetry file (*.dfs2)	Clar_2_branches_2018_5m_dem_NO_Foster_SB	
Initial surface elevation (*.dfs2)	2.75	
Resistance (*.dfs2)	2018_Clar_n	
Results (*.dfs2)	Clar_2018_NW_500yr_ARI_no_Fosters_SB_with_climate_change	Clar_2018_S_E_500yr_ARI_no_Fosters_SB_with_climate_change
Sources	-	Miller (390,896)→(390,900), Wharekiri (409,854)→(413,854) & (413,840)→(417,840), Stewart (475,509)→(476,509), Priams (394,1514) →(394,1515), Rika (746,928) →(746,929), May (887,918) →(888,918)
Drying depth (m)	0.01	
Wetting depth (m)	0.04	
Eddy viscosity	1	
Number of structures	-	
Simulation start time	1/1/2000 12:00am	
Simulation end time	2/1/2000 1:00pm	
Time step (s)	0.5	
Length of run (# time steps)	266400	

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Regional Council
Kaunihera Taiao ki Waitaha

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