



Otago Regional Council

Teviot Valley Debris Flood Risk Management Optioneering

Phase 1 - Long-list optioneering report

30-09-2026

CG2026/14



Document distribution

Otago Regional Council

Teviot Valley Debris Flood Risk Management Optioneering

Phase 1 - Long-list optioneering report

30-09-2026

CG2026/14

Prepared for

Otago Regional Council

Aonui/180 High Street
Central Dunedin
Dunedin 9016

Prepared by

WSP New Zealand Limited
12 Moorhouse Avenue, Christchurch, 8011
T +64 3 373 2007

Quality control	Name	Date
Prepared by:	Harley Porter, Geohazard Analyst	3 Sept 2026
Reviewed by:	Doug Mason, Principal Engineering Geologist	10 Sep 2026
Approved by:	Richard Woods, Project Director	15 Sep 2026

Revisions

Rev	Date	Details
1	2026-08-13	DRAFT for comment
2	2026-09-15	Revised following client review and stakeholder workshop
3	2026-09-30	Revised following client review

Table of contents

Executive summary	4
Project Summary	4
Key Findings	4
1. Introduction	6
1.1 Project Background	6
1.2 Scope	6
2. Debris Flood Risk Management	7
2.1 Background	7
2.2 Management Approaches	8
2.2.1 Structural (Engineered) Measures	9
2.2.2 Nature-Based and Catchment Management Approaches	17
2.2.3 Land Use Planning and Development Controls	19
2.2.4 Emergency Management, Monitoring, and Preparedness	22
2.3 Current Management in the Teviot Valley	28
2.3.1 Structural (Engineered) Measures	28
2.3.2 Land-Use Planning and Development Control	31
2.3.3 Emergency management and monitoring	32
2.4 Key Findings	33
3. Option Development and Screening	36
3.1 Overview	36
3.2 Long list	37
3.3 Development of Short-Listing Criteria	44
3.3.1 Short-Listing Philosophy	44
3.3.2 Proposed Assessment Themes	44
3.4 Next Stage	46
4. Conclusions	47
5. Limitations statement	49
6. References	50

Executive summary

Steep mountain catchments in the Teviot Valley, New Zealand, experience fast-moving floods containing high volumes of sediment, rocks, and debris. These types of events are known as debris floods. Recent work has highlighted the potential for debris floods to damage property and infrastructure and pose a risk-to-life in the Teviot Valley. An assessment is needed to identify feasible and appropriate options that can mitigate the risks posed by debris floods in the Teviot Valley.

Project Summary

This report outlines a long-list of debris flood management options that could be considered in the Teviot Valley. The long-list is based on a detailed literature review of national and international debris flood management options and best practice. The following types of management approaches were reviewed:

- **Structural or engineered measures** – Built options such as stopbanks, channel widening, and debris flood catch fences that alter debris flood behaviour and physically protect downstream areas.
- **Nature-based solutions and catchment management** – Solutions such as vegetation of channel margins and alluvial fans that reduce sediment delivery to downstream areas and can provide a layer of protection.
- **Land-use planning and development controls** – Regulations that restrict or avoid development in high-risk areas or requirements for resilient design within hazard zones.
- **Emergency management, monitoring, and preparedness** – Early warning, evacuation, and pre-event planning and preparation allowing lead time and community awareness before debris floods happen.

This report concludes with a discussion on short-list criteria development themes which were discussed with relevant stakeholders at a meeting in August 2026.

Key Findings

Key findings from the literature review and stakeholder engagement can be summarised as follows:

International debris flood management best practice

- **Integrated approaches represent international best practice.** No single measure is capable of eliminating debris flood risk. The most successful approaches combine structural works, land-use planning, catchment management, monitoring, emergency management, and community preparedness.
- **Sediment management is fundamental to debris flood risk reduction.** Many debris flood management measures ultimately depend on controlling sediment transport, deposition, channel aggradation, and avulsion. Ongoing maintenance and sediment removal are recurring requirements for many engineered solutions.

- **Structural measures can reduce consequences but do not eliminate risk.** Measures such as stopbanks, channel works, check dams, retention basins, and debris barriers can reduce debris flood impacts, but their effectiveness is often dependent on maintenance, available storage capacity, and performance during larger events.
- **Land-use planning is one of the most effective long-term risk management tools.** Internationally, there is a growing shift towards risk-based planning approaches that use hazard and risk information to guide development, reduce future exposure, and support adaptive management.
- **Nature-based solutions are generally most effective as complementary measures.** Vegetation management and catchment restoration can reduce erosion and sediment delivery but typically require long timeframes to become effective and are unlikely to provide sufficient protection against large debris floods when implemented in isolation.
- **Monitoring, warning systems, and emergency management play an important supporting role.** These measures can reduce life-safety risk and improve preparedness, however, the rapid onset of debris floods in steep catchments can severely constrain warning times and limit evacuation opportunities.
- **Current management in the Teviot Valley is broadly consistent with international practice.** Existing channel works, sediment management, culvert upgrades, emergency management arrangements, and recent hazard and risk assessments provide a strong foundation for future risk management decision-making.
- **Several opportunities for improvement remain.** Potential gaps include limited debris-flood-specific planning controls, monitoring and warning systems, fan-specific emergency management planning, and consideration of additional structural and non-structural measures identified through this review.

Short list criteria development

- **Stakeholders agreed that risk to life should remain the primary driver of future decision making.** However, wider benefits including protection of property, infrastructure resilience, and productive land use should also be considered when evaluating options.
- **Future option assessment should be tailored to individual fans.** Stakeholders recognised that risk, exposure, and consequence vary considerably across the Teviot Valley and that different locations may require different management approaches.
- **Whole-of-life cost and deliverability are critical considerations.** Options should be assessed not only on implementation cost, but also on long-term maintenance requirements, environmental and social impacts, community acceptance, and ease of delivery.
- **Integrated packages of measures are likely to provide the greatest overall benefit.** The preferred solutions are likely to comprise combinations of Protect, Avoid, Retreat, and Accommodate measures rather than reliance on any single intervention.
- The proposed short-listing themes of effectiveness, deliverability, whole-of-life cost and maintenance, environmental/social/cultural performance, implementation timeframe, and integrated outcomes provide a robust basis for refining the long list of options into a defensible shortlist for further assessment.

1. Introduction

1.1 Project Background

The Teviot Valley in Central Otago, New Zealand, often experiences debris floods in steep catchments typically following or during high intensity short duration rainfall events. Several historical debris floods have impacted buildings, property, and infrastructure in the Teviot Valley and require ongoing hazard management to protect communities and reduce event losses.

In early 2026, the Otago Regional Council (ORC) and WSP New Zealand Limited (WSP) completed a detailed debris flood risk assessment for 13 catchments and alluvial fans in the Teviot Valley to establish how risk varied on each fan (WSP, 2026). This concluded that some areas have a higher risk to debris floods and risk management measures should be considered to appropriately reduce risk.

In order to identify and evaluate potential debris flood management measures applicable to the Teviot Valley, ORC have asked WSP to undertake a 'long-list' optioneering assessment to identify and screen a broad range of debris flood management measures. This work forms part of a staged approach to establish an evidence-based risk management programme:

1. **Long-list optioneering phase – covered in this report**
2. Engagement and community feedback on the long-list,
3. Short-listing phase with workshop attended by stakeholders,
4. Analysis and assessment of short-listed options,
5. Engagement on short-list and way forward to implementation.

This report presents the findings of the long-list optioneering phase of the Teviot Valley debris flood programme.

1.2 Scope

The scope of work associated with this long-list optioneering phase and report includes:

- Literature review of New Zealand and global debris flood risk management approaches.
- Long-list development and initial feasibility screening.
- Short listing definition criteria.

The results of this work will be used for stakeholder engagement and community presentation to help screen and get community engagement with the options put forward in this report.

2. Debris Flood Risk Management

2.1 Background

The 2026 Roxburgh Debris Flow and Debris Flood Study report provides a detailed description of the characteristics, impacts, and risks associated with debris floods in the Teviot Valley. Key background information relevant to this current review is summarised below:

- Debris floods are potentially destructive fast-moving flows of rock, soil, and vegetation carried downstream by floodwaters often referred to as “flash floods” in the media (Church & Jakob, 2020).
- The Teviot Valley has experienced several debris floods (most notably in 1978 and 2017) which have had severe consequences for nearby communities (Figure 1).



October 1978 Debris Flood Reservoir Creek



November 2017 Debris Flood Reservoir Creek

Figure 1: Previous examples of debris flood events in the Teviot Valley.

- Debris flood risk management can involve a range of methods including:
 - Structural (engineered) measures such as catch fences, retention dams, and channel works.
 - Nature-based and catchment management such as naturalisation and vegetation management.
 - Land-use planning.
 - Emergency management, monitoring, and preparedness.
 - Integrated risk management approaches.
- Hazard management approaches typically align with the Protect, Avoid, Retreat, and Accommodate framework (PARA framework) used widely in natural hazard management (Figure 2).
- There has been a range of debris flood risk management implemented in the Teviot Valley over the past 50 years including stopbanks, channel works, and engineered chutes.

- This section presents a literature review of debris flood management approaches (Table 1) and an overview of the current management approach in the Teviot Valley.

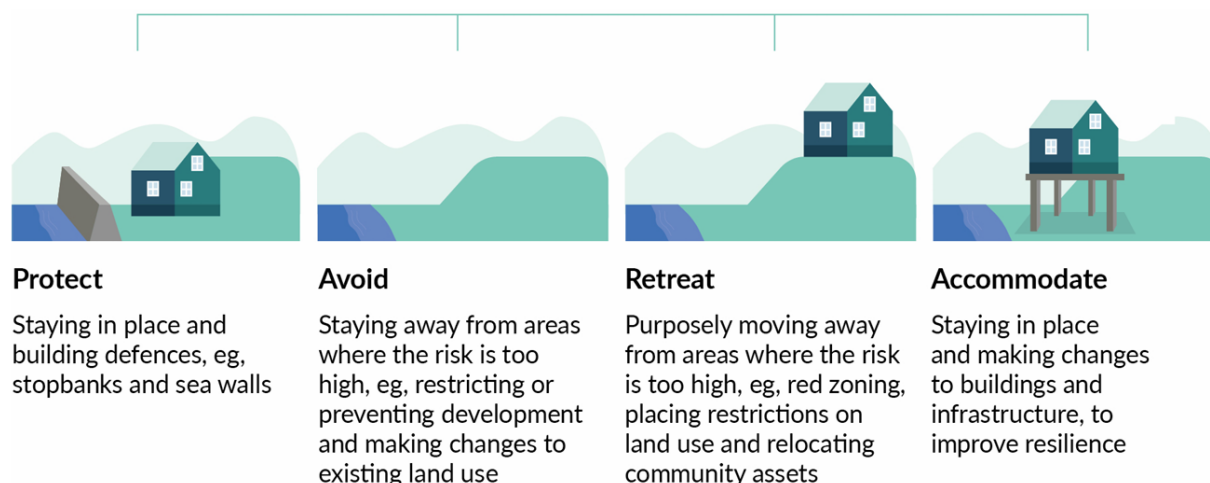


Figure 2: An illustration of each of the approaches in the PARA Framework (Ministry for the Environment, 2023).

Table 1: The debris flood risk management measures reviewed in this study by PARA category.

PARA Category	Measures Considered
Protect	Stopbanks, check dams, retention basins, debris barriers, diversion channels, channel modifications, bank protection, sediment management, nature-based erosion control and revegetation.
Avoid	Hazard mapping, planning controls, and risk-based planning frameworks
Retreat	Property acquisition, building relocation, infrastructure relocation, managed retreat, strategic retreat planning.
Accommodate	Property resilience measures, monitoring networks, warning systems, emergency planning, and community education and preparedness

2.2 Management Approaches

Debris flood risk management is inherently complex due to the variability in catchment characteristics, sediment availability, rainfall behaviour, debris flood magnitude, and the exposure and vulnerability of people, property, infrastructure, and productive land. As a result, there is no single measure that can eliminate debris flood risk in all situations. International experience demonstrates that effective risk reduction is generally achieved through a suite of complementary measures that work together to manage different aspects of risk, including hazard reduction, exposure management, preparedness, and

recovery. This section reviews the range of debris flood management approaches identified through the literature review, including structural and nature-based measures, land-use planning approaches, and emergency management, monitoring, and preparedness initiatives. These approaches provide the basis for the long list of options considered later in this report.

2.2.1 Structural (Engineered) Measures

Structural measures are widely used internationally to reduce the impacts of debris floods by controlling sediment transport, reducing flow energy, or diverting flows away from exposed assets and communities. These measures are generally implemented alongside non-structural approaches such as land-use planning, monitoring, warning systems, and emergency management.

2.2.1.1 Stopbanks

Stopbanks are engineered embankments commonly used to manage debris floods by containing, guiding, or diverting sediment-laden flows away from vulnerable infrastructure and communities (Takahashi, 2007) (Figure 4):

- In contrast to conventional flood management, debris flood stopbanks are designed to withstand elevated sediment loads, impacts from transported boulders and woody debris, rapid aggradation, and potential channel avulsion during extreme events (Vagnon, 2019). Unlike conventional flood stopbanks, debris flood stopbanks may require increased freeboard allowances, wider footprints, erosion protection, or reinforcement to accommodate rapid sediment aggradation, impacts from boulders and woody debris, and elevated flow velocities. Design requirements are highly dependent on expected debris volumes, sediment characteristics, and the consequences of overtopping or failure.
- Their primary function is not typically to stop debris floods directly, but rather to confine floods within designated corridors, prevent overbank flooding, and direct floodwaters towards areas where deposition can occur safely (Vagnon, 2019). These structures effectively narrow the flow path, increase hydraulic confinement, and direct debris floods toward retention structures or designated deposition zones.
- A key advantage of stopbanks is their ability to provide protection over relatively large areas while remaining comparatively straightforward to construct and maintain. They can often be retrofitted within existing river corridors and integrated with broader flood protection infrastructure.
- The effectiveness of stopbanks decreases as sediment concentrations and debris volumes increase (Takahashi, 2007). Debris floods can rapidly deposit sediment within confined channels, reducing conveyance capacity and increasing the likelihood of overtopping or avulsion. Unlike clear-water floods, debris floods can raise channel bed levels by several metres during a single event, substantially reducing the freeboard available within a stopbank system.
- While stopbanks can provide relatively cost-effective protection for existing communities and infrastructure, they can also concentrate flows and sediment within confined corridors, potentially increasing the consequences of overtopping, blockage, or avulsion if design capacities are exceeded.

- Historically, reliance on stopbanks has encouraged development on more marginal floodplain areas, indirectly increasing the exposure of certain communities to impacts (Figure 3) (Environment Canterbury, 2026), hence the need to integrate stopbanks within a broader suite of hazard management approaches such as land use planning.



Figure 3: Stopbanks along the Waiho River in Franz Josef, New Zealand and exposed infrastructure built on the exposed floodplain. Top: A stopbank with disused motel units built at original fan level (University of Canterbury). Bottom: The waste water treatment plant at Franz Josef currently protected with engineered stopbanks (Otago Daily Times).

- Internationally, stopbanks are most commonly used in conjunction with upstream measures such as check dams, debris basins, and flexible barriers (He, et al., 2025). This avoids reliance on stopbanks alone and reduces the risk of catastrophic failure if debris volumes exceed design capacity.



Figure 4: The Kroeger Canyon alluvial fan, Colorado with stopbanks following a fire in 2002 (Colorado Geological Survey, n.d.).

2.2.1.2 Check Dams and Grade-Control Structures

Check dams are barriers built across channels to reduce flow velocity, trap coarse sediment and boulders, stabilise channel gradients, and limit sediment delivery to downstream areas (Piton G. , et al., 2016):

- They are among the most commonly applied debris flood mitigation structures worldwide, particularly in Japan, Switzerland, Austria, China, and South Korea.
- Cascading systems comprising multiple check dams are frequently used to progressively dissipate energy and increase sediment storage capacity within a catchment (Figure 5) (Chen, et al., 2025; Charles, et al., 2025).
- Recent research has demonstrated that appropriately located check dams can significantly reduce debris volumes and downstream impacts (Lee, et al., 2025).
- Check dams can either be constructed with openings or gaps (open) allowing water to pass through or as closed structures that seal the channel and overtop during high flow events.

- Lee et al. (2023) evaluated the performance of open and closed check dams and found that both designs can reduce flow energy and trap sediment, although effectiveness depends on debris characteristics, sediment volumes, and structure configuration.
- Typically, open check dam structures can intercept debris while allowing normal water and sediment passage, thereby reducing maintenance requirements compared with conventional retention structures (Mark & Strouth, 2023).
- The effectiveness of check dams depends on adequate storage capacity and ongoing maintenance and inspection (Busslinger, et al., 2023). Sediment and boulder accumulation following repeated events can reduce performance, requiring periodic excavation and reconstruction to maintain design functionality (USEPA, 2021; Piton, et al., 2022). Further, successful implementation of check dams requires a detailed understanding of debris flood dynamics, sediment budgets, and the transition between erosional and depositional reaches. International experience has demonstrated that check dams located within actively eroding channels can be undermined or damaged during large events, highlighting the importance of appropriate siting and catchment-scale geomorphic assessment during design. Some studies suggest that check dams are a short-term solution that will eventually be overtopped, delivering much larger volumes of material to the fan than the smaller and more frequent events that occur if the check dams were not in place (Davies & McSaveney, 2008; Davies & Hall, 1992).



Figure 5: A cascade of check dams in the St Antione torrent upper basin (Piton G. , et al., 2017).

2.2.1.3 Debris Basins and Retention Structures

Debris basins, also referred to as retention basins, are designed to capture sediment, woody debris, and coarse material before floods reach vulnerable assets (e.g. Figure 6):

- These structures are widely used throughout Europe, North America, and Asia, where they provide temporary storage during debris flood events to reduce flow velocities, thus depositing sediment and

debris and reducing downstream sediment transport and debris-flow impacts (Barbini, Bernard, Boreggio, Da Re, & Gregoretti, 2023).

- Water is typically conveyed through controlled outlets while sediment and debris are retained within the basin.
- The principal advantage of debris basins is their ability to accommodate large sediment volumes while maintaining downstream channel conveyance. However, they generally require a substantial footprint, suitable access for maintenance, and frequent sediment removal following significant events (GNS, 2005).
- Their long-term effectiveness is strongly dependent on asset management and maintenance programmes.
- The capacity of a debris basin needs to carefully consider the entire sediment budget and runout potential as well as the design event of the catchment to avoid overtopping (Tecca, et al., 2006).
- A debris basin combined with a containment bund has been proven to substantially improve debris retention performance.



Figure 6: A retention basin in Los Angeles, California (Los Angeles County Public Works, n.d.)

2.2.1.4 Flexible Debris Flood Barriers

Flexible debris flood barriers have become increasingly common in mountainous regions of Europe and Asia over the past two decades. These structures typically comprise steel ring nets or cable-net systems designed to intercept boulders, woody debris, and sediment while dissipating impact energy through controlled deformation of the system (Figure 7):

- Compared with traditional concrete structures, flexible barriers are installed in steep, remote terrain with reduced environmental disturbance and lower construction requirements (Maccaferri, n.d.; Kane, McElhany, & Forsthoff, 2023).
- Flexible barriers are generally most effective where expected debris volumes are relatively modest, where regular maintenance access can be provided, and when employed alongside other measures such as check dams and retention basins (Evergreen, 2025).
- Following large events, deposited material often requires removal to restore the capacity of the structure or in some instances the structure may require replacement. For water-dominated debris floods and muddy slurries, flexible barriers may be less effective due to the sizing of the netting or mesh.
- Liu et al. (2023) found that using multiple debris barriers in series can improve sediment retention and reduce impact forces on individual structures.



Figure 7: A Geobrigg debris flow barrier in Reotier, France (credit: Geobrigg).

2.2.1.5 Channel Improvements and Conveyance Measures

The primary objective of channel improvements and conveyance is to confine debris floods within predictable pathways, reduce channel instability, minimise avulsion potential, and safely convey water and sediment past vulnerable communities and infrastructure (Takahashi, 2007; Vagnon, 2019). Literature emphasises that hazard management on active alluvial fans relies on controlling sediment processes rather than water flows alone (Davies & McSaveney, 2008). Aggradation and avulsion result from excess sediment delivery and reducing risk to development typically requires maintaining sediment transport through sediment management. Without a viable long-term sediment management strategy, sustainable development on active fans may not be achievable. Measures in this category often include diversion channels, channel enlargement and widening deflection bunds/berms, and bank stabilisation:

- **Diversion channels** seek to direct debris floods away from assets through predefined flow paths, storage areas, or lower-consequence environments (Boreggio, Barbini, Bernard, & Degetto, 2024).

Common examples include guide bunds, training walls, and engineered spillways. These measures are widely used in alpine regions where confined valleys provide opportunities to safely redirect debris floods and debris flows (e.g. Figure 8). Diversion measures can provide reductions in risk to specific assets, however, they require careful consideration of downstream impacts and residual risk (Li & Choi, 2023). Redirecting debris floods away from one location may increase hazard exposure elsewhere unless suitable deposition areas are available.

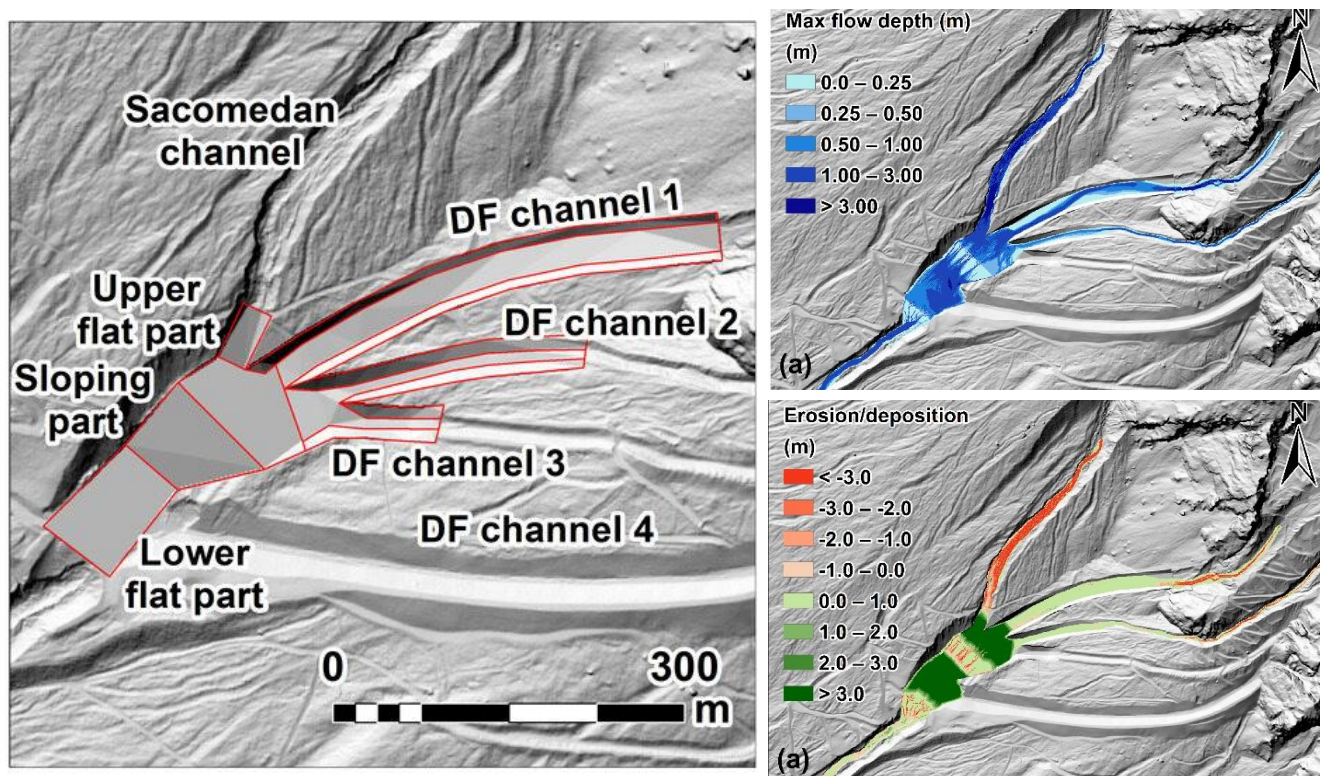


Figure 8: Proposed channel works for a debris flow catchment (Left) and subsequent hydraulic modelling (Right two frames) in the Dolomites, Italian Alps (Boreggio, Barbini, Bernard, & Degetto, 2024).

- **Channel enlargement and widening usually** involves excavating the channel creating capacity for debris but also reducing choke points (Figure 9). This measure forces debris to spread out, lose confinement, and significantly shorten its flow distance (Justice, 2021). Non-confined flows typically travel significantly less distance than a confined flow at the same gradient (VanDine, Debris Flow Control Structures for Forest Engineering , 1996).
- **Deflection berms or diversion bunds** are located along the lateral margins of debris flood paths and are designed to redirect debris floods away from critical assets (VanDine, Hungr, Lister, & Chatwin, 1997) (Figure 9). Physical modelling studies have shown that appropriately configured diversion bunds can significantly reduce deposition volumes in vulnerable locations and modify flow behaviour to reduce downstream consequences (Gao, et al., 2025). However, channel confinement may also increase flow depths, velocities, and impact forces, requiring careful hydraulic and geomorphic assessment during design (Vagnon, 2019).
- **Bank protection measures** such as rock riprap, gabions, rock armouring, and reinforced embankments can be utilised in high-energy streams where channel widening and lateral erosion

contribute to sediment production (deWolfe, et al., 2007). Studies from alpine environments indicate that stabilising actively eroding banks can reduce local sediment inputs and improve the long-term effectiveness of downstream mitigation structures. However, we note that, it may be impractical to treat long sections of the streambank with erosion protection to protect against debris floods which can run out (and impact the streambank) for tens of kilometres in some instances.

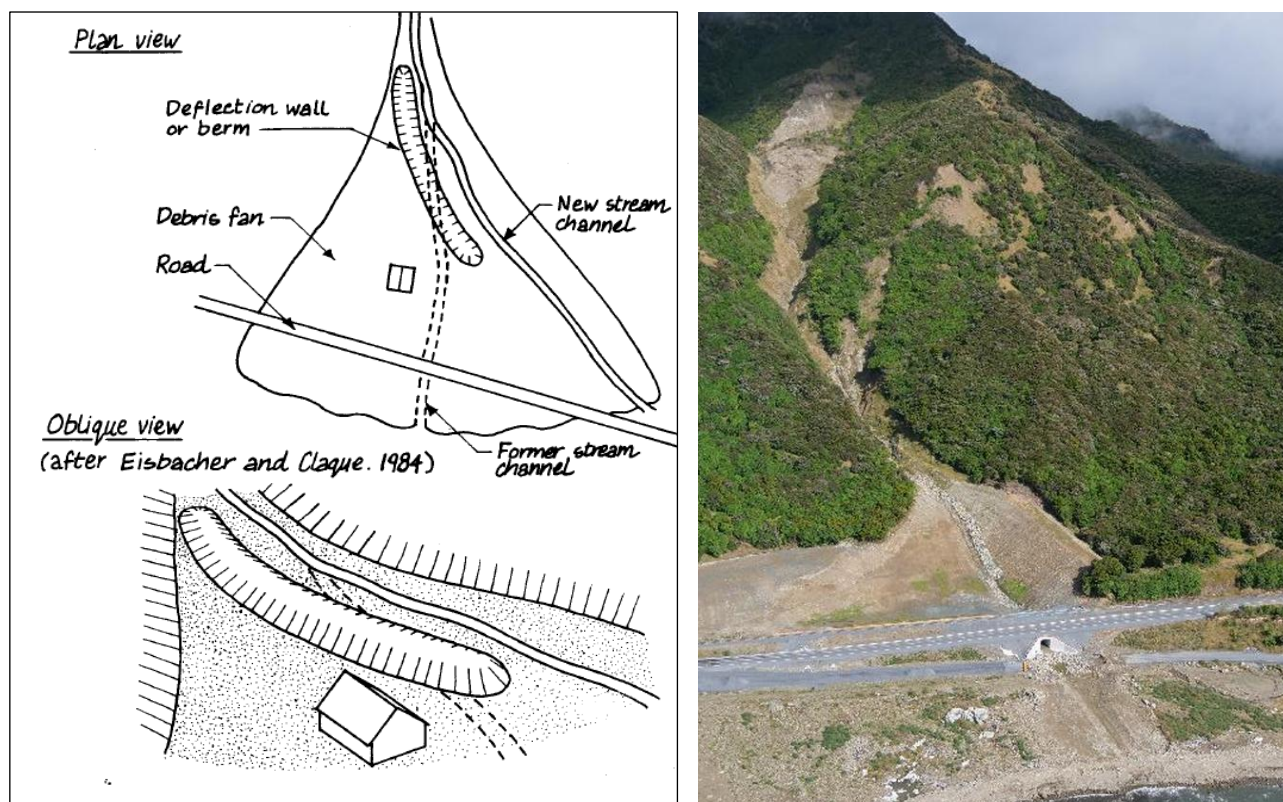


Figure 9: Typical schematics and photographs of conveyance structures. Left: A deflection berm schematic (VanDine, 1996). Right: Jacobs Ladder debris flow along SH1 in Kaikoura following channel widening works (Justice, 2021).

A key rationale for channelisation is the tendency for debris floods to undergo rapid channel adjustment during large events. Debris-laden floods can erode banks, deposit substantial quantities of sediment, and trigger channel avulsions that divert flows into previously unaffected areas. Research following major debris-flow and debris-flood disasters has shown that much of the resulting damage occurs when channels become unstable and floods leave their established courses rather than from flood depths alone (Jakob, et al., 2012; Fuchs, et al., 2007). Consequently, channel training works are frequently designed to maintain flow confinement and reduce the probability of flow breakout during extreme events.

Internationally, channel conveyance measures are rarely used as standalone solutions. Instead, they form part of integrated management systems that combine upstream sediment retention, debris barriers, check dams, and downstream conveyance infrastructure.

Despite their widespread application, conveyance-focused measures possess several limitations:

- First, they generally treat the consequences of sediment delivery rather than the underlying drivers of sediment generation within a catchment.

- Large volumes of material may continue to be supplied from landslides, eroding hillslopes, or unstable channels upstream.
- Channelisation can change the risk in areas that weren't previously exposed due to overtopping, embankment failure, or blockage by woody debris and large boulders.
- Maintaining channel capacity often requires ongoing excavation and sediment removal, resulting in long-term maintenance costs (Theule, et al., 2007). Stream and alluvial fan modifications must maintain the natural rate of sediment transport and removal to avoid disrupting sediment balance processes (Davies & McSaveney, 2008). Empirical observations and studies indicate that artificial alterations to stream channels can reduce sediment transport capacity, increasing the need for ongoing manual sediment removal. Consequently, developments involving modified stream systems may incur long-term maintenance requirements and associated costs, which should be incorporated into planning, development, and management decisions. These costs are typically recurrent and persist throughout the lifespan of the development.

2.2.2 Nature-Based and Catchment Management Approaches

Well targeted nature-based solutions (NbS) for debris flood management use natural and modified ecosystem processes to reduce erosion, interrupt sediment connectivity, manage runoff, provide space for deposition, dissipate flow energy and improve the performance and resilience of engineered measures. They may include protection and management of existing vegetation as well as targeting revegetation upper catchment areas or the fan surface can have different impacts on sediment delivery, flood energy dissipation, and erosion:

- **Source area stabilisation:** Nature-based measures can reduce sediment generation in source areas through rehabilitation of disturbed land, targeted revegetation of erosion-prone slopes, management of grazing pressure, protection of existing vegetation cover, and land management practices that avoid concentrating runoff into gullies. Recovering vegetation on bare soil slopes such as landslide areas in debris flood-prone catchments is known to decrease debris flood occurrence due to reduced erosion (Shen, et al., 2016; Yang, et al., 2018). Zhan et al. (2024) found that post-disturbance vegetation recovery reduced sediment connectivity and debris flow susceptibility in the Qipan catchment, China. This study also found that progressive revegetation of landslide source areas reduced sediment availability and was associated with a measurable increase in catchment stability following major debris flood events. Where vegetation alone is unlikely to establish, small-scale eco-engineering measures such as geotextiles or biodegradable erosion-control products may assist vegetation recovery. These measures are most effective for reducing shallow erosion and limiting ongoing sediment supply but are unlikely to stabilise large deep-seated landslides or rapidly moving slope failures.
- **Flow pathway management:** Vegetated buffers, riparian rehabilitation, roughened ground surfaces, sediment interception areas, and strategically placed sediment traps can interrupt sediment connectivity and reduce flow efficiency between source areas and downstream channels (Estrany, et al., 2019; Wang, et al., 2022). Vegetation is likely to be more influential on reducing sediment delivery in large, low-gradient catchments than in small steep ones (Davies & McSaveney, 2008). These measures do not prevent erosion from occurring but can reduce the volume of sediment reaching waterways and slow the transfer of water and sediment through the catchment.

- **Receptor and alluvial fan management:** On alluvial fans and depositional corridors, nature-based measures can provide space for debris floods, energy dissipation, and sediment deposition. Potential approaches include establishing designated deposition areas, sacrificial vegetation zones, setback areas, informal or engineered bunds, and vegetation designed to slow and disperse shallow overflows. Vegetation on the channel margins and alluvial fan surface can reduce flow mobility and contribute to sediment retention (Leonardi, et al., 2023). These approaches are most effective when integrated with land-use planning controls and designated bypass or overflow pathways.
- **Hybrid green-grey approaches:** Increasing evidence supports combining nature-based measures with engineered interventions such as check dams, sediment retention basins, debris barriers, bunds, roughened channels, and sediment traps. Hybrid systems have been shown to achieve greater reductions in flow energy, sediment transport, and debris flood magnitude than either structural or ecological interventions implemented independently (He, et al., 2026). For example, hybrid eco-geotechnical systems integrating vegetation filter strips with check dams were found to provide superior debris-flow retention compared with stand-alone ecological or structural interventions (Figure 10).

The role of NbS depends strongly on where they are located within the source-to-fan system. Measures in upper catchments may reduce chronic erosion or the connectivity between sediment sources and channels. Measures along channels may stabilise selected margins or trap smaller sediment fractions. Measures on alluvial fans may provide controlled space for shallow overflow, energy dissipation or deposition where this can occur without increasing risk to people, property or infrastructure.

Despite several benefits, NbS generally require significantly longer timeframes than other measures to become fully effective and may provide limited protection against large-magnitude debris floods. Following major disturbance events such as earthquakes, wildfire, or severe storms, sediment availability can remain elevated for years to decades, often exceeding the capacity of vegetation alone to control erosion and sediment transport (Hovius, et al., 2011; Tang, et al., 2009). Consequently, nature-based measures are increasingly viewed as complementary rather than standalone solutions.

Nature-based measures should not be assumed to prevent large-magnitude debris floods. In steep Teviot Valley catchments, extreme events may mobilise sediment volumes and flow energies that exceed the capacity of vegetation or distributed catchment measures. Their most credible role is therefore likely to be as one layer within an integrated package, including reducing recurring sediment inputs, maintaining the performance of downstream structures, creating redundancy and providing environmental, cultural and community co-benefits.

There may also be co-benefits of NbS, in that reduced sediment delivery may reduce the frequency of maintenance/debris clearance from engineered measures such as dams and barriers. The effectiveness of vegetation-based debris-flow mitigation is strongly influenced by vegetation type, density, and spatial arrangement, highlighting the importance of careful design when implementing nature-based solutions (He, et al., 2025).

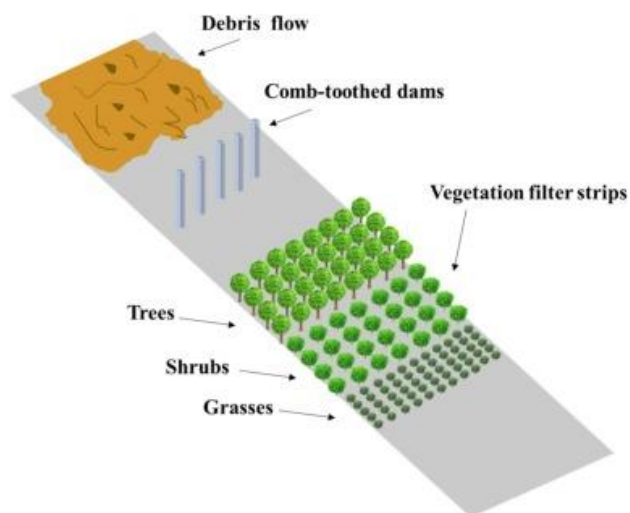


Figure 10: A schematic of combined engineered measures and nature-based solutions for debris flood management (He, et al., 2025).

These measures are not inherently low risk. Vegetation and woody material may become debris; increased roughness may alter water levels or deposition; sediment interception features may fill; and poorly located interventions may redirect flows or increase avulsion risk. Options therefore require catchment-specific geomorphic, hydrological, ecological and geotechnical assessment, together with consideration of establishment time, maintenance, land ownership, fire, drought, grazing, pest pressure and performance under exceedance conditions.

2.2.3 Land Use Planning and Development Controls

Local authorities and public works engineers, planners, and managers have a significant influence in building sustainable communities because of their responsibility for planning where communities are located, planning (and controlling) where infrastructure is located, and determining how the built environment is designed and constructed. Local authorities exert this influence through town and regional planning, land use zoning, building control and resource consent processes, and responsibility for infrastructure design and maintenance. Geohazard mapping is fundamental to understand the severity and spatial distribution of natural hazard impacts on land use and development.

The planning function of local authorities has a very important role to play in mitigating the effects of natural hazards, and land use planning is widely recognised as one of the most effective long-term approaches for reducing exposure to hazards such as debris floods. Planning mechanisms reduce risk by avoiding, limiting, or managing development within hazardous areas. Common planning tools include hazard zoning, development setbacks, building controls, minimum floor level requirements, and restrictions on vulnerable land uses within high-hazard zones.

Land use planning is key to minimise the risk to the community, both for existing and future development to help achieve a more resilient built environment. Consideration of natural hazards as one of the key criteria in the zoning of land for future use will enable:

- 1) Zoning relatively lower natural hazard areas for higher intensity built urban environment where building codes and standards can easily address the risks;

- 2) Zoning moderate hazards areas, where the risk to the built environment can be economically mitigated, for moderate intensity land use, with appropriate building controls;
- 3) Zoning higher hazard areas where the hazards can have severe effects on the built environment for low intensity land use.

Managing the resilience of development in existing areas is also important but requires a different approach as the properties have existing use rights. This requires the use of District Plan policies, rules, and building control measures to ensure that the natural hazard risks are taken into consideration and risks are mitigated appropriately. Provision of information and education would play an important part.

Mason et al. (2015) present an example in Whanganui where development of existing properties require consideration of the level of slope failure hazard, categorised as Land Stability Assessment (LSA) areas that are represented as hazard map overlays in the District Plan. Type A areas comprise land that is steep and shows evidence of instability, with a high risk of further instability and damage to property or life. The Council discourage subdivision and new dwellings in these higher-risk areas through District Plan objectives, policies, and rules. Type B areas have marginal slopes, which are still prone to instability, where the Council requires geotechnical investigations and detailed assessment of the slope stability hazards prior to any development proposal being submitted for resource consent. The investigations and assessment will determine the risk to property from landsliding, and whether the land is suitable for development, with mitigation measures implemented, or whether it is unsuitable for further development.

Land use planning for debris floods is often supported by integrated risk management and assessment. Nationally and internationally, two broad integrated risk management approaches are commonly used to manage alluvial fan and debris-flow hazards:

- **The first is a design-event approach**, whereby a specified hazard event (often defined by an annual exceedance probability or return period) is selected used to inform both development controls and the design of mitigation measures intended to withstand that event. Under this approach, land-use planning decisions and engineering interventions are typically based on whether the consequences of the selected design event can be managed to an acceptable level. This approach is widely adopted because it is relatively straightforward for practitioners, decision-makers, and communities to understand (Jakob, et al., 2017). However, it does not explicitly evaluate the consequences associated with events larger or smaller than the selected design event.
- **The second is a risk-based approach, which considers a range of hazard scenarios** and their associated probabilities, and evaluates the resulting consequences (e.g., life safety, economic loss, and infrastructure impacts). Risk reduction measures, including land-use planning controls and engineered mitigation works, are then assessed against defined risk tolerability criteria. Risk-based approaches are increasingly being adopted internationally as they provide a more comprehensive basis for decision-making and prioritisation of mitigation investment (Rudolf-Miklau et al., 2011; Porter et al., 2017).

Hazard mapping forms a critical component of land-use planning. Santos & Menéndez Duarte (2006) demonstrated that geomorphic and morphometric analyses can be used to identify debris-flow-prone channels and infrastructure exposed to hazard, providing a useful screening tool for regional planning.

Strouth et al. (2023) proposed a fan-sector approach for debris-flow hazard and risk assessment, demonstrating how spatial variations in hazard across alluvial fans can be used to inform zoning,

development controls, and risk-based land-use planning. Their approach recognises that hazard intensity and frequency can vary substantially across fan surfaces and that planning controls should be spatially targeted rather than applied uniformly across an entire fan.

Risk-based planning approaches are increasingly being adopted internationally. Rather than considering a single design event, risk-based frameworks evaluate a range of hazard scenarios and their associated consequences. Land-use decisions are then informed by risk tolerability objectives and acceptable levels of residual risk (Jakob & Hungr, 2005). At Cheekeye Fan, British Columbia, debris-flow hazards were assessed against predefined societal and individual risk tolerability criteria, and mitigation measures were designed to reduce residual risk to levels considered As Low As Reasonably Practicable (ALARP) (LeSueur, et al., 2025). Such approaches allow risk reduction measures, including avoidance, accommodation, and protection strategies, to be evaluated within a consistent decision-making framework.

Kowalski et al. (2023) advocate for reliability-based approaches to debris-flow risk management that explicitly consider uncertainty in hazard assessments and protection measures, supporting more robust decision-making and planning outcomes.

The importance of adaptive planning is increasingly recognised in response to climate change and evolving catchment conditions. R  ther et al. (2023) found that changing rainfall patterns can alter debris flood hazard occurrence and magnitude, suggesting that land-use planning frameworks should be periodically reviewed and updated to reflect evolving risk profiles. Kurilla & Fubelli (2023) project increasing debris flood susceptibility in some regions due to climate change, wildfire occurrence, and glacier retreat, highlighting the need for adaptive catchment management strategies that account for future hazard conditions.

In areas where risk cannot be reduced to tolerable levels through protection works or building controls, avoidance and managed retreat may represent the most appropriate long-term management response. These approaches seek to prevent the creation of new exposure and reduce existing exposure over time, recognising that some locations are inherently unsuitable for continued development.

Managed retreat example – Matat  , New Zealand

In response to the 2005 Matat   debris flows in Matat  , New Zealand, the Whakat  ne District Council, the Bay of Plenty Regional Council, and the Department of Internal Affairs led a managed retreat programme including a property acquisition package allowing property owners to relocate away from the impacted debris fan (Figure 11). The programme reduced exposure to debris flow risk through the voluntary purchase of high-risk properties at pre-hazard market value, supported by assistance for relocation and associated costs. The programme was accompanied by community engagement initiatives and statutory planning changes to prevent future residential development and occupation within the most hazardous areas of the Awatarariki fanhead.

PROPOSED TIMELINES FOR THE AWATARARIKI FANHEAD MANAGED RETREAT - MATATĀ COMMUNITY

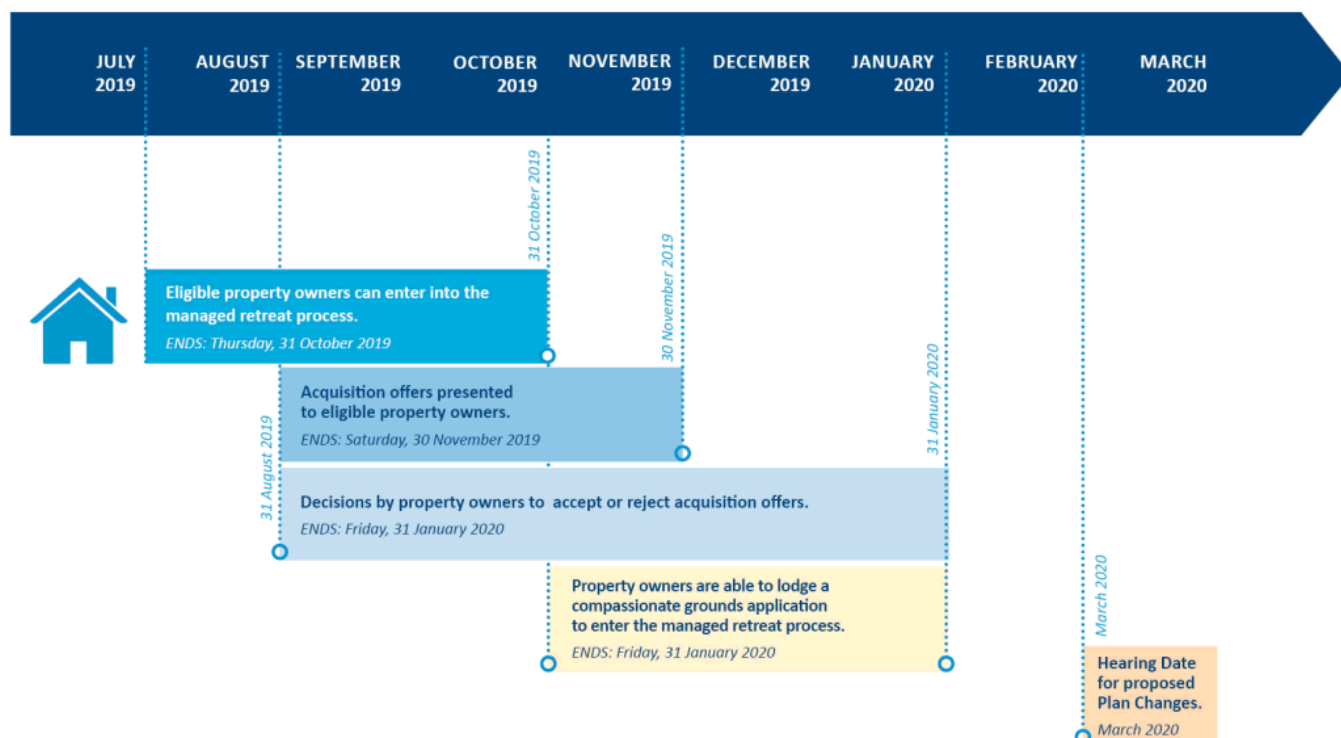


Figure 11: A timeline and key milestones of the Mātata managed retreat programme (Whakatāne District Council, 2020).

2.2.4 Emergency Management, Monitoring, and Preparedness

Emergency management, monitoring, and preparedness measures seek to reduce the consequences of debris flood events by improving awareness, forecasting, warning, response, and recovery capabilities. These measures are particularly important for debris floods, which can develop rapidly and may provide limited time for protective actions once triggered.

The World Meteorological Organisation (WMO) in collaboration with the United Nations Office for Disaster Risk Reduction (UNISDR) have developed a multi-hazard warning system checklist to help organisations develop and evaluate early warning systems (World Meteorological Organisation, 2018). The checklist outlines four elements of successful, end-to-end, and people centred early warning systems (Figure 12):

- Disaster risk knowledge
- Detection, monitoring, analysis, and forecasting of the hazards and possible consequences
- Warning dissemination and communication
- Preparedness and response capabilities

Together, these elements provide a framework for reducing loss of life and minimising the impacts of hazardous events through improved understanding of risk, timely warning, effective communication, and coordinated response actions.

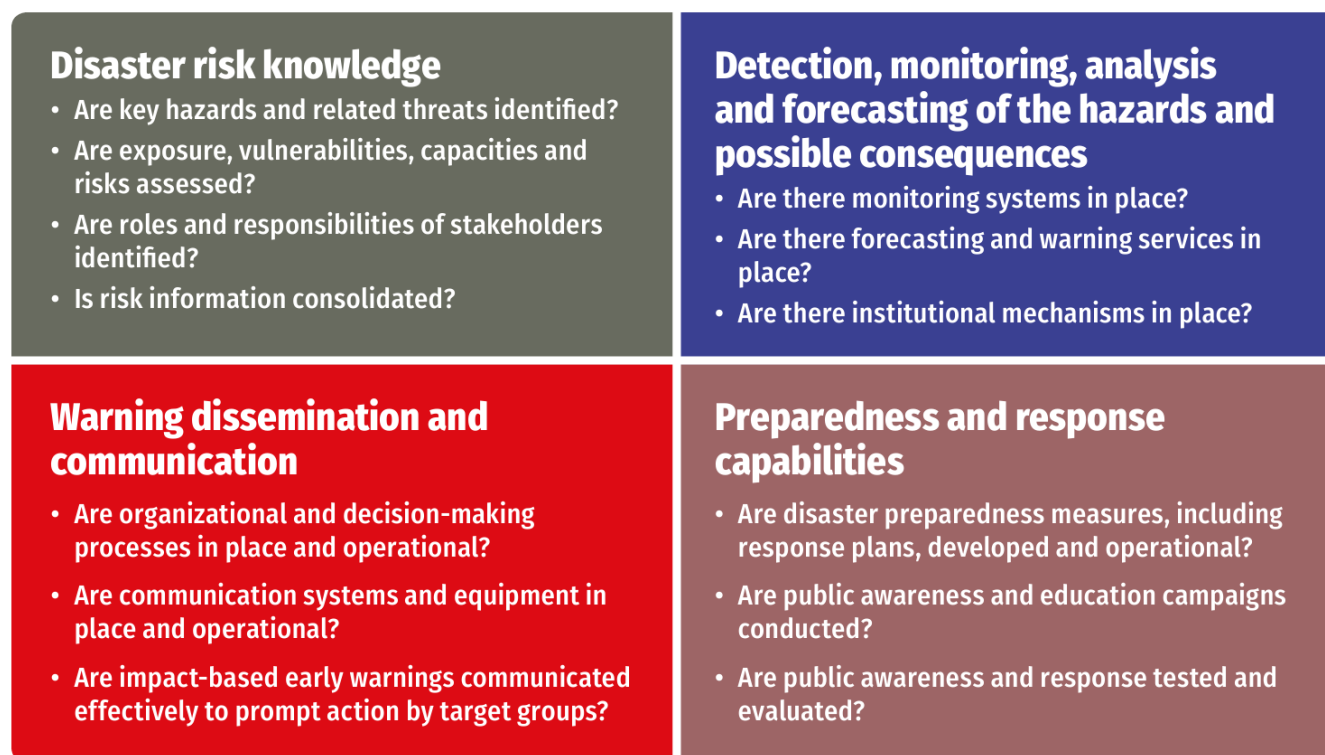


Figure 12: A breakdown of the four elements of successful early warning systems (World Meteorological Organisation, 2018).

2.2.4.1 Disaster risk knowledge

Risk is determined by the interaction between hazards, exposure, vulnerability, and a community's capacity to cope and adapt, and is further influenced by factors such as land-use change, environmental degradation, urbanisation, and climate change (World Meteorological Organisation, 2018). Effective risk assessments should therefore evaluate both physical impacts and social vulnerability, helping to identify at-risk populations and assets, inform evacuation planning and warning systems, and guide disaster risk reduction, preparedness, and response measures.

In Section 2.2.3 we outline several examples of debris flood studies and approaches that identify key hazards (e.g. hazard maps), and evaluate the exposure, vulnerability, and risk of people and assets (e.g. quantitative risk assessments). This information should be consolidated and incorporated into end-to-end early warning systems through centralised risk repositories that inform evacuation planning (i.e. hazard zones), identify vulnerable groups and assets, and establish a process on how new or emerging risks are ingested into the system.

Disaster risk knowledge should be maintained as a living information resource that is regularly updated as new hazard investigations, monitoring data, event observations, and risk assessments become available. Historical debris flood events can provide valuable information on event frequency, magnitude, impacts, and warning indicators, while ongoing monitoring can improve understanding of changing hazard conditions. Risk information should be readily accessible to emergency managers, infrastructure operators, and communities to support preparedness, planning, and response activities. Effective disaster risk knowledge provides the foundation for all other components of an early warning system. An

understanding of where debris floods may occur, who and what may be affected, and the potential consequences of different event scenarios is necessary to support hazard monitoring, forecasting, warning dissemination, emergency planning, and response decision-making.

2.2.4.2 Detection, monitoring, analysis, and forecasting of the hazards and possible consequences

Detection, monitoring, analysis, and forecasting are fundamental components of effective hazard management (World Meteorological Organisation, 2018). Continuous monitoring of hazard indicators and such as rainfall intensity, combined with analysis and forecasting, enables identification of hazards, supports early warning systems, and provides information on the potential consequences of events. The quality of a monitoring system can be evaluated by the following:

- Are there monitoring systems in place? (e.g. technical equipment and instrumentation, data sharing system).
- Are there forecasting and warning services in place? (e.g. data analysis and processing products, warning centres, warning messages).
- Are there institutional mechanisms in place? (e.g. monitoring network documentation, standardised process, roles and responsibilities).

For debris floods, monitoring and warning systems based on rainfall thresholds and flow detection can provide an important supplementary risk-reduction measure. Debris floods exhibit highly variable flow behaviour, meaning that monitoring data is valuable for improving hazard assessments and the design of mitigation structures (Nagl & Hubl, 2019). Sensors and measurement devices such as rain and flow gauges, accelerometers, satellite sensors, pull-cords, and seismic sensors have been utilised in several catchments around the world susceptible to debris flows and debris floods:

- Tecca et al. (2006) proposed a warning system based on rainfall thresholds and debris-flow-induced ground vibrations to support temporary road closures during hazardous conditions in Italy.
- Aaron et al. (2023) demonstrated the use of high-frequency LiDAR monitoring to measure debris flow velocities, depths, sediment dynamics, and channel changes in real time, highlighting the potential of advanced remote sensing technologies to improve understanding of debris flow behaviour and support the development of more effective monitoring and warning systems.
- Aiassa et al. (2023) developed a real-time debris-flow detection system based on optical fibre sensing, demonstrating the potential for automated event detection and rapid warning in debris-flow-prone catchments.
- Cazorzi et al. (2023) developed a model-based early warning framework that combines hydrological modelling and real-time monitoring data to support anticipation of runoff-generated debris-flow events.
- Tiranti et al. (2023) describe the territorial debris-flow warning system used in Piemonte, Italy, which integrates rainfall thresholds, monitoring networks, and operational response procedures to support emergency management.

- Cantonati et al. (2024) outlines a monitoring system used in the Rio Frejus catchment in the Italian Alps (Figure 13).

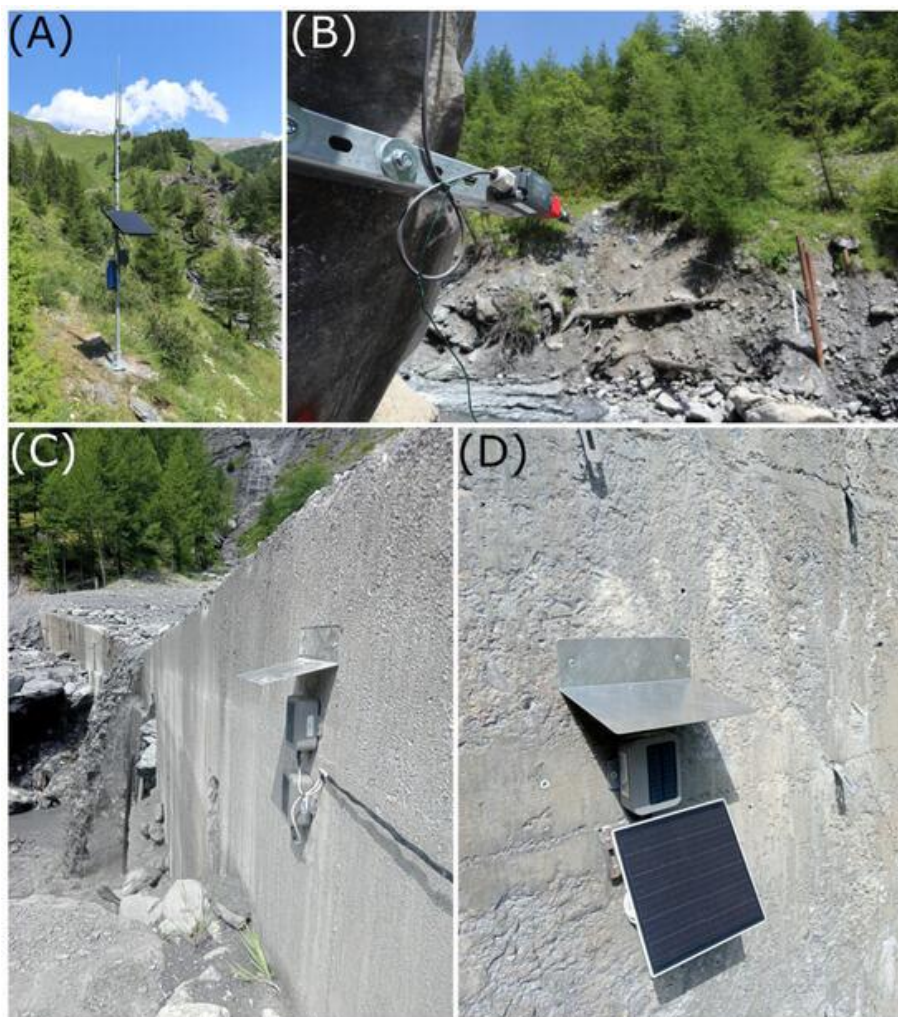


Figure 13: Examples of debris flood monitoring equipment installed in the Rio Frejus catchment in the Italian Alps. A) A telecommunication gateway linking the sensors to a remote data collecting centre. B) A pull-cord which measures the occurrence, time of arrival, and depth/height of a debris flood. This triggers an alarm if activated. C) An accelerometer and seismic sensor detecting flow arrival, velocity, volume, and destructive power. D) An additional accelerometer attached to a check dam.

Monitoring systems are most effective when integrated with warning protocols, response planning, and public communication frameworks (Coviello, 2023; Chen, et al., 2006). Relatively low-cost monitoring systems can successfully characterise debris-flow events, suggesting that effective monitoring need not rely solely on highly specialised infrastructure (Berti, Schimmel, Coviello, & Venturelli, 2023).

The location and quality of rainfall monitoring stations can significantly influence debris flood warning thresholds, emphasising the need for well-designed monitoring networks (Crema, et al., 2023). Further, the type of monitoring system and number of sensors in a monitoring network depends on having a thorough understanding of the catchment in which debris floods occur (Cantonati, et al., 2024).

Chmiel et al. (2023) highlight the value of monitoring active sediment source areas to better understand debris flood initiation mechanisms and support targeted catchment management interventions focused

on reducing sediment supply. Further, ongoing sediment monitoring can improve understanding of system behaviour and support adaptive management (Miwa, et al., 2023).

Debris floods in small, steep catchments are characterised by rapid onset, which can substantially limit the effectiveness of warning and evacuation systems (Davies & McSaveney, 2008). Historical events indicate that lead times between initiation and impact may be measured in minutes, providing little opportunity for safe evacuation (e.g. Matata 2005 Debris Flows). Consequently, reliance on emergency warning systems alone may not provide sufficient risk reduction for exposed communities. Although forecast-based evacuation triggered by intense rainfall is widely used its effectiveness may be constrained by the frequency of false alarms required to achieve an acceptable level of safety. Continued improvements in weather radar and technologies are expected to improve forecast reliability and reduce false alarm frequencies.

2.2.4.3 Warning dissemination and communication

Effective risk communication is a critical component of debris flood management. International experience demonstrates that communities with a clear understanding of local hazards, warning signs, evacuation procedures, and emergency response arrangements are often better able to respond to rapidly developing events (Chen, 2006). Because debris floods can occur with little warning following intense rainfall, communication systems must be capable of rapidly transmitting clear, actionable information to at-risk communities and responders.

The key drivers of successful warning dissemination and communication involve (World Meteorological Organisation, 2018):

- Are organisational and decision-making processes in place and operational?
- Are communication systems and equipment in place and operational?
- Are impact-based early warning communicated effectively to prompt action by target groups?

Effective warning systems require clearly defined responsibilities for monitoring, warning issuance, emergency management, and public communication. Warning messages should be concise, consistent, and communicated through multiple channels, such as emergency alerts, text messages, websites, social media, radio broadcasts, and direct engagement with affected communities. Communication strategies should focus not only on the likelihood of an event occurring, but also on the expected impacts, including threats to life safety, property, critical infrastructure, transportation networks, and access routes.

For debris floods, warning communication is often most effective when linked to predefined triggers and response actions (Chen et al., 2006). These may include rainfall intensity thresholds, debris flood forecasts, or observed catchment conditions that activate specific response measures such as increased monitoring, road closures, evacuation warnings, or evacuation orders. Establishing clear links between warning levels and required actions helps reduce uncertainty and supports timely decision-making by both emergency managers and the public.

The short response times of steep catchments can severely constrain warning times, meaning traditional warning systems may provide limited opportunity for evacuation. While natural warning signs, such as

sounds of slope failure, sudden reductions in streamflow from temporary channel blockages, or rapid rises in water level, may provide some indication of impending debris floods, these indicators are often unreliable and difficult to interpret in real time. Consequently, risk management should focus primarily on land-use planning, infrastructure design, and avoidance of high-hazard areas, supplemented where appropriate by monitoring and automated warning systems that can provide localised alerts. However, even with monitoring, warning lead times may only be on the order of minutes in some catchments.

2.2.4.4 Preparedness and response capabilities

Preparedness and response capabilities are essential components of an early-warning system, recognising that not all risk can be eliminated through land-use planning or structural mitigation measures. Effective preparedness and response arrangements aim to reduce the consequences of debris flood events by ensuring that agencies, infrastructure operators, and communities are equipped to respond rapidly and effectively when hazardous conditions occur. The WMO suggests the preparedness element of an early warning system should consider the following:

- Are disaster preparedness measures, including response plans, developed and operational?
- Are public awareness and education campaigns conducted?
- Are public awareness and response tested and evaluated?

Common preparedness approaches include community meetings, education campaigns, hazard mapping, public signage, preparedness guides, and targeted engagement with residents located in high-risk areas.

Public education programmes can improve hazard awareness, encourage household preparedness, support informed decision-making during emergencies, and increase community acceptance of mitigation measures.

Many jurisdictions have adopted community-based disaster risk management approaches, whereby local residents actively participate in hazard identification, emergency planning, evacuation exercises, and preparedness activities (Chen, et al., 2006; Chen & Hsu, 2019). Such approaches can improve local knowledge of hazards, strengthen relationships between communities and emergency management agencies, and increase the effectiveness of emergency response during rapidly evolving events.

Preparedness activities may also include the development of hazard-specific emergency response plans, identification of evacuation routes and assembly points, establishment of communication protocols, and regular training exercises involving emergency services and local communities. These measures help ensure that roles and responsibilities are clearly understood before an event occurs and can improve coordination during emergency response (Tiranti, et al., 2023).

In Taiwan, pre-emptive evacuations, identification of high-risk communities, and community preparedness programmes, are employed successfully as risk reduction methods, particularly where structural mitigation is unfeasible (Chen, et al., 2006). Such approaches recognise that timely warning and evacuation may represent the most effective means of reducing loss of life during extreme events (Chen & Hsu, 2019).

2.3 Current Management in the Teviot Valley

ORC and other agencies have led efforts to manage the ongoing risk associated with debris floods in the Teviot Valley including:

- Data collation (surveying, LiDAR, ortho-photography, rain gauge installation),
- Expert geomorphic, engineering, and risk assessment.
- Culvert upgrades at State Highway stream crossings.
- Engagement with residents.
- Physical channel work, comprising channel improvements and periodic channel maintenance/clearance.
- Emergency management and preparedness activities.

This section summarises recent debris flood management strategies in the Teviot Valley.

2.3.1 Structural (Engineered) Measures

A range of structural measures have been implemented within the Teviot Valley to reduce debris flood risk and improve the resilience of communities, infrastructure, and productive land located on alluvial fans. These measures have evolved over time in response to damaging historical events and include:

- Reservoir Creek conveyance structure (concrete-lined chute).
- Culvert and bridge upgrades.
- Channel training works.
- Sediment management activities.
- Locally constructed protection bunds.

Collectively, these interventions have sought to manage debris flood hazards by maintaining channel capacity, improving the conveyance of water and sediment, reducing the likelihood of channel avulsion, and protecting vulnerable assets from inundation and erosion.

Channel conveyance

There is a concrete-lined chute in Reservoir Creek that was constructed after a 1978 debris flood event, which caused channel aggradation and boulder deposition through residential areas of northern Roxburgh. The chute is approximately 180 m long and was designed to rapidly convey floodwater and sediment across the alluvial fan to the Clutha River (Figure 14).



Figure 14: The concrete-lined chute at Reservoir Creek installed in the late 70's pictured here in early 2026 during WSP fieldwork.

The 2017 event provided a real-world performance test of the structure. Mackey (2023) describes that:

- The chute initially conveyed debris-laden flows efficiently.
- Sediment accumulated where the chute discharged into the Clutha River.
- A depositional lobe formed at the outlet where the gradient abruptly changes.
- The lobe progressively blocked the chute outlet, causing backfilling.
- Reduced bridge capacity near SH8 then contributed to avulsion across the lower fan and through residential areas.

2017 Debris Flood Response

Following the November 2017 debris flood events, a coordinated response was undertaken by ORC, Central Otago District Council (CODC), NZ Transport Agency Waka Kotahi (NZTA), and technical specialists to reduce ongoing debris flood risk in the Teviot Valley. Initial actions focused on debris removal, restoring channel capacity, and reopening critical transport links. Additional channel excavation and sediment clearance works were undertaken in several catchments to improve conveyance and reduce the likelihood of future obstruction and avulsion. This included the removal of approximately 1,000 m³ of sediment from the base of Reservoir Creek in 2019 to increase storage capacity and reduce the likelihood of the chute backfilling.

Culvert and Bridge Upgrades

In response to the 2017 debris flood event and subsequent engineering assessments, NZTA upgraded several SH8 stream crossings within the Roxburgh area. Engineering investigations identified the Pumpstation Creek, Golfcourse Creek, and Black Jacks Creek culverts as having insufficient capacity to convey future flood and debris-flood events. Upgrades included replacement of the Pumpstation Creek culvert with a substantially larger 4 m × 2 m concrete structure and installation of larger culverts at Golfcourse Creek and Black Jacks Creek (Figure 15). These works were undertaken to improve conveyance of floodwater, sediment and coarse debris, reduce blockage and overtopping risk, and improve the resilience of SH8 during extreme rainfall events. However, engineering assessments recognised that culvert upgrades alone cannot address ongoing risks associated with sediment aggradation, channel avulsion and continued debris supply from the surrounding catchments.



Figure 15: Culverts upgrades and channel works undertaken in Pumpstation (left) and Golfcourse Creek (right top and bottom). Left image was taken in early 2026 while the right two images were taken in 2023 during WSP fieldwork.

Long-term mitigation investigations

A range of longer-term mitigation options have also been investigated for catchments throughout the Teviot Valley (Golder, 2019a; Mackey, 2021). These include protective bunding, increasing culvert capacity beneath SH8, continued channel maintenance, sediment retention structures, armouring of channel margins, and modifications to the existing concrete-lined channel in Reservoir Creek. Sediment retention structures and debris nets were also considered, however, their effectiveness is constrained by

the steep channel gradients, limited accessible storage areas, and the large sediment volumes available for mobilisation. As a result, current management has generally favoured a combination of monitoring, channel maintenance, targeted infrastructure improvements, and localised structural protection measures.

Local (informal) structural measures

In addition to formal engineering works, debris flood risk in the Teviot Valley has historically been managed by landowners through localised earth bunds and training banks constructed along active channels. These features are commonly formed using sediment and debris deposited during previous debris flood events and are periodically reworked to maintain channel alignment and reduce the likelihood of flow breakout onto productive land and developed areas.

2.3.2 Land-Use Planning and Development Control

The Teviot Valley Spatial Plan acknowledges the potential for debris floods on alluvial fans and doesn't provide any additional development opportunities within the areas subject to alluvial hazard notation (Central Otago District Council, 2024). The spatial plan also acknowledges that further work is required to be undertaken in these areas to better understand the risks to residents.

While hazard and risk maps have been publicly released by ORC, no specific debris flood zoning provisions, floor level requirements, or development restrictions based on this new information have been identified during this review.

To support future land-use planning and risk management decisions in the Teviot Valley, WSP completed detailed debris flood modelling and risk assessments across 13 alluvial fan systems in the Teviot Valley area (WSP, 2026). This work can be summarised as follows:

- The assessment integrated historical event records, geomorphological mapping, hydrological analysis, debris flood volume estimation, geotechnical investigations, and RAMMS numerical modelling to simulate debris flood inundation for a range of event magnitudes.
- The model outputs were subsequently used to undertake qualitative risk assessment in accordance with the ORC Regional Policy Statement (APP6) framework and quantitative risk assessment using Annual Individual Fatality Risk (AIFR) and Annual Property Risk (APR) methodologies.
- The resulting outputs provide a spatial representation of debris flood risk across each alluvial fan (Figure 16).
- The assessment demonstrated that risk is highly variable across the fan surfaces, generally increasing in proximity to active channels, fan apexes, and areas susceptible to channel avulsion, while decreasing with distance from primary flow paths.

Although planning measures specifically addressing debris flood hazards are limited, the completion of the recent debris flood hazard and risk assessment represents an important step towards risk-informed land-use planning. The availability of detailed hazard and risk mapping across the alluvial fans provides a spatial evidence base that can inform future consideration of hazard overlays, development controls, and other planning measures.

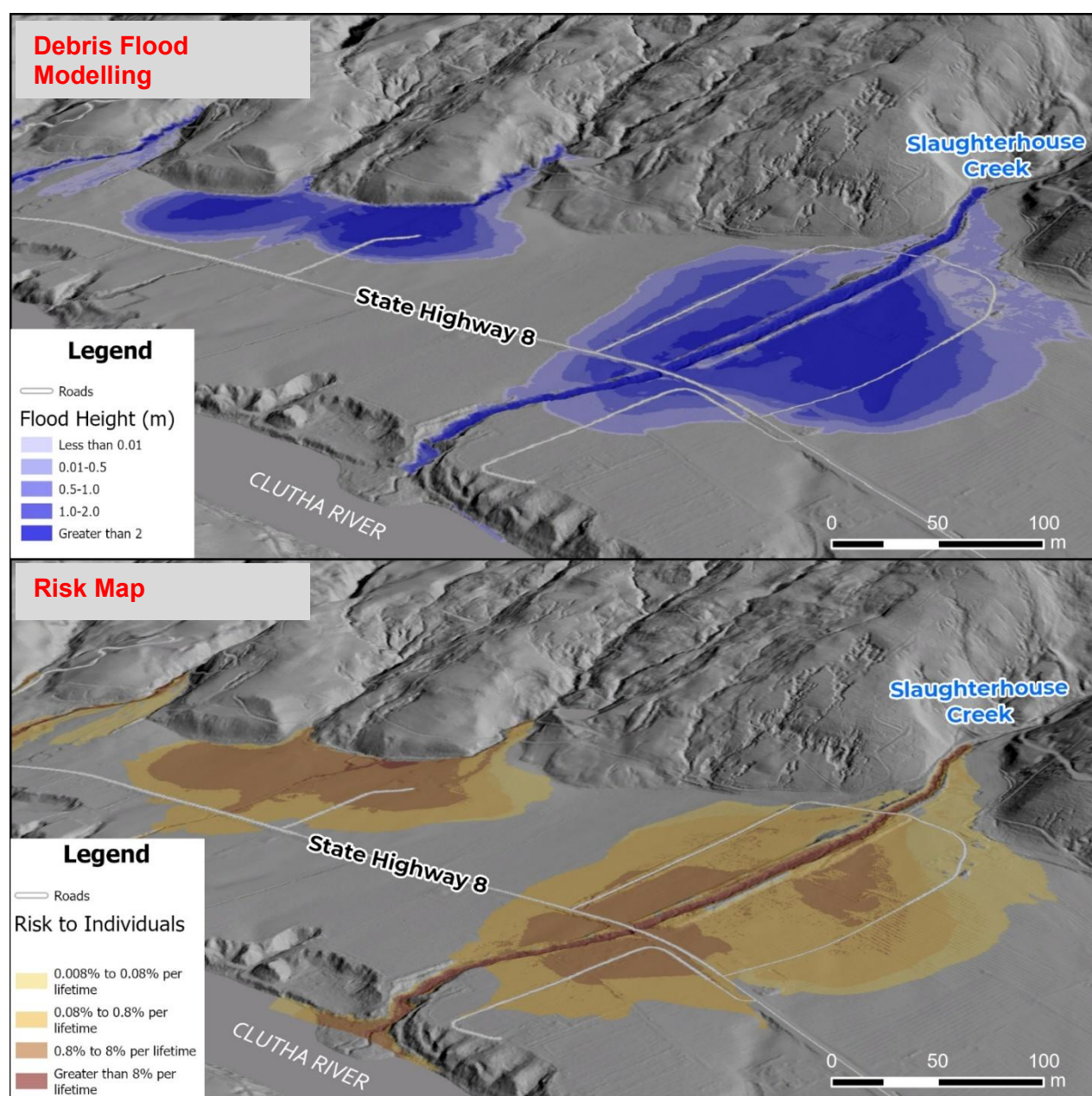


Figure 16: Debris flood modelling (top) and a risk map (bottom) for Slaughterhouse Creek and adjacent catchments north of Roxburgh township. Similar information for other alluvial fans in this study can be found in the technical report on the Otago Regional Council website.

2.3.3 Emergency management and monitoring

Emergency management arrangements for debris flood hazards are primarily coordinated through Central Otago District Council (CODC) and the Otago Civil Defence Emergency Management (CDEM) Group. Current activities focus on community preparedness, hazard awareness, emergency communications, and response planning for a range of natural hazards affecting the district, including debris floods. Residents are encouraged to prepare household emergency plans, maintain emergency supplies, and register for emergency alerts and warnings. Information during emergencies is disseminated through a range of channels including CODC, Otago CDEM, local radio stations, social media, and emergency notification systems.

The ORC Duty Flood Officer (DFO) provides coordinated monitoring, forecasting, communications, and warning functions during flood and severe weather events. Operating on a 24/7 roster, the DFO monitors weather forecasts, telemetry, rainfall and radar data, communicates potential risks to CDEM and other stakeholders, and helps coordinate operational responses during developing events.

During severe thunderstorm events, the DFO monitors MetService outlooks, watches, and warnings, and can alert CDEM to conditions that may generate intense, localised rainfall capable of triggering debris floods. The DFO can also track rainfall using radar and available rain gauges, providing updates on storm intensity, location, and potential consequences.

However, the effectiveness of the DFO role for debris flood warning is constrained. Debris floods are typically triggered by highly localised convective storms that may develop rapidly, with warning lead times often less than one hour and potentially only a few minutes. The Teviot Valley has limited rainfall monitoring coverage, with only one telemetered gauge located within a catchment capable of generating debris floods, and no specific trigger thresholds or response procedures currently exist for debris flood events. Consequently, the DFO's primary contribution is likely to be supporting preparedness and response through the dissemination of weather, rainfall, and hazard information, rather than providing a warning system capable of enabling evacuation before debris flood impacts occur.

Following completion of the 2026 WSP debris flood risk assessment, ORC, CODC, NZTA and Otago CDEM jointly engaged with the Roxburgh and Teviot Valley community to communicate the findings of the study and discuss implications for future risk management. Community sessions were attended by representatives from ORC, CODC, CDEM and NZTA, reflecting a multi-agency approach to preparedness and emergency management. Although no debris-flood-specific evacuation plans or warning systems have been identified, the recent hazard mapping and quantitative risk assessment provide an important evidence base to support future emergency planning, public education, evacuation decision-making and community resilience initiatives.

Subsequent management has emphasised monitoring and improved understanding of debris flood processes. This has included aerial inspections, repeat lidar surveys, orthophotography, bathymetric surveys of sediment deposition within the Clutha River, installation of a telemetered rain gauge in Reservoir Creek, installation of water level monitoring equipment in Reservoir Creek at the SH8 bridge crossing, and informal monitoring of large landslides activated by post-event channel erosion. Landslides are not currently being actively monitored by ORC, instead these are usually monitored post-event. These activities have provided information on channel recovery, sediment redistribution, rainfall thresholds, and ongoing sediment supply from unstable hillslopes.

2.4 Key Findings

- **Integrated approaches are international best practice.** The literature consistently demonstrates that no single mitigation measure can eliminate debris flood risk. The most successful approaches combine structural works, land-use planning, catchment management, monitoring, emergency management, and community preparedness within an integrated risk management framework.
- **Structural measures play an important role but have limitations.** Structural measures remain the most widely adopted debris flood mitigation tools internationally. Common approaches include stopbanks, check dams, debris retention basins, flexible barriers, and channel training works. These measures can reduce hazard consequences by controlling sediment transport, lowering flow energy,

trapping debris, and directing flows away from vulnerable assets. However, their effectiveness can be reduced when sediment volumes exceed design capacity, channels aggrade, or flow avulsion occurs.

- **Sediment management is critical.** A recurring finding across the literature is that debris floods differ fundamentally from conventional flooding because sediment transport controls much of the hazard behaviour. Sediment deposition can rapidly reduce channel capacity, block culverts and bridges, and trigger channel avulsions. Effective debris flood management therefore requires consideration of both water and sediment conveyance, with many mitigation systems relying on ongoing sediment removal and maintenance to remain effective. As channel alterations can reduce sediment conveyance capacity, ongoing artificial sediment removal may be required to maintain system function. This represents a recurring lifecycle cost that should be considered when evaluating development and management options.
- **Conveyance measures treat consequences rather than causes.** Channel widening, diversion channels, engineered chutes, deflection bunds, and bank protection measures are commonly used to contain and direct debris-laden floods. These measures can significantly reduce consequences for downstream communities and infrastructure. However, they generally do not address the underlying drivers of sediment production within a catchment and therefore often require ongoing maintenance and complementary upstream measures.
- **Nature-based solutions are most effective when used as complementary measures.** Well-targeted nature-based can reduce the frequency and magnitude of smaller debris flood events, decrease cumulative sediment delivery downstream, protect and support the long-term performance of engineered assets, provide space for flow spreading and deposition, and retain flexibility to adapt to future land-use and policy changes. While these approaches can contribute to long-term risk reduction, they generally require time to become effective and are unlikely to provide sufficient protection against large debris flood events when implemented in isolation. International research increasingly supports combining nature-based and engineered approaches to maximise overall performance.
- **Land-use planning is an effective long-term management measure.** The literature highlights land-use planning as one of the most effective and sustainable methods for reducing debris flood risk. Growth strategies, hazard zoning, development controls, building design requirements, and risk-based planning frameworks can prevent the creation of new exposure and reduce future exposure. There is also a growing international shift from design-event approaches toward risk-based planning frameworks that consider a range of hazard scenarios and associated consequences.
- **Monitoring and emergency management reduce life-safety risk.** Monitoring, warning systems, emergency response planning, and community preparedness programmes are widely recognised as important components of debris flood risk management. International case studies demonstrate that rainfall thresholds, flow detection systems, and real-time monitoring networks can provide valuable information for emergency response and improve understanding of catchment behaviour. These systems are most effective when integrated with clear warning protocols and community response procedures. However, the rapid onset of debris floods in small catchments can severely limit the effectiveness of warning and evacuation systems meaning that people will often have to rely on their own intuition. Public education, provision of information, and training activities are important to ensure response procedures are effective in a flood event.

- **Existing management in the Teviot Valley is consistent with international practice, but gaps remain.** The Teviot Valley has adopted a range of mitigation measures consistent with approaches used internationally, including channel conveyance works, culvert upgrades, sediment management activities, channel maintenance, and locally constructed bunds. The Reservoir Creek concrete chute, post-2017 channel works, SH8 culvert upgrades, and ongoing maintenance programmes all reflect a strategy focused on improving conveyance, reducing blockage risk, and limiting channel avulsion. Local landowners have also historically contributed to risk reduction through the construction and maintenance of informal earth bunds and channel training works.
- Recent investigations undertaken in the Teviot Valley have improved understanding of debris flood hazards. Data collection, geomorphic assessments, numerical modelling, and quantitative risk assessments have provided a detailed understanding of debris flood behaviour, exposure, and risk across the alluvial fans. This information provides an evidence base for future risk management and mitigation decision-making.
- Several limitations remain within the current management framework. While a number of State Highway 8 stream crossings have been upgraded following the 2017 events, several crossings still rely on relatively small culvert structures, and sediment accumulation is evident at the downstream ends of some culverts, creating the potential for reduced conveyance during future events. Existing stopbanks, bunds, and channel training works have generally been successful at confining sediment-laden flows to established channels, but this has also concentrated sediment deposition within those channels, necessitating ongoing excavation and maintenance to maintain their effectiveness.
- The Teviot Valley currently has no retention basins, check dams, or flexible debris barriers which could provide additional protection to communities.
- There are also currently limited formal land-use planning controls specifically addressing debris flood hazards on the Teviot Valley alluvial fans. Similarly, while emergency management arrangements exist at a district and regional level, there are no fan-specific debris flood emergency management or evacuation frameworks comparable to those described in international case studies. Finally, unlike several alpine regions in Europe, the Teviot Valley does not currently have a dedicated debris flood monitoring and warning network incorporating rainfall thresholds, flow sensors, debris detection systems, or automated warning capabilities. As a result, current management is largely reliant on physical mitigation works, periodic maintenance, and emergency response rather than proactive monitoring and warning systems.

3. Option Development and Screening

3.1 Overview

To support identification of future debris flood management options in the Teviot Valley, a long list of potential options has been developed and organised using the PARA framework. The long list includes both existing measures that could be expanded or modified, and new measures identified through the literature review and review of current management practices. At this stage, the objective is not to identify a preferred solution, but rather to establish a comprehensive set of potentially feasible options for further consideration.

Given the large number of potential measures available, an initial feasibility screening has been undertaken to identify options that warrant more detailed investigation. The screening is intended to provide a high-level assessment of each option's suitability within the Teviot Valley context, considering factors such as technical feasibility, alignment with local catchment conditions, likely effectiveness, constructability, land availability, environmental constraints, ongoing maintenance requirements, and potential community and stakeholder acceptance. Each option has been assigned a preliminary feasibility rating of High, Moderate, or Low (Table 2).

Table 2: The initial long-list screening criteria.

Rating	Meaning	Description
H	High Feasibility	Technically feasible in the Teviot Valley and likely to be implementable with currently available technology, land access, funding pathways, and stakeholder support. Suitable for progression to detailed assessment.
M	Moderate Feasibility	Potentially feasible but subject to constraints such as cost, land ownership, environmental effects, regulatory approvals, maintenance requirements, or uncertainty regarding performance. Requires further investigation.
L	Low Feasibility	Significant technical, economic, environmental, social, or operational constraints make implementation challenging within the Teviot Valley. Unlikely to be progressed beyond long-list assessment unless circumstances change.

3.2 Long list

The long list is presented in Table 3 and includes a range of structural, nature-based, planning, retreat, monitoring, and emergency management measures mapped to the PARA framework. Options are identified using a reference number corresponding to their PARA category, where:

- P = Protect (e.g., P01)
- A = Avoid (e.g., A01)
- R = Retreat (e.g., R01)
- AC = Accommodate (e.g., AC01)

For each option, a description of the measure, its primary benefit, key limitations, implementation type, and a preliminary feasibility rating based on the screening methodology described above is provided.

Table 3: A long list of debris flood management and screening for the Teviot Valley.

ID	Option	Type	Description	Main Benefit	Key Limitation	Screening
Protect						
P01	Channel maintenance and sediment management programme	Asset Management & Maintenance	Ongoing sediment removal, channel clearing and management of aggradation.	Maintains channel capacity.	Requires ongoing maintenance and funding. Limited effectiveness at mitigating major flood events	H
P02	Bunds and stopbanks	Structural	Construct, upgrade or extend bunds and stopbanks along channel margins.	Reduces overbank flow and avulsion.	Can alter channel dynamics, increasing deposition and/or scour within channels. May require access to private land.	H
P03	Reservoir Creek chute upgrade	Structural	Extend the chute and/or redesign the outlet to reduce backfilling.	Builds on existing infrastructure. Addresses observed 2017 performance issues.	Benefits limited to Reservoir Creek. Potentially expensive given the localised benefits.	M
P04	Channel modification works	Structural	Channel widening, deepening, realignment and training works.	Improves conveyance and reduces avulsion.	Requires ongoing maintenance.	H
P05	Diversion channels	Structural	Divert debris floods away from vulnerable assets and communities.	Can significantly reduce consequences.	Requires suitable discharge and new channel areas, with accompanying consenting and land acquisition/easement considerations.	M

ID	Option	Type	Description	Main Benefit	Key Limitation	Screening
P06	Bank stabilisation and channel armouring	Structural	Riprap, gabions and erosion protection works.	Reduces erosion and sediment generation.	Expensive over long reaches. Engineering design likely required.	M
P07	Check dams and grade-control structures	Structural	Install sediment-control structures within upper catchments.	Slows flow velocity and reduces sediment transport downstream.	Requires maintenance and sediment removal with difficult access. Potentially expensive engineered structures.	M
P08	Sediment retention basins	Structural	Capture sediment and debris before reaching developed areas.	Reduces downstream impacts.	Requires large footprint and maintenance. Land acquisition and consenting may be required.	M
P09	Flexible debris barriers	Structural	Debris nets and flexible barrier systems.	Suitable for steep terrain.	Limited storage capacity. May not be suitable for water dominated debris floods.	M
P10	SH8 crossing upgrades	Structural	Upgrade remaining culverts, bridges and crossings.	Improves resilience of key transport and 3 waters infrastructure and reduces likelihood of backup at crossings.	Does not reduce sediment supply. Costly and disruptive to community.	M
P11	Catchment sediment management programme	Asset Management & Maintenance	Identification, monitoring, and management of key sediment source areas, erosion hotspots, debris deposits, and sediment transfer pathways throughout the catchment.	Addresses long-term sediment accumulation.	Effectiveness may be limited by the scale of sediment sources, natural erosion processes, and access constraints in steep terrain.	M
P12	Nature-based erosion control and revegetation	Nature-Based	Targeted stabilisation and revegetation of active sediment source areas, treatment of sediment connectivity pathways,	Reduces sediment mobilisation and wider ecological benefits.	Benefits take time to develop. Limited effectiveness at mitigating	H

ID	Option	Type	Description	Main Benefit	Key Limitation	Screening
			management of overflow corridors and alluvial fans, and implementation of hybrid eco-geotechnical measures.		large flood events. Could be a source material	
Avoid						
A01	Regional policy statements and plans	Strategic Planning	Incorporate debris flood hazards and risk into regional planning frameworks, objectives, policies, and methods.	Provides strategic direction and consistency for long-term hazard and risk management.	Requires policy development, political support, and statutory planning processes.	H
A02	District plans and hazard overlays	District Planning	Use hazard overlays, objectives, policies, and rules to identify debris flood hazard areas and manage development accordingly.	Provides a clear and spatially explicit mechanism for managing development in hazard-prone areas.	Plan changes can be time-consuming and may be opposed by affected landowners.	H
A03	Land-use and subdivision consents	Resource Consenting	Use hazard and risk information to guide development towards lower-risk areas and ensure risks are appropriately assessed and managed during the consent process.	Prevents the creation of new exposure and supports risk-informed development decisions.	Can increase consenting complexity, assessment costs, and development constraints.	H
A04	Building and site design controls	Building Controls	Apply building setbacks, minimum platform levels, site layout requirements, and hazard-informed design controls.	Reduces vulnerability and improves resilience of future development.	Primarily applicable to new development and redevelopment rather than existing buildings.	H
A05	Hazard disclosure requirements	Policy & Governance	Formal disclosure of debris flood hazards and risk information to landowners, developers, and purchasers.	Improves risk awareness and supports informed decision-making.	Does not directly reduce hazard or risk.	H
Retreat						

ID	Option	Type	Description	Main Benefit	Key Limitation	Screening
R01	Voluntary property acquisition	Land Use & Planning	Purchase highly exposed properties.	Permanent risk reduction.	High cost and degree of uncertainty due to willingness of homeowner to sell to council.	M
R02	Relocation of vulnerable buildings	Land Use & Planning	Move buildings away from high-risk areas.	Removes exposure.	Disruptive and expensive.	L
R03	Managed retreat from highest-risk fan sectors	Land Use & Planning	Gradual withdrawal from intolerable-risk locations.	Long-term risk reduction.	Significant social and economic implications.	M
R04	Relocation of critical infrastructure	Land Use & Planning	Relocate key services and infrastructure.	Improves long-term resilience.	Very high capital cost.	L
R05	Strategic retreat and land acquisition planning	Policy & Governance	Establish future retreat pathways and triggers.	Enables adaptive management.	Long implementation timeframe.	M
Accommodate						
AC01	Property-level protection measures	Structural	Local bunds, barriers and diversion works around buildings.	Protects individual assets.	Limited community-wide benefit and uncertainty in who would cover the cost of individual protection measures.	H
AC02	Raised floor levels and building platforms	Land Use & Planning	Elevate new or redeveloped buildings.	Reduces damage consequences.	Limited effectiveness for large events.	M
AC03	Debris-resilient building design	Land Use & Planning	Building designs resistant to debris flood impacts.	Reduces vulnerability.	Primarily for new development. The effectiveness of debris flood-resilient building	M

ID	Option	Type	Description	Main Benefit	Key Limitation	Screening
					design is subject to considerable uncertainty, as there is currently no widely accepted design framework and limited evidence linking specific design measures to building performance	
AC04	Flood overflow corridors	Land Use & Planning	Designate areas where exceedance flows can be safely conveyed.	Manages residual risk.	Land use implications.	M
AC05	Debris flood monitoring network	Monitoring & Warning	Additional rainfall gauges, flow sensors and debris monitoring equipment.	Improves situational awareness.	Ongoing maintenance required.	H
AC06	Debris flood warning system	Monitoring & Warning	Rainfall thresholds and automated alerts.	Supports proactive response.	Potential false alarms, and/or highly localised thunderplumps may not be captured.	L
AC07	Fan-specific emergency management plans	Emergency Management	Response and evacuation planning for individual fans.	Improves preparedness.	Requires regular review.	H
AC08	Evacuation route planning and signage	Emergency Management	Identification and maintenance of evacuation routes.	Supports emergency response.	Limited effectiveness in isolation. Requires integration with flood monitoring/warning systems, as well as public education and training, and ongoing updates.	H
AC09	Community education and	Community & Education	Hazard awareness, preparedness information and training.	Improves community resilience.	Benefits depend on participation.	H

ID	Option	Type	Description	Main Benefit	Key Limitation	Screening
	preparedness programme					
AC10	Multi-agency response framework	Policy & Governance	Formal clarification of roles and responsibilities of ORC, CODC, NZTA and emergency services.	Ensures efficient and effective response during a debris flood event.	Requires ongoing commitment.	H

3.3 Development of Short-Listing Criteria

Following the completion of the long list of options described in Section 3 of this report, the next stage of the project (beyond the scope of this report) will consider short-listing of the options. The purpose of the short-listing process is to refine the long list of debris flood risk management options into a smaller number of viable options that warrant more detailed investigation during subsequent phases of the programme. This section summarises the results of early consideration of a short-listing approach and a discussion with stakeholders to set priorities for developing the short-listing criteria.

3.3.1 Short-Listing Philosophy

To inform the development of criteria for the short-listing process, a workshop was held with key stakeholders held on 21 August 2026. The workshop included representatives from Otago Regional Council (ORC), Central Otago District Council (CODC), New Zealand Transport Agency Waka Kotahi (NZTA), and Civil Defence Emergency Management (CDEM). The workshop consisted of an overview of the optioneering programme by ORC, a summary of the long list options by WSP, and then an open discussion. The purpose of the discussion was to gain consensus on the themes and principles that should underpin the future short-listing process, rather than to assess or select particular options.

A key issue that was identified in the stakeholder discussions was that different fans have different characteristics and risk levels, and therefore the short-listing process will need to recognise and account for those differences. Defining the problem that the risk management options need to address is a key step in setting the criteria to evaluate the options against for the short-list. During the workshop it was recognised that the impacts posed by debris floods on land, structures, economic activity etc. vary between the urbanised and rural fans. The short-listing framework should not assume that a single management approach will be appropriate across all locations; instead, options should be assessed against their ability to address the dominant risk drivers and community outcomes relevant to each fan.

A second key outcome of the workshop was that life safety risk needs to be the primary consideration when assessing each option. Broader benefits of the mitigation options – such as protection of property, infrastructure resilience, continuity of productive land use, and wider community wellbeing – should also be considered, and these may provide the meaningful differentiation between options. Overall, the stakeholder discussion concluded that a practical and proportionate assessment methodology is needed, which compares risk reduction, deliverability, cost, community values, and long-term resilience outcomes.

3.3.2 Proposed Assessment Themes

The workshop identified a series of high-level themes that could underpin the short-listing framework. These themes broadly align with technical, economic, environmental, and social considerations commonly used in multi-criteria assessments while remaining practical for application.

Effectiveness

Effectiveness considers how well an option addresses the identified debris flood risk and reduces the consequences of future events. Particular emphasis will be placed on the extent to which an option reduces life-safety risk, while also considering benefits to property, infrastructure, access, and

community resilience. The framework should favour options that address the primary hazard mechanisms and provide benefits in the areas of greatest risk.

Deliverability

Deliverability considers the practical challenges associated with implementing an option, including property access, constructability, consenting requirements, statutory approvals, ownership arrangements, and disruption during implementation. We note the importance of identifying options that are realistically achievable and avoiding the promotion of solutions that face substantial implementation barriers.

Whole-of-Life Cost and Maintenance

Considering whole-of-life costs rather than capital costs alone will be a key feature of the framework. The framework will therefore consider both implementation costs and ongoing maintenance requirements, recognising that many debris flood mitigation measures require continued sediment management, inspection, repair, partial replacement, or operational oversight throughout their lifespan. This is particularly important when comparing engineered protection structures against the ‘softer’ measures such as planning, preparedness, or passive options that accommodate debris floods.

Environmental, Social and Cultural Performance

The framework should consider the broader effects of the options on environmental, social, cultural, and landscape values. Community engagement and support will be key, particularly for options based on the principles of avoidance, planning-control, or retreat. Environmental and cultural effects may also influence the feasibility and desirability of some engineering measures, and introduce evaluation criteria previously not commonly associated with debris flood mitigation (e.g., water quality).

Implementation Timeframe

The framework should include a criterion that highlights opportunities that could deliver benefits in the near term, while also recognising that some options may require longer implementation periods but produce more durable outcomes. Accordingly, the framework will consider the likely timeframe required to design, consent, construct, and operationalise each option. This criterion will assist in identifying potential quick wins alongside longer-term strategic interventions.

Integrated Solutions

An important theme emerging from both the literature review and stakeholder discussions was that debris flood risk is unlikely to be managed through a single intervention alone. Rather, the preferred outcome may involve a combination of Protect, Avoid, Retreat, and Accommodate measures working together to reduce risk across the catchment. Consequently, the short-listing framework should remain open to evaluating integrated packages of measures where they provide greater overall benefits than individual options assessed in isolation. Examples include opportunities for shared protection measures that deliver benefits to both State Highway infrastructure and downstream communities, combined with planning, monitoring, and preparedness initiatives.

3.4 Next Stage

The proposed themes presented above provide the basis for developing a formal short-listing methodology. Following completion of stakeholder and community engagement activities, the criteria will be refined, weightings considered where appropriate, and a structured assessment framework developed to support the planned stakeholder short-listing workshop. This process will ultimately produce a defensible shortlist of options, together with indications of benefits, constraints, implementation responsibilities, indicative costs, and implementation timeframes.

4. Conclusions

The Teviot Valley has a documented history of debris flood activity, with the 2026 Debris Flood Hazard and Risk Study confirming that debris flood risk varies significantly across the alluvial fans and that some areas remain subject to elevated risk (WSP, 2026). This study has highlighted the need to consider additional measures to further reduce risk to people, property, infrastructure, and productive land.

This report reviewed a range of debris flood management options used nationally and internationally to develop a long-list of options for consideration in the Teviot Valley. Not all options are suitable for the Teviot Valley and therefore this report also discussed the relative feasibility of each option in the long list and a path to further refining the list. The key findings of this long-list options report include:

- The literature review demonstrates that there is no single solution capable of eliminating debris flood risk. International best practice increasingly favours integrated approaches that combine structural measures, land-use planning, monitoring and warning systems, emergency management, community preparedness, and where appropriate, nature-based interventions.
- A recurring theme throughout the literature is the importance of sediment management, with many successful mitigation systems relying on ongoing management of sediment transport, deposition, and channel stability.
- The review of current management practices indicates that the Teviot Valley has already implemented a range of measures consistent with international approaches, including channel conveyance works, culvert upgrades, sediment management, emergency management, and community engagement.
 - Opportunities remain to investigate additional measures, including upstream sediment retention, improved monitoring and preparedness arrangements, risk-informed planning controls, and other approaches identified through the long-list optioneering process.
- A total of 32 potential management options have been identified and screened across the Protect, Avoid, Retreat, and Accommodate (PARA) framework. The initial screening indicates that a range of options may warrant further investigation.
- Stakeholder engagement highlighted the importance of considering technical feasibility, whole-of-life costs, environmental and social effects, community acceptance, deliverability, and maintenance requirements.
- Importantly, many options are likely to be most effective when implemented as part of an integrated package rather than as standalone measures.

Nature-based solutions should remain cautiously framed and should not be presented as stand-alone protection against large debris floods. The next phase could assess source-area treatment, sediment-connectivity interruption, controlled fan-space management and hybrid eco-engineered packages as distinct options. Their value should be judged through measurable contributions to sediment management, structural-asset reliability, safe exceedance, adaptability and wider environmental, cultural and community outcomes.

The next phase of the programme will involve stakeholder and community engagement on the long list and proposed assessment criteria, followed by development of a structured short-listing methodology and workshop-based evaluation process. The outcome will be a defensible shortlist of options that can be progressed to more detailed assessment and ultimately support the development of a long-term debris flood risk management strategy for the Teviot Valley.

5. Limitations statement

This report ('Report') has been prepared by WSP New Zealand Limited ('WSP') exclusively for the Otago Regional Council (ORC) ('Client') in relation to Teviot Valley Debris Flood Optioneering Phase 1 ('Purpose') and in accordance with the Short Form Agreement with the Client dated 25 November 2024 ('Agreement'). The findings in this Report are based on and are subject to the assumptions specified in the Report and the Offer of Services dated 16 June 2026. WSP accepts no liability whatsoever for any use or reliance on this Report, in whole or in part, for any purpose other than the Purpose or for any use or reliance on this Report by any third party.

6. References

- Aaron, J., Spielmann, R., McArdell, B., & Graf, C. (2023). Debris-flow monitoring with high-frequency LiDAR scanners: A new method to infer the internal dynamics of debris flows. *8th International Conference on Debris Flow Hazard Mitigation (DFHM8)*. Retrieved from https://www.e3s-conferences.org/articles/e3sconf/abs/2023/52/e3sconf_dfhm82023_01001/e3sconf_dfhm82023_01001.html
- Aiassa, S., Antolini, F., Barla, M., Insana, A., Gaudino, R., Martella, G. R., & Pellegrini, S. (2023). A new real-time debris flow and avalanches detection system based on optical fiber sensing. *E3S Web of Conferences, Volume 415 – DFHM8*.
- Barbini, M., Bernard, M., Boreggio, M., Da Re, F., & Gregoretti, C. (2023). Design of two retention basins along the torrent Liera on the Gares Valley (Dolomites, North East Italy) after the storm Vaia. *8th International Conference on Debris Flow Hazard Mitigation (DFHM8)*.
- Berti, M., Schimmel, A., Coviello, V., & Venturelli, M. (2023). Characterization of a debris flow event using an affordable monitoring system. *E3S Web of Conferences, Volume 415 – DFHM8*.
- Boreggio, M., Barbini, M., Bernard, M., & Degetto, M. G. (2024). Proposed Solution for Stony Debris-Flow Control Works in Two Headwater Basins with Morphological Changes. *Geohazards*. Retrieved from <https://www.mdpi.com/2624-795X/5/4/64>
- Busslinger, M., Jakob, M., Singer, R., & Calder, R. (2023). Log Crib Check Dam Performance under Multiple Debris-Flow Loadings – East Gate Landslide, British Columbia, Canada. *E3S Web of Conferences, Volume 415 – DFHM8*. doi:10.1051/e3sconf/202341506002
- Cantonati, F., Lissari, G., Vagnon, F., Paro, L., Magnani, A., Rossato, I., . . . Tiranti, D. (2024). From Alpine Catchment Classification to Debris Flow Monitoring. *Hydrology*.
- Cazorzi, F., Barbini, M., Beinat, A., Bernard, M., Boreggio, M., Cesca, M., . . . Demmler, C. (2023). A model-based early warning system for runoff-generated debris-flow occurrence: Preliminary results. *E3S Web of Conferences, Volume 415 – DFHM8*.
- Central Otago District Council. (2024). *Teviot Valley Spatial Plan*.
- Charles, N., Zhi, I., Haiming, L., Sunil, P., Zhenyang, J., & Zhang, R. (2025). Effects of Barrier Deflectors on Impact Mechanisms against Debris Flow. Retrieved from <https://ascelibrary.org/doi/10.1061/JGGEFK.GTENG-13359>
- Chen, C., Lee, W., & Yu, F. (2006). Debris flow hazards and emergency response in Taiwan. *Monitoring, Simulation, Prevention and Remediation of Dense and Debris Flows*.
- Chen, J., Wang, J., Li, D., Tao, Z., Chen, H., & Zhao, W. (2025). A conceptual model for spatially regulating debris flow materials and energy by cascading check dams based on flume experiments. *Bulletin of Engineering Geology and the Environment*, 84. Retrieved from <https://link.springer.com/article/10.1007/s10064-025-04394-w>
- Chen, S.-T., & Hsu, C.-L. (2019). The Research of Debris Flow Disaster Prevention and Response System in Taiwan. *IOP Conference Series Earth and Environmental Science*.
- Chmiel, M., Husmann, L., Walter, F., Horgan, H., Belli, G., Marchetti, E., & Kienholz, C. (2023). Towards a better understanding of debris flow sediment sources: Monitoring of an active rock slope at Spitze Stei, Switzerland. *E3S Web of Conferences, Volume 415 – DFHM8*.
- Church, M., & Jakob, M. (2020). What Is a Debris Flood. *Water Resources Research*, 56(8). Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020WR027144>

- Colorado Geological Survey. (n.d.). *Debris and Mud Flows*. Retrieved from <https://coloradogeologicalsurvey.org/hazards/debris-flows/>
- Coviello, V. (2023). Debris-flow detection for early warning purposes: Recent advances, open problems, and future challenges. *E3S Web of Conferences, Volume 415 – DFHM8*.
- Crema, S., Coviello, V., Cesca, M., Dainese, R., Marchi, L., Pasuto, A., & Cavalli, M. (2023). When instrument location makes the difference on rainfall thresholds definition: Lessons learned at Cancia, Dolomites.
- Davies, T., & Hall, R. (1992). A realistic strategy for disaster prevention. *Interpraevent 1992 Bern Switzerland*.
- Davies, T., & McSaveney, M. (2008). Principles of sustainable development on fans. *Journal of Hydrology*, 43-65.
- deWolfe, V., Santi, P., Ey, J., & Gartner, J. (2007). Effective mitigation of debris flows at Lemon Dam, La Plata County, Colorado. *Geomorphology*. Retrieved from <https://www.sciencedirect.com/science/article/abs/pii/S0169555X07001924>
- Environment Canterbury. (2026). *Stopbanks*. Retrieved from <https://www.ecan.govt.nz/your-region/your-environment/flood-protection-and-community-resilience/flood-protection-assets-and-activities/stopbanks>
- Estrany, J., Ruiz, M., Calsamiglia, A., Carriquí, M., García-Comendador, J., Nadal, M., . . . Gago, J. (2019). Sediment connectivity linked to vegetation using UAVs: High-resolution imagery for ecosystem management. *Science of the Total Environment*, 1192-1205.
- Evergreen, M. (2025). *Integration of Debris-Flow Barriers with Check Dams and Retention Basins*. Retrieved from <https://evgcpl.com/integration-of-debris-flow-barriers-with-check-dams-and-retention-basins/>
- Fuchs, S., Heiss, K., & Hübl, J. (2007). Towards an empirical vulnerability function for use in debris flow risk assessment. *Natural Hazards and Earth System Sciences*. Retrieved from <https://nhess.copernicus.org/articles/7/495/2007/>
- Gao, X., Li, L., Pan, L., Yang, X., Zhou, H., Liu, J., . . . Rao, P. (2025). Experimental study on diversion dike to mitigate debris flow blocking river disaster. *Water*, 17(12). Retrieved from <https://www.mdpi.com/2073-4441/17/12/1736>
- GNS. (2005). *The 18 May 2005 debris flow disaster at Matata: Causes and mitigation suggestions*.
- Golder. (2019a). *Management and Reduction of Debris Flow Risk in Roxburgh, Otago*.
- He, S., Chen, W., Chen, X., Wang, D., Li, Y., Pei, Z., . . . Qi, Y. (2025). Mechanisms and benefits of segmented eco-geotechnical measures for debris flow mitigation. *Ecological Engineering*. Retrieved from <https://www.sciencedirect.com/science/article/abs/pii/S0925857425001090>
- He, S., Zou, S., Qi, Y., Li, Y., Pei, Z., Zhao, P., & Wang, D. (2026). Experimental study on the benefits of nature-based solutions for debris-flow mitigation via synergistic eco-geotechnical measures. *Engineering Geology*. Retrieved from <https://www.sciencedirect.com/science/article/abs/pii/S0013795226000062>
- Hovius, N., Meunier, P., Lin, C.-T., Chen, H., Chen, Y.-G., Dadson, S. J., . . . Lines, M. (2011). Prolonged seismically induced erosion and the mass balance of a large earthquake. *Earth and Planetary Science Letters*, 347-355.
- Jakob, M., & Hungr, O. (2005). *Debris-flow Hazards and Related Phenomena*.
- Jakob, M., Stein, D., & Ulmi, M. (2012). Vulnerability of buildings to debris flow impact. *Natural Hazards*. doi:<https://doi.org/10.1007/s11069-011-0007-2>
- Jakob, M., Weatherly, H., Bale, S., & Perkins, A. (2017). A Multi-Faceted Debris-Flood Hazard Assessment for Cougar Creek, Alberta, Canada. *Hydrology*. doi:10.3390/hydrology4010007

- Justice, T. (2021). Jacobs Ladder - A Case-History of Debris Flow in a Post-Seismic Environment. Retrieved from <https://www.nzgs.org/libraries/jacobs-ladder-a-case-history-of-debris-flow-in-a-post-seismic-environment/>
- Kane, W., McElhany, J., & Forsthoft, B. (2023). Field investigation and design of debris nets in an environmentally sensitive area. *E3S Web of Conferences, Volume 415 – DFHM8*.
- Kowalski, J., Zhao, H., & Yildiz, A. (2023). Towards reliability-management for debris flow risk assessment.
- Kurilla, L. J., & Fubelli, G. (2023). Future global debris flow susceptibility considering climate change, wildfire probability, and glacier retreat.
- Lee, S., An, H., & Kim, M. (2023). Analysis of mitigation effect of the open- and closed-type check dam. *E3S Web of Conferences, Volume 415 – DFHM8*.
- Lee, S., An, H., Kim, M., & Lee, J. (2025). Numerical evaluation of design factors for effective debris flow mitigation of closed-type check dams. *Frontiers in Earth Science, 13*. Retrieved from <https://www.frontiersin.org/journals/earth-science/articles/10.3389/feart.2025.1598919/full>
- Leonardi, A., Pasqua, A., Flammini, L., & Pirulli, M. (2023). Debris flow: Simulating the mitigation properties of vegetation. *E3S Web of Conferences, Volume 415 – DFHM8*.
- LeSueur, P., Strouth, A., Mark, E., Collier-Pandya, B., & Zubrycky, S. (2025). Risk-informed design of debris-flow mitigation at Cheekeye Fan. *Canadian Geotechnical Journal*.
- Li, R., & Choi, C. E. (2023). Flow-type landslides Impacting V-shaped Diversions: Physical Modelling. *E3S Web of Conferences, Volume 415 – DFHM8*.
- Liu, H., Choi, C. E., & Ng, C. W. (2023). Multiple debris-resisting barriers with basal clearance: A study on impact force. *E3S Web of Conferences, Volume 415 – DFHM8*.
- Los Angeles County Public Works. (n.d.). *Debris Basins*. Retrieved from <https://pw.lacounty.gov/core-service-areas/water-resources/sediment/debris-basins/>
- Maccaferri. (n.d.). *Debris Flow Barriers*. Retrieved from <https://www.maccaferri.com/solutions/debris-flow-barriers/>
- Mackey, B. (2021). *Managing ongoing debris flow risk in Roxburgh, Otago*.
- Mark, E., & Strouth, A. (2023). The Cheekeye Debris-Flow Barrier – unique features of a proposed open check dam in Canada. *E3S Web of Conferences, Volume 415 – DFHM8*.
- Mason, D., Brabharan, P., & Frampton, M. (2015). Land use planning for slope instability hazards in Wanganui. . *Australia New Zealand Conference on Geomechanics*. Wellington.
- Ministry for the Environment. (1991). *Resource Management Act 1991*. Retrieved June 6, 2026
- Ministry for the Environment. (2023). *Community-led retreat and adaptation funding: Issues and Options*.
- Miwa, K., Mikami, K., Nagayama, T., Furuya, T., Hayashi, S., Fujita, M., . . . Miyamoto, K. (2023). Long-term monitoring of sediment runoff for an active sediment control in Joganji River.
- Moarse, E., Strouth, A., & Jakob, M. (2018). Steep creek hazard mitigation case studies: some lessons learned from past events. *Geohazards 7*.
- Nagl, G., & Hubl, J. (2019). Debris-flow / structure interaction in the Gatria torrent. *Early warning systems for debris flows: state of the art and challenges*.
- New Zealand Government. (2025). *Resource Management (Consenting and Other System Changes) Amendment Act 2025*. Retrieved from <https://www.legislation.govt.nz/act/public/2025/41/en/latest/#LMS1014951>
- Piton, G., Carlados, S., Recking, A., Tacnet, J. M., Liébault, F., Kuss, D., . . . Marco, O. (2016). Why do we build check dams in Alpine streams? An historical perspective from the French experience. *Earth Surface Processes and Landforms*.

- Piton, G., Carlados, S., Recking, A., Tacnet, J. M., Liébault, F., Kuss, D., . . . Marco, O. (2017). Why do we build check dams in Alpine streams? An historical perspective from the French experience. *Earth Surf. Process. Landforms*.
- Piton, G., Goodwin, S. R., Mark, E., & Strouth, A. (2022). Debris Flows, Boulders and Constrictions: A Simple Framework for Modeling Jamming, and Its Consequences on Outflow. *JGR Earth Surface*.
- Porter, M., Jakob, M., Holm, K., & McDougall, S. (2017). Risk-based landslide safety assessments in Canada. *North American Symposium on Landslides, Roanoke, Virginia*.
- Rudolf-Miklau, F., Baek, R., Skolaut, C., & Schmid, F. (2011). Alpine Mass Movements: Implications for hazard assessment and mapping. *J. Torrent Avalanche Landslide Rock Fall Engineering*.
- Rüther, D. C., Rubensdotter, L., & Hefre, H. (2023). Extreme precipitation on dry ground in western Norway – characteristics of induced landslides call for adaptation of the Norwegian practice in landuse planning.
- Santos, R., & Menéndez Duarte, R. (2006). Topographic signature of debris flow dominated channels: implications for hazard assessment. *WIT Transactions on Ecology and the Environment*.
- Shen, P., Zhang, L., Chen, H., & Gao, L. (2016). Role of vegetation restoration in mitigating hillslope erosion and debris flows. *Engineering Geology*. Retrieved from <https://www.sciencedirect.com/science/article/abs/pii/S0013795216306871>
- Strouth, A., Zubrycky, S., & McDougall, S. (2023). Quantifying debris-flow hazard and risk based on fan sector. *E3S Web of Conferences, Volume 415 – DFHM8*.
- Takahashi, T. (2007). *Debris Flow: Mechanics, Prediction and Countermeasures*.
- Tang, C., Zhu, J., Li, W., & Liang, J. (2009). Rainfall-triggered debris flows following the Wenchuan earthquake. *Bulletin of Engineering Geology and the Environment*, 187-194.
- Tecca, P., Armento, C., & Genevois, R. (2006). Debris flow hazard and mitigation works in Fiames slope (Dolomites, Italy). *Monitoring, Simulation, Prevention and Remediation of Dense and Debris Flows*.
- Theule, J., Liebault, F., Loye, A., Laigle, D., & Jaboyedoff, M. (2012). Sediment budget monitoring of debris-flow and bedload transport in the Manival Torrent, SE France. *Natural Hazards and Earth System Sciences*. Retrieved from <https://nhess.copernicus.org/articles/12/731/2012/>
- Tiranti, D., Bertolotto, P., Cremonini, R., Gaeta, A. R., & Vela, N. (2023). The Territorial Debris Flow Early Warning System of Piemonte (North-western Italy). *E3S Web of Conferences, Volume 415 – DFHM8*.
- USEPA. (2021). Stormwater best management practice - check dams. Retrieved from <https://www.epa.gov/system/files/documents/2021-11/bmp-check-dams.pdf>
- Vagnon, F. (2019). Design of active debris flow mitigation measures: a comprehensive analysis of existing impact models. *Landslides*. Retrieved from https://www.researchgate.net/publication/335821218_Design_of_active_debris_flow_mitigation_measures_a_comprehensive_analysis_of_existing_impact_models
- VanDine, D. (1996). Debris Flow Control Structures for Forest Engineering .
- VanDine, D., Hungr, O., Lister, D., & Chatwin, S. (1997). Channelized Debris Flow Mitigative Structures in British Columbia, Canada. Retrieved from <https://www.scribd.com/document/438831007/Channelized-debris-flow-mitigative-structures-in-british-columbia-canada-pdf>
- Wang, C., Zhang, G., Zhu, P., Wang, Z., & Xing, S. (2022). Sediment connectivity of small watershed affected by gully development and vegetation restoration on the Loess Plateau. *Geoderma*.

- Whakatāne District Council. (2020). *Awatarariki Managed Retreat Programme*. Retrieved from <https://www.whakatane.govt.nz/residents/awatarariki-managed-retreat-programme>
- World Meteorological Organisation. (2018). *Multi-hazard Early Warning Systems: A Checklist*. Retrieved from https://community.wmo.int/sites/default/files/EWS_Checklist_0.pdf
- WSP. (2026). *Roxburgh Debris Flow and Debris Flood Study*.
- Yang, W., Qi, W., & Zhou, J. (2018). Decreased post-seismic landslides linked to vegetation recovery after the 2008 Wenchuan earthquake. *Ecological Indicators*, 438-444.
- Zhan, X., Hu, X., Jing, Z., Xu, W., Xia, D., & Ding, G. (2024). Variation in Debris-Flow-Prone Areas with Ecosystem Stability: A Case Study of the Qipan Catchment in the Wenchuan Earthquake Region. *Sustainability*. Retrieved from <https://www.mdpi.com/2071-1050/16/9/3855>

wsp



wsp.com