Hazard and risk assessment of the Roxburgh debris flows of 26th November 2017

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EXECUTIVE SUMMARY

Thunderstorms with lightning strikes, and short duration high-intensity rainfall occurred over and around Roxburgh, in Central Otago during the afternoon of 26th November 2017. A thunderstorm cell centred over Roxburgh delivered between 40 and 100 mm of rainfall between 4.00 pm and 5.00 pm. This high intensity, short duration rainfall caused debris flows in four stream catchments along the range front to the west of Roxburgh. In the last 20 years in New Zealand many homes and businesses have been impacted by debris flows and floods (Paekakariki, 2003; Matata, 2005; Port Ligar, 2011, Tasman District, 2018; Kaikoura District, 2018). During these 20 years no-one has been killed in their home by a debris flow. Three people have been killed by debris flows on walking tracks and roads.

Debris flows have occurred in at least one of the Roxburgh catchments previously (Reservoir Creek in 1978) and in an adjacent stream catchment (Slaughterhouse Creek, 1993). Changes were made after the 1978 debris flow to the stream path of Reservoir Creek by constructing a large box channel capable of passing most debris flows. This substantially reduced the impacts of the 2017 debris flows compared to the impacts experienced in 1978 and similar events elsewhere in New Zealand over the last 20 years.

The 2017 debris flow in Reservoir Creek probably exceeded the design capacity of the debris flow channel. However, the boulders and large woody debris were mostly confined to the debris flow channel. The constriction provided by the SH8 bridge over Reservoir Creek, allowed some water and fine-grained sediment to exit the channel. This water and sediment flowed down roads and entered properties causing silt and flood damage, including to the local school.

Similar rainfall on the 26th November 2017 in the Tima Burn area on the other side of the Clutha River did not cause debris flows. However, there is evidence of a flash flood in Tima Burn that damaged a small bridge in its path. The flatter stream gradients and lack of source material (gravel and boulders) in the stream beds means debris flows are less likely.

The specific engineering measures constructed to mitigate debris flows in Reservoir Creek are not present in the other affected creeks, particularly where they cross SH8. The culverts in two cases are less than 0.5 m in diameter and are not capable of passing a debris flow. A larger box culvert at Black Jacks Creek was also overwhelmed by the size and volume of material in the stream. Hence, the road was blocked at these sites by debris, when the blocked culverts and raised road embankment effectively acted as a dam allowing large volumes of material to accumulate at the road alignment.

Rainfall associated with ex-Tropical Cyclone Fehi in late January 2018 remobilised debris in the stream bed of Black Jacks Creek and resulted in further accumulation of debris at the SH8 road alignment. This debris was distinctly different in its grainsize composition, being limited to gravel in the 10-200 mm size range and is more accurately described as a debris flood deposit.

Based on the geomorphic and historic evidence it is near certain that debris flows will occur in these catchments again. The debris flows in these catchments have not completely stripped out the sediment from the stream bed. This provides source material for debris flow and debris flood events in the short to medium term. There is currently an elevated likelihood (lower threshold) for debris flow and debris flood events in these catchments because of the lack of vegetation as was demonstrated by the rain event in late January 2018 which remobilised sediment in Black Jacks Creek and again blocked SH8.

A range of mitigation options are available to address the risks posed by debris flows, debris floods and flash floods in the Roxburgh area. These include physical engineering works, such as the concrete debris flow channel across the debris flow fan of Reservoir Creek, re-establishing vegetation in the areas of bare ground in the stream channels and education to inform and encourage people to reduce their vulnerability to these hazards. The short steep character of the catchments where the debris flows occurred means there is no practical way to monitor these streams to provide an appropriate advance notice of a debris flow. The most appropriate warning is the nature of the rainfall which would have been exceptionally intense. It is the unusual (extreme) intensity of the rainfall that will provide the best indication of debris flow, debris flood and flash flood potential.

1.0 INTRODUCTION

1.1 Background

During the mid-late afternoon of Sunday 26th November 2017, a thunderstorm and heavy rainfall occurred near Roxburgh in Central Otago. The first lightning strike was recorded at 1527 NZDT and the last at 1814 NZDT, nearly three hours later. Rainfall records at three nearby locations show only the site at Roxburgh Motel being within the area impacted by this thunderstorm.

This high-intensity, short-duration rainfall in the hills to the west of Roxburgh resulted in several landslides and subsequent debris flows in at least four small stream catchments. The debris flows travelled down the stream channels, scouring out the channel in places and depositing debris on the fans at the base of the slope and on terraces of the Clutha River. Evidence shows some debris from all four catchments entered the Clutha River.

The deposition of sediment on debris flow fans at the base of the slope impacted State Highway 8, resulting in its closure for several days in at least three or four locations. Although no-one was injured or killed by the debris flows, buildings, including people's homes were flooded and subjected to silt damage.

1.2 Scope of Work

The Otago Reginal Council wants to better understand the ongoing near-term risks associated with landslides and debris flows in these catchments, including Reservoir Creek which runs through northern Roxburgh, and Black Jacks Creek which crosses State Highway 8 (SH8) ~3 km south of the town. In this report we:

- Place the debris flows in the context of similar events elsewhere in New Zealand.
- Document the rainfall, landslides and debris flows that occurred on 26th November 2017 and their consequences in the Roxburgh area.
- Provide maps of areas of landsliding, scour and deposition and quantifying the volumes involved and the extent of their impacts.
- Asses the likelihood of the rainfall triggering events (using NIWA's HIRDS platform) and discuss the likelihood of repeat events.
- Assess the consequences of future debris flows and fan activity for users of SH8 and for properties on the debris flow fans, considering people both indoors and outdoors.
- Provide preliminary options for appropriate mitigation measures designed to reduce the risks from future events will be provided along and discuss options to meet longer-term monitoring needs and objectives.

The need to create maps of the areas of landsliding was reduced because the sediment supply for the debris flows was derived almost entirely from the stream beds within the affected catchments of interest. The areas affected by scour and deposition from the debris flows can be seen in the aerial photography taken on the 28th December 2017, one month after the debris flows of 26th November 2017. This made the need to compile separate maps of landslides contributing sediment to the debris flows unnecessary.

2.0 PREVIOUS DEBRIS FLOWS IN NEW ZEALAND

Debris flows are common in New Zealand. A series of significant debris flows events, reported on behalf of GeoNet since July 2001, are summarised below. These debris flow events were recorded because they either resulted in deaths or were large enough in scale to cause significant damage to buildings and infrastructure. Many more debris flown are known to have occurred but as their impacts on people, buildings and other infrastructure was minimal they have not been investigated or reported on by GeoNet.

2.1 Reservoir Creek, Roxburgh, Otago Debris Flow of 13-16th October 1978

A storm event affecting the Otago and Southland areas in mid-October 1978, delivered 116 mm of rainfall in 24 hours to the Roxburgh area. Debris flows occurred through the town along Reservoir Creek. Debris escaped (avulsed) from the stream channel and blocked SH8 and piled up and around residential properties adjacent to the Creek (Woods, 2011). As a result of these debris flows a concrete channel capable of passing small to medium size debris flows was constructed through Roxburgh from the fan-head to the Clutha River.

2.2 Slaughterhouse Creek , Roxburgh, Otago, Debris Flow of 1993

A rainstorm affecting most of the South Island resulted in heavy rainfall near Roxburgh in late December 1993. A debris flow was reported in Slaughterhouse Creek on the northern outskirts of Roxburgh as a result of the rainfall (Brenstrum, 1994). When the debris flow hit the culvert under SH8 water and debris was reported shooting more than 10 m into the air. A 30-tonne boulder was left in the middle of the road (Brenstrum, 1994).

2.3 Rees River, Otago, Debris Flow of August 2002

Debris flows occurred on the northern flank of Cleft Peak in West Otago on 3rd January 2002 (McSaveney and Glassey, 2002). Relevant extracts from the abstract of the McSaveney and Glassey (2002) report are presented here:

> *"On the 3rd of January 2002, a tramper was killed by a debris flow while attempting to cross an unnamed headwater tributary of the Rees River in West Otago. High-intensity rain triggered many shallow landslides in a thin layer of loose weathered rock debris (regolith) overlying steeply dipping schist bedrock in many of the tributary headwaters in the area. These, in turn, initiated debris flows in many streams. The victim had the misfortune to be in a stream channel and about to cross one of these streams at a time when the debris flow approached at high speed."*

The full report of this event can be found at (accessed 7 December 2017):

https://static.geonet.org.nz/info/reports/landslide/SR_2002-003.pdf

2.4 Matata, Bay of Plenty, Debris Flows of May 2005

Debris flows occurred at Matata on 18th May 2005 (Figure 2.1) (McSaveney et al, 2005). Seventeen people were rescued from damaged buildings but it is worth noting, no buildings (homes) collapsed and no-one was caught in the open by a debris flow. Relevant extracts from the Executive Summary of the McSaveney et al (2005) report are presented here:

> *"On 18 May 2005, a band of intense rain passed over the catchments behind Matata. It triggered many landslips, and several large debris flows, which, with their associated flooding, destroyed 27 homes and damaged a further 87 properties in Matata. SH2 and the railway were closed for many days. The rainfall appears to be not more than a 500-year recurrence event (about 10% probability in 50 years), and it is convenient to treat the associated debris flows as having a similar recurrence interval. There is evidence that equally as large, and larger debris flows have occurred many times since 7000 years ago. Historical records indicate that probably four smaller debris-flows have occurred since 1860.*
>
> *The boulders carried by the debris flows came mostly from boulders that were buried in the stream beds and banks. They got there by falling from the bluffs above the stream at various times in the past. Most of the harder boulders are derived from strongly welded ignimbrite of the Matahina formation. The boulders eroded from the channels already are being replaced by collapse of the steep slopes, a continuing process. The supplies of boulders in the channels were depleted, but not exhausted on 18 May. Further debris flows are possible whenever there is rain with high enough intensity to trigger landslides on the steep slopes.*
>
> *Debris flows are more dangerous than floods. For two reasons they make the flooding associated with them much worse than it would be without a debris flow: (1) they travel faster than the flow of water in the same channel and pick up all of the floodwater in their path, thus delivering water to the catchment outlet faster than would be possible in a simple flood; (2) deposition of sediment from a debris flow can fill the normal stream channel and allow the draining water to flood into areas not normally accessible by floodwater.*
>
> *Effective engineering mitigation of the hazards to Matata requires integrating such protection with works associated with the railway and SH2. Of critical concern are bridges and culverts; where these are too small or misaligned, they obstruct flow, causing deposition and a somewhat random choice of path for flows that follow. For effective works, the debris path must be predictable and controlled, otherwise, restricting building is the only safe option."*

The full report of this event can be found at (accessed 7 December 2017):

https://static.geonet.org.nz/info/reports/landslide/CR_2005-071.pdf

2.5 Haast Pass, Westland, Debris Flows of September 2013

On 10th and 11th September 2013 severe weather, including heavy rain resulted in the closure of Haast Pass. Just prior to the closure a campervan with two occupants attempted to travel through Haast Pass on the evening of the 10th September. The evidence (Office of the Chief Coroner of New Zealand, 2015) suggests the campervan was struck by an "avalanche of rocks, trees and associated debris" and swept off the road and into the Haast River.

Other road-users reported heavy rainfall near the location where the campervan was swept into the river at about the time the tragedy most probably occurred. Rainfall of 61.3 mm was recorded for the 24 hours from 9.00 am on the 10th September through to 9.00 am on the 11th September 2013 at the Haast weather station on the coast. Rainfall in the mountains, in the area between the Gates of Haast and Haast Pass was probably much higher.

The evidence from weather records, site inspections and coronial enquiry show two people were killed when their vehicle was swept off the road by a debris flow or debris avalanche on the evening of 10th September 2013.

Figure 2.1 Debris flow deposit from the Awatarariki Stream behind Matata in the Bay of Plenty after heavy rainfall on the 18th May 2005. (Photo: G.T Hancox)

3.0 RAINFALL AND DEBRIS FLOW RESULTS

3.1 Rainfall

3.1.1 Rainfall measured at weather stations

Within the study area there are two weather stations close to Roxburgh, one at the Roxburgh Motel (data reported on Weather Underground) and a MetService weather station at the Roxburgh airfield. The data from these two sites is shown in Table 3.1.

Rain radar is a relatively recent innovation that provides a better spatial and temporal resolution of rainfall intensity and distribution. MetService (NZ) supplied rain radar images for the Roxburgh area on the afternoon of 26th November 2017 from the radar facility based in Invercargill. Rainfall intensity and distribution based on the radar data is shown in Figure 3.1. Based on the rain radar data it can be shown the Roxburgh Aero rainfall was on the margins of, and the Roxburgh Motel within the thunderstorm/rainfall cell nearest to Roxburgh on the afternoon of 26th November 2017.

Rainfall data derived from the statistical analysis of rainfall measurements was obtained from the National Institute of Water and Atmosphere's (NIWA) High Intensity Rainfall System V3 (HIRD). The NIWA HIRD's data (Table 3.2) shows the 3-hour rainfall at Roxburgh Aero had a return period of less than 50-years (40 mm / 2-hours).

The 2-hour rainfall recorded at the Roxburgh Motel (71 mm / 3-hours) is much closer to the 3-hour rainfall reported for the Reservoir Creek catchment from weather radar of (81 mm / 3-hours). This is consistent with the rain radar data which shows this weather station within the high-intensity rainfall cell on the afternoon of 26th November 2017.

Weather stations to the west of Roxburgh at Piano Flat and Hyde Rock (Figure 3.1) did not record significant rainfall on the afternoon of 26th November 2017.

Table 3.1 Rainfall data from weather stations in and around Roxburgh on the afternoon of 26th November 2017.

Location	Rainfall
Roxburgh Aero (MetService)	40 mm / 3 hours
Roxburgh Motel (Weather Underground)	71 mm / 2 hours

3.1.2 Rain radar data

The NZ MetService provided rainfall estimates for the afternoon of 26th November 2017 near Roxburgh based on rain radar data from the Invercargill weather radar facility. The rain radar data showed the highest intensity rainfall occurred between 4.00 and 5.00 pm (Figure 3.1). Although the time interval for this data is one hour the distribution of rainfall within that hour is unlikely to have been uniform. There are likely to have been short periods when the rainfall may have been more intense.

The cumulative rainfall, averaged over the catchment area for the three-hours from 3.00 to 6.00 pm for the four stream catchments to the west of Roxburgh that had debris flow activity are shown in Figure 3.2. The rainfall is noticeable for the increase in rainfall towards the south. This is consistent with the rainfall shown in Figure 3.1 where the individual catchments are shown in outline.

Nine hourly interval rain radar images, from 1.00 pm to 2.00 pm through to 9.00 pm to 10.00 pm, have been provided for the 26th November 2017. These images illustrate that high intensity rain fell over the catchments that experienced debris flows between 4.00 and 5.00 pm. The cumulative rainfall, averaged over the catchment area for the three-hours from 3.00 to 6.00 pm for each of these catchments is shown in Figure 3.2. The rainfall is noticeable for the increase in rainfall towards the south. This is consistent with the rainfall shown in Figure 3.1 where the individual catchments are shown in outline.

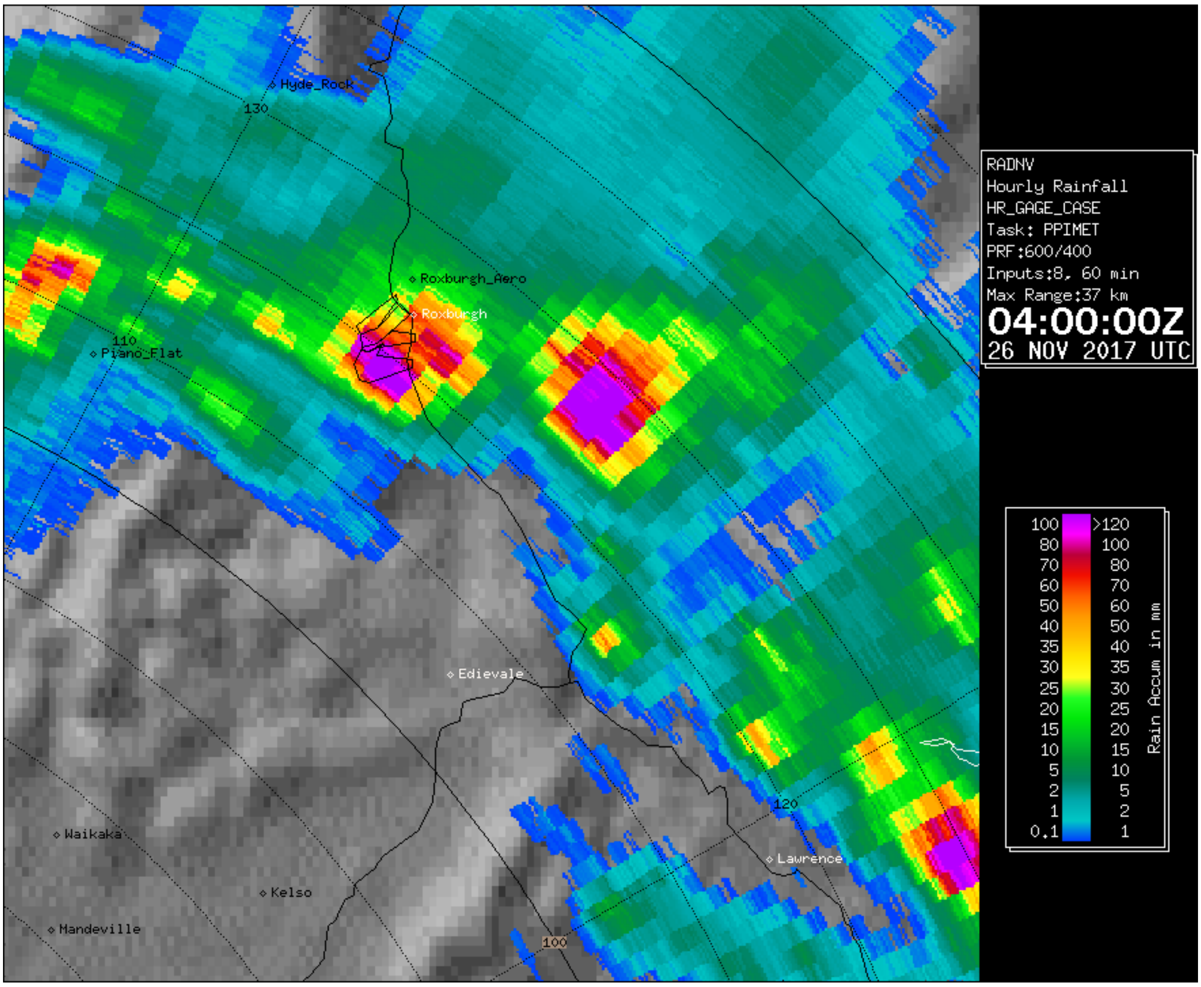

Figure 3.1 MetService weather radar one-hour estimated rainfall between 4.00 pm and 5.00 pm (NZDT) on Sunday 26th November 2017. In this image four thunderstorm cells are visible. The thunderstorm cell below Roxburgh Aero produced debris flows in the outlined catchments. The cell to the right of Roxburgh is the one near Tima Burn.

The other noticeable feature of the rainfall shown on Figure 3.1 is the presence of at least three other short-duration, high-intensity rainfall cells to the west and south of Roxburgh. None of these other rainfall cells resulted in debris flow activity.

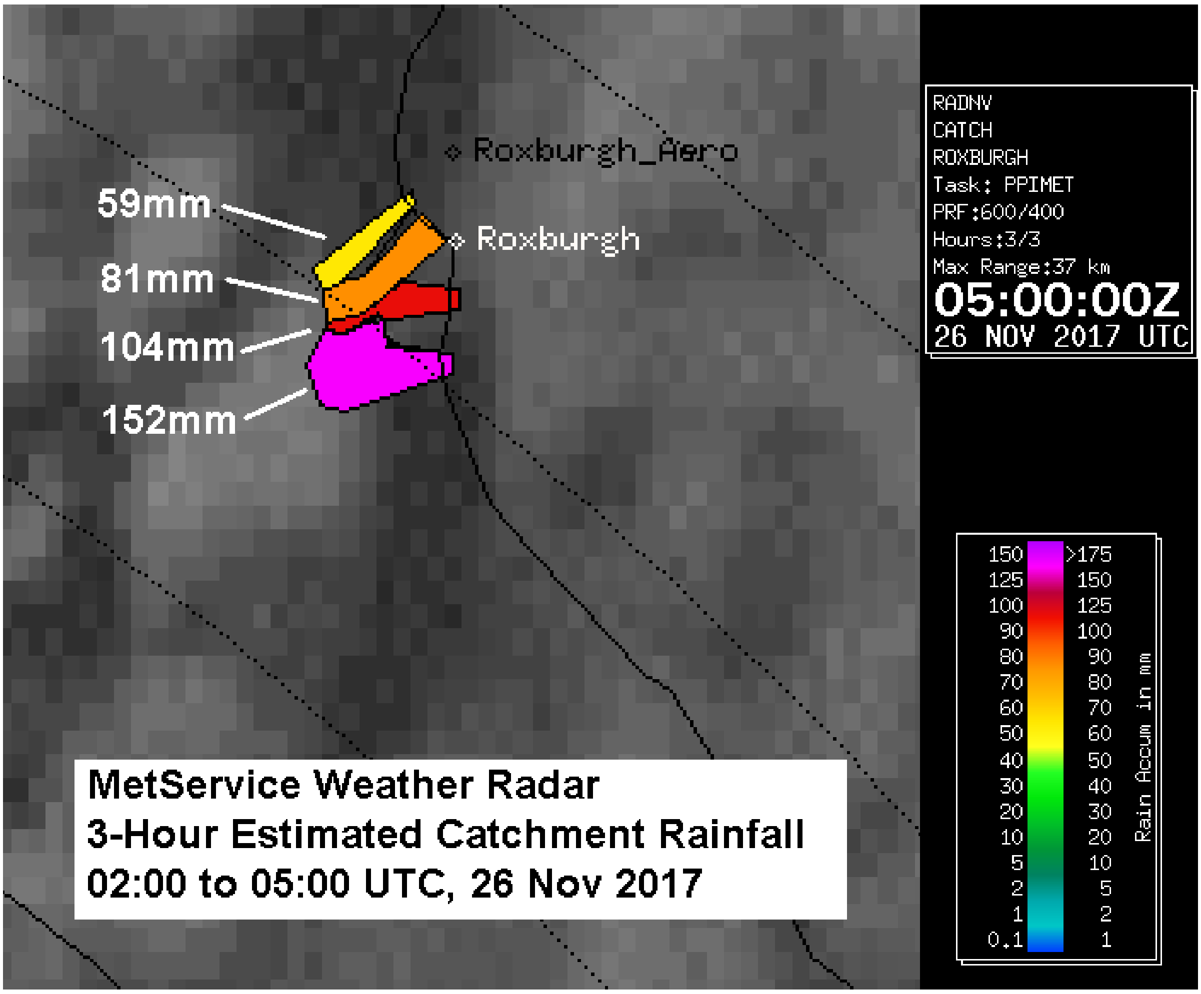

Figure 3.2 MetService weather radar three-hour (3.00 pm to 6.00 pm (NZDT)) estimated rainfall totals in the four stream catchments where debris flows occurred on Sunday 26th November 2017.

3.1.3 Annual Exceedance Probabilities (Return Periods)

Statistical rainfall patterns for Roxburgh was obtained from the National Institute of Water and Atmosphere (NIWA) High Intensity Rainfall System V3 (HIRD). The NIWA HIRD's data (Table 3.2) shows the 60-minute rainfall at the 100-year return period as 42 mm/hour. The one-hour rainfall estimated from Figure 3.2 shows the rainfall in the catchment that received the least amount of rain (Pump Station Creek) was about 40 mm/hour (Table 3.3).

HIRD data does not extend beyond the 100-year return period as very few data points are available to calculate longer return periods. An indicative calculation was performed to provide a broad estimate to plausible rainfall for a 500-year return period. A two-hour rainfall at the 500-year return period gave a nominal depth at Roxburgh of 85 mm. This implies the rainfall in Black Jacks Creek and the Golf Course Creek (Table 3.3)) had a probable return period of more than 500 years.

Table 3.2 Rainfall data derived from the statistical analysis of rainfall measurements (in mm) for Roxburgh from the NIWA's High-Intensity Rainfall Data System V3.

		Duration			
ARI (years)[1]	**Aep[2]**	**60 min**	**2 hour**	**6 hour**	**12 hour**
10	0.100	19 (±1)	24 (±1)	35 (±1)	45 (±1)
50	0.020	34 (±4)	40 (±2)	54 (±3)	66 (±4)
100	0.010	42 (±6)	50 (±3)	65 (±5)	77 (±6)

[1]ARI: Annual Return Period

[2]Aep: Annual exceedance probability

Table 3.3 Rainfall (in mm) estimated from rain radar in 60-minute and 3-hour periods in the four catchments with debris flow activity near Roxburgh on the 26th November 2017.

	Duration	
Location	**60 min (est)**	**3 hour**
Black Jacks Creek	100	152
Golf Course Creek	80	104
Reservoir Creek	60	81
Pump Station Creek	40	59

Although there are large uncertainties in the calculation the maximum hourly rainfall within the catchments with debris flows was extreme given that it greatly exceeded the 100-year return period. At longer durations the (2-hour, Table 3.2; 3-hour, Table 3.3)) the rainfall also appears to exceed a 100-year return period but this is mostly a function of the extreme 60-minute rainfall and the time needed for the rainfall to decay.

3.2 Landslides and Debris Flows

Short duration (one hour), high intensity (more than 40 mm/hour) rainfall can cause debris flows in vulnerable stream catchments. In the Roxburgh area this type of rainfall event on the 26th November 2017 caused debris flows in four catchments at the southern end of the Old Man Range west of Roxburgh. The streams had their headwaters at elevations from 950 to 1150 m above sea level and all terminated in the Clutha River at an elevation of about 80 m. All four catchments were roughly 4 km in length with a fall height ranging from 870 to 1070 m. The debris flows in each of the catchments is described separately below.

Sally Dellow from GNS Science met Ben Mackay in Roxburgh on 11th December 2017 to undertake a field survey of the debris flows and consequential damage. The observations made during the field visit are reported below.

3.2.1 Black Jacks Creek Debris Flow

The Black Jacks Creek catchment recorded the highest three-hour rainfall total (152 mm), two-thirds of which (>100 mm) probably fell in one hour or less between 4 and 5 pm. The debris flow at Black Jacks Creek overwhelmed the culvert beneath State Highway 8 (Figure 3.3 and Figure 3.4). The debris flow deposited many large boulders on the debris fan, some of which had maximum dimensions close to 2 m (Figure 3.5).

A comparison of pre-event and post-event aerial photography (Figure 3.6) has been used to assess the nature of the event (Figure 3.6). The photos show the loss of vegetation cover in the creek was limited to the stream channel for about two-thirds of its length. Many of the landslides observed were strongly coupled to the stream channel. In many instances, the lowest part of their source areas were coincident with the channel, indicating streambank erosion rather than ground saturation probably triggered their failure. No landslide source areas disconnected from the stream channel were observed in the post-event photos (Figure 3.7). This is thought to reflect the short-duration of the rainfall not allowing time for the soil structure to become saturated. At such intensities most of the rain that fell quickly flowed over the ground surface into the stream channel and the rapid accumulation of water in the channel led to scour of the stream bed, stripping the vegetation (Figure 3.8). This stripping of vegetation exposed sediment in the stream bed which then became entrained by the high water-flows in the debris flows.

The debris flows travelled down the stream bed unimpeded until they encountered the raised embankment of SH8, constructed to allow the stream to pass through a culvert beneath SH8. The volume and size of debris overwhelmed the culvert, with some of the larger boulders too big to pass through the culvert. The debris accumulated behind the road embankment until a low point could be found over the roadway. The volume of debris was such that the road was buried to a depth of 1-2 m over 50-70 m, and consequently became impassable. The total volume of debris shifted by the debris flow is difficult to determine as a large amount ended up in the Clutha River.

The volume of material in the Black Jacks Creek debris flow is estimated by assuming upper and lower bounds on the material removed from the stream bed (Table 3.4). A minimum volume is assessed by assuming a scoured catchment length of approximately 3,000 m, a channel width of 5 m and a scour depth of 1 m. This yields a minimum volume of 15,000 m^3. A maximum volume is assessed assuming a scoured catchment length of approximately 3,500 m, a channel width of 15 m and a scour depth of 5 m. This yields a minimum volume of 262,500 m^3. The most probable value in this range is about 100,000 m^3.

The exposed stream bed, stripped of vegetation by the 26th November rainfall event and debris flows, allowed rainfall associated with ex-Tropical Cyclone Fehi in late January 2018 to further scour the stream bed, transporting gravel down to the debris fan. It was noticeable that the size of the material moved by the rainfall in January 2018 was much smaller (gravel clasts up to 200 mm) than the boulders (up to 2 m) moved during the November 2017 debris flows. The lack of vegetation in the stream bed increased the impact of the January 2018 rainfall event. If the January rainfall had occurred prior to November it probably would have gone unnoticed.

Figure 3.3 Black Jacks Creek looking upstream from the culvert over SH8. The height of the un-vegetated channel banks provides some indication of the amount of aggradation caused by the debris flows close to the fan-head (Photo: S.Dellow 13/12/2017).

Table 3.4 The estimated debris flow volumes in the catchments on the southern end of the Old Man Range, west of Roxburgh on 26th November 2017.

Catchment	Minimum Volume (m^3)	Maximum Volume (m^3)	Probable volume (m^3)
Black Jacks Creek	15,000	262,500	120,000
Golf Course Creek	1000	2000	1500
Reservoir Creek	30,000	350,000	160,000
Pump Station Creek	1000	2000	1500

Figure 3.4 The culvert beneath SH8 at Black Jacks Creek. Note the height of the culvert in relation to the size of the largest boulders in the figure below (Photo: S.Dellow 13/12/2017).

Figure 3.5 Large boulders entrained in the Black Jacks Creek debris flows. The largest sizes are nearly two metres in diameter and the total number of boulders is probably in the hundreds as many ended up in the Clutha River (Photo: S.Dellow 13/12/2017).

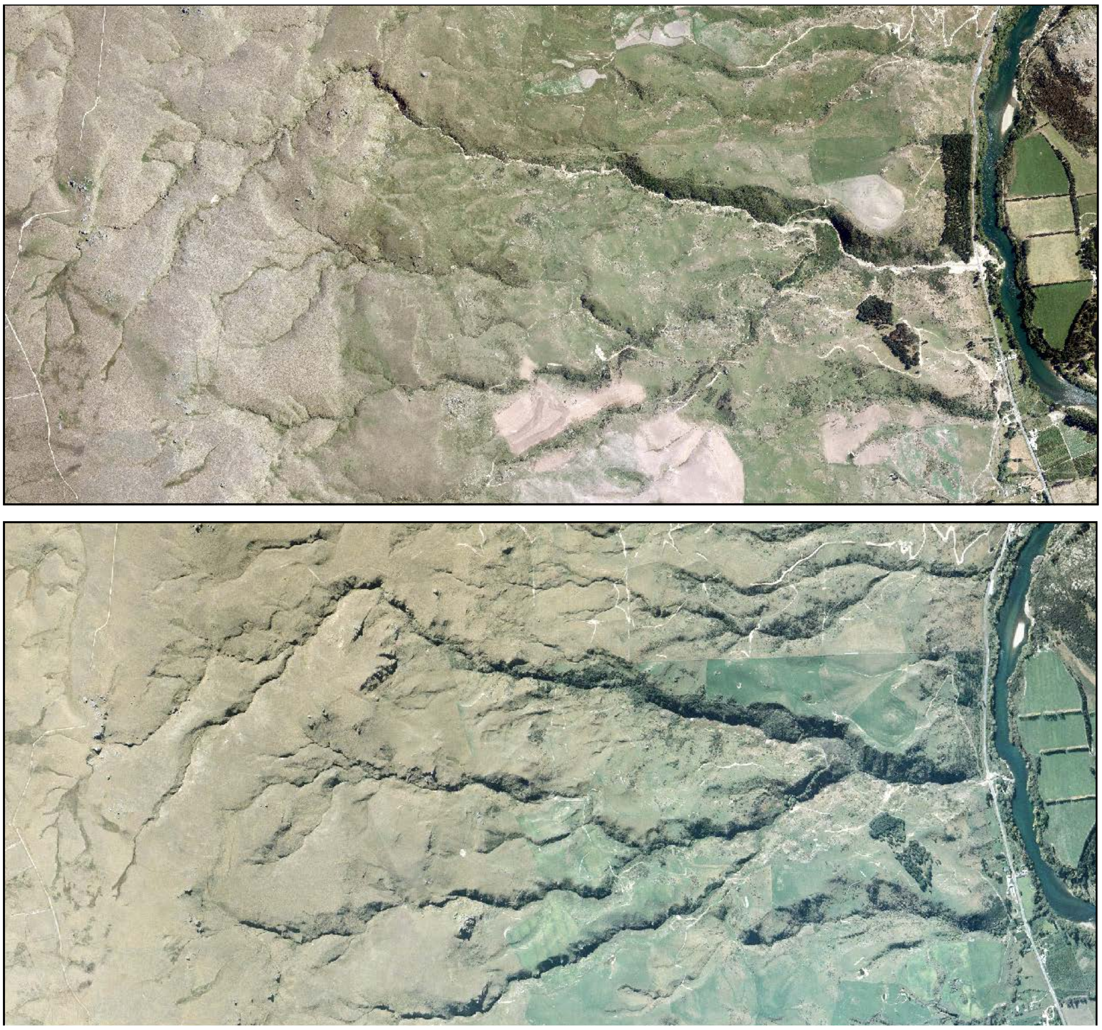

Figure 3.6 Before (bottom; 30th March 2006) and after (top; 28th December 2017) photos vertical aerial photographs of Black Jacks Creek catchment. The features of note in the post-event image are the lack of landslides on slopes away from the main channel and the absence of scour in the southern branches of Black Jacks Creek. This indicates the rainfall was of higher intensity over the northern branch of the catchment.

Figure 3.7 The upper reaches of Black Jacks Creek showing the lack of landslides in the country around the creek, and by contrast the scoured out creek bed with the vegetation gone and shallow landslides adjacent to the creek bed (Photo: Ben Mackey, ORC; 27/11/2017).

Figure 3.8 Before (bottom; 30th March 2006) and after (top; 28th December 2017) photos of the lower part of Black Jacks Creek including the debris flow fan across the Clutha River terrace.

3.2.2 Golf Course Debris Flow

The Golf Course debris flow occurred in the smallest catchment where a limited volume of water was able to accumulate quickly. This is reflected in the size of boulders transported during the event with very few exceeding 0.5 m, and most less than 0.3 m in diameter. Again, the bare ground is mostly confined to the stream bed and lower sections of the adjacent slopes suggesting that stream bed a bank erosion was the main cause of landsliding within the catchment (Figure 3.9).

The debris travelled down the stream bed largely unimpeded until they encountered the culverts beneath SH8. The debris flows exceeded the capacity of these small culverts and quickly blocked, forced the debris to accumulate behind the slightly raised road embankment. As a consequence, the debris flowed across the road using several pathways and deposited sediment on a rugby field, golf course and along the margins of the original stream course (Figure 3.10).

The volume of material in the Golf Course Creek debris flow is estimated by assuming upper and lower bounds on the material on the debris fan (Table 3.4). A minimum volume is assessed by assuming a debris fan length of 500 m, a debris width on the debris fan of 20 m and a debris depth of 1 m. This yields a volume of 1,000 m^3. A maximum volume is assuming at least half the debris entered the Clutha River. This yields a minimum volume of 2000 m^3. A median value in this range is about 1,500 m^3.

Figure 3.9 The creek bed between SH8 (left of the picture) and the Clutha River showing the results of scour and deposition on the Golf Course Creek fan (Photo: Aerial Surveys, 28th December 2017).

Figure 3.10 Boulder field from the debris flows in Golf Course Creek on the uphill side of SH8 (Photo: S.Dellow 13/12/2017).

3.2.3 Reservoir Creek Debris Flow

The Reservoir Creek debris flows were broadly similar in the size and volume of material to the Black Jacks Creek debris flows (Figure 3.11). The Reservoir Creek catchment had the second lowest assessed three-hour rainfall of 81 mm, two-thirds of which (>50 mm) probably fell in one hour or less between 4 and 5 pm. The size and power of the debris flows were substantial based on the evidence of the stripping in the floor of the valley and the size of the boulders on the debris fan, some of which had maximum dimensions close to 2 m.

Aerial photography was flown on 28th December 2017 to help understand the nature of the event (Figure 3.12). In Reservoir Creek the loss of vegetation cover (when compared to a pre-event photograph) was limited to the stream channel for about two-thirds of its length. A number of landslides were observed strongly coupled to the stream channel because the lowest part of their source areas were in the channel indicating streambank erosion as the likely trigger for failure (rather than ground saturation). Landslide source areas distant from the stream channel were not present. This is thought to reflect the short-duration of the rainfall not allowing time for the soil structure to become saturated. Any rain that fell quickly flowed into the stream channel and the rapid accumulation of water in the channel led to scour of the stream bed, stripping the vegetation. This stripping of vegetation exposed sediment in the stream bed which then became entrained by the high-water flows as debris flows.

The volume of material in the Reservoir Creek debris flow is estimated by assuming upper and lower bounds on the material removed from the stream bed (Table 3.4). A minimum volume is assessed by assuming a scoured catchment length of approximately 3,000 m, a channel width of 10 m and a scour depth of 1 m. This yields a minimum volume of 30,000 m^3. A maximum volume is assessed assuming a scoured catchment length of approximately 3500 m, a channel width of 20 m and a scour depth of 5 m. This yields a minimum volume of 350,000 m^3. A median value in this range is about 160,000 m^3.

The concrete debris flow channel constructed after the 1978 debris flows performed well (Figure 3.13), but the debris flow events of 26th November 2017 may have been larger than the design event for the channel. However, the channel kept all the large debris (vegetation, boulders and gravel) within it course. This function of the debris flow channel probably reduced the clean-up costs and time by an order of magnitude based on anecdotal evidence from other events where a debris flow channel was not present (e.g. Matata, 2005; Port Ligar, 2011; Marehau-Motueka, 2018).

Figure 3.11 The Reservoir Creek debris fan the day after the debris flow event. There are two excavators in the photo, one at the SH8 bridge over Reservoir Creek and one on the lower fan clearing the concrete channel (Photo: Ben Mackey, ORC; 27/11/2017).

Figure 3.12 Before (bottom; 30th March 2006) and after (top; 28th December 2017) photos of the Reservoir Creek debris flows of 26th November 2017. The debris is largely confined to the stream channel which stands in contrast to the 2005 Matata debris flows shown in Figure 2.1.

Figure 3.13 The cleared concrete debris flow channel two weeks after the debris flows of 26th November 2017 (Photo: S.Dellow 13/12/2017).

3.2.4 Pump Station Creek Debris Flow

The debris flows at Pump Station Creek were similar to those described in Golf Course Creek with similar boulder sizes (in the order of 0.5 m diameter). This again reflects the smaller catchment size of Pump Station Creek compared to Black Jacks Creek and Reservoir Creek. Pump Station Creek also had the lowest intensity of the four catchments with the one-hour rainfall of 40 mm (within one standard deviation of the 100-year return period rainfall). It is probable the rainfall in Pump Station Creek is close to (just above) the threshold rainfall for debris flows of this type (caused solely by short duration, high intensity rainfall).

The debris flows at Pump Station Creek are notable because avulsion occurred at two sites. The first was close to where a small farm bridge crossed the creek and evidence suggests the flow was constricted at this location at some point, probably later in the cycle of the debris flow event (Figure 3.14). The second site was at the culvert beneath SH8 where the culvert quickly blocked, forcing the debris flow to find a way over the road and as a consequence spreading out across the fan and depositing debris around at least one house (Figure 3.15 and Figure 3.16).

The volume of material in the Pump Station Creek debris flow is estimated by assuming upper and lower bounds on the material on the debris fan (Table 3.4). A minimum volume is assessed by assuming a debris fan length of 500 m, a debris width on the debris fan of 20 m and a debris depth of 1 m. This yields a volume of 1,000 m^3. A maximum volume is assuming at least half the debris entered the Clutha River. This yields a minimum volume of 2000 m^3. A median value in this range is about 1,500 m^3.

The other notable feature of the 26th November 2017 rainfall event in Pump Station Creek was the incipient movement of a large landslide a few hundred metres above the fan-head (Figure 3.17). The local land owner had noticed small scarps in the area prior to the 26th November but observed that they got larger after the rainfall of 26th November. This incipient landslide has the potential to block the stream channel and form a small landslide dam should it fail suddenly. It is recommended that it be observed and photographed at least once a month and more frequently if rainfall of more than 20 mm / 24 hours occurs.

Figure 3.14 Pump Station Creek debris flow deposit at the farm bridge on the upper part of the debris flow fan (Photo: S.Dellow 13/12/2017).

Figure 3.15 The upper site where stream avulsion occurred in Pump Station Creek. View downstream from near the farm implement shed in mid-upper part of Figure 3.16 (Photo: S.Dellow 13/12/2017).

Figure 3.16 The Pump Station Creek debris flow fan showing the two avulsion sites, one near the fan-head and the other at SH8 (Photo: Ben Mackey, ORC; 27/11/2017).

Figure 3.17 An old landslide headscarp (aa) with recent incipient movement within the old landslide debris lobes in Pump Station Creek. A more recent headscarp (rs) has developed with recently active secondary scarps (ss) within the reactivated debris (Photo: S.Dellow 13/12/2017).

3.2.5 Tima Burn Flash Flood

The MetService weather radar showed that a rainfall cell similar to the one over Roxburgh was present in the Tima Burn area (Figure 3.1). Field inspection found evidence for a flood event in Tima Burn on the 26th November 2017. The evidence included damage to the post and railings on the deck on a small bridge 2 to 3 m above the stream channel (Figure 3.18 and Figure 3.19). Farther down the valley evidence for a thin layer of silt deposition was observed.

The physiographic characteristics of Tima Burn are quite different to the creeks on the range front of the southern end of the Old Man Range west of Roxburgh. The two key differences are the average gradient in Tima Burn (17H:1V) which is much less steep than in the creeks to the west of Roxburgh (4H:1V). The second difference is the lack of alluvial material in the bed of Tima Burn which is incised into the schist peneplain surface. These characteristics preclude the development of debris flows (sediment with some water), and probably debris floods (water with some sediment) but do allow flash floods (water with minimal sediment) to occur.

Figure 3.18 A small bridge across Tima Burn about halfway up the catchment. The stream bed is 2 to 3 m below the bridge deck. The damage to bridge railings provide evidence of flows down the creek large enough and fast enough to rip railings and posts off the top of the bridge structure (Photo: S.Dellow 13/12/2017).

Figure 3.19 The small bridge over Tima Burn showing evidence for a large volume of water passing over the bridge, destroying posts and railings and stripping soil and pasture off the banks of the stream, exposing bare rock, rather than alluvium (Photo: S.Dellow 13/12/2017).

4.0 DEBRIS FLOW IMPACTS

4.1 Houses

Although no houses were structurally damaged by the debris flows several suffered minor water and silt damage. At Black Jacks Creek and Golf Course Creek no buildings were directly in the debris flows path. At Pump Station Creek the cladding on a farm shed suffered minor damage and at least two houses had debris surround them but otherwise property damage was minimal.

At Reservoir Creek through Roxburgh, the mobilised sediment (vegetation debris and boulders and gravel) largely remained confined to the concrete debris flow channel (Figure 4.1). Water and fine-grained sediment (sand and silt), however did exit the channel near the SH8 bridge. This flowed down the highway and local roads and through several properties, including the local school. Some of these buildings suffered water damage and showed evidence of silt deposition several centimetres thick in places (Figure 4.2) but these had mostly been cleaned up two weeks later, at the time of the field visit. It is inferred that the bridge created a limited constriction and caused water to overtop the channel edges and flow out of the channel, particularly on the southern side of the creek.

Compared to the photos of damage to buildings after the 1978 debris flows in Reservoir Creek, including debris over one metre thick surrounding some houses, the damage to buildings in November 2017 was minor and quickly cleaned up and the homes and classrooms returned to a serviceable state.

Figure 4.1 Undamaged fence on top of the concrete channel on the Reservoir Creek fan (Photo: S.Dellow 13/12/2017).

Figure 4.2 Evidence of silt and water damage on a building exterior. Depth of inundation appears to be about 100 mm (Photo: S.Dellow 13/12/2017).

4.2 Roads

The most significant impact of the debris flows on the road network was to make SH8 impassable at Black Jacks Creek, Golf Course Creek and Pump Station Creek. In all three cases the culverts beneath SH8 were too small to pass the size and volume of debris that came down the stream channels and resulted in debris accumulating on the road.

At Black Jacks Creek the size and volume of debris (boulders up to two metres across) resulted in rapid aggradation of the fan 2-3 m deep over a width of 50-70 m at the road. This was the largest blockage of the road (Figure 4.3).

At Golf Course Creek and Pump Station Creek, the catchments were smaller, the debris flow volumes were smaller, the boulders were smaller (generally less than 0.3 m) and the thickness and width of the debris at the road consequently much smaller (0.5 m thick and 20-30 m wide) (Figure 4.4).

At Reservoir Creek all the large debris passed down the concrete debris flow channel and only a few centimetres of silt was deposited on the roadway which was quickly cleared and the road made serviceable.

Figure 4.3 Debris blocking SH8 at Black Jacks Creek (Photo: Ben Mackey, ORC; 27/11/2017).

Figure 4.4 Debris blocking SH8 at Golf Course Creek has been cleared sufficiently to allow single lane traffic flow the day after the debris flows (Photo: Ben Mackey, ORC; 27/11/2017).

5.0 DISCUSSION

5.1 Causes

The debris flows in four stream catchments to the west of Roxburgh on the range front of the southern end of the Old Man Range were caused by short duration (one hour or less), high-intensity (40-150 mm) rainfall. The stream catchments were conducive to the formation of debris flows because they were short (4 km in length) and steep (~1000 m of elevation change).

The rainfall did not cause widespread landslides to form on the open hill slopes. Instead, the relatively few landslides that did develop were generally small and strongly coupled to the stream channels. In most cases the toe of the landslide was observed to be either adjacent or within the stream channels. Debris flow materials were sourced almost entirely from the stream channel bed. This suggests that entrainment (the picking up of debris) and consequently bulking of the debris flows occurred as they moved rapidly down the channel.

In three streams (Black Jacks, Golf Course and Pump Station Creeks) the debris flows left the stream channel (they avulsed) when they reached culverts beneath SH8 which restricted their flow and were rapidly blocked by large boulders. In addition to the road was elevated above the debris flow fans which allowed debris to build up until a low point across SH8 could be found. These low points did not coincide with the position of the culverts and as a consequence debris from the debris flows was distributed over a large area.

A concrete channel at reservoir Creek allowed most of the large debris to remain within the channel. However, it appears that the bridge on SH8 over Reservoir Creek acted as a minor constriction and water and fine-grained sediment (sand and silt) left the channel and flooded some properties between SH8 and the Clutha River. If the debris flow channel had not been present the scene after the debris flows would have been more like Figure 2.1.

On the other side of the Clutha River in the Tima Burn, while similar rainfall occurred, the catchments and stream beds were distinctly different. Tima Burn is over 10 km long and has a maximum fall height of about 600 m, making for a much gentler gradient overall. Tima Burn is also often incised into the schist peneplain surface and there is very little sediment present in the stream bed. Debris flows did not occur but there is some evidence that a flash flood occurred. While the recovery from a flash flood was much quicker than from the debris flows, the flash flood would have created a similar risk to anyone in the stream bed at the time.

In Black Jacks Creek, the stream bed exposed by the stripping of vegetation in the November 2017 debris flows, allowed rainfall associated with ex-Tropical Cyclone Fehi in late January 2018 to further scour the stream bed and transport material onto the debris fan. The lack of vegetation in the stream bed after the November 2017 debris flows increased the impacts of the January 2018 rainfall event. If the January rainfall had occurred prior to November it probably would have gone unnoticed.

5.2 Existing Physical Protection Works

The debris flow channel installed along Reservoir Creek, through Roxburgh prevented large debris (boulders and vegetation) from escaping the channel. However, the size of the event probably exceeded its design capacity, and as a consequence, some water and fine-grained sediments (sands and silts) did escape the channel and flood nearby properties, including the school.

5.3 Monitoring

Given that the debris flows occurred in short, steep catchments it is not practical to develop monitoring systems that provide adequate warning of potential debris flow events. The best warning is the nature of the rainfall. Forecasting short duration, high intensity rainfall provides the best indication that debris flows are possible and is likely to provide the most suitable approach to identifying potential debris flows events. For example, the November 2017 debris flows have shown us that for the catchments west of Roxburgh anything above about 40 mm of rain falling within an hour is likely to trigger debris flows given similar stream bed and antecedent rainfall conditions.

5.4 Likelihood of Future Events

The steep catchments on the southern end of the Old Man Range, west of Roxburgh, have repeatedly generated debris flows. The evidence includes the debris flow fans formed by pre-historic debris flows and, more recently, historical events where there are written records of the impacts. Based on the geomorphic and historic evidence it is near certain that debris flows will occur in these catchments again.

The debris flows in these catchments have not completely stripped out the sediment from the stream bed. This provides source material for debris flow and debris flood events in the short to medium term.

The rainfall threshold for triggering debris flows will vary based on the state of the stream beds. However, if they were return to a similar state as they were prior to the 26th November 2017 debris flows then the triggering threshold for debris flows in these catchments would be about 40 mm of rain an hour, which equates to a return period of 100 years. The threshold for debris flow initiation may also vary based on catchment size, with the larger catchments having a lower threshold. This is based on the historic events in Reservoir Creek and Slaughterhouse Creek occurring without triggering debris flows in the smaller catchments. The rainfall on 26th November 2017 well exceeded the probable threshold for debris flows of 40 mm in an hour in three of the four affected catchments (Table 3.3).

The rainfall threshold will be lower when there is little or no vegetation cover in the stream beds. The threshold will be higher if the stream beds are covered in woody vegetation. However, there will almost certainly be rainfall events that will exceed the highest threshold and the protection provided by woody vegetation will then potentially increase the detrimental impacts of debris flows because large woody debris will be incorporated in the debris flows. There is currently an elevated likelihood (lower threshold) for debris flow and debris flood events in these catchments because of the lack of vegetation as was demonstrated by the rain event in late January 2018 which remobilised sediment in Black Jacks Creek and again blocked SH8.

Climate change driven variation in rainfall patterns may also have an impact on the future likelihood of debris flows in these catchments. If the frequency of extreme rainfall events increases than the likelihood of debris flows increases.

There is a relationship between rainfall, vegetation cover and maximum grainsize of the material in debris flows that will have an impact on the severity and extent of the debris flow and debris flood impacts. This relationship would need to be developed in catchment specific debris flow hazard assessments.

5.5 Future Mitigation and Risk Management

A risk-based approach to the selection and implementation of specific mitigation measures is recommended. The mitigation measures used will depend on the risks being considered.

There are two potential risks for users of SH8. These are the loss of service because the road has been blocked for a few days and the potential for loss of life if a highway user is hit by a debris flow. The life safety risk to users of the road can be calculated if traffic volumes and the length of time users are potentially exposed to debris flows (vulnerability) is multiplied by the frequency of debris flows impacting the road. This data can also be used to calculate the length of time the road is likely to be out of service because of debris flows. There are three options. The first is to build a structure large enough to pass debris flows beneath it so the road is not affected. This is the most expensive of the options but will potentially eliminate both the loss of service risk and the life safety risk. The second option is to install a warning system which will reduce the life safety risk but not do anything to reduce the loss of service risk. This option will be less expensive, but could have high maintenance costs over time if the need to provide redundancy to ensure reliability of operation is required. The third option is to accept the risks.

Properties in the Roxburgh area have been affected by debris flows in the past and during this event. There are several ways to reduce the risk to property from the debris flows. The first is to avoid future development in areas prone to debris flows. For existing properties, the provision of engineered channels designed to pass debris flows through developed areas such as the one that takes Reservoir Creek through Roxburgh can reduce the risk of property damage. Another option for reducing risk is to remove buildings, as happened in the Port Hills of Christchurch after the 2011 earthquake, for example. The risk can also be transferred through to insurers, although it needs to be noted that insurers are beginning to look closely at the hazards individual properties are exposed to and are pricing insurance accordingly.

And finally, in relation to individuals it can be noted that in the last twenty years in New Zealand many homes and businesses have been impacted by debris flows and floods (Paekakariki, 2003; Matata, 2005; Tasman District, 2018; Kaikoura District, 2018). During these twenty years no-one has been killed in their home. However, three people have been killed by debris flows on walking tracks and roads. Individuals and families can reduce their risk of being killed by a debris flow by seeking shelter during heavy rain.

5.5.1 Physical Protection Works

The provision of physical engineering works specifically designed to accommodate small to medium sized debris flows significantly reduces the impacts of debris flows. Appropriate design of culverts (to consider debris flows potentials) is essential. The size and volume of debris appears to be more a function of catchment size rather than the rainfall intensity so this needs to be a major consideration in culvert design.

There will always be the possibility that an event will exceed the design capacity of any engineered works. However, any engineering works, even if their design capacity is exceeded will reduce the impacts of debris flows on vulnerable communities.

5.5.2 Education

Many places in New Zealand are vulnerable to debris flows and flash floods. When people and vehicles are caught in debris flows, fatalities can occur. In the last twenty years, close to one hundred homes (or more) have been impacted by debris flows and debris floods. Although the time frame is short, there have been no fatalities when people are in buildings (note: that refers to debris flows only - people have been killed by other types of landslides in their homes (e.g. slumps, rockfalls and soil slides).

Educating people to stay away from streams and rivers during extreme rainfall (short duration, high intensity) and if possible to seek shelter indoors or well away from waterways is behaviour that will reduce their risk of being killed or injured by a debris flow or debris flood.

Often debris flows, debris floods and flash floods occur during extreme rainfall events that have been forecast prior to the event, allowing time to prepare and seek safety before they occur.

5.5.3 Vegetation

The planting of woody vegetation can provide some protection from debris flows and landslides. The presence of woody vegetation (as opposed to pasture and other grasses or even worse, bare ground (c.f. Black Jacks Creek in late January 2018)) raises the rainfall threshold for the initiation of debris flows. This provides some protection from lower intensity rainfall. However, if the raised threshold is exceeded (and the evidence from Black Jacks and Reservoir Creeks in November 2017 is that it was) then the woody debris may become entrained in the debris flow. This can make managing debris flows even more challenging as the size and shape of woody debris (trees) means logjams can form and result in larger pulses of debris when the logjam breaks, or act as a barrier, creating the opportunity for the debris flows to leave the existing stream channel and avulse into areas considered safe.

6.0 SUMMARY AND CONCLUSIONS

Thunderstorms with lightning strikes, and short duration high-intensity rainfall occurred over and around Roxburgh, in Central Otago during the afternoon of 26th November 2017. The storm cell centred over Roxburgh delivered between 40-100 mm of rainfall between 4.00 pm and 5.00 pm. This high intensity, but short duration rainfall caused debris flows in four stream catchments along the southern end of the Old Man Range front to the west of Roxburgh. Debris flows have occurred in these catchments previously (e.g. Reservoir Creek in 1978) as well as in another adjacent stream catchment (e.g. Slaughterhouse Creek, 1991).

After the 1978 Reservoir Creek debris flow a large box channel capable of passing most similar sized debris flows was constructed. Although the 2017 debris flow probably exceeded its design capacity, the large boulders and woody debris were confined to the channel. The constriction provided by the SH8 bridge over Reservoir Creek, allowed some water and fine-grained sediment to exit the channel. This water and sediment flowed down roads and entered properties in the flow path, including the local school.

The debris flow mitigation measures engineered for Reservoir Creek have not been constructed in any of the other affected creeks, particularly where they cross SH8. The culverts in two cases are less than 0.5 m in diameter and are not capable of containing a debris flow. The culvert at Black Jacks Creek is a larger box culvert, but this was still overwhelmed by the size and volume of material that came down the stream. Hence, the road being blocked at these sites by debris, when the blocked culverts and raised road embankment effectively acted as a dam allowing large volumes of material to accumulate at the road alignment.

Rainfall associated with ex-Tropical Cyclone Fehi in late January 2018 remobilised debris in the stream bed of Black Jacks Creek and again resulted in the accumulation of debris at the SH8 road alignment. This debris was quite different in its grainsize composition, being limited to gravel in the 10-200 mm size range. These deposits are more common in debris flood deposits. The removal of vegetation from the floor of Black Jacks Creek in November 2017 left gravel exposed that was then mobilised by the lower (and very localised) rainfall that accompanied ex-Tropical Cyclone Fehi in this area.

Similar rain fell in the Tima Burn area on the other side of the Clutha River during the November 2017 event and caused a flash flood that was observed to have damaged a small bridge in the catchment. This flood did not result in debris flows. The flatter stream gradients and lack of source material (gravel and boulders) in the stream beds suggests debris flows are less likely to occur.

Based on the geomorphic and historic evidence it is near certain that debris flows will occur in these catchments again. The debris flows in these catchments have not completely stripped out the sediment from the stream bed. This provides source material for debris flow and debris flood events in the short to medium term. There is currently an elevated likelihood (lower threshold) for debris flow and debris flood events in these catchments because of the lack of vegetation as was demonstrated by the rain event in late January 2018 which remobilised sediment in Black Jacks Creek and again blocked SH8.

A range of mitigation options are available to address the risks posed by debris flows, debris floods and flash floods in the Roxburgh area. These include physical engineering works, such as the concrete debris flow channel across the debris flow fan of Reservoir Creek, re-establishing vegetation in the areas of bare ground in the stream channels and education to inform and encourage people to reduce their vulnerability to these hazards.

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