REPORT

Management and Reduction of Debris Flow Risk in Roxburgh, Otago

Engineering Options Report (Conceptual Design)

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Summary and Recommendations

The engineering options presented for each site discussed in the report are a result of the findings presented in the geomorphological assessment report (Golder Associates (NZ) Ltd, 2019). The proposed recommendations listed below are also partially incorporating findings stated in the Geomorphological Assessment Report referenced above.

Three SH8 crossings (Pumpstation Creek, Golfcourse Creek and Black Jacks Creek) have insufficient capacity (NZTA clear-water peak flow event) based on current preliminary modelling. Increasing the capacity is likely to help their functionality during flood and small debris flood events. However, aggradation of sediment on the debris fans and further upstream is still a recurring process that can cause channel avulsion during future events, which will be partially mitigated by increasing the culvert capacity at the crossings.

To effectively manage and reduce the risk of debris flows/floods in Roxburgh in the future it is likely that a site-specific combination of possible measures provided in this report will need to be implemented following a detailed assessment as part of detailed design.

It should be the aim mid-to long-term to reduce surface water run-off in the catchments. This will contribute to the reduction of sediment erosion along the channel banks and slopes; therefore, decrease the risk of debris flows and debris floods. Options to achieve this could be to limit grazing and to carry widespread afforestation of the slopes along the channels that are currently showing evidence of instability.

In the interim, to achieve a best possible site-specific solution, we recommend prioritising the following:

- Excavate creek channels along the debris fans at regular intervals and after flooding events that cause aggradation to re-establish/maintain channel capacity; and therefore, to reduce the risk for channel avulsion during future events (on-going maintenance required).

  Order of priority (based on possible impact on residential dwellings and infrastructure): Reservoir Creek, Pumpstation Creek, Golfcourse Creek, Stevensons Creek, Black Jacks Creek.

- Reservoir Creek:
  - Excavate debris fan material at confluence of Clutha River; re-establish capacity following future events that lead to aggradation of debris in this area (on-going maintenance required).
  - Re-establish and maintain channel capacity upstream of the concrete channel as well as adequately armour the channel banks along this section of the creek to prevent further undercutting and sediment entrainment.
- Pumpstation Creek:
  - Construct deflection levees above residential dwellings and the Pumpstation infrastructure that are at risk of inundation by debris during future events
- Golfcourse Creek:
  - Construction of lateral training levees along the true left channel bank starting downstream of the farm access track that crosses the creek and ending above SH8 to protect residential dwellings to the north of the creek.

To further mitigate the debris flow risk to residents and infrastructure, we also recommend the following actions are undertaken:

- It is essential to conduct a detailed debris flow hazard and risk assessment including cost-benefit assessment for mitigation measures and identification of hazard zonation prior to detailed design stage. This will also be beneficial in the perspective of long-term land use planning in these debris fan areas.
- Regularly monitor the slope instabilities at Pumpstation Creek and Golfcourse Creek.
- Monitor the creeks by highway patrol crews during adverse weather conditions and implementing preventative highway closures as necessary.
- Monitor flows in at least one of the relevant creeks, to verify preliminary results of clear-water peak flow estimations prior to detailed design of mitigation measures.
- Regularly monitor creek channels (e.g., level of aggradation, changes in channel morphology).
- Consider implementing an early-warning (pre-event) system that correlates rainfall data with debris flow occurrence based on current information of past events. Radar tracking of storm cells can be used to warn of possible high rainfall intensity events that may trigger debris flows/floods and put relevant authorities on alert. A more detailed assessment of current and future relationships between rainfall and debris flow/flood occurrence is likely necessary to optimize this approach.
- Survey relevant SH8 crossings (upstream and downstream channels, as well as the road levels) to allow detailed hydraulic capacity assessment prior to detailed design of mitigation measures.
- Consider the upgrade of SH8 crossings that currently do not meet NZTA clear-water flow capacity for 1/100-year events such as Pumpstation Creek, Golfcourse Creek and Black Jacks Creek.

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1.0 INTRODUCTION

As authorized by Otago Regional Council (ORC), Golder Associates (NZ) Limited (Golder) has carried out an assessment of the ongoing debris flow hazard and identifed 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 that are part of this assessment are: Pumpstation Creek, Reservoir Creek, Golfcourse Creek, Black Jacks Creek and Stevensons Creek. 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, resulting in damage to buildings and property.

This report is based on Golder's findings in the Geomorphological Assessment Report (Golder Associates (NZ) Ltd, 2019) and provides information that will guide concept design for any mitigation work. The assessment did not include any quantitative risk assessment, detailed hydrological modelling or detailed hazard zonation planning, nor did it include any detailed design or detailed costing of remedial measures.

1.1 Debris Flow Protection Measures – An Introduction

Due to its topography and geomorphological setting, Roxburgh and the surrounding areas are frequently affected by debris flow and debris flood events. Within the last 40 years two large debris flow / debris flood events (1978 and 2017) have impacted on infrastructure and the public in Roxburgh.

In the European Alpine countries, protection measures that aim to reduce potential damage arising from hydrogeomorphologically driven processes in steep mountain channels, such as debris flows and debris floods, are well established (Rickenmann, 2016). Protective measures are required in order to protect people and infrastructure from natural hazards such as debris flow and debris floods (including hyper-concentrated flows).

A stepwise approach is generally used that leads to the planning process of protective measures against these hazards and follows the following concept (Wendeler, 2016):

1) Hazard identification and documentation – *What can happen?*

2) Risk assessment – *How frequently could something happen and how severe could it be?*

3) Action planning – *How can we protect ourselves?*

   a. **Active measures** involve protection concepts that interfere actively with the hazardous process. These measures may affect the initiation, transport or deposition of debris flows and can therefore modify the magnitude and frequency characteristics. This can be achieved by either changing the probability of occurrence, e.g., through actively stabilizing the initiation zones or by manipulating the flow process itself, e.g., through installation of structural measures such as retention or diversion structures. Active measures can have a permanent effect.

   b. **Passive measures** are implemented to reduce potential losses by altering the vulnerability to the hazard. This can be achieved for example by hazard-adapted use of land and hazard zoning and can provide a permanent effect.

   c. **Emergency measures** are acting primarily a redundancy if protection systems fail but will also contribute to the reduction of vulnerability. Such measures are for example the implementation of evacuation procedures, early-warning systems, or the setup of a procedure for rapid disaster relief.

In the following section some of the common protection concepts are presented which are also optional mitigation measures to manage and reduce the risk of debris flows in Roxburgh. In order to fulfil the demands of protecting a site, i.e., to reduce the existing risk to an acceptable level of residual risk, the best combination of protection measures must be identified (Huebl & Suda, 2008).

The implementation of active mitigation measures is assessed following the approaches below:

- FORESTRY MEASURES, SOIL-BIOENGINEERING AND AGRICULTURAL MEASURES

  Afforestation has proven to be very successful in other parts of the world to significantly decrease surface runoff and to reduce bedload in debris flow prone catchments.

  The afforestation in the catchments of the creeks can be a long-term option to actively mitigate against debris-flows in the Roxburgh region.

  Soil bioengineering addresses the technologies and applications of dead and live plants for erosion control. Examples range from seeding in channels to stabilisation through live brush mattresses, living slope grids, fascines, brush layering and palisade constructions. In combination with structural slope stability measures such as geotextile mats and anchoring systems, this type of mitigation will minimize erosion and govern groundwater supply (Huebl & Fiebiger, 2010). Soil bioengineering measures are costly and are preferably used when engineered structural elements are implemented and slope stability has been provided.

  Another option to better protect the catchment from excessive erosion is the implementation of agricultural measures, such as grazing management especially of slopes along the channels that are already exposed to increased erosion.

- TRANSVERSE AND RETENTION STRUCTURES

  Transverse structures, such as check dams are built in the initiation and transport zone of debris flows to prevent stream bed erosion, to raise channel beds, and to reduce the stream gradients. The transport of material is interrupted, and material is forced to deposit before it reaches the debris fan. This aggradation minimizes future scour of channel and banks. Hence check dams generally require less maintenance than retaining structures which are described below but would in the case of the catchment setup in the Roxburgh area very expensive due to access limitations.

  Retention structures are built in an area above the debris fan where it can provide an upstream retention space for material deposition during a debris flow / flood event. The retention structure is designed and dimensioned for a specific retention volume and includes a strainer structure to provide passage of finer sediment and to drain the retained debris. After an event the material needs to be removed from the retention space in order to provide functionality during future events; ongoing maintenance costs need to be considered for the removal of material.

  Retention structures can be rigid or flexible structures. Rigid structures can be built e.g., as concrete dams, concrete or steel pillars, see Figure 1 below.

Figure 1: top left: concrete retention structure with central steel rake to separate debris material from water (source: Herzog Ingenieure, Davos, Switzerland);top right: concrete sediment retention structure in Switzerland (source: (Wendeler, 2016)); bottom: series of check dams in European Alps (Comiti, Lenzi, & Mao, 2013).

A staircase-like sequence of check dams (see Figure 1) are constructed of concrete, fences, gabions or other materials in order to control channel bed incision and to retain sediment volume within the channel upstream of the sensitive fan areas. Stream transport capacity is reduced and sediment is deposited in the reach immediately upstream of the check dam. This leads to a reduction of channel and sidewall scour and it also minimizes debris flow occurrence in those reaches. Check dams are usually built in reaches where debris flows would initiate in order to reduce the potential for debris flows to occur in the first place. Difficult site access will increase construction costs which will be the case in Roxburgh where site access to the upper reaches of the catchments is limited.

Potential environmental constraints are to be considered. At this preliminary stage, Golder is not aware of any environmental constraints that are present in the assessed catchments.

Flexible ring net barriers (see Figure 2) are commonly used for rockfall protection but are also utilised to provide protection against debris flows. The ring net barrier deforms upon impact of a debris flow and progressively deforms while absorbing the energy of the debris flow. Flexible ring-net barriers are a light support structure that can be installed within a short period of time. If installed in series at multiple sections across the channel in the catchment area, the retention volume can be increased. Ring net barrier systems can retain coarse grained debris while providing drainage of the retained material. Therefore, downstream reaches of the channel are exposed to considerably lower dynamic impact. Access is needed for maintenance, ideally from upstream of the installed structure, and to re-establish retention volume by removing retained debris after an event.

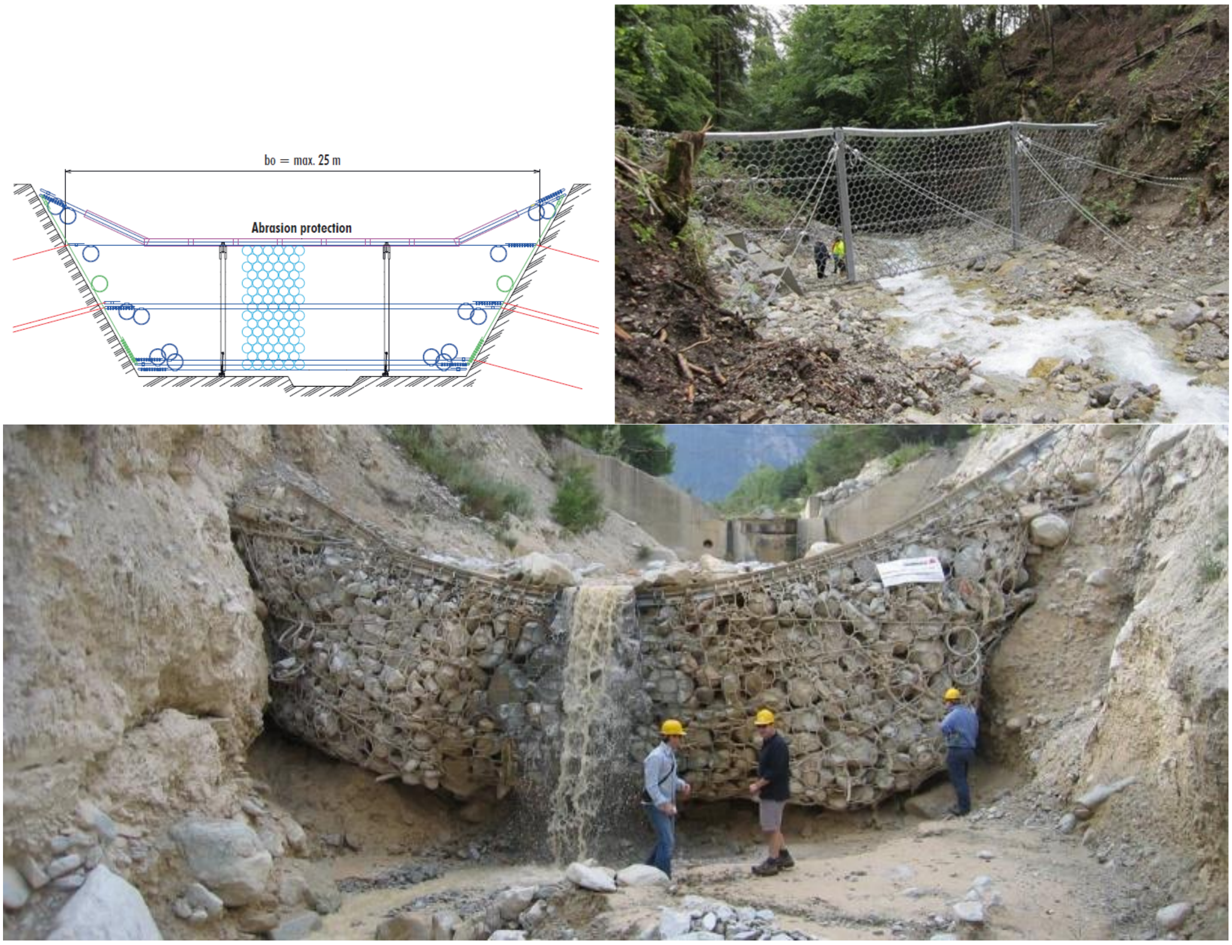

Figure 2: Pictures and schematic setup of ring net barrier systems used for debris flow protection; sourced from www.geobrugg.com.

Depending on the capacity of barrier required, the structure can be put in place to suit span widths of up to 25 m and an installation height of up to 6 m. Spiral rope anchors or self-drilling anchors with flexible anchor heads are used to anchor the debris flow barrier in the channel flanks. The installation does not require heavy construction machinery. A 3.5-5 t mini digger is capable of sufficiently supporting the installation process. Material is prefabricated and can be flown to site by helicopter where access is difficult.

- DIVERSION

Diversion or deflection structures are intended to redirect a debris flow in a controlled manner away from infrastructure to be protected. The diversion structure can be constructed from concrete blocks or locally available material, precast concrete elements, reinforced concrete, or gabion basket systems and need to be placed, with or without additional fasteners, above the infrastructure that requires protection.

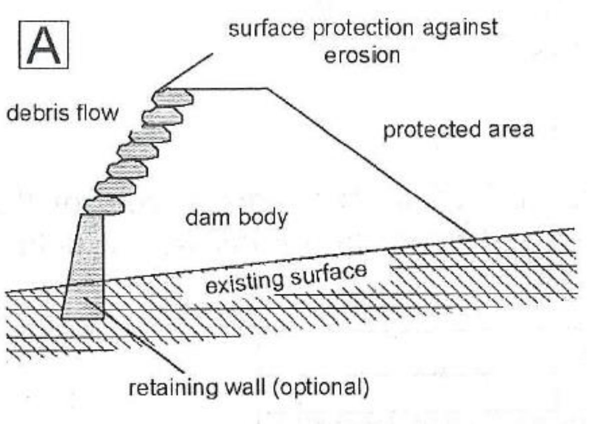

Figure 3: Schematic cross section of a deflection dam structure (sourced from Huebl & Suda, 2008).

To guarantee functionality of the structure, surface protection on the stressed side (facing the hazardous process) must be installed; e.g., riprap or reinforced concrete retaining wall (see Figure 3). Diversion structures can be placed along existing channel banks to protect against channel avulsion or upstream of dwellings to actively divert/guide the debris flow/debris flood past infrastructure.

Any level of reinforcement needed and information on specific setup for the deflection structures proposed in the following section on mitigation measures will need to be outlined on a case-by-case basis as part of detailed design.

2.0 GEOMORPHOLOGICAL SUMMARY AND GUIDANCE ON MITIGATION OPTIONS TO REDUCE THE RISK OF DEBRIS FLOWS

In this section, a summary of the geomorphological and hydraulic background information for each site at Roxburgh is presented. Hazards for each site are discussed and guidance given on mitigation of risk. For additional information, please refer also to the preliminary risk assessment presented in the "Geomorphological Assessment Report" (Golder Associates (NZ) Ltd, 2019). Photographs taken of the relevant SH8 crossings and immediate upstream as well as downstream sections of the creeks are presented in Appendix A.

Following multiple debris flow / debris flood events in recent human history (i.e., 1978 and 2017) Golder was asked by ORC to assess the geomorphological and hydrological background of the catchments of the creeks listed above. The geomorphological assessment of the catchments showed that the November 2017 event caused disturbance in the catchments leading to channel scour, entrainment of sediment through undercutting of channel banks and initiation of shallow slope instability in colluvium along the creek channels. Although debris reached the fan areas during this event leading to aggradation of debris and channel avulsion at the debris fans, sediment deposition also occurred within gentler channel reaches upstream of the debris fan areas. Therefore, sediment that could be entrained in future debris flow / debris flood events is readily available. For each catchment a summary of channel characteristics e.g., sediment source areas, evidence of sediment transport and sections of the current creek where sediment deposition occurs is given in Table 1. This summary also includes an estimation of available sediment volumes along each channel based on estimated yield rates (erosion cross-sectional area per metre channel length) of each catchment. These estimates do not include potential entrainment due to bank erosion and/or slope failure.

Table 1: 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 - 600 m asl: No evidence of recent erosion. 600 - 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
Golfcourse Creek	980 - 650 m asl: No evidence of recent erosion.	20,000

Creek	Channel characteristics	Estimated available channel sediment volume [m³]
	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.	
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

The preliminary assessment of the current SH8 crossings hydraulic capacity for clear-water peak flows (please refer to Table 2) showed that the 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 do not allow passage of 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 evaluated clear-water peak flow events.

Table 2: 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
Pumpstation Creek	Arched culvert	3.00	yes	yes	yes	yes
Reservoir Creek	Trapezoidal concrete channel/bridge	266	No	no	no	no

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
Golfcourse Creek (N)	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;
tc = time of concentration.

Due to the entrainment of sediment and debris, discharge during debris flow / debris flood events can be multiple factors greater than equivalent clear water peak flows (e.g., 2-3 times for debris floods, 5-40 times for debris flows (Arksey, R. & VanDine, D., 2008)).

The outcomes from the preliminary assessment is consistent with anecdotal information from the November 2017 event, in (GNS Science Consultancy, 2018). For further information about the catchment hydrology of the creeks discussed in this report please refer to the “Geomorphological Assessment Report” (Golder Associates (NZ) Ltd, 2019).

Details about site specific debris flow and debris flood related hazards, and conceptual mitigation options for discussion purposes are presented for each site in the following sections. It has to be noted that the deposition and aggradation of material at the debris fans is an ongoing natural process. Channel slope angles at the debris fans vary between 5 and 10 degrees in the different catchments and allow debris deposition and aggradation of debris depending on grain size and water flow. Due to the geomorphologic setting (colluvium and exposed schist) in each catchment, sediment is readily available to be transported or entrained during a future rainstorm event. The literature review and desktop study has shown that the debris flow/flood event in 1978 in Roxburgh has caused many slips along the channels and exposed and mobilised a lot of sediment. Increased sediment transport was visible during the following five years after this event as channel beds were not reoccupied by vegetation. Vegetation regrowth along the channel and in areas of exposed sediment (slips in colluvium) was visible after five years following this event.

The November 2017 event has mobilised and exposed a similar or even larger amount of sediment. Some of the existing slips were reactivated and existing vegetation cover (shrubs and tussock grass) removed. Large sections in colluvium along the channel slopes are now exposed due to slips that occurred due to undercutting of the creeks. An increased sediment influx during future rainstorm events is expected in the upcoming years; therefore, sediment deposition and aggradation of debris along the debris fans and within channel sections of lower slope angles (e.g., below 10 degrees) can be expected. The severity of future rainstorm events and associated surface runoff will control the erosional and depositional processes along the channel and the vulnerable debris fan areas of the discussed catchments. It is likely that the influence of climate change and potential upcoming years of more severe weather events will prolong the time of the catchments being exposed to increased sediment erosion before regrowth of vegetation can occur.

The mitigation options are presented looking at a cost-benefit perspective in regard to risk mitigation. A combination of measures will be required to maximise total risk reduction. Stabilisation of the catchment through planting and engineering structures in the upper catchment is not discussed in detail due to the likely excessive cost and long duration to establish vegetation. It has to be noted that the reduction of surface water runoff in combination with the stabilisation of the channel slopes as well as bedload control in the initiation and transport zone has to be the long-term goal to effectively be able to better control the effects on the debris fan areas.

Indicative costing is given for each mitigation measure based on estimates from manufacturers of proprietary structures (e.g., flexible ring net structures, pre-cast concrete culvert elements) and typical machinery costs. Site specific consent requirements for individual mitigation options must be clarified with local authorities as part of detailed design.

2.1 Pumpstation Creek

During the November 2017 event, sediment aggradation and channel avulsion occurred at the apex area of the debris fan, at the farm bridge crossing and the SH8 crossing.

Based on the preliminary assessment of the hydraulic capacity of the culvert at the SH8 crossing during clear water peak flow events, the current culvert does not meet the NZTA requirements for a 1/100-year design event.

Based on the geomorphological assessment of the catchment as well as the experience during recent debris flow/debris flood events, the preliminary hazard and risk assessment revealed that multiple residential dwellings and one critical infrastructure element (the Roxburgh/Roxburgh Village water supply pump station) are at risk of being damaged/inundated by debris in a future debris flow/debris flood event. The preliminary risk assessment concluded that the life risk for residential dwelling occupants adjacent to Pumpstation Creek is probably unacceptably high and that engineering options should be considered to reduce the risk.

Options to mitigate the risk as well as indicative cost estimates are presented in Table 3. Please also refer to Figure 4.

Table 3: Pumpstation Creek Mitigation Options - Indicative costs and benefits (refer also to Figure 4)

Option	Recommendations	Benefit	Comments	Indicative costs
1 Excavation of creek channel	Remove debris in creek channel bed from above the residential farm dwelling at 3746 Fruitlands-Roxburgh Road to the confluence with the Clutha River.	■ Maintain / increase channel capacity to counteract aggradation of debris within channel ■ Reduction of risk of channel avulsion	The excavated material can be positioned laterally along the channel banks to increase the channel capacity (see option 3). This will need to be repeated following future flood events.	NZ$ 20,000 – 30,000 (machinery, operation + material transport)
2 Replacement of existing SH8 culvert	The current capacity of approximately 3 m^3/s at the SH8 crossing could to be sufficiently increased to a high capacity type culvert such as box – or metal box type.	■ NZTA compliant ■ Reduces risk of culvert blockage and channel avulsion ■ Reduces risk of damage to residential dwelling below SH8 ■ Reduces risk of damage to Pumpstation infrastructure	Allow significant contingency in flow volume during detailed design so still functionality during debris flow event guaranteed.	NZ$ 250,000 – 300,000 (based on recent Humes indicative pricing for: 1 concrete pre-cast box culvert 4.0 m span x 2.0 m rise x 10.85 m long: $85,000 + GST + delivery and installation: $150,000 + consent and detailed design: $ 20,000
3 Installation of lateral deflection levees	The excavated material from clearing the creek channel can be utilised to build up and construct lateral deflection levees along the true left bank of the creek (similar to existing levees at Stevensons Creek).	■ Protection of residential dwellings / farming infrastructure ■ Reduces risk of harm to residents ■ Reduces risk of channel avulsion	The channel slope near the dwelling at 3746 Fruitlands-Roxburgh Road is between 5 and 10 degrees and deposition of debris is prominent along this reach. Therefore, the risk of channel avulsion above the dwelling is present and	NZ$ 40,000 – 60,000 (machinery, operation + material transport; material from excavation could potentially be used; therefore, costs reduced)

Option	Recommendations	Benefit	Comments	Indicative costs
	It should be considered to install a deflection structure above the residential farm dwelling at 3746 Fruitlands-Roxburgh Road to protect against channel avulsion and inundation by debris.		inundation of the property by debris and harm to residents is likely. A lateral deflection structure will direct a possible debris flow / debris flood past the dwelling. This is generally a cost-effective measure and excavated material from the channel can likely be used. Suitable armouring is likely to be required to avoid entrainment. Freeboard allowance: 2-3 m depending on design event.	
4 Installation of deflection / diversion structure	The construction of a deflection or diversion structure, such as engineered concrete wall, gabion baskets or earth embankment to protect the Pumpstation and residential dwelling at 3763 Fruitlands-Roxburgh Road downstream of SH8 crossing.	■ Protection of critical infrastructure ■ Reduces risk of disruption of services to residents ■ Reduces risk of harm to residents	At the current state, the SH8 crossing cannot cope with debris flows or debris floods adequately and avulsion and inundation by debris is likely to occur and potentially harm the residential dwelling as well as the Pumpstation infrastructure which are located downstream of the SH8 crossing in a future event. Freeboard allowance: 2-3 m depending on design event. Final dimensioning and setup of such a structure will be part of an	NZ$ 50,000 – 70,000 (based on a gabion system incl. foundation, individual elements: 2 m high, 2 m wide, 1 m deep at $500/m: Pumpstation, approx. 20 m required: $10,000 Residential dwelling, approx. 35 m required: $17,500 + consent and design: $20,000)

Option	Recommendations	Benefit	Comments	Indicative costs
			assessment during detailed design.	
5 Change of land use	A detailed hazard and risk assessment will be required to provide hazard zonation details for future land use planning. Existing properties could be acquired that are at unacceptable risk.	■ Reduces risk of harm to residents and infrastructure	The existing debris fan area will need to be subject to detailed evaluation of land use planning in the future.	NZ$ 400,000 per dwelling (based on current median house price in the area)
6 Installation of retaining structures	Retaining structures such as flexible ring net barrier or rigid concrete structures can be constructed to retain coarse-grained debris in the creek catchment above the debris fan. Installation of multiple systems can multiply retention volume capacity.	■ Actively reduces volume of coarse debris material to reach the debris fan ■ Reduces risk of harm to residents / infrastructure ■ Reduces sediment aggradation in channel at debris fan ■ Reduces risk of channel avulsion	Access tracks are needed for regular maintenance of any retaining structure. Concrete structures are more expensive, require heavy machinery or/and helicopter support and can only be priced as part of detailed design. Potentially high maintenance costs if regular replacements are required if damaging events occurs with high frequency.	NZ$ 250,000 - 500,0000 (Indicative cost estimate provided by Geobrugg: single ring net barrier UX120-H6: $110,000 + installation: $100,000 + 10 % maintenance costs/year

2.2 Reservoir Creek

A debris flow / debris flood event in October 1978 inundated the debris fan area at Reservoir Creek with debris. Subsequently, in the early 1980s, a concrete flume was constructed to protect residential dwellings and infrastructure and to guide any future debris flows / debris floods through the debris fan area in a controlled manner.

In November 2017, an intense rainfall event triggered a debris flow / debris flood event in the catchment. The concrete channel initially guided the debris as planned through to the confluence with the Clutha River but debris started to accumulate at the downstream end of the concrete channel (up to a few metres in height, anecdotal evidence). This led to debris filling the channel. Subsequently, the creek crossing at the bridge was blocked due to aggradation of debris and channel avulsion occurred upstream of the bridge leading to flooding of parts of Roxburgh with water and fine debris. In addition, bank erosion and undercutting occurred in the debris fan area upstream of the entrance to the lined concrete channel.

The preliminary assessment of the hydraulic capacity of the crossing at the SH8 during clear water peak flow events showed that the current bridge crossing has sufficient capacity to allow passage of clear-water peak flow events greater than 1/500 years. Aggradation of sediment within the concrete channel reduces its capacity, making channel avulsion more likely.

Based on the geomorphological assessment of the catchment as well as the experience during recent debris flow / debris flood events, the preliminary hazard and risk assessment suggest that occupants of dwellings on the debris fan at Reservoir Creek probably have unacceptably high life risk if an avulsion occurred and there may be a high probability of debris impacting more than one dwelling. Therefore, engineering options should be considered to reduce the risk.

Options to mitigate the risk of channel avulsion and the associated potential damage to residential dwellings and infrastructure, and to mitigate potential harm to the public are listed in Table 4. Please also refer to Figures 5, 6.

Table 4: Reservoir Creek Preliminary Mitigation Options - Indicative costs and benefits (see also Figures 5 and 6).

Option	Recommendations	Benefit	Comments	Indicative costs
1 Excavation of debris fan material at confluence with the Clutha River	Excavate accumulated debris material downstream of the lined concrete channel to allow efficient removal of debris by the Clutha River and to minimise early accumulation of debris during future events. Avoid undercutting of existing concrete lined channel by Clutha River. Expected volume of material that needs to be removed: 5,000-6,000 m^3 = about 10,000-15,000 t	■ Increase channel capacity ■ Reduces risk of channel avulsion ■ Reduces risk of harm to residents / infrastructure	The removal of excess material at this point will contribute to increase the capacity of the creek and reduce the risk to residents and infrastructure. This removed material could potentially be used to provide material for other suggested mitigation measures (e.g., lateral deflection levees, option 4). Repeat removal of excess debris material needs to take place after every event that results in substantial deposition of debris in this area.	NZ$ 10,000 – 20,000 (machinery, operation + material transport)
2 Excavation of creek channel along debris fan at regular intervals (including the concrete flume)	The removal of aggrading debris along the creek channel bed at regular intervals and after flooding events is recommended. We suggest to clear the length of the concrete lined channel after aggradation occurs to reinstate full capacity and extend the removal to upstream of the concrete channel.	■ Maintain / increase channel capacity to counteract aggradation within channel ■ Reduction of risk of channel avulsion ■ Reduction risk of harm to residents / infrastructure	Removing excess material from the channel will increase the capacity; therefore, allow for more sediment to be deposited during future event before avulsion can occur. This measure already has been proven to be successful at Stevensons Creek.	NZ$ 10,000 (machinery, operation + material transport)

Option	Recommendations	Benefit	Comments	Indicative costs
3 Installation of channel armouring	We recommend to install engineered stabilisation measures, such as engineered rock armour (plain or concreted) or gabion basket systems, along both channel banks upstream of the concrete flume. The currently implemented rock stabilisation along the true left bank above the lined concrete channel will likely be entrained in a future debris flow / flood event as it is not reinforced or fixed in place.	■ Reduction of channel bank erosion and entrainment of debris ■ Reduction of risk of channel avulsion ■ Reduction of risk of harm to residents / infrastructure	The channel armouring will contribute to the stabilisation of the banks in this area and prevent entrainment of material and undercutting of the banks. This mitigation measure will be necessary to reduce the risk of channel avulsion and potential inundation of residential dwellings. Entrainment of material from this area will also further decrease the capacity of the concrete flume. The channel armouring will also reduce the risk of further undercutting of the access farm track.	NZ$ 120,000 – 180,000 machinery, operation + material cost and transport: (e.g., riprap revetment, suggested length required along both banks: left bank 200 m, right bank 100m, average of 2 m height = approx. 600 m^3): $100,000 + consenting and design costs: $20,000 + 10 % maintenance / year
4 Vertical extension of lateral protection along concrete flume	Installation of vertical flow-guiding elements along both sides for the total length of the concrete lined channel. Such elements can improve the capacity of the existing channel (detailed assessment required) and can be installed as a backup mitigation measure. Constructed with cast-in-place reinforced concrete segments, concrete blocks, gabion basket	■ Increase of channel capacity ■ Reduce risk of channel avulsion ■ Reduce risk of harm to residents / infrastructure	The installation of vertical flow-guiding elements along the existing concrete channel will increase the channel capacity based on the height of the installed elements. This will not eliminate the risk of avulsion but will transfer the risk of channel avulsion, based on our current knowledge of the aggradation process in the channel during a debris flow/flood event, towards	NZ$ 100,000 - 180,000 (based on 1m height extension with reinforced concrete or gabion basket system at indicative $500/m Approximate length below bridge: 2 x 90 m + above bridge: 2 x 55 m = 290 m: $145,000 + consent and design: $ 20,000)

Option	Recommendations	Benefit	Comments	Indicative costs
	systems or wood and steel elements.		the SH8 crossing at the bridge. If breakage of the flow-guiding elements along the flume would occur during an event then avulsion will likely lead to inundation with debris and water at this location. The effectiveness of a specific flow-guiding element setup must be determined during detailed design.	
5 Installation of lateral training levees	Engineer and construct and lateral levees along the channel banks upstream of the concrete flume to guide future debris flow/flood material towards the lined concrete channel and to protect residential dwellings. Should be considered only in combination with channel excavation and armouring (options 2 and 3) as an added level of protection.	■ Reduces risk of channel avulsion ■ Increases channel capacity ■ Reduces of risk of harm to residents / infrastructure	This measure could an additional option to further reduce the risk of channel avulsion above the entrance of the concrete flume. Freeboard allowance: 2-3 m depending on design event. Land ownership must be clarified before construction can commence.	NZ$ 100,000 – 150,000 (machinery, operation + material cost and transport: $80.000 + consent, design etc.: $20,000 + 10 % maintenance / year
6 Installation of retaining structures	Construct retaining structures such as flexible ring net barriers or rigid concrete structures to retain coarse-grained debris in	■ Can actively prevent bouldery debris flow fronts from reaching the debris fan	This option will actively disrupt the debris transport and reduce the impact of the debris flow/flood at the debris fan area. Material is	NZ$ 250,000 - 500,0000 (Indicative cost estimate provided by Geobrugg:

Option	Recommendations	Benefit	Comments	Indicative costs
	the creek catchment above the debris fan. The installation of multiple systems can multiply retention volume capacity.	■ Actively reduces of volume of coarse debris material reaching the debris fan and associated sediment aggradation in channel. ■ Reduce coarse-grained sediment deposition at confluence with Clutha and associated risk of aggradation within existing concrete flume ■ Reduces risk of harm to residents / infrastructure ■ Reduces risk of channel avulsion	held back upstream; therefore, more channel capacity is readily available at the fan area. Possibly substantial costs can arise for maintenance and potential removal of debris after an event. Indicative installation requirements for flexible net barriers above the fan: ▪ section of the channel needs to be as straight as possible to assure clear flow conditions and banks are loaded equally ▪ channel gradient should be as flat as possible to allow maximum retention capacity and simultaneously a small loading of the net ▪ sufficiently high channel banks to avoid flow diversion around the net during an event ▪ Access tracks are required for maintenance of any retaining structure. Indicative locations were selected in this preliminary assessment	single ring net barrier UX120-H6: $110,000 + installation: $100,000 + 10 % maintenance costs/year)

Option	Recommendations	Benefit	Comments	Indicative costs
			based on the requirements stated above (see Figure 6) but these need to be verified and finalised during detailed design.	
7 Change of land use	Acquire existing properties with an unacceptable risk. A detailed hazard and risk assessment will be required to provide hazard zonation details for future land use planning.	■ Reduces risk of harm to residents	In this case potential avulsion can impact a large number of residential dwelling. A detailed hazard assessment will lead to a hazard map indicating zones of unacceptable risk. This will be required to further proceed with this mitigation measure.	NZ$ 400,000 per dwelling (based on current median house price in the area)

2.3 Golfcourse Creek

During the November 2017 event, sediment aggradation and channel avulsion occurred upstream of the apex area of the debris fan and upstream of the SH8 crossing. Debris blocked the double-level culvert setup. Bouldery debris inundated the farm access track parallel to the channel and SH8. Flood water and fine debris reached areas to the north (rugby field) and south of the crossing.

Based on the preliminary assessment of the hydraulic capacity of the culvert at the SH8 crossing during clear water peak flow events, the current culvert does not meet the NZTA requirements for a 1/100-year design event.

Based on the geomorphological assessment of the catchment as well as the experience during recent debris flow / debris flood events, the preliminary hazard and risk assessment revealed that multiple residential dwellings are at risk of being damaged / inundated by debris in a future debris flow / debris flood event.

The preliminary risk assessment concluded that the life risk for residential dwelling occupants adjacent to Golfcourse Creek is probably unacceptably high and that engineering options should be considered to reduce the risk.

Options to mitigate the risk as well as indicative cost estimates are presented in Table 5. Please also refer to Figure 7.

Table 5: Golfcourse Creek Preliminary Mitigation Options - Indictive costs and benefits (see also Figure 7).

Option	Recommendations	Benefit	Comments	Indicative costs
1 Excavation of creek channel	The creek channel needs to be cleared of aggrading debris at regular intervals and after flooding events that cause aggradation of debris. Clear the length of the creek channel from above the fan apex to the crossing at SH8.	■ Maintain / increase channel capacity to counteract aggradation of debris within channel ■ Reduces risk of channel avulsion	The excavated material can be positioned laterally along the channel banks to further increase the channel capacity and potentially reduce risk of avulsion.	NZ$ 20,000 – 30,000 (machinery, operation + material cost and transport)
2 Installation of lateral deflection levees	Construct lateral levees along the true left channel bank starting downstream of the farm access track that crosses the creek and ending above SH8 to protect residential dwellings to the north of the creek.	■ Protection of residential dwellings / horticultural infrastructure to the north of the creek ■ Reduces risk of harm to residents ■ Reduces risk of channel avulsion to the North	If the priority lies on the safety of residents than this mitigation measure will be required to protect existing dwellings in combination with option 1 to increase channel capacity and protect against avulsion. Freeboard allowance: 2-3 m depending on design event. Sourcing of local material preferred to reduce costs.	NZ$ 55,000 – 80,000 (machinery, operation + material transport: $30,000 + consent and design etc.: $20,000 + 10 % maintenance / year
3 Replacement of existing culverts	To increase the current hydraulic capacity at the SH8 crossing consider replacing of the existing culverts with a high capacity type culvert such as box – or metal box type should be considered.	■ Increase of capacity to above NZTA minimum design requirements	The existing “double-level” culvert system setup with the two current culverts at SH8 and the old road above the current SH8 level will cause avulsion due to the lack of capacity. A re-design will increase the capacity; however,	NZ$ 500,000 – 600,000 (based on recent HUMES indicative pricing for: 1 concrete pre-cast box culvert 4.0 m span x 2.0 m rise x 10.85m long = $85,000 + GST + delivery and installation:

Option	Recommendations	Benefit	Comments	Indicative costs
		■ Reduces risk of culvert blockage and channel avulsion	deposition of debris will still occur above and below the crossing due to the low slope angle along the channel in this area.	$150,000 + consent and design $30,000
4 Installation of retaining structure	Construct retaining structures such as flexible ring net barriers or rigid structures (retaining dam) to retain coarse-grained debris in the creek catchment above the debris fan apex. Access tracks are needed for maintenance of any retaining structure. Installation of multiple systems can multiply retention volume capacity. Flexible ring net barriers could be installed in the upper reaches whereas a retaining dam structure (such as a slot barrier) could be constructed in the lower reaches above the fan apex (see Figure 9).	■ Actively prevent bouldery debris flow fronts from reaching debris fan ■ Active reduction of volume of coarse debris material reaching the debris fan and associated sediment aggradation in channel ■ Reduces risk of harm to residents / infrastructure ■ Reduces risk of channel avulsion	The installation of sediment retaining structures can be a long-term mitigation method to reduce the sediment deposition on the fan and to further reduce the risk of inundation of residential dwellings and infrastructure on the fan. Potentially high maintenance costs for flexible barriers have to be considered at detailed design stage.	NZ$ 250,000 - 1.500,000 (Indicative cost estimate provided by Geobrugg: single ring net barrier UX120-H6: $110,000 + installation approx.: $100,000 + design, consent, etc.: $20.000 retaining dam structure / slot or sectional barrier: $ 800,000 - 1.300,000 incl. design)
5 Change of land use	Acquire existing properties at unacceptable risk. A detailed hazard and risk assessment will be required to provide hazard	■ Reduces risk of harm to residents	The existing debris fan area will need to be subject to detailed evaluation of land use planning in the future. Currently the	NZ$ 400,000 per dwelling (based on current median house price in the area)

Option	Recommendations	Benefit	Comments	Indicative costs
	zonation details for future land use planning. Future land use: prohibit further residential development on the debris fan area to the south of the creek upstream of SH8.		dwellings to the North of the channel are at risk of being affected by debris during a future debris flow event. A detailed hazard assessment will lead to a hazard map indicating zones of unacceptable risk and will essential to further proceed with this mitigation measure.	

2.4 Black Jacks Creek

During the November 2017 debris flow / flood event, sediment aggradation resulted in channel avulsion at the apex area of the debris fan and upstream of the SH8 crossing. Bouldery debris blocked the existing culvert and inundated SH8 and the rest area below SH8.

Based on the preliminary assessment of the hydraulic capacity of the culvert at the SH8 crossing during clear water peak flow events, the current culvert does not meet the NZTA requirements for a 1/100-year design event. It is likely that channel avulsion and inundation of debris will affect SH8 during future events but there is a low probability that road users will be harmed.

The preliminary hazard and risk assessment revealed that there are no residential dwellings located within the preliminary hazard zones (see Figure 10).

The preliminary risk assessment concluded that engineering options should be considered to reduce the risk of channel avulsion.

Options to mitigate the risk as well as indicative cost estimates are presented in Table 6. Please also refer to Figure 8.

Table 6: Black Jacks Creek Preliminary Mitigation Options - Indicative cost benefit (see also Figure 8).

Option	Recommendations	Benefit	Comments	Indicative costs
1 Change of land use	Consider not reopening this area to the public as it is at high risk of inundation by debris during future events.	■ Reduces risk of harm to the public on SH8	The former public rest area below SH8 was closed after the November 2017 debris flow / flood event.	NONE
2 Excavation of creek channel	The removal of aggrading debris along the creek channel bed at regular intervals and after flooding events is recommended to maintain or re-establish channel capacity.	■ Maintain / increase channel capacity to counteract aggradation of debris within channel ■ Reduces risk of channel avulsion	Consider removing excess debris along the length of the creek channel from the fan apex to the confluence with the Clutha River. Due to the size of the catchment and availability of sediment in the catchment it is likely that channel avulsion will continue to inundate SH8 during large-scale debris flow / flood events.	NZ$ 10,000 – 20,000 (machinery, operation + material cost and transport)
3 Replacement of existing SH8 culvert	The current capacity at the SH8 crossing needs to be significantly increased to high capacity type culvert such as concrete box – or metal box type.	■ Increase of capacity to beyond NZTA minimum design requirements ■ Reduces risk of culvert blockage and channel avulsion during smaller debris flow / flood events	A replacement will likely reduce the risk of blockage at the SH8 crossing but not eliminate the risk of avulsion and debris inundation onto SH8 during future events as an abundance of sediment is available in the catchment.	NZ$ 250,000 – 300,000 (based on recent Humes indicative pricing for: 1 concrete pre-cast box culvert 4.0 m span x 2.0 m rise x 10.85 m long: $85,000 + GST + delivery and installation: $150,000 + consent and detailed design: $20,000

2.5 Stevensons Creek

A debris flow / debris flood event in October 1978 inundated the debris fan area with blocky and coarse-grained sediment, scoured and entrained sediment along the creek. Subsequently lateral levees were constructed upstream from the SH8 crossing using the coarse-grained debris material.

During the November 2017 event, sediment aggradation occurred within the channel but the creek remained within the existing channel bed.

The preliminary assessment of the hydraulic capacity of the crossing at the SH8 during clear water peak flow events showed that the current bridge crossing has sufficient capacity to allow passage of clear-water peak flow events greater than 1/500 years.

However, the process of aggradation of sediment within the channel can lead to reduction of otherwise sufficient hydraulic capacity of the crossing and avulsion may harm residential dwellings during future events; therefore, engineering options should be considered to reduce the risk.

Options to mitigate the risk as well as indicative cost estimates are presented in Table 7. Please also refer to Figure 9.

Table 7: Stevensons Creek Preliminary Mitigation Options - Indictive cost benefit (see also Figure 9).

Option	Recommendations	Benefit	Comments	Indicative costs
1 Excavation of creek channel	The removal of aggrading debris along the creek channel bed at regular intervals and after flooding events is recommended to maintain or re-establish channel capacity. Maintain channel capacity to the east of SH8 to avoid channel avulsion and harm to residential dwellings.	■ Maintain / increase channel capacity to counteract aggradation of debris within channel ■ Reduces risk of channel avulsion	Clear the length of the creek channel from the fan apex to the confluence with the Clutha River. Due to the size of the catchment and availability of sediment in the catchment it is possible that channel avulsion can affect SH8 if the existing culvert capacity is exceeded during large-scale debris flow / flood events. This mitigation method will be essential to reduce the risk of channel avulsion during future events.	NZ$ 40,000 – 50,000 (machinery, operation + material cost and transport)
2 Installation / extension of lateral training levees	The lateral levees along both channel banks upstream of the existing levees could be extended to protect residential dwellings to the north of the creek.	■ Protection of residential dwellings / horticultural infrastructure to the north of the creek ■ Reduces risk of harm to residents ■ Reduces risk of channel avulsion to the North	This measure will only be effective in combination with mitigation option 1. This is generally a cost-effective measure and excavated material from the channel can likely be used.	NZ$ 40,000 – 60,000 (machinery, operation + material transport; material from excavation could potentially be used; therefore, costs reduced)

Option	Recommendations	Benefit	Comments	Indicative costs
3 Installation deflection structures	Engineer and construct a deflection or diversion structure, such as engineered concrete walls, earth berms or gabion baskets systems to protect the residential dwelling at 4441 Roxburgh-Ettrick Road just downstream from the SH8 crossing.	■ Protection of residential dwellings / horticultural infrastructure to the south of the creek ■ Reduces risk of harm to residents	This option could be implemented to further reduce the risk of inundation by debris in a future event if channel avulsion occurs. Dimensions and design have to be determined at a detailed design stage.	NZ$ 60,000 – 80,000 (based on 2 m high, 2 m long, 1 m thick gabion system at indicative $500/m, approx. length of deflection structure 80 m: $40,000 + consent and design: $20,000)
4 Installation of retaining structures	Retaining structures such as flexible ring net barriers or rigid structures (retaining dam) to retain bouldery debris in the creek catchment above the debris fan apex could be constructed. Installation of multiple systems can multiply retention volume capacity. Flexible ring net barriers could be installed in the upper reaches of the main channel whereas a retaining dam structure could be constructed in the lower reaches above the fan apex (see Figure 09).	■ Can actively prevent bouldery debris flows fronts to reach lower reaches at debris fan ■ Active reduction of volume of coarse debris material to reach the debris fan ■ Reduction of risk of harm to residents / infrastructure ■ Reduction of coarse-grained sediment aggradation at debris fan ■ Reduction of risk of channel avulsion	The installation of sediment retaining structures can be a long-term mitigation method to reduce the sediment deposition on the fan and to further reduce the risk of inundation of residential dwellings and infrastructure on the fan. Access tracks are required for regular maintenance of any retaining structure. Potentially high maintenance costs for flexible barriers must be considered at detailed design stage. Currently indicative placement will need to be verified during detailed design.	NZ$ 200,000 – 1.500,000 (Indicative cost estimate provided by Geobrugg: single ring net barrier UX120-H6: $110,000 + installation approx.: $100,000 + design, consent, etc.: $20.000 retaining dam structure: $1.000,000 – 1.500,000 incl. consent and design)

Option	Recommendations	Benefit	Comments	Indicative costs
5 Change of land use	Existing properties at unacceptable risk could be acquired. Future land use: prohibit further residential development on the debris fan area without conducting a detailed hazard and risk assessment.	■ Reduction of risk of harm to residents	A detailed hazard and risk assessment will be required to provide hazard zonation details for future land use planning.	NZ$ 400,000 per dwelling (based on current median house price in the area)

3.0 LIMITATIONS

Your attention is drawn to the document, “Report Limitations”, as attached (Appendix B). 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.

4.0 REFERENCES

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Golder Associates (NZ) Limited

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FIGURES

APPENDIX A

Roxburgh SH8 Crossings Overview

As per scope outlined by ORC, the SH8 (State Highway) crossings of Pumpstation Creek, Reservoir Creek, Golfcourse Creek, Black Jacks Creek and Stevensons Creek were inspected during a field investigation on 25 February to 1 March 2019. Topographic data was collected to assist a preliminary verification of culvert capacity at the crossings at SH8. Approximate slope measurements were taken using a handheld clinometer. Distances were measured using a measuring tape. Elevation levels were extrapolated from LIDAR imagery from 2008 that was supplied to Golder by ORC. SH8 culvert details were supplied by WSP OPUS (email correspondence WSP OPUS, 18 February 2019).

The following paragraphs describe the state of the crossings at SH8 during the time of the field investigation.

1.0 PUMPSTATION CREEK

- Channel slope US: 5˚
- Channel slope DS: 6˚
- Culvert Slope: 3˚
- Road level (LIDAR 2008): 95.3 m
- Culvert US invert elevation: 93.2 m
- Culvert DS invert elevation: 93.0 m
- Elevation above culvert crest: 94.4 m

Table 1: Pumpstation Creek - NZTA culvert details.

X-Coordinate	1311051.106
Y-Coordinate	4951299.514
Structure Type	Culvert
Culvert/Bridge No.	11
Culvert Shape	Arched
Culvert Length (m)	13.2
Culvert Size (mm)	1720
Culvert Width (mm)	1580
Culvert Area (m^2)	NA

Figure 1: Pumpstation Creek – SH8 crossing, view from upstream.

Figure 2: Pumpstation Creek – SH8 crossing, panoramic view from upstream.

Figure 3: Pumpstation Creek - view from SH8 upstream.

Figure 4: Pumpstation Creek – SH8 crossing, culvert, views from upstream.

Figure 5: Pumpstation Creek – SH8 crossing, view from downstream.

Figure 6: Pumpstation Creek - view of creek channel, downstream from SH8 crossing.

Figure 7: Pumpstation Creek – after 26 November 2017 event, looking upstream from SH8 (source: Withington, Teviot Valley Tempest, 2018).

2.0 RESERVOIR CREEK

- Channel slope US: 6˚
- Channel slope DS: 5˚
- Culvert Slope: 6˚
- Road level (LIDAR 2008): 98.9 m
- Culvert US invert elevation: 96.3 m (=2.2 m + 0.4 m)
- Culvert DS invert elevation: 94.6 m (=3.9 m + 0.4 m)
- Elevation above culvert crest: 98.5 m
- Concrete channel length: approx. 180 m

Table 2: Reservoir Creek - NZTA culvert details.

X-Coordinate	1311785.807
Y-Coordinate	4950807.377
Structure Type	Bridge – Concrete precast – double hollowcore
Culvert/Bridge No.	3674
Bridge span (m)	9
Bridge width (m)	13

Figure 8: Reservoir Creek – UAV image, view of channel upstream of entrance to lined concrete flume.

Figure 9: Reservoir Creek - SH8 crossing, view from upstream.

Figure 10: Reservoir Creek - SH8 crossing, view from downstream.

Figure 11: Reservoir Creek - SH8 crossing, view downstream.

Figure 12: Reservoir Creek, UAV view of debris fan into Clutha River.

Figure 13: Reservoir Creek, view of fan area at confluence to Clutha River.

Figure 14: Reservoir Creek - View from bottom end of channel upstream.

Figure 15: left: Aggradation of debris at entrance to concrete channel after 26 November 2017 event (source: Withington, Teviot Valley Tempest, 2018); right: Channel status 26 February 2019.

Figure 16: Aggradation of debris above SH8 crossing and avulsion of water and fine debris on 26 November 2017 (source: Withington, Teviot Valley Tempest, 2018).

3.0 GOLFCOURSE CREEK

- Channel slope US: 8˚
- Channel slope DS: 6˚
- Culvert 1 (old, upslope SH8) Slope: 5˚
- Culvert 2 (SH8) Slope: 3˚
- Old road level (LIDAR): 108.4 m
- SH8 level (LIDAR): 106.9 m
- Culvert 2 (SH8) US invert elevation: 105.9 m (= 0.6 m + 0.4 m)
- Culvert 2 (SH8) DS invert elevation: 105.1 m (= 1.4 m + 0.4 m)
- Elevation above culvert 2 crest: 108.0 m

Table 3: Golfcourse Creek – NZTA culvert details.

X-Coordinate	1312349.5	1312349.631
Y-Coordinate	4948669.87	4948668.879
Structure Type	Culvert	Culvert
Culvert/Bridge No.	18	1
Culvert Shape	Box shaped	Box shaped
Culvert Length (m)	9.8	9.7
Culvert Size (mm)	1150	1400
Culvert Width (mm)	1850	1800
Culvert Area (m^2)	2.13	2.52

Figure 17: Golfcourse Creek - Culvert at old road above SH8 level, view from upstream.

Figure 18: Golfcourse Creek - channel, view upstream from SH8 crossing.

Figure 19: left: old road culvert, view from upstream; right: old road culvert, view from SH8.

Figure 20: Golfcourse Creek, SH8 crossing, view from old road/old culvert, downstream.

Figure 21: Golfcourse Creek – SH8 crossing, view from downstream.

Figure 22: Golfcourse Creek - channel, view downstream.

Figure 23: Golfcourse Creek - November 2017, left: looking from downstream at old road culvert; right: looking at channel upstream (source: Withington, Teviot Valley Tempest, 2018).

4.0 BLACK JACKS CREEK

- Channel slope US: 8˚
- Channel slope DS: 11˚
- Culvert Slope: 3˚
- Road level (from LIDAR 2008): 88 m
- Culvert US invert elevation: 86.7 – 86.4 m (=0.9 to 1.2 m + 0.4 m)
- Culvert DS invert elevation: 86.3 m (= 1.3 m + 0.4 m)
- Elevation above culvert crest: 87.6 m

Table 4: Black Jacks Creek – NZTA culvert details.

X-Coordinate	1312339.053
Y-Coordinate	4946576.831
Structure Type	Bridge – Concrete cast insitu
Culvert/Bridge No.	3721
Bridge Span (m)	4.9
Bridge Width (m)	7.3

Figure 24: Black Jacks Creek - SH8 crossing, view from upstream.

Figure 25: Black Jacks Creek – channel, view upstream.

Figure 26: Black Jacks Creek – left: SH8 crossing, view from downstream; right: channel, view downstream of SH8.

Figure 27: Black Jacks Creek - Nov 2017, left: view SH8 and upstream; right: view from SH8 downstream (source: Withington, Teviot Valley Tempest, 2018).

5.0 STEVENSONS CREEK

- Channel slope US: 5˚
- Channel slope DS: 6˚
- “Culvert” Slope: 6˚ (bridge with natural stream bed underneath)
- Road level SH8 (LIDAR 2008): 110 m
- Culvert US invert elevation: 107.5 m (=2.1 m + 0.4 m)
- Culvert DS invert elevation: 106.6 m (= 3.0 m + 0.4 m)
- Elevation above culvert crest: 109.6 m

Table 5: Stevensons Creek - NZTA culvert details.

X-Coordinate	1312710.355
Y-Coordinate	4945397.353
Structure Type	Bridge
Culvert/Bridge No.	3734
Culvert Shape	Bridge – Concrete cast insitu, double hollowcore
Bridge Span (m)	10
Bridge Width (mm)	9.2

Figure 28: Stevensons Creek - SH8 crossing, view from upstream.

Figure 29: Stevensons Creek - channel, view upstream from SH8.

Figure 30: Stevensons Creek - SH8 crossing, view from downstream; channel recently cleared by heavy machinery.

Figure 31: Stevensons Creek - channel, view downstream of SH8 crossing.

APPENDIX B

Report Limitations

Report Limitations

This Report/Document has been provided by Golder Associates (NZ) Limited ("Golder") subject to the following limitations:

i) This Report/Document has been prepared for the particular purpose outlined in Golder's proposal and no responsibility is accepted for the use of this Report/Document, in whole or in part, in other contexts or for any other purpose.

ii) The scope and the period of Golder's Services are as described in Golder's proposal, and are subject to restrictions and limitations. Golder did not perform a complete assessment of all possible conditions or circumstances that may exist at the site referenced in the Report/Document. If a service is not expressly indicated, do not assume it has been provided. If a matter is not addressed, do not assume that any determination has been made by Golder in regards to it.

iii) Conditions may exist which were undetectable given the limited nature of the enquiry Golder was retained to undertake with respect to the site. Variations in conditions may occur between investigatory locations, and there may be special conditions pertaining to the site which have not been revealed by the investigation and which have not therefore been taken into account in the Report/Document. Accordingly, if information in addition to that contained in this report is sought, additional studies and actions may be required.

iv) The passage of time affects the information and assessment provided in this Report/Document. Golder's opinions are based upon information that existed at the time of the production of the Report/Document. The Services provided allowed Golder to form no more than an opinion of the actual conditions of the site at the time the site was visited and cannot be used to assess the effect of any subsequent changes in the quality of the site, or its surroundings, or any laws or regulations.

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