Environment Canterbury Regional Council
Kaunihera Taiao ki Waitaha

TECHNICAL REPORT Science Group

Kaikōura Fans flood modelling investigation

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February 2020

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Summary

Background
During flood events, the Kaikōura alluvial fans (Kaikōura Fans) drain flood waters from the Kowhai River, as well as the smaller Mt Fyffe streams and Ewelme Stream, to the coast. During large flood events, Lyell Creek receives breakout flows from the Kowhai River, and from some Mt Fyffe streams, with Kaikōura Township flooding at least 15 times since 1917. The recent addition of the Kaikōura Township flood wall provides protection against all but very large flood events. During these more extreme flood events, Lyell Creek flows are dramatically increased by the addition of breakout flows from the Kowhai River.

A better understanding of flooding from local rivers was required to inform the current review of the natural hazards provisions of the Kaikōura District Plan. This modelling investigation was undertaken to quantify the extent and depth of flooding for land located on the Kaikōura Fans, including the impact of Kowhai River and Ewelme Stream overflows on the Peketa area.

What we did
This study used a combined 1-dimensional and 2-dimensional hydraulic computer model to estimate flood extent, depths, and flood levels, for 50 and 500 year Average Recurrence Interval (ARI) flood events. Climate change impacts were included, as well as sensitivity tests to address the considerable uncertainty contained within the modelling results. Sources of uncertainty include, but are not limited to, inadequate hydrological data, limited calibration data, and the dynamic landscape.

Although the Mt Fyffe streams and fans were included in the modelling, it was not possible to reliably determine flood levels and high hazard areas on these more steeply sloping alluvial fans along the foot of the Mt Fyffe Range (mainly above Postmans Road); the models are not able to simulate flooding where significant volumes of debris and/or bed material are entrained in flood waters (i.e. where debris flows and debris floods occur).

What we found
During a 500 year ARI flood, breakout flows are likely to occur from the Kowhai River and the Mt Fyffe Streams. Breakout flows to the true left of the Kowhai River, in The Bluff area, will divert some flood water towards Middle Creek, with the remainder flowing towards Lyell Creek. Further downstream, around Middle Ford, any breakout flows over the true left bank will divert towards Lyell Creek. This will have the most significant impact on flooding in the more developed area along Lyell Creek, and in Kaikōura Township. Breakout flows to the true right of the Kowhai River, at Fernleigh Dip, will largely flow towards Ewelme Stream (Stoney Creek). For a 500 year ARI breakout flow at Fernleigh Dip, some flood water flows parallel to the railway line towards Peketa.

Ponding areas are relatively small. Flood levels in these areas are therefore particularly sensitive to inflow volumes and outlet conditions (e.g. constrictions such as bridge structures).

What does this mean?
Maps showing predicted 50 and 500 year ARI flood levels, depths, and high hazard areas, will assist land use planning for the Kaikōura Fans. The model results will provide information that will assist in the recommendation of appropriate floor levels for new buildings and extensions. The model could also be used to analyse existing or proposed flood protection works, or for emergency planning purposes.

As modelling cannot consider all possible flood scenarios (i.e. is not able to consider all conceivable breakouts, impacts of blockages, scour, erosion and aggradation), the results should be used in conjunction with experienced engineering judgement and a detailed knowledge of the modelling limitations.

How we have considered climate change

To allow for climate change to 2120, current design peak flow estimates have been increased by 25%. Sea levels have also been increased by 1 m. It is recommended that these climate change assumptions are updated as further information becomes available.

Kowhai Fan – looking east towards Kaikōura Township and Peninsula

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1 Introduction

During large flood events, the Kaikōura alluvial fans (Kaikōura Fans) drain flood waters from the Kowhai River, and the smaller Mt Fyffe streams and Ewelme Stream, to the coast. Lyell Creek, which flows through Kaikōura Township, can receive overflows from the Kowhai River and Mt Fyffe streams. When these flows exceed the capacity of Lyell Creek and the SH1 bridge, water backs up behind the bridge, potentially flooding properties in this area. Once the SH1 bridge is overtopped, floodwater flows along the main road into the Kaikōura Township area located downstream of the bridge. This happened most recently in December 1993, but the Township has also flooded many other times prior to the installation of the flood protection wall through the commercial area.

A better understanding of flooding from local rivers was required to inform the current review of the natural hazards provisions of the Kaikōura District Plan. This modelling investigation has been undertaken to quantify the extent and depth of flooding on the Kaikōura Fans. However, limitations of the computational modelling software mean flooding on the steeper alluvial fans cannot be accurately modelled. The study focuses on overflows from Ewelme Stream, Kowhai River and the Mt Fyffe streams, but does not adequately model overflows onto the steeper Mt Fyffe alluvial fans where debris flows and debris floods occur (Figure 1-1).

Figure 1-1: Kaikōura Fans study area

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 Kaikōura Fans for 50 and 500 year average recurrence interval (ARI) flood events. Areas defined as high hazard (see Glossary) are also quantified. Note that other high hazard areas may exist, or develop, during a flood event. This is more likely to occur in areas adjacent to the Kowhai River, or on the steeper slopes of Mt Fyffe, where overflows from the main watercourse carry significant volumes of debris. These fast-flowing and destructive overflows can cause extensive scouring and erosion, altering overland flow paths. This may produce additional flooding on the Kaikōura Fans in areas not identified in this study.

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. The current Kaikōura District Plan requires floors in certain areas to be above the 500 year ARI flood level. The CRPS also requires new development to be avoided in high hazard areas.

The information from this modelling investigation will assist with land use planning (e.g. defining minimum floor levels and high hazard areas), emergency management planning (e.g. evacuation) and earthquake remediation work.

2 Background

2.1 Study area

The study area for this flood modelling investigation is shown on Figure 1-1. This alluvial fan system (Kaikōura Fans) was formed by the coalescing alluvial fans of the Kowhai and Hāpuku gravel-bed rivers, as well as the alluvial fans of the steeper Mt Fyffe streams and interfan streams (Wright, 1980). Figure 2-1 identifies the alluvial fans included in the Kaikōura Fan System, and Figure 2-2 defines the catchment areas for the watercourses included in the study. The various watercourses are described below.

2.1.1 Harnetts Creek

The tributaries of Harnetts Creek drain the slopes of Sawyer Ridge, flowing towards the sea along a depression that has formed between the Hāpuku and Waimangarara fans (Figure 2-1). The creek becomes more entrenched as it approaches the coast. A lack of channel capacity at Bay Paddock Road has been noted in previous Canterbury Regional Council reports, and the ability of the SH1 road bridge to carry large flood flows (possibly including Waimangarara River overflows and debris) is also an issue. The Old Beach Road vehicle and rail bridges also have a history of flood overflows and washouts. At present, any ponding of water upstream of these bridges is not likely to be of concern, as the land is largely undeveloped.

2.1.2 Waimangarara River

The Waimangarara River is the largest catchment draining the south-eastern face of the Mt Fyffe Range. During flood events, large volumes of sediment are transported over the alluvial fan, and Postmans Road, into the downstream gravel sediment trap (Figure 2-3).

A series of lateral and echelon banks are located along both sides of the river to encourage the river to remain in its current position, rather than spreading out across its alluvial fan (Figure 2-3). However, for large flood events, with an average recurrence interval of greater than ~20 years, breakouts from the watercourse are inevitable. Due to degradation (or incising) of the riverbed in more recent years, the uppermost locations where breakouts from the river are likely to occur are ~200 m upstream of the Maori Creek Echelon (on the true right bank) and ~150 m upstream of the highest spur groyne attached to the Upper Spurred Lateral Bank (on the true left bank). Additional sediment from recent earthquake activity will almost certainly cause this area to start a further phase of aggradation.

2.1.3 Luke and Middle Creeks

Luke Creek and Middle Creek have quite different characteristics due to the location of their upper catchments. The characteristics of these two creeks are described below.

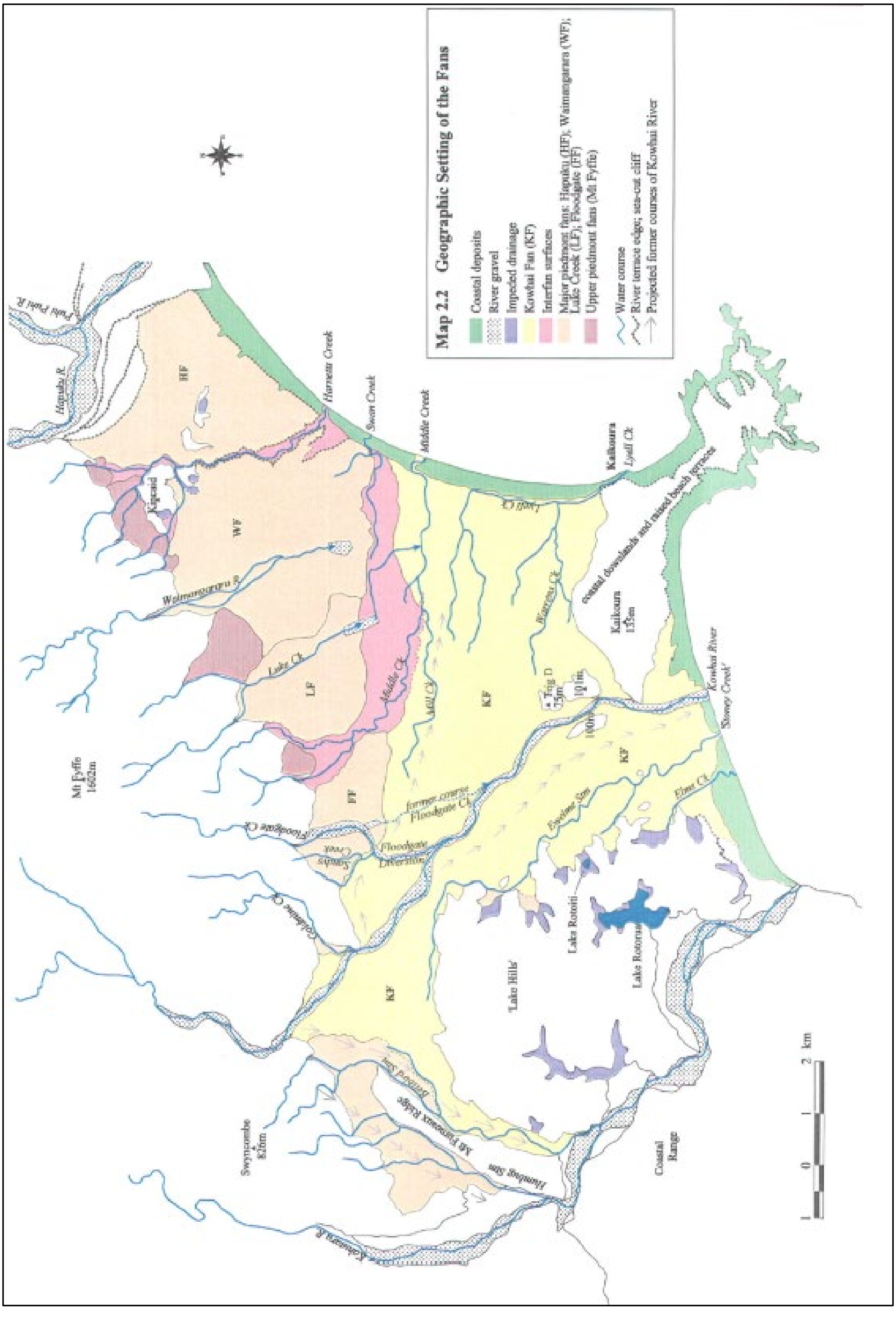


Figure 2-1: Geographic setting of the Kaikōura Fans [Source: CRC (1999)]

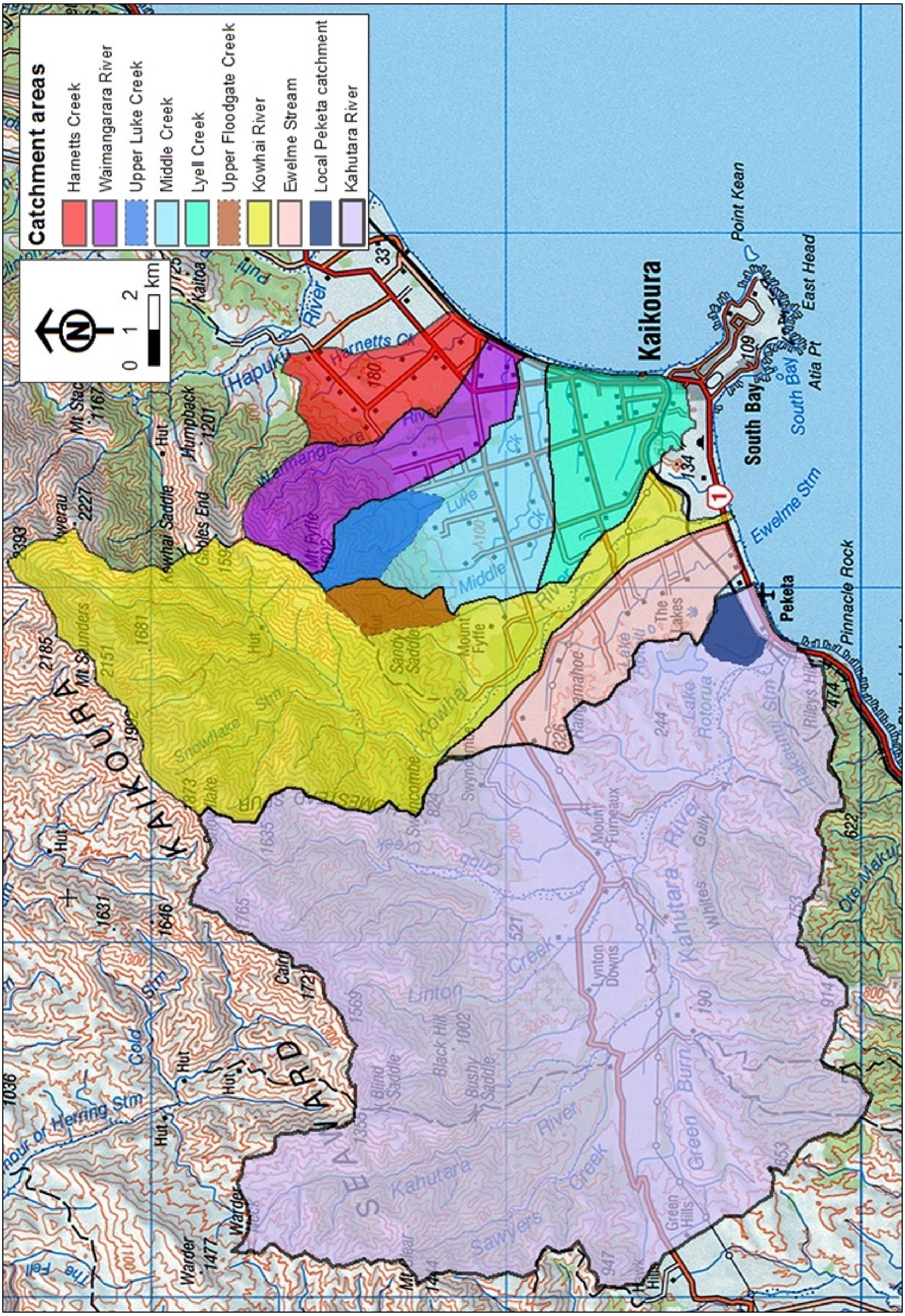


Figure 2-2: Catchment location map

Figure 2-3: Location map for Kaikōura Fans (bold lines = stopbanks)

Luke Creek
The south-western face of Te Rakaomaru Spur (Mt Fyffe Range) drains into Luke Creek along two tributaries. The western branch is the main source of material forming the Luke Creek alluvial fan, while debris from the eastern branch has formed a steep fan which extends over the east bank down to Topline Road (overlying the Waimangarara River Fan). Further south from Topline Road, the eastern Luke Creek Fan is confined to a relatively narrow width by the Waimangarara River Fan. To the west, the alluvial fan extends almost to Middle Creek (Figure 2-1).

A gravel sediment trap is located downstream of Postmans Road (including a relatively recent extension to the sediment trap to the south, Figure 2-4). This removes gravel from the watercourse before it flows into Middle Creek. Several training and echelon banks have been constructed along the watercourse to prevent breakouts up to a ~20 year ARI flood event (Figure 2-3).

Figure 2-4: Luke Creek, looking upstream towards Luke Creek sediment trap, 18 April 2014 (Easter 2014 flood)

Middle Creek
Like Harnetts Creek, Middle Creek is an interfan stream confined by the Luke and Floodgate Creek fans (Figure 2-1). The creek is largely entrenched, and sinuous, and does not tend to carry large quantities of sediment during floods (due to a limited sediment supply in the upper catchment). However, disturbances in the upper catchment such as earthquakes, deforestation, and the effects of freezing and thawing, create sediment supplies.

Although there is evidence of overbank flows, particularly downstream of Postmans Road, there are no bank protection works – except in the reach downstream of the Luke Creek confluence (Figure 2-1).

Figure 2-5: Luke Creek, looking upstream from Postmans Road, May 2014 (post-Easter 2014 flood)

Figure 2-6: Luke Creek gravel sediment trap, looking downstream from below Postmans Road, May 2014 (post-Easter 2014 flood)

2.1.4 Floodgate Creek

Floodgate Creek drains the Mt Fyffe Range between Fenceline and Te Hakuwai spurs. The Floodgate Creek Fan used to extend further west but has been eroded by the Kowhai River. To the east, the Floodgate Creek Fan has dominated the landscape, extending as far as Middle Creek near the Red Swamp Road and Postmans Road intersection (Figure 2-1).

The steepest slope along the Floodgate Creek Fan is downslope towards Postmans Road. Floodgate Creek previously passed flows (and sediment) along this more direct line toward the Kowhai River until the 1980s, when a new Floodgate Creek channel diverted flows further westwards - reducing the channel slope (and ability to transport sediment). The diversion does, however, provide additional echelon bank protection from the Kowhai River west of Chapmans Road (Figure 2-3).

Figure 2-7: Floodgate Creek, looking upstream at Chapmans Road, 18 April 2014 (Easter 2014 flood)

2.1.5 Lyell Creek

Lyell Creek has a natural catchment area of ~16 km^2 but has experienced overflows from the much larger Kowhai River catchment on many occasions. This spring fed creek drains the south eastern part of the Kowhai Fan, exiting through Kaikōura Township to the coast (Figure 2-2). A flood protection wall has been constructed along Lyell Creek where it passes through the township (Figure 2-8), designed to contain a flow of ~160 m^3/s. As 500 year ARI flows for Lyell Creek are less than this design flow capacity, the flood protection wall is not expected to be overtopped without a breakout flow from the Kowhai River.

Figure 2-8: Lyell Creek flood protection wall

2.1.6 Kowhai River

The Kowhai River (including Floodgate Creek) has a catchment area of approximately 80 km^2, extending back to the Seaward Kaikōura Range, which rises to over 2100 m (Figure 2-2). The upper catchment consists predominantly of greywacke and argillite bedrock materials, with the river confined by the steep, mountainous terrain (Figure 2-9). This catchment has a high rate of erosion, due to earthquakes and other natural erosion processes.

Figure 2-9: Upper catchment of the Kowhai River, looking downstream from near the Kowhai Saddle

Downstream of the Mt Fyffe Range, the Kowhai River slope decreases and the river flows over the Kowhai Fan (Figure 2-1 and Figure 2-10). Along this river reach, the channel is less confined, and becomes braided.

Figure 2-10: Looking north towards the Kowhai River as it exits the Mt Fyffe Range and passes over the Kowhai Fan

A series of echelon banks currently provide flood protection to the Kowhai Fan for events with an ARI up to around 20 to 50 years. However, these river control works are likely to be compromised in larger flood events due to reduced channel capacity, from gravel deposition, and/or lateral erosion of the banks (Sutherland, 2006). Section 2.4 provides further information on river control works.

Cross sections along the Kowhai River have been surveyed in 1987, 1995, 2002, 2011 and 2015, with some cross sections also surveyed earlier than this. Except for a small area upstream of Kowhai Ford Rd, cross section surveys show a general trend of degrading bed levels. This trend may reverse with the additional sediment supply generated by the 2016 Kaikōura Earthquake Sequence. At present, the additional landslide debris (generated by the 2016 earthquakes) is being transported into the river system in the upper catchment during high-intensity rainfall events (e.g. during Tropical Cyclone Gita). The downstream impact of the additional sediment is currently unknown. This impact is being investigated in an Endeavour Fund programme looking at earthquake-induced landslides and landscape dynamics. Part of this investigation will include examining the movement of sediment from the landslides to the coast. As the 5 year programme is not yet complete, the results of the study are not yet available.

At present, there are no formal minimum bed levels to manage gravel extraction from the Kowhai River. For gravel extraction purposes, it is possible to extract any material that has aggraded since 1987. Areas that have degraded should not be extracted until such time that conditions change, or minimum bed levels are set in accordance with the principles set out in the Canterbury Gravel Management Strategy.

2.1.7 Ewelme Stream (Stoney Creek)

Spring-fed Ewelme Stream has a catchment area of 18 km^2 (Figure 2-2). The stream drains the hilly catchments to the south-west, with water ponding in the valleys along the base of these hills. This ponding occurs as flood water is not able to drain effectively – a direct impact of the Kowhai Fan depositing gravel along the northern face of the Lake Hills.

During flood events, flows from the Kowhai River have historically overflowed into Ewelme Stream in the Fernleigh Dip area.

Figure 2-11: Ewelme Stream between Main North Railway and Kowhai Ford Road, 24 December 1993

2.1.8 Peketa local inflows

Three ~50 to 100 hectare hilly catchment areas are located behind the railway line. Flood water from these catchments drains into the Kahutara River via a small stream flowing under the railway line and through the Peketa settlement and campground. The low-lying land along the base of the hills also ponds flood water (Figure 2-12).

2.1.9 Kahutara River

The Kahutara River extends from the coast to ~27 km upstream, with the small coastal settlement of Peketa located near the river mouth (Figure 2-13). The river has a catchment area of ~233 km^2, with the northern portion of the catchment draining the southern face of the Seaward Kaikōura Range (Figure 2-2). This northern part of the catchment includes the Cribb Creek, Linton Creek, and Sawyers Creek tributaries.

Figure 2-12: Peketa ponding areas (behind the railway line) with the Kahutara River in the background, 24 December 1993

Figure 2-13: Kahutara River mouth – looking west towards the Kahutara floodplain and Peketa settlement

At least 11 landslide dams were observed in the upper Kahutara River catchment after the 2016 Kaikōura Earthquake Sequence. One of the main monitored landslide dams was located on Linton Creek at an elevation of 340 m. Between 4 and 6 April 2017, rainfall associated with ex-Tropical Cyclone Debbie caused the Linton landslide dam to overtop, scouring a significant channel through the toe of the landslide. Flood risk in the downstream catchment has now returned to a similar level as before the 2016 Kaikōura Earthquake Sequence.

2.2 Historic flooding

High flows in the Kaikōura Fan rivers usually occur when there are widespread, high-intensity, southerly or easterly rainfall events. Depressions, formed from tropical cyclones, can also produce extremely high-intensity rainfall along the Kaikōura coast. These tend to cause flooding (and sediment and landslide issues) for the smaller streams and creeks draining the steep mountainous slopes near the coast.

Since 1917, Kaikōura Township has been flooded at least 15 times from Lyell Creek overflows (McPherson, 1997). The current Lyell Creek flood protection wall, located downstream of the SH1 road bridge, should now protect the commercial area from flooding from Lyell Creek, unless there is a significant breakout from the Kowhai River contributing to the flows. Information on notable flood events in the Kaikōura area is summarised below, with a more detailed account of flooding in the Kaikōura area provided in McPherson (1997). Due to the dynamic nature of the heavily sediment laden Kaikōura rivers and streams, it is challenging to accurately measure flood flows. The limited flood flow information presented below is indicative only.

2.2.1 February 1868

This was the first documented flood event after European settlement in the area. It was described as '*the greatest flood ever recorded on the Marlborough coast'* by Sherrard (1966) in McPherson (1997, p 7). Excerpts from an eyewitness account written by Mrs V Boyd of Ramiford, Kaikōura – as told by her mother (McPherson, 1997) …

'*The Kowhai waters tore over from south of Postman's Road, down to Blackguard's corner, where it was turned by extremely heavy swamp, then flowed down what was later Mt Fyffe Road, and took a wide spread towards Lyell Creek. The heavy swamp halted the shingle after it crossed Mill Road.*

The Kowhai waters then turned to the other side of the country, and took a sweep towards the "Elms" and left that also a riverbed. Finally the water took a straight course for the sea, and cut a deep gulch into what is now the Kowhai riverbed.'

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.

2.2.2 September 1917

In 48 hours, 200 mm of rainfall was recorded. The Kowhai River was reported to have broken through the flood protection works. Lyell Creek overflowed its banks, and the main street was submerged to a depth of 0.5 m. Surrounding low-lying land was also submerged (McPherson, 1997).

2.2.3 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. The Kowhai River broke its banks around Postmans Road, flowing into Lyell Creek and flooding the town (Figure 2-14). Water was up to 0.9 m deep in the town, and 480 mm higher than ever before at the West End. Shops on the seaward side of the road had up to 1.2 m of water inside (McPherson, 1997).

Middle Creek rose higher than the bridge, which became impassable on the North Road, and the Kowhai River overflowed the bridge on the South Road. Low-lying land between the Kowhai River and Lyell Creek was submerged. The Kahutara, Hāpuku, Kowhai and Clarence River road and/or rail abutments washed out, as well as two spans of the Clarence River and Oaro road bridges and four spans of the Kahutara road bridge. Nearly every bridge in the County was damaged (McPherson, 1997).

Figure 2-14: 1923 flood - West End, Kaikōura [Source: Kaikōura Historical Society]

2.2.4 August 1939

Quoted as the biggest deluge since May 1923 in Marlborough Catchment Board documents (McPherson, 1997). Heavy rain on 25-26 August caused rivers and creeks in the Kaikōura District to rise rapidly (SCRCC, 1957). Lyell Creek overflowed and flooded Kaikōura Township (Figure 2-15). Low-lying land between the Lyell Creek bridge (SH1) and Hawthorne Road was also inundated, with properties upstream as far as Mill Road flooded (McPherson, 1997).

Figure 2-15: 1939 flood - West End, Kaikōura [Source: Kaikōura Historical Society]

2.2.5 December 1939

During this event, '*Heavy rain, accompanied by a strong south-easterly wind, swept the district but caused little damage'* (SCRCC, 1957). The highest rainfall intensities appear to have been around Ward (SCRCC, 1957). The larger rivers in the Kaikōura District (i.e. Clarence, Hāpuku, Kowhai and Kahutara) all had high flows, and were bank to bank. Waimangarara Stream also *'overflowed its banks, changed its course, and poured its flood water along the eastern portion of Postman's Rd, thence to Athelney Road, to below Mr H. Gibson's property, causing scouring several feet deep on each side of the road. Had the rain continued a little longer, Athelney Road would have become a turbulent stream*'

(McPherson, 1997 pp 53-54). Figure 2-16 illustrates flood damage at Athelney Road (SH1). Lyell Creek did not have significantly high flows (McPherson, 1997).

Figure 2-16: 1 February 1941 – North End of Athelney Road (SH1), Kaikōura [Source: Kaikōura Historical Society]

2.2.6 November 1952

A southerly storm, described as the worst southerly storm to hit the area for many years, hit the Kaikōura coast and Marlborough. At Grange Road, 129 mm of rain fell in 48 hours. The Kowhai River broke its banks, flowing into Lyell Creek and flooding the town. Water was up to 1.2 to 1.5 m deep, in the town, causing the worst damage in the West End since 1923. Water also went further down the street than in any previous flood (i.e. 1923, 1939 and 1941). Low-lying land between the Kowhai River and Lyell Creek was submerged (McPherson, 1997).

The Kowhai River also broke its banks below "Swyncombe", converting over 100 acres of fertile farmland to riverbed and cutting a deep channel across the Kaikōura-Waiau Inland Road. The often-dry Goodwin's Creek also carried considerable flows (McPherson, 1997).

The Waimangarara broke its banks with scouring where storm water crossed the roads (McPherson, 1997).

2.2.7 January 1953

Prolonged, heavy, rainfall along the east coast caused widespread flooding. There was over 254 mm of rainfall recorded at Grange Road over 72 hours (McPherson, 1997), and widespread rainfall over the entire Clarence River catchment (Thomson, 1966). Yet again, the Kowhai River broke its banks below The Bluff and at Kowhai Ford (Middle Ford). Flood water flowed over Red Swamp Road, and downstream into Lyell Creek, flooding the town (Figure 2-18 and Figure 2-19). The Kahutara River also rose 2.7 m at the railway bridge (SCRCC, 1957).

Figure 2-17: After 1952 and 1953 floods – The Inland Road reformed across Kowhai River flood debris at Fernleigh Dip [Source: Kaikōura Historical Society]

Figure 2-18: January 1953 flood – Old Lyell Creek Bridge in foreground [Source: Kaikōura Historical Society]

Figure 2-19: January 1953 flood – West End Kaikōura [Source: Kaikōura Historical Society]

Fortunately, very little water entered West End and only a few shops were affected. The Kowhai River also broke its banks, to the south, at Fernleigh Dip. Flood waters from the Waimangarara River, Luke Creek, and Floodgate Creek caused considerable damage to the roads crossed by these flood waters.

2.2.8 December 1954

The Kowhai River broke through both north and south banks following heavy rain. However, the north bank breakout at The Bluff found a new course before considerable damage could occur.

2.2.9 May 1966

During this southerly rainfall event, the Kowhai River stopbanks were breached with overflows at Fernleigh Dip. The in-river Kowhai River flow was estimated to be ~650 m^3/s, and the Fernleigh Dip overflow was ~60 m^3/s (McPherson, 1997). Figure 2-20 shows the Kowhai River after the peak.

Figure 2-20: May 1966 flood – Kowhai River several hours after the peak [Source: Marlborough Catchment Board]

2.2.10 March 1975

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

As the high intensity rainfall was limited to the coastal area, the Clarence River did not flood 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).

2.2.11 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).

The Kowhai River breached an 80 m section of stopbank at Kowhai Ford (Middle Ford) for a short time between 7am and 4pm. Training banks were also damaged. Kowhai overflows passed into Lyell Creek, without causing any flooding to Kaikōura Township (McPherson, 1997). Floodgate Creek, Luke Creek, and the Waimangarara River all transported, and deposited, large volumes of sediment and broke out of their channels (McPherson, 1997).

2.2.12 March 1987

During this event ‘*a weak ridge of high pressure crossed New Zealand on 1 March 1987 and was followed by a shallow trough within which a depression formed. This caused high intensity rainfall in the head water catchments of the Kowhai River*’ (McPherson, 1997).

This flood event seriously damaged the Kowhai River control works, with an estimated peak flow of 350 m^3/s (Marlborough Catchment Board), which was considered equivalent to a 5 year ARI flood on the Kowhai River (Williman and Duncan, 1987). Several of the echelon banks (including Kennedy’s and Harnetts) were reinstated on a new alignment to reduce water velocities and the likelihood of future erosion (Marlborough Catchment Board, 1987).

The nearby Rosy Morn recorder did not record significant flows, suggesting the storm event was localised (Williman and Duncan, 1987).

2.2.13 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 catchment, further north, 300 mm of rainfall was recorded for this event (McPherson, 1997).

During the morning of 23 December 1993, the Kowhai and Waimangarara Rivers were rising, producing big floods by 1pm. Meanwhile, Luke Creek and Floodgate Creek only had small freshes (Wright, 1994). Not long after 3pm, the Kowhai River breached its stopbank at Kowhai Ford (Middle Ford) and flowed across the Kowhai Fan to Lyell Creek (Figure 2-21 and Figure 2-22). As flood water rose, the SH1 road bridge over Lyell Creek acted as a constriction. Flood water ponded upstream of the bridge, inundating several properties including two schools, a church, houses, and some commercial and industrial buildings. Around 7pm, the small stopbank (along the township side of Lyell Creek, downstream of SH1), overtopped flooding the Kaikōura Township commercial area. At the peak of the flood, up to 0.5 m of water flowed over the deck of the SH1 bridge (Reid and Scholes, 1994). High river levels prevented river works at Kowhai Ford, to divert the Kowhai River back to its original course, until the morning of 24 December. This work was completed mid-morning on 24 December (Wright, 1994).

Figure 2-21: 24 December 1993 - after the breach occurred near Kowhai Ford Road (showing the path leading to Lyell Creek and Kaikōura Township)

Figure 2-22: 24 December 1993 - after the breach near Kowhai Ford Road occurred (showing damage to farmland below Kowhai Ford/Middle Ford)

Figure 2-23: December 1993 flood – water flowing under the railway bridge into West End Kaikōura around the flood peak

Figure 2-24: December 1993 flood – looking down onto Ludstone Road and Grays Lane

2.2.14 July 2008

A deepening low, to the northwest of New Zealand, travelled in a southerly direction across the central part of the country. This low brought heavy rain to Marlborough and Canterbury late on 30 July and 31 July 2008, with the greatest volumes of rain in North Canterbury and the Kaikōura Coast. 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).

In the Kahutara River, floodwaters washed out riverbank trees and erosion protection structures, resulting in significant riverbank erosion, and some loss of farmland. Floodwaters were also observed to have overflowed across the true left bank onto low lying land upstream of the railway line (Figure 2-25 and Figure 2-26).

Figure 2-25: Looking downstream along the Kahutara River, 31 July 2008

Figure 2-26: Looking towards the Kahutara River mouth, 31 July 2008

2.2.15 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). Heavy rain was also noted in the Awatere Valley.

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).

2.2.16 April 2014

Flooding was caused by the remnants of Cyclone Ita passing over the country. The worst affected area was the West Coast. Heavy rain between Kaikōura and Picton lead to 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). There was also a large volume of sediment transported into the Mt Fyffe sediment traps during this event.

2.2.17 February 2018

The remnants of Tropical Cyclone Gita passed across the Kaikōura area, causing significant rainfall along parts of the Kaikōura coast. Rainfall for this event varied spatially, with Rosy Morn recording 269 mm in 12 hours, while only 156 mm was recorded at Luke Creek over 12 hours. For the more extreme rainfall at Rosy Morn, the 12 hour total was estimated to have a 100 to 200 year ARI. Although no flows were recorded, both Rosy Morn Stream and Kie Kie Stream carried significant volumes of gravel, which accumulated upstream of the railway line, blocking the railway culverts and 'filling' the stream channels. Excess water and gravel flowed over the small, confined, alluvial fan areas adjacent to the streams, entering dwellings beside each stream (https://www.stuff.co.nz/national/101645608/extropical-cyclone-gita-causes-landslips-destroys-two-homes-near-kaikura, accessed 7 January 2019).

2.3 Historic earthquakes

The 2016 Kaikōura Earthquake Sequence generated a considerable number of landslides and rockfalls in the Kaikōura District. This has provided a large volume of additional sediment to many rivers and streams. Although there is very little documented evidence of the impacts of historic earthquakes in this area, Marlborough Catchment Board notes from 17 June 1937 made several observations after the Cheviot earthquake in 1901 (McPherson, 199, page 31)

> *'At that time I was on a sheep station just south of Kaikōura near the Kowhai River. The station house was situated at the foot of a hill near a small creek, and the banks of the creek where it issued from the hill were steep and about 20 ft deep. It was from this creek that the water supply of the house was drawn, and the bed of the creek was rock formation.*
>
> *During the first heavy rain after the earthquake, large quantities of shingle commenced to come down the creek and spread fanwise over the almost level land below, covering several acres. As the shingle gradually accumulated below, much of it began to be deposited in the bed of the creek higher up, till at least the shingle was level with the top of the bank that had been, before the shingle began to flow, at least 20 ft above the bed of the creek. The same thing happened in the Kowhai River, after the earthquake, large quantities of shingle being brought down the river and deposited on the flats, and soon the bed of the river was raised up higher than the main road that runs alongside the river.'*

2.4 Kaikōura river control and drainage schemes

The Kaikōura river control and drainage schemes consist of both a fan crest system and a channelized system. The location and objectives of both systems are described in Table 2-1.

Table 2-1: Summary of Kaikōura river control and drainage scheme

Part of scheme	Location	Scheme objective
Fan crest system	Mainly located in the upper catchment where the channel is on top of a typical fan/convex cross section	To constrain the active channels to present courses on the crest of their respective fans, and to mitigate the adverse effects of flood overflows and shingle encroachment.
Channelised system	Mainly located in the lower catchment where the channel is at the bottom of a concave cross section	To carry specified flows (within major channel beds) without exceeding banks, and to allow the control of the water table to maximise the productive use of adjoining land by providing effective outfall (drainage) to properties in the scheme area. Also, to convey up to 160 m^3/s to the sea in Lyell Creek, downstream of SH1.

The various components of the river control scheme and drainage network are described below. Additional details, including the background to the development of the scheme, are available in the Canterbury Regional Council Asset Management Plan (CRC, 2017).

2.4.1 River control scheme

The river control scheme consists of flood control structures (i.e. stopbanks and echelon banks) and erosion control (i.e. rock and tree protection). Vegetation and shingle movement are also controlled to maintain channel capacity and suitable channel alignments.

In May 2017, the 34.2 km of stopbanks and echelon banks were estimated to have a value of $7.3m. The 343,000 tonnes of rock protection, 2.3 km of tree protection and 677 ha of tree poles also had a combined value of ~$16.2m.

2.4.2 Drainage scheme

The drainage scheme includes natural streams and constructed tributary channels. Vegetation and silt/debris are controlled as part of the drainage scheme maintenance. The scheme, including culverts, consists of 57.9 km of maintained drains. In May 2017 it was estimated to have a value of ~$1.0m.

2.4.3 Existing standards

The Kaikōura river control and drainage schemes aim to reduce the impact of smaller events up to approximating a 20 year ARI. However, the river control works are constructed in a very high-energy environment with the purpose of resisting, and absorbing, some of that energy. No matter what the standard of maintenance, damage to such works is inevitable – even for flood events smaller than a 20 year ARI.

2.4.4 Protected assets

In June 2017, the capital value of the protected land and buildings was estimated to be ~$961m.

2.4.5 Additional flood protection works

The Kahutara River is not included in the Kaikōura River Rating District. However, there are flood protection works along the true left bank of the Kahutara River - extending from near the river mouth to 1.2 km upstream of the SH1 road bridge (Figure 2-27). This stopbank was constructed after the 2008 flooding to protect the railway line, superseding an existing ~100 m long stopbank at the upstream limit of the floodplain (located on the landward side of the new stopbank). Since the 2016 Kaikōura Earthquake Sequence, additional material has been placed along the length of this new stopbank to 'reinforce' it. The structural integrity of this stopbank is unknown.

Historic imagery from 1942 clearly shows a historic flow path beyond the recently constructed Kahutara river flood protection works (Figure 2-27).

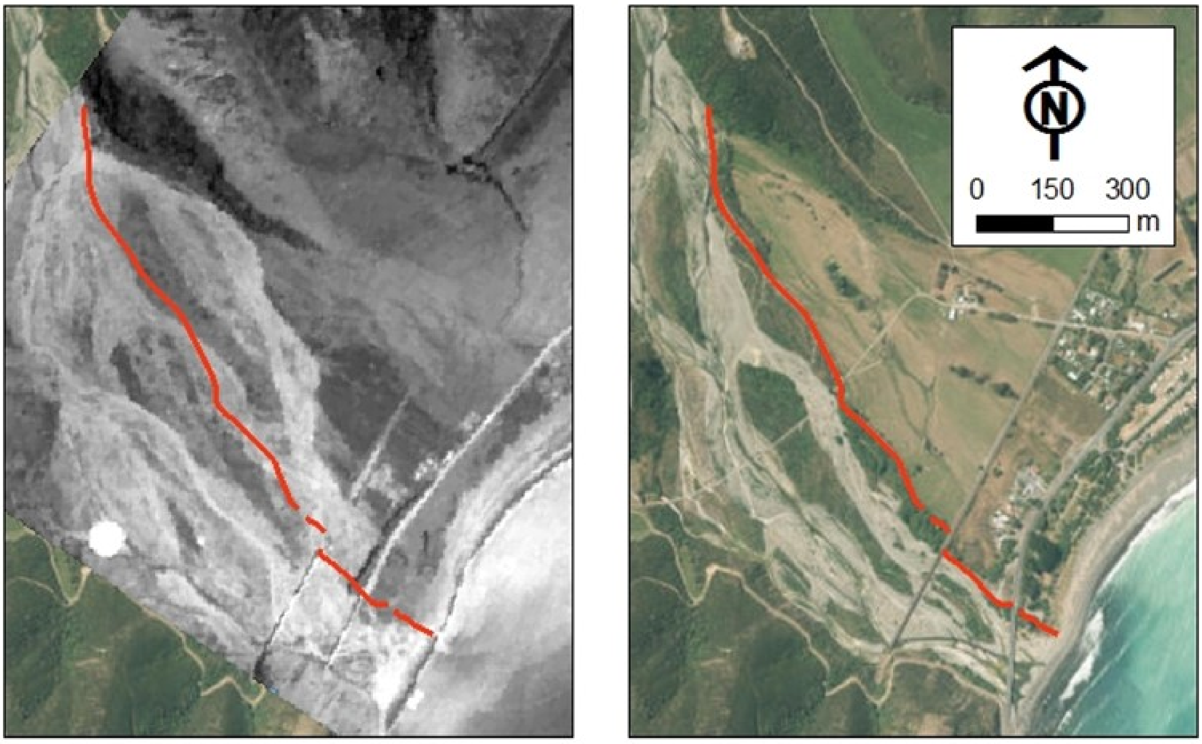


Figure 2-27: Location of existing flood protection works, along the true left bank of the Kahutara River, superimposed on aerial imagery from 1942 (left) and 2016 (right)

2.5 Climate change

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

<u>Air temperature</u>
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.

<u>Rainfall</u>
Rainfall tends to vary 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 contains ~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 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, 100 years from now, what is currently considered to be a 100 year ARI rainfall event may become a 50 year ARI rainfall event.

Current climate change estimates for the Kaikoura area show climate change (to 2120) may increase peak rainfall by the order of 22 to 35%, for the RCP 8.5 scenario (for storm durations of 24 hours to 1 hour, respectively). However, the relationship between increased peak rainfall, and the resulting increase in peak flood flows, is not likely to be linear – with peak flood flows tending to increase by a greater percentage than peak rainfall. For example, a recent modelling study by Gardner and Henderson (2019) showed that, in the Wairarapa, a 17% increase in peak rainfall increased peak flows by 17 to 27% (depending on catchment characteristics). Further work, in the form of a detailed hydrologic model, would be required to better define this relationship for the Kaikōura watercourses.

<u>Sea level</u>
Sea level rise is a combination of increased sea temperatures (expanding sea water), retreating glaciers and loss of polar ice sheets from Greenland and Antarctica (PCE, 2015). 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).

Most of the Kaikōura rivers have relatively steep gradients, thus any increases in sea level, due to climate change, should not have a significant impact on flood levels upstream of river mouths. By comparison, Lyell Creek has a relatively gentle gradient making it more susceptible to sea level increases. However, during the November 2016 Kaikōura Earthquake Sequence, ground levels at the Lyell Creek mouth uplifted by around 0.8 m relative to sea level. Therefore, any impacts on flooding due to sea level rise are likely to be minimal – especially since the SH1 bridge over Lyell Creek acts as a constriction to flood flows, limiting the flow able to be conveyed along Lyell Creek to the sea.

3 Methodology

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

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

- Compilation of historical flood event information (Section 2.2)
- Estimation of flood hydrology/design flows (Section 3.1)
- Construction of a computational hydraulic model (Section 3.3)
- Limited validation of the hydraulic model (Section 3.4)
- Modelling of design flood events using the hydraulic model (Section 3.5)
- A sensitivity analysis (Section 3.6)

3.1 Flood hydrology

The rivers and streams most likely to cause flooding on the Kaikōura Fans include the Kowhai River, Lyell Creek, and those draining the south-eastern slopes of the Mt Fyffe Range (Pearson and Thompson, 1994). Since the focus of this investigation was determining the likely extent and depth of flooding on the Kaikōura Fans for land use planning purposes, 50 and 500 year ARI flood flows were calculated for these water courses. The derivation of the design flows is outlined below for the various water courses. Note there is considerable uncertainty in these estimates due to limited flow records in these catchments, and a reliance on regional flood estimation methods (despite significant geographic and orographic differences).

3.1.1 Lyell Creek

Recent work by Surman and Heslop (2017) calculated a Lyell Creek mean annual flood from 11 years of recorded water level/flow data from Site 63001, located on Lyell Creek (downstream of the Warren Creek confluence). This gave a mean annual flood of 12.8 m^3/s. Because of the short record, Surman and Heslop (2017) scaled this mean annual flood up to 13.8 m^3/s using a mapped mean annual flood estimate derived from Griffiths *et al.* (2011).

As ~18% of the catchment is located downstream of the recorder, the mean annual flood flow, Q_{MAF}, was increased further using a mean annual flood factor, q_{MAF}, of 1.32, which was calculated using

$$q_{MAF} = \frac{Q_{MAF}}{A^{0.9}}$$

Where Q_{MAF} = 13.8 m^3/s
A = 13.5 km^2

For a catchment area of 16.4 km^2, the mean annual flood flow, Q_{MAF}, is 16.4 m^3/s. Using this mean annual flood flow, and the regional dimensionless growth curves recommended by Pearson and Thompson (2005, Table 8), the following design flows for Lyell Creek are derived (Table 3-1).

Within the Lyell Creek catchment, Surman and Heslop (2017) defined four main sub-catchments. These are approximated in Figure 3-1, and the derived Lyell Creek sub-catchment flows are summarised in Table 3-2.

Table 3-1: Present-day Lyell Creek design flows

Average Recurrence Interval (ARI)	Recommended regional dimensionless growth curves, Q/Q_{MAF} (Pearson & Thompson, 2005, Table 8)	Lyell Creek flow (m^3/s)
Mean annual flow		16.4
50 year	3.20	53
100 year	3.84	63
200 year	4.56	75
500 year	5.61	92

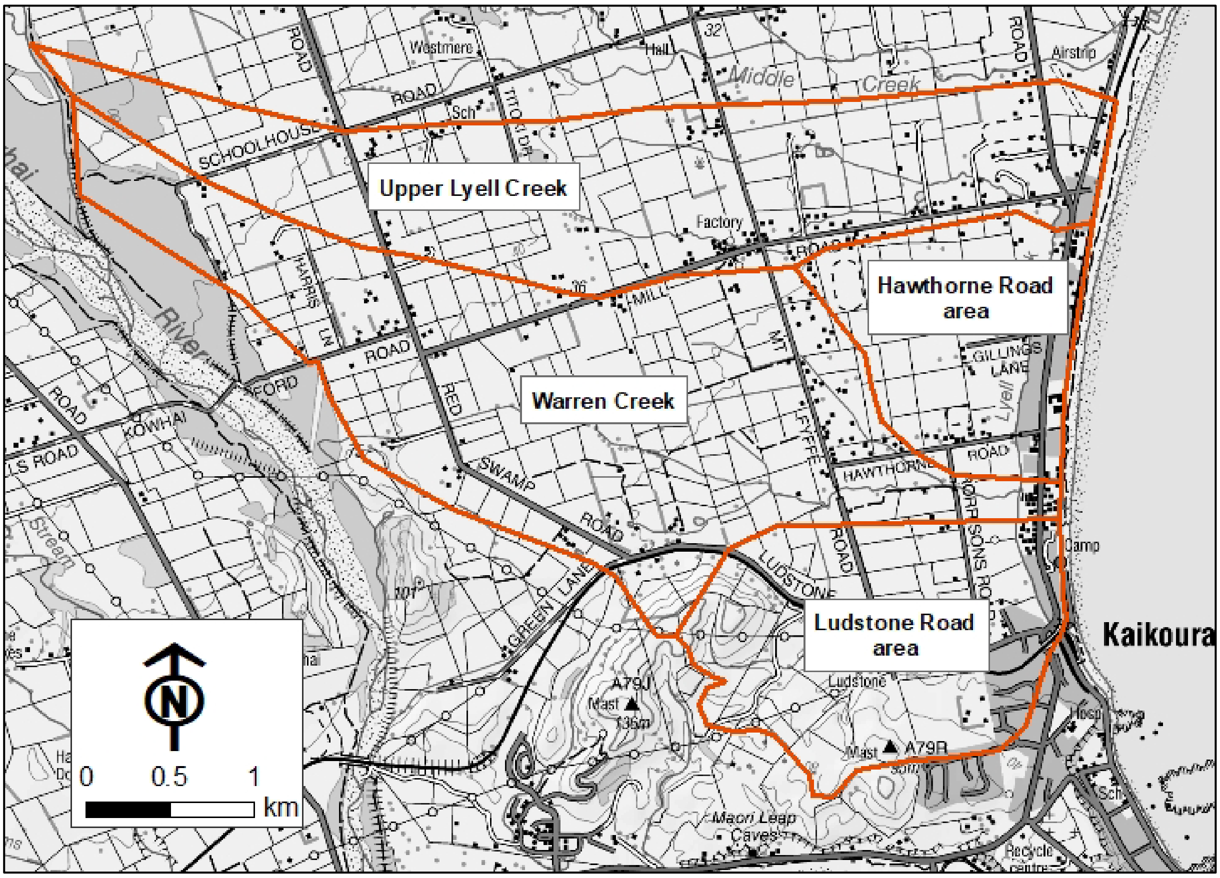


Figure 3-1: Lyell Creek sub-catchment location map

Table 3-2: Present-day Lyell Creek sub-catchment design flows

Event Probability (ARI)	Peak Flow m^3/s			
	Upper Lyell Creek	Hawthorne Road area	Warren Creek	Ludstone Road area
Catchment area, A (km^2)	*5.2*	*1.9*	*6.4*	*2.9*
Proportion of flow (%)	*32*	*11*	*39*	*18*
50 year	17	6	21	9
100 year	20	7	25	11
200 year	24	9	29	13
500 year	29	11	36	16

3.1.2 Mt Fyffe and Ewelme streams

The Mt Fyffe and Ewelme stream catchment areas were divided into areas that were considered to have either a steep or a gradual slope (Table 3-3).

Table 3-3: Mt Fyffe and Ewelme stream catchment characteristics

Water course	Total Catchment area (km^2)	Area (km^2)	
		Steep slope	Gradual slope
Harnetts Creek	11.3	2.6	8.7
Waimangarara River	18.4	9.5	8.9
Luke Creek	4.8	4.8	-
Middle Creek[a]	22.1	7.0	15.1
Floodgate Creek	4.2	4.2	-
Goldmine Creek	3.9	3.9	-
Ewelme Stream	18.2	4.2	14.0

[a] Includes Luke Creek

For the catchment areas with a steep slope, the Tonkin and Taylor (2017) factors for the Kowhai River at Orange Grove were used to derive the peak flows (i.e. q_{MAF} = 1.9, q_{100} = 4.0, q_{50} = Q_{50}/Q_{MAF} = 3.4, and q_{500} = Q_{500}/Q_{MAF} = 5.2). Where catchment areas had a gradual slope, the Lyell Creek factors were used to derive the peak flows (i.e. q_{MAF} = 1.3, q_{50} = 3.2, q_{100} = 3.8, and q_{500} = 5.6). As the catchment areas are relatively small, it was assumed that the peak flow for each catchment was the sum of the steep and gradually sloping areas of each catchment. Table 3-4 summarises the derived design flood peak flows for these water courses.

Table 3-4: Present-day Mt Fyffe and Ewelme Stream design flows

Water course	Mean Annual Flood, Q_{MAF}(m^3/s)	50 year ARI Q_{50} (m^3/s)	100 year ARI Q_{100} (m^3/s)	500 year ARI Q_{500} (m^3/s)
Harnetts Creek	14	45	53	75
Waimangarara River	24	80	94	127
Luke Creek	8	27	31	40
Middle Creek[a]	27	89	105	145
Floodgate Creek	7	24	28	35
Goldmine Creek	6	22	26	33
Ewelme Stream	21	69	82	115

[a] Includes Luke Creek

3.1.3 Kowhai River

Tonkin and Taylor (2017) derived design flood flow estimates for the Kowhai River at Below Orange Grove, which has a catchment area of 75 km^2. The total Kowhai River catchment area, including Goldmine and Floodgate Creeks, is ~87 km^2. Tonkin and Taylor (2017) derived the following information for the Kowhai River at Orange Grove:

- Mean annual flood factor q_{MAF} ($Q_{MAF}/A^{0.9}$) of 1.9
- 100 year ARI growth factor q_{100} (Q_{100}/Q_{MAF}) of 4.0

Using an EV1 distribution, the Kowhai River at Orange Grove design flood flows were produced (Table 3-5). Using a catchment area of 87 km^2, together with the Orange Grove q_{MAF} and growth factors, design flows were calculated for the Kowhai River at the river mouth. Table 3-5 shows that these latest estimates for the Kowhai River design flows compare well with previous design flows produced by Pearson and Thompson (2005), which used a slightly smaller catchment area of 79.7 km^2.

Table 3-5: Present-day Kowhai River design flows

Event Probability (ARI)	**Flow m³/s**		
	Kowhai River at Orange Grove (Tonkin & Taylor, 2017, Table 7.2.5)	**Kowhai River at river mouth (based on Tonkin & Taylor, 2017)**	**Kowhai River (Pearson and Thompson, 2005, Table 10)**
Catchment area, A (km²)	*75*	*87*	*80*
Mean annual flow	93	106	
50 year	320	370	360
100 year	370	420	420
200 year	420	480	490
500 year	480	550	590

Kowhai River breakout flows

After the December 1993 flood event, Barnett Consultants (1994) completed a flood hindcasting study. As part of this study, a 1D computer model was constructed to model the 1993 Kowhai River breakout flow. Although no flood levels, or the breach geometry, were measured at the time of the breakout, peak flood levels were recorded in the Kaikōura Township area. Barnett Consultants (1994) made several assumptions, based on the flood log and the estimated Kowhai River ARI flow of ~10 years, to construct a realistic breakout flow hydrograph that was calibrated to the peak flood levels. The resulting breakout flood hydrograph is shown in Figure 3-2.

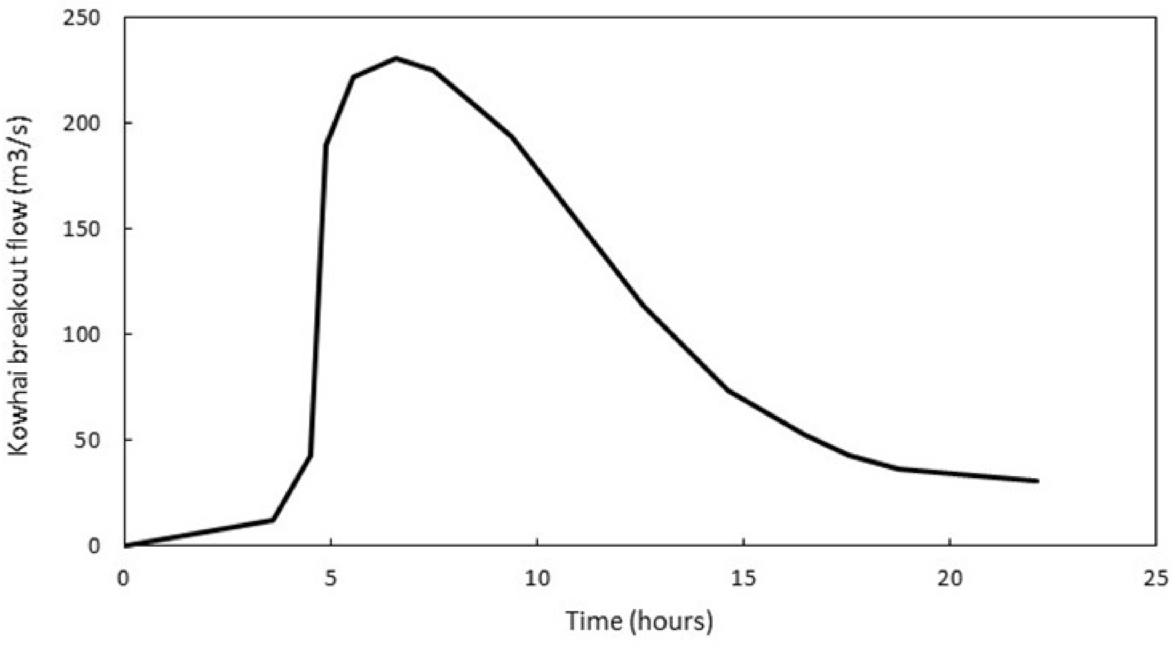


Figure 3-2: December 1993 Kowhai River breakout flow hydrograph (extracted from Barnett Consultants, 1994)

Barnett Consultants (1994) derived a peak Kowhai River breakout flow of 230 m^3/s for a Kowhai River peak flow estimated to be 390 m^3/s (i.e. approximately 60% of the flow was estimated to have exited onto the Kowhai Fan). More recent modelling work was completed by Environment Canterbury in 2004 for the design of the Lyell Creek flood wall. This work used a revised December 1993 Kowhai River peak breakout flow of 190 m^3/s.

Table 3-6 presents peak Kowhai River breakout flows for present-day design flood events, assuming approximately 60% of the Kowhai River flow (excluding Goldmine and Floodgate Creek, which are likely to peak earlier) passes onto the Kowhai Fan. Based on Table 3-6, the December 1993 breakout would be considered equivalent to a 50 year ARI present-day breakout flow.

Table 3-6: Present-day Kowhai River and breakout design flows

Event Probability (ARI)	Kowhai River peak flow – including Goldmine and Floodgate Creeks (m^3/s)	Kowhai River peak flow – excluding Goldmine and Floodgate Creeks (m^3/s)	Kowhai River peak breakout flow (m^3/s)
50 year	370	320	190
100 year	420	370	220
500 year	550	480	290

3.1.4 Peketa local inflows

Peketa inflows from the three main local sub-catchments were calculated using the same method as described in Section 3.1.2 for the Mt Fyffe and Ewelme Stream catchment flows. As the only flat, or gradually sloping, parts of the sub-catchments are the ponding areas, and as there is no data to calibrate the sub-catchment flows to, it was assumed that the entire area of each sub-catchment was steeply sloping (i.e. Kowhai River at Orange Grove factors were used to derive the peak flows). Table 3-7 summarises the Peketa local design flows.

Table 3-7: Present-day Peketa local sub-catchment design flows

Event probability (ARI)	Peak Flow m^3/s		
	Sub-catchment 1	**Sub-catchment 2**	**Sub-catchment 3**
Catchment area, A (km^2)	*0.75*	*0.53*	*1.04*
Mean annual flood	1.5	1.1	2.0
50 year	5.0	3.7	6.8
100 year	5.8	4.3	7.8
500 year	7.6	5.6	10.2

3.1.5 Kahutara River

Tonkin and Taylor (2017) derived design flow estimates for the Kahutara River at Railway Bridge, which has a catchment area of 232 km^2. The results of Tonkin and Taylor (2017) are summarised in Table 3-8. The following factors were used by Tonkin and Taylor (2017) to derive the present-day design flows for the Kahutara River at Railway Bridge:

- Mean annual flood factor q_{MAF} ($Q_{MAF}/A^{0.9}$) of 1.2
- 100 year ARI growth factor q_{100} (Q_{100}/Q_{MAF}) of 4.0

Table 3-8: Present-day design flows for the Kahutara River at Railway Bridge

Event Probability (ARI)	Flow (m^3/s)
Mean annual flood	161
50 year	560
100 year	645
500 year	840

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 is 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). This data has a 'data zero' value of 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.

Barnett Consultants (1994) derived an equation for Kaikōura tide levels based on the 1993/94 Nautical Almanac. Relationships between Lyttelton and Kaikōura tides were used to produce a sinusoidal curve that replicated Kaikōura tides at the time of the December 1993 flood event. The equation derived was:

$$Tide\ Level\ (m) = 1.025 + 0.375 \sin\left(\frac{2\pi t}{T} - \frac{\pi}{2}\right)$$

where: t = time in minutes from high or low tide
T = tide period (688 minutes on rising tide and 800 minutes on falling tide)

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).

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 demonstrated that the higher recorded storm tides tend to occur during a perigean tide combined with relatively small storm surges of 0.1 to 0.3 m (Bell, 2010).

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

3.3 Hydraulic model construction

The Mike Flood modelling package combined 1-dimensional (1D) modelling for some of the main watercourses with 2-dimensional (2D) modelling for the alluvial fans and floodplain. The 1D and 2D models were linked using lateral links. For example, along Lyell Creek from 90m upstream of Mill Road to the coast. These lateral links allow flood water to move between water courses and the floodplain. A schematic of the 1D model areas, including lateral links, is shown in Appendix A. A more detailed description of the model is given below.

3.3.1 1D river channel models

The 1D model of Lyell Creek extends from Mill Road to the coastal boundary at Kaikōura Township (Appendix A, Figure A-1). Lyell Creek flood flow hydrographs are input further upstream, in the 2D model, near the upper limits of the main Lyell Creek tributaries.

Design cross sections, developed to restore the Lyell Creek channel to its pre-earthquake capacity, have been used in the model construction. As of March 2019, the Lyell Creek channel has been excavated with bank battering from the true right bank to restore most of the capacity. Additional work is still to be undertaken along the true left bank. The cross section locations are shown in Appendix A (Figure A-2 to Figure A-5), along with Table A-1 which summarise the cross section information.

Harnetts Creek, Middle Creek, and Ewelme Stream also have 1D models connecting the lower reaches of the watercourses to the sea. Cross section locations are shown in Appendix A (Figure A-6 to Figure A-8),

Channel roughness

A Manning's n number of 0.035 has been used for the vegetation-free open channel bed resistance and 0.052 for more heavily vegetated berm areas. Variations in resistance due to vegetation have been accounted for by using relative resistances for each cross-section.

Structures

The Mill Road, Gillings Lane, Hawthorne Road and SH1 road bridges have been included in the Lyell creek 1D model as well as two footbridges downstream of SH1 and two access bridges upstream of Gillings Lane. These bridges could be partially blocked, overtopped and/or destroyed during a large flood event.

The Lyell Creek SH1 bridge overflows have been modelled slightly differently as overflows onto the bridge deck are able to pass along the road and down into the Township. The bridge overflows have therefore been modelled as a short channel over the deck with weirs allowing flows onto the bridge, and back into the creek downstream of the bridge. Flow is also able to pass from the bridge deck, along the road, and into the Township via a lateral link to the 2D model grid.

Harnetts Creek, Middle Creek, and Ewelme Stream all include bridge structures immediately downstream of where the 2D model links to the 1D model.

3.3.2 2D model for alluvial fans and floodplains

The 2D component of the model covers the Kaikōura Fans area shown in Figure 1-1. The topography and roughness used in the model are described below.

Topography

To realistically model alluvial fan and 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 Kaikōura Fans, high resolution topographic data was obtained from a LiDAR (aerial laser scanning) survey. 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. An example of the detail provided by LiDAR data is shown in Figure 3-3.

Overland water levels and flows 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 topography.

A 5 m grid was chosen for this study to allow for a reasonable degree of topographic detail, while keeping the model run time to a maximum of 4 days. As the Kaikōura Fans contain elevated topographic features capable of impeding flows (e.g. roads and stopbanks), the 5 m model grid was modified using the maximum values from the 1 m grid to represent features not fully represented by the 'averaged' 5 m grid. Minimum values from the 1 m grid were also used to represent bed levels for the more significant watercourses and drains located in the 5 m grid, to ensure better conveyance of flood flows for smaller flood events.

The 5 m grid does have some limitations, pertaining to representation of some features such as smaller drains. Where these drains are not able to be represented, it is generally assumed that this is equivalent to the drain being either blocked or at full capacity due to local rainfall runoff. This is considered a reasonable assumption – especially for the larger and less frequent storm events.

For the full model set-up of the Kaikōura Fans, the 2D model includes 24 culverts and 18 weir structures. There are also 6 bridges and 4 culverts included in 1D structure links (i.e. since the structures were generally wider than one 5 m grid cell, they were included as part of short 1D channels). Other culverts in the study area have not been included, as the proportion of the flow carried in the smaller drains during large flood events is relatively minor compared to the surrounding overland flows.

Comparisons were made with the detailed LiDAR data to ensure important topographic features (e.g. banks, terraces, roads and railways, and historic flow paths) were correctly represented in the 5 m grid. The grid cells have also been corrected where there are obvious inaccuracies due to crop effects.

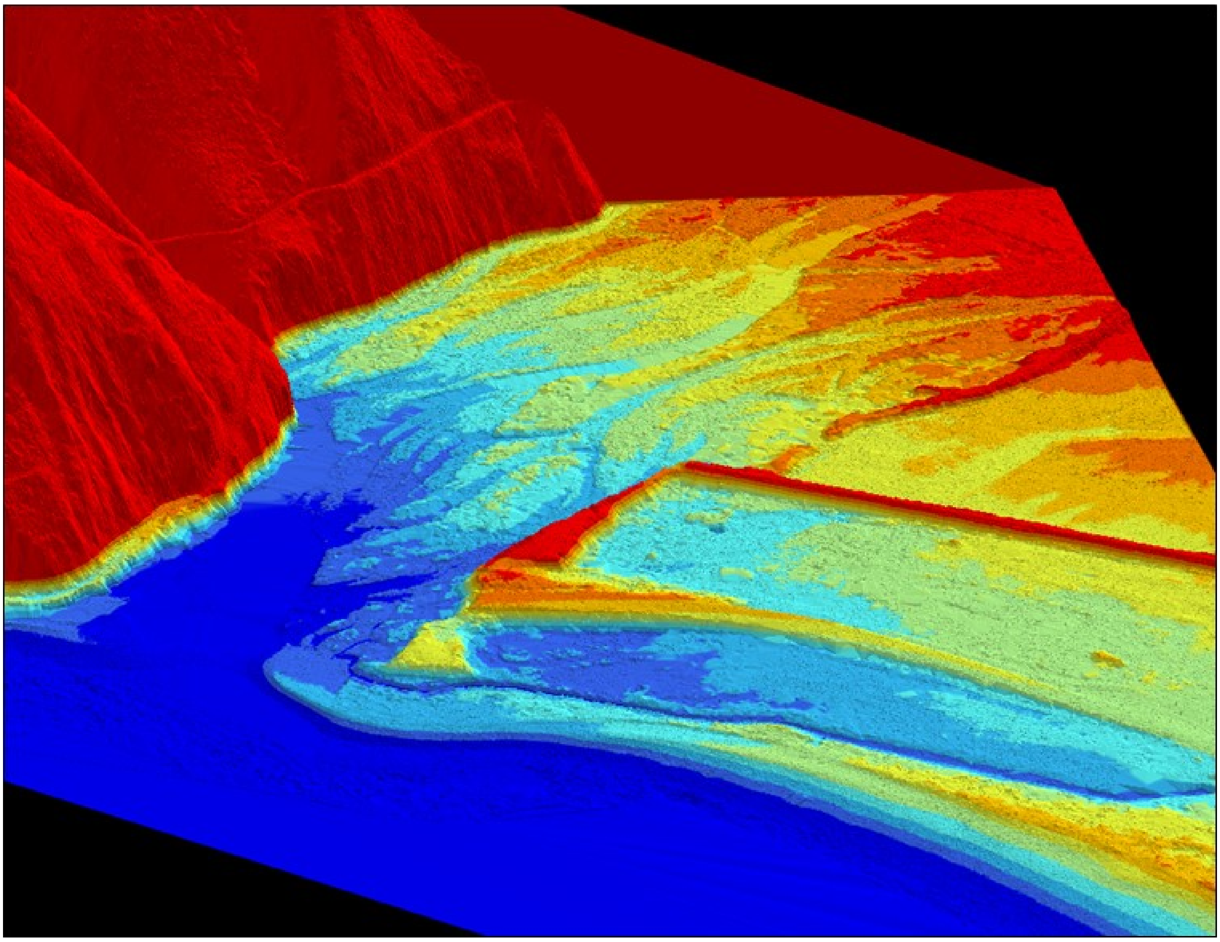


Figure 3-3: 3D image of the Kahutara River mouth and floodplain LiDAR data (with bridge structures removed and vertical scale exaggerated by a factor of 2)

Roughness (surface resistance)

Alluvial fan and floodplain flow and depths are influenced by the hydraulic resistance of the ground cover and other obstructions, such as buildings and trees. Resistance values (i.e. Manning's n values) were assigned to the various ground surfaces 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 was increased, to increase the surface resistance. Likewise, where there were smoother surfaces (e.g. roads) the Manning's n value was decreased to reduce surface resistance. For this study, a Manning's n value of 0.05 was used to represent the fans and floodplain as they are predominantly land used for grazing/pasture. Localised increases in water level due to obstructions (i.e.

buildings) were accounted for by increasing Manning's n to 0.20, and 'smooth' roads have been given a lower Manning's n of 0.015. The Kowhai River was assigned a Manning's n of 0.07, the Kahutara River and Ewelme Stream 0.040, and the lower reaches of Harnetts Creek, Waimangarara River and Middle Creek 0.035. Only structures, vegetation and roads within the potentially floodable area were digitised to produce adjusted Manning's n values. Figure 3-4 shows the Manning's n values in the Kaikōura Township area.

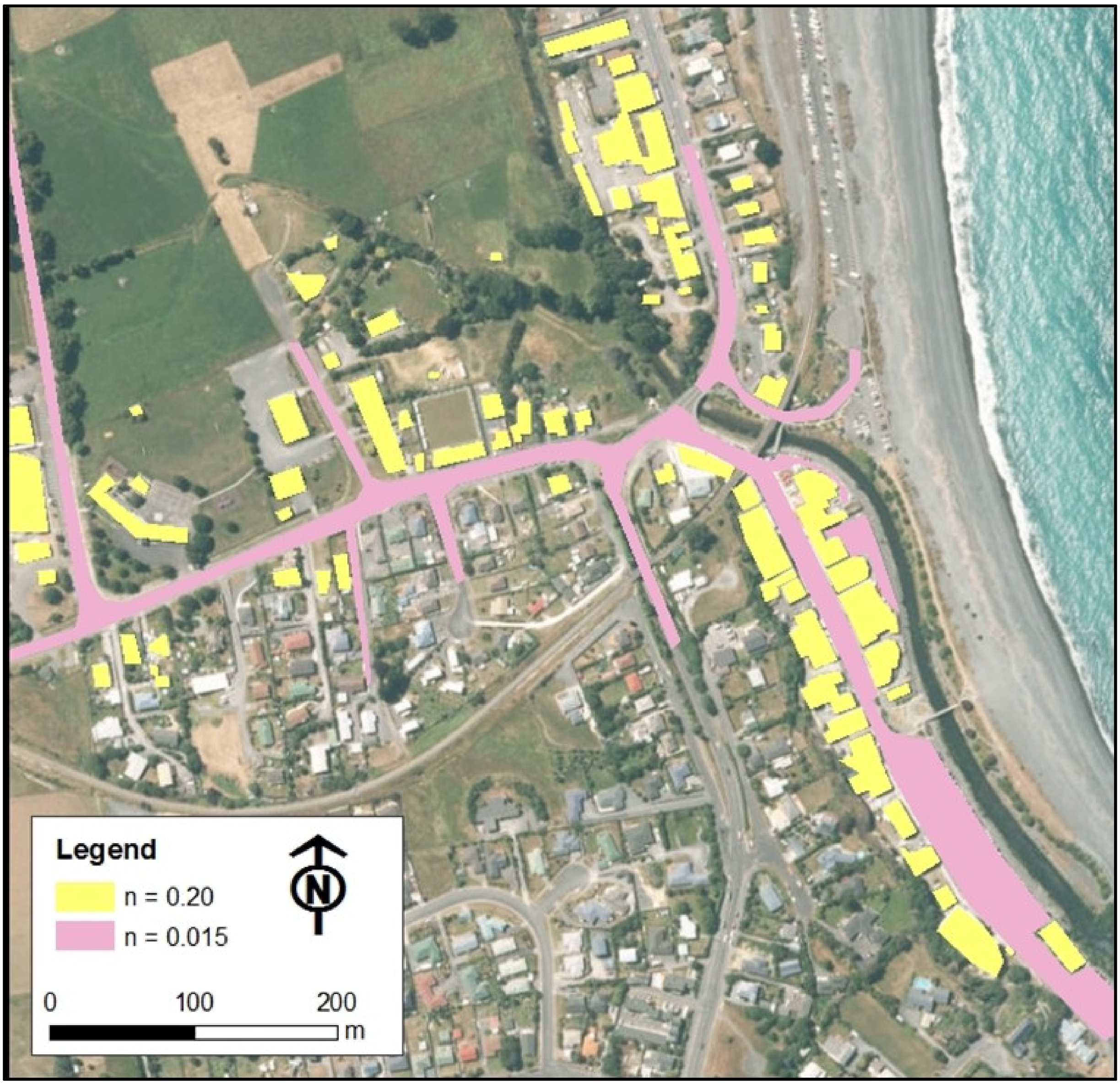


Figure 3-4: Manning's n roughness in the Kaikōura Township area

Model inflow locations
Flood flows in the water courses were input as a flow source into the 2D model grid cells. The location of the inflows is shown in Figure 3-5 with the portion of flow input at each location described in Table 3-9. For most water courses, the inflows were divided between several locations, and over several grid cells.

Model breakout flow locations
When Kowhai River breakout flows were included in the modelling, the breakout flows were input as a flow source into the 2D model grid cells. Figure 3-6 indicates the location of the breakout flows. The breakout locations are discussed in more detail in Section 3.5.2.

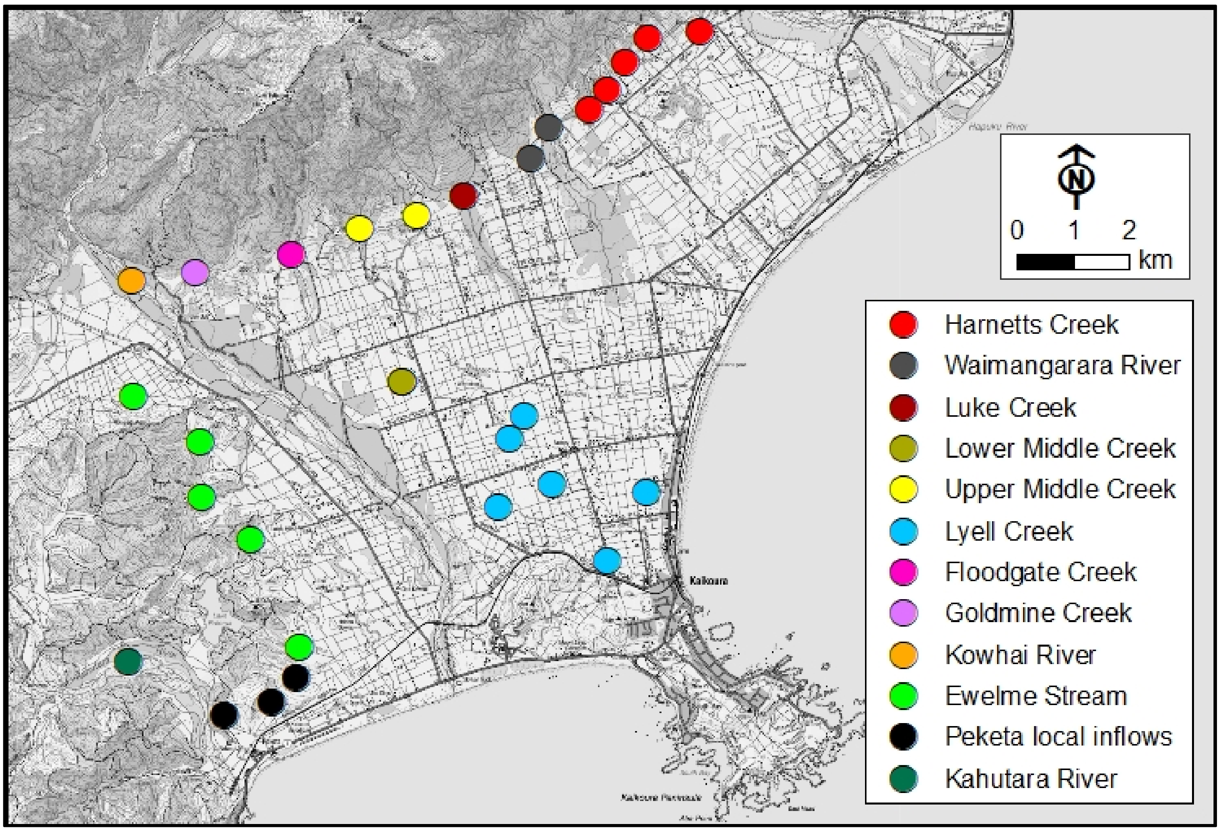


Figure 3-5: Location of inflows for 2D fan and floodplain model

Table 3-9: Distribution of model inflows

Watercourse	Number of inflow locations	Percent of inflow at each input location
Lyell Creek	(6)	
Upper Lyell Creek	2	50
Hawthorne Road	1	100
Warren Creek	2	50
Ludstone Road area	1	100
Mt Fyffe streams	(13)	
Harnetts Creek	5	20
Waimangarara River	2	87.5 (main channel), 12.5 (tributary)
Luke Creek	1	100 (+ 20 Middle Creek lower catchment)
Upper Middle Creek	2	50 (upper catchment) + 20 (lower catchment)
Lower Middle Creek	1	40 (lower catchment)
Floodgate Creek	1	100
Goldmine Creek	1	100
Ewelme Stream	5	20
Peketa local inflows	(3)	
Sub-catchment 1	1	100
Sub-catchment 2	1	100
Sub-catchment 3	1	100

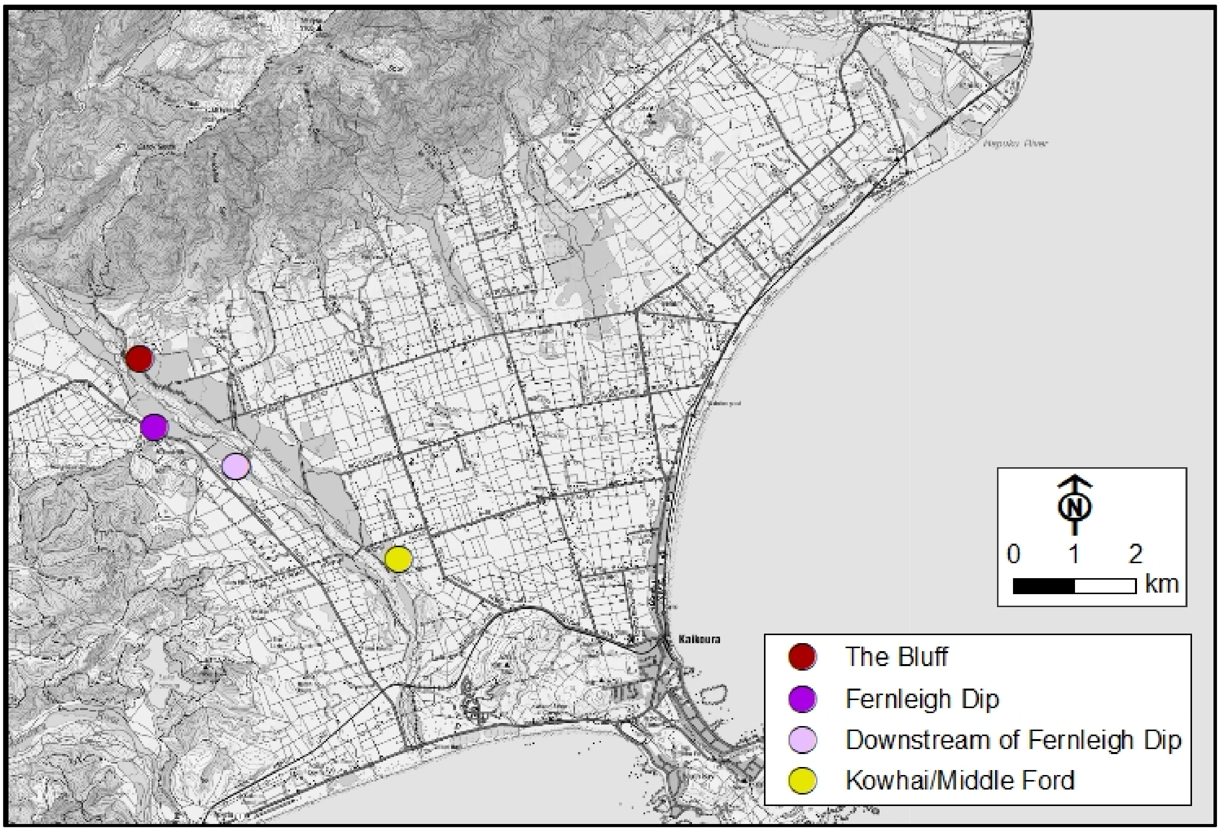


Figure 3-6: Location of breakout flows for 2D fan and floodplain model

3.3.3 Limitation of model for steep Mt Fyffe Fans

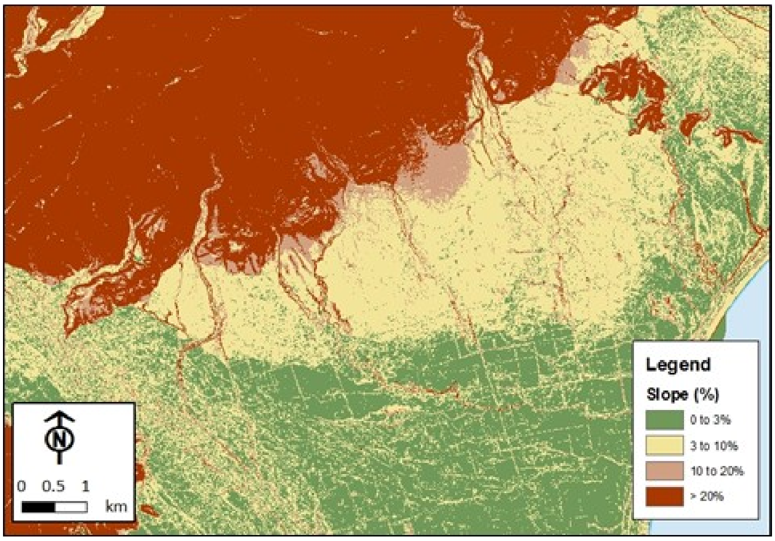
During extreme flood events, catchments with a ready supply of gravel will carry large volumes of gravel along their steep, confined streams. As stream slope decreases and channel width increases, usually around the apex of the alluvial fan (where the stream exits the steep, mountainous, upper catchment), gravel being transported as a debris flow or debris flood is deposited. Between significant flood events, the stream will then incise into the deposited gravel, and the material is redistributed further downstream over the lower fan. Several of the Mt Fyffe streams have alluvial fans that are 'actively growing' this way. These are described in CRC (2000, p14):

> *'Floodgate Creek, Luke Creek, and the Waimangarara River, are all vigorous fan-building streams which drain the seaward face of Mt Fyffe. The fans are steep and actively continue to grow in size as the streams flowing on top of them bring down a never-ending supply of rock debris eroded out of their unstable upper catchments. These fans have extended so far seawards that they now overtop and cover areas of the Kowhai fan surface to below Postmans Road'* (Figure 2-1).

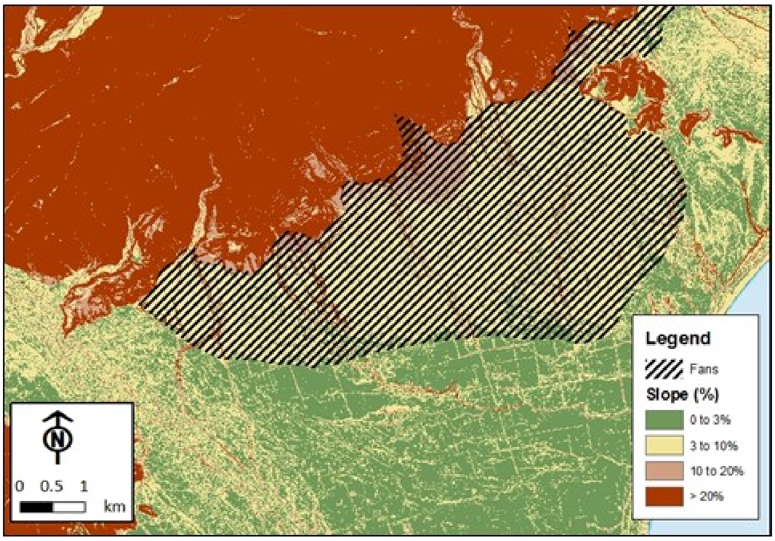
Middle Creek and Harnetts Creek have been described previously as being less active fans as they have smaller catchments that are at a lower elevation. They are, instead, *'incised into their beds and flow along the interface between the fans built by their larger, and more vigorous, neighbours'* (CRC, 2000, p14).

To identify the Mt Fyffe alluvial fans, ground slopes were plotted as a percentage slope (i.e. rise in elevation was divided by horizontal distance and then multiplied by 100 to convert to a percentage). Figure 3-7 identifies the Mt Fyffe alluvial fan areas as being those where the ground slope is between 3 and 20%. This defined fan area closely matches the extent of the Brideau *et al.* (2020) debris flow and debris flood fans for the Mt Fyffe area. In these areas, where sediment may aggrade and scour the dynamic landscape during flood events, a fixed bed computer model is unable to accurately simulate flood flow depths, or the changes in the landscape.

(a) Location map



(b) Slope (%) map based on 5 m model grid



(c) Active alluvial fans defined by slope (%) of 3 to 20%

Figure 3-7: Identification of Mt Fyffe alluvial fans based on slope (%)

This is even more so if the stream flowing across the alluvial fan should avulse (i.e. relocate to another location on the fan). When this occurs, the flood risk for a property could completely change for the next significant flood event. Pennington (2009 & 2010) both reiterate this and endorse avoidance of development as a flood mitigation option in these areas.

Figure 2-4 to Figure 2-6 illustrate that in a flood event with an ARI significantly less than 500 years (April 2014), Luke Creek can transport large quantities of material downstream to the sediment trap, as well as aggrading the river channel. For larger flood events, or if a second flood event occurs before the channel and sediment trap are cleared, the channel capacity may be exceeded (i.e. it becomes easier for flood waters to overflow and form a new flow path downstream).

Although these alluvial fans have been included in the models used in this investigation, it was mainly to ensure the inflows from all the Mt Fyffe streams were contributing to the total flow volumes on the downstream Kowhai Fan, as well as in the Lyell Creek ponding area. Flood modelling results for the area highlighted as 'Fans', in Figure 3-7, should be discarded and other methods used for addressing flooding issues. For example, Pennington (2009) proposed alternative, more practical, solutions rather than modelling.

Further information about the Kaikōura debris flow and debris flood alluvial fans is provided in Brideau *et al.* (2020).

3.4 Model validation – December 1993

To provide confidence in model predictions, models should be calibrated using historical flood events to ensure they are realistic. A brief summary of the December 1993 flood event is given in Section 2.2.13, and Figure 2-21 to Figure 2-24 show the breakout location, and some of the flooding that occurred around the Lyell Creek SH1 bridge. A more detailed description of the December 1993 flood event is given in Barnett Consultants (1994).

Although there are observed flood extent and flood level information for the December 1993 flood event, the model produced for this investigation may not necessarily be able to fully simulate the event as accurately as if it was set up using pre-2016 Kaikoura Earthquake Sequence ground levels and 1993 stopbank/floodwall profiles. The main changes that have occurred between 1993 and 2019 are:

- Significant uplift of the Kowhai Fan relative to sea level (of the order of 0.8 m across the study area) due to the 2016 Kaikōura Earthquake Sequence. Although uplift of ground levels varied spatially over the Kowhai Fan, the changes were very gradual on the fans (excluding localised subsidence). This uplift is considered unlikely to have a noticeable impact on flood flows on the Kaikōura Fan during a large Kowhai River breakout flow. Note, observed 1993 flood level information needs to be adjusted to account for the earthquake uplift and the 'new' New Zealand Vertical Datum 2016 (NZVD 2016) that replaces Lyttelton Vertical Datum 1937 (LVD 37).

- Construction of the Lyell Creek flood protection wall downstream of SH1, along the Township side of the creek.

Despite the above changes since December 1993, it was considered appropriate to attempt to validate the model using this flood event. The validation model is outlined below.

3.4.1 Model inputs

The Mt Fyffe and Ewelme stream flows have not been modelled. The reason for this is that comparisons can only be made between observed and modelled flows in the area along the Kowhai River breakout flow path, and around Lyell Creek (which did not include flow contributions from these water courses). The flows and sea levels used in the December 1993 model are described below.

<u>Lyell Creek</u>
The Barnett Consultants (1994) Lyell Creek hydrograph for the December 1993 flood event peaked approximately 3 hours before the Kowhai River, and 3.5 hours before the Kowhai River breakout flow. By the time the Kowhai River breakout flow peaked, Lyell Creek flows had receded to around 5 m^3/s,

after earlier peaking around 35 m^3/s. The Lyell Creek total flow was therefore considered insignificant, compared to the Kowhai River breakout flow, and was not included for this calibration scenario.

Kowhai River breakout flows
A Kowhai River peak breakout flow of 190 m^3/s was used to scale the Barnett Consultants (1994) breakout flow hydrograph profile.

Sea level
The Kaikōura design sea level was based on the tide equation (see Section 3.2.1) and a maximum storm tide level of 1.75 m NZVD2016 (which incorporates a storm surge of 0.4 m and a 0.1 m seasonal/ENSO water level fluctuation). The high tide was timed to occur around the time that the peak breakout flood flows reach the coast. Initial sensitivity model runs suggest sea level is not likely to have a significant impact on maximum flood levels in Lyell Creek – particularly upstream of SH1.

Model run time
Using the model inputs described above, the Mike Flood model was run for 19.5 hours to cover the December 1993 flood event (i.e. enough time to allow the ponded flood levels upstream and downstream of SH1 to peak as the breakout flow passes out to the sea along Lyell Creek).

3.4.2 Discussion and results

Figure 3-8 details the observed flooding for the December 1993 flood event, based on flood photographs and ground observations. Figure 3-9 shows the maximum modelled flood depths for the 190 m^3/s Kowhai breakout flow. When the two sets of flood information are overlaid (Figure 3-10) there is a good relationship between areas modelled as being flooded and areas observed to have flooded. Minor variations in flood extent are observed, particularly in the area around Gillings Lane downstream to Hawthorne Road. This could be because the maximum inundation extent occurred at night, there were no habitable dwellings at this location, and the photos used to map the observed flood extent do not show flooding at its peak. Figure 3-11 and Figure 3-12 show the flood extent for a smaller peak breakout flow of 180 m^3/s, and Table 3-10 summarises observed and modelled flood elevations for some of the measured flood level locations given in Appendix B.

Table 3-10: Comparison of measured and modelled flood levels

Location	Measured level m NZVD2016	Modelled level (peak flow = 190 m^3/s) m NZVD2016	Modelled level (peak flow = 180 m^3/s) m NZVD2016
Willowbank Motel – 183 Beach Road	~5.81 *(5.41 m LVD37)*	5.88	5.75
129 Beach Road	~5.88 *(5.48 m LVD37)*	5.91	5.79
65 Ludstone Road	~6.00 *(5.60 m LVD37)*	5.95	5.83
The Adelphi	~4.20/4.42 *(3.80/4.02 m LVD37)*	4.50	4.41
Westend Motors – 48 West End	~4.10 *(3.70 m LVD37)*	4.48	4.41

Considering all the assumptions and uncertainties, there is good agreement between modelled and observed flooding for a 180 to 190 m^3/s breakout flow.

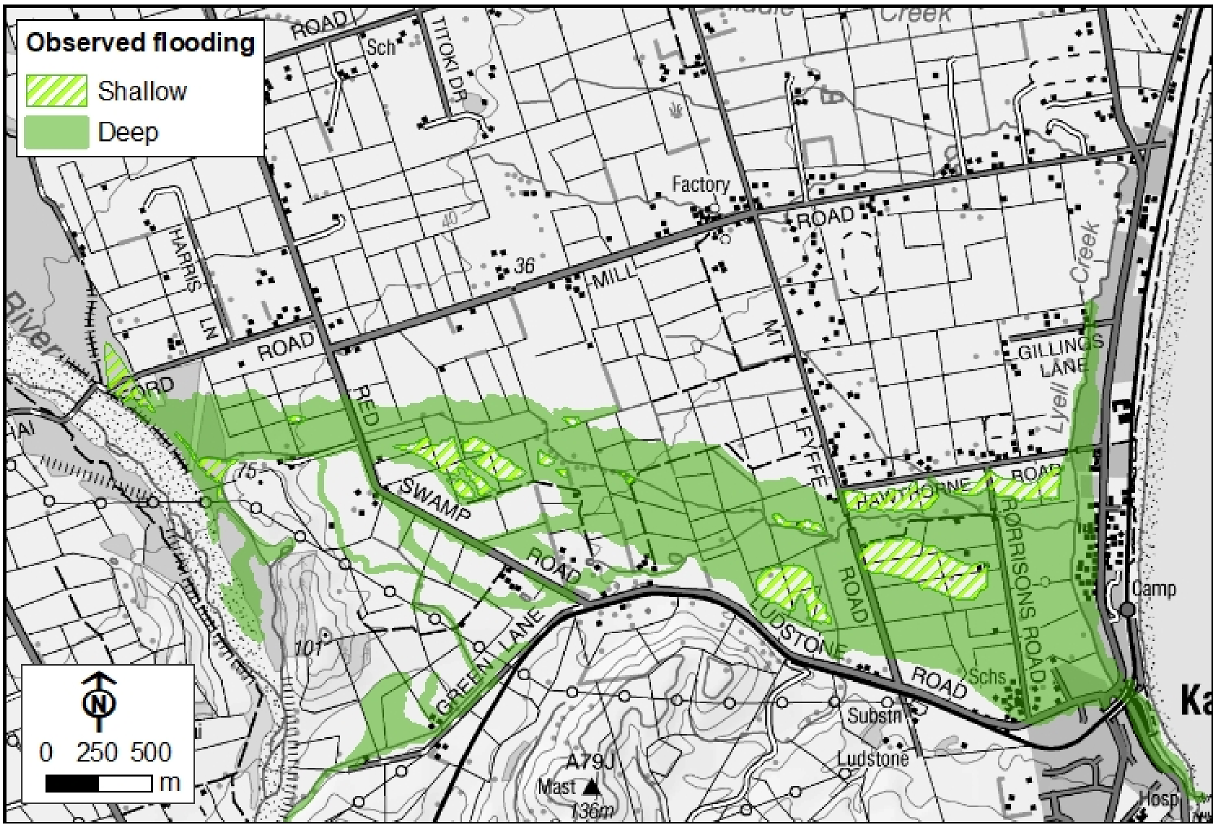


Figure 3-8: Observed flooding for the December 1993 flood event

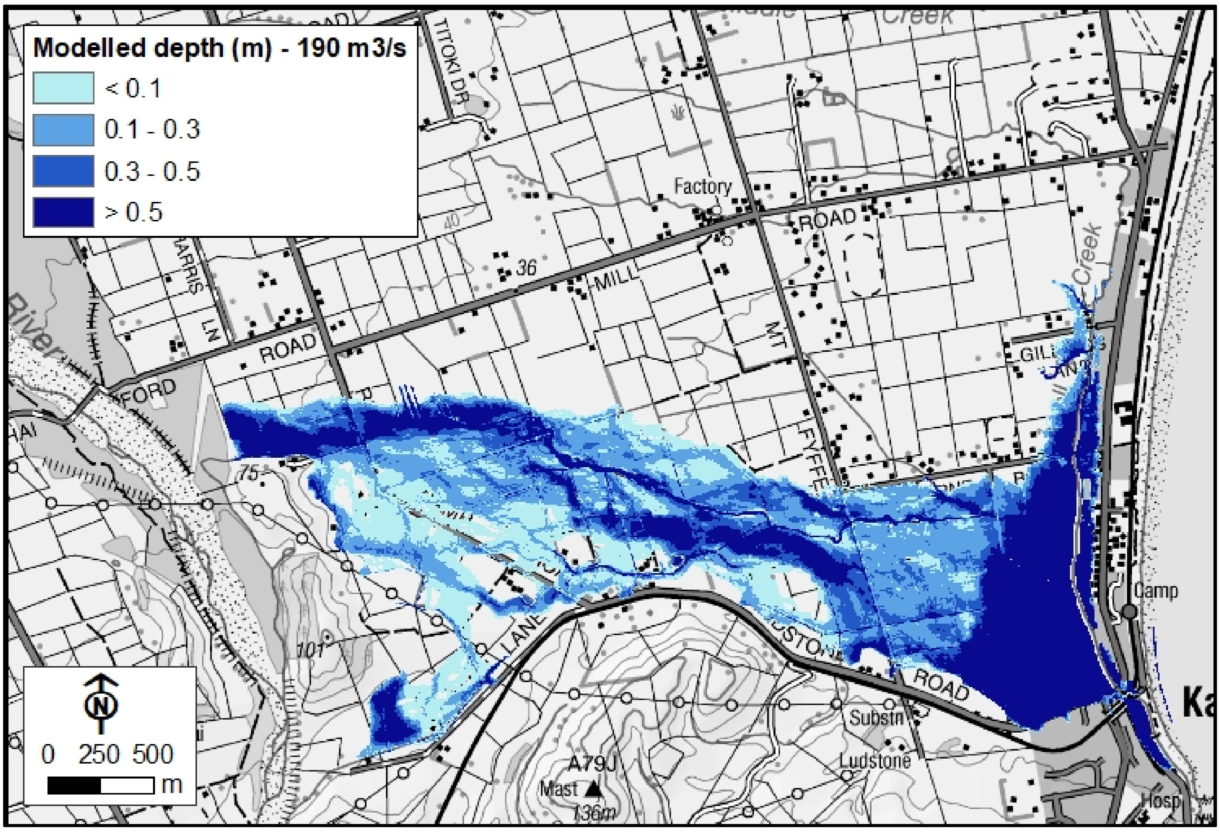


Figure 3-9: Modelled flood depths for the December 1993 flood event (Breakout of 190 m^3/s)

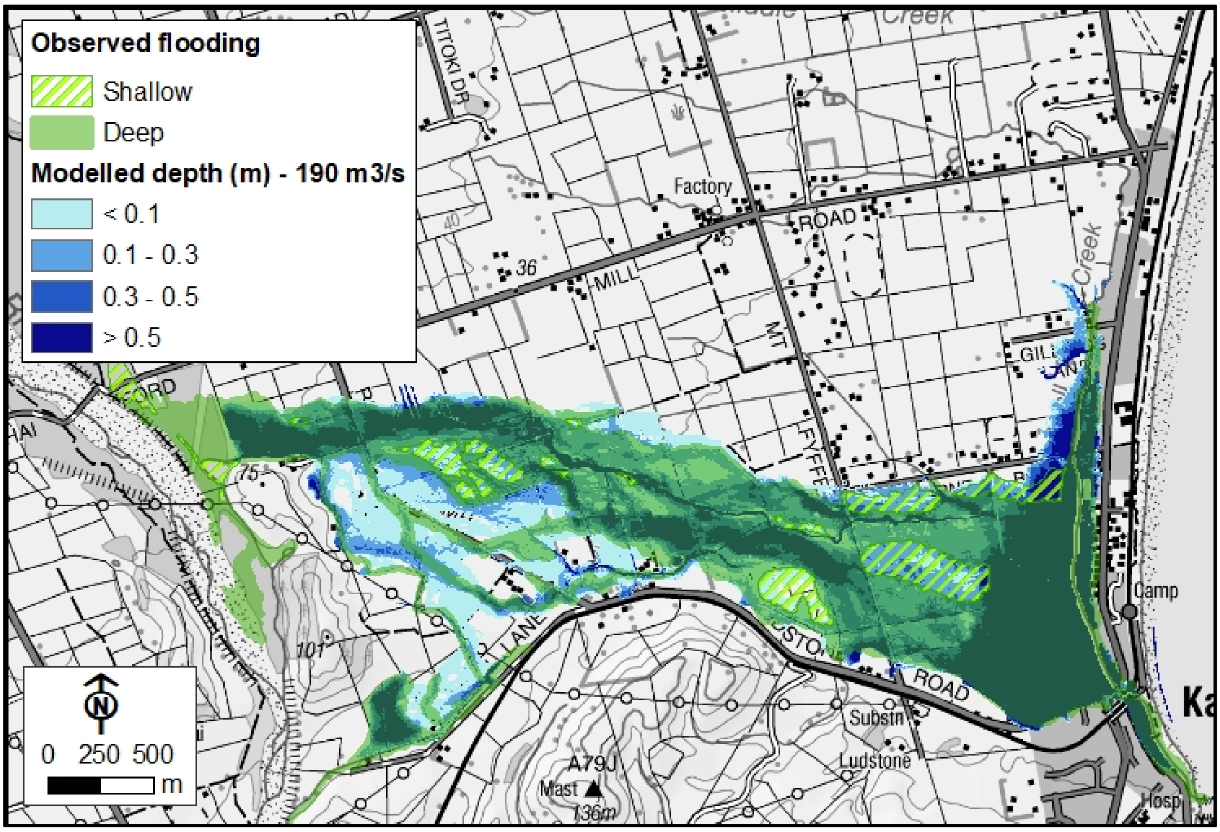


Figure 3-10: Comparison of observed and modelled flooding for the December 1993 flood event with a Kowhai River breakout of 190 m^3/s

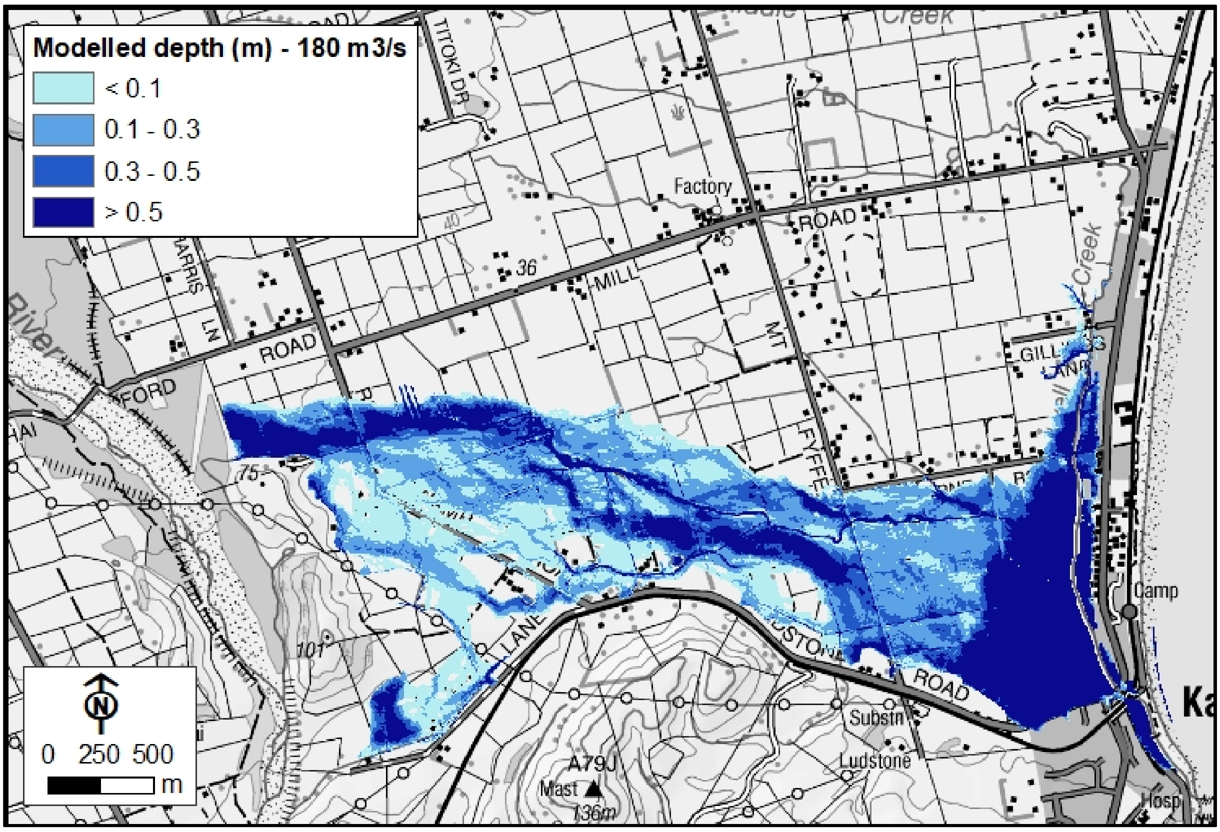


Figure 3-11: Modelled flood depths for the December 1993 flood event (Breakout of 180 m^3/s)

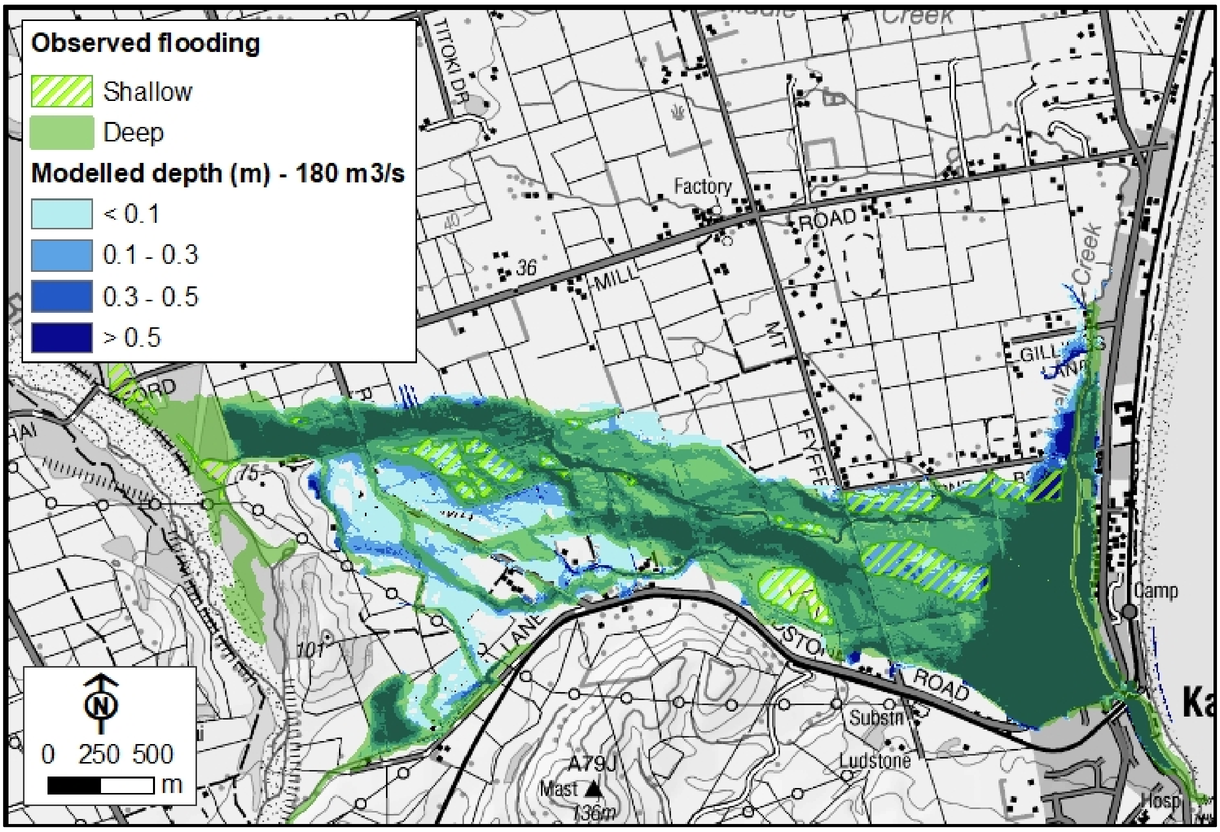


Figure 3-12: Comparison of observed and modelled flooding for the December 1993 flood event with a Kowhai River breakout of 180 m³/s

3.5 Modelling of design flood events (with climate change to 2120)

Both 50 and 500 year average recurrence interval (ARI) events have been modelled for land use planning and flood mitigation purposes. The design storm events were simulated over a 19.5 hour period with most model simulations based on a 0.5 second time step (1 second time step for Fernleigh Dip breakout scenarios), to ensure stability. Model results were saved every 15 minutes over the full storm event. Computer run times for each simulation were long (i.e. up to 2.5 days).

Model run times can be reduced by using a smaller number of grid cells, and by reducing the number of 'wet' cells where calculations are made. To reduce model run times, the Fernleigh Dip breakout scenarios used a cropped grid that excluded flooding to the north of the Kowhai River. The Middle Ford and The Bluff breakout scenarios used the full extent of the model grid but did not include any inflows to the south of the Kowhai River. The 'no breakout' scenarios were the only models that used the full model extent and inflows to all watercourses.

3.5.1 Flow hydrographs

The derivation of the design flow hydrographs used in the model is outlined below. To allow for climate change to 2120, all present-day design flows from Section 3.1 were increased by 25%. This percentage increase is consistent with the higher range RCP air temperature projections presented in MfE (2016). A 2018 update (MfE, 2018) incorporates very extreme rainfall results from the "HIRDS" report (Carey-Smith *et al.,* 2018). This shows extreme rainfall increasing with climate change in all areas, with shorter duration events likely to have the more significant increases in rainfall. The 25% flow increase used in this study, to account for climate change to 2120, may therefore be more representative of a mid to lower range RCP air temperature projection for the modelled watercourses, which are capable of producing larger peak flows from short duration, higher-intensity, rainfall events (compared to longer duration, lower-intensity, rainfall events).

Lyell Creek, Mt Fyffe Streams and Ewelme Stream design flows

To produce design flow hydrographs, hydrographs for several of the larger recorded flows on Lyell Creek (Site 63001) were scaled by their peak flows to produce non-dimensional unit hydrographs. These hydrographs are shown in Figure 3-13.

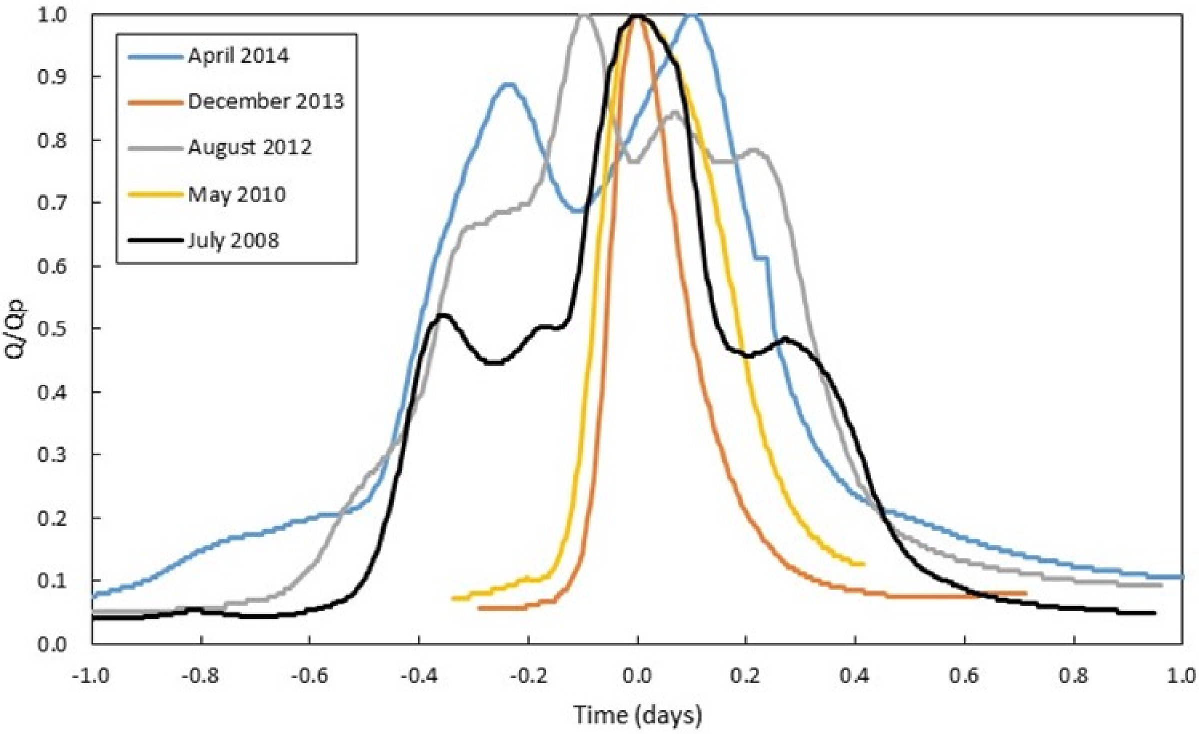


Figure 3-13: Non-dimensional Lyell Creek flood flow hydrographs

Figure 3-13 indicates that there are two typical hydrograph shapes for Lyell Creek – a single peaked hydrograph and a longer duration multi-peaked hydrograph. For the design flood events examined in this study, the peak flow is assumed to occur during a storm event that has a relatively long duration, and large spatial extent. The July 2008 hydrograph was, therefore, chosen to represent these design events as:

- the peak had a similar shape to the single peaked hydrographs.
- the event extended over the longer time frame, with flows 50% of the magnitude of the peak flow occurring both before and after the event (i.e. covers a range of shorter and longer duration scenarios without being overly conservative at high flow).
- It was the largest flood event with a peak flow of 29.7 m^3/s.

The July 2008 flow hydrograph for Lyell Creek was scaled to produce design flood hydrographs with peak flows as specified in Table 3-11.

Kowhai River breakout design flows

The Kowhai River breakout hydrograph shown in Figure 3-2 is scaled to match the Kowhai River breakout design flows provided in Table 3-11.

Kowhai River design flows

As the Goldmine Creek, and Floodgate Creek, flows are input separately into the 2D model, along with the other Mt Fyffe streams, the Kowhai River at Orange Grove design peak flows are used to represent the magnitude of the Kowhai River design inflows.

The greatest extent of flooding within the Kowhai riverbed will occur when there are no breakouts. For the breakout scenarios, the Kowhai River flows remaining in the riverbed/main channel have been simply set to a constant flow equal to the difference between the Kowhai River peak design flow (excluding Goldmine and Floodgate Creeks) and the breakout peak flow.

Table 3-11: Kaikōura Fans design flows (with climate change to 2120)

Watercourse	**50 year ARI (m^3/s)**	**500 year ARI (m^3/s)**
Lyell Creek		
Upper Lyell Creek	21	36
Hawthorne Road	8	14
Warren Creek	26	45
Ludstone Road area	11	20
(Total)	(66)	(115)
Mt Fyffe streams		
Harnetts Creek	56	94
Waimangarara River	100	159
Luke Creek	34	50
Middle Creek (incl Luke Ck)	111	181
Floodgate Creek	30	44
Goldmine Creek	28	41
Ewelme Stream	86	144
Kowhai River		
Kowhai River (excluding Goldmine & Floodgate Creeks)	400	600
Kowhai River breakout	240	360
Kowhai River residual	160	240
Kahutara River	700	1050
Peketa local inflows		
Sub-catchment 1	6.3	9.5
Sub-catchment 2	4.6	7.0
Sub-catchment 3	8.5	12.8

3.5.2 Breakout locations

When modelling large design flood events, a judgement must be made as to whether the existing river protection works are likely to effectively contain the river flows or fail. Breakouts (also known as stopbank breaches) are very difficult to predict as they result from a complex interaction between water in the river and the bank structure. In Canterbury, most river stopbank breaches are due to overtopping, high lateral flow velocities, or large water level differences across the stopbank. When a breach does occur, the downstream flood extent is predominantly determined by the rate at which water is released, the total volume of water and the topography of the flooded area.

The Kaikōura River Control Scheme currently provides flood protection for events with an ARI up to around 20 to 50 years. For any flood event with an ARI of 50 years or more, the scheme is likely to be compromised. River control works may also fail during smaller flood events.

Historic flood information (McPherson, 1997), and geomorphic mapping, suggest breakouts from the Kowhai River are most likely to occur at the following locations:

1. True left bank at 'The Bluff' (e.g. February 1868, January 1953, December 1954, March 1987)
2. True left bank at Kowhai/Middle Ford (e.g. January 1953, October 1956, March 1980, December 1993)
3. True right bank at Fernleigh Dip (e.g. February 1945, April 1949, January and June 1953, December 1954, May 1966)

Figure 3-14 is a flood hazard map for the Kowhai River, based on a subjective geomorphic interpretation of detailed field mapping and consultation with local Environment Canterbury field staff. This clearly shows the Kowhai River breakout locations and overland flow paths identified above. Flood hazard categories shown on Figure 3-14 are described in Table 3-12. Flood hazard categories are not shown for areas where the study identified Kowhai River overland flows to be less likely.

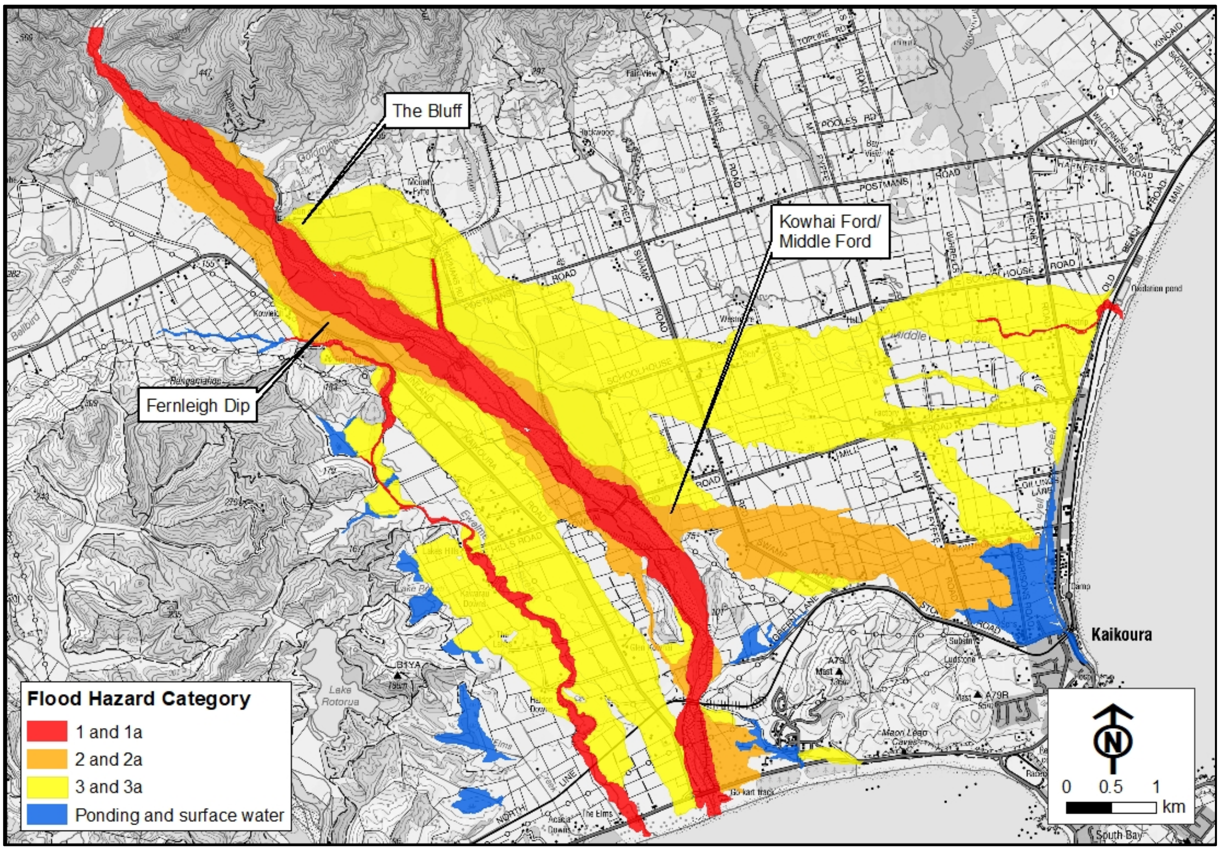


Figure 3-14: Kowhai River flood hazard map showing likely overland flow paths (McPherson, 2000)

Table 3-12: Description of flood hazard categories for the Kowhai River (McPherson, 2000)

Flood Hazard Category	Description
1 and 1a	Active, bare or scrubby riverbed and extent of riverbed before construction of flood protection works.
2 and 2a	Overbank flood routes at high risk of re-occupation, and areas where flood risk is dependent on size of breakout
3 and 3a	Former major riverbed and historic flood ways, and areas of floodplain with numerous imprints of overflow. Re-occupation is considered less likely than Category 2 flood routes.
Ponding	Significant areas at risk of ponding

Note that, since the mapping, the likelihood of a breakout at the Middle Ford area has been reduced by the construction of an additional bank (as outlined in CRC, 2000).

3.5.3 Sea level

The Kaikōura design sea level was based on the tide equation (see Section 3.2.1) and the maximum storm tide level of 1.75 m NZVD2016 (which incorporates a storm surge of 0.4 m and a 0.1 m seasonal/ENSO water level fluctuation).

To account for climate change to 2120, all design flood events used the sinusoidal storm tide with an additional 1 m of sea level rise. This gave a high tide sea level of 2.75 m NZVD2016. The high tide was timed to occur around the time that the peak breakout flood flows reach the coast.

3.5.4 Timing of peak flows

The time at which the water course flows, and Kowhai River breakout flow, peak will be dependent on many variables including:

- Spatial distribution of rainfall
- Temporal distribution of rainfall (e.g. whether it is a high-intensity short duration storm, a less intense but longer duration storm, or a storm event made up of several high-intensity 'bursts' of rainfall).
- The unpredictable nature of any stopbank breach that allows flow to pass out of the water courses onto the adjacent alluvial fan.
- Antecedent conditions (i.e. how wet the ground already is at the start of the storm event).

A brief examination of the flow data for Lyell and Middle Creeks, and the water level record for the Kowhai River, shows that for the shorter single peak events, the water courses tend to peak around the same time. For the longer duration storm events, consisting of several rainfall bursts, Lyell Creek and Middle Creek respond more rapidly, although the spatial distribution of the rainfall means they do not necessarily both produce peak flows that are proportional to each other (e.g. if there are two peaks during an event, they will not necessarily both have a higher peak for the first versus second peak). Meanwhile, the Kowhai River may respond more slowly as a longer duration, single peaked hydrograph.

Initial modelling showed that for a 500 year ARI flow down the Kowhai River, the flood peak takes approximately 1 hour to travel from upstream of Goldmine Creek to the SH1 road bridge. Kowhai River breakout flows at Kowhai/Middle Ford take approximately 1 hour to reach land around Lyell Creek at Beach Road, with peak levels upstream of the SH1 road bridge occurring 4 to 5 hours after the initial breakout occurs. It also takes approximately 1 hour for the local Lyell Creek flow peak to travel from Mill Road to the SH1 bridge.

To ensure the model does not overestimate peak flows, and water levels, it has been assumed that the peak flows into Lyell Creek (and all other Mt Fyffe and Ewelme stream water courses) occurs around:

- 3 hours before the peak breakout flow from the Kowhai River at Kowhai Ford/Middle Ford.
- 2 hours before the peak breakout flow from the Kowhai River at The Bluff and Fernleigh Dip.

As breakouts are unpredictable, the breakout flow magnitude, timing of the peak, and location of all possible breakouts cannot be included in this investigation.

3.5.5 Model results

Maximum modelled flood depths for 50 year ARI flood events are shown on Figure 3-15 to Figure 3-17. The model results show that:

- If there were no stopbank failures (and no aggradation in the riverbed) on the Kowhai River, only minor overflows would occur. These flows would mostly be diverted back to the river by echelon banks. The main exception is downstream of the railway line where overflows on the true left bank pass onto land between the railway line and SH1. Without bank failures, there is also very limited flooding upstream of the SH1 road bridge at Lyell Creek, and no flooding downstream of the SH1 road bridge in the main commercial area.

- The Mt Fyffe Streams, Lyell Creek and Ewelme Stream do not fully contain a 50 year ARI flow, but ponding upstream of the SH1 road bridge at Lyell Creek, is relatively minor.

- With 1 m of channel aggradation in the Kowhai River, there is an additional ~320 hectares of the Kaikōura Fans submerged under flood waters. The reason for this is that there are significant overflows at Kowhai/Middle Ford and greater areas of the Kowhai riverbed and berm areas inundated, as well as some additional flooding where other flood protection works are overtopped or outflanked.

- The main ponding areas are upstream of SH1 (at Lyell Creek), Middle Creek (upstream of the railway line), the area around the intersection of Mill Road & SH1, the north side of Green Lane, and the Ewelme Stream and Peketa ponding areas.

- Breakout flows at The Bluff spread out over a wide area of the Kowhai Fan, with overflows draining into both Middle Creek and Lyell Creek.

Maximum water depths for 500 year ARI flood events are shown on Figure 3-18 to Figure 3-20. The model results show that:

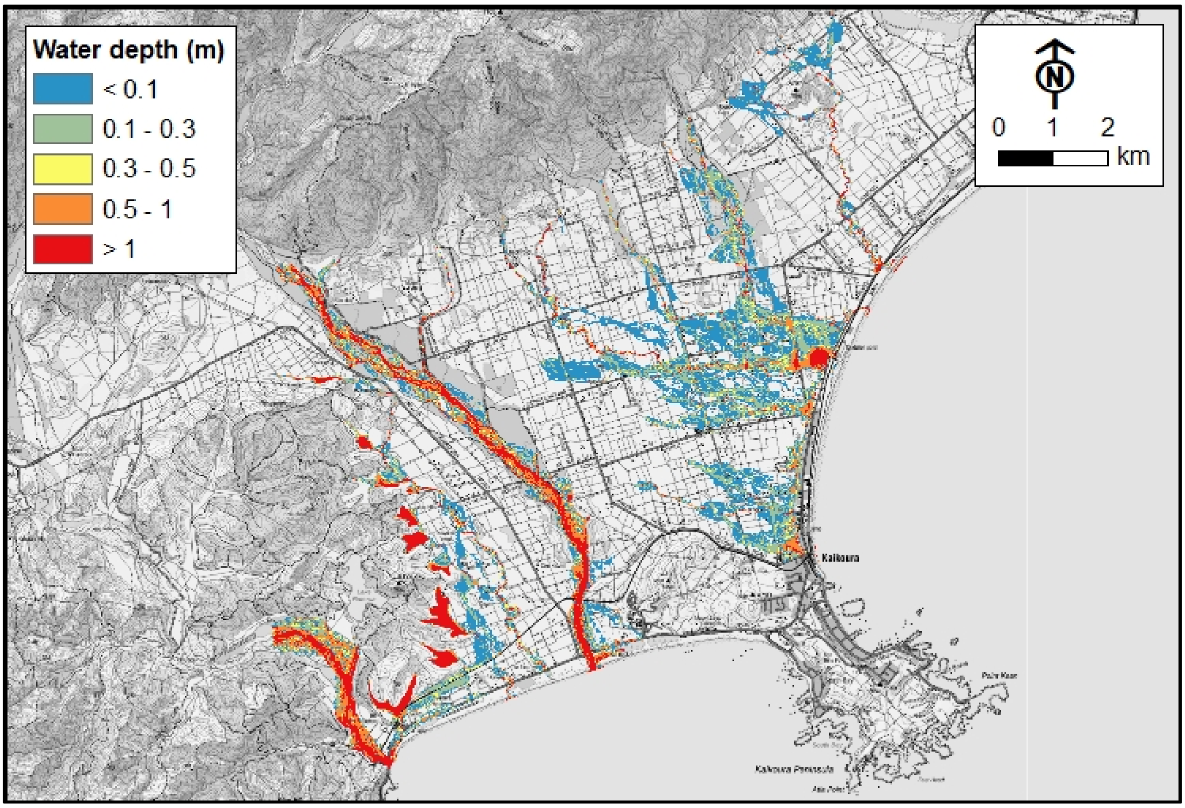
- In the unlikely (hypothetical) event that there were no stopbank failures on the Kowhai River, some overflows would still occur. However, these flows would mostly be diverted back to the river by echelon banks. The main exceptions are overflows at Fernleigh Dip and downstream of the railway line (where overflows on the Kowhai River true left bank pass onto the land between the railway line and SH1). Overflows at Kowhai/Middle Ford start to occur and the ponding area to the north of Green Lane begins to fill.

- With 1 m of channel aggradation in the Kowhai River, combined with the unlikely (hypothetical) scenario of no stopbank failures, there is an additional ~370 hectares of the Kaikōura Fans submerged under flood waters, compared to the no stopbank failure scenario with no aggradation. This is because there are significant overflows at Kowhai/Middle Ford, and some of the other flood protection works are overtopped or outflanked. Overflows occur at Fernleigh Dip, and into the Green Lane ponding area.

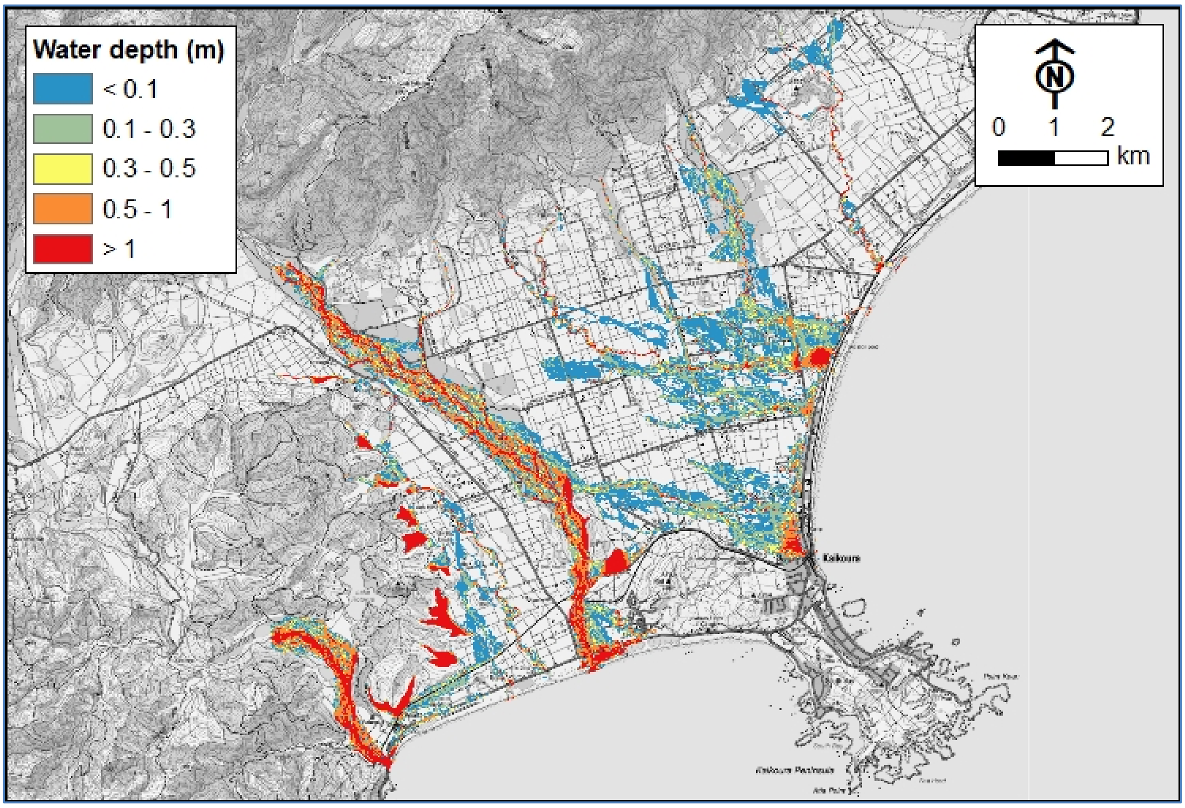
- Breakout flows around the Fernleigh Dip area tend to flow into Ewelme Stream, or return to the Kowhai, with mainly minor overflows either side of the Kaikōura Inland Road. Breakouts 1.5 km downstream of Fernleigh Dip are more likely to generate greater water depths in this area.

- The greatest depths upstream of the SH1 road bridge, in the Lyell Creek ponding area, occur when there is a breakout at Kowhai/Middle Ford.

- The greatest water depths in the ponding areas upstream of the railway bridge at Middle Creek, and around the Mill Road/SH1 intersection, occur when there is a breakout at The Bluff.

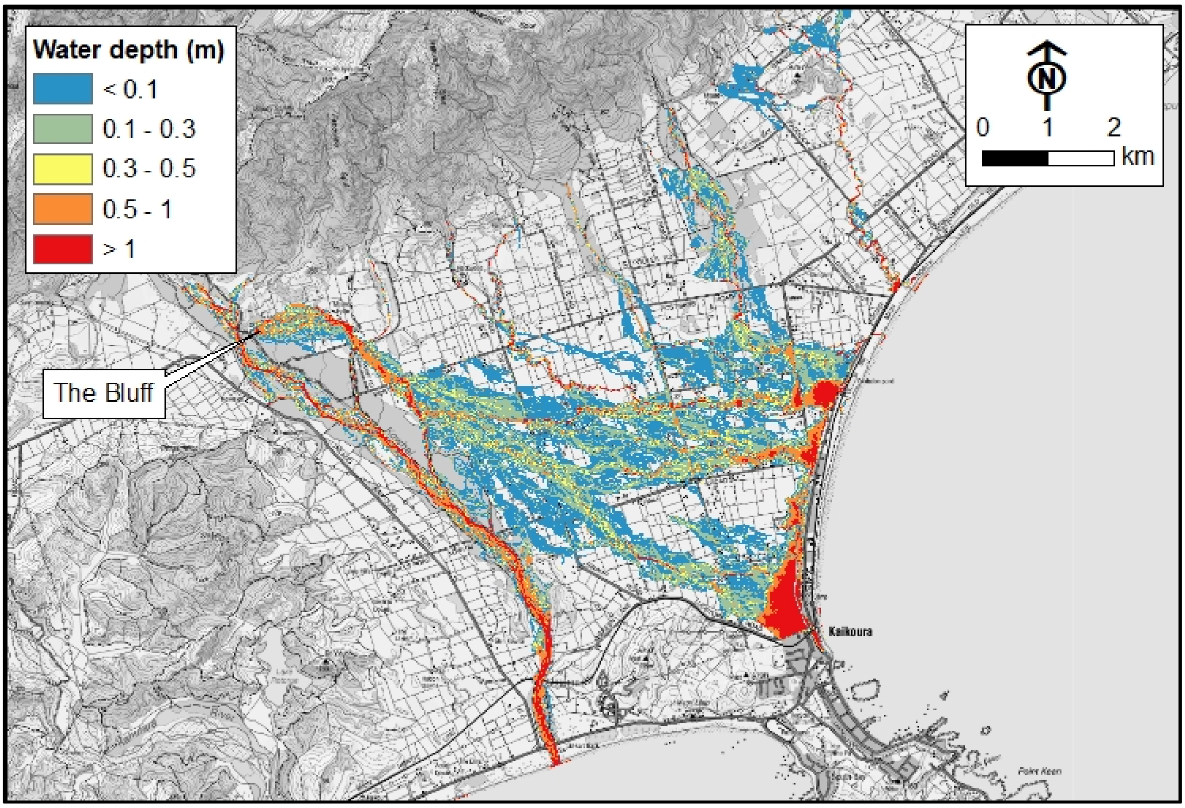


(a) No Kowhai River aggradation

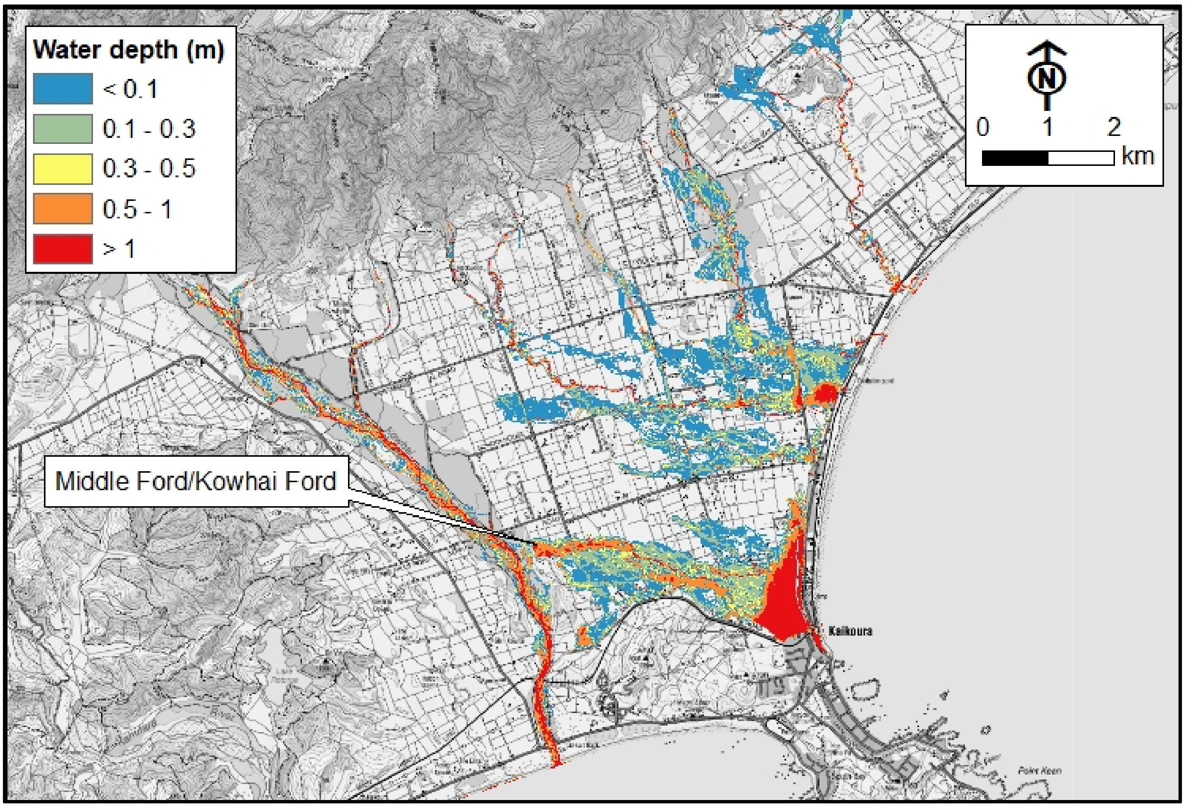


(b) With 1 m of aggradation in the Kowhai River

Figure 3-15: Kaikōura Fans - 50 year ARI maximum water depths – no breakouts (only overflows)

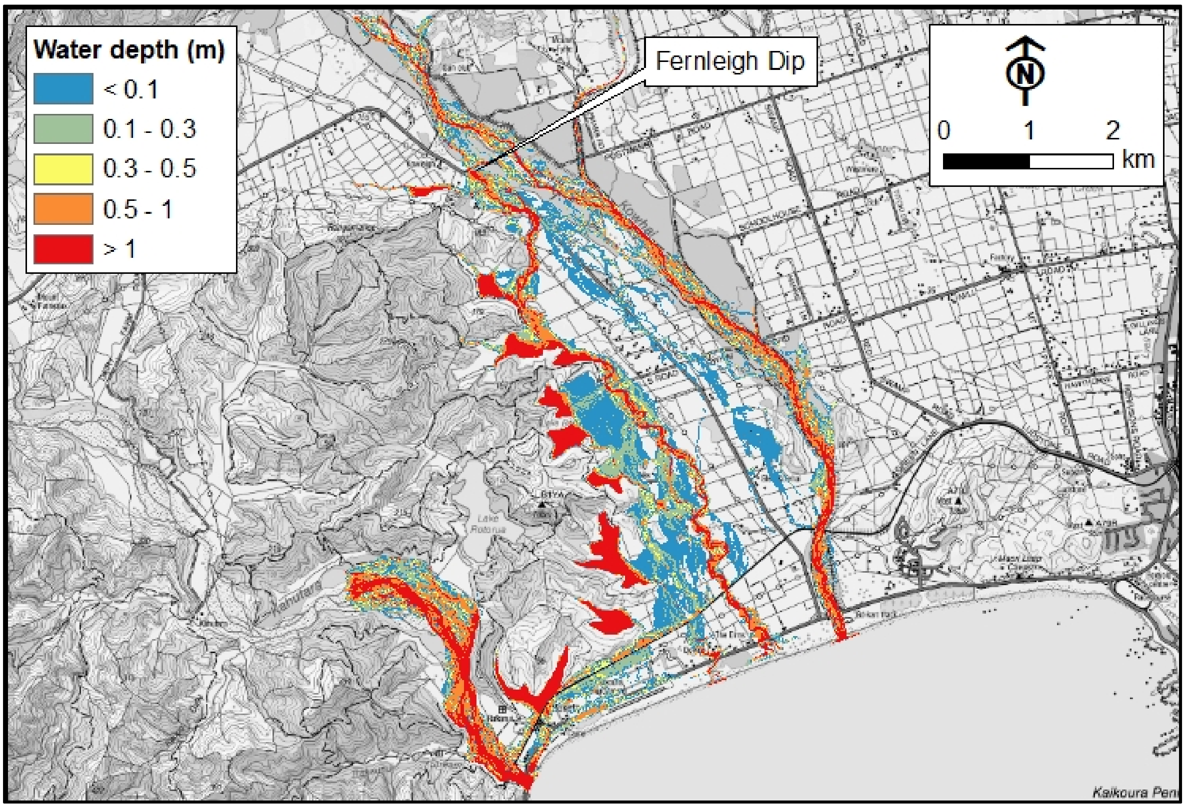


(a) Breakout at The Bluff

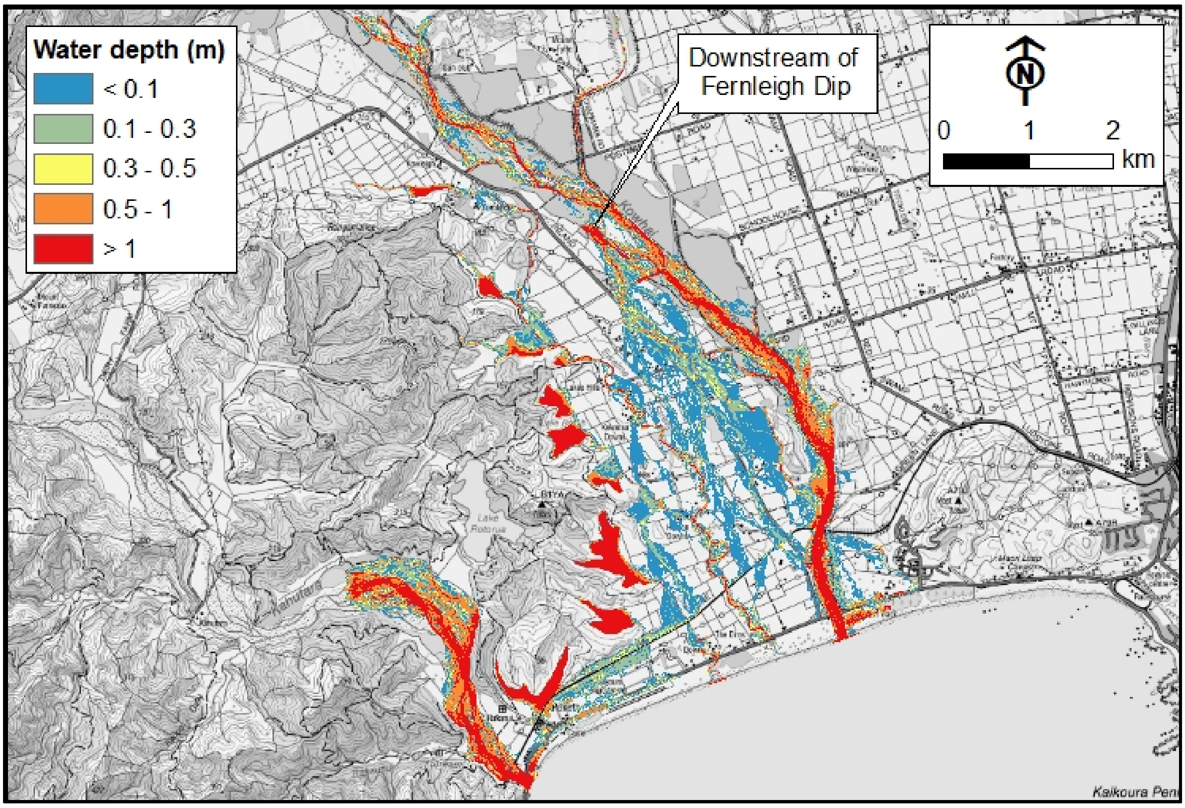


(b) Breakout at Kowhai Ford/Middle Ford

Figure 3-16: Kaikōura Fans - 50 year ARI maximum water depths – breakouts to the true left

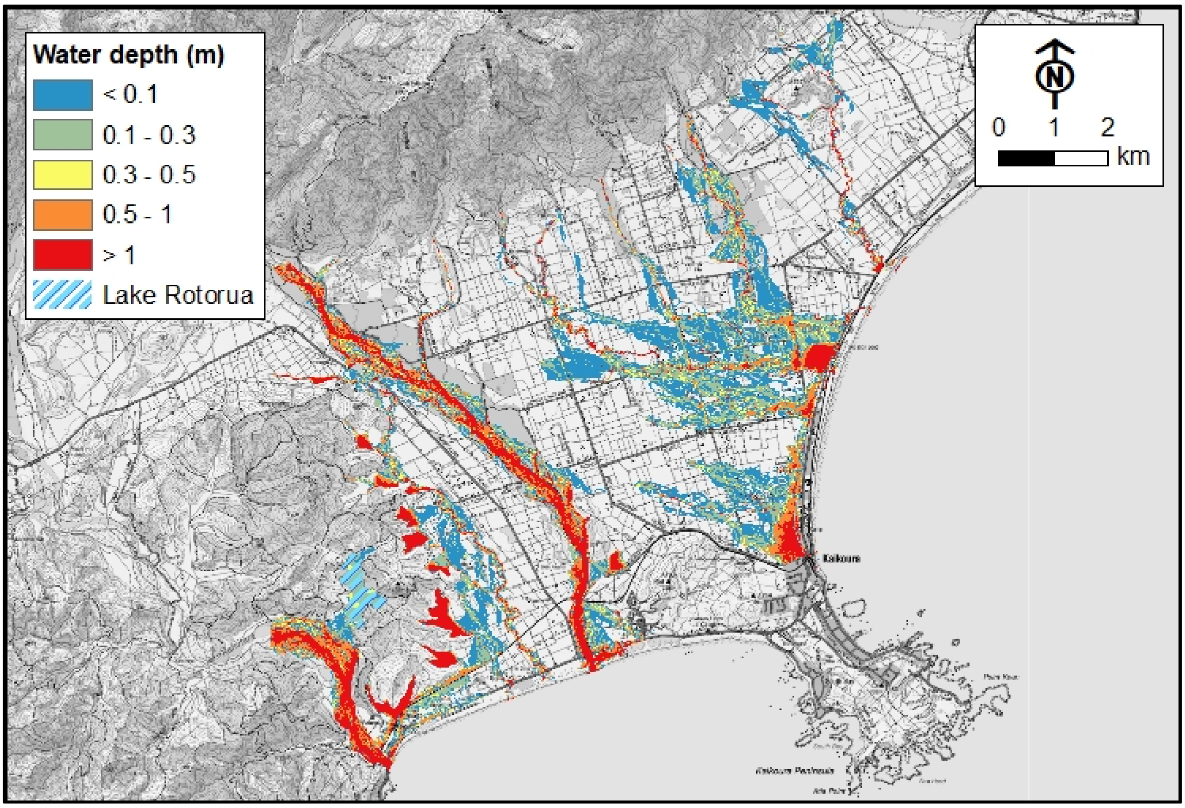


(a) Breakout at Fernleigh Dip

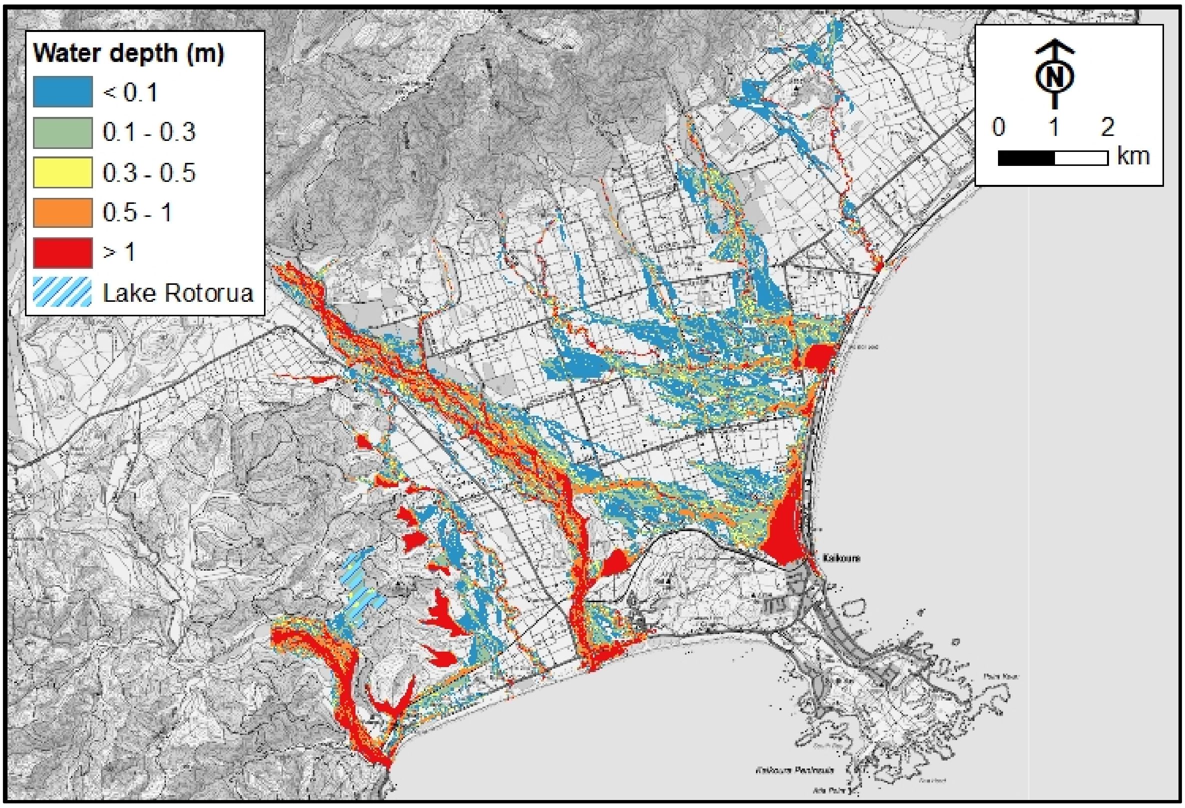


(b) Breakout 1500 m downstream of Fernleigh Dip

Figure 3-17: Kaikōura Fans - 50 year ARI maximum water depths - breakouts to the true right

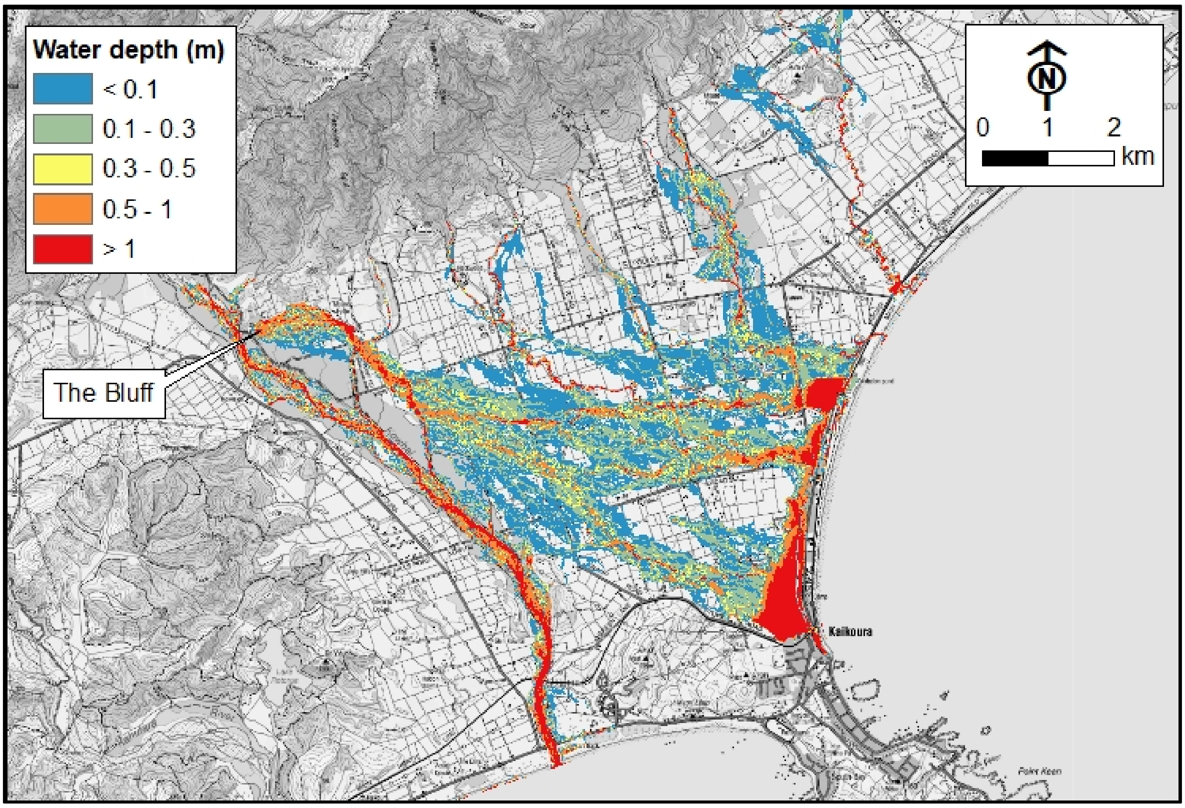


(a) No aggradation

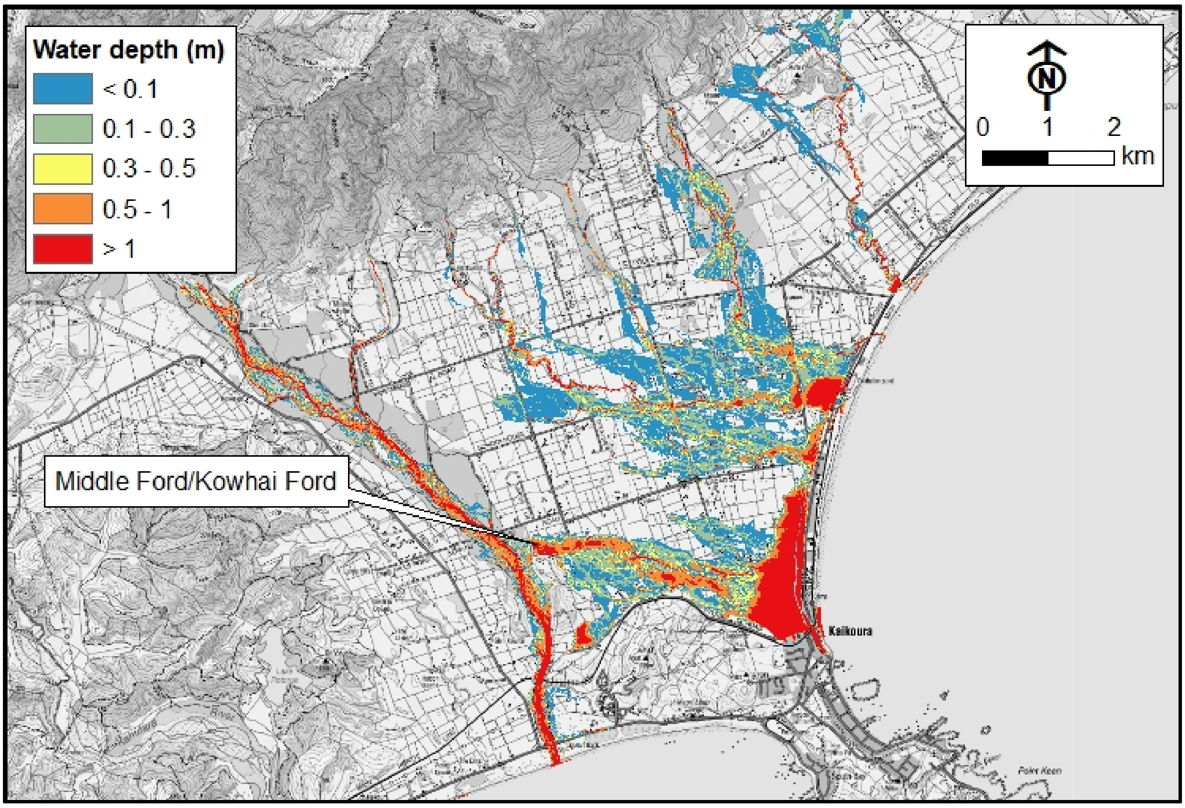


(b) With 1 m of aggradation in the Kowhai River

Figure 3-18: Kaikōura Fans - 500 year ARI maximum water depths – no breakouts (only overflows)

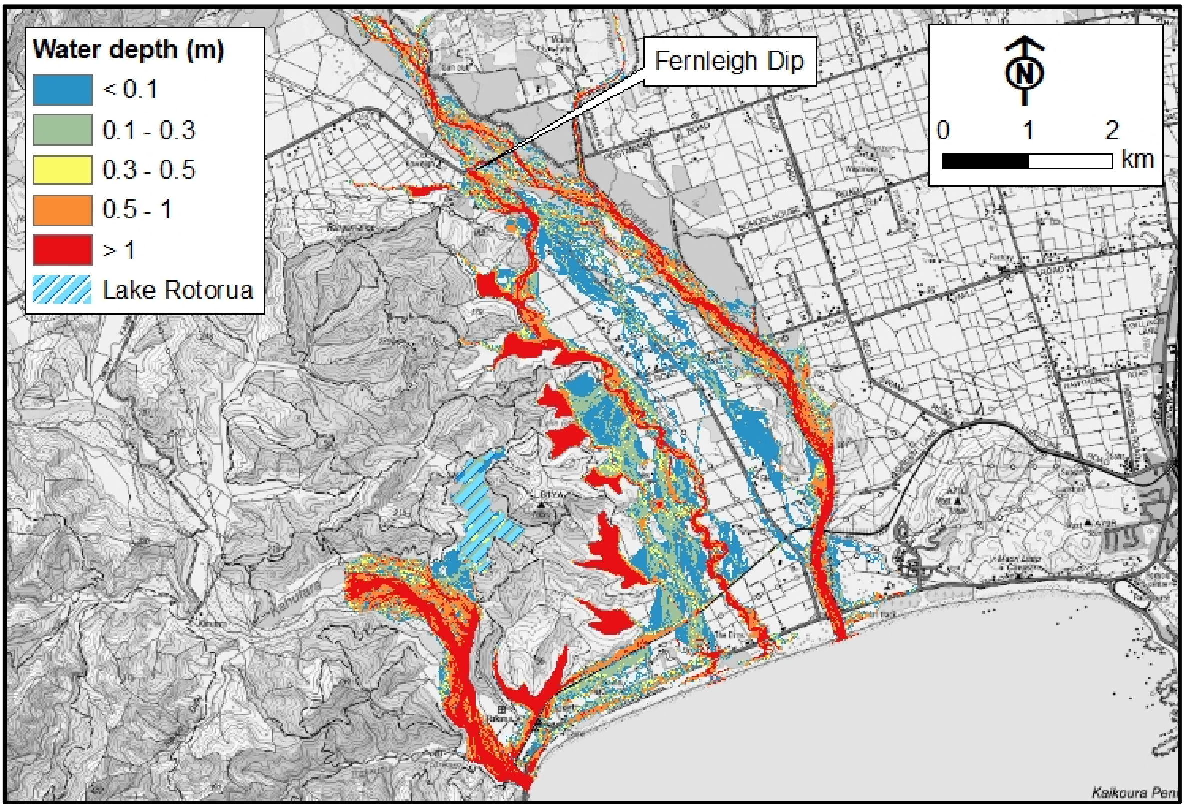


(a) Breakout at The Bluff

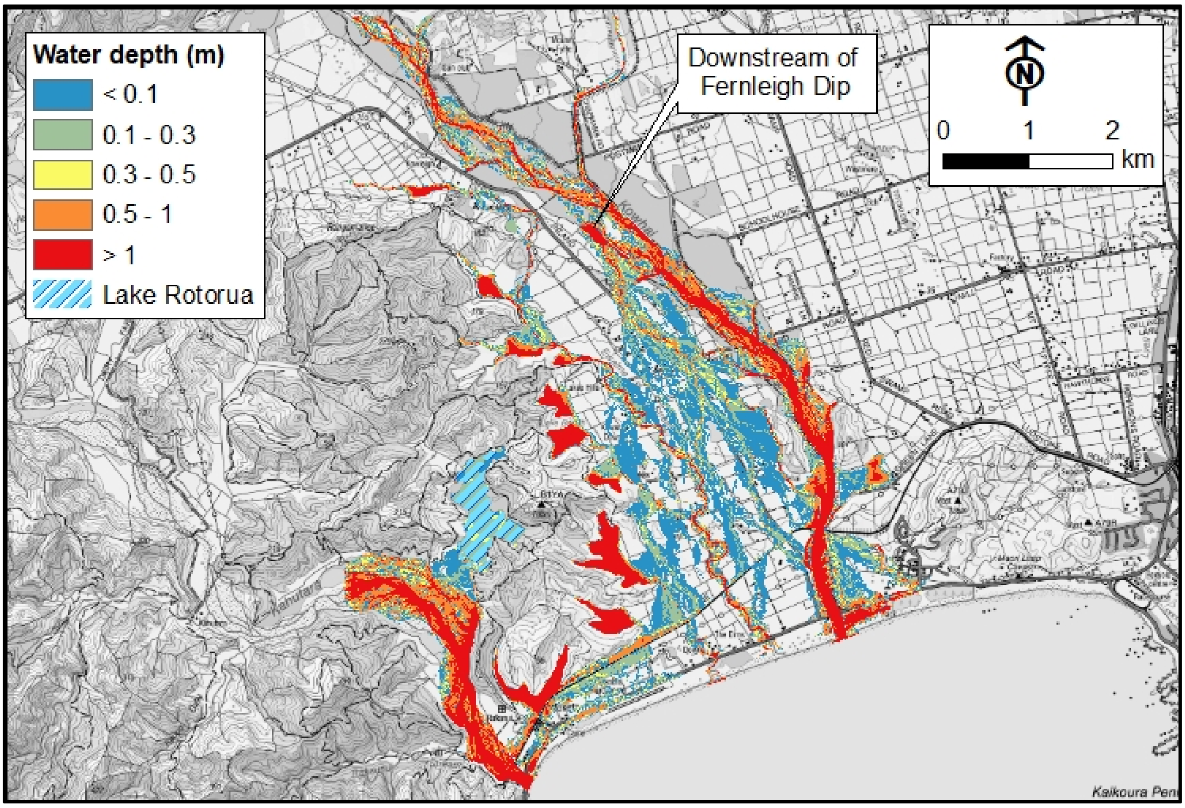


(b) Breakout at Kowhai Ford/Middle Ford

Figure 3-19: Kaikōura Fans - 500 year ARI maximum water depths – breakouts to the true left



(a) Breakout at Fernleigh Dip



(b) Breakout 1500 m downstream of Fernleigh Dip

Figure 3-20: Kaikōura Fans - 500 year ARI maximum water depths - breakouts to the true right

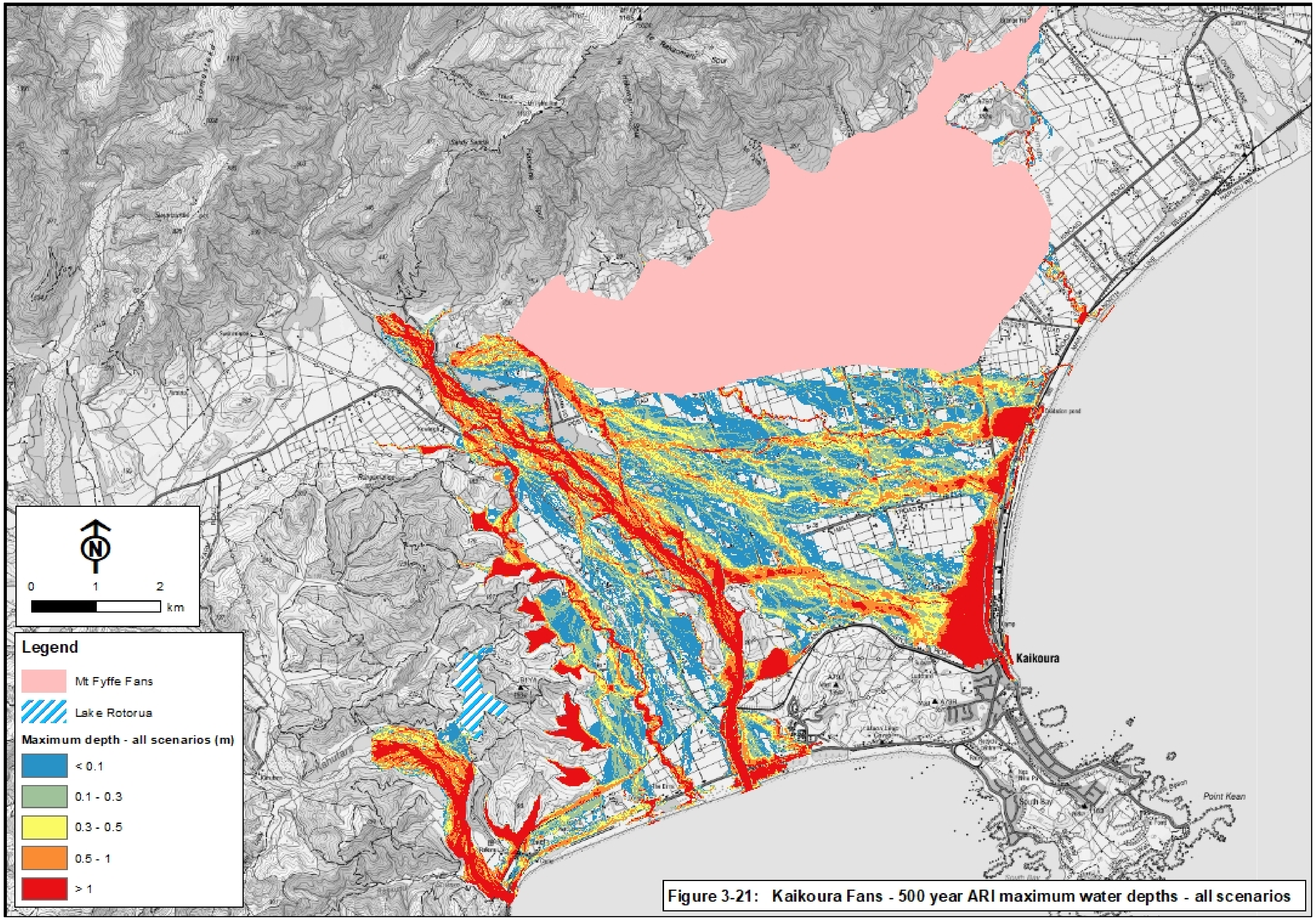


Figure 3-21: Kaikōura Fans - 500 year ARI maximum water depths – modelled scenarios

3.6 Model sensitivity analysis

Several scenarios were modelled to determine the sensitivity of flood inundation to various model parameters and assumptions. These are described below.

3.6.1 Alluvial fan and floodplain roughness increased

The Kaikōura Fans Manning's n roughness values are described in Section 3.3.2. The floodplain values were increased by 20% for the alluvial fans and floodplain areas (i.e. Manning's n increased from 0.05 to 0.06, and 0.10 to 0.12). Several 500 year ARI flood events were modelled:

a) No breakout flows
b) Breakout flows at Kowhai/Middle Ford
c) Breakout flows at Fernleigh Dip

Figure 3-22 illustrates that when roughness is increased by 20%, maximum water depths generally increased by less than 0.1 m, with greater increases mainly occurring where the more confined flows have higher velocities and depths (e.g. along the main Kowhai/Middle Ford breakout flow path, and in the Mt Fyffe streams). Water depths can also increase more dramatically in ponding areas where maximum water levels haven't 'filled' the depression (e.g. when water levels haven't reached the point that they are overflowing out of the ponding area into other areas).

Increasing the Kahutara River Manning's n from 0.04 to 0.05 raises the Kahutara River maximum water levels by up to 0.2 m but does not have a significant impact on maximum water levels in the Peketa campground and settlement.

3.6.2 No climate change

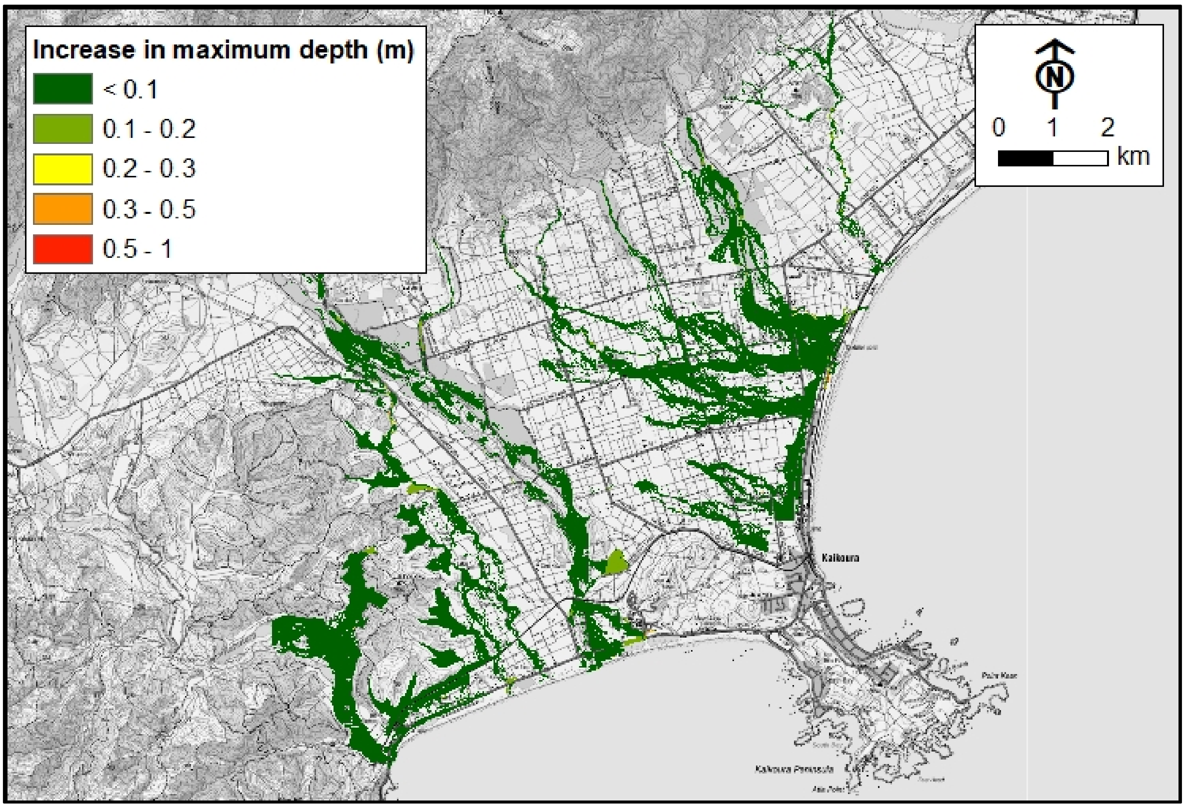
Estimated climate change impacts are incorporated into all design model runs as climate change is generally expected to increase peak runoff and elevate sea levels. Section 2.5 briefly summarises the likely impacts we can expect by 2120.

If climate change does not occur (i.e. peak flows do not increase by 25% and sea level does not rise by 1 m), maximum water depths are likely to reduce. Figure 3-23 shows that, for a 50 year ARI flood event with a Kowhai River breakout at either Kowhai/Middle Ford or Fernleigh Dip:

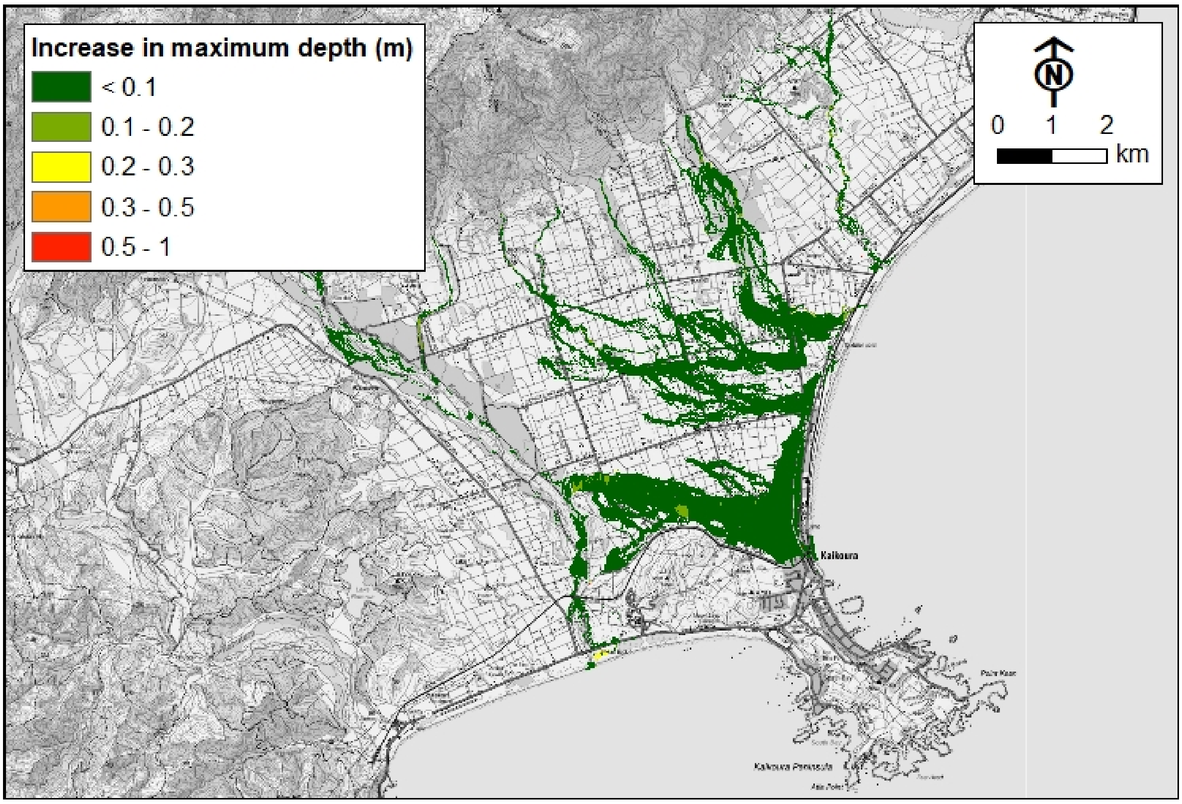
- the most significant impact on maximum water level would occur in confined watercourses, around river mouths, and in ponding areas. For the Kowhai/Middle Ford breakout, the Lyell Creek ponding area upstream of the SH1 bridge may have maximum water levels reduced by 0.3 m, and the West End commercial area reductions of 0.7 m could occur. The Middle Creek ponding area (upstream of the railway line) could also see maximum water levels reduced by over 0.1 m.
- overland flows are likely to have water depths ~0.1 m less.
- ponding depths in the Peketa / Ewelme Stream area are likely to be around 0.2 m lower.

3.6.3 Climate change ***without*** sea level rise

To distinguish between the impact of increased surface water runoff and increased sea level, an additional scenario was modelled where climate change did not include 1 m of sea level rise. This scenario was modelled for the 50 year ARI Kowhai River breakout at Kowhai/Middle Ford. Figure 3-24 shows that if sea levels did not rise, maximum water levels in the Lyell Creek and Middle Creek ponding areas would not reduce significantly (i.e. decreases in water levels would be less than 0.05 m). Increased flows into the ponding areas have a much greater influence on the maximum flood levels than sea level rise.

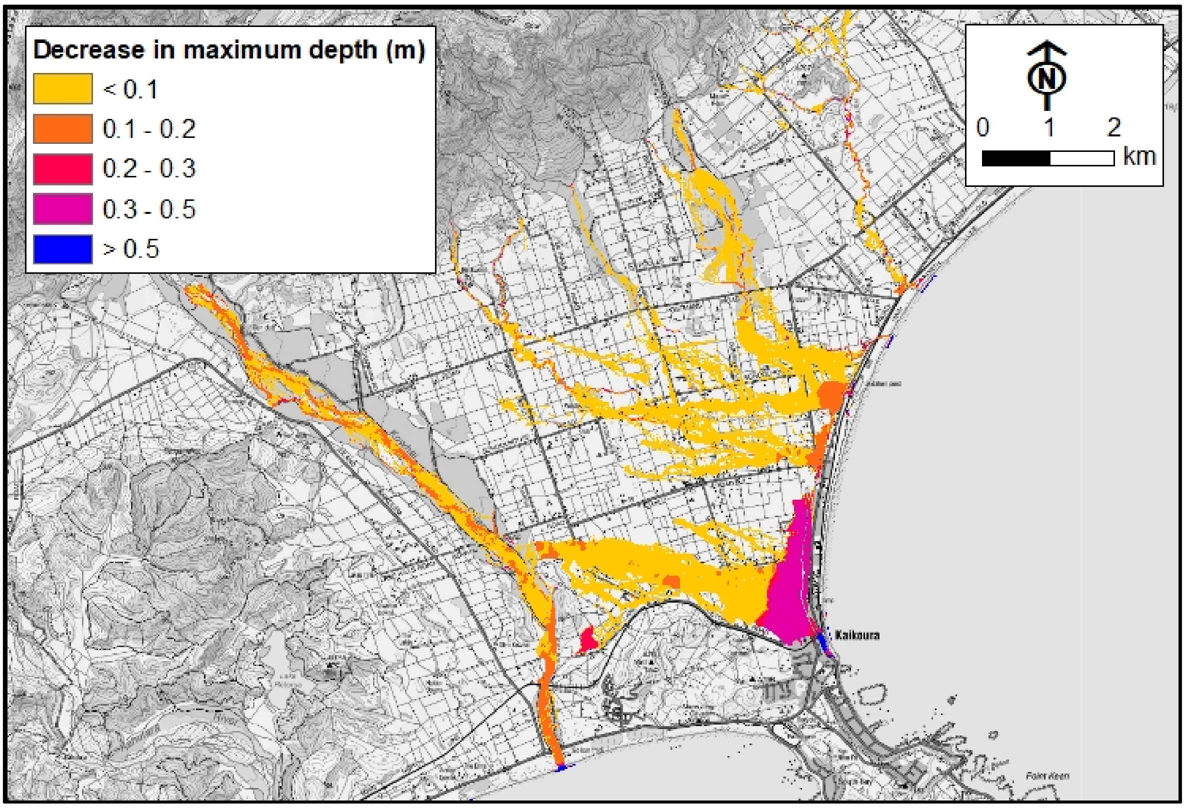


(a) No breakout

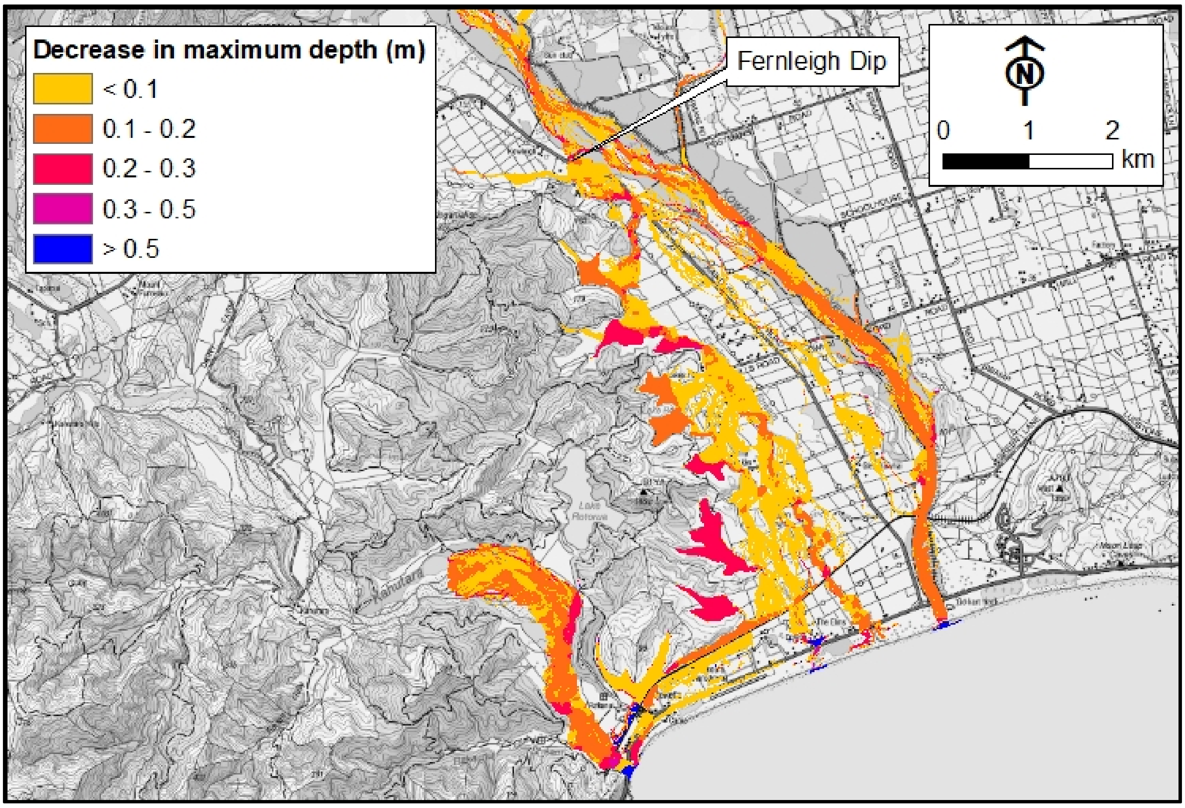


(b) Breakout at Kowhai Ford/Middle Ford

Figure 3-22: Increase in maximum water depths when alluvial fan and floodplain roughness is increased by 20% for 500 year ARI flood scenarios



(a) Breakout at Kowhai/Middle Ford



(b) Breakout at Fernleigh Dip

Figure 3-23: Decrease in 50 year ARI maximum water depths should no climate change occur

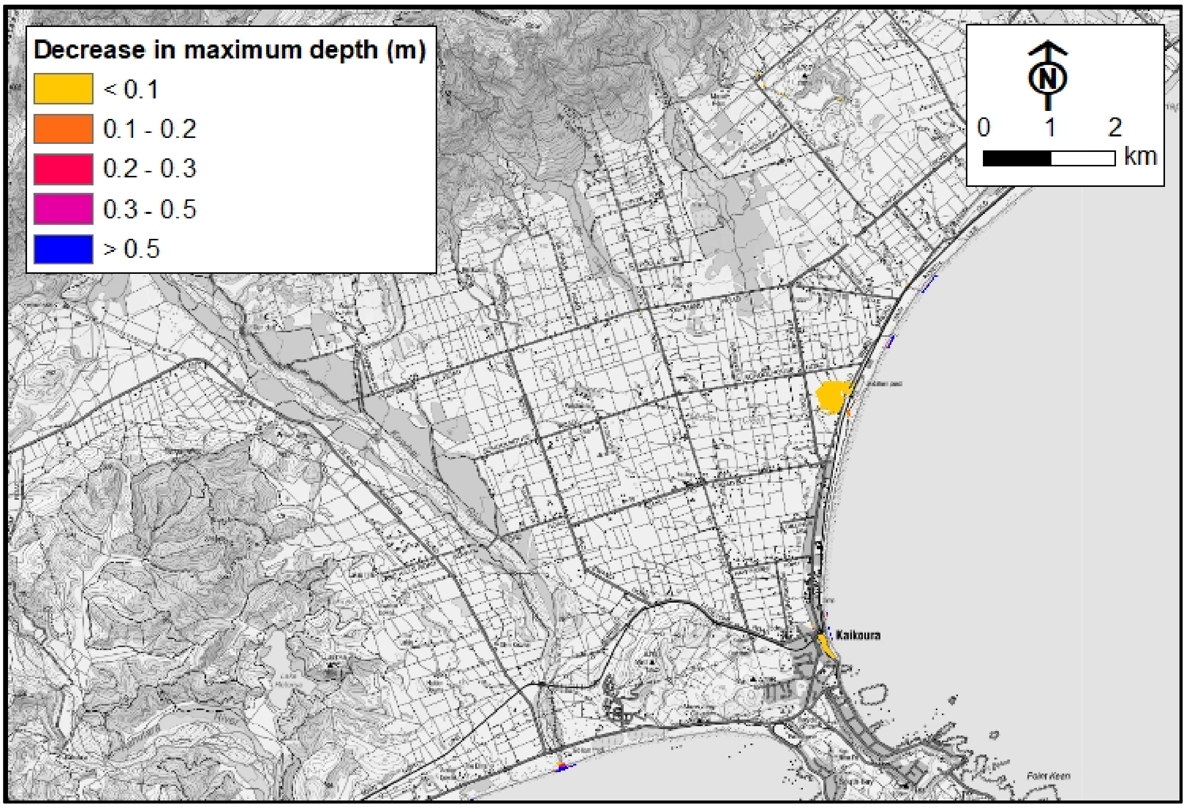


Figure 3-24: Decrease in maximum water depths for a 50 year ARI breakout at Kowhai/Middle Ford should climate change occur, *excluding* any sea level rise

3.6.4 Watercourse flows increased by 25%

Given the level of uncertainty in the hydrology, and the likely magnitude of any breakout, a 50 year ARI 'no breakout' model run was undertaken to examine the increase in flood water levels likely should modelled flows be 25% larger. Figure 3-25 shows that for a 50 year ARI flood event with flows increase by a further 25%, floodplain flows are likely to spread out, only increasing floodplain flow depths by up to 0.1 m. However, flows within confined watercourses are likely to increase by up to 0.2 m, and ponding/storage areas may have greater increases in flood depth.

3.6.5 Channel aggradation

Where there is demand for gravel from industry, this is directed to areas of known aggradation including sediment traps (e.g. Kowhai River, Floodgate Creek, Luke Creek and Waimangarara River), so that capacity change risks are limited where possible. However, aggradation exceeds demand in some places, and aggradation can occur over a short period and take time to remove, so risks can increase over time or be temporarily elevated. Detailed modelling and aggradation in the smaller Mt Fyffe watercourses have not been covered in this study as these steep alluvial fan streams have considerable scour, erosion and deposition that cannot be modelled using the flood modelling software used in this investigation. However, riverbed levels in the Kowhai River were increased by 1 m for 50 and 500 year ARI flood events with no breakouts (only overflows) to gain some insight into how aggradation would impact on river flood capacity. Figure 3-26 shows the modelled increases in water depths. For both 50 and 500 year ARI flood events there were significant increases in water levels in the areas where flows are contained by the river protection and echelon banks. There were also significant overflows at Kowhai/Middle Ford, which resulted in a considerably larger area of the Kowhai Fan becoming inundated, as well as significantly increasing water levels in the ponding areas upstream of SH1 (at Lyell Creek) and at Green Lane.

Localised instances of 1 m of aggradation would be possible for some of the Kaikōura rivers when there is a 50 to 500 year ARI flood event. For example, Figure 2-5 shows around 1 m of channel aggradation in Luke Creek during the April 2014 flood event. Initial Endeavour Fund programme research has also observed significant additional volumes of sediment in catchments along the Seaward Kaikōuras since the November 2016 earthquakes. In the Kowhai River catchment this material has, so far, mainly been dispersed along the river system during large storm events (e.g. Tropical Cyclone Gita). No significant aggradation has been observed downstream at Orange Grove as of early 2019. It is not known what impact future high-intensity rainfall/storm events will have on Kowhai River bed levels as material in the upper catchment is transported downstream to the sea.

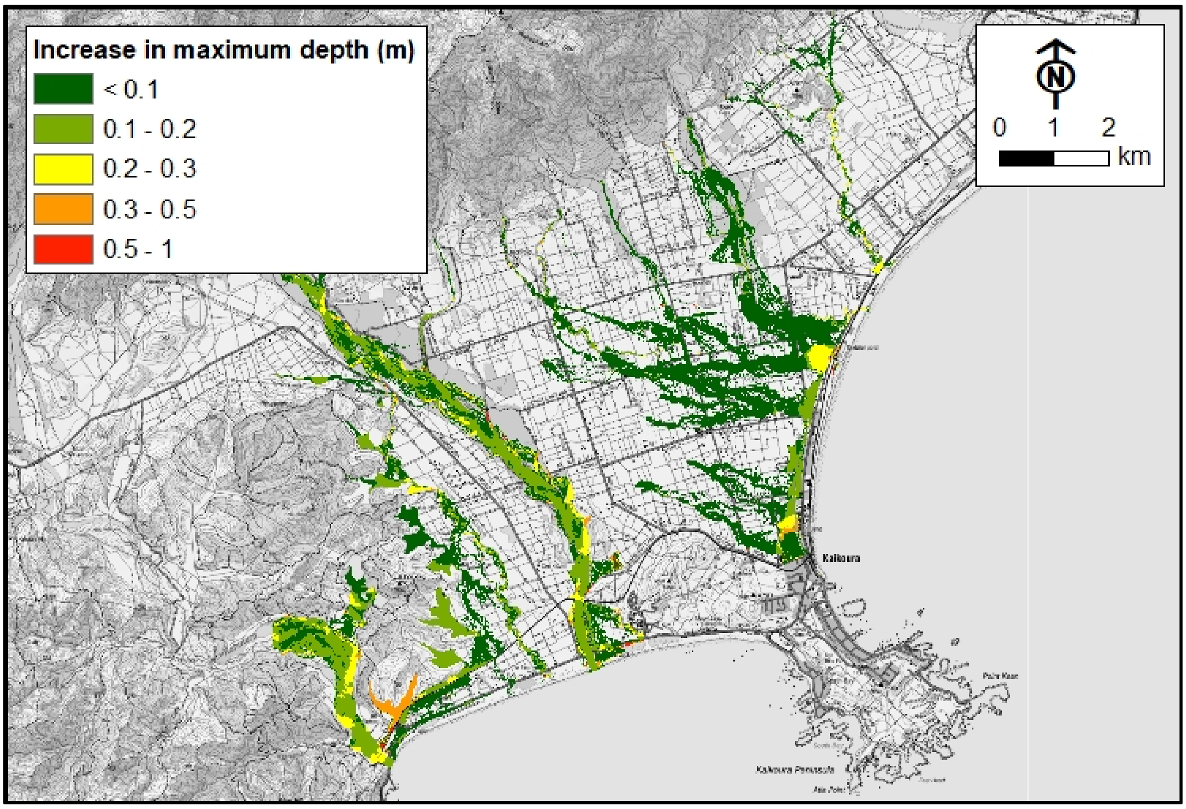
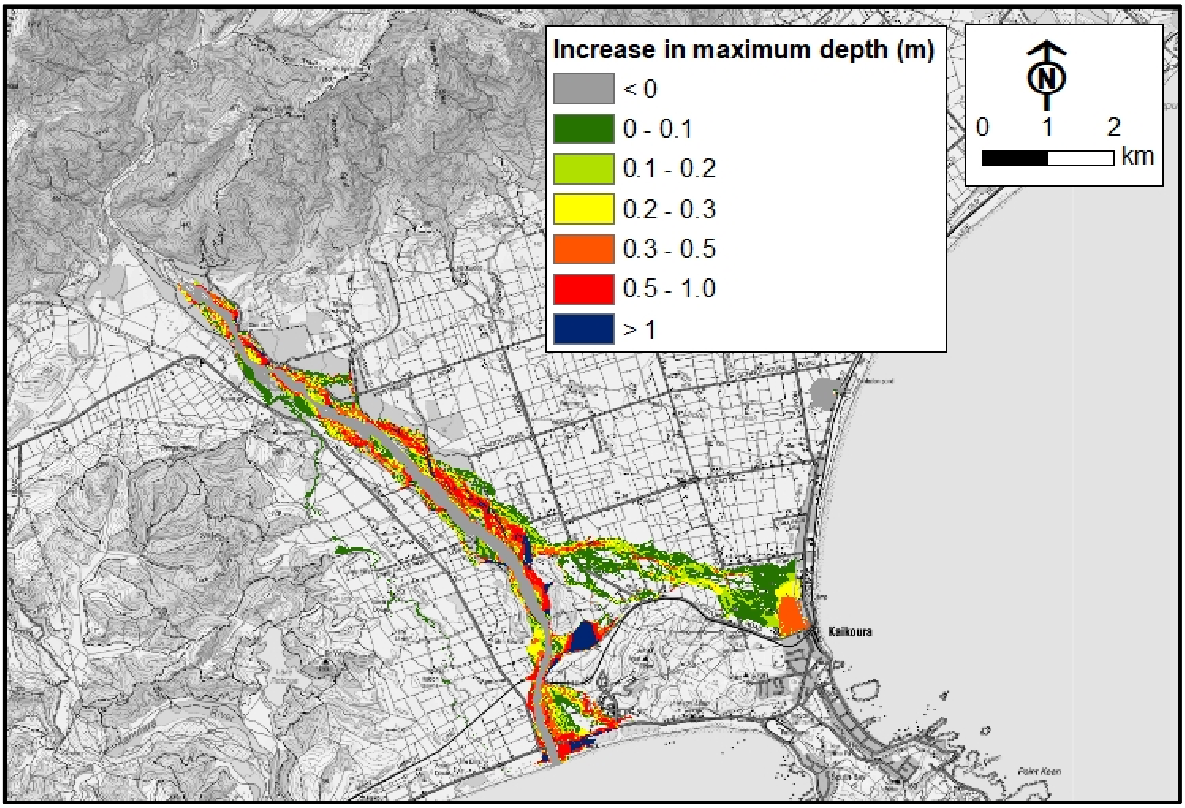
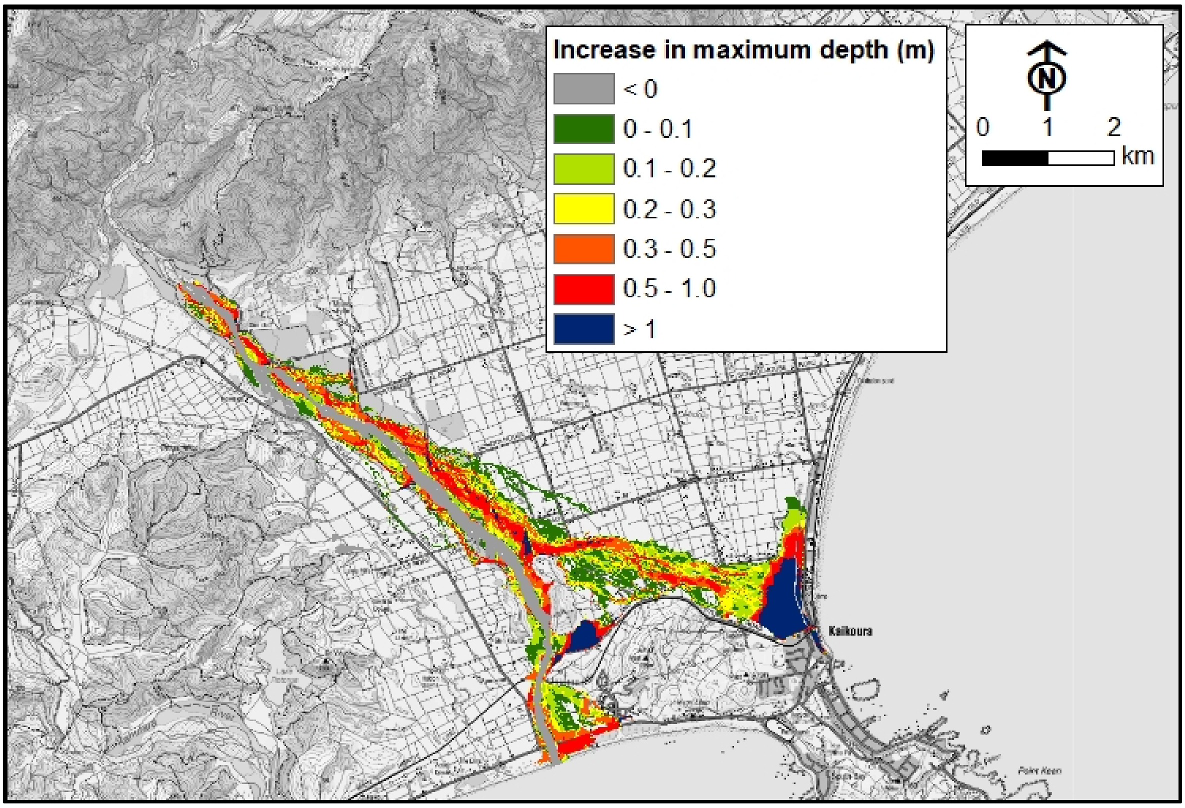


Figure 3-25: Increase in maximum water depths for a 50 year ARI no breakout scenario with all flows 25% greater than the estimated magnitude



(a) 50 year ARI



(b) 500 year ARI

Figure 3-26: Increase in maximum floodplain water depths when 1 m of aggradation is added to the Kowhai River - no breakout (only overflows)

3.7 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, it is highly likely that the Kowhai River and Mt Fyffe Stream bank protection works will fail. Significant scour, erosion and aggradation will also occur throughout the Kaikōura Fan System.

To allow for climate change, and realistic extreme flood conditions, the modelled high hazard area for the Kaikōura Fan System includes:

- a 25% increase in the peak 500 year ARI flows (both river systems and breakout flows),
- 1 m of sea level rise,
- Failure of the bank protection works at the main breakout locations (i.e. The Bluff, Kowhai/Middle Ford or Fernleigh Dip).
- The 'no stopbank failure' scenario for the Kowhai River with, and without, 1 m of aggradation. These scenarios have been included for completeness since the other breakout scenarios have some of the Kowhai River flows removed from the river system to compensate for the flow removed during a breakout flow.

Figure 3-27 identifies areas on the Kaikōura Fan System that meet the CRPS definition of high hazard, based on the flood modelling and the above assumptions, for a 500 year ARI flood event.

As the computer model used in this investigation has a fixed bed, and only a limited number of breakout locations have been modelled (when scour/aggradation may force flood flows to breakout at other locations), not all possible high hazard areas will have been identified by the modelling of 500 year ARI flood events in this investigation.

Additional areas of the Kaikōura Fan System, particularly areas within the riverbed as well as in the area identified as 'Mt Fyffe Fans', are likely to meet the high hazard classification should breakout flows (or a complete channel avulsion) occur. In the Mt Fyffe Fans area, highlighted in pink on Figure 3-27, it is difficult to quantify the flood hazard. The reasons for this are described in more detail in Section 3.3.3. The computer models used in this study cannot simulate the accumulation of debris or erosion/scouring of existing ground levels.

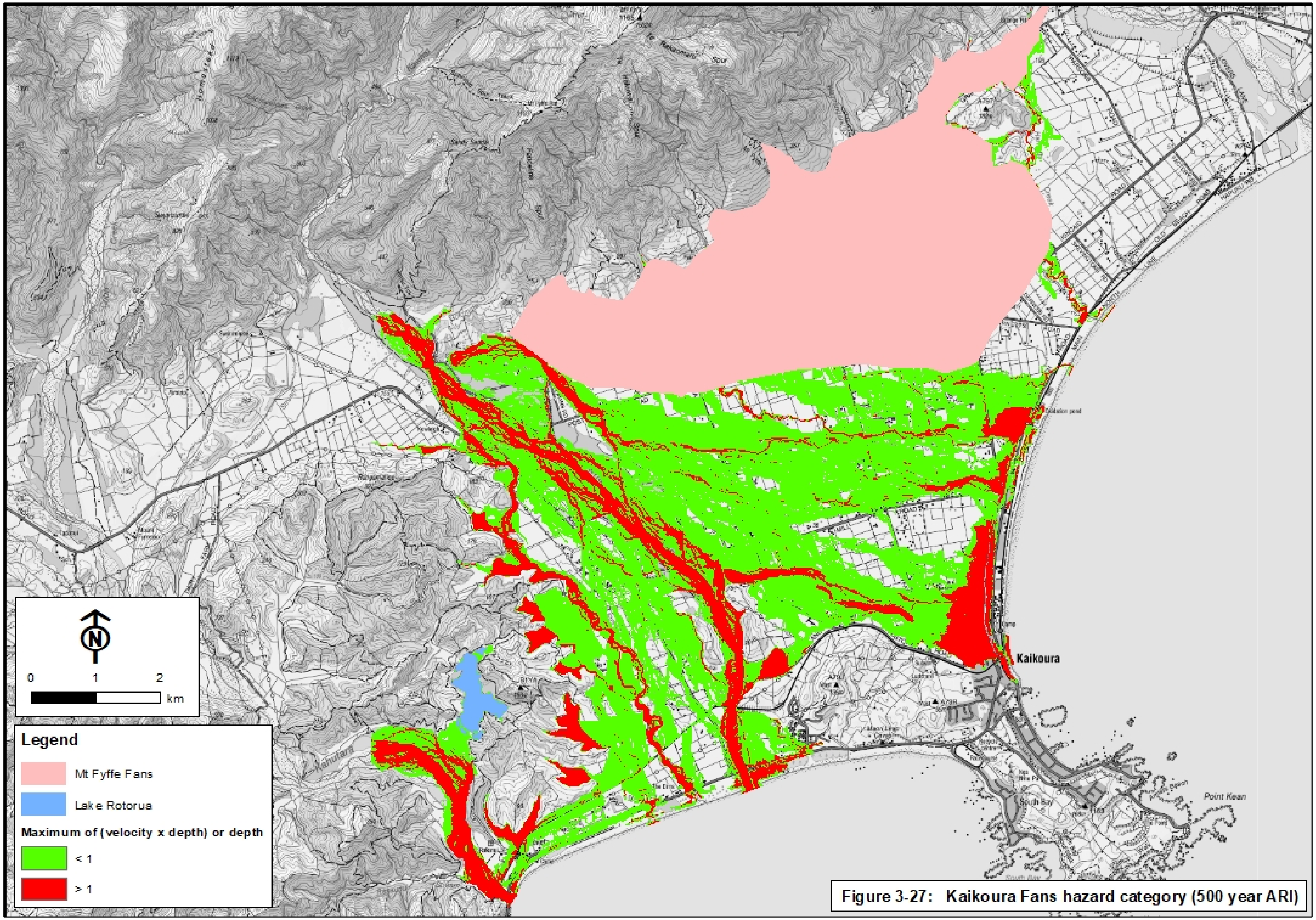


Figure 3-27: Kaikōura Fans high hazard areas for modelled scenarios (500 year ARI)

4 Discussion

The modelling has clearly demonstrated that there is likely to be little warning time before inundation occurs. This is due to the small and flashy nature of the Mt Fyffe streams during high-intensity rainfall events, and the proximity of the population to Kowhai River breakout locations.

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

4.1 Model uncertainty

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

- Model inputs (e.g. stopbank breach locations and sizes, flow magnitude and hydrograph shape, roughness values, energy loss parameters, and climate change predictions).
- Topographic data (e.g. LiDAR data and estimated submerged riverbed levels). The model uses a fixed bed level so cannot account for scour and aggradation due to high-energy flood flows.
- 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).

Sources of uncertainty that are particularly relevant for this study include:

- Flood flow magnitudes – given the limited available flow information for this study, most flood flows have been estimated using a regional flow estimation approach.
- River mouth profiles during flood events – some attempts have been made in this study to 'scour' out the river mouths to better represent the bed profile during a flood event. This is very subjective and may impact on flood levels in the vicinity of the river mouths (e.g. levels in the Peketa/Kahutara River mouth area).
- Vegetation in active river channels – the extent of vegetation within the watercourses is highly variable. This vegetation provides some resistance to river flows and could potentially elevate flood levels. It has been assumed for this study that the extent of vegetation will remain similar in the future.
- Input location for Mt Fyffe stream flood flows – flood flows have been input into the currently active watercourses. During flood events it is possible that these active watercourses could fill with sediment and the watercourse could move to another location, allowing flood waters to take a new path over the alluvial fan. This could direct additional floodwater towards some properties, reducing flooding at other properties.
- Stopbank breaches – except for the modelled breakout flows at The Bluff, Fernleigh Dip and Kowhai/Middle Ford, it has been assumed that all stopbanks, roads and railway embankments remain intact during flood events. This is not realistic for a large flood event so there is likely to be additional flooding directed towards some properties within the study area during a large flood event.
- Bridge and culvert blockages – during large flood events it is likely that some bridges and culverts will become partially or fully blocked, When these blockages occur, flood waters may back up behind the structure or, in some cases, may erode the material adjacent to the structure and create a new flow path. It is not possible to model all possible outcomes, so it has generally been assumed that all significant structures are not blocked. Localised backing up of flow behind structures may need to be considered for flood hazard assessments, and some culverts may have not been included in the model.

- Channel aggradation – post-2016 Kaikōura Earthquake Sequence, there is a large volume of landslide material in the upper catchments of some of the rivers (e.g. Kowhai and Hapuku rivers). At present it is unknown whether this material will raise riverbed levels over time and, consequently, increase the likelihood of breakouts.

- Surface water runoff – in some areas additional surface water runoff, generated by high-intensity rainfall, will have a significant impact on overland flows. This local rainfall runoff is not included in the models.

Not all feasible scenarios can be modelled so it is possible that, in a large flood event such as a 50 to 500 year ARI flood, other areas within the study area could be inundated with flood water (i.e. not all areas of possible inundation are necessarily covered by this study). Sensitivity tests can help address uncertainty, though modelling results should generally be interpreted and used by those who are familiar with all aspects of the modelling.

4.2 Data required to better calibrate the model

To enable the model results to be used more confidently, monitored water level/flow recorders for all the watercourses would be required to more accurately determine flood flows, ideally over a long period of time. Unfortunately for the larger Kaikoura Rivers this is extremely difficult to do accurately. Previous attempts to produce a relationship between Kowhai River water levels and flood flows were considered challenging – largely because of the difficulty measuring flood flows when there is a large volume of bed material and debris moving along the watercourse. Figure 4-1 shows the Kowhai River during the May 1966 flood.

Figure 4-1: Kowhai River during the May 1966 flood

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

- Photographs of flood inundation, along with the time that the photographs were taken.
- Pegging, or marking the peak water levels.
- Observations of any stopbank breaches (i.e. size, time).
- Cross section profiles or topographical data (e.g. LiDAR data).

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

Specialised research organisations may also be able to address river mouth and alluvial fan behaviour that have not been included in this study.

5 Conclusions

The models used in this study have a fixed bed level and do not simulate changes in bed levels due to scour, aggradation, or channel avulsions - all processes that will occur during a large flood event in a steep, gravel-bed rivers and on alluvial fans. The model has also been based on limited recorded flow data and was only partially validated against the December 1993 flood event. Consequently, there is considerable uncertainty in the predicted extent and depth of flood water for all modelled scenarios.

Despite all model uncertainties outlined above, and in Section 4, the modelling does provide a good insight into how flood waters are likely to behave for a range of flood scenarios. It identifies preferential flow paths and areas where significant depths of inundation are likely during 50 to 500 year ARI flood events.

Main findings for a 500 year ARI flood event include:

- One of the main areas susceptible to breakout flows is the ponding area upstream of the SH1 bridge at Lyell Creek. When the breakout flows entering Lyell Creek exceed the capacity of the SH1 bridge, water levels increase in the ponding area. The rate at which the water level in this ponding area increases is very much dependent on the breakout flow magnitude, the length of time that large breakout flows are flowing into this ponding area, and the size of the SH1 road bridge constriction.
- Climate change (i.e. increases in flow) has a more significant impact on flood depths in the ponding areas compared to in areas where there are more widespread, unconfined, overland flows.
- Alluvial fan and floodplain roughness have a relatively minor impact on flood water levels, except in areas where water is deep and flowing fast, or where the increase in roughness increases water depths, allowing greater overflows into ponding areas.
- If the Kowhai River flood protection works were not compromised (i.e. didn't fail), flooding downstream of the SH1 bridge in Kaikōura Township is unlikely. Failure of flood protection works on any of the Mt Fyffe streams are unlikely to lead to flooding downstream of SH1 in Kaikoura Township; breakout flows are not likely to exceed the capacity of the flood protection wall without Kowhai River breakout flows contributing.
- Harnetts Creek flows do not appear to contribute to any flooding south of Harnetts Road.
- A breakout from the Kowhai River at The Bluff divides overland flows between the Lyell Creek catchment and the Middle Creek catchment, while the Kowhai/Middle Creek breakout flows only pass into the Lyell Creek catchment. Flooding is therefore more extreme in the ponding area upstream of the Lyell Creek SH1 road bridge for a Kowhai/Middle Ford breakout.
- 1 m of channel aggradation in the Kowhai River can have a significant impact on water levels in the ponding area upstream of the Lyell Creek SH1 bridge – even when flood protection works are only overtopped rather than failing catastrophically.
- Climate change is likely to have a relatively small impact (<0.1 m) on overland flows passing over wide, unconfined floodplain areas. One metre of sea level rise is also only likely to have an impact on flood levels at the coast, and a relatively minor (< 0.1 m) impact on flood levels in ponding areas adjacent to the coast. For example, in the Lyell Creek Township and upstream of SH1 ponding areas. The main impact of climate change will be in the ponding areas where flood levels may increase by greater than 0.5 m due to increased flood flows.

6 Recommendations

Due to the limitations of the modelling, the results should be used in conjunction with historic flood information and practical, scientific judgement.

Possible future improvements to the model, that could increase the accuracy of the modelling results, include:

- Re-assessing design flood depths, extents and high hazard areas at a future date when additional climate change, hydrological and riverbed information becomes available.
- Undertaking more precise modelling of bridge/culvert structures (e.g. the Lyell Creek SH1 bridge), and the Lyell Creek flood wall. However, there would still be considerable uncertainty due to breakout flow estimates.
- Incorporating the effects of the earthquakes (e.g. transport of catchment landslide material along the water courses) into the modelling as the impacts are researched, and more clearly understood. This would allow future bed levels to be modelled more accurately.
- Developing a rainfall runoff model of the Kaikōura Fans catchments. This could better simulate the timing of peak flows from the various watercourses, during flood events, and examine the relationship between climate change-induced increases in peak rainfall, and the resulting increases in peak flows.
- Completing a joint probability analysis to determine the probability of coincidence of ARI flood events in the various water ways (LRSC, 2020).

Other Kaikōura Fan flood investigations could include:

- Examining the uppermost Kowhai River true right bank overflow path that has historically diverted breakout flows into the Kahutara River (Figure 2-1).
- A scientific study to better define the river mouth profiles during flood events, and due to climate change (i.e. increased sea level).

The geomorphic study undertaken by GNS (Brideau *et al.,* 2020) provides some guidance for assessing the feasibility of development in the Mt Fyffe alluvial fan areas where fixed-bed flood models are of limited use. A site-specific geomorphic study may need to be undertaken, to better understand the debris flow or debris flood hazard, for sites identified as being susceptible to these hazards.

7 Acknowledgments

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

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

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

8 External peer review

An external peer review of the computational hydraulic model was completed by Matt Gardner of Land River Sea Consulting Ltd (LRSC, 2018). This review provided several recommendations regarding improvements to the model setup. These included:

- Reprocessing the underlying DEM so that key topological features were correctly enforced.
- Adding culverts under state highway as 1D structures linked in MIKE Flood rather than as openings.
- Modifying the State highway 1 bridge setup to remove the instability in the 1D results.
- Changing eddy viscosity to 1.
- Changing the boundary condition at both south and north coast from a lateral link to a standard link.
- Correcting the 1m aggradation setup files.

As a result of the review, the model grid has been regenerated and additional bridge, weir and culvert structures have been incorporated into the model (as 1D structures, where required). These changes have made the model more stable, and better simulated the road barriers. The mass balance issues have also been resolved. Eddy viscosity has also been increased from 0.5 to 1.0 for the runs with a time step of 0.5 seconds.

A second review of the revised model (LRSC, 2020) confirms that the above recommendations have been implemented. LRSC (2020) also included a review of the inflow and breakout assumptions along with the recommendations/conclusions. The main conclusions of the review were:

'Overall I consider the model to be fit for purposes of identifying potential flood hazard areas for a 1 in 500 year event'. It was also recommended that consideration be given to:

- Sensitivity run with an allowance for further increases in peak flow to be representative of an upper range RCP scenario.
- A range of large-scale flood maps be produced which allow the reader to visualise changes in flood depth and extent for the sensitivity runs.
- A map is produced which shows an overall combined flood extent of all the sensitivity scenarios.

To address these recommendations:

- A sensitivity run has been completed for a 50 year ARI 'no breakout' scenario with 25% added to the inflows (see Section 3.6.4). This represents an upper range RCP scenario.
- A range of large-scale maps will be made available online to be viewed in conjunction with the report.
- A3 maps of maximum water depths and high hazard categories (calculated by combining the main modelled scenarios) are shown on Figure 3-21 and Figure 3-27, respectively. For this report the sensitivity runs have not been included on the maps. However, the advantage of computation modelling and mapping is that, depending on a specific issue or area of concern, the existing sensitivity model runs, and any additional sensitivity runs and/or model refinements, can be used to better present information, as required.

LRSC(2020) also '*recommended that any final maps of flood extent/depth made available to the public online, or in other domains, clearly state the limitations of the modelling as well as clearly demarcate the model extent, to ensure that areas not included in the model extent are not assumed to be free of flooding*.' Other recommendations for future work have been noted in Section 6 of the report.

9 Glossary

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

Alluvial fan: Cone-shaped deposit of unconsolidated material deposited by debris flows and floods. These alluvial fans form where confined, mountainous, water courses exit onto more gently sloping, less confined, land. As alluvial fans have a steep gradient (compared to braided river floodplains), and floodwaters contain significant volumes of debris, flooding is usually more damaging compared to other river floodwaters.

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 chance of one-in-twenty) of a peak flood discharge of 500 m^3/s or larger 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.

Debris flows and floods: Debris flows, and debris floods, tend to occur in steep, non-vegetated catchments containing loose debris. Rainfall can saturate the loose debris and mobilise it. The saturated, mobilised, debris can then rapidly erode and entrain further material as the high-velocity flows pass along any steep, confined, mountainous channel. As the concentration of the sediment-laden debris flow (which can include enormous boulders) decreases, the debris flow becomes a debris flood or a flood. Further information on debris flows and floods is given in Brideau et al. (2020).

Degradation: Scouring of shingle or other sediment from a riverbed, lowering the riverbed 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 riverbed that carries the majority of any flood flow. There is often a maintenance program in place for clearance of vegetation such as willows, gorse and broom from the fairways.

Floodplain: The area of relatively flat land, adjacent to the fairway, that is inundated by flood waters 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*'.

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. This point data is used to generate very accurate, high resolution, digital elevation maps which enable subtle 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 surrounding land resulting from a stopbank failure (usually due to overtopping or lateral erosion/scour).

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Appendix A: Model cross section locations

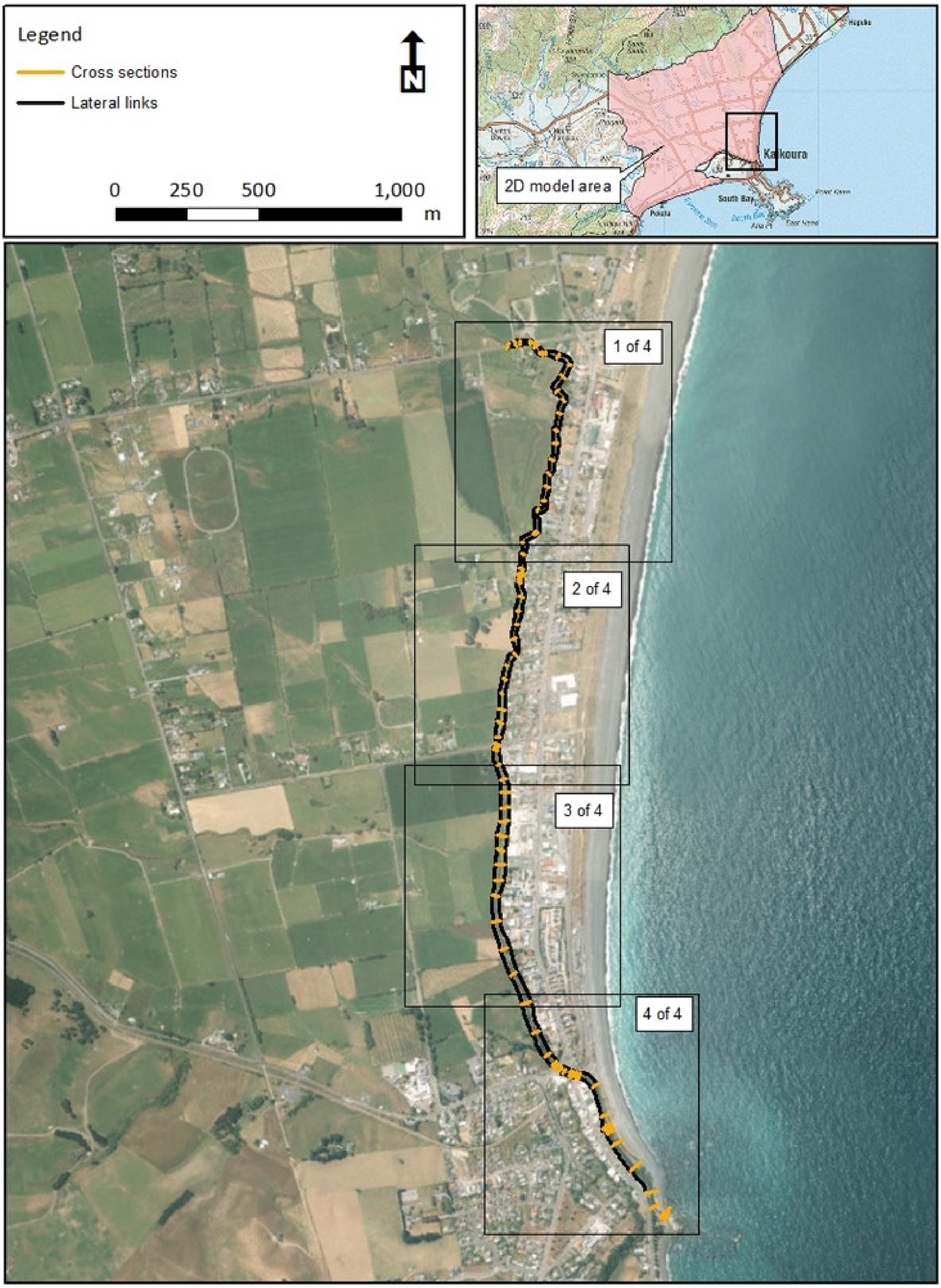

Figure A-1: Overview of Lyell Creek Mike 11 model cross sections and overflows (represented by 'lateral links')

Figure A-2: Lyell Creek model schematic (1 of 4)

Figure A-3: Lyell Creek model schematic (2 of 4)

Figure A-4: Lyell Creek model schematic (3 of 4)

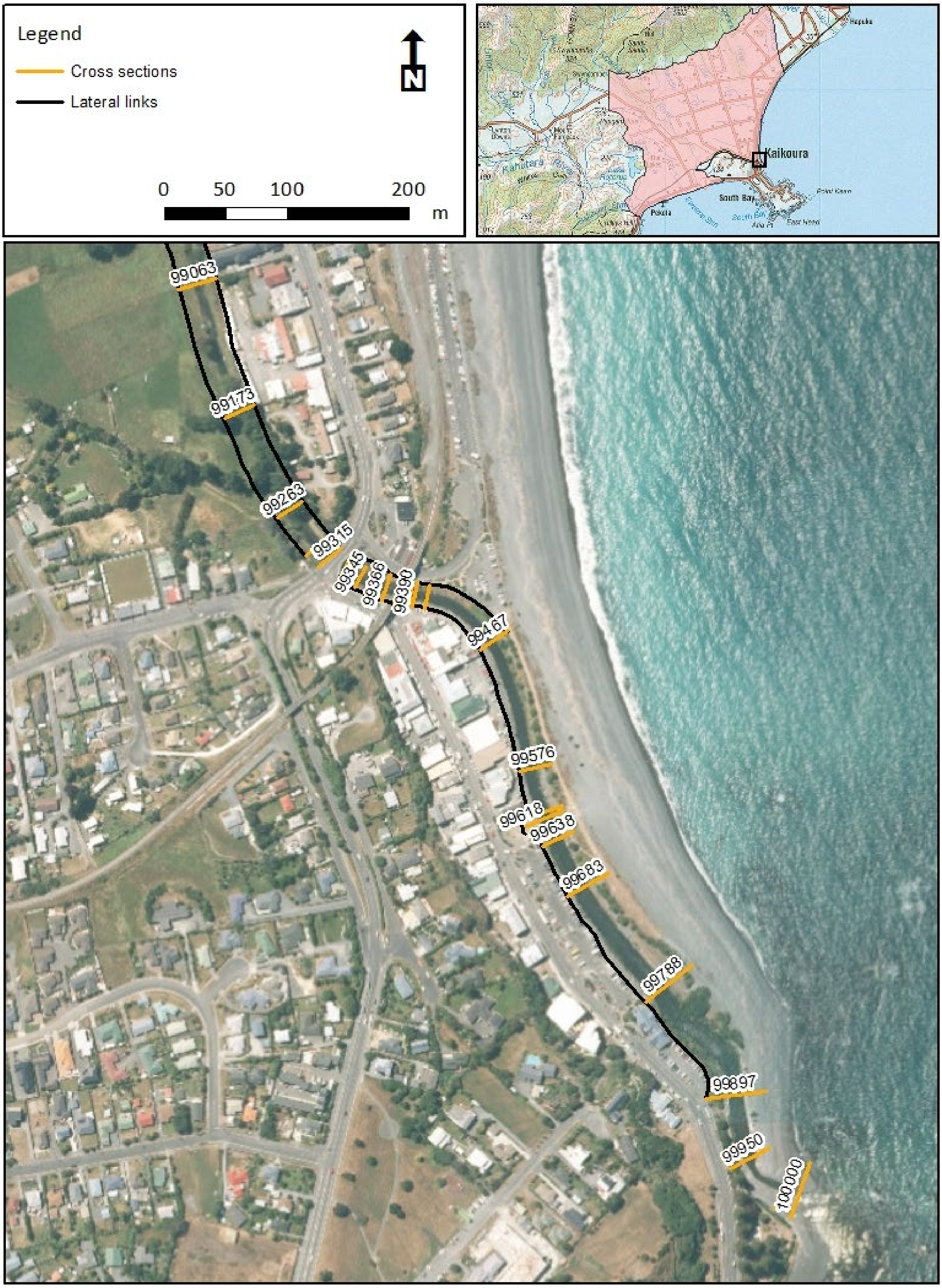

Figure A-5: Lyell Creek model schematic (4 of 4)

<u>Note:</u> SH1 bridge overflow weirs, cross sections, and lateral link connecting bridge to road grid cells, are not shown on this schematic.

Table A-1: Summary of Mike 11 cross section information for Lyell Creek

Mike 11 chainage	Survey chainage	Location/Description
96418	3582	Top of Mike11 model - upstream of driveway access bridge
96462	3538	
96496	3504	Upstream of Mill Road bridge
96502		Cross section 96496 copied downstream
96509		Mill Road bridge
96522	3478	
96551		Cross section 96571 copied upstream
96559		Miscellaneous bridge 2
96571	3429	Downstream of miscellaneous bridge 2
96613	3387	
96669	3331	Downstream of Drain G
96719	3281	
96775	3225	
96823	3177	
96873	3127	
96932	3068	
96979	3021	
97036	2964	
97090	2910	
97137	2863	
97187	2813	
97242	2758	
97326	2674	Upstream of miscellaneous bridge 1
97330		Miscellaneous bridge 1
97336	2664	
97390	2610	Upstream of Drain F
97431	2569	Downstream of Drain F
97484	2516	
97499	2501	Upstream of Gillings Lane bridge
97505		Gillings Lane bridge
97509	2491	
97521	2479	
97531	2469	
97586	2414	Upstream of Drain E
97636	2364	
97685	2315	
97735	2265	
97794	2206	
97847	2153	
97894	2106	
97947	2053	
98004	1996	
98050	1950	
98102	1898	Upstream of Hawthorne Road bridge & Drain D
98126	1874	
98131		Hawthorne Road bridge
98136	1864	
98150	1850	
98201	1799	
98255	1745	
98301	1699	
98354	1646	
98402	1598	

Mike 11 chainage	Survey chainage	Location/Description
98453	1547	Upstream of Drain C confluence
98505	1495	
98556	1444	
98610	1390	
98668	1332	
98756	1244	Upstream of Drain B confluence
98860	1140	
98953	1047	
99063	937	
99173	827	Upstream of Drain A confluence
99263	737	Upstream of SH1 bridge
99300		Cross section 99263 copied downstream
99322		SH1 bridge
99345		Cross section 99366 copied upstream
99366	634	Upstream of railway overbridge and Foot bridge 1
99377		Cross section 99366 copied downstream
99387		Footbridge 1
99397		Cross section 99399 copied upstream
99399	601	
99467	533	
99576	424	
99613	376	Upstream of Footbridge 2
99624		Footbridge 2
99628		Modified 99616
99683	317	
99788	212	
99897	103	
99950	50	
99974	26	
100000	0	Lyell Creek mouth

Figure A-6: Harnetts Creek model schematic

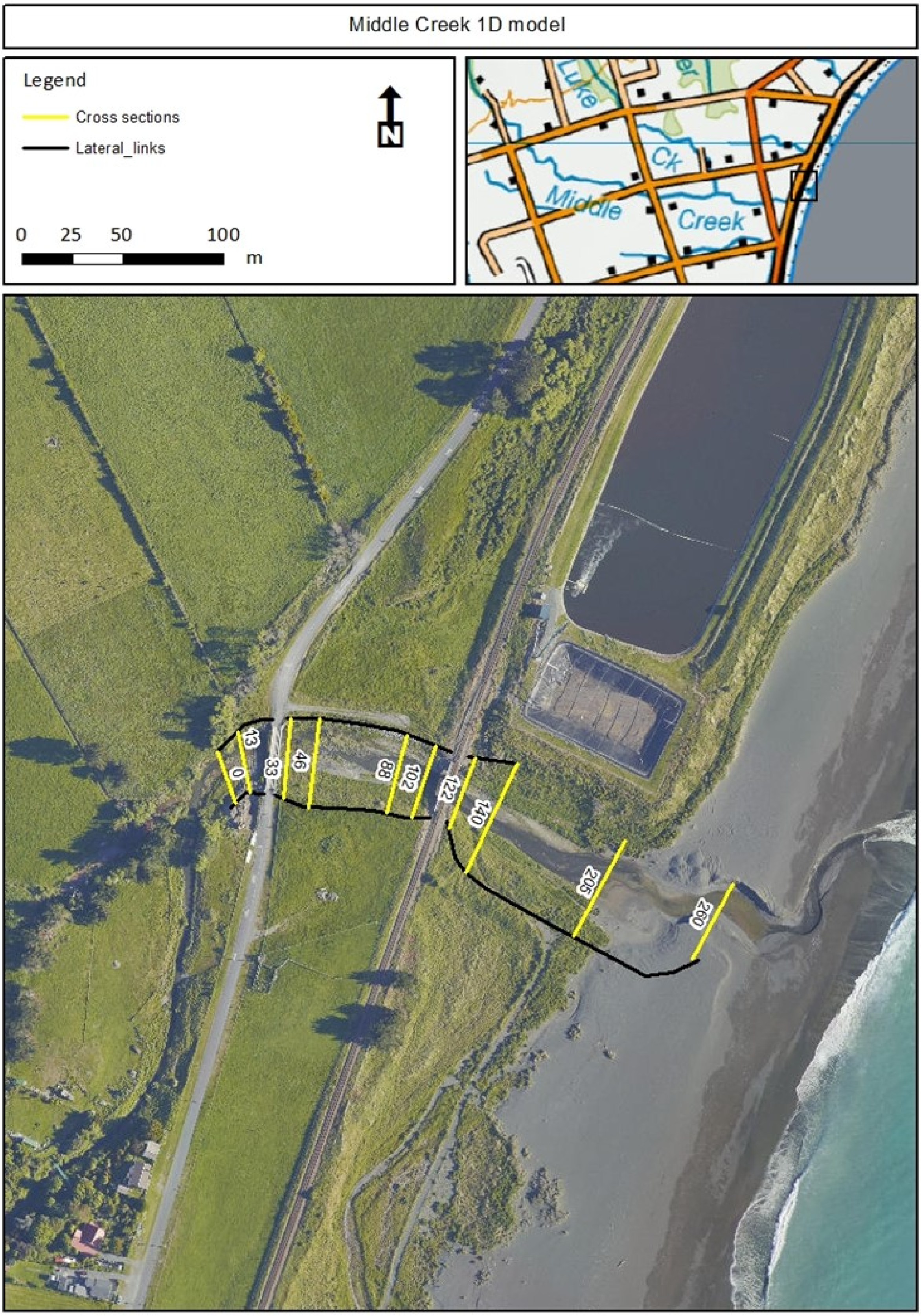

Figure A-7: Middle Creek model schematic

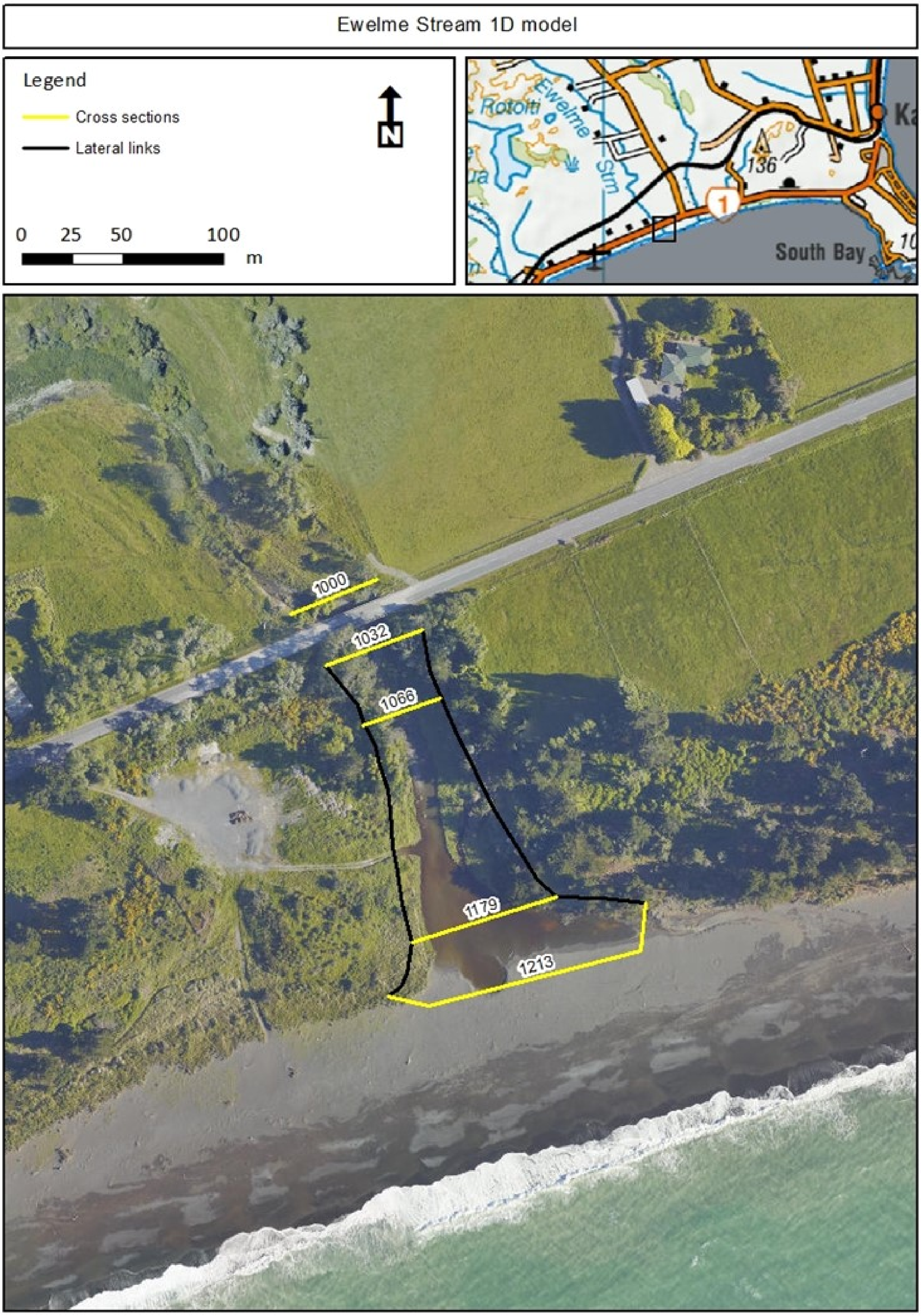

Figure A-8: Ewelme Stream model schematic

Appendix B: December 1993 flood levels

Table B-1: Measured flood level marks

Location	Reduced level (a.m.s.l.)
Westend Motors	3.70
Eades Garage	4.25
Adelphi	3.80/4.02
Pharmacy	3.79
Mitre 10	3.54
Old & Interesting	3.77
Ally @ Peppermill Café	3.93
Knowle’s Dairy	4.26
Florist	4.28
Photo & Frame, Lotto Shop	4.21
Chris Guthrie, Ludstone Rd	5.37
65 Ludstone Road	5.60
Willowbank Motel Beach Road	5.41
129 Beach Road	5.48
Des Cuff, Hawthorne Road	5.47
Coastline Dairy	3.74/3.84
Dolphin Encounter	3.60

Appendix C: Model run files

Model extents:

Kaikoura Fan model (all): (1646200 mE, 5301700 mN) to (1658150 mE, 5315700 mN)

Fernleigh Dip model: (1646200 mE, 5301700 mN) to (1653200 mE, 5310905 mN)

Inflow locations:

Harnetts Creek	(2057,2792), (1865,2705), (1782,2615), (1720,2517), (1656,2453)
Waimangarara River	(1525,2380)→(1531,2380), (1447,2282)
Luke Creek	(1211,2151)→(1212,2151)
Middle Creek	(1049,2057)→(1052,2057), (845,2031)→(848,2031), (993,1491)
Floodgate Creek	(604,1934), (605,1934)
Goldmine Creek	(258,1860), (258,1861)
Kowhai River	(38,1835)→(49,1835), (79,1842)→(90,1842)
Ewelme Stream	(44,1439), (283,1278), (284,1079), (459,931), (630,549)
Lyell Creek	(1426,1364), (1374,1289), (1526,1126), (1337,1043), (1860,1099), (1725,853)
Kahutara River	(38,512) →(38,471)
Peketa local inflows	(621,428), (530,330), (375,282)

Breakout locations:

Kowhai - The Bluff	(264,1708) →(264,1689)
Kowhai - Middle Ford	(1109,1054) →(1109,1035)
Kowhai - Fernleigh Dip	(307,1469), (308,1469), (308,1470), (309,1470), (309,1471), (310,1471), (310,1472), (311,1472), (311,1473), (312,1473)
Kowhai - downstream of Fernleigh Dip	(577,1342)→(586,1342)

December 1993 calibration files

	Breakout of 190 m^3/s	Breakout of 180 m^3/s
	Middle Ford breakout with a 190 m^3/s peak flow, no contributing flows from Lyell Creek.	Middle Ford breakout with a 180 m^3/s peak flow, no contributing flows from Lyell Creek.
MikeFlood		
Couple file (*.mf)	FINAL_Kaik_Fan_Cal_1993_Middle_Ford_BO_190_cumecs_mf	FINAL_Kaik_Fan_Cal_1993_Middle_Ford_BO_180_cumecs_mf
Mike11		
Simulation file (*.sim11)	FINAL_Kaik_Fan_Cal_1993_Middle_Ford_BO_190_cumecs	FINAL_Kaik_Fan_Cal_1993_Middle_Ford_BO_180_cumecs
Network file (*.nwk11)	FINAL_Kaikoura_2019_NWK	
Cross section file (*.xns11)	FINAL_Kaikoura_2019_XS	
Boundary file (*.bnd11)	FINAL_Kaikoura_2019_SL_1_75m	
HD parameter (*.hd11)	FINAL_Kaikoura_HD_SL_1_75m_IC_1_42	
Results file (*.res11)	FINAL_Kaik_Fan_Cal_1993_Middle_Ford_BO_190_cumecs	FINAL_Kaik_Fan_Cal_1993_Middle_Ford_BO_180_cumecs
Mike21		
Simulation file (*.21)	FINAL_Kaik_Fan_Cal_1993_Middle_Ford_BO_190_cumecs	FINAL_Kaik_Fan_Cal_1993_Middle_Ford_BO_180_cumecs
Bathymetry file (*.dfs2)	FINAL_2017_5m_MIDDLE_FORD_BO	
Initial surface elevation (*.dfs2)	FINAL_2017_5m_MIDDLE_FORD_BO_initial_WL_1_42	
Resistance (*.dfs2)	k19_5m_n_v15	
Results (*.dfs2)	FINAL_Kaik_Fan_Cal_1993_Middle_Ford_BO_190_cumecs	FINAL_Kaik_Fan_Cal_1993_Middle_Ford_BO_180_cumecs
Sources	Middle Ford breakout	
Drying/Wetting depth (m)	0.01/0.03	
Eddy viscosity	1	
Simulation time	1/1/2000 1:30pm to 2/1/2000 9:00am	
Time step (s)	0.5	
Length of run (# time steps)	140400	

Kaikōura Fans 50 year ARI design flood events

	No breakout	No breakout but 1 m aggradation
	No breakout but overflows, Sea level = 2.75 m	No breakout but overflows, Kowhai River bed levels +1 m. Sea level = 2.75 m
MikeFlood		
Couple file (*.mf)	FINAL_Kaik_Fan_50yr_NO_BO_mf	FINAL_Kaik_Fan_50yr_NO_BO_w_1m_Kow_agg_mf
Mike11		
Simulation file (*.sim11)	FINAL_Kaik_Fan_50yr_NO_BO	FINAL_Kaik_Fan_50yr_NO_BO_w_1m_Kow_agg
Network file (*.nwk11)	FINAL_Kaikoura_2019_NWK	
Cross section file (*.xns11)	FINAL_Kaikoura_2019_XS	
Boundary file (*.bnd11)	FINAL_Kaikoura_2019_SL_2_75m	
HD parameter (*.hd11)	FINAL_Kaikoura_HD_SL_2_75m_IC_2_42	
Results file (*.res11)	FINAL_Kaik_Fan_50yr_NO_BO	FINAL_Kaik_Fan_50yr_NO_BO_w_1m_Kow_agg
Mike21		
Simulation file (*.21)	FINAL_Kaik_Fan_50yr_NO_BO	FINAL_Kaik_Fan_50yr_NO_BO_w_1m_Kow_agg
Bathymetry file (*.dfs2)	FINAL_2017_5m_	FINAL_2017_5m_1m_Kow_agg
Initial surface elevation (*.dfs2)	FINAL_2017_5m_initial_WL_2_42	FINAL_2017_5m_1m_Kow_agg_initial_WL_2_42
Resistance (*.dfs2)	k19_5m_n_v15	
Results (*.dfs2)	FINAL_Kaik_Fan_50yr_NO_BO	FINAL_Kaik_Fan_50yr_NO_BO_w_1m_Kow_agg
Sources	Harnetts Creek, Waimangarara River, Luke Creek, Middle Creek, Floodgate Creek, Goldmine Creek, Kowhai River, Lyell Creek, Ewelme Stream, Peketa local inflows and Kahutara River	
Drying/Wetting depth (m)	0.01/0.03	
Eddy viscosity	1	
Simulation time	1/1/2000 1:30pm to 2/1/2000 9:00am	
Time step (s)	0.5	
Length of run (# time steps)	140400	

Kaikōura Fans 50 year ARI design flood events

	The Bluff breakout	Middle Ford breakout
	Breakout at The Bluff, Sea level = 2.75 m	Breakout at Kowhai/Middle Ford, Sea level = 2.75 m

MikeFlood		
Couple file (*.mf)	FINAL_Kaik_Fan_50yr_The_Bluff_BO_mf	FINAL_Kaik_Fan_50yr_Middle_Ford_BO_mf

Mike11		
Simulation file (*.sim11)	FINAL_Kaik_Fan_50yr_The_Bluff_BO	FINAL_Kaik_Fan_50yr_Middle_Ford_BO
Network file (*.nwk11)	FINAL_Kaikoura_2019_NWK	
Cross section file (*.xns11)	FINAL_Kaikoura_2019_XS	
Boundary file (*.bnd11)	FINAL_Kaikoura_2019_SL_2_75m	
HD parameter (*.hd11)	FINAL_Kaikoura_HD_SL_2_75m_IC_2_42	
Results file (*.res11)	FINAL_Kaik_Fan_50yr_The_Bluff_BO	FINAL_Kaik_Fan_50yr_Middle_Ford_BO

Mike21		
Simulation file (*.21)	FINAL_Kaik_Fan_50yr_The_Bluff_BO	FINAL_Kaik_Fan_50yr_Middle_Ford_BO
Bathymetry file (*.dfs2)	FINAL_2017_5m_THE_BLUFF_BO	FINAL_2017_5m_MIDDLE_FORD_BO
Initial surface elevation (*.dfs2)	FINAL_2017_5m_THE_BLUFF_BO_initial_WL_2_42	FINAL_2017_5m_MIDDLE_FORD_BO_initial_WL_2_42
Resistance (*.dfs2)	k19_5m_n_v15	
Results (*.dfs2)	FINAL_Kaik_Fan_50yr_The_Bluff_BO	FINAL_Kaik_Fan_50yr_Middle_Ford_BO
Sources	Harnetts Creek, Waimangarara River, Luke Creek, Middle Creek, Floodgate Creek, Goldmine Creek, Kowhai River, Lyell Creek + The Bluff Breakout	Harnetts Creek, Waimangarara River, Luke Creek, Middle Creek, Floodgate Creek, Goldmine Creek, Kowhai River, Lyell Creek + Middle Ford Breakout
Drying/Wetting depth (m)	0.01/0.03	
Eddy viscosity	1	
Simulation time	1/1/2000 1:30pm to 2/1/2000 9:00am	
Time step (s)	0.5	
Length of run (# time steps)	140400	

Kaikōura Fans 500 year ARI design flood events

	No breakout	No breakout but 1 m aggradation
	No breakout but overflows, Sea level = 2.75 m	No breakout but overflows, Kowhai River bed levels +1 m. Sea level = 2.75 m
MikeFlood		
Couple file (*.mf)	FINAL_Kaik_Fan_500yr_NO_BO_mf	FINAL_Kaik_Fan_500yr_NO_BO_w_1m_Kow_agg_mf
Mike11		
Simulation file (*.sim11)	FINAL_Kaik_Fan_500yr_NO_BO	FINAL_Kaik_Fan_500yr_NO_BO_w_1m_Kow_agg
Network file (*.nwk11)	FINAL_Kaikoura_2019_NWK	
Cross section file (*.xns11)	FINAL_Kaikoura_2019_XS	
Boundary file (*.bnd11)	FINAL_Kaikoura_2019_SL_2_75m	
HD parameter (*.hd11)	FINAL_Kaikoura_HD_SL_2_75m_IC_2_42	
Results file (*.res11)	FINAL_Kaik_Fan_500yr_NO_BO	FINAL_Kaik_Fan_500yr_NO_BO_w_1m_Kow_agg
Mike21		
Simulation file (*.21)	FINAL_Kaik_Fan_500yr_NO_BO	FINAL_Kaik_Fan_500yr_NO_BO_w_1m_Kow_agg
Bathymetry file (*.dfs2)	FINAL_2017_5m_	FINAL_2017_5m_1m_Kow_agg
Initial surface elevation (*.dfs2)	FINAL_2017_5m_initial_WL_2_42	FINAL_2017_5m_1m_Kow_agg_initial_WL_2_42
Resistance (*.dfs2)	k19_5m_n_v15	
Results (*.dfs2)	FINAL_Kaik_Fan_500yr_NO_BO	FINAL_Kaik_Fan_500yr_NO_BO_w_1m_Kow_agg
Sources	Harnetts Creek, Waimangarara River, Luke Creek, Middle Creek, Floodgate Creek, Goldmine Creek, Kowhai River, Lyell Creek, Ewelme Stream, Peketa local inflows and Kahutara River	
Drying/Wetting depth (m)	0.01/0.03	
Eddy viscosity	1	
Simulation time	1/1/2000 1:30pm to 2/1/2000 9:00am	
Time step (s)	0.5	
Length of run (# time steps)	140400	

Kaikōura Fans 500 year ARI design flood events

	The Bluff breakout	Middle Ford breakout
	Breakout at The Bluff, Sea level = 2.75 m	Breakout at Kowhai/Middle Ford, Sea level = 2.75 m
MikeFlood		
Couple file (*.mf)	FINAL_Kaik_Fan_500yr_The_Bluff_BO_mf	FINAL_Kaik_Fan_500yr_Middle_Ford_BO_mf
Mike11		
Simulation file (*.sim11)	FINAL_Kaik_Fan_500yr_The_Bluff_BO	FINAL_Kaik_Fan_500yr_Middle_Ford_BO
Network file (*.nwk11)	FINAL_Kaikoura_2019_NWK	
Cross section file (*.xns11)	FINAL_Kaikoura_2019_XS	
Boundary file (*.bnd11)	FINAL_Kaikoura_2019_SL_2_75m	
HD parameter (*.hd11)	FINAL_Kaikoura_HD_SL_2_75m_IC_2_42	
Results file (*.res11)	FINAL_Kaik_Fan_500yr_The_Bluff_BO	FINAL_Kaik_Fan_500yr_Middle_Ford_BO
Mike21		
Simulation file (*.21)	FINAL_Kaik_Fan_500yr_The_Bluff_BO	FINAL_Kaik_Fan_500yr_Middle_Ford_BO
Bathymetry file (*.dfs2)	FINAL_2017_5m_THE_BLUFF_BO	FINAL_2017_5m_MIDDLE_FORD_BO
Initial surface elevation (*.dfs2)	FINAL_2017_5m_THE_BLUFF_BO_initial_WL_2_42	FINAL_2017_5m_MIDDLE_FORD_BO_initial_WL_2_42
Resistance (*.dfs2)	k19_5m_n_v15	
Results (*.dfs2)	FINAL_Kaik_Fan_500yr_The_Bluff_BO	Kaik_Fan_500yr_Middle_Ford_BO
Sources	Harnetts Creek, Waimangarara River, Luke Creek, Middle Creek, Floodgate Creek, Goldmine Creek, Kowhai River, Lyell Creek + The Bluff Breakout	Harnetts Creek, Waimangarara River, Luke Creek, Middle Creek, Floodgate Creek, Goldmine Creek, Kowhai River, Lyell Creek + Middle Ford Breakout
Drying/Wetting depth (m)	0.01/0.03	
Eddy viscosity	1	
Simulation time	1/1/2000 1:30pm to 2/1/2000 9:00am	
Time step (s)	0.5	
Length of run (# time steps)	140400	

Kaikōura Fans 500 year ARI sensitivity tests

	Fan/floodplain roughness increased by 20%, no breakout	Fan/floodplain roughness increased by 20%, breakout at Middle Ford
	No breakout, Manning's n increased by 20%, sea level = 2.75 m	Middle Ford breakout, Manning's n increased by 20%, sea level = 2.75 m

MikeFlood		
Couple file (*.mf)	FINAL_Kaik_Fan_500yr_NO_BO_fp_n_plus_20perc_mf	FINAL_Kaik_Fan_500yr_Middle_Ford_BO_fp_n_plus_20perc_mf

Mike11		
Simulation file (*.sim11)	FINAL_Kaik_Fan_500yr_NO_BO_fp_n_plus_20_perc	FINAL_Kaik_Fan_500yr_Middle_Ford_BO_fp_n_plus_20_perc
Network file (*.nwk11)	FINAL_Kaikoura_2019_NWK	
Cross section file (*.xns11)	FINAL_Kaikoura_2019_XS	
Boundary file (*.bnd11)	FINAL_Kaikoura_2019_SL_2_75m	
HD parameter (*.hd11)	FINAL_Kaikoura_HD_SL_2_75m_IC_2_42	
Results file (*.res11)	FINAL_Kaik_Fan_500yr_NO_BO_fp_n_plus_20_perc	FINAL_Kaik_Fan_500yr_Middle_Ford_BO_fp_n_plus_20_perc

Mike21		
Simulation file (*.21)	FINAL_Kaik_Fan_500yr_NO_BO_fp_n_plus_20_perc	FINAL_Kaik_Fan_500yr_Middle_Ford_BO_fp_n_plus_20_perc
Bathymetry file (*.dfs2)	FINAL_2017_5m_	FINAL_2017_5m_MIDDLE_FORD_BO
Initial surface elevation (*.dfs2)	FINAL_2017_5m_initial_WL_2_42	FINAL_2017_5m_MIDDLE_FORD_BO_initial_WL_2_42
Resistance (*.dfs2)	k19_5m_n_v15_fp_n_incr	
Results (*.dfs2)	FINAL_Kaik_Fan_500yr_NO_BO_fp_n_plus_20_perc	FINAL_Kaik_Fan_500yr_Middle_Ford_BO_fp_n_plus_20_perc
Sources	Harnetts Creek, Waimangarara River, Luke Creek, Middle Creek, Floodgate Creek, Goldmine Creek, Kowhai River, Lyell Creek, Ewelme Stream, Peketa local inflows and Kahutara River	Harnetts Creek, Waimangarara River, Luke Creek, Middle Creek, Floodgate Creek, Goldmine Creek, Kowhai River, Lyell Creek, Middle Ford Breakout
Drying/Wetting depth (m)	0.01/0.03	
Eddy viscosity	1	
Simulation time	1/1/2000 1:30pm to 2/1/2000 9:00am	
Time step (s)	0.5	
Length of run (# time steps)	140400	

Kaikōura Fans 50 year ARI sensitivity tests – no climate change

	No breakout, no climate change	Middle Ford breakout, no climate change
	No breakout, present-day flows and sea levels	Middle Ford breakout, present-day flows and sea levels

MikeFlood		
Couple file (*.mf)	FINAL_Kaik_Fan_50yr_NO_BO_no_CC_mf	FINAL_Kaik_Fan_50yr_Middle_Ford_BO_no_CC_mf

Mike11		
Simulation file (*.sim11)	FINAL_Kaik_Fan_50yr_NO_BO_no_CC	FINAL_Kaik_Fan_50yr_Middle_Ford_BO_no_CC
Network file (*.nwk11)	FINAL_Kaikoura_2019_NWK	
Cross section file (*.xns11)	FINAL_Kaikoura_2019_XS	
Boundary file (*.bnd11)	FINAL_Kaikoura_2019_SL_1_75m	
HD parameter (*.hd11)	FINAL_Kaikoura_HD_SL_1_75m_IC_1_42	
Results file (*.res11)	FINAL_Kaik_Fan_50yr_NO_BO_no_CC	FINAL_Kaik_Fan_50yr_Middle_Ford_BO_no_CC

Mike21		
Simulation file (*.21)	FINAL_Kaik_Fan_50yr_NO_BO_no_CC	FINAL_Kaik_Fan_50yr_Middle_Ford_BO_no_CC
Bathymetry file (*.dfs2)	FINAL_2017_5m_	FINAL_2017_5m_MIDDLE_FORD_BO
Initial surface elevation (*.dfs2)	FINAL_2017_5m_initial_WL_1_42	FINAL_2017_5m_MIDDLE_FORD_BO_initial_WL_1_42
Resistance (*.dfs2)	k19_5m_n_v15	
Results (*.dfs2)	FINAL_Kaik_Fan_50yr_NO_BO_no_CC	FINAL_Kaik_Fan_50yr_Middle_Ford_BO_no_CC
Sources	Harnetts Creek, Waimangarara River, Luke Creek, Middle Creek, Floodgate Creek, Goldmine Creek, Kowhai River, Lyell Creek, Ewelme Stream, Peketa local inflows and Kahutara River	Harnetts Creek, Waimangarara River, Luke Creek, Middle Creek, Floodgate Creek, Goldmine Creek, Kowhai River, Lyell Creek, Middle Ford Breakout
Drying/Wetting depth (m)	0.01/0.03	
Eddy viscosity	1	
Simulation time	1/1/2000 1:30pm to 2/1/2000 9:00am	
Time step (s)	0.5	
Length of run (# time steps)	140400	

Kaikōura Fans 50 year ARI sensitivity tests – no sea level rise & increased flows

	Middle Ford break out, no sea level rise	No break out, flows increased by 25%
	Middle Ford breakout, flows taking climate change into consideration but present-day sea levels	No breakout flow scenario, taking climate change into consideration and increasing flows by a further 25%

MikeFlood		
Couple file (*.mf)	FINAL_Kaik_Fan_50yr_Middle_Ford_BO_no_SLR_mf	FINAL_Kaik_Fan_50yr_NO_BO_Qp_plus_25_perc_mf

Mike11		
Simulation file (*.sim11)	FINAL_Kaik_Fan_50yr_Middle_Ford_BO_no_SLR	FINAL_Kaik_Fan_50yr_NO_BO_Qp_plus_25_perc
Network file (*.nwk11)	FINAL_Kaikoura_2019_NWK	
Cross section file (*.xns11)	FINAL_Kaikoura_2019_XS	
Boundary file (*.bnd11)	FINAL_Kaikoura_2019_SL_1_75m	FINAL_Kaikoura_2019_SL_2_75m
HD parameter (*.hd11)	FINAL_Kaikoura_HD_SL_1_75m_IC_1_42	FINAL_Kaikoura_HD_SL_2_75m_IC_2_42
Results file (*.res11)	FINAL_Kaik_Fan_50yr_Middle_Ford_BO_no_SLR	FINAL_Kaik_Fan_50yr_NO_BO_Qp_plus_25_perc

Mike21		
Simulation file (*.21)	FINAL_Kaik_Fan_50yr_Middle_Ford_BO_no_SLR	FINAL_Kaik_Fan_50yr_NO_BO_Qp_plus_25_perc
Bathymetry file (*.dfs2)	FINAL_2017_5m_MIDDLE_FORD_BO	FINAL_2017_5m_
Initial surface elevation (*.dfs2)	FINAL_2017_5m_MIDDLE_FORD_BO_initial_WL_1_42	FINAL_2017_5m_initial_WL_2_42
Resistance (*.dfs2)	k19_5m_n_v15	
Results (*.dfs2)	FINAL_Kaik_Fan_50yr_Middle_Ford_BO_NO_SLR	FINAL_Kaik_Fan_50yr_NO_BO_Qp_plus_25_perc
Sources	Harnetts Creek, Waimangarara River, Luke Creek, Middle Creek, Floodgate Creek, Goldmine Creek, Kowhai River, Lyell Creek, Middle Ford Breakout	Harnetts Creek, Waimangarara River, Luke Creek, Middle Creek, Floodgate Creek, Goldmine Creek, Kowhai River, Lyell Creek, Ewelme Stream, Peketa local inflows and Kahutara River
Drying/Wetting depth (m)	0.01/0.03	
Eddy viscosity	1	
Simulation time	1/1/2000 1:30pm to 2/1/2000 9:00am	
Time step (s)	0.5	
Length of run (# time steps)	140400	

Fernleigh Dip 50 year ARI design flood events

	Fernleigh Dip breakout	Breakout downstream of Fernleigh Dip
	Breakout at Fernleigh Dip (with climate change to 2120),	Breakout downstream of Fernleigh Dip (with climate change to 2120),
MikeFlood		
Couple file (*.mf)	FINAL_Fernleigh_Dip_50yr_BO_mf	FINAL_Dstm_Fernleigh_Dip_50yr_BO_mf
Mike11		
Simulation file (*.sim11)	FINAL_Fernleigh_Dip_50yr_BO	FINAL_Dstm_Fernleigh_Dip_50yr_BO
Network file (*.nwk11)	FINAL_Fernleigh_Dip_BO_NWK	
Cross section file (*.xns11)[a]	FINAL_Fernleigh_Dip_BO_XS_mod	
Boundary file (*.bnd11)	FINAL_Fernleigh_Dip_BO_SL_2_75m	
HD parameter (*.hd11)	FINAL_Fernleigh_Dip_BO_SL_2_75m_IC_2_42	
Results file (*.res11)	FINAL_Fernleigh_Dip_50yr_BO	FINAL_Dstm_Fernleigh_Dip_50yr_BO
Mike21		
Simulation file (*.21)	FINAL_Fernleigh_Dip_50yr_BO	FINAL_Dstm_Fernleigh_Dip_50yr_BO
Bathymetry file (*.dfs2)	FINAL_Fernleigh_Dip_BO	FINAL_Dstm_Fernleigh_Dip_BO
Initial surface elevation (*.dfs2)	FINAL_Fernleigh_Dip_BO_initial_WL	FINAL_Dstm_Fernleigh_Dip_BO_initial_WL
Resistance (*.dfs2)	Fern_Dip_5m_n_v15_crop	
Results (*.dfs2)	FINAL_Fernleigh_Dip_50yr_BO	FINAL_Dstm_Fernleigh_Dip_50yr_BO
Sources	Ewelme Stream + Kowhai River + Peketa local inflows + Kahutara River+ Fernleigh Dip Breakout	Ewelme Stream + Kowhai River + Peketa local inflows + Kahutara River + Breakout downstream of Fernleigh Dip
Drying/Wetting depth (m)	0.01/0.03	
Eddy viscosity	0.5	
Simulation time	1/1/2000 1:30pm to 2/1/2000 9:00am	
Time step (s)	1	
Length of run (# time steps)	70200	

Fernleigh Dip 500 year ARI design flood events

	Fernleigh Dip breakout	Breakout downstream of Fernleigh Dip
	Breakout at Fernleigh Dip (with climate change to 2120),	Breakout downstream of Fernleigh Dip (with climate change to 2120),
MikeFlood		
Couple file (*.mf)	FINAL_Fernleigh_Dip_500yr_BO_mf	FINAL_Dstrm_Fernleigh_Dip_500yr_BO_mf
Mike11		
Simulation file (*.sim11)	FINAL_Fernleigh_Dip_500yr_BO	FINAL_Dstm_Fernleigh_Dip_500yr_BO
Network file (*.nwk11)	FINAL_Fernleigh_Dip_BO_NWK	
Cross section file (*.xns11)[a]	FINAL_Fernleigh_Dip_BO_XS_mod	
Boundary file (*.bnd11)	FINAL_Fernleigh_Dip_BO_SL_2_75m	
HD parameter (*.hd11)	FINAL_Fernleigh_Dip_BO_SL_2_75m_IC_2_42	
Results file (*.res11)	FINAL_Fernleigh_Dip_500yr_BO	FINAL_Dstm_Fernleigh_Dip_500yr_BO
Mike21		
Simulation file (*.21)	FINAL_Fernleigh_Dip_500yr_BO	FINAL_Dstm_Fernleigh_Dip_500yr_BO
Bathymetry file (*.dfs2)	FINAL_Fernleigh_Dip_BO	FINAL_Dstm_Fernleigh_Dip_BO
Initial surface elevation (*.dfs2)	FINAL_Fernleigh_Dip_BO_initial_WL	FINAL_Dstm_Fernleigh_Dip_BO_initial_WL
Resistance (*.dfs2)	Fern_Dip_5m_n_v15_crop	
Results (*.dfs2)	FINAL_Fernleigh_Dip_500yr_BO	FINAL_Dstm_Fernleigh_Dip_500yr_BO
Sources	Ewelme Stream + Kowhai River + Peketa local inflows + Kahutara River+ Fernleigh Dip Breakout	Ewelme Stream + Kowhai River + Peketa local inflows + Kahutara River + Breakout downstream of Fernleigh Dip
Drying/Wetting depth (m)	0.01/0.03	
Eddy viscosity	0.5	
Simulation time	1/1/2000 1:30pm to 2/1/2000 9:00am	
Time step (s)	1	
Length of run (# time steps)	70200	

Fernleigh Dip – sensitivity test for Fernleigh Dip breakout – no climate change

50 year ARI with no climate change
50 year ARI breakout at Fernleigh Dip (with no climate change)

MikeFlood	
Couple file (*.mf)	FINAL_Fernleigh_Dip_50yr_BO_no_CC_mf

Mike11	
Simulation file (*.sim11)	FINAL_Fernleigh_Dip_50yr_BO_no_CC_mf
Network file (*.nwk11)	FINAL_Fernleigh_Dip_BO_NWK
Cross section file (*.xns11)[a]	FINAL_Fernleigh_Dip_BO_XS_mod
Boundary file (*.bnd11)	FINAL_Fernleigh_Dip_BO_SL_1_75m
HD parameter (*.hd11)	FINAL_Fernleigh_Dip_BO_SL_1_75m_IC_1_42
Results file (*.res11)	FINAL_Fernleigh_Dip_50yr_BO_no_CC_mf

Mike21	
Simulation file (*.21)	FINAL_Fernleigh_Dip_50yr_BO_no_CC_mf
Bathymetry file (*.dfs2)	FINAL_Fernleigh_Dip_BO
Initial surface elevation (*.dfs2)	FINAL_Fernleigh_Dip_BO_no_CC_initial_WL
Resistance (*.dfs2)	Fern_Dip_5m_n_v15_crop
Results (*.dfs2)	FINAL_Fernleigh_Dip_50yr_BO_no_CC_mf
Sources	Ewelme Stream + Kowhai River + Peketa local inflows + Kahutara River + Fernleigh Dip Breakout
Drying/Wetting depth (m)	0.01/0.03
Eddy viscosity	0.5
Simulation time	1/1/2000 1:30pm to 2/1/2000 9:00am
Time step (s)	1
Length of run (# time steps)	70200

Fernleigh Dip – sensitivity tests for Fernleigh Dip breakout – increase roughness

	500 year ARI – Kahutara River roughness increased	500 year ARI – floodplain roughness increased
	500 year ARI breakout at Fernleigh Dip with Kahutara Manning 'n' increased from 0.04 to 0.05.	500 year ARI breakout at Fernleigh Dip with floodplain roughness increased from 0.05 to 0.06.

MikeFlood		
Couple file (*.mf)	FINAL_Fernleigh_Dip_500yr_BO_incr_kahu_n_mf	FINAL_Fernleigh_Dip_500yr_BO_incr_fp_n_mf

Mike11		
Simulation file (*.sim11)	FINAL_Fernleigh_Dip_500yr_BO_incr_kahu_n	FINAL_Fernleigh_Dip_500yr_BO_incr_fp_n
Network file (*.nwk11)	FINAL_Fernleigh_Dip_BO_NWK	
Cross section file (*.xns11)	FINAL_Fernleigh_Dip_BO_XS_mod	
Boundary file (*.bnd11)	FINAL_Fernleigh_Dip_BO_SL_2_75m	
HD parameter (*.hd11)	FINAL_Fernleigh_Dip_BO_SL_2_75m_IC_2_42	
Results file (*.res11)	FINAL_Fernleigh_Dip_500yr_BO_incr_kahu_n	FINAL_Fernleigh_Dip_500yr_BO_incr_fp_n

Mike21		
Simulation file (*.21)	FINAL_Fernleigh_Dip_500yr_BO_incr_kahu_n	FINAL_Fernleigh_Dip_500yr_BO_incr_fp_n
Bathymetry file (*.dfs2)	FINAL_Fernleigh_Dip_BO	
Initial surface elevation (*.dfs2)	FINAL_Fernleigh_Dip_BO_initial_WL	
Resistance (*.dfs2)	Fern_Dip_5m_n_v15_incr_kahu_n_0_05_crop	Fern_Dip_5m_n_v15_incr_fp_n_0_06_crop
Results (*.dfs2)	FINAL_Fernleigh_Dip_500yr_BO_incr_kahu_n	FINAL_Fernleigh_Dip_500yr_BO_incr_fp_n
Sources	Ewelme Stream + Kowhai River + Peketa local inflows + Kahutara River + Fernleigh Dip Breakout	Ewelme Stream + Kowhai River + Peketa local inflows + Kahutara River + Breakout downstream of Fernleigh Dip
Drying/Wetting depth (m)	0.01/0.03	
Eddy viscosity	0.5	
Simulation time	1/1/2000 1:30pm to 2/1/2000 9:00am	
Time step (s)	1	
Length of run (# time steps)	70200	

Environment Canterbury Regional Council
Kaunihera Taiao ki Waitaha

Facilitating sustainable development in the Canterbury region

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