REPORT

Management and Reduction of Debris Flow Risk in Roxburgh, Otago

Geomorphological Assessment Report

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1.0 INTRODUCTION

As authorized by Otago Regional Council (ORC), Golder Associates (NZ) Limited (Golder) carried out an assessment of the ongoing debris flow hazard to identify specific mitigation measures to reduce the debris flow risk in Roxburgh, Central Otago.

Following a regional intense rainfall event on 26 November 2017, debris flow / debris flood events were triggered in five catchments near the Roxburgh township. The streams carried significant volumes of debris which resulted in aggradation of sediment, blockage of culverts and avulsion of stream beds. Subsequently water and debris inundated and blocked SH8 and other roads in Roxburgh and damaged buildings and property.

This report represents a summary of Golder's findings from our review of existing information, observations during the field investigation and provides information that will guide concept design for any mitigation work.

The scope of this assessment is limited to the assessment of debris flow/flood hazards based on our review of available relevant information and visual examination of site conditions. The assessment did not include any subsurface geotechnical investigations or detailed design of remedial measures, nor did it include any environmental investigation and analytical testing to assess possible soil or groundwater contamination, or biological or archaeological services. Golder has the ability to carry out such services, if required.

2.0 DEFINITIONS

Technical words used in this report are defined as follows:

- Catchment area: Topographically defined area of the catchment [km^2].
- Catchment length: The planimetric straight line length from the fan apex to the most distant point on the catchment boundary [km].
- Catchment relief: The elevation difference between the highest and lowest points in a catchment [km].
- Melton Ratio: Catchment relief [km] divided by the square root of catchment area [km^2].
- Relief Ratio: Catchment relief [km] divided by catchment length [km].

Definitions of relevant hydromorphometric processes are used as described in Table 1 ((Arksey, R. & VanDine, D., 2008), (Wilford et al., 2004), (Hungr, Leroueil, & Picarelli, 2017)):

Table 1: Hydromorphometric Processes – Selected attributes.

Hydromorphometric Process	Typical Sediment concentration by weight [%]	Flow velocity [m/s]	Description
Debris Flows	70 - 90	2 - 20	Complex, heterogeneous sediment-water mixtures with bouldery front. Peak discharges can be 5 to 40 times greater than water floods. Debris flows develop high impact forces and present a significant hazard to structures. Debris flows characteristically result in the formation of marginal levees and terminal lobes.
Hyperconcentrated Flows[1]	40 - 80	1 - 10	Represent transitional process between debris flow and debris flood. Afterflow soon after deposition of boulder flow front. Involves mostly fine sediments. In contrast to debris flows, selective deposition according to grain size as flow velocity decreases. High erosive capability in steep terrain and subsequent high potential for rapid river bed aggradation.
Debris Floods	20 - 40	Up to 5	Occur when most of the streambed sediment is mobilised by high water flow but mixing of the water and sediment is not complete. Discharges can be 2 to 3 times greater than peak water floods. Sediment deposited as bars, fans, sheets and splays. Stream channels have a large width-to-depth ratio. Compared to debris flows, debris floods do not develop high impact forces and potential damage to structures is limited.
Floods	< 20	1-3	Water floods in gravel, cobble or boulder channels rarely mobilise the entire streambed. Sediment deposited as bars, fans, sheets and splays; clasts can be imbricated. Stream channels have a large width-to-depth ratio. The channel can generally contain the sediment load.

[1] For the purpose of this report, we refer to this process as debris flood.

3.0 WORK CARRIED OUT

3.1 Review of Existing Information

In preparation for the field investigation, a desktop study was undertaken to review existing topographic, geologic and hydrologic data of the catchments involved in this study (see Figure 1). ORC defined the following catchments to be part of this assessment:

- Pumpstation Creek
- Reservoir Creek
- Golfcourse Creek
- Black Jacks Creek
- Stevenson Creek

The following report and assessment information were reviewed for this assessment:

- Hazard and risk assessment of the Roxburgh debris flows of 26 November 2017, GNS Science Consultancy Report 2018/65, May 2018.
- Otago Alluvial Fans Project: Supplementary maps and information on fans in selected areas of Otago, GNS Science Consultancy Report 2009/052, April 2009.
- Otago Alluvial Fans: High Hazard Fan Investigation, Otago Regional Council, June 2011.
- Roxburgh – Preliminary Assessment of Flood and Erosion Hazards in Clutha River, DAMWATCH, 22 December 2017.
- Roxburgh video footage analysis, S. Dellow (GNS Science), Email correspondence with Ben Mackey (ORC), 18 December 2018.

ORC provided the following digital and spatial information:

- Reservoir Creek – Roxburgh Proposed Channel Improvement Plans, L9493, L9645/1 – L9645/11, L 9746, Otago Catchment Board,1980.
- Reservoir Creek – Bridge at RP 365/2.43 Design Report (provisional plan), L9663/1 and L9663/2, Ministry of Works and Development, Civil Engineering Dunedin,1980.
- Reservoir Creek – Roxburgh Proposed Flume Topping Layer Details, L11051, Otago Catchment Board,1984.
- Photos taken by ORC after the debris flow events on 26 November 2017 in Roxburgh.
- Video footage taken from a helicopter fly-over by ORC across the relevant catchment areas on 21 November 2018.
- Photogrammetric DEM of the Roxburgh area made by GNS Science, 2006 & 2017.
- LIDAR data along Clutha River and lower part of the relevant catchments, captured 20-21 August 2008.
- Aerial photography of the Roxburgh area captured January 2018, sourced through ORC.

Golder also reviewed information that was available online about historic debris flow / flooding events in Roxburgh. A summary listing links to webpages that contain supplementary information is presented in Appendix C.

3.2 Interpretation of Aerial Photography

An assessment of the historical behaviour of the five relevant stream catchments was carried out and included the review of historical air photos from 1945 to 2018 for Roxburgh and the surrounding area. The air photos were obtained from RETROLENS (http://retrolens.nz) and Land Information New Zealand (LINZ) Data Service (https://data.linz.govt.nz/). The purpose of the review of the air photos was to gather historical evidence of debris flow/flood events, slope instability such as landslides and rockfall, changes in channel morphology such as aggradation, bank erosion or avulsion, and changes in vegetation within and adjacent to the channels. An inventory of previous events was then prepared to assist in developing event return period and magnitude estimates.

A summary of the air photo review including geomorphologic observations is provided in Appendix A.

3.3 Field Investigation

Flo Buech (Senior Engineering Geologist) carried out a field investigation of Pumpstation Creek, Reservoir Creek, Golfcourse Creek, Black Jacks Creek and Stevensons Creek between 25 February and 1 March 2019.

On 25 February 2019, a helicopter inspection across the Roxburgh area and relevant catchment areas was carried out to gather information about the current state of the geomorphological processes in each catchment and to be able to demarcate areas that need further ground-based investigation. The helicopter inspection was carried out using an Airbus H120 Colibri helicopter owned and operated by HELIVIEW Flights in Cromwell, New Zealand. The helicopter had an on-board camera setup that allowed both forward facing conventional video footage as well as 360˚high resolution photo capture utilising a GARMIN VIRB 360 camera in time laps (at 1 sec intervals); selected photographs are included in Appendix B.

Tim McMorran (Principal Engineering Geologist) of Golder and Ben Mackey (Manager Natural Hazards) of ORC joined the helicopter inspection.

On 26 February 2019, Flo Buech participated in a meeting between ORC (Ben Mackey) and Teviot Valley Community Board members Raymond Gunn (Chair) and Stephen Jeffrey to gather local information about previous debris flow/flood events in and around Roxburgh and to obtain information about the community's expectations of ORC's actions in regards to reducing the risk of future inundation of infrastructure by debris flows/floods in Roxburgh.

On the afternoon of 26 February 2019, Ben Mackey and Flo Buech met with the land owners to conduct site visits of the relevant creek and catchment areas and to gather information about the extent and impact of the 26 November 2017 event and previous debris flow/flood events to assist in developing event return period and magnitude estimates.

During the field investigation, Golder conducted ground-based field mapping to characterise the specific geomorphological processes that are occurring within each catchment and along each creek. Emphasis was put on characterising:

- Potential sediment sources for landslides initiating debris flows.
- Existing slope instabilities and their mechanism.

- Areas of recent material erosion / accumulation.
- Existing channel morphology in the catchment areas as well as in the vicinity of existing road crossings.

Approximate slope measurements were taken using a handheld clinometer and distances were measured using a measuring tape. Structural measurements of insitu rock mass were taken using a BRUNTON compass.

The weather during the field investigation was generally clear with some cloudy periods, good visibility and some periods of light rain (mainly on Wednesday, 27 February 2019).

During the time of the field investigation light flows were observed in all relevant creeks.

4.0 LOCAL SITE CONDITIONS

4.1 Geology and Terrain

The catchments of the relevant creeks are located at the eastern flank of the Old Man Range. The Old Man Range and Mt Benger comprise an anticlinal ridge in the underlying Triassic Caples Terrane (TZIII) schist that contains well foliated psammitic and pelitic schist with minor greenschist and metachert (Turnbull, 2000). Foliation of the underlying schist on a regional scale is dipping unfavourably towards the Clutha River. Large scale landslides are prevalent in the area and consequently a thick mantle of landslide debris is available as a material source contributing to the current debris flow / flood hazard.

The debris from eroding bedrock of the Old Man Range has provided sediment to build alluvial fans onto old river terraces along the Clutha River.

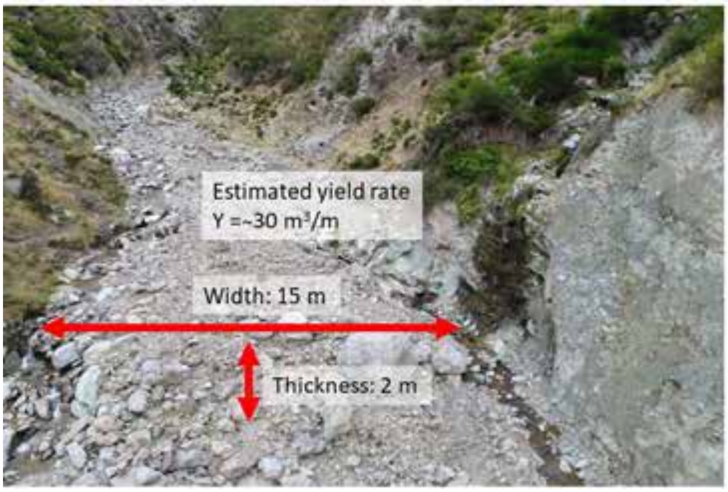
The catchment areas of the creeks that are part of this investigation, range in elevation from their highest point of elevation at about 1000 – 1200 m asl to between 70 and 90 m asl at the confluence to the Clutha River. The catchments of Pumpstation Creek and Reservoir Creek drain in a northeast direction whereas the catchments of Golfcourse Creek, Black Jacks Creek and Stevensons Creek drain the slopes of the Old Man Range in an east direction.

The upper catchment areas are dominated by terrain with alpine tussock grass whereas areas below about 800 m asl are utilised for pastoral farming. Some terraced areas in Stevensons and Black Jacks Creek catchment areas are actively irrigated (based on verbal information) and used for agriculture and pasture for cattle.

4.2 Geomorphology

The channels are divided into sections of similar geomorphological characteristics describing the elevation range of each section, the length of the channel section, the material composition within the channel, the channel gradient, the channel width, areas that represent sediment source areas for potential debris flows and the predominant type of erosional process that is present along each section of the creek.

Additionally, the yield rate and available volume of debris for each section is estimated; in total a maximum event volume is estimated for each creek site. Yield rates were estimated by assessing the volume of erodible material per meter of channel length following the method of (Hungr & Jakob, 2010) by using both a GIS-based desktop analysis and observations made during the field investigation. A channel specific sediment volume was then calculated based on specific yield rates along the length of similar reaches of the creek channels (Table 2). The concept is shown in Figure 2 below. This approach is limited as the volume estimate refers to the time of the investigation.



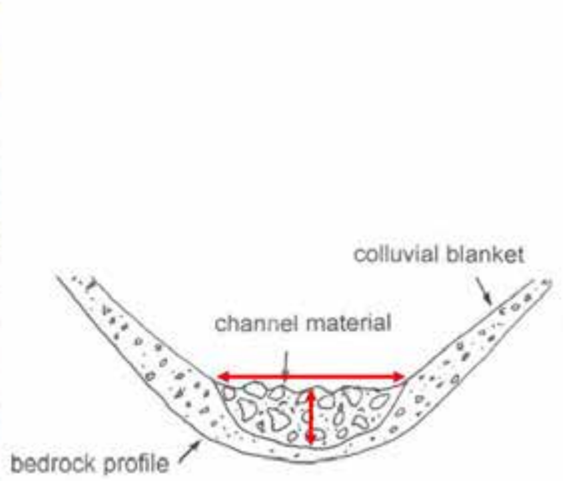


Figure 2: Yield rate concept (Hungr & Jakob, 2010) where a yield rate Y is estimated across a given channel cross-section. Left: Example of an estimation of yield rate at Reservoir Creek; right: Amended schematic cross-section of a creek channel showing sources of erodible material that can be entrained during a debris flow event (after (Hungr & Jakob, 2010)).

An overview of each creek site with photographs taken during the field investigation from 25 February until 1 March 2019 as well as photos supplied by ORC is presented in Appendix B.

4.2.1 Pumpstation Creek

Pumpstation Creek drains the northeast-facing slopes of the Old Man Range that rise to an elevation of about 970 m asl in its catchment area. The length of the main channel from its origins (920 m asl) to the fan apex, which is located at about 140 m asl, is approximately 3750 m.

The debris fan of the creek starts at about 140 m asl, the creek crosses SH8 at about 95 m asl and reaches the Clutha River at about 80 m asl.

The estimated area of the catchment is 2.6 km^2.

For an overview of the catchment and its geomorphologic sections as described below, please see Figure 3. An overview of the main geomorphic processes that contribute to the debris flow hazard in the catchment are presented in Figure 4.

In this assessment only the main creek channel to the South has been assessed as the North Branch has not shown any evidence of debris flow/flood activities in recent times, although it is contributing to the hydrological input of the main channel.

Section 5: 920 – 600 m asl

The upper reaches of the catchment from the top of the Old Man Range at about 970 m asl to an elevation of about 600 m asl are characterised by terrain that is dominated by tussock grass. The creek channel and its tributaries are incised in the gentle north-eastwards facing slopes. The channel width is less than 5 m. Outcrops of schist bedrock are visible along the creek. The upper creek channel and small tributaries are often vegetated and covered by topsoil and grass. Where the channel bed is exposed, boulders and cobbles are present. No recent erosional features are visible along the adjacent slopes or within the creek bed in the upper reaches of the catchment.

Section 4: 600 – 300 m asl

Along this section of the creek undercutting of slopes, active soil slips and slumping of adjacent slopes are present. The channel is up to 5 m wide with slope angles greater than 15 degrees. Bedload material consists mainly of boulders, cobbles and gravel. Slopes along the true left are partially vegetated with shrubs and small trees. Bedrock is visible along some areas of this channel section. Most soil slips and old slumping features are located along the true right slopes within the colluvium. The exposed colluvial materials mainly consist of sandy gravel with cobbles and some boulders and represents the main source of bedload along this section of the creek.

Section 3: 300 – 190 m asl

The width of the creek bed increases along this section to between 5 m and 10 m. The channel is stepped, and channel gradients are above 10-15 degrees. The bedload consists mostly of boulders, some have a diameter greater than 1.5 m. Undercutting and erosion of adjacent slopes and soil slips in colluvium are common. An active landslide area in colluvium (sandy gravel with cobbles and some boulders) is present along the true left of the creek. This landslide has been re-activated after the November 2017 rainstorm event. Entrainment of material due to erosion of the toe of the landslide and scour within the creek bed are dominant processes along this section of the channel. Bedrock is visible along some length of this channel section.

Section 2: 190 – 140 m asl

The lower reaches of the catchment from the fan apex at about 140 to about 190 m asl are dominated by the deposition of debris material, mainly boulders with cobbles, gravel and some sand. The channel is between 10 to 15 m wide and its gradient flattens to between 8 and 10 degrees. Scour and incision into older debris deposits and erosion along adjacent slopes are visible along the channel bed.

Section 1 / Debris Fan: 140 - 80 m asl

The current creek channel runs along the true right slope, is up to 5 m wide and has a gradient of about 8 to 10 degrees. A levee (up to 1.5 m high and 2 m wide) is located along the true left of the channel until a wooden bridge, used to access farmland, crosses the creek at about 125 m asl. From this location downstream, the creek has eroded about 2 m into the fan deposits and drains in approximately the east direction. The gradient flattens to about 5 degrees at approximately 105 m asl before it crosses SH8 through a culvert at 95 m asl. The width of the channel bed ranges between 2 and 5 m. Boulders (up to 1 m in diameter) and cobbles are present in a gravelly matrix with some sand. Below SH8, the creek channel widens to between 5 and 10 m before it reaches the Clutha River at about 80 m asl at an average gradient of about 6 degrees. The distance from the fan apex until the channel reaches the Clutha River is about 450 m.

4.2.2 Reservoir Creek

Reservoir Creek drains the northeast-facing slopes of the Old Man Range that rise to an elevation of about 1020 m asl in its catchment area. The length of the main channel from its origins (980 m asl) to the fan apex, which is located at about 120 m asl, is approximately 5300 m.

The last reach of Reservoir Creek is contained within a 180 m long concrete flume (built 1980/81 and upgraded1984 (Woods, 2011). The debris fan of Reservoir Creek starts at about 120 m asl. The top of the concrete channel starts at about 105 m asl, crosses the SH8 bridge at about 95 m asl and reaches the Clutha River at about 78 m asl.

The estimated area of the catchment is 3.6 km^2.

For an overview of the catchment and its geomorphologic sections as described below, please see Figure 5. An overview of the main geomorphic processes that contribute to the debris flow hazard in the catchment are presented in Figure 6.

Section 4: 980 – 700 m asl

The upper reaches of the catchment from the top of the Old Man Range at about 980 m asl to an elevation of about 700 m asl are characterised by terrain that is dominated by tussock grass. The creek channel and its tributaries are incised into the gently north-eastwards dipping slopes. The channel width is less than 5 m. Outcrops of schist bedrock are visible along the creek. The upper creek channel and small tributaries are often vegetated and covered by topsoil and grass. Where the channel bed is exposed, boulders and cobbles are present. Only few erosional features are visible along the adjacent slopes or within the creek bed in the upper reaches of the catchment at about 690 m asl. Multiple tributaries in the upper reaches of the catchment contribute to the main channel.

Section 3: 700 – 280 m asl

The channel in this section is stepping down steeply, at angles greater than 15 degrees. The channel is 5-10 m wide. Slopes are partially vegetated with shrubs and small trees. Bedrock is exposed along on both sides of the creek bed of this channel section. Bedload material consists mainly of boulders (up to 3-4 m in diameter), cobbles and gravel. Soil slips, old slumping features and shallow landslides are located along slopes within colluvium. The creek is undercutting and eroding the toe of these landslide features. The exposed colluvial materials mainly consist of sandy gravel with cobbles and some boulders and represents the main source of bedload along this section of the creek. Scour and entrainment of debris through undercutting along adjacent slopes are the main processes of debris transport in this section.

Section 2: 280 - 120 m asl

Deposition of material has occurred in this section as the channel widens (average width 15-20 m) and the slope gradient of the creek bed flattens from about 10 degrees at about 250 m asl to an average of 5-7 degrees from about 200 m asl downwards. The thickness of the deposited debris within the channel ranges between 1 to 4 m, based on visible exposure of bedrock along the slope, channel geometry, an estimated bedrock profile and incision into older deposits along the channel. Scour and incision into older deposits is visible along the channel. Bedrock is mainly exposed along the true left of the channel. At about 140 m asl the current creek bed is diverted from the left-hand side of the channel to the right-hand side of the channel. Exposed bedrock along this section of the true left slope reaches into the current bed and forms a natural barrier; therefore, diverts the current creek bed to the right bank. Also, at this section of the creek, a farm access track crosses the creek. The creek is incised into the channel bed along the right bank. Slopes along the true right bank show erosion through undercutting. Entrainment of material is visible along both slopes. The bedload consists mostly of cobbles, gravel and boulders with sizes of up to 3 m in diameter at about 250 m asl and up to 1.5 m in diameter below about 160 m asl.

Section 1 / Debris Fan: 120 - 78 m asl

At the top of the fan area at about 120 m asl to the start of the concrete channel at about 105 m asl, the channel is undercutting the slope along the true right and the access track along the true left. Currently the channel bed is located about 4 m below access track level. The channel has a width of about 5 to 10 m and slopes at about 6-7 degrees towards the northeast before it enters the concrete flume. Debris material within the channel is currently dominated by cobbles and gravel with boulders (up to 1 m in diameter) and some sand. The slope along the true left has been lined with boulders along a distance of about 35 m above the entrance to the concrete flume. The concrete channel starts at an elevation of about 105 m asl, is about

180 m long, crosses the SH8 under a bridge at about 97 m asl and has an average slope angle of about 6 degrees. The last 40 m of the creek is unlined before it joins the Clutha River and is currently eroded into reworked debris fan material (mostly cobbles and gravel with some sand) that was mostly deposited following the November 2017 debris flow / debris flood event. The last 20 m of this reformed channel has a gradient of only about 2 degrees before it joins the Clutha River at about 78 m asl. The total distance from the fan apex until the creek reaches the Clutha River is approximately 330 m.

4.2.3 Golfcourse Creek

Golfcourse Creek drains the east-facing slopes of the Old Man Range that rise to an elevation of about 1020 m asl in its catchment area. The length of the main channel from its origins (980 m asl) to the fan apex, which is located at about 140 m asl, is approximately 3700 m.

The debris fan of the creek starts at about 140 m asl, the creek crosses the old SH8 at about 110 m asl and immediately below SH8 at about 107 m asl before it cuts through the current local golf course and reaches the Clutha River at about 76 m asl.

The estimated area of the catchment is 2.2 km^2.

For an overview of the catchment and its geomorphologic sections as described below, as shown in Figure 7. An overview of the main geomorphic processes that contribute to the debris flow hazard in the catchment are presented in Figure 8.

In this assessment only the main creek channel to the North and its tributaries have been assessed as the southern channel has not shown any evidence of debris flow/flood activities in recent times.

Section 6: 980 – 650 m asl

The upper reaches of the catchment are dominantly covered by tussock grass. No recent erosion is visible along and within the channel bed along this section of the creek. The channel is incised (up to 10-15 m) within the eastwards dipping slopes of the Old Man Range. Schist bedrock outcrops are visible along the channel that is up to 5 m wide. Within this section of the catchment the bedload of the channel appears to be dominated by boulder and cobble sized debris.

Section 5: 650 – 330 m asl

Along this section the channel is generally steeper than 15 degrees and steps in bedrock are visible. Undercutting of slopes, active soil slips in colluvium and slumping of adjacent slopes are present along both sides of the creek. The channel is generally between 2 and 5 m wide and its bedload material is dominated by boulders (up to 1-2 m in diameter) and cobbles. In the lower reaches of this section the number of soil slips in colluvial material (gravel with cobbles and sand) and the erosion along the banks increases as sections of the adjacent slopes are steeper than 30 degrees. Between 340 to about 380 m asl the channel bed runs down exposed bedrock and stepped sections (with vertical drops of 2-4 m) in bedrock. Along both sides of and within the channel insitu bedrock outcrops are exposed. The slopes are generally vegetated with tussock grass, shrubs and small trees.

Section 4: 330 – 220 m asl

The channel gradient generally is between 15 to 17 degrees in this section. Boulders up to 2 m in diameter are present in the stepped channel bed. Along the true left slope, a reactivated active landslide in colluvium (sand and gravel) is present. Aerial footage, dated 21 November 2018, from ORC of a reconnaissance helicopter flight after a heavy rainfall event show that fresh scarps and tension cracks have developed above a reactivated sliding mass in this area. The landslide is in colluvium (gravel and sand) and shows likely shallow rotational to translational movement that is leading to narrowing of the creek channel along the toe of the sliding mass. The volume of the active landslide is estimated to be approximately 20,000 m^3. Bank erosion through undercutting of the landslide toe and entrainment of debris are the main erosion processes along this section. Some vegetation and small trees are likely to be entrained in debris along this section of the creek.

Section 3: 220 – 180 m asl

Below about 220 m asl, the channel slope angle decreases from about 15 degrees to about 10 degrees. The width of the channel ranges between 10 and 15 m. Scour and incision (up to 1 m) into older debris deposits within the creek bed as well as undercutting and erosion, mostly along the right bank within colluvial material (gravel, sand with cobbles) of the creek channel, are dominant along this section. Deposition of cobbles, gravel and bouldery (up to 1.5 m in diameter) debris within the channel is visible.

Section 2: 180 – 140 m asl

The channel gradient decreases from a slope angle of about 10 degrees to about 6-8 degrees at the fan apex at about 140 m asl. This section is dominated by deposition of cobbles, gravel and boulders (up to 1.5 m in diameter) as the channel width increases to 20 – 25 m on average. Incision (up to 1.5 m) into old debris deposits within the channel and erosion along the banks are present.

Section 1 / Debris Fan: 140 – 75 m asl

The apex of the existing debris fan is located at about 140 m asl. Here, the current creek bed becomes narrow (width between 3-5 m) as it enters a forested area above the SH8 crossing. The average slope angle of the creek bed is 8 degrees. The current creek is incised (up to 1-2 m) into old debris (gravel with cobbles and sand and some boulders, mostly < 1m in diameter) and erosion of the along the banks is present along this section above the SH8 crossing. Recent deposition of debris (tree trunks are buried up to 1 m by debris) and impact marks on tree trunks are visible in the forested area above the SH8 crossing. Above the SH8 crossing, levees (between 0.5 – 1 m high) have been built from existing debris material to channelise the creek. The creek crosses the old SH8 road at about 110 m asl through a circular culvert, then immediately crosses SH8 below through a boxed culvert at about 107 m asl. Downstream from SH8, the creek (width here about 2-4 m) crosses an area of the local Golfcourse before it reaches the Clutha River at an elevation of about 75 m asl. The distance from the fan apex until the creek channel reaches the Clutha River is approximately 630 m.

4.2.4 Black Jacks Creek

Black Jacks Creek drains the east-facing slopes of the Old Man Range that rise to an elevation of about 1170 m asl in its catchment area. The length of the main channel (north branch) from its origins (1050 m asl) to the fan apex, which is located at about 100 m asl, is approximately 4300 m.

Two main central tributaries and one south branch contribute to the drainage of the catchment of Black Jacks Creek. The central tributaries join the southern branch at about 300 m asl before they reach the main channel at an elevation of about 185 m asl.

The debris fan of the creek starts at about 100 m asl; the creek crosses SH8 at about 90 m asl and reaches the Clutha River at about 74 m asl.

The estimated area of the catchment is 6.1 km^2.

The different tributaries to the main channel are described separately as follows below.

For an overview of the catchment and its geomorphologic sections as described below, please see Figure 9. An overview of the main geomorphic processes that contribute to the debris flow hazard in the catchment are presented in Figure 10.

South Branch

Section 8: 1120 – 650 m asl

The top of the catchment of the south branch of Black Jacks Creek does not have visible recent erosion along the channel. This section also includes some smaller tributaries and is mainly covered by tussock grass. In some areas insitu schist bedrock outcrops are visible. The channel beds are generally up to 5-10 m incised into the adjacent topography.

Section 7: 650 – 180 m asl

The channel is up to 5 m wide in this section. The slope angle of the channel is mostly steeper than 10-15 degrees. Some slips in colluvium are present along true right-hand slopes. Bedrock is exposed along true left-hand slopes.

Central Tributaries

Section 6: 1100 – 560 m asl

The area of the upper catchment of the central tributaries does not have any evidence of recently active erosion along or within the channels. Channel widths are generally less than 5 m. The channels are incised into gently eastwards sloping topography that is dominated by tussock grass. Some schist bedrock outcrops are visible.

Section 5: 560 – 300 m asl

Channel width in this section is generally up to 5 m. The channel beds mostly have slope angles greater than 15 degrees. Some soil slips in colluvium are visible along the channels. Undercutting of adjacent slopes and erosion mostly along right hand banks in colluvium are present. Insitu schist bedrock is exposed along the left bank of the channel. The channels are often vegetated, and small bushes and shrubs cover the immediate adjacent slopes.

North Branch

Section 4: 1040 – 700 m asl

The upper reaches of the catchment from the top of the Old Man Range at about 1040 m asl to an elevation of about 700 m asl are characterised by terrain that is dominated by tussock grass and schist bedrock outcrops. The creek channel and its tributaries are incised (up to 5-10 m compared to the surrounding topography) in the gently eastwards facing slopes. The channel is mostly less than 5 m wide. Outcrops of schist bedrock are visible along the creek. The upper creek channel and small tributaries are often vegetated and covered by topsoil and grass. Some larger recent soil slips are visible along the channel below an elevation of about 800 m asl. Where visible, the channel bed is often dominated by boulders and cobbles.

Section 3: 700 – 245 m asl

This section of the channel is dominated by an increase in bank erosion and the presence of soil slips in colluvium, mostly along the true right bank. The slope angle of the channel, which is up to 5 m wide along this section, is generally greater than 15 degrees. Dominant processes along the channel are undercutting of the banks and erosion mainly along the true right slope as well as scour of debris within the creek bed. The bedload contains boulders (up to 1.5 – 2 m in diameter) and cobbles and sandy gravel which are sourced from colluvium and insitu rock. Some localised rockfall is present along the true left slope. The true left slopes are mostly vegetated with shrubs, bushes and smaller trees.

Section 2: 245 – 100 m asl

The channel width increases to between 5 m and 10 m in this section. Slope angles of the channel are generally about 8-10 degrees. Deposition of debris is visible along this section. The bedload consists mostly of gravel, cobbles and boulders (up to 1.5 – 2 m in diameter). Insitu schist bedrock is visible along the true left of the channel. This section of the creek is dominated by undercutting and entrainment of colluvium along the true right bank of the channel. Slumping processes are visible mainly along the true right slopes along the channel in colluvium. The colluvium consists of gravel with cobbles sand and some boulders. The true left slopes of the channel are mostly covered in vegetation (bushes and small trees).

Section 1 / Debris Fan: 100 – 74 m asl

The depositional debris fan of Black Jacks Creek is located at about 100 m asl, about 100 m upslope from the SH8 crossing, which is located at an elevation of about 93 m asl. The average slope angle of the fan is 8 degrees. The current creek bed is about 10 to 15 m wide and well incised (up to 5-6 m) into multiple older debris deposits which are visible along the true right bank of the current channel. The debris deposits along the banks mostly consist of gravel with sand, cobbles and some boulders. The bedload of the current channel in the fan apex area is dominated by boulders with a diameter of up to 1.5 m in diameter and cobbles. The channel slope angle below the SH8 crossing is about 11 degrees then flattens towards the confluence with the Clutha River. The channel below SH8 is 5 to 10 m wide, incised by about 0.5-1.5 m and dominated by boulders, cobbles and gravel. The distance from the fan apex to the Clutha River is about 230 m.

4.2.5 Stevensons Creek

Stevensons Creek drains the east-facing slopes of the Old Man Range that rise to an elevation of about 1150 m asl in its catchment area. The length of the main channel from its origins (about 1050 m asl) to the fan apex, which is located at about 140 m asl, is approximately 3600 m.

Two tributaries to the north and one south branch contribute to the drainage of the catchment of Stevensons Creek. The south branch starts at an elevation of about 1035 m asl and reaches the main channel at about 230 m asl.

The debris fan of the creek starts at about 140 m asl and extends over a wide area that is currently used for pasture and horticulture, eastwards towards the Clutha River; the creek crosses SH8 at about 108 m asl and reaches the Clutha River at about 74 m asl.

The estimated area of the catchment is 4.5 km^2.

The different tributaries to the main channel are described separately as follows below.

An overview of the catchment and its geomorphologic sections as described below and shown in Figure 11. An overview of the main geomorphic processes that contribute to the debris flow hazard in the catchment are presented in Figure 12.

South Branch

Section 6: 1030 – 800 m asl

The upper reaches of the catchment are dominantly covered by tussock grass. No recent erosion is visible along and within the channel bed and along this section of the creek. The channel is incised (up to 5 -10 m) within the gently eastwards dipping slopes of the Old Man Range. Schist bedrock outcrops are visible along the channel that is up to 5 m wide in this upper section. The bedload of the channel appears to be dominated by boulder and cobble sized debris.

Section 5: 800 – 230 m asl

The channel is up to 5 m wide and the slope angle of the channel bed becomes steeper than 10-15 degrees as the channel is incised to about 20 m below the surrounding topography. Soil slips in colluvium along adjacent slopes are visible, especially along the true right bank. The adjacent slopes show evidence of slumping activity. Schist bedrock outcrops are present along the true left bank of the channel. Erosional processes that are present in this section of the channel are mostly undercutting and entrainment of material along the adjacent slopes.

North Branch

Section 4: 1050 – 750 m asl

Like the upper catchment area of the south branch, this section is dominated by gently eastwards dipping topography of the Old Man Range. The upper catchment does not show noticeable erosion along the channel. The channel width ranges between 2 and 5 m. The creek bed and its small tributaries, as well as the surrounding slopes, are mainly covered by tussock grass. The channels are incised (up to about 5 m below adjacent terrain levels) and bedload appears to be dominated by boulders and cobbles where visible. Some schist bedrock outcrops are present along the channel.

Section 3: 750 – 330 m asl

The channel becomes steeper and is up to 5 m wide in this section of the catchment and generally 15-30 degrees steep. Some areas of rockfall are present along the channel at about 700 m asl as well as a debris fan that shows recent deposition of material. Below about 700 m, the channel crosses an area that is known locally as the “Blue Slip”; an area of active mass movement (likely shallow translational movement) that, especially along the true right slopes, shows recent slips. Undercutting of adjacent banks and entrainment of landslide material in colluvium as the channel cuts (incision of up to about 5 m) through the sliding material along the toe are the main processes along this section of the channel.

Section 2: 330 – 140 m asl

Below an elevation of about 330 m asl the channel width increases to about 10-20 m. Deposition of debris material is present as the slope angle of the creek bed flattens to about 5-10 degrees. Two northern tributary channels, which are about 2-3 m wide, and are on average steeper than 15 degrees drain the northern areas of the catchment and reach the main channel at elevations of about 310 m asl and 270 m asl respectively. Some soil slips are present along adjacent slopes of these tributaries. The main channel then further widens, and deposition of debris is present in an area that is generally up to about 50 m wide. The bedload is dominated by cobbles and gravel with boulders of up to 1.5-2 m in diameter. Channel bed erosion and entrainment of debris within the channel and along the banks are dominant in this section.

The south branch reaches the main channel at about 230 m asl.

Below about 230 m the current channel is up to 15 m wide and incised (up to 2 m) into older debris.

Section 1 / Debris Fan: 140 – 74 m asl

The apex of the debris fan is located at about 140 m asl. The fan slope angle is about 8 degrees. The channel is incised (1-2 m) into older fan deposits but lateral levees have been built below the fan apex along the banks using debris deposits after the 1978 debris flood event to protect surrounding farmland and dwellings. The current level of the creek bed is up to 2-4 m lower than the surrounding topography. Above the SH8 crossings the levees are about 3-4 m high and about 10 m wide. Debris got recently removed from the channel bed by heavy machinery to increase its capacity and placed along the banks from an elevation of about 135 m to the confluence with the Clutha River. Above the SH8 crossing, the channel bed is currently about 5-7 m wide and has a slope angle of about 5 degree. The bedload consists of cobbles, gravel with sand and some boulders (up to 0.5 m in diameter). Below the SH8 crossing the channel becomes up to 10-15 m wide. The average slope angle of the channel is 5 degrees. The channel is incised, and the channel bed level is about 2 m below the surrounding banks. Lateral levees are present along both banks until an elevation of about 80 m asl; these are up 2 m high. Below about 80 m asl, the channel width increases to about 20 m before it reaches the Clutha River at about 74 m asl. The bedload of Stevensons Creek below the SH8 crossing is dominated by cobbles and gravel with sand. Some boulders with a width of up to 0.5 m are visible in this section. Scour and erosion along the banks is the dominant process of erosion in this section. The distance from the fan apex until the channel reaches the Clutha River is approximately 970 m.

4.2.6 Summary – Geomorphological characteristics of relevant catchments

The table below summarises the general characteristics of each catchment focused on areas of sediment availability for potential debris flow / debris flood events and common erosional processes along sections of the channel. Sediment volumes are presented based on estimated yield rates of each catchment, not including entrainment due to bank erosion and/or slope failure.

Table 2: Summary – Geomorphological characteristics of catchments.

Creek	Channel characteristics	Estimated available channel sediment volume [m^3]
Pumpstation Creek	920 - 600 m asl: No evidence of recent erosion. 600 - 190 m asl: Slope instabilities, bank erosion, scour. 190 - 140 m asl: Deposition of debris, slope instabilities, bank erosion, scour. 140 - 80 m asl: Debris fan, deposition of debris bank erosion, scour.	18,000
Reservoir Creek	980 - 700 m asl: No evidence of recent erosion. 700 - 280 m asl: Slope instabilities, bank erosion, scour. 280 - 120 m asl: Deposition of debris, slope instabilities, bank erosion, scour. 120 - 105 m asl: Debris fan, deposition of debris, bank erosion, scour. 105 – 85 m asl: Concrete channel. 85 – 78 m asl: Deposition of debris.	50,000

Creek	Channel characteristics	Estimated available channel sediment volume [m^3]
Golfcourse Creek	980 - 650 m asl: No evidence of recent erosion. 650 - 220 m asl: Slope instabilities, bank erosion, scour, active landslide area at 330 – 220 m asl. 220 - 140 m asl: Deposition of debris, slope instabilities, bank erosion, scour. 140 - 75 m asl: Debris fan, deposition of debris bank erosion, scour.	20,000
Black Jacks Creek	1120 - 700 m asl: No evidence of recent erosion. 700 - 245 m asl: Slope instabilities, bank erosion, scour. 245 - 100 m asl: Deposition of debris, slope instabilities, bank erosion, scour. 100 - 74 m asl: Debris fan, deposition of debris, bank erosion, scour.	24,000
Stevensons Creek	1050 - 800 m asl: No evidence of recent erosion. 800 - 330 m asl: Slope instabilities, bank erosion, scour 330 - 140 m asl: Deposition of debris, slope instabilities, bank erosion, scour. 140 - 74 m asl: Debris fan, deposition of debris, bank erosion, scour, lateral levees from about 135 m asl.	33,000

4.3 Catchment Hydrology – Clear-Water Peak Flows at SH8 Crossings

This section documents the clear-water peak flows at the six State Highway 8 (SH8) crossings: at Pumpstation Creek, Reservoir Creek, Golfcourse Creek North Branch, Golfcourse Creek South Branch, Black Jacks Creek and Stevensons Creek. The purpose of defining these flows is to:

1) Verify what flows in these catchments may have triggered debris flow events;
2) Provide a basis for defining debris flood flows; and
3) Undertake a preliminary verification of the capacity of the crossings at SH8. The scope of assessment for the clear-water peak flows includes estimating which recurrence and duration of rainfall events caused historical debris flood events, as well as estimating proposed design events for potential upgrade of the crossings at SH8. The requirement for the upgrade will be informed by the outcome of this assessment. Actual design of the upgrades is excluded from this scope of work.

4.3.1 Design Assessment Criteria

4.3.1.1 Clear-water peak flow estimation

Table 3 sets out the estimation of clear-water peak flow events as part of this hydrological assessment. Following the table, justification and background information for the proposed clear-water peak flows estimation is provided.

Table 3: Definition of clear-water peak flow events to estimate.

Clear-water peak-flow event	Description
NZTA design event for SH8 crossings (for the serviceability limit state)	ARI [(1)] of 100 years for the critical duration for the catchment (to be defined for each catchment) [(2)]
Events which triggered the November 2017 debris floods	ARI of 100 years duration 1 hour (for Pumpstation Creek) and 500 years duration 1 hour (for Black Jacks Creek, Golfcourse Creek and Reservoir Creek).
Potential/Proposed design events relevant for debris floods	ARI of 200 and 500 years of duration 1 hour.

Notes:

1) Annual recurrence interval.
2) As per (NZTA, 2019), SH8 is classified as Arterial. This implies that the SH8 crossings of interest are categorised under 'Bridges on highways classified as National, Regional, Arterial, Primary Collector or Secondary Collector in the One Network Road Classification (ONRC)'. SLS 2 for floodwater actions.

4.3.1.2 River crossing design criteria

NZTA Design event: The design criteria for river crossings along SH8 is set out in the New Zealand Transport Agency (NZTA) Bridge manual (NZTA, 2019).

4.3.1.3 Events triggering debris flood

Events which triggered the November 2017 debris floods: The debris flood that occurred in Roxburgh in November 2017 and documented in (GNS, 2018) provides relevant information to define which clear-water peak flows should be estimated as part of this assessment:

- The debris flood event was caused by a rainfall event greater than 40 mm in 1 hour, which corresponds to an annual recurrence interval (ARI) of about 100 years.
- The estimated ARIs of the debris flood events in each of the catchments of interest are:
  - Greater than 500 years (in Black Jacks Creek, Golfcourse Creek and Reservoir Creek catchments).
  - Around 100 years in the Pumpstation creek catchment.

  The estimated return period of the event is not documented for Stevensons Creek.

Potential design events relevant for debris floods: We propose to estimate the 200-year and 500-year ARIs of duration 1 hour (this duration is associated with the duration required to trigger a debris flow based on the November 2017 event) as potential design events for SH8 crossing infrastructure. The selection of a design event is a trade-off between acceptability of risk of exceeding the serviceability limit of the infrastructure and cost of the infrastructure. This should be considered if a further design stage goes ahead.

4.3.2 Data

The data available for this assessment included:

- Topographical information for the catchments of interest: LIDAR data along Clutha River and lower part of the relevant catchments, captured 20-21 August 2008 (provided by ORC) and 1:50 000 contours from Land Information New Zealand's (LINZ) data service.
- Rainfall statistics from the National Institute of Water and Atmosphere (NIWA) High Intensity Rainfall Design System (HIRDS) vs 4.
- Soil type information from Land Resource Information System (LRIS) FSL New Zealand Soil Classification.
- Geometry, dimensions and elevations of SH8 crossings:
  - Measured during the site visit undertaken by Golder between 25 February and 01 March 2019.
  - Partial culvert information available (WSP OPUS, 2019).
- Monitoring flow data at Benger Burn, 7 years of data from 2011 to 2018 (ORC, 2019). This data was considered but deemed not relevant for the catchments of interest. This is because its catchment characteristics are significantly different from those of the catchments of interest (namely in regard to size, land use and catchment slope) and also because the length of record is insufficient to generate statistics for the annual exceedance probabilities of the peak flows to estimate.
- Anecdotal information regarding historical floods obtained from residents during the Golder site visit on 25 February 2019 until 1 March 2019.
- Previous reports, documenting historical debris flood events (GNS, 2018) and issues in the catchment (Woods, 2011).

4.3.3 Method

This section outlines the methodology for estimating clear-water peak flows and for estimating the hydraulic capacity of the SH8 crossings.

Typically, the most accurate method for determining flow statistics is to make use of available flow monitoring data in the area of interest. In this case, no relevant flow data is available; therefore, the approach is to estimate flow based on two methods 1) the rational method and 2) a hydrological model. The step-process is set out below.

4) Rainfall statistics for Roxburgh are obtained from HIRDS vs 4 (NIWA, 2018) for the recurrence intervals and durations outlined in Table 4 (Section 4.3.4).

5) The hyetographs (temporal distribution of rainfall events) for different durations are determined based on the approach outlined in HIRDS vs 4 (NIWA, 2018).

6) The time of concentration of each of the catchments is estimated using the methodology outlined in (DBH, 2003) section 2.3.6. The time of concentration is defined as:

$$\mathbf{t_c = 0.0195*(L^3/H)^{0.385}}$$

Where t_c is the time of concentration in minutes, L is the length of the catchment (m) measured along the flow path and H is the rise from the bottom to the top of the catchment (m).

7) The clear-water peak flow for the events with durations equivalent to the time of concentration of each catchment is calculated using the rational method. Based on this method, the peak flow is defined by:

$$Q=0.278*C*h_i*A$$

Where Q is the peak flow (m^3/s), C is the runoff coefficient (unitless), h_i is the intensity of the rainfall event (mm/h) for the duration equivalent to the catchment's time of concentration and A is the catchment area (km^2).

8) The clear-water peak flows for events with durations greater or equal to 1 hour (for which temporal distributions of rainfall are available in HIRDS vs 4) are calculated with a hydrological rainfall-runoff model. The hydrological model used the United States Army Corps of Engineers' (USACE) Hydrologic Engineering Center – Hydrological Modelling System, commonly referred to as the HEC-HMS platform (USACE, 2019). The model simulates hydrological processes such as rainfall, infiltration, storage and evaporation in order to define the resulting direct runoff on the catchment, from which the flow is obtained. The loss model used in this case is the Soil Conservation Service (SCS) Curve Number Loss Model, which estimates precipitation excess as a function of cumulative precipitation, soil cover, land use and antecedent moisture.

9) To estimate the hydraulic capacity of the SH8 crossings, specifications of the crossings were obtained from WSP OPUS (WSP OPUS, 2019) as well as for basic measurements taken during Golder's site visit, between 25 February – 1 March 2019. These measurements are not the result of a detailed survey and should therefore be taken as preliminary. When the crossings were standard culverts, their capacity was assessed with HY-8 Culvert Hydraulic Analysis Program (FHWA 2016). When the crossings were bridges, their capacity was assessed with the Manning equation as below:

$$Q=(AR^{2/3}S^{1/2})/n$$

Where: A is the cross-sectional area of flow (m^2), R is the hydraulic radius (m), S is the slope of the channel at the point of measurement (m/m), n is the surface roughness and Q is the flow (m^3/s).

10) The maximum capacity of the crossings was defined as below:

   a. For standard culverts: the maximum flow that the culvert can pass without surcharging the inlet (and involving backwatering in the upstream channel). This criterion indirectly assumes that no flow (overtopping) on the road is possible.

   b. For bridge-crossings, the maximum flow that the bridge can pass without overtopping on the road.

4.3.4 Analysis

The analysis undertaken to estimate clear-water peak flows and the capacity of SH8 crossings is presented in detail in Appendix D. This includes data, assumptions and calculations pertaining to climate, hydrology and hydraulics. Key information is summarized here:

4.3.4.1 Climate

Rainfall statistics at Roxburgh and associated temporal patterns for the relevant durations were defined based on HIRDs vs 4 (NIWA, 2018). Statistics for events relevant to this assessment are presented in Table 4. Further statistics are presented in Appendix D.

Table 4: Rainfall statistics – Roxburgh (NIWA, 2018).

Event (ARI, duration)	Rainfall depth (mm)
100 yr, 10 min	20
100 yr, 20 min	26
100 yr, 25 min	29
100 yr, 30 min	31
100 yr, 1 h	39
200 yr, 1h	50
500 yr, 1h	59

4.3.4.2 Hydrology

- Catchment areas range from 0.5 km^2 (Golfcourse Creek South) and 6.16 km^2 (Black Jacks Creek). These were determined in AutoCAD based on 1:50 000 contours and LIDAR data provided by ORC. Figure 1 shows the catchment areas.
- All six catchments assessed are relatively uniform, meaning that these following characteristics were judged to be similar:
  - The catchments all have steep slopes, ranging from 19 to 23 % along their longest flow path.
  - Flow path lengths range from 2.6 km (Golfcourse Creek South) to 5.9 km (Black Jacks Creek).
  - Land use includes small bushes and alpine tussocks in the upper, steep catchment, with no significant areas of forest present. In the lower catchment (on the alluvial fan), short grasses and pasture appears to be the dominant land use. Small urban areas (Roxburgh) are present in the lower catchment, in the immediate vicinity of SH8 crossings.
  - A review of drainage characteristics based on LRIS FSL NZ Soil Classification showed that soils present in the steep upper catchment are classified as D3 drainage class and soils in the lower catchment are classified as D4. Based on this, soils in the upper catchment have imperfect drainage and soils in the lower catchment are moderately well drained.
- Due to uniformity of the catchment characteristics and owing to the preliminary nature of this assessment, a unique Curve Number (CN) of 73 for all catchments was assumed for input into the hydrological model. This CN was catchment-weighted based on the relative contribution of land uses. For the same reason, a runoff coefficient of 0.27 was selected for all catchments and was adjusted (increased) to account for steep catchment slopes as per (DBH, 2003).
- Times of concentration were estimated to range from 15 minutes (Golfcourse Creek South) to 35 minutes (Reservoir Creek and Stevensons Creek).

4.3.4.3 Hydraulics

SH8 crossings at the creeks of interest include bridges (Reservoir, Black Jacks, Stevensons) and culverts (Pumpstation and Golfcourse North). In addition, the crossing at Reservoir Creek includes a trapezoidal concrete channel that was designed to pass debris flood events.

4.3.5 Results Summary

This section summarizes the results of the clear-water peak flow assessment. Table 5 presents the summary of estimated clear-water peak flows at SH8 crossings near Roxburgh. Table 6 summarises the assessed maximum clear-water flow capacity of each of the SH8 crossings. Table 6 also indicates whether the road is overtopped during each of the estimated clear-water peak flow events. No specifications relating to the Golfcourse South crossing were available; therefore, this crossing is not included in Table 6.

Table 5: Summary of estimated clear-water peak flows at SH8 crossings in the vicinity of Roxburgh.

Creek	Duration	Clear-water peak flows (m^3/s)			
		Time of concentration (2)	1 hour		
	Estimation method	Rational method	Hydrological model		
	AEP (1) / ARI	1 % AEP 100 year	1 % AEP 100 year	0.5 % AEP 200 year	0.2 % AEP 500 year
Pumpstation Creek		21.1	5.2	8.9	16.1
Reservoir Creek		17.6	4.7	8.7	16.5
Golfcourse Creek North Branch		10.4	2.8	4.9	8.9
Golfcourse Creek South Branch		4.7	1.1	1.9	3.4
Black Jacks Creek		33.6	10.3	18.2	33
Stevensons Creek		25.3	6.2	11.4	21.5

Notes:

1) AEP: Annual exceedance probability.
2) Times of concentration for each catchment vary between 15 minutes and 35 minutes. These are documented in Appendix D.

Table 6: Summary of culvert capacities and results of overtopping on the road during clear-water peak flow events.

Crossing	Type of crossing	Estimated capacity (m^3/s)	Overtopping of the road (SH8) during clear-water peak flow events (1)			
			100 yr tc	100 yr 1h	200 yr 1h	500 yr 1h
Reservoir Creek	Trapezoidal concrete channel/bridge	266	no	no	no	no
Pumpstation Creek	Arched culvert	3.00	yes	yes	yes	yes
Golfcourse N Creek	One circular culvert and one boxed culvert	1.18	yes	yes	yes	yes
Black Jacks Creek	Bridge	26	yes	no	no	yes
Stevensons Creek	Bridge	71	no	no	no	no

Note 1: No means there is no overtopping of the road (SH8), yes means that there is overtopping of the road.

4.3.6 Interpretation of results

The results show that the critical clear-water peak flow event is the 100-year ARI of duration equivalent to the time of concentration for each of the catchments, which is the required clear-water peak flow design event for SH8 crossings as per (NZTA, 2019).

Times of concentration for each of the catchments are less than 35 minutes, and associated rainfall depths for durations equivalent to the times of concentration range from 23 mm to 32 mm. According to the information provided in (GNS, 2018), debris floods are initiated with heavy rainfall (minimum 40 mm depth) lasting at least one hour. This shows that the critical clear-water peak flow event may not be the critical peak flow event for debris floods (35 minutes is not enough time to develop a debris flood, and rainfall depth may not be enough). Note that this information and comparison is solely based on the debris flood event that occurred in Roxburgh in November 2017.

The preliminary assessment of the current SH8 crossings hydraulic capacity showed that crossings at Pumpstation Creek, Golfcourse Creek and Black Jacks creek are not designed to pass the NZTA clear-water peak flow event. Furthermore, Pumpstation Creek and Golfcourse Creek (North) do not allow to pass either of the 1-hour duration 100-year, 200 year and 500-year events. Black Jack's creek crossing can pass the 100 year and 200-year 1-hour events, but not the 500-year 1-hour event. On the other hand, Reservoir Creek and Stevensons Creek appear to pass all tested clear-water peak flow events. The outcomes from the preliminary assessment is consistent with anecdotal information from the November 2017 event. In (GNS, 2018), it is mentioned that SH8 was overtopped at Black Jacks, Golfcourse North and Pumpstation Creek, but not at Reservoir Creek. Historical accounts also stated that the crossing at Stevensons Creek was over topped.

This comparison is indicative only, as it is limited by the fact that the November 2017 was a debris flood event and not a clear-water flood event. It is expected that debris-loaded water will involve greater water depths.

It should be noted that although the 2017 debris flood event appeared to be generated by a rainfall event of at least 100-year ARI, this does not exclude that smaller events (therefore, lower recurrence interval events ex. 5-year, 10-year) with a higher probability of occurrence may trigger debris floods. The current assessment of clear-water peak flows was aimed at estimating the clear-water peak flows that may have occurred during the 2017 event, but also to estimate potential design flows for the SH8 crossing (which are of higher recurrence intervals).

4.3.7 Limitations and recommendations

Limitations pertaining to this assessment are listed below, and recommendations are presented to address these limitations.

- The estimation of the clear-water peak flows is highly sensitivity to the definition of hydrological parameters, and particularly of the curve number (for the use in the hydrological model) and of the runoff coefficient (for use in the rational method). These parameters were assumed based on catchment information available and on engineering judgement. We would recommend that this information be confirmed with short-term monitoring of flows in at least one of the relevant creeks if designs in a next stage of the project are to be undertaken based on these flows.
- The hydraulic capacity assessment is preliminary in nature, as it is based on specifications of the SH8 crossings inferred from site visit data, photos and LIDAR data. No survey of the infrastructure was undertaken. If a design phase is to be undertaken, we recommend surveying SH8 crossings, particularly the upstream and downstream channels as well as the road.
- The hydraulic assessment verified the capacity of SH8 crossings and did not include the assessment of capacity of the stream channels upstream and downstream of the crossings. The channels were assumed to convey all flows to the crossings (no overflows, water losses or attenuation by ponding or flooding were considered). Additionally, no potential backwatering effects were considered.

5.0 PRELIMINARY HAZARD ASSESSMENT

Based on the desktop study and the field investigation that we conducted for this project, a range of geologic and hydrologic hazards is present in the catchment areas of the relevant creeks. The focus for this report is set on channelised hazards such as debris flows, debris floods and floods. The definitions for these processes are listed in Section 2.0.

Debris flows are recognised as a highly destructive form of landslide that frequently causes damage and loss of life around the world. New Zealand has experienced many debris flows in recent decades resulting in damage or destruction of homes and infrastructure and loss of several lives. The hazard associated with debris flows relates to the high velocity, impact energy and carrying capacity of debris flows. While debris flows typically occur in steep mountainous terrain, debris floods are often the dominant process affecting the gentler sloping alluvial fan areas where residential development and associated infrastructure is located.

Debris floods (including hyperconcentrated flows) are a process where steep fast flowing streams carry high sediment loads and can be highly damaging due to high flow velocities, high carrying capacity of sediment and debris and rapid deposition of sediment. Debris floods often occur as a distal process associated with debris flows (i.e., debris flow processes affect the steeper part of a mountain terrain and translate to a debris flood process as the gradient reduces near the lower slopes).

As demonstrated during the 2017 event, heavy local rainfall can generate high flows in the various catchments. Where these high flows lead to erosion in the catchments, debris flows and debris floods can result and potentially affect residential property and infrastructure in Roxburgh. Damage can occur due to high flows in the existing channels, and combined sediment and water flows exceeding the capacity of the channel or conveying structures. When the channel capacity is exceeded, streams can temporarily or permanently change alignment (avulsion) and lead to rapid erosion and sedimentation.

5.1 Characterisation of Hydrogeomorphic Hazards

There are two key aspects that have to be described when assessing the potential hazard of debris flows:

a) debris flow occurrence

b) characteristics of the flow process

Main factors to evaluate the occurrence of debris flows are the identification of possible initiation zones, the evaluation of critical rainfall conditions for debris flow initiation, identification of sediment sources that can be mobilised and entrained along the channel as well as the frequency of events (Rickenmann, 2016).

Common sediment sources within the catchment areas which contribute to these hazards at Roxburgh are shallow slope instabilities along the banks of the creeks, localised rock fall along the channels as well as erosion along steep channel beds. Landslides are present within the weathered schist bedrock and colluvium along the slopes within the catchments. The steep slopes along the incised creek beds are often undercut by the creeks causing bank erosion, localised shallow soil slips and entrainment of debris along the slopes. Sources of boulder sized debris (up to about 2 m in diameter were observed during the November 2017 debris flow / flood event) are localised areas of rock fall from exposed bedrock cliffs above the channels, entrainment along sections of exposed bedrock or bouldery colluvium along the adjacent banks, or scour within the creek beds.

In order to better understand and identify and predict the hydrogeomorphic processes that contribute to the hazards in the study area, we used a Geographic Information System (ESRI Arc GIS) to derive topographic information such as catchment area and catchment length, and calculated the Melton Ratio and Relief Ratio (definition, see chapter 2.0) for each creek catchment. A combination of these basic catchment morphometrics was used to identify the hydrogeomorphic hazard that is likely to occur at the fan of each catchment. Previous case studies (Wilford et al., 2004) have found that an approach of using catchment length combined with Melton Ration and Relief Ratio can successfully differentiate if catchments are likely to be prone to debris flows or debris floods.

The class boundaries and the catchment details and classifications are listed in Table 7 and Table 8 respectively.

Table 7: Class boundaries for hydrogeomorphic process (Wilford et al., 2004).

Variables	Class boundaries - Hydrogeomorphic process		
	Flood	Debris flood	Debris flow
Melton ratio and length	< 0.3	0.3 – 0.6 When Melton ratio > 0.6, catchment length ≥ 2.7 km	Melton ratio > 0.6 and catchment length < 2.7 km
Relief ratio and length	< 0.15	0.15 – 0.35 Relief ratio > 0.35 then catchment length > 2.7 km	> 0.35 and catchment length < 2.7 km

Table 8: Catchment details and derived classification after (Wilford et al., 2004).

Catchment	Catchment area [km^2]	Catchment length [km]	Catchment relief [km]	MELTON Ratio	Relief ratio	Dominant Hydrogeomorphic Hazard
Pumpstation Creek	2.5	3.6	0.84	0.53	0.23	Debris flood
Reservoir Creek	3.6	4.2	0.88	0.46	0.21	Debris flood
Golfcourse Creek	2.2	3.8	0.88	0.59	0.23	Debris flood
Black Jacks Creek	6.1	4.3	1.07	0.43	0.25	Debris flood
Stevensons Creek	4.5	3.9	1.01	0.48	0.26	Debris flood

Based on the use and comparison of basic catchment morphometrics as described above, the fan areas of the catchments that are part of this geomorphic assessment are likely to be affected by debris floods (including hyperconcentrated flows) rather than debris flows. This is supported by observations that were made during the 2017 event and during the field investigation that we conducted (e.g., imbricated structures of buried old debris deposits). This does not imply that debris flow processes are not present in the assessed catchments. It is likely, however, that due to the presence of long and often wider channel sections with channel gradients less than 10 degrees, the deposition of bouldery debris flows can occur further up the catchments and transition into debris flood processes before reaching the fan apex.

5.2 Potential Consequences of Debris Flows and Debris Floods

The preliminary assessment of the current SH8 crossings hydraulic capacity showed that crossings at Pumpstation Creek, Golfcourse Creek and Black Jacks creek are not designed to pass the NZTA clear-water peak flow event.

High sediment and debris loads during debris floods (including hyperconcentrated flows) and debris flows can greatly increase the flow magnitude and exceed the available capacity of the channel or block culverts. This can put at risk the people and infrastructure that are located on or in close proximity to the fan of each catchment.

The main elements at risk in Roxburgh that we have identified are:

- Road (SH8) infrastructure can be overwhelmed, buried and potentially eroded by flows that exceed the channel or culvert capacity. Road users attempting to cross the flood flows could potentially be injured or killed.
- People within the steeper parts of the stream catchments could be impacted by fast moving debris flows or overwhelmed by flood flows. The catchments are sparsely populated and it is generally unlikely that people will be within the high risk areas. However, it is possible that farm workers, hunters or hikers could be unexpectedly hit by a sudden, rapid increase in flow and debris.
- People are most vulnerable to debris flow or flood impact if they are outdoors and unaware of the hazard (for example at night). This could include campers in tents or vehicles within the potential inundation areas of the various fans.
- Most of the dwellings and commercial buildings in Roxburgh are located in areas that have a low likelihood of being inundated by debris flows or floods. However, the 2017 debris floods highlighted dwellings in the immediate vicinity of the various streams that are at risk from future similar events. Also, channel overflows affected locations well away from the main stream channels. Potential consequences of severe debris flows or debris floods include damage or destruction of dwellings or commercial buildings and potentially injury or death of occupants. In addition, people who are outdoors may be unable to escape from sudden avulsion of a nearby stream, particularly people who are vulnerable such as children and the elderly.
- Critical infrastructure, such as the water supply pump station near to Pumpstation Creek could be damaged or destroyed by a large event. This could lead to an extended loss of amenity for the entire population of Roxburgh.
- Aggradation within the channels following a significant flood can reduce the capacity of the channel in the time following the event. Over time the channel may erode; however, the general trend for alluvial fans will be aggradation. Therefore, there is likely to be a need for mechanical removal of excess sediment that accumulates following significant debris flood events at regular intervals.

5.3 Evidence for Magnitude Frequency Relationship for the Catchments

Frequency-magnitude estimation relates the volumes or peak discharges of mass movements (e.g., debris flows) to specific return periods (or annual frequencies) of their occurrence (Jakob, Holm, & McDougall, 2016). It is a core element of the hazard assessment but subject to many uncertainties and difficult to assess as often detailed records of past debris flow events and their volumes (magnitude) are rarely available.

Aerial imagery was used in conjunction with historical, anecdotal accounts of residents as well as information which we received from ORC to describe the occurrence of recent debris flow / flood events.

A list of air photos reviewed with observations is provided in Appendix A.

Based on available information, an event inventory was created and is listed below:

- Prior 1978: Although ongoing erosional processes (large-scale landslides, localised soil slips along the creeks) were visible in the catchments and along the channels, no evidence of debris flow/debris flood events was visible prior to 1978. The creek beds appeared to be vegetated, no bank erosion or scour within the creek channels was visible.

- Oct 1978: A debris flow / debris flood event at Reservoir Creek overwhelmed the existing creek channel and impacted residential properties on the fan surface above and below SH8 (Woods, 2011). Subsequently, the concrete flume was constructed in early 80/81. At Stevensons Creek, channel incision and bank erosion were evident. Deposition of boulder-sized debris occurred in the area below the fan apex (historical anecdotal evidence, Bruce McGregor). The levees along Stevensons Creek channel above and below the SH8 crossing were constructed subsequently to minimise further bank erosion and possible avulsion.
- 1983: A storm event in the Reservoir Creek catchment caused damage to the lined concrete flume. Further improvement works were undertaken by the Otago Catchment Board at the concrete flume in 1984 (Woods, 2011).
- 1992: A localised heavy rainstorm caused a debris flood event at Slaughterhouse Creek, to the North of Pumpstation Creek.
- 26 November 2017: An extreme 60-minute rainstorm event within the catchments (up 100 mm, (GNS, 2018)) triggered debris flows / debris floods in all five catchments. The SH8 crossings of all creeks discussed in this report were overwhelmed, blocked by debris and subsequently resulted in avulsion of the channel and deposition of debris across SH8 and adjacent areas. Drinking water supply and power supply was disrupted.

  At Pumpstation Creek, channel avulsion due to aggradation of sediment occurred near the fan apex, above the bridge that allows farm access and at the SH8 crossing. Debris damaged a farm shed and flooded the access road and subsequently parts of SH8 further downstream. SH8 was inundated with debris after the culvert at SH8 was overwhelmed. Further, the piping from the Pumpstation, which is located just below the SH8 crossing, that pumps water to a drinking water reservoir further uphill, was damaged and subsequently drained the reservoir. Drinking water supply for both Roxburgh and Roxburgh village was interrupted.

  At Reservoir Creek, channel avulsion occurred above the SH8 crossing. The capacity of the concrete flume was exceeded due to aggradation of debris within the channel. The aggradation of debris started at the confluence to the Clutha River and proceeded upstream. Once debris deposition exceeded the capacity of the concrete flume, flood water and fine debris exited the channel above the SH8 bridge and inundated and damaged properties at lower lying topography to the north and south (e.g., the school building) of the SH8 crossing as well as further downstream along the concrete flume towards the confluence with the Clutha River. Several residential properties were evacuated.

  At Golfcourse Creek, channel avulsion occurred just above the fan apex. The crossing at SH8 was overwhelmed and debris inundated SH8 and parts of an orchard just to the north of the crossing. Flood waters and fine debris inundated the lower lying sports grounds and some farming areas to the north.

  At Black Jacks Creek, aggradation of debris and subsequently channel avulsion occurred in the area of the fan apex. Additionally, the crossing at SH8 was overwhelmed. Debris inundated the SH8 to the north and south as well as inundated a rest area below SH8 (this rest area has been closed since).

  At Stevensons Creek, aggradation of sediment occurred within the channel but the creek remained within the existing channel bed.
- February 2018: Cyclone FEHI caused a rainstorm event that had some effects on SH8 crossings at Golfcourse Creek where the culverts were blocked by debris and debris (gravel to cobble size) was deposited on SH8, and at Black Jacks Creek where the culvert was overwhelmed. At the other creeks,

flooding / debris flooding was evident but did not impact existing infrastructure as crossings were kept clear by heavy machinery during the event.

- November 2018: Following a rainstorm event, SH8 crossings at Golfcourse Creek and Black Jacks Creek were overwhelmed and debris was deposited across SH8. Coarse debris material was noted to be transported during that event in the creeks. Aggradation of debris at the lower section of the Reservoir Creek concrete channel occurred but was limited due to the use of heavy machinery which kept the toe of the fan at the confluence to the Clutha River clear (anecdotal evidence, Trevor Crossan – ORC Roxburgh).

Based on the limited available information listed above, we believe that debris floods affect Roxburgh infrequently. This is consistent with the low rainfall and infrequent heavy rainfall events. However, we are aware of several significant debris flood events affecting Roxburgh since historic records began. These events occurred in October 1978 and in November 2017; a lesser event occurred in 2018.

Based on information by NZTA (email John Jarvis, NZTA from 20/06/2019), several events occurred between 1995 and 2017 at Black Jacks Creek which have also involved road closures, significant damage and reinstatement of road infrastructure. There might have been further events in the area that were not recorded and are not listed in this desktop study.

These recorded historical records suggest that potentially damaging debris flow/flood events affect Roxburgh with a recurrence interval of a few decades. We are not aware that debris flow/floods larger than the 2017 event have affected Roxburgh in approximately the last 150 years.

5.4 Expected Catchment Behaviour

Based on historical accounts and on data presented after the November 2017 event (GNS, 2018), large debris flow / debris flood events are linked to very localised high intensity rainfall events that are exceeding the hydroclimatic threshold for debris flow initiation in the catchments. The rainfall during the November 2017 event exceeded a 100-year return period and, in case of Black Jacks and Golfcourse Creek, exceeded even a return period of 500 years (GNS, 2018). It is possible that larger debris flows/floods could affect the catchments, but we infer these might have recurrence intervals of a thousand years or more. We can also infer that the average aggradation rate of the alluvial fans in Roxburgh is in the order of 1 m per 1000 yrs since the end of the last glaciation approximately 18,000 years ago.

The short- or mid-term behaviour of the catchments and especially occurrence of debris flows and -floods is subject to availability of erodible sediments, the occurrence probability of soil slides along the channel as well as the frequency at which hydroclimatic thresholds are exceeded.

The assessment of the catchments after the November 2017 event and subsequent smaller events in 2018 has shown that soil slips in colluvium were triggered adjacent to the creeks and sediment was mobilised along the channels within the catchments. There is no vegetation present along these exposed areas to stabilise the exposed sediment. Further erodible sediment is readily available in these areas; and therefore, the catchments are currently vulnerable to the initiation of debris flow / debris floods whenever a critical hydroclimatic threshold (e.g., through an intense rainfall event) is exceeded.

Global climate change can also further increase the probability of debris flow initiation in the near future if the occurrence of high rainfall events on a regional scale increases.

We therefore infer that the likelihood of debris flow / debris floods occurring in the catchments is now higher than prior to 2017 and may remain so for some years or indefinitely.

6.0 PRELIMINARY RISK ASSESSMENT

We have completed a preliminary risk assessment for debris flow/flood affecting Roxburgh. There are many considerations that could be taken into account in a risk assessment, such as risk to road users, risk of property damage or infrastructure damage. For this preliminary assessment we have assumed that individual life risk is the dominant subset of total risk and have used this to evaluate whether total risk is likely to be acceptable for each of the alluvial fans in the study area. Our preliminary risk assessment follows the general methodology of Australian Geomechanics Society (Australian Geomechanics Society, 2007) for assessment of the life risk to building occupants. This method combines the consequences of an event with the likelihood using several terms in the following formula:

$$\mathbf{R_{(DI)} = P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V_{(D:T)}}$$

where

$R_{(DI)}$ = risk of loss of life of an individual

$P_{(H)}$ is the annual probability of a hazardous event (in this case debris flow/flood)

$P_{(S:H)}$ is the probability of spatial impact (of the debris flow/flood with a dwelling, occupant or individual)

$P_{(T:S)}$ is the probability of a dwelling being occupied

$V_{(D:T)}$ is the vulnerability of the individual given a debris flow/flood impact

Ratings for temporal probability (the probability that a building is occupied at the time of a debris flood) and vulnerability (of the building to impact by a debris flood) are combined to derive a consequence rating. For residential buildings in Roxburgh we have assumed that the probability of the building being occupied at the time of a debris flood is >50 %, which gives a rating of T1 in accordance with Table 11 of RMS (2014).

The likelihood terms include the annual probability ($P_{(H)}$) of a debris flow/flood large enough to avulse from the channel given the existing configuration and protection is based on our assessment of historical performance Table 9 presents the likelihood ratings used in this assessment). The term P(S:H) takes into account the probability that a debris flow/flood will impact a dwelling on each fan. Where there are many dwellings on the fan, such as the case of Reservoir Creek, this term is approximately 1, whereas other fans have few dwellings and we infer that it is unlikely a debris flow/flood will impact a dwelling.

Table 9: Likelihood ratings and descriptions used in this risk assessment (after (Roads and Maritime Services, 2014), Table 6).

Likelihood rating	Indicative annual probability	Description
L1	0.9	The event is expected to occur within a short period under average circumstances (at least once every few years).
L2	0.1	The event is expected to occur within a moderate period (from a few years to no more than about 30 years).
L3	0.01	The event could be expected to occur within a 100-year period under normal conditions (estimated return period between 30 and 300 years).

Likelihood rating	Indicative annual probability	Description
L4	0.001	The event would not be expected to occur within about a 1000-year period under normal conditions (estimated return period between 300 and 3000 years).

Table 10 presents vulnerability and consequence ratings for buildings and occupants, combining Tables 16 and 17 in (Roads and Maritime Services, 2014). The vulnerability of the residential buildings and occupants to impact by debris floods is based on observations of the avulsion of Black Jacks Creek, Pumpstation Creek and Golfcourse Creek in November 2017; we assume that Reservoir Creek would carry similar bouldery gravel material and result in rapid deposition in the area of the avulsion. For a building impacted by avulsion, we infer that consequence rating of C1 or C2 is appropriate for the types of residential buildings on the five alluvial fans at Roxburgh.

Table 10: Vulnerability and consequence ratings for building occupants following RMS (2014).

Vulnerability Rating	Probability of death of occupant	Definition	Consequence Rating
V1	>0.5	Person in open unable to evade rapid inundation by debris, engulfed in a building collapse. Injury or fatality judged likely.	C1
V2	0.1 – 0.5	Partial building collapse. Person in open may be able to evade debris accumulation. Injury or fatality judged possible.	C1
V3	0.01 – 0.1	Building impacted, no collapse. Emergency evacuation possible. Most people able to evade debris. Injury or fatality judged unlikely.	C2
V4	0.001 – 0.01	Buildings impacted with moderate damage, repairable.	C3
V5	<0.001	Buildings impacted but minor damage only, repairable.	C4
Note: Consequence rating assumes that buildings are occupied more than 50 % of the time.			

The results of this assessment are summarised in Table 11. Our best estimate of each of the terms in the above formula and the individual life risk score are presented. Given the preliminary nature of this assessment, we have coloured the results red (high) and green (low). An annual life risk of 0.0001 is considered the maximum acceptable value in accordance with (Australian Geomechanics Society, 2007). The results suggest that Reservoir Creek, Pumpstation Creek and Golfcourse Creek probably present unacceptably high life risks for occupants of dwellings. This is particularly the case for Reservoir Creek where there may be a high probability of impacting more than one dwelling if an avulsion event occurred.

Table 11: Summary of the results of a preliminary risk assessment for individual life risk.

Alluvial Fan	P(H)	P(S:H)	P(T:S)	V(D:T)	R(DI)
Pumpstation Creek	0.1	0.1	> 50 %	0.2	0.002
Reservoir Creek	0.01	1	> 50 %	0.2	0.002
Golf Course Creek	0.1	0.1	> 50 %	0.2	0.002
Black Jacks Creek	0.1	0.001	> 50 %	0.2	0.00002
Stevensons Creek	0.025	0.01	> 50 %	0.2	0.00005

In addition to the life risk to occupants of dwellings in Roxburgh there is some risk to road users. However, we believe it is likely that flooding associated with heavy rainfall will close the road before inundation by debris flow/flood impacts the road. The assessment of stream crossing hydraulic capacity presented above (Section 4.3) indicates that Pumpstation Creek, Golfcourse Creek and Black Jacks Creek are likely under-designed and have the highest likelihood of debris flow/flood inundation. No detailed assessment of risk to road users has been conducted.

Essential Services

The risk of interruption of essential services by damage from debris flows/floods is not captured in Table 11. We have identified the water supply pump station and electrical infrastructure adjacent to Pumpstation Creek as being potentially at risk from avulsion. Severe damage to the facility could result in interruption of the water supply to Roxburgh and Roxburgh Village for at least several weeks.

7.0 SUMMARY AND RECOMMENDATIONS

As authorized by Otago Regional Council (ORC), Golder carried out an assessment of the ongoing debris flow hazard to identify specific mitigation measures to reduce the debris flow risk in Roxburgh, Central Otago.

The geomorphological assessment that Golder carried out included an initial desktop study to review existing topographic, geologic and hydrologic data of the catchments at Pumpstation Creek, Reservoir Creek, Golfcourse Creek, Black Jacks Creek and Stevensons Creek. Additionally, historic aerial photos, existing reports and assessments and online information about past debris flow/flood events were reviewed. Digital and spatial information, such as LIDAR data, digital elevation models generated by GNS, recent aerial imagery as well as video and photo footage of recent debris flow/flood events was supplied by ORC and utilised to conduct this assessment.

A field investigation was carried out (25 February – 1 March 2019) and initiated with a helicopter inspection across the Roxburgh area and relevant catchment areas to gather information about the current state of the geomorphological processes in each catchment. Video and photographic footage was taken during the reconnaissance flight and later used in combination with ground-based field mapping to delineate sections of each creek of similar geomorphological characteristics, such as the channel gradient, the channel width, sediment characteristics of the bedload, areas that represent sediment source areas for potential debris flows and the predominant type of erosional process that is present along each section of the creek. Ground-based field mapping was conducted in each catchment and across the debris fan areas to further investigate:

- Potential sediment sources for landslides initiating debris flows,
- Existing slope instabilities and their mechanism,
- Areas of recent material erosion / accumulation,
- And existing channel morphology in the catchment areas as well as in the vicinity of existing road crossings.

In addition, information about historic debris flow / flood events was obtained during a meeting with local community board members and through communication with residents.

Findings

The geomorphological, hydrological and the preliminary risk assessment of each catchments have shown the following:

- In recent history, two large debris flow / debris flood events occurred (1978, 2017) and linked to very localised high intensity rainfall events.
- Historical records suggest that potentially damaging debris flood events affect Roxburgh with a recurrence interval of a few decades.
- Following the November 2017 debris flow / flood event, all catchments shown an increased number of erosional processes along the banks of the creek channels starting from an elevation of between 600 – 700 m asl continuing downstream to the debris fan areas. The resulting sediment input is mostly generated by shallow slope instabilities in colluvium due to undercutting and entrainment along the channel banks and scour within the channel bed. Sediment that can be entrained in a future debris flow / flood event is readily available in all catchments.
- Review of historic aerial imagery has shown that a similar increase of erosional activity in the catchments occurred after the 1978 debris flow / flood event, lasting a few years before erosional activity decreased and vegetation covered former exposed sediment along the slopes and channel banks.
- The preliminary assessment of the current SH8 crossings hydraulic capacity showed that crossings at Pumpstation Creek, Golfcourse Creek and Black Jacks creek are not designed to pass the NZTA clear-water peak flow design event.
- Deposition and aggradation of debris at the debris fan and upstream of the fan apex is present in all catchments.
- Aggradation within the channels following a significant flood can reduce the capacity of the channels in the time following the event and can result in channel avulsion. Areas of possible channel avulsion have been identified and are shown in the Engineering Options Report. Inundation by debris as a result of avulsion can result in damage or destruction of dwellings, commercial buildings and critical infrastructure (Pumpstation and associated electrical infrastructure) and potentially injury or death of occupants.
- Results of the preliminary risk assessment suggest that Reservoir Creek, Pumpstation Creek and Golfcourse Creek probably present unacceptably high life risks to occupants of adjacent dwellings. This

is particularly the case for Reservoir Creek where there may be a high probability of impacting more than one dwelling if an avulsion event occurred.

Next Steps Recommended

Guidance on implementation of engineering options to mitigate the debris flow risk in Roxburgh are presented separately in the Engineering Options Report (Conceptual Design) and not discussed as part of this assessment. The following recommendations are presented to further increase the knowledge about the existing hazard and geomorphological and hydrological processes involved. Further information will be required to guide detailed design of engineering options and will help the decision-making process to adequately reduce the debris flow / flood risk in Roxburgh.

Recommended next steps are:

- Delineate potentially endangered areas at the Reservoir Creek debris fan in more detail: Generate detailed hazard intensity map supported by debris flow runout prediction modelling
- Assessment towards detailed design of mitigation measures (including detailed cost-benefit analysis)
- Acquire hydraulic data: Installation of flow monitoring in at least one of the relevant creeks to further increase the accuracy of hydrological data for detailed design of mitigation measures
- Acquire survey of relevant SH8 crossings: survey of upstream and downstream channels section as well as road levels at relevant SH8 crossings to further increase data quality for detailed design of mitigation measures.

Limitations

This study is of preliminary nature and following uncertainties and limitations are associated with the findings presented above.

- The hydraulic capacity assessment is preliminary in nature, as it is based on specifications of the SH8 crossings inferred from site visit data, photos and LIDAR data.
- The frequency-magnitude analysis is limited to the presentation of an event inventory as detailed records of past debris flow events and their volumes (magnitude) were not available.
- The risk assessment presented in this report is limited to a preliminary evaluation of individual life risk to building occupants.

Your attention is drawn to the document, “Report Limitations”, as attached (Appendix E). The statements presented in that document are intended to advise you of what your realistic expectations of this report should be, and to present you with recommendations on how to minimise the risks to which this report relates which are associated with this project. The document is not intended to exclude or otherwise limit the obligations necessarily imposed by law on Golder Associates (NZ) Limited, but rather to ensure that all parties who may rely on this report are aware of the responsibilities each assumes in so doing.

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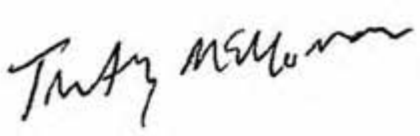

Tim McMorran
Associate | Principal Engineering Geologist

FIGURES

APPENDIX A

Air Photo Review

Date [dd/mm/yyyy]	**Scale**	**Number** (Source)	**Observations / Comments**
09/04/1945	23200	SN291_754_42-59 (Sourced from http://retrolens.nz and licensed by LINZ CC-BY 3.0)	**Pumpstation Creek:** Active slumping processes of slopes visible on both sides along the creek from about 200 m – 600 m asl. Creek bed appears to be vegetated. Creek from fan apex to confluence with Clutha vegetated. **Reservoir Creek:** Active slumping processes of slopes visible on both sides along the creek from about 150 m – 600 m asl. Creek bed appears to be vegetated. Creek from fan apex to confluence with Clutha vegetated. **Golfcourse Creek:** Some active slope movement visible on both sides along the creek from about 200 m – 450 m asl. Creek bed appears to be vegetated. Fan not built on (no houses); signs of previous avulsion / re-direction of creek bed from fan apex towards the north. **Black Jacks Creek:** Active slumping processes of slopes visible especially on the southern sides along the creek from about 100 m – 600 m asl. Creek bed appears to be vegetated. **Stevensons Creek:** “Blue slip” with recent activity at about 600 m asl. Slumping processes visible in catchment area around “Blue slip”. Mostly vegetated along creek in catchment area.
16/02/1959	44500	SN1053_0_22-24 (Sourced from http://retrolens.nz and licensed by LINZ CC-BY 3.0)	Slightly oblique **Pumpstation Creek:** Some slumping processes of slopes on both sides along the creek visible. Creek bed appears to be vegetated. **Reservoir Creek:** Some slumping processes of slopes on both sides along the creek visible. Creek bed appears to be vegetated. **Golfcourse Creek:** Some slumping processes of slopes on both sides along the creek visible. Creek bed appears to be vegetated. Fan area to the North now partially occupied by buildings.

Date [dd/mm/yyyy]	**Scale**	**Number** (Source)	**Observations / Comments**
			Black Jacks Creek: Slumping processes of slopes along the southern side of the creek visible. Creek bed appears to be vegetated. **Stevensons Creek:** No coverage.
23/12/1980 24/12/1980	17000	SN5820_A_5-6, B_1-6 (Sourced from http://retrolens.nz and licensed by LINZ CC-BY 3.0)	**Pumpstation Creek:** Recent landslide activity visible along slope to the true left of the creek between about 230 m - 500 m asl. Visible bank erosion, widening of creek bed. Loss of vegetation along creek bed. **Reservoir Creek:** Visible bank erosion, widening of creek bed / aggradation from about 300 m asl downwards. Recent deposition of debris fan at confluence into Clutha (approx. 15 m of new material). Some recent sliding activity along slopes visible. **Golfcourse Creek:** Active slides into the creek visible along the slopes from about 370 m asl downwards. Visible bank erosion and widening of the creek bed / aggradation from about 250 m asl. Possible avulsion just to the North of SH8 crossing. **Black Jacks Creek:** Visible bank erosion and widening of the creek bed / aggradation from about 280 m asl. Possible avulsion to the North just above SH8 crossing. No coverage of the upper catchment areas. **Stevensons Creek:** Visible bank erosion and widening/incision of the creek bed / aggradation from about 230 m asl. No aerial photo coverage of the upper catchment areas.
04/04/1983	50000	SN8215_C_3-4, D_4-5 (Sourced from http://retrolens.nz and licensed by LINZ CC-BY 3.0)	**Pumpstation Creek:** Possible avulsion at SH8 crossing and aggradation of debris in the area just North of the confluence with the Clutha River. **Reservoir Creek:** Visible recent fan deposition into Clutha River (concrete channel already existing).

Date [dd/mm/yyyy]	**Scale**	**Number** (Source)	**Observations / Comments**
			Golfcourse Creek: No specific observations. **Black Jacks Creek:** Visible recent fan deposition into Clutha River. Some sliding activity visible along the slopes along the creek. **Stevensons Creek:** Visible bank erosion and widening/deepening of the creek bed / aggradation from about 600 m asl downwards. Channel avulsion visible below SH8 crossing. Recent deposition of debris visible at confluence of Clutha River. Recent sliding activity visible in the area of the "Blue slip" on the southern side of the creek.
30/03/2006	5000	0750_CD13_5K_0704-0706 & 0804-0806, 0904-0906 *"Sourced from LINZ. CC BY 4.0"*	**Pumpstation Creek:** Creek bed appears to be mostly vegetated; shrubs and bushes along the creek in the lower reaches and the fan area. Slumping processes of slopes visible on both sides of the creek from approx. 400 m – 200 m asl. **Reservoir Creek:** Creek bed appears to be mostly vegetated. Slumping processes of slopes visible on both sides along the creek from approx. 600 m – 200 m asl. **Golfcourse Creek:** Creek bed appears to be mostly vegetated. Fan at confluence to Clutha River not vegetated. **Black Jacks Creek:** Creek bed appears to be mostly vegetated. Some recent slips at slopes along the southern / southeastern side of the creek visible at isolated locations from below approx. 400 m asl downwards. Recent deposition of debris visible immediately above the SH8 crossing and below towards the confluence of the Clutha River. The recent creek activity appears to have mainly affected the southern side of the fan above the SH8 crossing. **Stevensons Creek:** Creek bed not vegetated. No recent deposition at the confluence to the Clutha River visible. Potential recent deposition of debris visible within the creek bed at about 700 m asl. Some sliding activity visible in the area of the "Blue slip" on the southern side of the creek.

Date [dd/mm/yyyy]	**Scale**	**Number** (Source)	**Observations / Comments**
20/03/2015	5000	CD13_5K_0704-0706, 0804-0806 *“Sourced from LINZ. CC BY 4.0”*	**Pumpstation Creek:** Creek bed appears to be mostly vegetated. Some slumping processes of slopes visible especially on the southern side of the creek from approx. 400 m – 200 m asl. Recently fresh cut access tracks within the slumping area to the northwest side of the creek between approx. 380 m – 320 m asl. Creek bed not vegetated anymore and re-worked below property and access bridge (130-100 m asl). Vegetation reduced below SH8 crossing to confluence with Clutha River. **Reservoir Creek:** No recent activity / change visible. **Golfcourse Creek:** No recent activity / change visible. Some loss of vegetation at the confluence to the Clutha River. **Black Jacks Creek:** Some recent slips at slopes along the southern / southeastern side of the creek visible at isolated locations from below approx. 500 m asl downwards. Some regrowth of vegetation along the creek bed above and below from SH8 crossing. Some aggradation of material at the confluence to the Clutha River.
10/04/2016	5000	CD13_5K_0804-0806, 0904-0906 *“Sourced from LINZ. CC BY 4.0”*	**Stevensons Creek:** Some sliding activity visible in the area of the “Blue slip” on the southern side of the creek and along the tributary creek to the south. Some aggradation of material within the creek bed between approx. 220 m asl and 150 m asl. Some regrowth of vegetation along the creek bed.
15 & 29/01/2018	1000	CD13_1000_3121-3730 (sourced from Otago Regional Council)	Coverage limited to area in the vicinity of Roxburgh township (catchment aerial photo coverage to max. approx. 400 m asl.) **Pumpstation Creek:** Re-activated landslides along the northern slopes at approx. 300 m asl. (recent scarps visible, debris entrainment along toe of landslide). Areas with visible entrainment of debris along both sides of the creek bed from 300 m asl. Visible bank erosion and widening of creek bed. Loss of vegetation along creek bed. Possible avulsion visible at about 130 m asl (access

Date [dd/mm/yyyy]	**Scale**	**Number** (Source)	**Observations / Comments**
			bridge crossing, south of the farm shed); debris deposition visible along access road to farm. Avulsion visible at SH8 crossing; debris deposition below the SH8 crossing to the north and south of the creek bed. Recent fan deposition at confluence to Clutha River. **Reservoir Creek:** Areas with visible entrainment of debris along both sides of the creek bed from 300 m asl downwards. Visible bank erosion and widening of creek bed. Loss of vegetation and debris deposition along creek bed. Avulsion visible at SH8 crossing; debris deposition below the SH8 crossing to the north and east of the concrete channel. Recent fan deposition beyond the end of the concrete channel at the confluence to the Clutha River. **Golfcourse Creek:** Recent landslide activity visible along the slopes to the North of the creek bed at approx. 340 m asl; entrainment of debris along toe of landslide. Areas with visible entrainment of debris along both sides of the creek bed from 300 m asl downwards. Visible bank erosion and widening of creek bed. Loss of vegetation and debris deposition within the creek bed. Avulsion visible above fan apex (approx. 150 m asl). Avulsion visible at SH8 crossing; debris deposition towards north along SH8 to lower lying sportsground and towards the south along SH8. Creek widening, entrainment along creek bed and deposition of debris visible along Golfcourse Creek below SH8 crossing. Recent debris fan deposition at confluence to Clutha River. **Black Jacks Creek:** No coverage **Stevensons Creek:** No coverage

APPENDIX B

Field Photo Overview

Figure 1: Pumpstation Creek - Upper catchment above 600 m asl, dominated by incised channels and tussock grass vegetation; bedrock is exposed along some sections of the creek; no recent erosion is visible in the upper reaches of the catchment.

Figure 2: View of the catchment from about 450 m asl with visible active soil slips in colluvium along the true right slopes of the main channel. Slopes along the true left of the main channel are partially vegetated with shrubs and small trees.

Figure 3: View of the catchment from about 300 m asl. Recent slips in colluvium visible along true right channel slopes. Slopes adjacent to the creek are generally vegetated by grasses and shrubs. Agriculture is present in this area of the catchment on both sides of the creek.

Figure 4: View of the catchment from about 200 m asl. The red shaded areas delineate areas of recently reactivated slope instabilities.

Figure 5: View from the landslide area at about 300 m asl towards the Clutha River showing recent bank erosion along both sides of the creek.

Figure 6: Channel at about 250 m asl looking upstream towards the active landslide area; in-situ rock is exposed along some length of this creek section; the bedload contains boulders of up to 2 m in diameter.

Figure 7: Channel at about 230 m asl looking upstream (left) and downstream (right). Bedload consists of bouldery material with individual boulders reaching diameters of up to 2 m.

Figure 8: Visible bank erosion and entrainment of colluvium along the channel.

Figure 9: Damage marks on trees within creek channel (approx. 200 m asl.) extending to approx. 1.5 m above current creek bed level.

Figure 10: Channel bank erosion along the true right bank at about 180 m asl and deposition of boulders up to approx. 1.5 m in diameter; looking upstream.

Figure 11: Channel looking upstream from debris fan apex at about 170 m asl; widening of the channel and deposition of debris. Max. diameter of deposited boulders are about 0.5 m in diameter. Erosion along true left bank visible.

Figure 12: Fan apex area looking upstream at about 150 m asl showing creek bed along true right bank and erosion along this bank. A levee has been built up along the left bank of the creek channel by excavation of creek material.

Figure 13: Looking downstream from fan apex area; about 150 m asl. Visible signs of erosion along the true right bank. Max boulder size are up to 0.7 m in diameter.

Figure 14: Aerial view of debris fan area with SH8 and Clutha River. Visible bank erosion and scour along the channel bed at the debris fan. The channel changes direction near the farm access track bridge in the center of the picture. In Nov 2017 avulsion occurred upstream of the farm bridge and damaged the farm shed (white roof).

Figure 15: View from about 130 m asl upstream of farm access bridge towards fan apex showing steep banks and erosion along channel bed. This section of the channel towards the confluence with the Clutha river was cleared by heavy machinery out after the November 2017 event.

Figure 16: View downslope from about 130 m asl at farm access bridge. Boulders in the channel are up to 1 m in diameter. Erosion along channel banks visible.

Figure 17: Upstream view at about 100 m asl; boulder max. size about 1.5 m in diameter. Average slope angle of the creek channel here about 5-7˚.

Figure 18: Exposed true left channel bank showing sequence of previous debris deposition structures (left); View just upstream of SH8 looking towards SH8 crossing from about 100 m asl.

Figure 19: Creek channel bed above SH8 crossing looking upslope. Material deposition at channel slope angle of about 5˚. Largest boulders are about 1 m in diameter.

Figure 20: Upslope panoramic view of the current culvert infrastructure at the SH8 crossing. Debris has been excavated after the Nov 2017 event to reinstate channel capacity.

Figure 21: View of existing culvert at SH8 crossing from the downstream side.

Figure 22: Creek channel below SH8 crossing, view towards Clutha River. The average channel slope is 6˚ at this section of the channel. Deposition and bank erosion visible along the true left bank.

Figure 1: Upper catchment area – view from about 800 m asl showing in this area typical alpine tussock vegetation. No evidence of recent erosion visible along this section of the channel.

Figure 2: View of the upper reaches of the catchment at about 700 m asl. First evidence of recent bank erosion and soil slips along the true right bank.

Figure 3: Channel section at about 500 m asl with evidence of recently active soil slips and shallow landslides along the adjacent slopes. Schist bedrock outcrops are visible along the creek and are a source for bouldery debris.

Figure 4: Evidence of a shallow slip in colluvium and undercutting of slope along true left of creek at about 490 m asl. Deposition of bouldery debris visible along the creek bed in this section. Slope are partially occupied by trees and shrubs.

Figure 5: Aerial view of Reservoir Creek and adjacent slopes upslope from about 450 m asl. Partial vegetation with shrubs present along the true left slopes in this section of the channel. Recent erosion along channel banks are visible.

Figure 6: View from about 300 m asl upslope. The channel in this section shows evidence of erosion and deposition of material as the width increases. Slope instabilities are present along both sides of the creek.

Figure 7: Channel at about 270 m asl, view upslope; boulders in creek bed up to 2-3 m in diameter. Schist bedrock visible along both channel banks.

Figure 8: Widening of channel (up to 25 m in this area) and deposition of bouldery debris (up to 3 m in diameter) at about 250 m asl. Channel slope angle about 10 ˚ in this section; view in upslope direction. Orange arrow: Indicating position of drone operator for scale

Figure 9: View downstream from about 230 m asl. Visible bank erosion in colluvium, predominantly along the true right of the channel. Deposition of bouldery debris present along this section. True left slopes are vegetated by shrubs and bushes. Schist bedrock along true left banks is present.

Figure 10: Aerial overview of channel section from about 150 m asl upwards. Vegetation mostly along true left slopes in this visible section of the creek channel. Depositional areas are present along this section of the channel.

Figure 11: View of the creek channel at about 160 m asl in upslope direction. Boulder sizes up to 1.5 m in diameter; bedrock exposed along true left. Deposition of debris visible as channel widens in this section.

Figure 12: View from about 160 m asl in downslope direction showing depositional section upstream from the start of the debris fan. Left bank dominated by schist bedrock whereas right bank dominated by colluvium.

Figure 13: UAV image looking towards Roxburgh and top of the fan area from about 150 m asl. Undercutting and erosion of both banks is visible as a result of the November 2017 and February 2018 events.

Figure 14: View upstream from fan apex at about 120 m asl. Undercutting and steepening of the access track along the true left bank occurred during the November 2017 event.

Figure 15: Undercutting and erosion along the access track at the true left of the channel at about 120 m asl.

Figure 16: Looking upstream from about 110 m asl. Erosion along both banks of the creek along this section of the fan just upstream of the concrete channel. True left bank has been preliminary stabilised by placement of loose rock armour.

Figure 17: Looking downstream from the fan apex area at about 120 m asl towards the start of the concrete channel. Preliminary reinstatement of bank stability along true left banks with loose rock armour. Undercutting and erosion visible along true right bank.

Figure 18: UAV image of the concrete flume with SH8 crossing and the Clutha River in the background.

Figure 19: Debris fan downstream of the concrete flume and confluence with the Clutha River at about 80 m asl which built up during the November 2017 event.

Figure 20: Photo looking up the debris fan and concrete flume at the confluence with Clutha River. Fan material consists mostly of sand, gravel and cobbles.

Figure 21: Aerial overview of Roxburgh and Reservoir Creek and the SH8 crossing in the center, looking south. Clearly visible is the debris fan at the confluence with the Clutha River that built up and extended itself into the Clutha River during the November 2017 event. Also visible are the widening of the channel bed and erosion of channel banks upstream of the concrete channel on the debris fan.

Figure 1: Upper catchment area - Golfcourse Creek – view from about 750 m asl showing typical tussock grass vegetation. No recent erosion is visible along this section of the channel.

Figure 2: View of the upper reaches at about 600 m asl. Some evidence of recent erosion is visible within the creek channel and along the channel banks.

Figure 3: Visible erosion along channel banks - view at about 400 m asl. Also deposition of debris is present along this section of the channel.

Figure 4: Narrow channel section in exposed schist bedrock at about 380 m asl and source area for bouldery debris. Recent bank erosion and soil slips are present along both sides of the channel.

Figure 5: Overview of section along reactivated landslide in colluvium (highlighted area) at approx. 250 m asl.

Figure 6: Oblique view from the south of the area of the reactivated landslide (head scarps were visible after a heavy rainfall in late November 2018) along the true left slope of the channel between about 220 - 330 m asl. Undercutting and entrainment of debris along the banks is a prominent erosional process in this area.

Figure 7: View from the landslide area at about 300 m asl downstream towards the Clutha River. Schist bedrock is present along both sides of the channel in this section but slopes are dominantly consist of colluvium.

Figure 8: Overview, looking upstream, of the wide depositional area of the channel above the fan apex (above about 140 m asl).

Figure 9: Channel at about 190 m asl looking upstream, showing evidence of bank erosion and deposition of boulders of up to 1,5 m in diameter.

Figure 10: UAV image of channel at about 190 m asl, looking downstream along the start of a depositional area along the channel and sections of visible bank erosion and soil slip activity in colluvium.

Figure 11: UAV image of channel section between 180 - 140 m asl, looking downstream. Deposition of debris is dominant in this section of the channel.

Figure 12: Channel just upstream of the debris fan, looking downslope from about 160 m asl. Depositional environment but also source area for entrainment of debris during lager flood events.

Figure 13: Channel at about 170 m asl, looking downstream. Boulder sizes of the bedload that is present in the channel in this section are up to 1,5 m in diameter. Channel width about 25-30 m along this section.

Figure 14: Channel at about 160 m asl, looking upstream. Channel bed erosion visible in debris deposits within the existing creek. Boulders are up to 1 m in diameter.

Figure 15: Incision of current stream into existing debris at about 145 m asl, looking downstream. Deposits along the true right of the current channel overtopped during the November 2017 event.

Figure 16: Narrowing of current creek bed at fan apex area (about 140 m asl), looking downstream from farm access track crossing. Residential dwellings are located downstream along the true left of the channel.

Figure 17: View upstream from about 130 m asl. Forest is present along this section of the debris fan along both sides of the channel. Visible inundation by debris along existing trees.

Figure 18: View downstream at about 130 m asl. Channel bank erosion is visible along both sides of the current creek bed.

Figure 19: Recent debris deposition and impact marks on trees visible; channel at about 125 m asl.

Figure 20: Creek bed above the culvert of the old SH8 road, looking downstream from about 115 m asl.

Figure 21: View of culvert area above SH8 crossing, at about 115 m asl. Bouldery debris is present in the channel with a diameter of up to 1 m.

Figure 22: Channel above SH8 crossing, looking upstream from about 115 m asl. Current creek bed is about 1 m below the channel banks.

Figure 23: View of SH8 culvert setup and old road crossing with circular culvert, looking upstream.

Figure 24: Aerial view of SH8 crossing and fan area upstream. Also visible are the residential dwellings on the northern section of the debris fan.

Figure 25: Overview of Golfcourse Creek looking upstream from above SH8 with the debris fan and the current path of the creek through the center.

Figure 26: Golfcourse creek below SH8, looking downstream from about 104 m asl with recent deposition of gravel and cobbles.

Figure 27: Creek crossing the local golf course above the confluence with Clutha River downstream of the SH8 crossing; view downstream at about 95 m asl.

Figure 28: Aerial image (Jan 2018) showing the lower section of Golfcourse Creek (highlighted) from the debris fan to the confluence with the Clutha River (aerial image is courtesy of ORC). Recent erosion and deposition of debris along the channel is visible.

Figure 1: Top of the catchment at about 1100 m asl. Insitu schist bedrock visible. No recent erosion is present in this section of the catchment.

Figure 2: Upper reaches of the catchment; view from about 1050 m asl downslope towards the Clutha River. The area is dominated by tussock grass vegetation. Incised channels don’t show recent erosion.

Figure 3: View from about 530 m asl, looking upstream. Undercutting and erosion is present along the true right banks of the channel. Channel slopes partially covered by shrub and bush vegetation, predominantly along the true left slopes.

Figure 4: View of the catchment area above 350 m asl, looking upstream. Recent erosion is limited to the true right banks as the true left slopes are covered by vegetation.

Figure 5: Overview of the area above about 200 m asl, looking upstream into the catchment areas of the north branch as well as the south branch and central tributaries. The main north branch shows areas were the channel widens and deposition of debris is present.

Figure 6: Overview of the lower reaches of the creek between about 230 m asl and the confluence with the Clutha River. Deposition of debris and erosion along the banks is visible along the main channel.

Figure 7: Aerial view of the debris fan area at the SH8 crossing and confluence with the Clutha River. Recent channel bed erosion and deposition along the channel is visible upstream and downstream of SH8.

Figure 8: View of the fan apex area, looking upstream, at about 95 m asl. Terraced, partially reworked older debris deposits are visible in the background (marked lines) above current creek bed level along the fan.

Figure 9: Bouldery bedload at fan apex area at about 100 m asl. Some boulder are up to 1.5 m in diameter.

Figure 10: left: Bedload with boulders (up to 1.5 m in diameter) and insitu schist along the true left bank at about 100 m asl; right: profile through debris fan deposits along true right bank at about 95 m asl.

Figure 11: Upstream view from debris fan (average slope angle of 8 ˚) towards the crossing at SH8.

Figure 12: View from SH8 upstream to towards the fan apex and above. SH8 is located about 90 m from the fan apex. Multiple depositional surfaces are exposed along the true right banks of the current channel on the fan.

Figure 13: Downstream view of SH8 crossing and current culvert setup at Black Jacks Creek.

Figure 14: View of SH8 crossing from downstream at about 90 m asl. Boulders are present with diameters of up to about 1.5 m.

Figure 15: View from SH8 crossing downstream towards the Clutha River. Recent bank erosion is visible along the creek channel.

Figure 16: Inundation with debris at former rest area to the south below SH8 crossing. The area has been buried by debris as a result of avulsion of the creek after culvert blockage during the November 2017 event.

Figure 17: View of channel, looking upstream from confluence at Clutha River. Incision of the current creek bed into debris deposits on the fan below SH8.

Figure 1: Upper catchment area, looking towards the top of Old Man Range from about 850 m asl. No recent erosion is visible in this area of the catchment.

Figure 2: View from Old Man Range downslope into upper reaches of the south branch of Stevensons Creek from about 950 m asl. This area is still dominated by tussock grass vegetation. No recent erosion is visible.

Figure 3: View downstream into the South branch from about 760 m asl; starting evidence of erosion and soil movement along the banks of the channel.

Figure 4: Debris fan in the upper catchment at about 690 m asl below a knickpoint of the channel. The debris fan shows evidence of recent debris deposition.

Figure 5: Overview of the catchment from about 500 m asl looking into the upper reaches of the Blue Slip area. Visible evidence of recent erosion along the channel banks as well as slope instabilities on both sides of the main channel.

Figure 6: View of catchment from about 250 m asl upslope. The channel banks show evidence of recent bank erosion.

Figure 7: Aerial view of the of the main catchment below Blue Slip and the confluence of the south branch at about 230 m asl. The channel witdh of the North Branch increases below the are of the "Blue Slip" and deposition of debris is present.

Figure 8: Aerial view downstream from the confluence with the south branch at about 230 m asl showing areas of deposition and recent erosion along the channel bed until the creek reaches the Clutha River.

Figure 9: View looking upstream from about 210 m asl where the current creek has incised into older debris deposits. Boulder sizes are up to 1.5 m in diameter along this reach.

Figure 10: Channel at about 200 m asl, looking downstream, showing recent erosion along the channel banks.

Figure 11: View of channel at about 175 m asl looking upstream. Undercutting and erosion of the true left bank into colluvium is visible.

Figure 12: Aerial overview of the catchment from about 145 m asl, looking upstream. Land use on either side of the channel is dominated by farmland.

Figure 13: Aerial overview of the channel and the debris fan area from 145 m asl towards the confluence with the Clutha River. Recent erosion along the channel is visible along the creek's length to the Clutha River.

Figure 14: Aerial view looking at the channel and the indicative extend of the debris fan upslope from SH8.

Figure 15: View of channel looking upstream from SH8 at about 115 m asl. The channel bed has been recently reworked and cleaned out by heavy machinery. The lateral levees have been implemented after the October 1978 event that caused widespread erosion and channel incision along this section.

Figure 16: View of channel from SH8 crossing at 110 m asl looking upstream. Recent work within the channel has reinstated capacity after the November 2017 event.

Figure 17: Example of existing bedload at Stevensons Creek near the SH8 crossing.

Figure 18: View of the channel looking downstream towards the SH8 crossing. The channel has been recently cleared to reinstate capacity at the culvert.

Figure 19: Aerial overview of Stevensons Creek below SH8 towards confluence with Clutha River; deposition of debris is prominent along this section of the channel as the channel slope decreases and the channel width increases.

Figure 20: SH8 crossing, looking upstream from about 105 m asl; yellow marker indicates the channel bed level after the November 2017 event.

Figure 21: Channel looking downstream from about 105 m asl. Levees are located along both banks of the creek. Creek level is about 2,5 m below the current banks in sections.

Figure 22: Older debris deposits along the bank below SH8 crossing at about 105 m asl.

Figure 23: View of channel and SH8 crossing, looking upstream from about 95 m asl. Current channel level is about 2-3 m below the banks along this section.

Figure 24: View of Stevensons Creek looking towards the Clutha River from about 95 m asl. The height of the banks decreases towards the confluence of the Clutha River.

Figure 25: Channel, looking upstream from about 90 m asl.

Figure 26: Built up levees along the bank of the channel at about 90 m aslo, looking upstream. Approximate height of up to 1 m along this section.

Figure 27: View of the channel towards the Clutha River. The channel bed and banks have been recently reshaped by heavy machinery.

Figure 28: View of the channel near the confluence with the Clutha River looking upstream. The bedload is dominated by gravel and sand at this section of the channel.

APPENDIX C

Online Review

Topic	Publisher / Date	URL
YouTube video footage - Roxburgh Debris Flood event 26/11/2017	One News / 26 Nov 2017 RNZ Checkpoint / 26 Nov 2017 RNZ Checkpoint / 27 Nov 2017 Channnel 39 / 27 Nov 2017 NZ National Party / 03 Dec 2017	https://www.youtube.com/watch?v=Dx88cCd0hTA https://www.youtube.com/watch?v=Whc-HsrdbTI https://www.youtube.com/watch?v=QsCJRp13ONI https://www.youtube.com/watch?v=MY5InkdX1v8 https://www.youtube.com/watch?v=DORl3-YI7Bc
Various news articles including video footage - Roxburgh Debris Flood event 26/11/2017	NZ Herald / 26 Nov 2017 Whatsoninvers / 27 Nov 2017 One News / 27 Nov 2017 Floodlist / 27 Nov 2017 Central Otago District Council / 27 Nov 2017 Newshub / 27 Nov 2017 Otago Daily Times / 28 Nov 2017 Stuff / 28 Nov 2017	https://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=11948132 https://whatsoninvers.nz/roxburgh-flood-update-with-aftermath-photos/ https://www.tvnz.co.nz/one-news/new-zealand/video-town-cut-off-flooding-slips-cause-considerable-damage-central-otago-roads http://floodlist.com/australia/new-zealand-flood-central-otago https://www.codc.govt.nz/your-council/news/Pages/Roxburgh-Flooding-Event---Update.aspx https://www.newshub.co.nz/home/new-zealand/2017/11/surging-roxburgh-creek-uproots-huge-tree-amid-flash-flooding.html https://www.odt.co.nz/regions/central-otago/torrents-leftovers-revealed https://www.stuff.co.nz/national/99296048/roxburgh-flash-flood-like-a-train-going-past-as-water-rocks-rushed-into-homes-school https://www.stuff.co.nz/national/99304963/chance-of-another-thunder-storm-for-floodstricken-roxburgh

Topic	Publisher / Date	URL
NZ Historic weather events catalog	NIWA / 2018	https://hwe.niwa.co.nz/search/summary/Startdate/n-a/Enddate/n-a/Regions/South+Island/Hazards/all/Impacts/all/Keywords/roxburgh/numberOfEvents/20/page/1
NZ Climate Data Nov 2017	NIWA / 12 Dec 2017	https://www.niwa.co.nz/climate/nzcu/new-zealand-climate-update-222-december-2017/current-climate-november-2017

APPENDIX D

Clear-Water Peak Flow Assessment

This appendix documents the analysis undertaken to estimate clear-water peak flows and the SH8 crossing capacities. The data, assumptions and calculations pertaining to climate, hydrology and hydraulics are presented in the following format:

- Climate:
  - Table 1 presents the rainfall statistics at Roxburgh. Figure 1 presents the rainfall hyetographs tor the 1-hour 100 year, 200 year and 500 year ARIs. Both these were based on HIRDS vs 4 (NIWA 2018).
- Hydrology:
  - Table 2 presents the input parameters for the HEC-HMS hydrological model.
  - Table 3 presents the input parameters for calculation of clear-water peak flows with the rational method.
- Hydraulics
  - Table 4 presents the SH8 crossing characteristics.

Climate

Table 1: Rainfall statistics for Roxburgh catchments of interest (Source: HIRDS vs4, NIWA 2018).

ARI (years)	AEP (%) / Duration	Depths (mm)				
		10m	20m	25m	30m	1h
1.58	63%	4.33	6.08	--	7.39	10.2
2	50%	4.95	6.91	--	8.37	11.5
5	20%	7.38	10.1	--	12.1	16.4
10	10%	9.53	12.9	--	15.4	20.5

ARI (years)	AEP (%) / Duration	Depths (mm)				
		10m	20m	25m	30m	1h
20	5%	12.1	16.2	--	19.1	25.2
30	3.3%	13.8	18.4	--	21.6	28.4
40	2.5%	15.2	20.1	--	23.6	30.7
50	2.0%	16.3	21.5	--	25.1	32.7
60	1.7%	17.2	22.7	--	26.5	34.4
80	1.2%	18.8	24.7	--	28.8	37.1
100	1.0%	20.2	26.3	*28.6*	30.6	39.4
200	--	--	--	--	--	*47.1*
250	0.4%	26.5	34.1	--	39.3	49.8
500	--	--	--	--	--	*59.1*

Legend: Values in *blue italics* were either calculated from the relationship provided in HIRDS vs4 (for ARI less or equal than 250 year) and extrapolated for ARIs greater than 250 years. – indicates that values were not calculated.

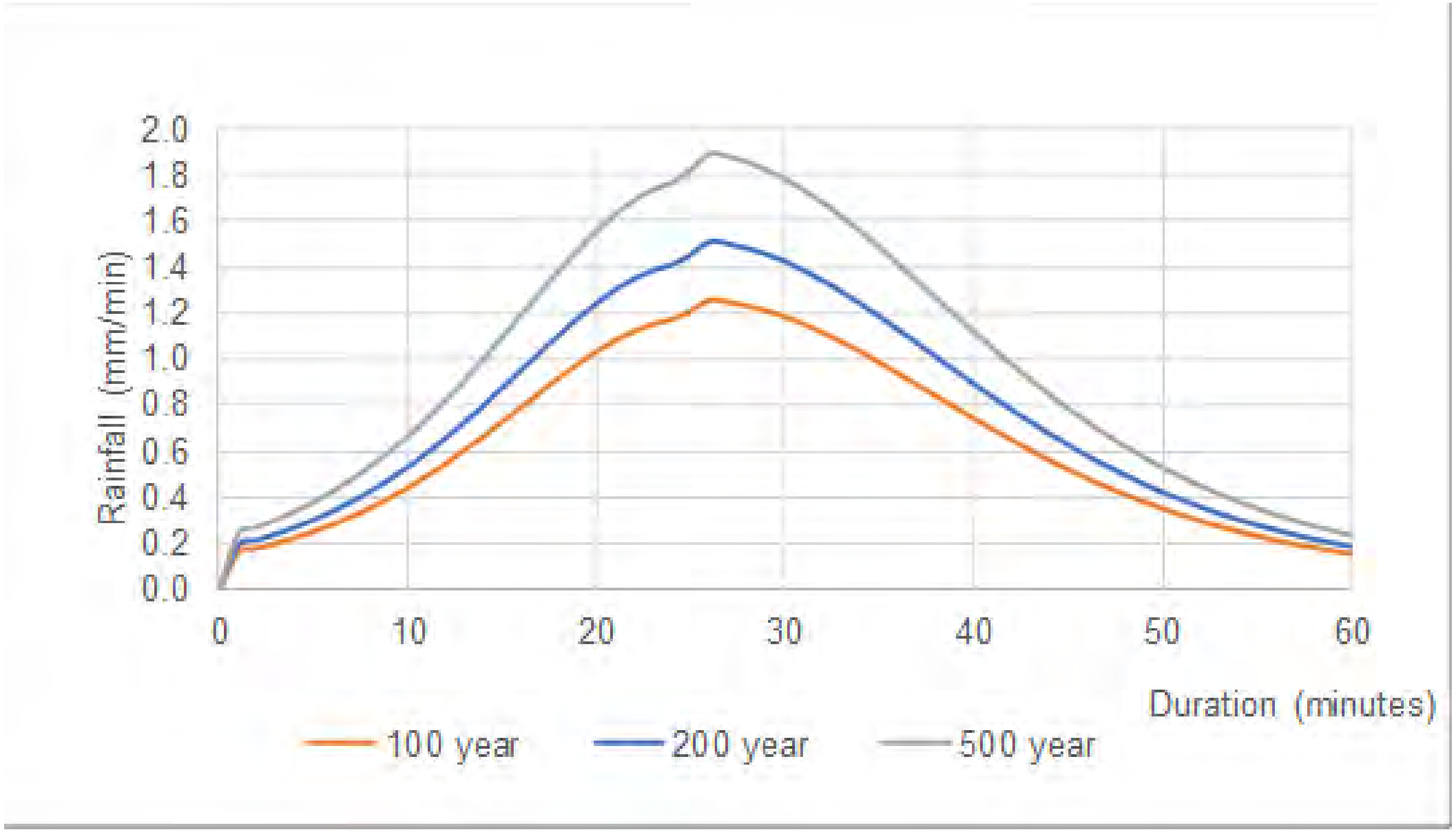

Figure 1: Roxburgh hyetographs (temporal distribution of rainfall) for 1 in 100 year, 1 in 200 year and 1 in 500 year events of 1 hour duration.

Hydrology

Table 2: Input parameters for HEC-HMS hydrological model.

Parameter	Unit	Pumpstation Creek	Reservoir Creek	Golf Course Creek North	Golf Course Ck South	Black Jacks Creek	Stephensons Creek
Catchment Area (A)	km^2	2.59	3.59	1.65	0.50	6.16	4.48
Curve Number (CN) (1)	-	73	73	73	73	73	73
Soil storage parameter (S)	mm	93.9	93.9	93.9	93.9	93.9	93.9
Initial abstraction (I_a)	mm	18.8	18.8	18.8	18.8	18.8	18.8
Time of concentration (t_c)	minutes	20	35	30	15	30	35
Lag time/time to peak (t_p) (2)	minutes	14	24	19	11	20	23

Notes:

1) The CN number was catchment-weighted based on the relative contribution of land uses. Land uses were split into the alluvial fan (smoother slope) and the steep upper catchment. For both land use types, the hydrological soil group was defined as B, with a fair to poor hydrological condition. The cover type for the alluvial fan was defined as *Pasture, lightly grazed, good grass cover* (CN=61) as per Auckland Council TP108. The cover type for the steep upper catchment was defined under arid and semi-arid rangelands as herbaceous, mixture of grass, weed, and low growing brush, with brush the minor element (CN 70 to 80). The resulting CN of 73 is the result of catchment-weighting of these values.
2) The time to peak is related to the time of concentration by the following equation: *tp=2/3*tc* .

Table 3: Parameters for analysis of peak flows with the rational method.

Parameter	Unit	Pumpstation Creek	Reservoir Creek	Golf Course Creek North	Golf Course Creek South	Black Jacks Creek	Stevensons Creek
ARI design event (NZTA)	years	100	100	100	100	100	100
Time of concentration	minutes	20	35	30	15	30	35
Rainfall depth for duration of time of concentration	mm	26	32	31	23	31	32
s - catchment slope	%	23%	19%	23%	22%	19%	19%
A - Total Catchment Area	km^2	2.59	3.59	1.65	0.50	6.16	4.48
h_i - Rainfall intensity	mm/h	78.9	55.0	61.2	93.0	61.2	55.0
$C_{initial}$ - Initial runoff coefficient (without adjustments) (1)	--	0.27	0.27	0.27	0.27	0.27	0.27
Adjustment factor for catchment slope (to add to Cinitial) (2)	--	0.10	0.05	0.10	0.10	0.05	0.10
C_{final} - runoff coefficient (including adjustement for catchment slope)	--	0.37	0.32	0.37	0.37	0.32	0.37
Q_{p100} - Peak flow for 1 in 100 years ARI *(Qp=0.278*C*hi*A)*	m^3/s	21.1	17.6	10.4	4.7	33.6	25.3

Notes:

1) Based on DBC (2003), assuming catchment-weighted runoff coefficient based on C=0.25 (Natural surface types - Medium soakage soil types - bush and scrub cover) and 0.3 (Natural surface types - Medium soakage soil types - pasture and scrub cover).
2) Based on DBC (2003). Steep slopes involve higher runoff coefficients.

Hydraulics

Table 4: Specifications of SH8 crossings.

Parameter/ Creek	Pumpstation Creek	Reservoir Creek	Golfcourse Creek North - Culvert 1 only	Black Jacks Creek	Stevensons Creek
Crossing type and dimensions	Arched culvert with span of 1.6 m and rise of 1.2 m and length of 13.2 m	Trapezoidal concrete channel/bridge. Bottom width 3.2m, side slopes 1.4H:1V, effective depth 2.0 m.	Two culverts: a higher circular concrete and steel culvert (diameter 1.4 m) discharging (chute) into a boxed culvert (1.7 m wide x 0.6 m high). Only culvert 1 assessed (1). Culvert 1 is 12 m long.	Bridge, rectangular channel. Bottom width 4.5 m, height 0.9 m.	Bridge/rectangular channel. Bottom width 2.6m, height 2.1 m.
Material and Manning's n	Concrete (0.016)	Concrete (0.016)	Concrete (0.016)	Bottom is riprap/concrete (0.035) and banks are concrete (0.016)	Bottom riprap/creek bed material (0.035), banks concrete (0.016)
Crossing slope	5.20%	10%	5.20%	5%	10.5%
Elevation of road	0.9 m above culvert crest	about 2.2 m above channel invert	0.3 m above culvert crest (this is the old road upstream of SH8)	1.3 m above channel invert	2.5 m above channel invert

Notes: Culvert 1 is assumed to be the restriction. The crossing as a whole (culvert 1 – culvert 2) was not assessed for this reason.

APPENDIX E

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Report Limitations

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