Project Number: 6-XO015.00

Shepherds Hut Creek

Debris Flow Hazard Report

14 September 2022

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150 YEARS IN AOTEAROA

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0	Issue for Client comment
1	Updating report following Client comments (Section 5.1 added)

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Disclaimers and Limitations

This report ('**Report**') has been prepared by WSP exclusively for Otago Regional Council ('**Client**') in relation to debris flow hazard assessment associated with Shepherds Hut Creek ('**Purpose**') and in accordance with the Offer of Service letter dated 6 May 2022. The findings in this Report are based on and are subject to the assumptions specified in the Report and Offer of Service. WSP accepts no liability whatsoever for any reliance on or use of this Report, in whole or in part, for any use or purpose other than the Purpose or any use or reliance on the Report by any third party.

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1 Introduction

1.1 Background

During the morning hours on 21 April 2022, a period of heavy rain fall occurred near Glenorchy, Central Otago. This rainfall event initiated a debris flow in the Shepherds Hut Creek catchment.

This debris flow travelled down the creek channel where it was constrained by a 1.8 m diameter culvert beneath the Glenorchy – Queenstown Road. This culvert was rapidly blocked, and debris then backed up and inundated the road depositing a significant volume of debris requiring emergency response work to re-open the road.

1.2 Scope of works

As set out in our offer of service dated 6 May 2022, we have undertaken the following works:

- Desktop study reviewing the available online information, including the underlying geology, aerial photography, and local and regional authority natural hazard portals.
- Site aerial inspection of alluvial fan and upper catchment, a site walkover carried out in areas accessible from the roadway.
- Preparation of a report to document the following items:
    - Description of event processes, debris characteristics, channel characteristics and associated impacts.
    - Estimation of debris extents/depths, and volumes, based largely on contractor work records and observations made immediately after the event.
    - Assessment of upstream drivers and debris sources.
    - Comment on the hazard/risk posed by this type of event.
    - High-level recommendations relating to requirement for further assessments or management actions.

2 Recent Debris Flow Events

This is the second rainstorm to trigger a debris flow in the Shepherds Hut Creek catchment within the last 5 years.

In July 2018 a debris flow occurred which resulted in a temporary closure of the road. Subsequently minor remedial works were undertaken to clear debris on the road and reinstate the culvert.

In April 2022 a short duration heavy rainstorm caused a debris flow to occur which resulted in full loss of service to the road for approximately 36 hours and extensive clearing works costing approximately NZ$200,000. Records provided by Downer indicate that approximately 3400 m^3 of debris was cleared from the road and from within the creek bed immediately upstream following the debris flow. An emergency inspection was undertaken by WSP Geotechnical Engineer, Maddison Phillips, on 26 April 2022. It was observed during this inspection that the debris that inundated the carriageway and was cleared, was typically dominated by cobble to boulder size material. At the time of the initial emergency response inspection, there was also a notable amount of woody debris blocking the inlet to the culvert. Debris was deposited above existing road level (~3.0m debris height from existing creek bed level) on the upstream side of the culvert. Subsequently water was flowing onto the road and downhill toward Glenorchy.

A ground-based inspection of the creek channel undertaken on 17 May 2022 identified that a significant amount of finer material (sand to gravel size) was also transported by the debris flow and deposited within the creek channel.

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3 Site Description

3.1 Geological Setting

The published geological map[1] for the area identifies that the road and culvert have been constructed over Holocene fan deposits which are described as "Loose, commonly angular, boulders, gravel, sand and silt forming alluvial fans; grades into scree upslope & valley alluvium".

To the east of the fan, the geology consists of undifferentiated Caples Terrane TZIIB semischist which is described as "*Well foliated psammitic and pelitic semischist; phyllite; minor greenschist, metachert and metaconglomerate; TZ2B*".

The alluvial fan has been formed by eroding into schist bedrock and building out onto moraine and river terrace deposits. The published geology is consistent with observations made on-site.

3.2 Geomorphology

The Shepherds Hut Creek catchment trends east to west and drains part of the western flank of the Richardson Mountains. Upstream from the culvert the catchment is characterised by a west facing slope which extends from Wire Saddle (~1800 m asl) down to Lake Wakatipu (~320m asl). The catchment is drained by Shepherds Hut Creek and a number of smaller tributaries. As the topography flattens out in the lower reaches of the catchment, the creek fans out into Lake Wakatipu.

The catchment is relatively steep with an overall gradient of 20-40˚, around 15-25˚ on the true left hand back in the upper section which is dominated by large slow creeping mass movements and 20-40˚ on the true right bank, with localised steeper sections. Downstream from the fan apex the fan is sloping at a shallow gradient (approximately 5- 15˚). An oblique image of the site is shown in Figure 1 highlighting key features in the catchment

Upstream from the fan apex, the vegetation cover in the upper reaches of the catchment is largely tussock on bare soil, with beech forest bounding the stream up to ~1000 m elevation. The banks confining the creek on both sides become steep (~30 – 50˚). Where the catchment and banks become steeper, there is extensive evidence of soil erosion and toppling of trees.

Slope processes within the catchment appear to be primarily soil creep and shallow, translational landslides which provide adequate sediment supply to result in aggradation of the stream bed. Aggradation of material can block the creek and trigger break out floods. From the apex of the fan downstream toward Glenorchy Road the stream gradient flattens out, resulting in a loss of energy and subsequent deposition of sediment and increased bedload. Aerial imagery shows there is another channel which originates from the fan apex and crosses Glenorchy-Queenstown Road further to the north. It is likely this channel flows ephemerally.

3.3 Existing Infrastructure

Shepherds Hut Creek passes beneath the Glenorchy-Queenstown Road via a 1.8m diameter concrete culvert with stacked stone wing walls and head walls. There is a swale drain on the right-hand shoulder which drains to a 600mm diameter culvert that was upgraded following the debris flow event in 2018.

At the time of the site walkover this culvert was clear, and the creek immediately upstream had been cleared and reformed.

[1] Turnbull, I.M. (compiler) 2000. Geology of the Wakatipu area. Institute of Geological and Nuclear Sciences 1:250,000 geological map 18. Lower Hutt, New Zealand.

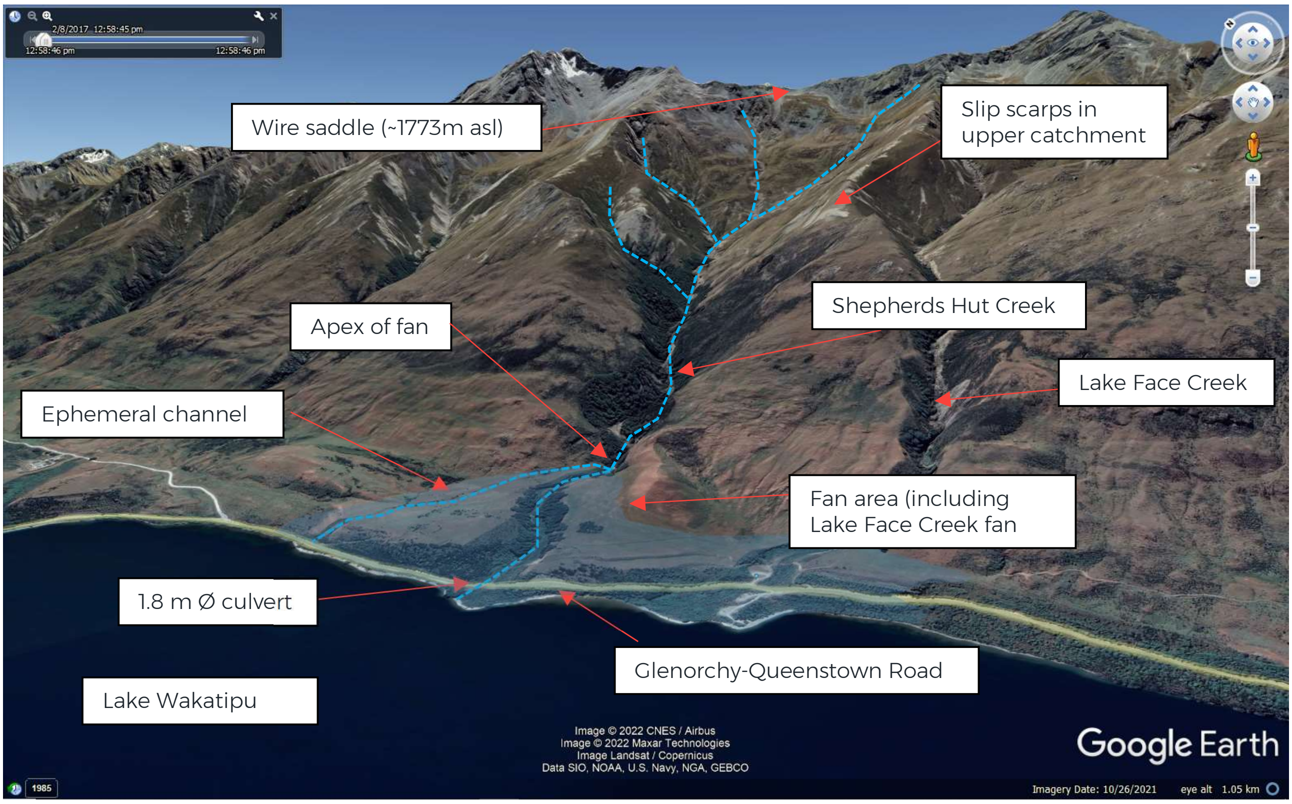

Figure 1: Shepherds Hut Creek catchment (source: Google Earth, 2022).

3.4 Melton Ratio

The Melton Ratio (watershed relief divided by the square root of watershed area) is used to estimate a catchments capacity to generate debris flows and differentiate between catchments which are prone to debris floods vs debris flows[2]. Typically, catchments which produce debris flows have a Melton ration of > 0.6.

The 20m interval topographic map[3] was used to estimate the catchment relief area. The relief was found to be approximately 1.48 km (i.e., 1800 – 320m asl) and the catchment area was estimated at 4.08 km^2 using QLDC's GIS viewer. The resulting Melton ratio for Shepherds Hut Creek is 0.73. This suggests the catchment is able to generate debris flows as opposed to debris floods. This is consistent with the historic evidence of the site.

3.5 Natural Hazards Database

As part of the desktop study, a search was made of the relevant local authority natural hazard maps (Otago Regional Council and Queenstown Lakes District Council hazard) portals. The following natural hazards are associated with the site:

- The QLDC and ORC natural hazards portal identifies that the site is situated within an active, alluvial fan area. The alluvial fan has been characterised as a debris-dominated fan. (GNS Report)[4]. This is consistent with the observations made on-site.
- The QLDC hazards portal identifies the site as being possibly susceptible to liquefaction. (Opus Report).

[2] Millard, T.H., D.J. Wilford and M.E. Oden. 2006. *Coastal fan destabilization and forest management*. Res. Sec., Coast For. Reg., BC Min. For., Nanaimo, BC. Tec. Rep. TR-034/2006
[3] https://www.topomap.co.nz/
[4] Opus International Consultants Ltd. 2009. *Otago Alluvial Fans Project*. Dunedin (NZ). Ref: 6CWM03.58

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3.6 Historic Aerial Imagery

Aerial photographs from 1959 to 2001 were obtained from RETROLENS (https://retrolens.co.nz/) for Shepherds Hut Creek and the surrounding area. The purpose for the aerial photography review was to gather information regarding the behaviour of the creek and to gather evidence indicative of debris flow and debris flood events such as areas of slope instability that may provide source material or contribute towards damming of the stream, changes in the morphology of the catchment (e.g., stream bed aggradation, bank erosion and avulsion) and changes in vegetation cover within the catchment.

No significant changes in the catchment or size and shape of the alluvial fan were noted in the aerial imagery other than some apparent changes in the vegetation cover downstream of the culvert in the 2001 image suggestive of a potential event having occurred between 1988 - 2001. The historic aerial images are included in Appendix A.

4 Field Investigations

4.1 Creek Survey

A channel survey was undertaken by walking up Shepherds Hut Creek from the culvert, taking into consideration the recent activity in the catchment. A reach of approximately 300 – 500 m upstream from the culvert was inspected on foot. This section showed evidence of debris heights up to 2 – 3 m above the creek bed in places where discolouration was noted on the vegetation.

A logjam was noted approximately 300 to 500 m upstream from the culvert. It was observed that this tree had trapped a significant volume of sediment and woody debris. Whilst it is likely that this tree and sediment will slowly erode, breaching of this sediment trap under debris flow conditions has the potential to mobilise a significant volume of material. Entrainment of this material would result in a large volume of material inundating the road.

4.2 Aerial Inspection

An aerial inspection was completed on 26 May 2022 with WSP Engineering Geologist, Mark Shaw, Hugo Bloor (ORC), Ben Greenwood (QLDC) and Jim Garland (Downer). The purpose of the aerial inspection was to assess the upstream debris flow drivers and identify the presence of potential debris sources as well as gain an understanding of the general channel morphology. The findings from the aerial inspection and creek survey are summarised below:

Section 320m – 360 m above sea level (asl)

In the lower reaches of the stream the channel has been cleared and widened to a width of approximately 10 m. This section of the channel is directly upstream of the culvert and dominated by deposition of cobbles and boulders. Moderately steep banks typically 15 - 20˚ along the channel comprise sands, gravels, and cobbles with occasional boulders (shown in Figure 2). The channel walls are vegetated mainly with native shrubs. There is no evidence of the debris flow having overtopped the channel through this section during the most recent event.

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Figure 2: Section 320 – 360 m asl - Lower reaches of Shepherds Hut Creek, looking downstream towards Glenorchy-Queenstown Road culvert and Lake Wakatipu.

Section 360 – 380 m asl

Through this section, the creek narrows and tends to step down over deposited boulder weirs (Figure 3). The stream channel is approximately 1m to 6 m wide. The bedload is dominated by boulders and cobbles. Sections of the channel are incised up to approximately 1.0 m. Silty deposits are visible on the vegetation bounding the creek channel to a depth of approximately 1 m above the existing creek level.

Figure 3: Section 360 – 380 m asl of Shepherds Hutt Creek showing incision of current stream of approx. 1m into bouldery debris fan material.

Section 380 – 470 m asl

Approximately 300 m upstream from the road the creek channel widens, and a large wooden log jam was present (Figure 4). Upstream of the log jam a significant volume of sand to boulder sized sediment has been deposited as well as a more woody debris (Figure 5). Water channels have begun to incise behind this log jam.

It is considered likely that following a further significant rainfall event this natural dam has the potential to breach suddenly and mobilise a significant amount of material towards the road.

Steep bluffs along the banks of the channel in this section are present and comprise loose colluvial and alluvial deposit. Mature vegetation is present along the crest of the bluffs. The bluffs show noticeable evidence of instability (overhanging trees, tree jacking and erosion and undercutting of the bluff below trees). These bluffs provide a significant amount of loose, erodible material which can be entrained in a future debris flow event adding to the bedload of the creek. Through this section the vegetation begins to transition from shrubbery to established beech.

Figure 4: Section 380 – 470 m asl - Large logjam damming a significant volume of debris upstream.

Figure 5: Section 380 – 470 m asl - View upstream of the logjam, showing a significant number of wooden debris and sediment has been deposited.

Section 470 – 900 m asl

This section is bound by forest on the true right-hand side of the stream with evidence of ongoing erosion and extensive soil creep and shallow translational failures on the true left-hand bank. Both the left-hand and right-hand banks are steep through this section (e.g., 30 - 50°)

The depth of overburden soils overlying bedrock appears moderate (up to 3 – 5 m) here and capable of contributing large volumes of material in the event of a landslide occurring in the steep bare soils in the true left-hand bank (Figure 6). Beech forest is present along the channel and wooden debris has entered the creek. The forest is beginning to thin out and transition into tussock.

There is still significant bedload through this section with some exposed bedrock on the true right-hand bank and the creek cutting down to bedrock in places. Some of the scarps appear quite large (>100 m in length – shown in Figure 7).

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Figure 6: Section 470 – 900m asl - Exposed bedrock on right left-hand bank and steep eroding soil on true left-hand bank.

Figure 7: Section 900 – 1400m asl - Extensive evidence of shallow mass movements with distinct scarps on slopes along the true left-hand bank

Section 900 – 1400m asl

This section is steep (>30°) with the stream narrowing and incised down to bedrock. Numerous slip scarps bound the creek and add boulders to the creek channel particularly at the confluence of the main tributaries. The scarps appear shallow, approximately 1.0m deep. The vegetation through this section is dominated by alpine tussocks.

Figure 8: Section 900 – 1400 m asl - Widespread erosion along banks in the upper catchment and evidence of creeping mass movements.

Figure 9: Section 900 – 1400 m asl - Erosion within colluvium along banks in the upper catchment.

Section 1400 – 1800 m asl

This section within the upper catchment of Shepherds Hutt Creek has minimal (approximately 1 – 2.0m of topsoil and colluvium) soil cover and predominantly displays exposed schist bedrock. It is considered this section provides little contribution of material due to relatively low degree of weathering compared to the lower reaches of the catchment, however there is still a notable amount of loose material that can be entrained during a high intensity rainfall event as shown in Figure 10.

Figure 10: 1400 – 1800 m asl - Photograph of the upper slopes with transition from tussock to exposed bedrock. Colluvium and soil cover estimated to be up to max. 1m. Evidence of active bank erosion present along channels that are incised into bedrock (low volume of erodible bedload).

5 Debris Flow Hazard

Based on the aerial inspection and site walk over, the likelihood of further debris flows occurring subsequent to an extreme weather event is considered to be high. Such an event could be a short duration high intensity rainfall event or prolonged persistent rainfall.

Numerous slip scarps and exposed soils are present in the upper catchment. These are considered likely to mobilise during a significant rainfall event. Additionally, there is a significant volume of sediment and woody bedload material in the creek channel which is likely to become entrained during future flood events.

Based on the inspections completed following the 2022 debris flow event, only a small volume of material was able to be transported through the culvert. It is considered likely that the culvert was very quickly blocked by woody debris and dammed which resulted in rapid overtopping of the road and diversion of the flood flows around the culvert.

For these reasons, the debris flow hazard is still developing and should be considered an active site and as such should be subject to periodic monitoring and ongoing management.

Monitoring is expected to be completed on an annual basis and following major or persistent rain events, routine monitoring could be tied into the QLDC bridge and structures asset management contract.

5.1 Monitoring and On-going Maintenance

Monitoring of the catchment and creek is recommended. Inspections should focus on the general channel condition (e.g., channel width and bed load, particularly woody debris) in the lower catchment (approximately 50 m upstream from the existing culvert). It is considered that an annual site walkover would be sufficient to provide an indication of potential aggradation of the bedload and to determine when proactive management should be undertaken. These inspections can be completed as part of routine asset management inspections of the culvert or future structure.

These inspections typically include comment on the condition of the waterway and level of aggradation/erosion. It is expected that the need for any specific maintenance operations would be identified during these routine inspections. Routine inspections would be required for any future structure development or replacement as part of a conventional asset management programme.

It would also be prudent to supplement the routine inspection programme with annual or biannual helicopter inspections of the upper catchment and with additional inspections being completed following severe weather events as part of a Trigger Action Response Plan, (TARP). A typical TARP would include various trigger event scenarios, for example a rainfall trigger event of 100mm rainfall in 24 hours or 3 days of rain fall greater than 50mm per day.

It is recognised that due to the nature of the catchment, source material is considered essentially unlimited, and whilst on going monitoring and periodic maintenance is not likely to prevent a future event, it is intended that structured waterway management procedures would reduce the severity of future debris flows on existing infrastructure.

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6 Hydrology

A hydrological assessment of the catchment and rainfall data as well as hydraulic assessment of the culvert was completed by Senior Water Engineer, Jeremy Boxall. An excerpt of this is included below. The full assessment in included as Appendix B.

The Shepherds Hut Creek catchment area was delineated using the NZ 8m Digital Elevation Model (2012)[5] and aerial imagery downloaded from LINZ Data Service.

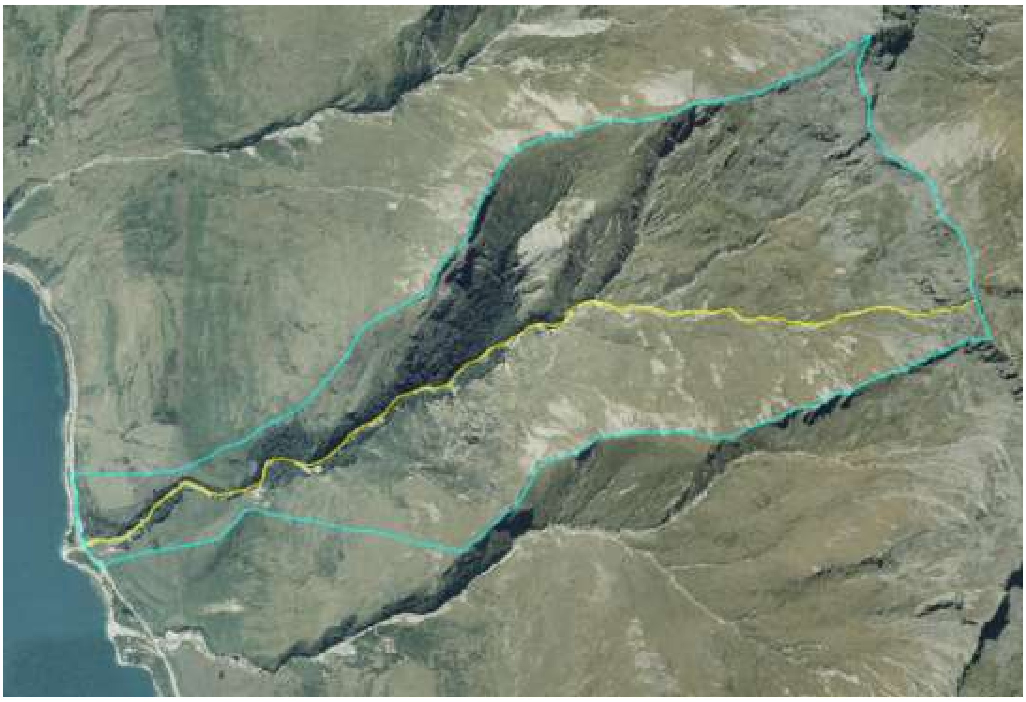

Figure 11: The Shepherds Hut Creek catchment obtained from LINZ Data Service.

HIRDS V4 rainfall intensity from NIWA's database was used with the RCP 6.0 climate change scenario (2081-2100 horizon) to estimate catchment runoff. The nearest rain gauge is within 5 km of the catchment.

There is no currently available data for the catchments soil storage capacity on S-MapOnline. The available data for similar catchments in the region discharging into the lakes are primarily well drained soils. The soil storage capacity was conservatively determined to be moderately well-drained or soil class B. The estimated terminal infiltration rate is 72 mm/hr. This resulted in a weighted fixed C value of 0.55 and CN curve number of 69.

[5] LINZ Data Service: https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/

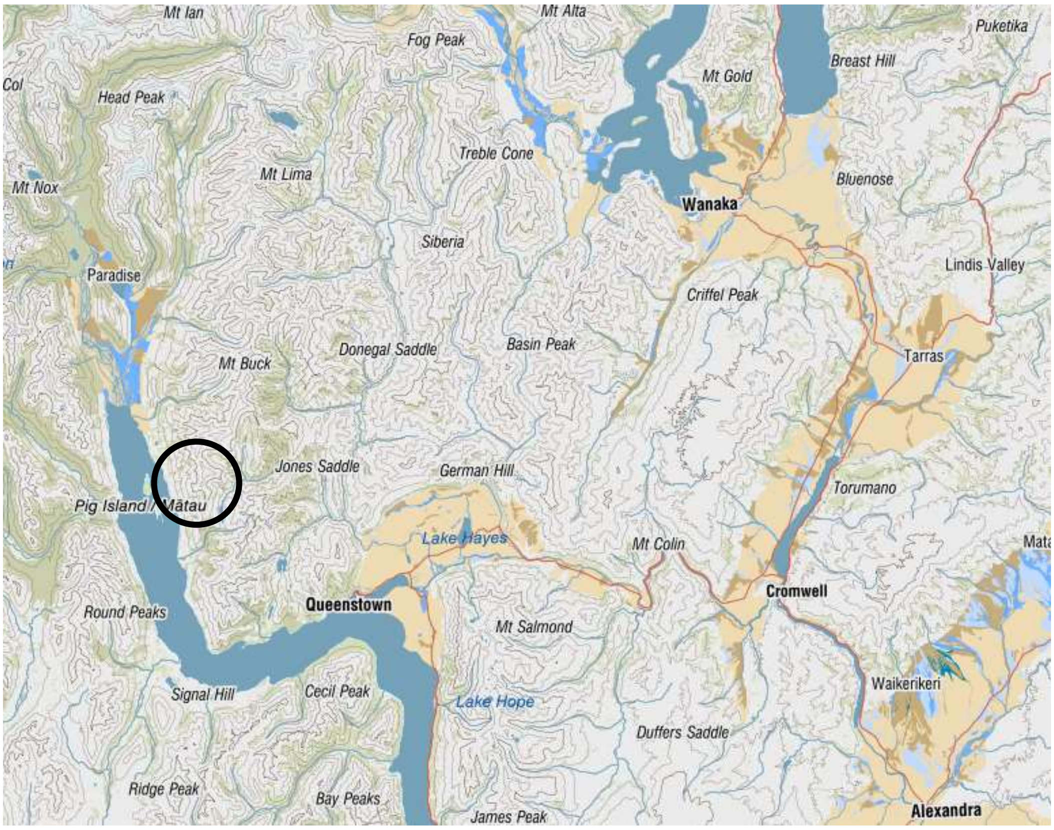

Figure 12: The Shepherds Hut Creek catchment (black circle) identified using S-MapOnline.

Discharge values for the Shepherds Hut Creek catchment were calculated using several methods including a modified rational method adapted for rural catchments, based on Griffith & McKerchar (2012). A summary of these calculations is illustrated in Table 1Error! Reference source not found..

Table 1: Summary calculations determined using the modified rational method for rural catchments

Catchment Area (km^2)	Slope (m/m)	T_c, Griffith & McKerchar (mins)	C value	i, 10 min, 50% AEP (mm/hr)	50% AEP Q (m^3/s)
4.08	0.344	48.31	0.55	15.0	9.4

Using NIWA's online river flood statistics, the flow gauge data of four different sites were obtained and scaled to the study catchment area. NIWA's regional method results (Table 2) are interpolated between these gauges that are located on two rivers, the Dart and Shotover. The donor sites have significantly larger catchment areas and different catchment characteristics and are therefore likely unsuitable for use as donor sites.

Results from three run-off model methods that account for initial and fixed infiltration capacity are shown in Table 2.

Table 2: Comparison of all discharge results for the 1% AEP event

Hydrological Method	1% AEP Discharge [m^3/s]
Griffith & McKerchar (2012)[1] with 2090 RCP6.0 rainfall	25
Regional Flood Frequency Method (NIWA stream explorer)	12
Dart River at the Hillocks (Scaled gauged stream site)	40
Shotover River at Peat's Hut (Scaled gauged stream site)	11
Shotover River at 16 Mile Gorge (Scaled gauged stream site)	21
Shotover River at Bowens Peak (Scaled gauged stream site)	14
SCS CN Method (TR-55)	17
Horton Soil Infiltration Model	11
Fixed Run-off Coefficient Method (Rational Method)	19

The existing culvert has an estimated capacity of approximately 11 m^3/s and has overtopped at least twice in the last few years, indicating that flood flows have exceeded this value, though potentially in combination with partial or complete blockage or bulked due to sediment transport.

7 Hazard Risk Assessment

Preliminary qualitative and quantitative risk assessments have been undertaken in general accordance with the methodology described in Appendix 6 of the June 2021 Proposed Otago Regional Policy Statement (RPS). Appendix 6 outlines a four-step process to determine the natural hazard risk. Each step of this process is outlined below:

7.1 Qualitative Risk Assessment

Table 6 of Appendix 6 in the proposed RPS was used to determine the likelihood of a debris flow originating in the Shepherds Hut Creek catchment reaching the carriage way of Glenorchy-Queenstown Road. Based on the site walkover and site history it is anticipated that debris flows are likely to occur on a sub-decadal to decadal scale. This equates to a likelihood of "almost certain" (i.e., up to once every 50 years or 2% AEP).

Table 7 of Appendix 6 in the proposed RPS was used to assess the potential consequence of a debris flow inundating the carriageway. The only infrastructure observed in the immediate vicinity of the debris flow path is associated with the road network, namely an existing 1.8m diameter culvert and the Glenorchy-Queenstown Road. The two main consequences of a debris flow relate to closure of the road, essentially cutting off Glenorchy residents and impacts to road users, with the worst-case potential resulting in the death of road users.

Table 8 of Appendix 6 in the proposed RPS was used to assess whether the natural hazard scenario have a level of risk which is acceptable, tolerable, or significant to people, property, and communities. The result of this assessment is included in Table 1.

Table 3: Risk assessment based on the process outlined in ORC proposed regional policy statement APP6

Risk Item	Likelihood	Consequence	Risk
Debris flow originating in Shepherds Hut Creek overwhelming the existing culvert and inundating the road.	Almost Certain (i.e., up to once every 50 years or 2% AEP).	Glenorchy Queenstown Road closed for 1 day to 1 week (affecting > 20% of the town population) = Moderate impact.	Tolerable
		Debris flow inundating the road at the same time as a road user is present resulting in death of the vehicle operator/passengers (2-11 people) = Moderate impact.	Tolerable

As the risk level has been assessed as being tolerable, a quantitative risk assessment is not required, however for comparison a preliminary quantitative risk assessment has been completed in Section 7.2.

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7.2 Quantitative Risk Assessment

A preliminary quantitative risk assessment has been undertaken in general accordance with the methodology presented in the Australian Geomechanics Society's Practice Note Guidelines for Landslide Risk Management (2007d) [6]. The risk of loss of life of an individual has been assumed to be the most critical aspect and has estimated based on the calculation below:

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

Each of the parameters in the calculation above are described in Table 2.

Table 4: Annual probability of loss of life of an individual due to a debris flow generated in the Shepherd Hut Creek catchment.

Parameter	Description	Probability	Assumptions	Comments
$P_{(H)}$	Probability of debris flow occurring annually.	0.2000	Assuming a debris flow reaching the road occurs on a sub-decadal time scale (5-year ARI).	Debris flow also requires accumulated mobilizable debris, and some pre-saturation of catchment, so actual probability is likely to be less.
$P_{(S:H)}$	Probability that the location is impacted by debris flow.	1.00	This is within the debris flow path so will definitely be hit.	
$P_{(T:S)}$	Probability that the outdoor area impacted by debris flow is occupied by the most at-risk individual at the time of the event.	0.001389	The most at-risk individual is assumed to be an individual who commutes between Glenorchy and Queenstown daily spending 2 mins per day in the debris flow path.	Conservative, as does not consider holidays, sick days, weather warnings or noticing flood conditions, etc. 2 minutes per day in the flow path is also conservative.
$V_{(D:T)}$	Probability of loss of life of the individual if location hit by debris flow.	0.30	The individual is not completely buried by debris.	As per AGS (2007d) Practice Note Guidelines
$R_{(LoL)}$	Annual probability of loss of life (death) of most at risk individual.	8.33E-05		This is considered to be within tolerable limits.

7.3 Hazard Assessment Results

The results of this preliminary assessment suggest that the annual risk to life is 0.00008 which is below the maximum acceptable value of 0.0001 recommended in AGS (2007) Practice Note Guidelines. The findings of both the qualitative and preliminary quantitative assessments suggest the risk it within acceptable to tolerable levels.

[6] Australian Geomechanics Society, 2007: "Commentary on Practice Note Guidelines for Landslide Risk Management 2007"; AGS (2007d); Journal and News of the Australian Geomechanics Society, Volume 42 No 1, March 2007.

8 Conclusions and Recommendations

Otago Regional Council engaged WSP to carry out an investigation of a debris flow event that occurred at Shepherds Hut Creek on the Glenorchy Road near Queenstown in April 2022. The aim of the investigation was to establish a better understanding of the debris flow hazard and the risk posed to the road and travelling public. As part of the investigation a desktop study, ground-based survey and an aerial inspection of the catchment area was completed.

The catchment shows extensive evidence of on-going erosion and shallow slope instability. It was identified that there is a significant bedload of sediment including potentially large woody debris currently present in the creek channel. Much of which is readily available to contribute to the debris flow hazard in future high intensity rainfall events.

A qualitative and preliminary quantitative hazard risk assessment was completed in accordance with the methodology presented in the proposed Otago Regional Policy Statement (June 2021) and the AGS (2007) guidelines.

The risk analysis concluded that the risk posed to Glenorchy residents using the road sits within the tolerable range.

The annual risk of a fatality based on the most vulnerable individual has been considered with the person most at risk being a daily commuter driving between Glenorchy and Queenstown. The preliminary risk assessment results suggest the risk of fatality due to a debris flow inundating the road at the same time a commuter is present sits within the acceptable range.

A hydrological and hydraulic assessment of the catchment and culvert was also completed which concluded that the existing culvert is undersized for clear water flows (not incorporating bulking factors to include debris load). In order to reduce disruption to road users the culvert could be upgraded. This is further substantiated by the observations of debris deposition following the most recent event and rapid overtopping of the road.

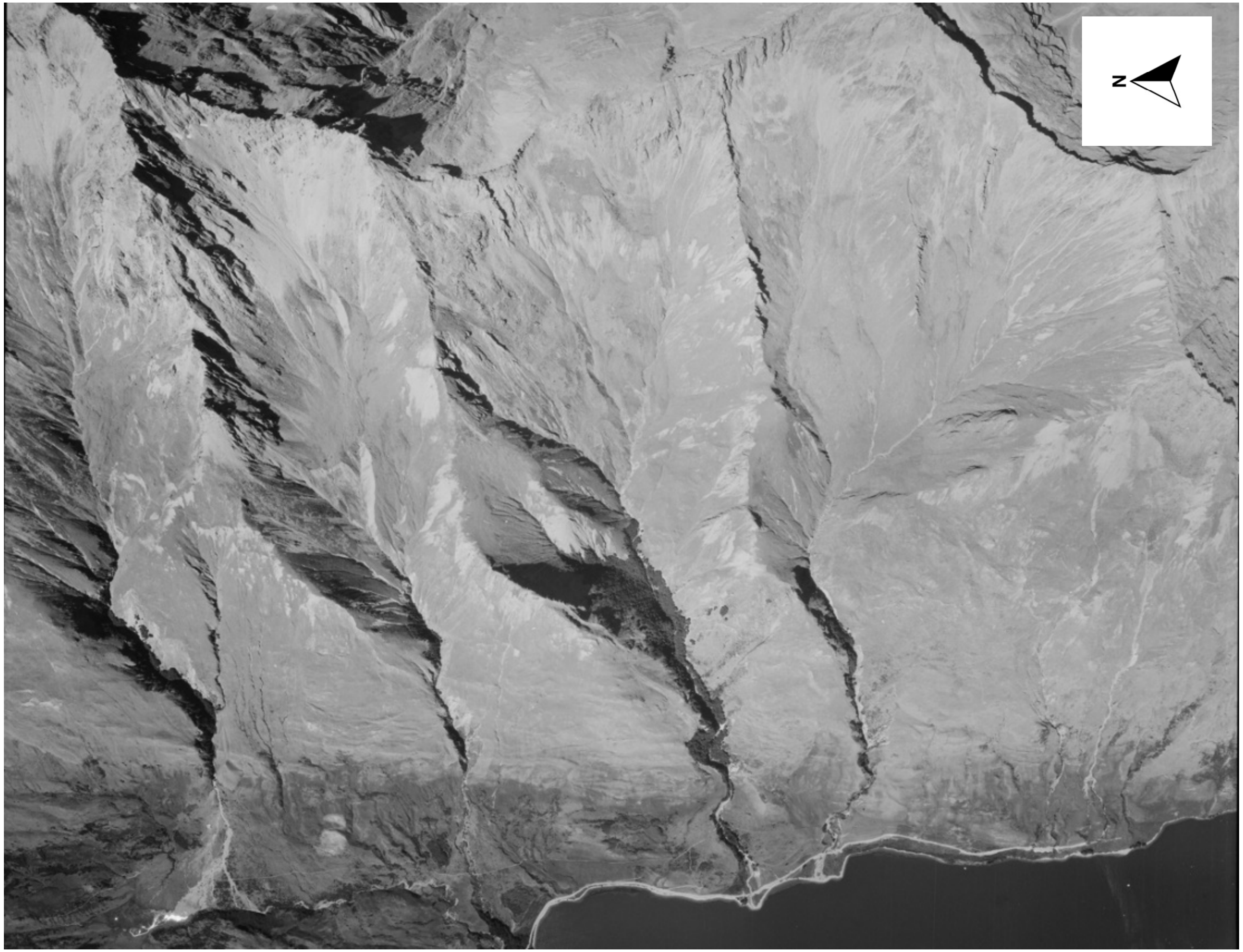
The debris flow catchment is considered to be active and future events are considered likely to occur under significant rainfall events. As such further monitoring and possibly mitigation is considered warranted, as noted in section 5 of this report.

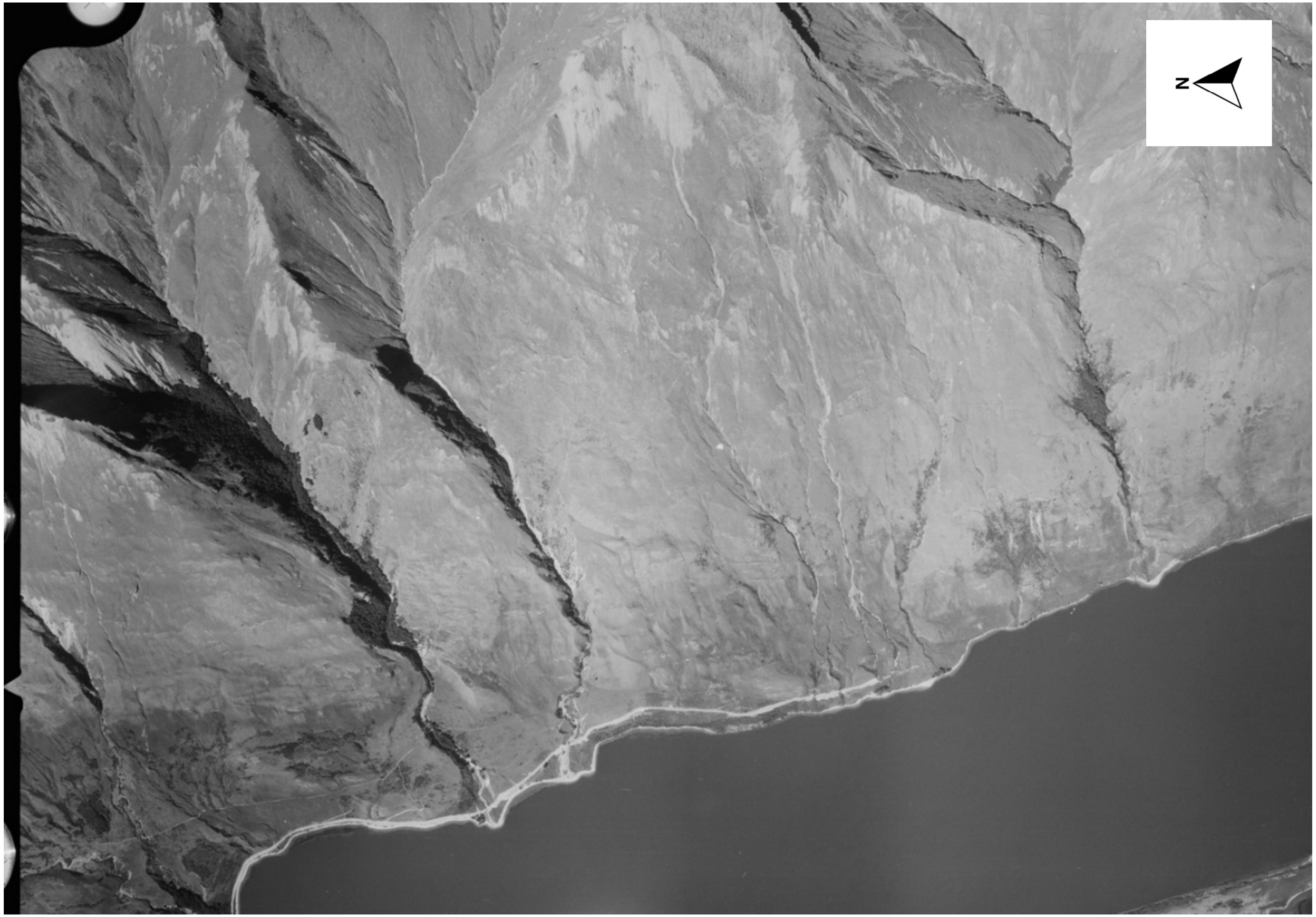
Early warning systems can be considered, such a signage, to alert road users of the debris flow hazard through this section of the road. This may include no stopping during flood conditions. Alternatively, barriers can be considered to close the road in the event of a debris flow closing the road.

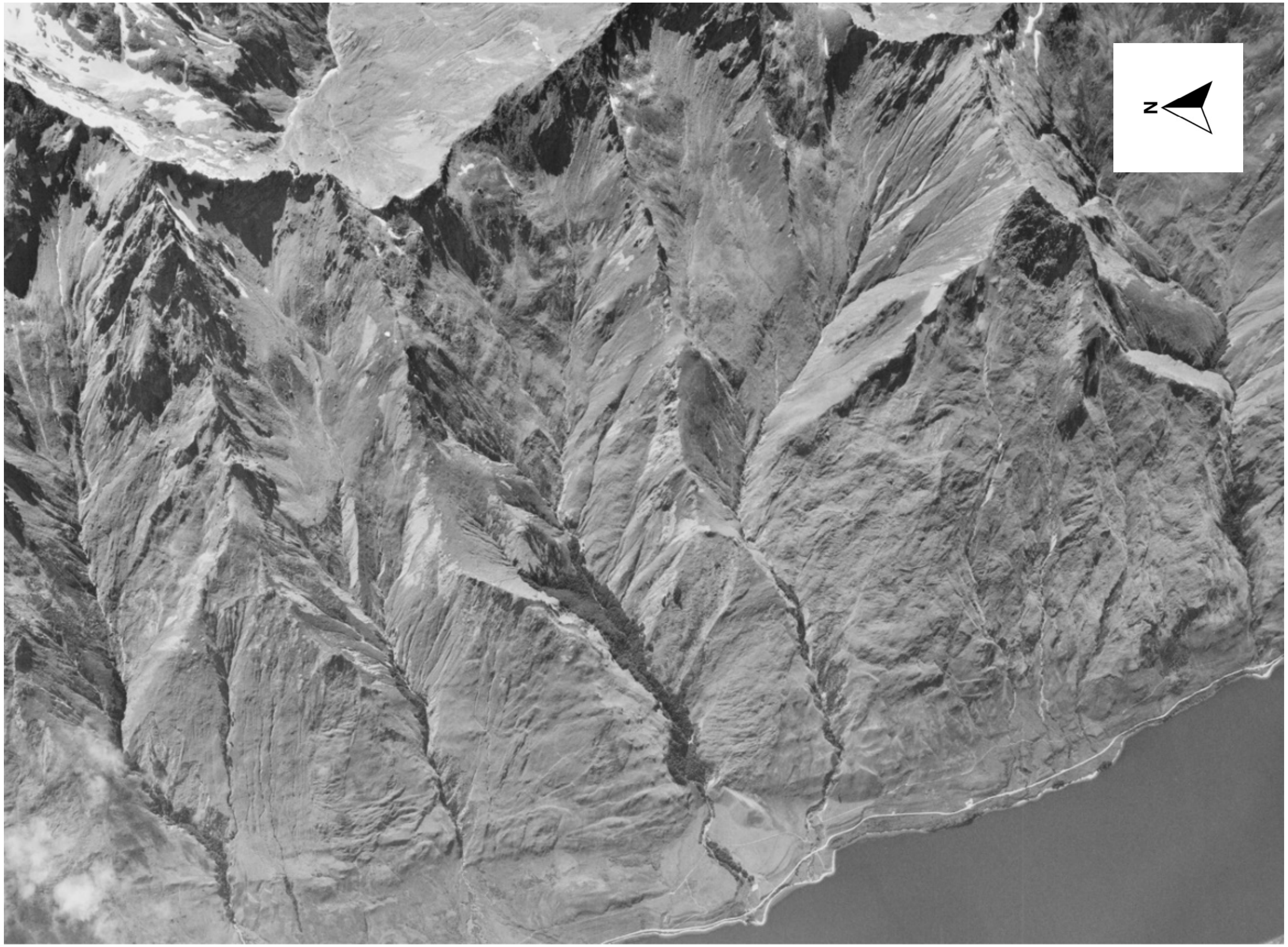
Improved preparedness and regular maintenance of the creek channel (removal of debris) to maintain capacity of the creek channel will assist in reducing the severity of future debris flow events. Given the essentially unlimited supply of sediment in the catchment and large contribution of woody debris, it is likely that an upgraded culvert would more likely than not still be blocked in a future debris flow event.

Detailed optioneering for improving the resiliency of this section of road is outside the scope of this report, possible options for upgrading the culvert and road have been considered in a separate report prepared by WSP titled “*Shepherds Hut Creek Optioneering Report*” (Reference: 6-XY024.05) prepared for Queenstown Lakes District Council.

Appendix A
Historic Aerial Images

Date/source	Photograph/comments
1959 – Retrolens	

Date/source	Photograph/comments
1966 - Retrolens	

Date/source	Photograph/comments
1969 - Retrolens	

Date/source	Photograph/comments
1988 - Retrolens	

Date/source	Photograph/comments
2001 – Retrolens **Note:** Some changes in vegetation cover at outlet of culvert. Potentially suggestive of a debris flow between 1988 and 2001. Lake level is also lower.	

Appendix B
Culvert Capacity Memorandum

Memorandum

To	WSP Queenstown
Copy	Mark Groves
From	Jeremy Boxall
Office	Christchurch
Date	30 May 2022
File/Ref	6-XY024.05, 005GX
Subject	Shepherds Hut Creek Culvert Capacity Assessment

1 Introduction

This memorandum follows a request to replace the existing 1800Ø concrete pipe under the Glenorchy-Queenstown Road that conveys flow from the Shepherds Hut Creek catchment.

2 Hydrology

The Shepherds Hut Creek catchment area was delineated using LiDAR (8m DEM) and aerial imagery (Figure 1).

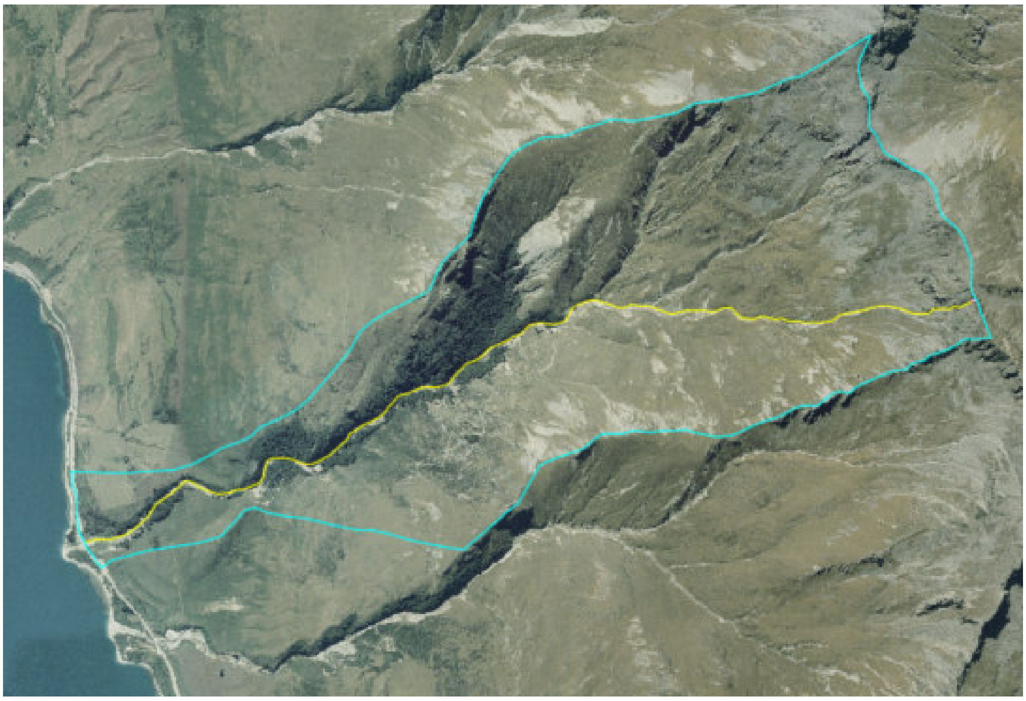


Figure 1. The Shepherds Hut Creek catchment obtained using LINZ data.

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150 YEARS IN AOTEAROA

HIRDS V4 rainfall intensity from NIWA's database was used with the RCP 6.0 climate change scenario (2081-2100 horizon) to estimate catchment runoff. The nearest rain gauge is within 5 km of the catchment.

There is no currently available data for the catchments soil storage capacity on S-MapOnline (Figure 2). The available data for similar catchments in the region discharging into the lakes are primarily well drained soils. The soil storage capacity was conservatively determined to be moderately well-drained or soil class B. The estimated terminal infiltration rate is 72 mm/hr. This resulted in a weighted fixed C value of 0.55 and CN curve number of 69.

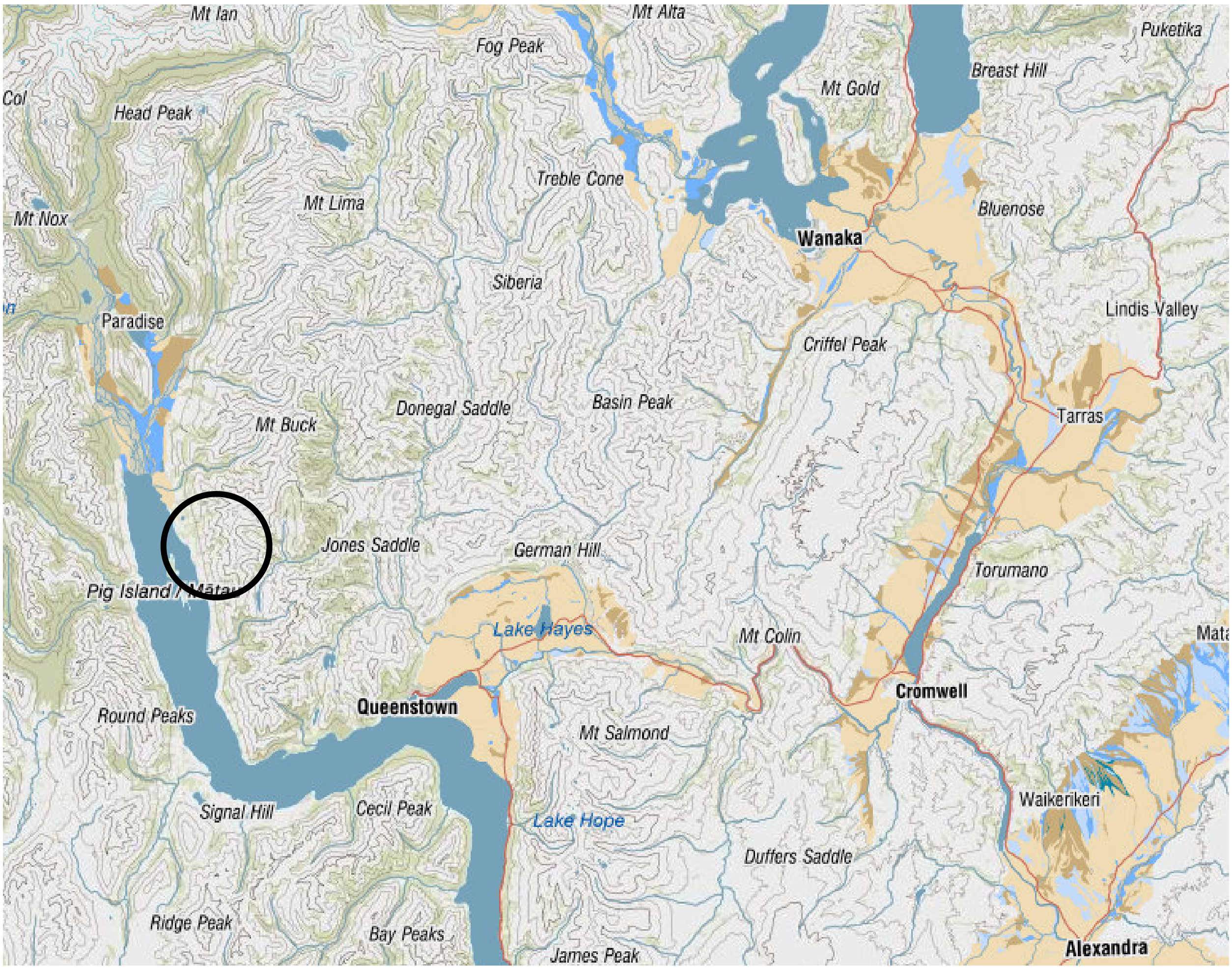

Figure 2. The Shepherds Hut Creek catchment (red circle) identified using S-MapOnline.

Discharge values for the Ram Hill Stream catchment were calculated using several methods including a modified rational method adapted for rural catchments, based on Griffith & McKerchar (2012). A summary of these calculations is illustrated in Table 1.

Table 1. Summary calculations determined using the modified rational method for rural catchments.

Catchment Area (km^2)	Slope (m/m)	T_c, Griffith & McKerchar (mins)	C value	i, 10 min, 50% AEP (mm/hr)	50% AEP Q (m^3/s)
4.08	0.344	48.31	0.55	15.0	9.4

Using NIWA's online river flood statistics, the flow gauge data (Figure 3) of four different sites were obtained and scaled to the study catchment area (Table 2). NIWA's regional method results (Table 2) are interpolated between these gauges that are located on two rivers, the Dart and Shotover. The donor sites have significantly larger catchment areas and different catchment characteristics and are therefore likely unsuitable for use as donor sites.

Figure 3. The four flow gauges (black and white circles) within proximity of Shepherds Hut Creek catchment (black circle), from which data was obtained.

The 50% AEP discharge determined using the modified rational method for rural catchments was scaled using the regional flood frequency model (RFFM) growth factors. The results of this scaling are shown in Table 2.

Results from three run-off model methods that account for initial and fixed infiltration capacity are shown in Table2.

Table 2. Comparison of all discharge results for the 1% AEP event

Hydrological Method	1% AEP Discharge [m^3/s]
Griffith & McKerchar (2012)[1] with 2090 RCP6.0 rainfall	25
Regional Flood Frequency Method (NIWA stream explorer)	12
Dart River at the Hillocks (Scaled gauged stream site)	40
Shotover River at Peat's Hut (Scaled gauged stream site)	11
Shotover River at 16 Mile Gorge (Scaled gauged stream site)	21
Shotover River at Bowens Peak (Scaled gauged stream site)	14
SCS CN Method (TR-55)	17
Horton Soil Infiltration Model	11
Fixed Run-off Coefficient Method (Rational Method)	19

The existing culvert has an estimated capacity of approximately 11 m^3/s (see Section 3 below) and has overtopped at least twice in the last few years, indicating that flood flows have exceeded this value, though potentially in combination with partial or complete blockage or bulked due to sediment transport.

Based on the above assessment, a design flood flow of 25 m^3/s is proposed, assuming clear flow conditions. This represents the upper bound value for the theoretical methods applied and is recommended in this case due to the known history of overtopping and debris accumulation.

3 Hydraulics

The existing culvert was modelled using HY-8 software to determine its discharge capacity. The existing culvert is a 1800Ø concrete culvert pipe of unknown slope. The natural slope upstream and downstream of the culvert is estimated as 15%. The culvert is assumed to be 4 m deep (invert to overtopping point over the road) and on a 3.3% slope (note that under inlet control the pipe slope has minimal impact on culvert capacity).

The existing culvert was predicted to overtop at a total discharge of 11.9 m^3/s (Figure 4Error! Reference source not found.). This is approximately the lowest estimated discharge in Table 2.

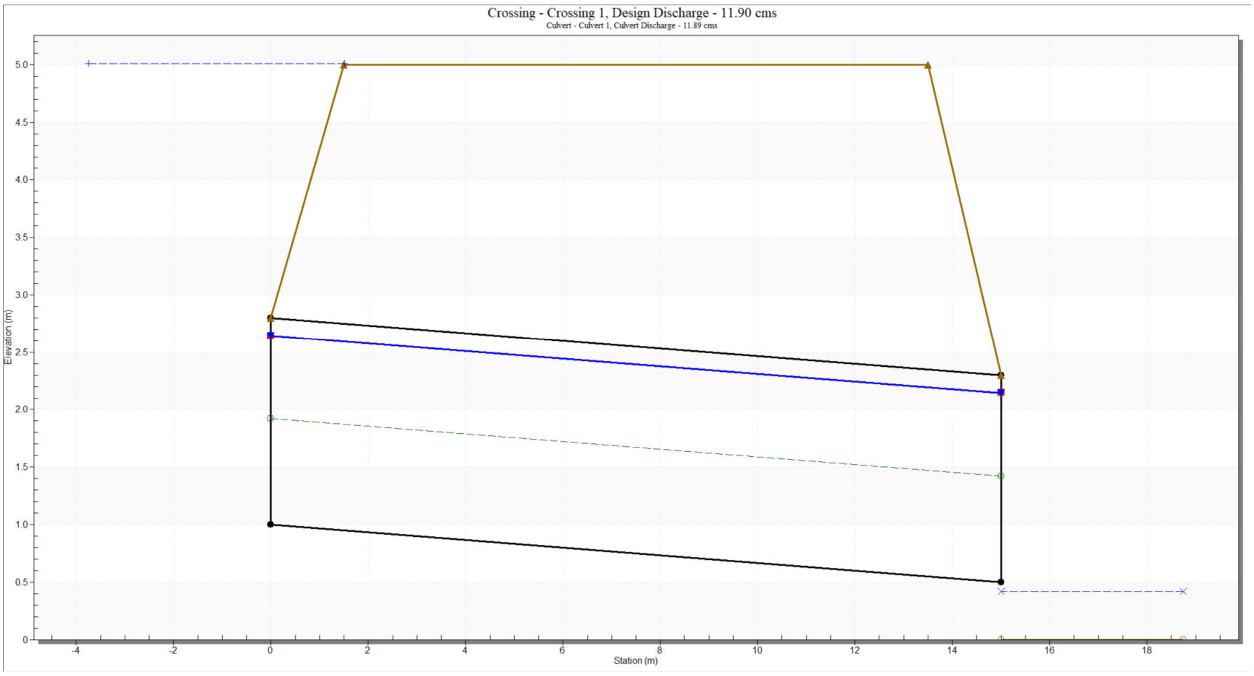

Figure 4. The existing 1800Ø culvert overtopping at a 11.9 m^3/s discharge.

Assuming a 200 mm accumulated depth of debris material in the culvert the total discharge reduces to 8.8 m^3/s (Figure 45Error! Reference source not found.). This is lower than all estimated flood flows in Table 2.

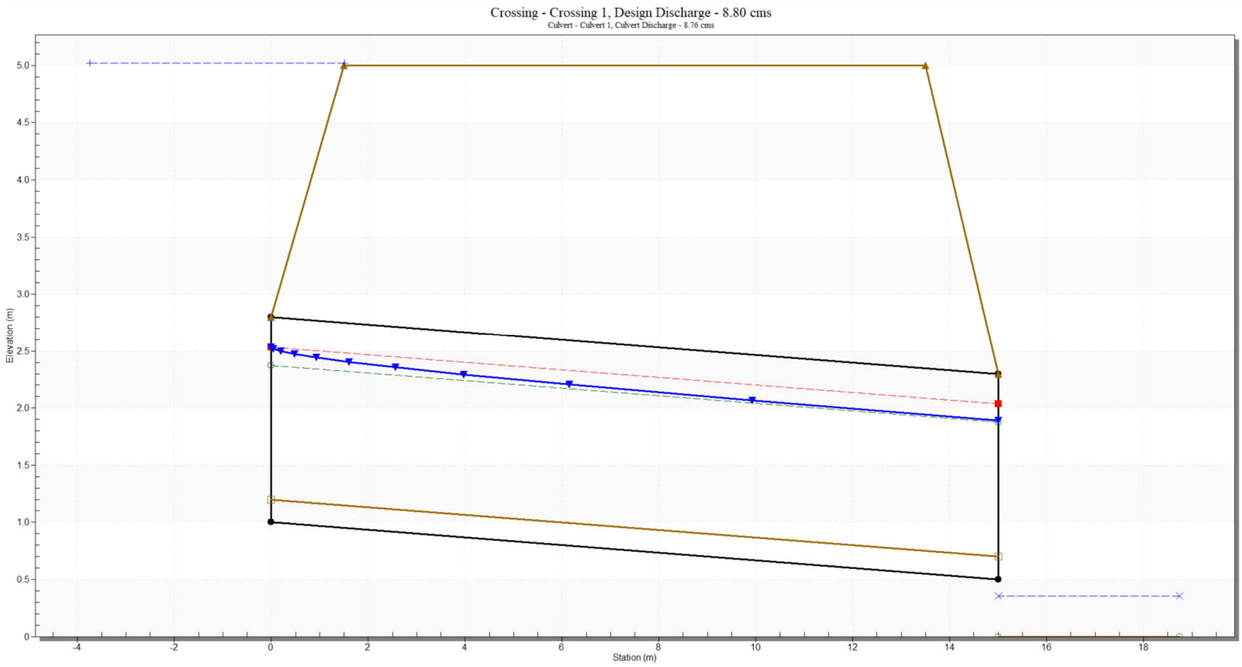

Figure 5. The existing 1800Ø culvert overtopping at a 8.8 m³/s discharge.

To assess options to increase discharge capacity, new culvert options were modelled using HY-8. Figures 6-8 show the results of different culvert replacement options.

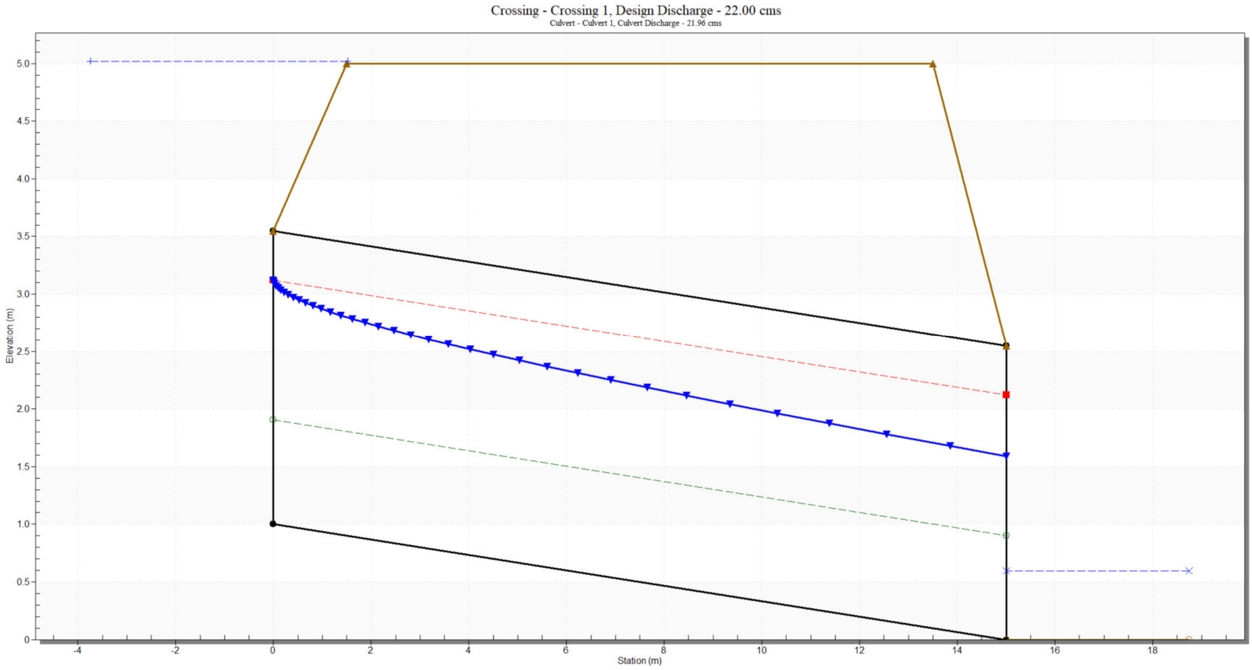

Figure 6. A new precast skid-ring joint concrete 2550Ø overtopping at 22 m³/s discharge.

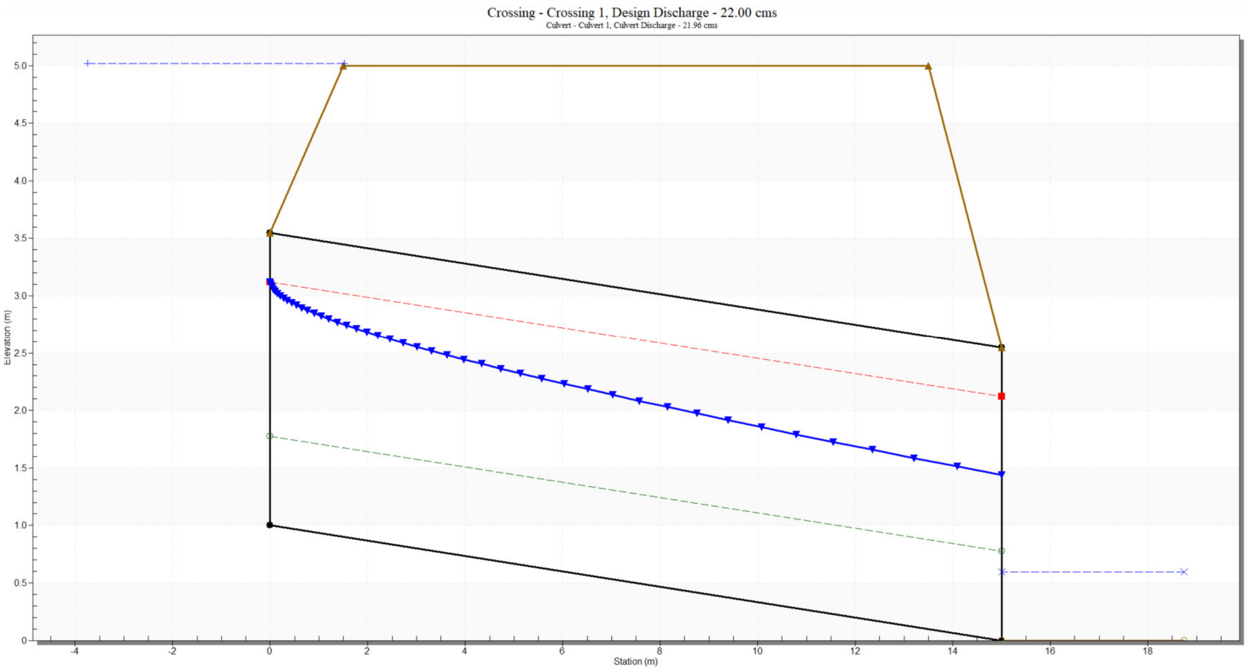

Figure 7. A new smooth GRP (or similar) 2550Ø overtopping at 22 m³/s discharge.

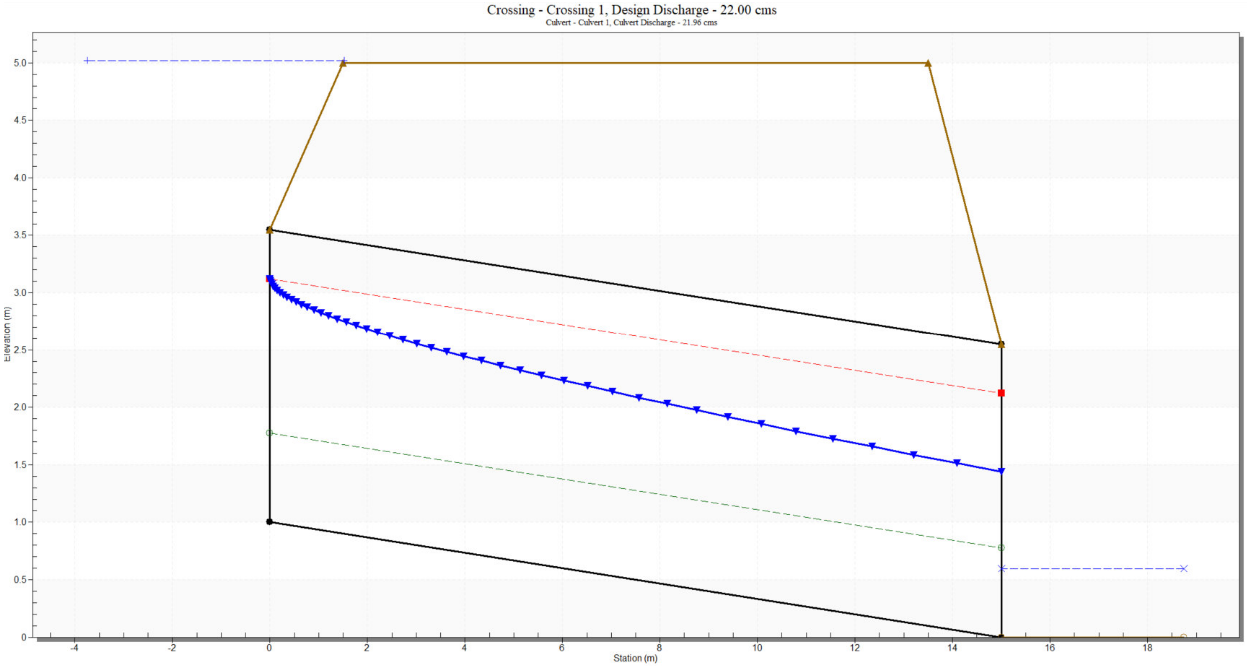

Figure 8. A new 3 m x 2.5 m concrete box culvert overtopping at 27.5 m³/s discharge.

Note that as the culvert is inlet controlled during flood events, hence the culvert slope has little effect on the total discharge.

Steeper slopes (like the 6.6% modelled) will increase velocities through the culvert and improve sediment and debris transport through the culvert, though also increasing abrasion. The estimated outlet velocity for a flat slope is 4.23 m/s compared to 7.05 m/s for a 6.6% slope.

4 Other Considerations

Any new culvert structure will have to be designed to accommodate fish passage. As per the Freshwater National Environmental Standard (NES) structures less than 4 m in height require an embedment depth 25% of culvert height. The capacity of the box culvert reduces to 19.5 m³/s if embedded 25%, though this embedment depth may be reduced using concrete sill baffles to trap and retain substrate. Otherwise, at least 500 – 700 mm embedment will be required to accommodate large enough rock material and prevent its loss during floods.

Consideration of potential abrasion and maintenance activities is also required, due to the live bed conditions and infrequent clearance activities. A box culvert with additional cover (e.g. 100 mm) to the invert steel is likely the best option in this situation.

5 Conclusions

The results of the above assessment indicate that the existing 1800Ø culvert is unsuitable for all estimated design discharges. By comparison, modelling determined that a new circular 2550Ø culvert would improve overall discharge capacity but, fail to satisfy the design discharge of 25 m^3/s. Further modelling indicated that a new precast 3 m x 2.5 m (H x W) box culvert will satisfy the estimated design flow.

Given the known debris issue at this location we would recommend that a box culvert is installed, with an allowance for embedment below the stream bed.

We would also recommend the following:

1. The downstream pavement edge and embankment slope is reinforced to prevent erosion damage.
2. The cover to the invert steel is increased to say 100 mm to accommodate abrasion. The box culvert is installed at an increased gradient to improve sediment transport through the culvert.

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