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SLOPE STABILITY GEOTECHNICAL GUIDANCE SERIES

UNIT 6 – DEBRIS FLOW ASSESSMENT, ANALYSES AND MITIGATION

AN INDUSTRY REFERENCE DOCUMENT COMPILED AND PUBLISHED BY THE NEW ZEALAND GEOTECHNICAL SOCIETY (NZGS)

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COVER IMAGE: Deposition from the February 2020 Debris Flow above Gunns Camp, Fiordland

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1 INTRODUCTION

Debris flows occur in all regions with steep relief and at least occasional heavy or prolonged rainfall. Their high flow velocity, impact forces, and long runout, combined with poor temporal predictability, mean that debris flows are one of the most hazardous landslide types.

1.1 SIGNIFICANCE OF DEBRIS FLOW HAZARDS

There are many examples of destructive debris flows in New Zealand, of which a notable one was at Matata, documented in McSaveney et al (2005). Other New Zealand debris flow events are described in Bowman (2010) and Pierson (1980) as examples.

Residential infrastructure in many areas in New Zealand is developed on alluvial fans, the landform developed at the base of many steep creek catchments, deposited where the stream leaves its confined channel. Alluvial fans have moderate to gentle gradients compared to the surrounding uplands and generally have perennial streams as a reliable water source, good foundation conditions, and a scenic outlook. Consequently, fans have increasingly become much-desired locations for dwellings in mountain valleys in New Zealand. These areas are vulnerable to hazards associated with high runoff including debris flows and debris floods, and there are numerous recent examples of debris impact on residential developments constructed in such areas (Figure 1 as an example). As developers progressively build into these areas, there is an increasing need for thorough and robust assessment of the hazards and risks from debris flows and associated phenomena. This becomes increasingly more critical when the effects of climate change are considered.

FIGURE 1. Debris flow impact on a timber framed house and inundation of road and rail (foreground) at Rosy Morn Stream, south of Kaikoura, following Cyclone Gita (February 2018). Photograph courtesy of NCTIR.

1.2 PURPOSE AND CONTEXT OF UNIT 6

Unit 6 summarises current good practice in geotechnical engineering with a focus on New Zealand conditions, regulatory framework, and established methodologies when undertaking assessment of debris flow hazards and related phenomena. The purpose is to provide technical and practical guidance to geoprofessionals (engineers, engineering geologists, hydrogeologists) and other professionals involved in assessing and managing debris flow risks in a New Zealand context. The guidance document helps to ensure that debris flow assessments are performed in a competent manner, using established good practices and current technical knowledge.

Unit 6 forms part of the NZGS Slope Stability Guidelines Units. It includes cross references to the other Units of the series, where complementary or related information is included. The other documents of the series are listed below:

- **Unit 1 – General Guidance:** provides a general overview of the problem.
- **Unit 2 - Landslide Recognition, Identification and Field investigations:** discusses the techniques and methods to identify the type of landslide that may be present and the different field investigation techniques that are available.
- **Unit 3 - Slope Stability Analysis:** focuses on methods of slope stability analysis and target performance of slopes.
- **Unit 4 – Slope Instability Mitigation:** focuses on design of engineering measures and solutions to mitigate slope instability and landslides.
- **Unit 5 – Rockfall Assessment and Analysis:** complements the existing guidance on rockfall analysis and design of mitigation measures.
- **Unit 7 – Special Cases and Materials:** focuses on specific regions and geological formations encountered in New Zealand.

The main parts of Unit 6 comprise:

- Definitions for debris flow, debris floods and other hydrogeomorphic processes.
- Description of initiating mechanisms for debris flows and related processes.
- A description of the geomorphological characteristics of steep stream catchments subject to debris flows.
- Engineering Geological Assessment of debris flow systems.
- Hydrological assessment.
- Numerical debris flow modelling.
- Estimating debris flow hazards and resulting risks.
- Debris flow mitigation, including an outline of design approaches for common debris flow protection measures within a New Zealand context.

Debris Avalanche landslides are intended to be discussed in Unit 5.

Unit 6 does not concentrate on hillslope (or open slope) debris avalanches[1], however many of the design criteria are similar for the two types of landslide phenomena.

This guidance document is principally based on current European and North American practices where there is considerable experience in dealing with debris flood and debris flow hazards. As with other units of the Slope Stability Guidance series, it is not the intent of this unit to provide a prescriptive format for the assessment or mitigation of debris flow. Rather, the intent is to outline elements that the geoprofessional may need to consider when assessing debris flow hazards and developing mitigation strategies.

[1] Refer definitions in Section 2.1.

2 NATURE OF DEBRIS FLOW HAZARDS

Debris Flows, Earth Flows, Mud Flows, Debris Floods and Lahars (volcanic debris flows) are all types of landslides that can develop in mountainous watersheds. They all involve movement of a dense fluidised mass composed of materials from clay and silt sized to boulders (or larger), as well as entrained vegetation and variable amounts of water. Common to all is that they exhibit flow-like, or fluidised behaviour rather than relatively brittle movement typical of many other landslide processes. Collectively they are described as "hydrogeomorphic processes[2]" (Sidle and Onda, 2004).

2.1 CLASSIFICATION AND CHARACTERISTICS OF HYDROGEOMORPHIC HAZARDS

Hydrogeomorphic hazards that involve a mixture of water and debris / sediment occur in channels and steep creeks in mountainous terrain, typically after intense or long rainfall events (BGC, 2020). Steep creeks are defined by Moase (2017) as having channel gradients steeper than 3°, although in reality the initiation and transport zones of the debris flow catchment (or watershed) will likely be considerably steeper than this.

As shown in Figure 2, there is a spectrum of hydrogeomorphic hazards, from clear-water floods to debris floods and eventually to debris flows as sediment / debris content increases. Conversely, dilution of a debris flow through partial sediment deposition on lower gradient (approximately less than <15°) channels, and tributary injection of water can lead to a transition towards hyper-concentrated flows and debris floods and eventually floods (BGC, 2020).

Hungr et al (2014) and others provide the following definitions:

[2] Hydrogeomorphology is an interdisciplinary science that examines the interaction between hydrologic processes (such as water flow) and landforms or earth materials (Sidle and Onda, 2014). It focuses on how geomorphic processes (like erosion and sediment transport) are influenced by surface and subsurface water. Essentially, it involves the study of landforms shaped by water.

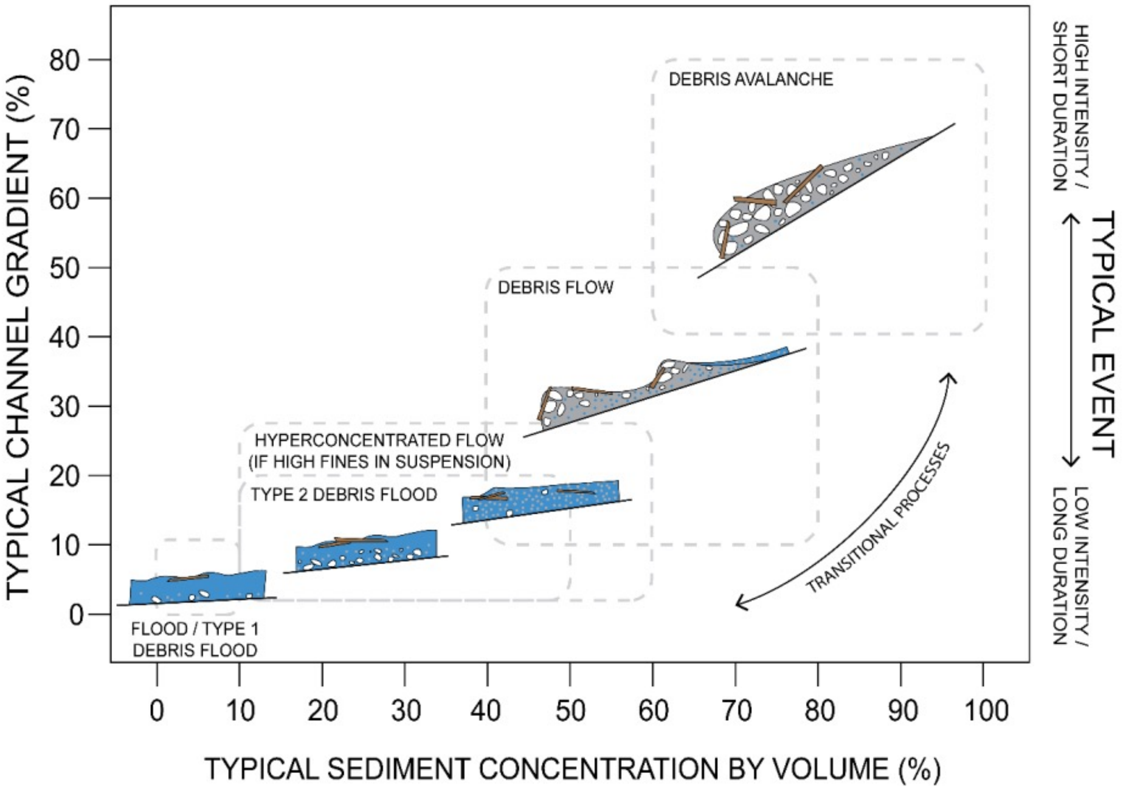


FIGURE 2: Main types of hydrogeomorphic hazards in steep creeks and catchments (figure supplied by BGC, 2020; artwork by S. Zubrycky).

Debris Avalanche: "*Very rapid to extremely rapid shallow flow of partially or fully saturated debris on a steep slope, without confinement in an established channel*". Occurs at all scales.

The term 'Debris Avalanche' describes a landslide with characteristics similar to a snow avalanche. Debris avalanches initiate as a shallow surface slide when an unstable slope fails and evacuates downslope. The fragmented debris develops into a rapidly moving flow but does not move into a channel. Debris Avalanches occur in mountainous areas with steep slopes, including on very steep volcanoes, and are characterised by very high velocities of over 20 m/s (Hungr et al 2014). Debris avalanches initiate as debris slides and are associated with failures of regolith including residual soil, colluvial, pyroclastic, or organic veneer. Debris avalanches do not repeatedly occur in the same location, and their deposits are unconstrained alluvial aprons.

Debris flow: "*Very rapid to extremely rapid surging flow of saturated debris in a steep channel. Strong entrainment of material and water from the flow path*".

The important feature of a debris flow is that it moves downslope by upward dispersive pressure. This upwards force is created by the collisions of soil and rock particles in the flow a process unique to debris flows, pyroclastic flows and avalanches. By this method very large clasts (gravel and boulders) can be transported when there are sufficient quantities of smaller particles such as clay, silt and sand. Upward dispersive flow causes the flow to expand and lift upwards in a process called dilatancy. Other gravity flows move by different processes such as turbulent flow or laminar flow.

Moase (2017) suggests that "saturated" in this context means that the water content of a debris flow is typically between 30 and 50%. Further, "debris" may include sediment ranging from clay to large boulders, as well as timber and other organics. However, the fines content of the flow must have a plasticity index less than 5% to maintain the 'debris flow' classification.

Debris flows can be described as a slurry-like moving mass that, depending on available debris material in the catchment and along the channel, has a rapidly advancing bouldery front (Figure 3). Peak discharges can be two to three times higher for debris floods and up to 50 times higher for debris flows compared to peak discharges during clear-water flood events (Hungr et. al, 2005).

Hyperconcentrated Flow: Turbulent subaerial flow that transports large quantities of coarse sediment (sand and gravel) at high concentrations in intermittent dynamic suspension. These flows lie in the continuum between floods and debris flows (Jakob & Hungr, 2010).

A flood transitions into a hyperconcentrated flow when particles on the bed begin to move together, en masse, and coarse sediment becomes suspended in the flow. Water flood behaviour begins to be affected by sediment when particle concentrations reach about 4% by volume (Pierson, 2005). Most deposits are poorly to very poorly sorted and are either massive or horizontally stratified and generally fine downstream.

Debris flood: "*Floods during which the entire bed, barring the very largest clasts, becomes mobile for at least a few minutes and over a length of at least 10 times the channel width*" (Church and Jakob, 2020)

Debris floods represent flood flows with high transport of gravel to boulder size material. Debris floods typically occur on creeks with channel gradients between 5 and 30% (3 and 17º) but can also occur on lower gradient gravel bed rivers. While debris floods as per the definition of Hungr et al. (2014) are attributable to steep watersheds, commonly less than 100 km^2, full gravel bed mobilisation can also occur in mountain rivers with several thousand square kilometres of watershed area.

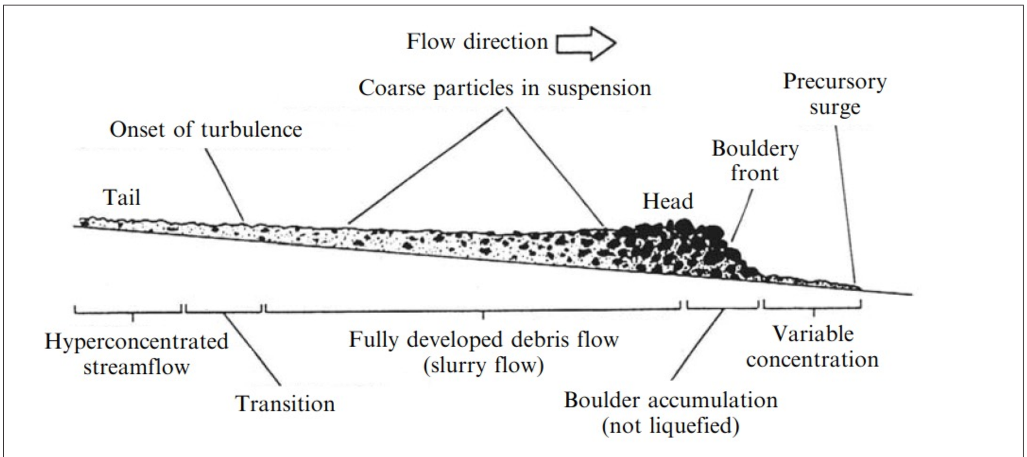


FIGURE 3: Cross-section of a typical debris-flow surge (Hungr, 2005)

Due to their initially relatively low sediment concentration, debris floods can be more erosive along low-gradient alluvial channel banks than debris flows. Channel and bank erosion introduce large amounts of sediment to the fan where they accumulate (aggrade) in channel sections with decreased slope. Debris floods can also be initiated on the fan itself through rapid bed erosion and entrainment of bank materials, as long as the stream power is high enough to transport some of the largest clasts in the channel bed (the grain size diameter for which 84% of the grain sizes are finer (D84) (MacKenzie, et al 2018). Because typical long-duration storm hydrographs fluctuate several times over the course of the storm, several cycles of aggradation and remobilisation of deposited sediments on channel and fan reaches can be expected during the same event (Jakob et al., 2016). Similarly, debris floods triggered by outbreak floods may lead to single or multiple surges irrespective of hydrograph fluctuations that can lead to cycles of bank erosion, scour and infill. This is important for interpretations of field observations as only the final deposition or scour can be measured.

A DEBRIS FLOW BY ANY OTHER NAME...

There are several terms for hydrogeomorphic hazards that have been frequently used around the world for different flow types, materials and over time, including: Debris torrent, Mud Spate, Alpine Mud Flow, Slurry Flow, Sediment Flow, Doeski-Ryū (Japan), Lahar (Indonesia), Murgang (German); Coulée de débris (French).

Understanding the name of a hydrogeomorphic process is less important than recognizing the hazard and level of risk it presents. In Unit 6, the term "debris flow" is commonly used, although not always strictly applied. It's worth noting that the dangers, potential damage, and mitigation strategies for debris floods and debris flows can vary greatly. Identifying whether the process is primarily driven by water or sediment is crucial.

Church and Jakob (2020) developed a three-fold typology for debris floods. Identifying the correct debris-flood type is key in preparing for numerical modelling and hazard assessments. **Type 1** debris floods are a result of flows with a sufficient magnitude and shear stress to mobilize the channel bed. **Type 2** debris floods are initiated by the transition of a debris flow to a debris flood in the channel or from a debris flow in a tributary channel entering a larger channel. **Type 3** debris floods are associated with landslide dam outbreak floods (LDOF).

Mud Flow: *"Very rapid to extremely rapid surging flow of saturated plastic soil in a steep channel, involving significantly greater water content relative to the source material. Strong entrainment of material and water from the flow path (Plasticity Index > 5 %)".*

In regions where eroded material may contain significant content of fines and be measurably plastic (Bull 1964), mudflows, rather than debris flows may be the dominant mechanism. These soils drain more slowly and remain longer in a liquid condition, leading to longer travel and lower slope angles in the deposition area (Hungr et al, 2014). Mud flows tend to be more common in areas with deep weathering, or in other regions with predominantly fine-grained surficial sediments.

Earth Flow: *"Rapid or slower, intermittent flow-like movement of plastic, clayey soil, facilitated by a combination of sliding along multiple discrete shear surfaces, and internal shear strains. Long periods of relative dormancy alternate with more rapid "surges"*

As described in IAEG commission 37, and shown in Figure 2.12 of Unit 1, the term 'Earth' can be used for material that is 80% or more composed of material smaller than 2 mm (the boundary between coarse sand and fine gravel in accordance with the NZGS Field description for soil and rock). In the same diagram, "debris" is defined as material that is composed of greater than 20% particles larger than 2 mm. Hungr et al (2002) indicates that while debris typically contain less than 30% silt and clay, no distinction can be made between mud flows and earth flows on the basis of particle size, suggesting that earthflows are plastic (IL< 0.5) and relatively slow moving (less than 0.1 m/s) while mudflows are liquid (IL> 0.5) and faster (greater than 1 m/s).

Lahars

As described in Hungr et al (2014), *"large mud flows or debris flows from volcanic sources are often referred to by the Indonesian term "lahars"*. Lahars can occur during eruptions ("hot lahars") or during periods of high surface water runoff while the volcano is dormant ("cold lahars"). The term does not imply either a dominant particle size or a travel speed. Lahars can differ in origin, frequency, runout, and size from debris flows in non-volcanic terrain. Lahars can exceed a cubic kilometre in volume and travel more than 300 km from source (Vallance, 2024).

2.2 FLOW BEHAVIOUR

Clear water floods and debris floods exhibit Newtonian fluid behaviour. Conversely, debris flows exhibit non-Newtonian behaviour and it's crucial to understand this difference, especially when comparing debris flows to clear water flows.

Newtonian fluid behaviour

Newtonian fluids are those that have a constant viscosity and do not change in response to shear forces. For Newtonian fluids, a chart of shear stress as function of shear rate will be a straight line passing through the origin, meaning flow behaviour is consistent and predictable, with a viscosity similar to water. Because Newtonian fluids have zero yield stress, they flow at any shear stress.

Non-Newtonian flow

Non-Newtonian fluids are those such as tomato sauce or paint whose viscosity can behave in different ways when subjected to different shear rates. The frictional interactions in non-Newtonian flows, such as debris flows, lead to a non-linear stress-strain relationship. This means that as the stress increases, the strain (or deformation) does not increase proportionally. These interactions can cause the flow to behave more like a solid under certain conditions, which is a stark contrast to the behaviour of clear water flows.

For coarse-grained hydrogeomorphic processes that contain significant amounts of sediment, the flow behaviour is often approximated by a Bingham fluid. Bingham fluids possess a characteristic yield stress (τ_o), which is the minimum shear stress required to initiate flow. Below the yield stress, a Bingham fluid behaves like a solid, resisting deformation. Once the yield stress is exceeded, the fluid flows with a constant plastic viscosity. Coulomb Viscous behaviour in fluids refers to a combined resistance model where the total shear stress comprises a constant yield stress (Coulomb friction) and a linear viscous term proportional to the shear rate Coulomb-viscous behaviour becomes important in flows where frictional grain interactions dominate over cohesive forces.

The initial yield stress is one of the factors that can help explain why the behaviour of hydrogeomorphic processes is different from that of normal streamflow. Yield stress increases with increasing sediment concentrations. Sediment in the flow is mainly supported by buoyancy, dispersive stress and turbulence.

At very high sediment concentrations, as is the case in debris flows, the flow has large yield stress (or cohesion) and internal friction, while in less concentrated flows like debris floods, frictional grain interactions and turbulent drag dominate the rheological behaviour.

For debris flows turbulence is usually greatly suppressed and the most important sediment supporting processes are buoyancy, dispersive stress, structural support and cohesion. Solids and water move together as a single viscoplastic body from which there is hardly any sedimentation.

Table 1 provides a summary of typical parameters of clear water floods, hyperconcentrated flows and debris flows. The listed parameters include flow behaviour and type, grain size, physical properties as well as sedimentological descriptions.

Table 1. Characteristics of hydrogeomorphic hazards in steep stream watersheds (modified from Austrian Standards International, 2009; Hübl, 2018 and Costa, 1988).

Flow Type	Clear Water Flood	Hyperconcentrated Flows and Debris Floods	Debris Flows
Flow Behaviour	Newtonian	Newtonian to Non-Newtonian (Bingham)	Non-Newtonian (Coulomb Viscous)
Max grain size	mm-cm	-dm	-m
Bulk Density (kg/m³)	1010 – 1300	1300 – 1800	1800 – 2300
Determination of water discharge possible?	Yes	No	No
Flow Type	Turbulent	Turbulent/laminar	Laminar
Q_{max}/Q_{flood} (m³/s)	1	2-5	>3 - 50
Dynamic Viscosity (Pa.s)	< 0.2	0.2 – 2	> 2
Shear Strength	None	None	Yes/Present
Relevant Stresses	Turbulence/shear stress	Buoyancy, turbulence, shear stress, collisional forces	Buoyancy, viscous, collisional and frictional forces
Vertical Distribution of Sediment	Close to channel bed (rolling, jumping, sliding); fine sediment suspended over height of flow	Coarse bedload with finer sediment suspended along height of flow	Coarse sediment suspended along height of flow
Deposition Pattern	Layered deposits	Bars and lobes, mostly clast supported, coarse sediment up to maximum flow depth, imbrication	Coarse boulder fronts, levees and lobes, clast or matrix-supported, sharp borders of depositions, U-shaped cross sections
Sorting of deposits	Yes	Massive, occasionally crudely fining upward	Massive/homogenous (may have inverse grading)

2.3 DEBRIS FLOW INITIATION

Debris flow initiation can be linked to a variety of mechanisms depending on the geology and geomorphological setup in the catchment (see Figure 4).

Initiating events for debris flows and related hydrogeomorphic process can be described as either primary or secondary. Primary influences are events that directly trigger debris flows, such as intense rainfall or rapid snowmelt. Secondary influences such as antecedent rainfall or antecedent snowmelt can influence whether or not a debris flow will be triggered during an earthquake, volcanic event or intense rainstorm (Wieczorek and Glade, 2005).

2.3.1 Primary Events
Rainfall and / or Snowmelt

Intense Rainfall: One of the most common triggers for debris flows is intense or prolonged rainfall. When rainwater infiltrates the soil, it increases pore water pressure, reducing the soil's shear strength and leading to slope failure (e.g., debris slide / avalanche, rock slide / avalanche) on the valley side slopes. Where such

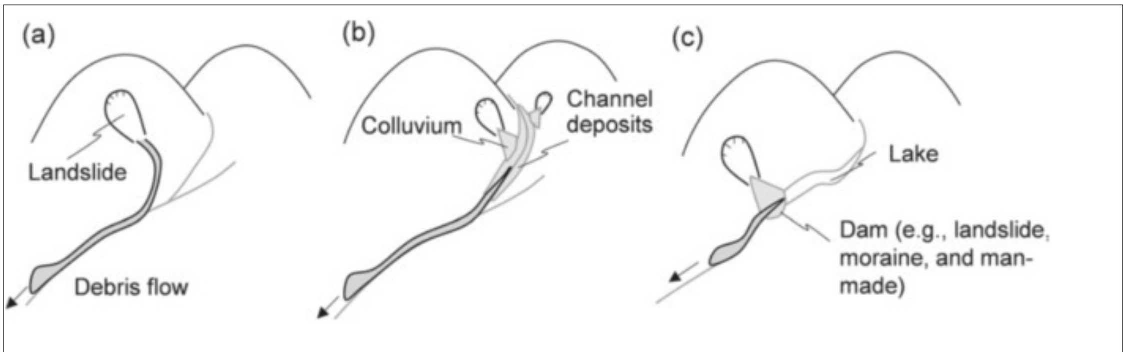


FIGURE 4: Schematic presentation - Initiation mechanisms of debris flows. (a) Landslide sediments directly evolving into debris flows during their movement downslope. (b) Debris flows in low-order streams triggered by overland flow. (c) Dam failure and lake outburst floods (Kang et al, 2004) In-channel debris flow initiation is possible but generally a very rare event.

landslides hit the mainstem channel at an oblique angle, their momentum is transferred to the downstream channel, initiating a debris flow. Debris flows typically grow in size as they move downstream through entrainment of valley bottom sediment and streamflow. This process is particularly prevalent in regions with steep terrain and loose, unconsolidated material.

The rainfall volume, duration and intensity significant for debris flow initiation is generally not consistent between regions, or even within regions, and is dependent on the specific geological and hydrological properties of the catchment.

Rapid Snowmelt: Similar to intense rainfall, rapid snowmelt can saturate the soil, leading to increased pore water pressure and slope instability. This is often observed in mountainous regions during the spring thaw when temperatures rise quickly, causing snow to melt rapidly.

Antecedent Rainfall and Soil Moisture

The soil moisture prior to a storm event has been identified as a contributing factor in debris flow initiation (Wieczorek and Glade, 2005). Antecedent rainfall is often used as a proxy for soil moisture. In continental regions soil moisture can change seasonally, with moisture levels increasing during the wet season. In mountainous temperate regions such as New Zealand, seasonal variations in soil moisture are less predictable.

Several studies have linked soil moisture and antecedent rainfall to debris flow initiation (e.g.; Crozier, 1999; Jakob and Weatherly, 2003) by providing prime conditions for the initiation of a landslide on the valley side slopes. The antecedent rainfall volume and the period of accumulation significant for debris flow initiation is generally not consistent between regions, or even within regions, but is dependent on the specific geological and hydrological properties of the catchment.

Dam Failure

The sudden release of ponded water associated with rapid failure of a dam can result in debris flow formation. Several types of dam failure scenario exist:

- **Natural Dams**
  Natural dams can form through the blockage of stream channels by landslides or avalanches. They typically fail by either seepage-related piping or erosion due to water flow over the top of the dam.

  The debris flow volume created by the water released by a breached dam can be an order of magnitude greater than the volume of water released during dam failure. The traditional approach of flood inundation assessment will be inadequate if a debris–mud flow is generated by the pulse of water released by a failed dam (Tannant and Skermer, 2013). A good New Zealand example was the Tangiwai Disaster of 1953 that killed 151 people.

- **Artificial Dams**
  Accidental failure of artificial dam structures can release large volumes of water that may initiate debris flows downstream. Debris may originate from entrainment of sediment in the stream channel, erosion of stream banks or from the dam structure itself. Tailings dams or dams that are largely filled with sediment during operation can form debris flows if the impounded material is released. Tailings are typically sand size or finer and there have been numerous historical examples of tailings dam breach that have led to inundation of the downstream environment with tailings. Dam breach assessments of tailings dams can require numerical modelling of the non-Newtonian flow of the entrained tailings to assess the likely extent of downstream inundation. This modelling requires assessment of the likely behaviour of the liquefied tailings including geomechanical characteristics of grain size, particle density and consolidation.

- **Glacial Lake Outburst Flood (Jökulhlaup)**
  The sudden release of water associated with the phenomena of glacial lake outburst floods (also known as Jökulhlaup or GLOFs) can generate debris flows within the downstream channel and floodplain. Although the likelihood of debris flow events occurring from glacial lake outburst floods in New Zealand is expected to be low, owing to the fact that there are only a handful of suitably glaciated valleys from which a glacial lake outburst flood could occur with a volume significant for debris flow initiation, it is worth noting that glacial lake outburst flood events have previously been documented at Franz Josef (Goodsell et al 2005) and at Kea Point (Mt Cook) in 1913 (Williams et al. 2022).

2.3.2 Secondary Events

The susceptibility of catchments to debris flow hazard has been observed to increase following various types of "precursor events". Generally, precursor events act to increase the susceptibility of catchments to debris flows by increasing the available sediment supply, either by altering the amount of loose material in the catchment, or by decreasing resistance to erosion (for example de-vegetation of slopes).

Catchment Slope Instability (may be primary or secondary)

Large landslides can generate large volumes of loose material that increase the available sediment supply within a catchment. The increase in the available sediment can result in an increased likelihood of debris flow formation (Nishiguchi et al, 2012).

Earthquakes

Earthquake shaking can trigger landslides within a catchment and can damage slopes making them more susceptible to future failure due to weakening of the rock mass or soil structure and infiltration of water into ground cracks. As a result, the prevalence of debris flows has been observed to increase in regions that have suffered recent large earthquakes. The 2018 debris flow at Jacobs Ladder, north of Kaikoura provides a New Zealand example. As shown in Figure 5, significant landsliding occurred in the Jacobs Ladder catchment as a result of the 2016 Kaikōura Earthquake, making the catchment more susceptible to future debris flow, as well as increasing the resultant size of the debris flow.

Volcanic Eruptions (may be primary or secondary)

Volcanic activity can trigger debris flows through several mechanisms. Pyroclastic flows and lava can melt snow and ice, generating large volumes of water that mix with volcanic debris to form lahars. Additionally, volcanic eruptions can deposit loose tephra on slopes, which can then readily be mobilised by rainfall.

Vegetation Clearance and Wildfires

Debris flows formed post-harvest (clear felling) of forestry resources are well documented in New Zealand (see for example, Phillips et al, 2016) and commonly involve the mobilisation of slash (harvesting residue) on slopes and in channels downslope to neighbouring properties as well as resulting in exposure of large areas of disturbed ground leading to an increase in sediment erodibility.

A longer-term issue in regard to vegetation clearance is the decay of tree roots subsequent to logging causing a reduction in the shear strength of the soil water system. This makes the terrain more prone to debris flow initiating shallow landslides until revegetation occurs.

Wildfires can dramatically change the hydrological response of catchments, making them more susceptible to debris flow formation (see Cannon et al, 2010, for example). Loss of forest canopy and organic soil cover, intensive drying of soil can affect the infiltration rates of soils and increase surface runoff resulting in increased

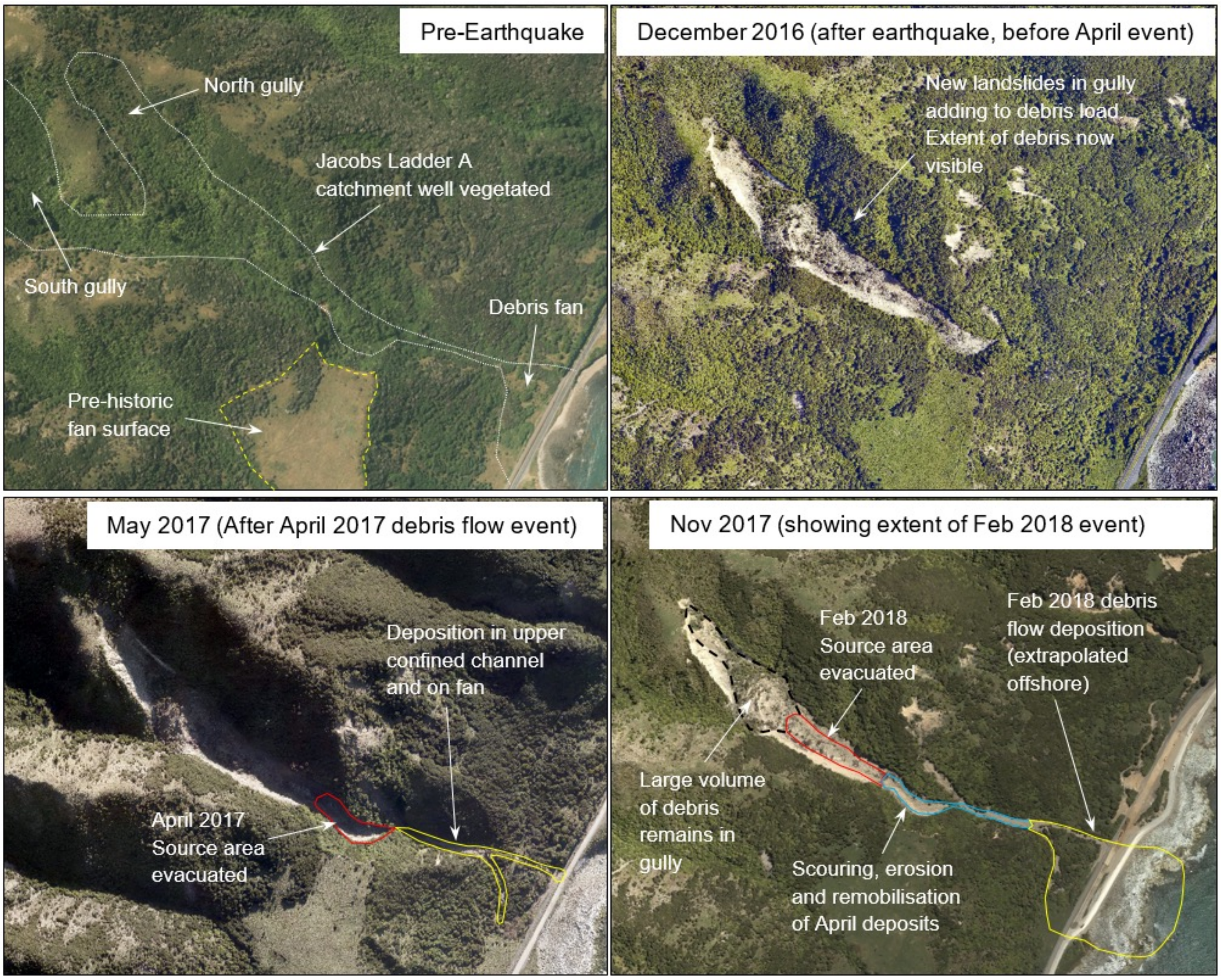


FIGURE 5. Historical aerial photographs at Jacobs Ladder showing changes after the November 2016 earthquake and following April 2017 and February 2018 debris flow events (Justice, 2021)

erosion. Furthermore, removal of obstructions through consumption of vegetation can increase the erosive power of overland flows. The threshold for rainfall-triggered debris flows is significantly lower in burned areas compared to unburned areas.

Most runoff-generated post-wildfire debris floods and debris flows typically occur within the first two to three years following a fire (see for example, Graber et al, 2023). Widespread landslide-generated debris-flow activity is less likely, but possible in the decades following the fire due to the decay of burned or partially burned tree roots, which reduce soil cohesion (DeGraff et al., 2015; Hancock & Wlodarczyk, 2025).

Human Activities

Construction, urbanisation and mining can destabilise slopes and increase the likelihood of debris flows. These activities often remove vegetation, alter drainage patterns, and create loose debris that can be easily mobilised by runoff.

2.4 DEBRIS FLOW VOLUME

The size of debris flow events can differ within a catchment, usually increasing in size with longer return periods (Jakob, 1996, Jakob, 2005). Table 2 and Figure 6 below provide a size classification and describe potential consequences. Jakob (2005) provides more detailed descriptions of the various classes.

Table 2. Size Classes for debris flows (modified from Jakob, 2005). V is the total volume, Qb and Qv are the peak discharge for bouldery and volcanic debris flows, respectively, Bb and Bv are the areas inundated by boulder and volcanic debris flows, respectively. Jakob (2005) notes that Class 6 debris flows are the largest size classification for bouldery debris flows. Larger flows are known only from volcanoes.

Size class	*V*, range (m^3)	Q_b, range (m^3/s)	Q_v, range (m^3/s)	B_b (m^2)	B_v (m^2)	Potential Consequences
1	$< 10^2$	< 5	< 1	$< 4 \times 10^2$	$< 4 \times 10^3$	Very localised damage, known to have killed forestry workers in small gullies, damage small buildings
2	10^2-10^3	5-30	1-3	4×10^2 - 2×10^3	4×10^4 - 2×10^4	Could bury cars, destroy small wooden buildings, break trees, block culverts, derail trains
3	10^3-10^4	30-200	3-30	2×10^3 - 9×10^3	2×10^4 - 9×10^4	Could destroy larger buildings, damage concrete bridge piers, block or damage highways and pipelines
4	10^4-10^5	200-1,500	30-300	9×10^3 - 4×10^4	9×10^4 - 4×10^5	Could destroy parts of villages, sections of infrastructure corridors, bridges, could block creeks
5	10^5-10^6	1,500-12,000	300 - 3×10^3	4×10^4 - 2×10^5	4×10^5 - 2×10^6	Could destroy parts of towns, destroy forests of 2 km^2 in size, block creeks and small rivers
6	10^6-10^7	N/A	3×10^3 - 3×10^4	$> 2 \times 10^5$	2×10^6 - 3×10^7	Could destroy towns, obliterate valleys or fans up to several tens of km^2 in size, dam rivers

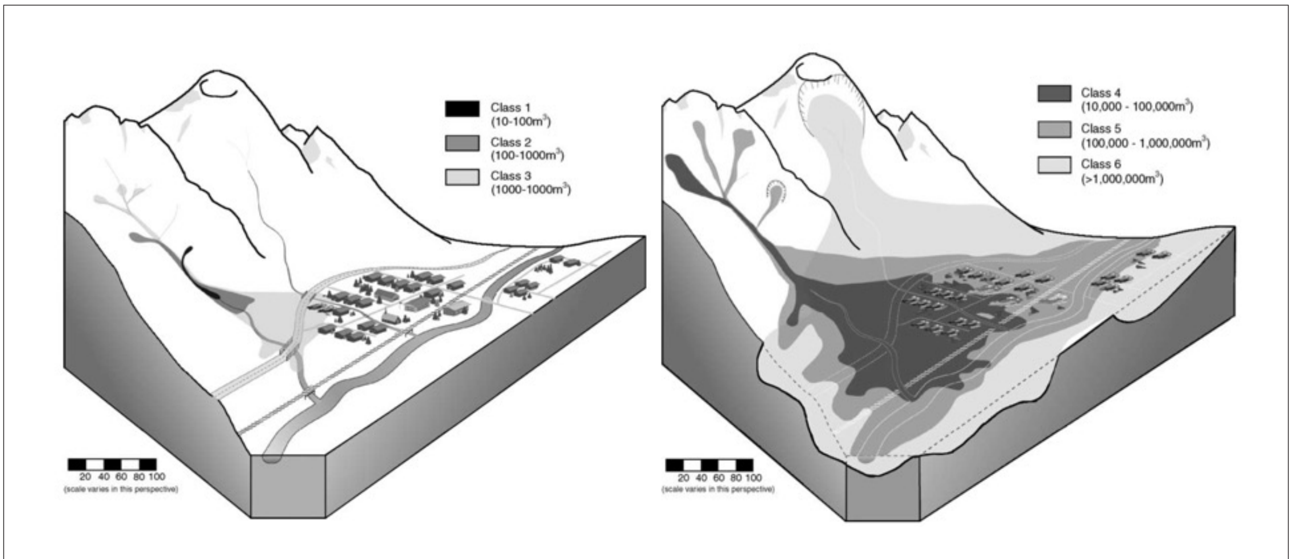


FIGURE 6: Conceptual debris flow inundation area in relation to class size (modified from Jakob, 2005).

3 CHARACTERISTICS OF WATERSHEDS SUBJECT TO DEBRIS FLOW HAZARD

3.1 CATCHMENT GEOMORPHOLOGY

Debris flow generating systems consist of a catchment area which is delineated by the watershed of a main channel and its tributaries / reaches and an associated debris fan system. Within this system, the path of a debris flow is separated into three main zones (initiation, transport, deposition) as shown in Figure 7 and Figure 10. Each zone is described as follows.

Initiation Zone – Source area for debris flow in a specific watershed / catchment. Mass movements in the catchment provide rock, sediment and debris by the process of falling, toppling, sliding, spreading and / or flowing. Failure of unconsolidated material in response to a high intensity rainfall event can generate a debris flow in the catchment.

Transportation Zone – Main channel and tributaries (reaches) confining debris flow. Area of sediment bulking through sediment entrainment along the channel banks through undercutting or channel bedload scour; often includes areas of partial or temporary debris deposition along the channel.

Deposition Zone – Depositional landform formed downstream from the topographical apex of an alluvial / debris fan of a steep stream catchment due to loss of lateral confinement and lower gradient leading to a reduction in velocity. This depositional fan is characterised by channel systems in which the bulk of the debris moves, and by adjacent levees that are constructed during sediment transport. The levees in general confine the sediments to the channel, but they can also be overtopped or breached for a variety of reasons. In these situations the sediment spreads out away from the channel as overbank flows. A break in the levee may continue to develop in these cases the channel may finally move to a new location (alvusion). Conversely the damage to the levee may not be too severe and the channel reconstructs the integrity of the levee as a channel margin. Levees and overbank sediment transport may also occur in the lower reaches of the transportation zone especially when not underlain by bedrock. The resultant deposit is fan shaped and is typically referred to as an alluvial fan. When an alluvial fan meets a standing body of water in it's lower reaches it is referred to as a fan delta.

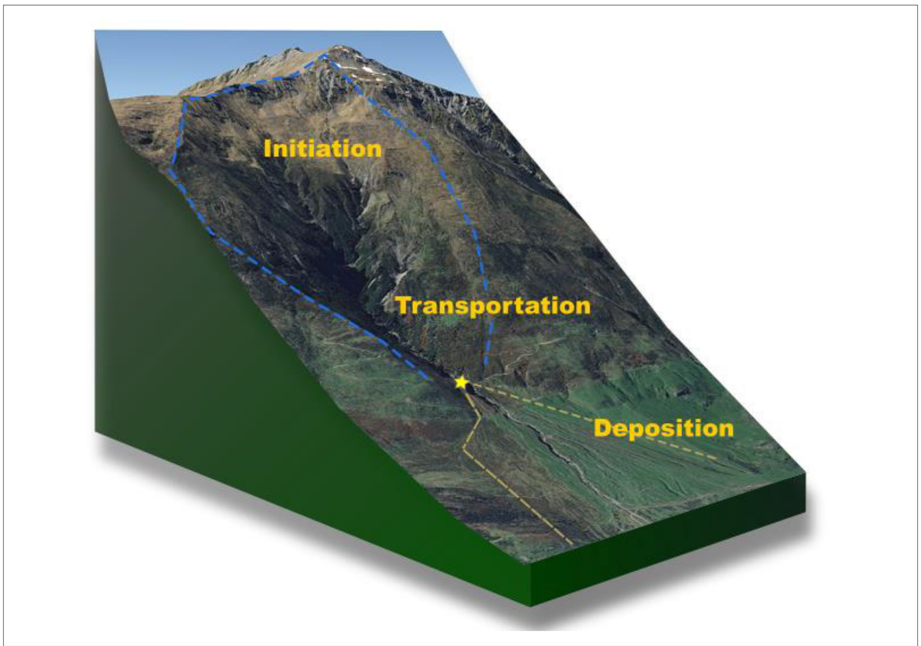


FIGURE 7: Typical debris flow zones in a mountainous catchment. The watershed / catchment (blue dotted line) delineates the hydrological source area of a steep mountain stream system. The fan apex (yellow marker) is located at the transition of the confined main channel to the debris fan below (its lateral boundaries, areas where active channels can be present or move to, are shown with dotted yellow lines).

3.2 CATCHMENT CHARACTERISTICS

Debris flows originate in a diverse range of mountainous watersheds / catchments and sediment may be available and produced from various sources, including primary weathering of bedrock, landsliding, soil erosion, and remobilisation of unconsolidated sediment sources, for example glacial and volcanic sediments or talus slopes (De Haas et al, 2024). Elements that need to be understood and contribute significantly to debris flows initiation are:

- **Morphometry -** the watershed / catchment slope angles, size and length, channel gradient, fan gradient; i.e. steep slopes that provide enough potential energy to mobilise debris and maintain debris flow movement until reaching the main channel outlet at the fan apex.
- **Geology -** the availability of sufficient volume of sediment, including knowledge about geological and geotechnical characteristics of available rock and sediment (i.e. grain size distribution, mineralogical and petrographic composition), mass movement mechanisms in the catchment, volume estimation of material vulnerable to entrainment).
- **Hydroclimatic Setting -** the probability of high intensity rainfall events to generate high runoff rates that surpass the intensity threshold required to generate significant runoff rates and initiate landslides.

3.2.1 CATCHMENT MORPHOMETRY

As a first-order estimate, empirical correlations utilising morphometric parameters of the catchment can be employed to assess the dominant hydrogeomorphic process (clear water flood, debris flood, debris flow) in a watershed, i.e. a catchments ability to generate debris flows. It should be noted that these processes often coexist within the same watershed.

Some morphometric parameters describing the watershed characteristics that may affect the dominant hydrogeomorphic process are (De Haas et al, 2024):

- Watershed relief (relief, mean slope, relief ratio).
- Watershed geometry (length, area, perimeter, shape).
- Drainage characteristics (stream length, number of streams, stream length ratio, Rho coefficient (mean stream length ratio divided by the mean bifurcation ratio), stream frequency, drainage intensity).

These parameters are only a selection to indicatively assess the type of hydrogeomorphic hazard of a specific catchment. There are additional parameters describing regional watershed and climatic characteristics which may affect the resulting dominant watershed process:

- Sediment availability / erodibility (geology, rock strength, vegetation cover, seismic intensity, distance to faults, land use).
- Specific hydroclimatic factors (mean annual temperature, mean annual precipitation, maximum daily rainfall, moisture index).

Melton Ratio

A widely used indicator that can be statistically analysed (applying GIS techniques to a DEM) to determine whether a watershed is likely to produce debris flows, is the Melton Ratio (R) (Melton, 1957; Wilford et al., 2004). Melton ratio analyses can be applied to a whole catchment or to catchment segments in a stream network (Davies et al., 2024). The Melton Ratio is a normalised index of the gravitational energy of a specific watershed, usually used in combination with the watershed length and fan slope, and is defined as:

$$R = \frac{H_b}{\sqrt{A_b}}$$

Where:
H_b is the watershed relief (difference in elevation between the highest point in the watershed and the elevation of the fan apex) and A_b is the watershed area in plan.

Morphometrically, catchment systems with high values of Melton Ratio and shorter length (defined as the planimetric straight-line length from the fan apex to the most distant point on the watershed boundary above the apex) are mostly prone to debris flows, and those with lower values of R and longer catchment lengths are mostly prone to floods (debris or clear water).

Table 3 indicates the typical class boundaries between floods, debris floods and debris flows as developed by Welsh and Davies (2011), but these can regionally vary (De Haas et al., 2024).

This information is also presented graphically in Figure 8 (from Jacob et al, 2022).

Table 3. Class boundaries of hydrogeomorphic processes using Melton ratio and total stream network length (BGC, 2019 with consideration for NZ conditions based on Welsh and Davies, 2011).

Process	Melton Ratio	Catchment Length (km)
Clear Water Floods	< 0.2	All
Debris Floods	0.2 to 0.5	All
	> 0.5	> 3
Debris Flows	> 0.5	≤ 3

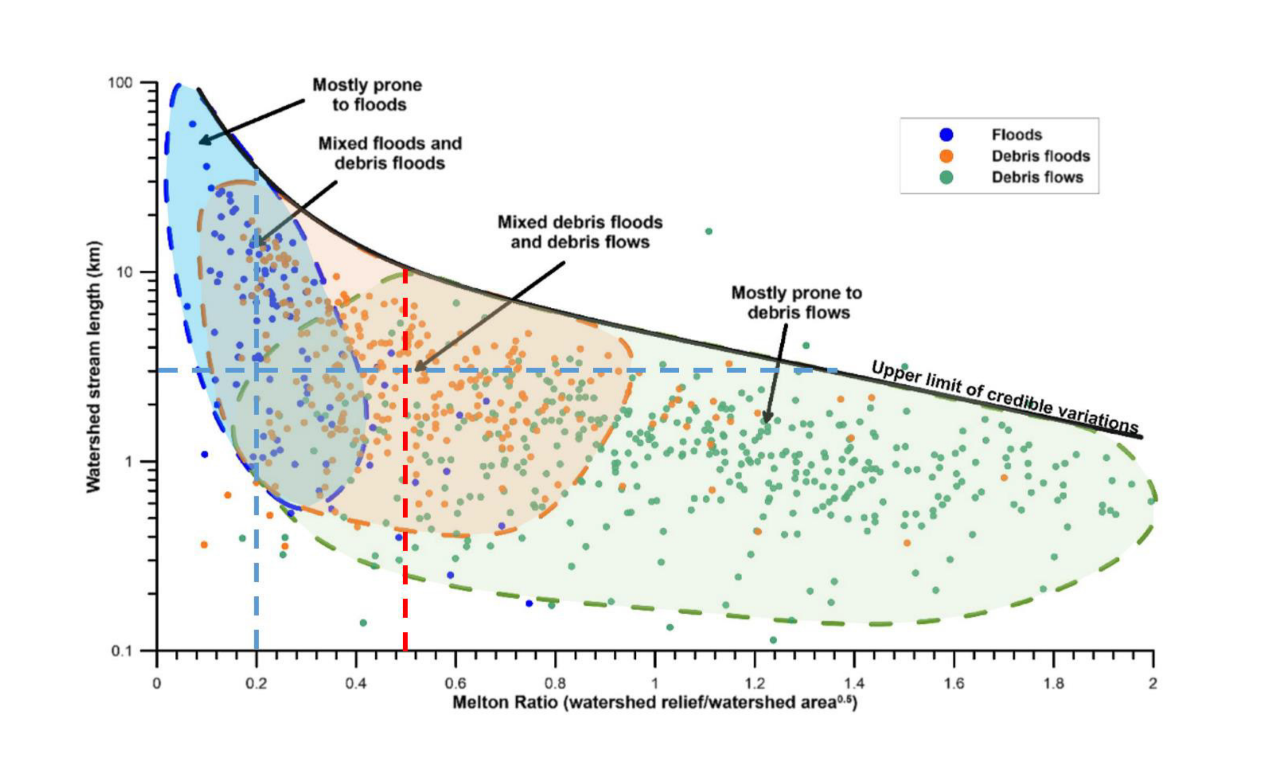


FIGURE 8: Steep creek processes as a function of Melton Ratio and Stream Length based on data from Canada (Jakob et al, 2022); with class boundaries as indicated on Table 3. Melton Ratio of 0.5 is highlighted in red.

There is considerable overlap between the areas defined by the morphometric parameters provided in Table 3, so any morphometric assessment should only be considered as an initial tool to assess potential catchment behaviour. In addition, Welsh and Davies (2011) indicate that a Melton Ratio of > 0.5 for debris flow may only apply to steep catchments set in mountain ranges characterised by long slopes at about the angle of repose and not incised coastal catchments (such as the catchments that generated the Matata debris flows in 2005).

The Melton Ratio has also been used as a screening tool to assess risk-to-life in relation to international practices (Davies et al., 2024). Where developments potentially exposed to unacceptable debris-flows risks are identified, more sophisticated methods – including modelling – have to be used to assess the risks and develop management strategies for those specific locations.

3.2.2 SEDIMENT SUPPLY

Apart from morphometric factors, sediment production rates / yield and the bedrock geology of the watershed may guide whether debris or water floods are generated in a specific watershed. For example, steep watersheds with small catchment areas may not generate debris flows where they are underlain by highly competent bedrock with low sediment yield. On the other hand, high yield rates can be present in watersheds with thick colluvial cover, deeply weathered bedrock, loess deposits, volcanic sediments and recently burnt areas, channels with high bank erosion or when the occurrence of large landslides coincides with an extreme hydroclimatic event (e.g. Hungr et al. 2005). In addition, the production of fine sediment fractions (clay to fine silt) can have significant control on the rheology of mobile sediment-water mixtures and thus the occurrence of debris flows (De Haas et al, 2024).

Bedrock, sediment and debris are typically delivered into steep creek channels by mass movement processes such as falling, sliding and / or flowing.

The morphometry of a catchment is generally constant over relatively short time scales (hundreds to thousands of years) whereas the availability and recharge rates of sediment may be more dynamic over time. Therefore, and based on the availability of sediment, catchments that are subject to debris flows can broadly be categorised (e.g. Bovis and Jakob 1999, Jakob et al 2005) as being either:

- **Supply-limited:** meaning that generation of debris flows is constrained by a slow or volumetrically limited production of unconsolidated material. These catchment types require a significant recharge period of sediment volumes prior to each debris flow event and therefore exhibit a lower frequency of debris flow activity.

- **Transport-limited (supply-unlimited):** meaning that there is always an abundance of unconsolidated material along a channel and in source areas so that whenever a critical rainfall threshold (or another triggering event) is exceeded, an event can occur. Debris flow activity is controlled more directly by the magnitude and frequency of hydroclimatic events.

Figure 9 illustrates the concept of watershed dynamics and debris flow activity, magnitude and return period as a result of changes in sediment recharge and hydroclimatic intensity / debris flow triggering threshold.

It should be noted that initially supply-limited watersheds can transition into transport-limited systems due to increased sediment availability such as in the event of a wildfire, large-scale deforestation or a large landslide event in the catchment that generates a long-lasting sediment supply.

3.2.3 CHANNEL AND FAN GRADIENTS

Catchments that are affected by debris flow hazards require a minimum slope and channel gradient for initiation and transport of debris. As indicated by Figure 10, Van Dine (1996) suggests:

- Debris flow initiation generally requires a channel gradient greater than 20° (36%);
- Transportation and erosion generally require a gradient of greater than 15° (27%). Skermer et al (2002) noted that debris transport occurs in the Glencoe Stream gorge at Mt Cook at minimum slope angles in the range 18 to 20°;
- Partial deposition, in the form of lateral levees, generally occurs at a gradient of less than 15° (27%); while
- Deposition on the debris fan usually begins once the gradient flattens to less than 10° (18%).

Gradients of fans predominantly formed by debris flow processes have, however, been found to vary significantly depending on the composition of the debris flow material. For example, minimum threshold values for fan gradient of around 4° were found by Jackson et al. (1987) in the Canadian Rockies, in contrast to thresholds of 7-8° identified by de Scally and Owens (2004) in the Southern Alps of New Zealand. This variation is mainly related to the lithological characteristics of the contributing catchment. Volcanic debris flows (lahars) may form fans with slopes as low as 1-2°, while debris flow fans formed in granitic terrain may show average fan gradients several degrees higher than the 4° quoted for the Canadian Rockies.

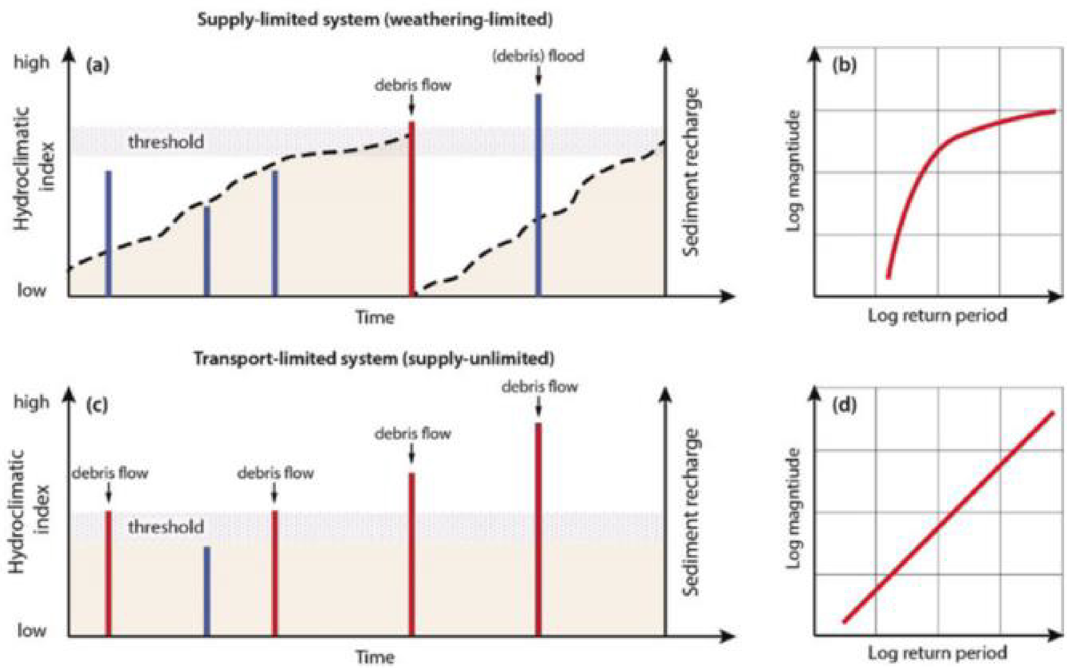


FIGURE 9. Conceptual debris flow initiation frequency between supply-limited and transport-limited catchments. Bars indicate rainfall-triggered events, rising lines indicate cumulative sediment recharge (modified after Bovis and Jakob, 1999; Jakob et al. 2022).

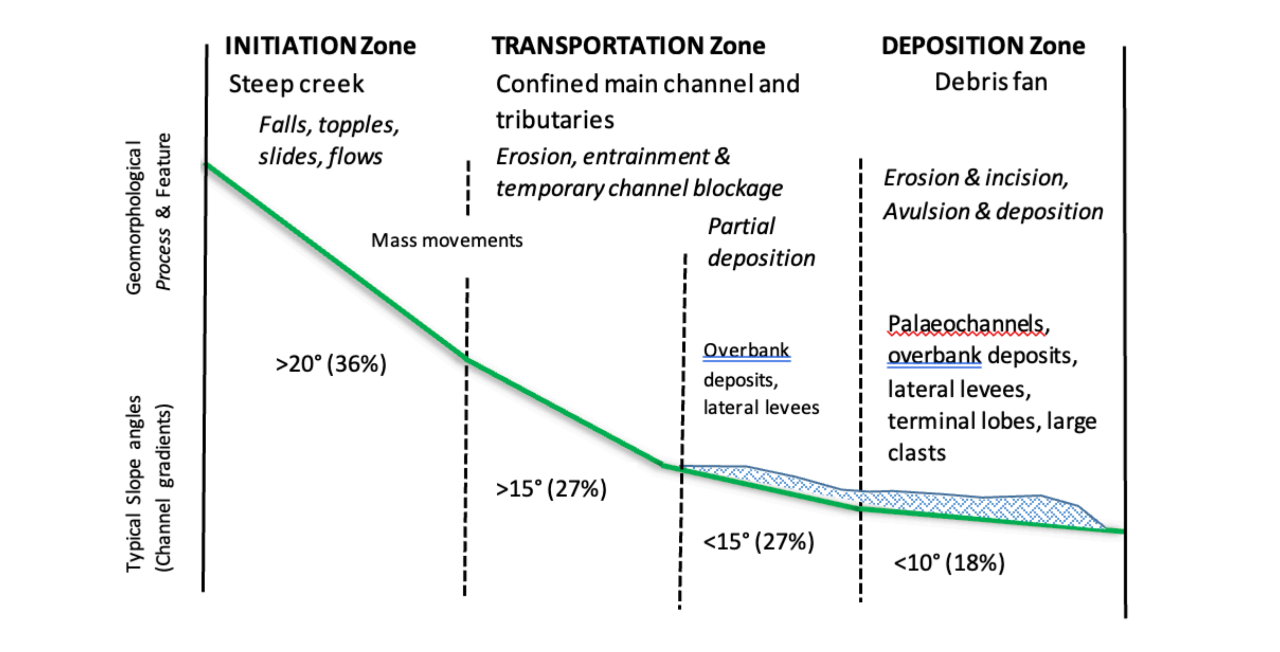


FIGURE 10. Geomorphological characteristics of steep stream catchments subject to debris flow hazards (modified from Van Dine, 1996)

3.3 MAIN CHANNEL CHARACTERISTICS

The main channel comprises the confined transportation zone of the debris flow or flood, where sediment bulking may occur between the initiation zone (the catchment) and the depositional zone on the alluvial fan. Sediment bulking is the process by which rapidly flowing water entrains bed and bank materials either through erosion or preferential "plucking". The volume of the flowing mass is thereby increased (bulked) until a certain sediment conveyance capacity (saturation) is reached. Large boulders (up to several metres in diameter) can be transported within the high-density flow. Further sediment entrainment may still occur through bank undercutting and transitional deposition of debris, with a zero net change in sediment concentration. Bulking may be limited to partial channel substrate mobilisation of the top gravel layer or, in the case of debris flows, may entail entrainment of the entire accumulated loose channel debris. Channels that have a recent history of debris flow activity are typically relatively large and incised (or even scoured to bedrock) compared to the size of the stream flows, have steep banks, evidence of periodic erosion such as stripping of vegetation, damage to existing vegetation (e.g. impact scars on bark high on trunks and branches of trees), channel bank undercutting, evidence of active mass movements along the channel banks and can contain oversized lag deposits of boulders ("megaclasts") much larger than could have been transported by flood flow, providing evidence of a previous debris flow, and other large size debris such as tree trunks (Figure 11 to Figure 13).

3.4 FAN CHARACTERISTICS

The debris or alluvial fan forms a semi-conical depositional landform beneath the apex (the outlet of the confined section of the system) of a steep stream catchment (Figure 14). The fan comprises the unconfined area of the system and represents the approximate extent of sediment deposition from the history of past events.

Deposition and runout extent of debris flows are governed by several factors, but are mainly controlled by a loss in gradient and flow confinement, leading to a transition from debris flow behaviour along the steep parts of the fan to debris flood and eventually clear-water flood processes where slope gradients are too low (generally less than 15°), the channel is unconfined and velocities are too low to support transport of high sediment loads.

As shown in some of the photos of Fig.14, fans may spread out in the unconfined toe regions (Fig. 14a), or are trimmed by subsequent stream flow (Fig. 14b), or flow into standing bodies of water (Fig. 14c) and in the latter case are referred to as fan deltas.

The front of the rapidly advancing debris flow is steep and commonly followed by several secondary surges that form due to particle segregation and upwards or outwards migration of boulders (or "megaclasts").

FIGURE 11: Left - Evidence of bank erosion and large–scale active slope instability of colluvium along a debris flow affected channel; Right – Partial deposition: Large boulder and woody debris deposits in the main channel of a steep creek.

FIGURE 12: Left – Active bank erosion and partial deposition of debris in a debris flow affected channel; Right – Incised channel showing active bank erosion in colluvium.

FIGURE 13: Left – Impact scars along vegetation above current channel level; Right – Active bank erosion in colluvium and partial deposition of bouldery debris within the main channel.

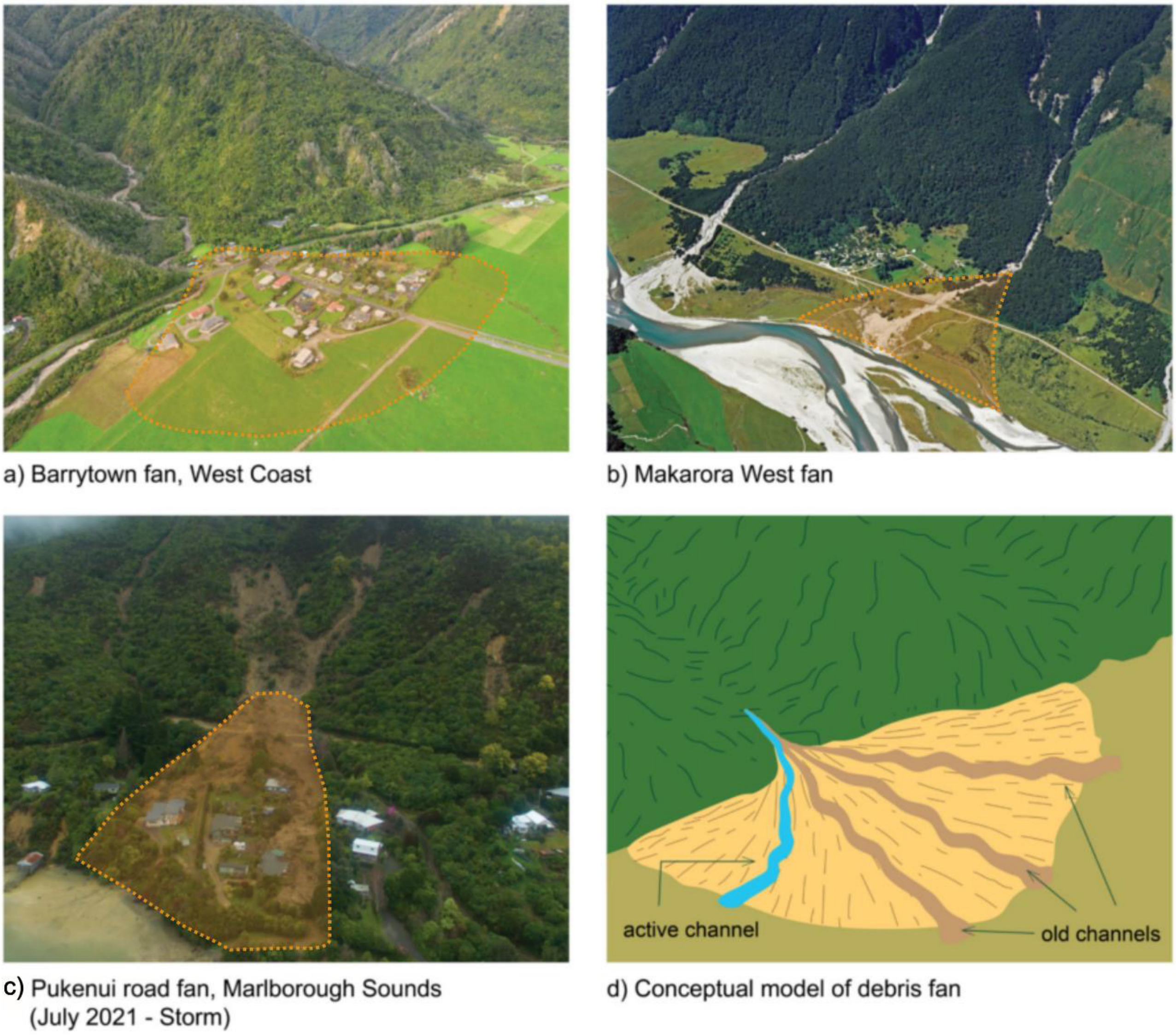


FIGURE 14. Examples of debris fans (approximate extent marked) in New Zealand and conceptual model of a debris fan (modified from De Vilder et al. 2024).

Hence, one of the distinguishing characteristics of coarse granular debris flows is vertical inverse grading, in which larger particles are concentrated at the top of the deposit. This characteristic behaviour leads to the formation of lateral levees by upward dispersive pressure along the channel that become part of the debris flow depositional record (de Haas et al., 2024). Similarly, depositional lobes are formed where frictional resistance from unsaturated coarse-grained or large organic debris-rich fronts is high enough to slow and eventually stop the motion of the trailing liquefied debris.

Very coarse-grained debris flows, typically originating in small catchments, may start to deposit at gradients as high as 27°, while lahars may travel several tens of kilometres, arresting at gradients of only a few degrees (Jakob & Hungr, 2005).

The deposition of coarse-grained material can lead to blockage of the channel (channel plugs) and subsequent avulsion (channel breakout) during individual debris flows and/or repeat flow surges. Avulsion typically occurs in unconfined channel sections, at the outside of channel bends, at channel plugs or at under-dimensioned infrastructure (e.g., culverts) leading to development of alternative flow paths on the fan. It is crucial to identify locations on the fan surface where avulsion is most likely or has happened in the past. However, evidence (paleo-channels, levees and lobes) can be well obscured by vegetation or removed by human activity. Analysis of LiDAR data often reveals historic geomorphological features left by past debris flows.

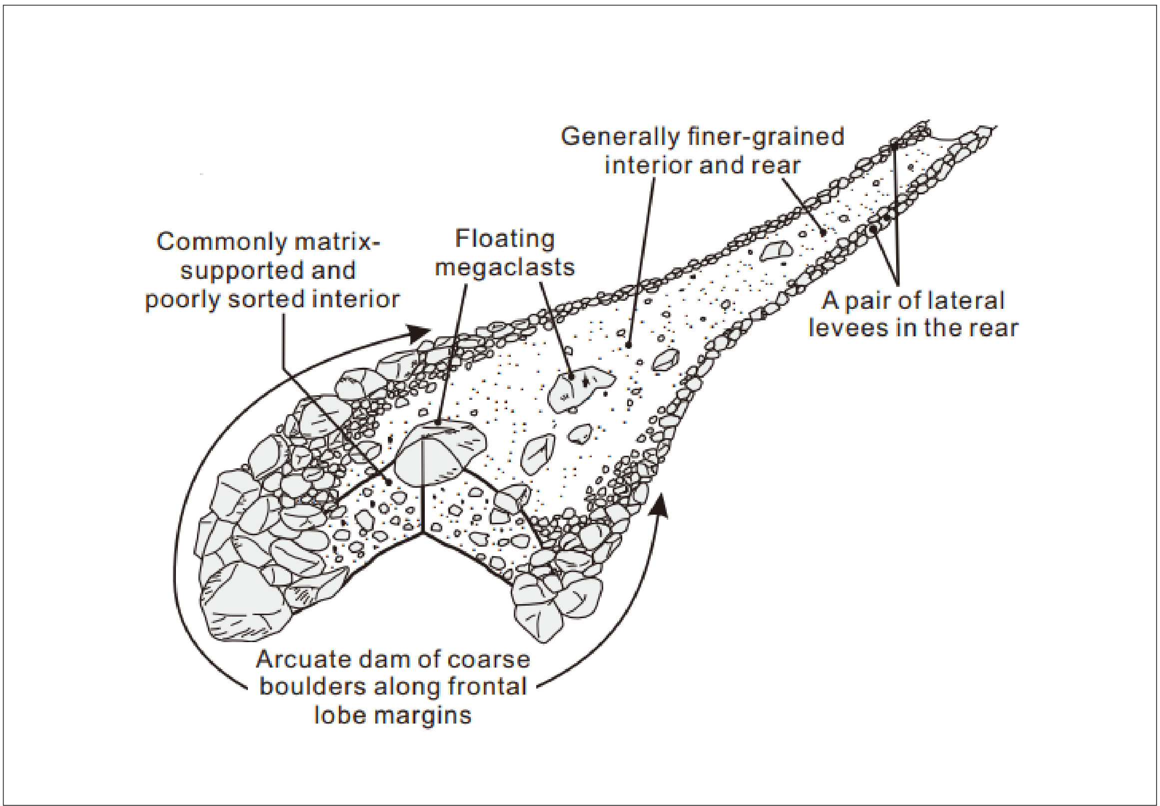


FIGURE 15. Typical Characteristics of a debris flow lobe. Debris flow deposits are characterised by an arcuate dam of boulders along the lobe margins and by parallel levees in the rear. Their interior is composed of commonly matrix-supported and poorly sorted deposits with floating megaclasts (Kim et al, 2021)

The dynamic nature of debris flow fans may pose a significant hazard to people and infrastructure (above and in ground) located on them; as areas that were inactive (and have since been built on) can reactivate and start actively eroding or receiving sediments.

Table 4 provides a summary of common characteristics that can be utilised to differentiate debris flow fans from colluvial and fluvial fans. Examples of typical morphological features observed on a fan affected by debris flows are illustrated in Figures 16 to 21.

Table 4: Overview of characteristics used to differentiate debris flow fans and fluvial fans (De Haas et al., 2024).

Fan Characteristics	Debris Flow	Debris Flood / Flood
Radial length	Range: 0.5 – 10 km	Range: 1 – 100 km
Fan slope	Average: 5-15° Range: 1 – 30°	Average: 2-7° Range: generally less than 10°
Morphology	Channels, lobes, levees	Channels, braid-like channel features, terraces, bank erosion or migration
Common grain sizes	Clay to boulder, biggest clasts can be larger than the expected bank full depth of stream flow, coarser grained at lobe fronts and along levees.	Sand to boulder
Grain angularity	Subrounded to angular	Rounded to subrounded
Sediment morphology	Matrix supported (clast supported rarely), no clast imbrication, inversely graded deposits + poorly sorted	Clast supported, clast imbrication, normally graded deposits

FIGURE 16: Left – Evidence of multiple flow paths/active channels on the fan and deposition of lateral levees and boulders following a debris flow event; Right – Incised channel on debris fan showing deposition of matrix supported boulders.

FIGURE 17: Left – Overgrown lateral levees (typically coarse-grained deposits) located just downstream of the fan apex; Right- Lateral Levee, Gunns Creek debris flow.

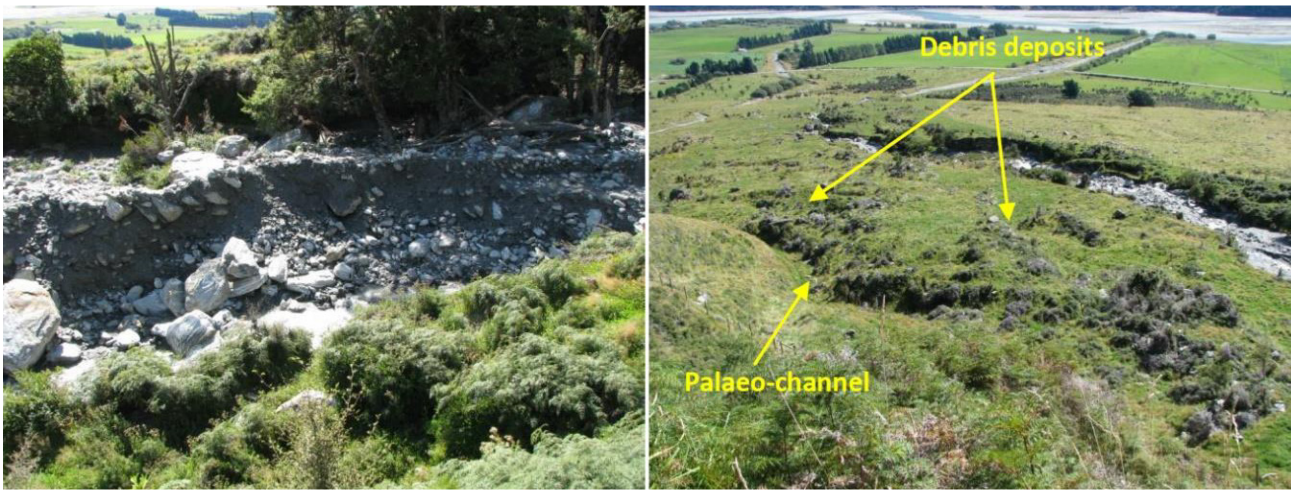


FIGURE 18: Left - Flaxmill Alluvial Fan, showing recent channel aggradation;
Right – Coarse-grained debris deposits and paleo-channel, ORC (2014).

FIGURE 19: Debris flow affected fan with overbank deposits engulfing trees, deposition of large clasts and impact / abrasion damage to tree trunks.

FIGURE 20: Debris height from past events represented by tree scars on the Brewery Creek alluvial fan, Queenstown (Beca, 2019).

FIGURE 21: Left - Very large boulder (megaclast) within mix of sand, gravel, cobbles and boulders material deposited from the 2007 Matata debris flow (McSaveney et al, 2005); Right - Debris Flow Deposit overlain by Clay and Silt / Sand horizons (Page et. al, 2012).

3.5 EFFECTS OF CLIMATE CHANGE ON DEBRIS FLOW OCCURRENCE

Climate change effects need to be incorporated into debris flow risk assessments - each debris flow prone watershed has its own characteristics that may change in response to climatic change.

Climate models predict that many regions will experience more extreme weather events, including intense rainfall and prolonged droughts. These changes are likely to increase the frequency and / or severity of debris flows. Areas that are already vulnerable may face heightened risks, necessitating improved monitoring and management strategies to mitigate potential disasters (Stoffel et al. 2024).

Quantifying debris flow activity changes in a warming climate is highly complex and subject to much uncertainty. Whereas for some supply-limited watersheds an increase in debris flow frequency may result in a decrease in magnitude and runout distance, in other environments higher rainfall intensities may result in larger debris flow activity and magnitude. Stoffel et al (2024) visualised a hypothetical example of three debris flow affected watershed types and the effects climate change may have on debris flow frequency-magnitude relationships and associated risk to infrastructure (Figure 22). This showed that climate change may not always result in increased risk and therefore a deep understanding of the local watershed, its processes and debris flow history is required to project potential future activity.

Changing climate parameters can influence the susceptibility of watersheds to produce debris flows in a changing climatic environment (Figure 23), such as:

- Studies have shown that regions prone to debris flows are likely to see an increase in the intensity of rainfall, which can trigger debris flows more frequently (Iverson, 2000).
- Combining snowmelt with more frequent rain-on-snow events, a more direct runoff and rapid influx of water into the soil and further saturating will increase the likelihood of debris flows (Stoffel et al., 2024).
- A reduction in summer precipitation frequency in the future is expected to lead to sediment buildup in channels, increasing the likelihood of debris flows later in the season (Stoffel et al., 2024).
- Vegetation loss, whether due to drought, deforestation, wildfires, or pest outbreaks exacerbated by climate change, reduces the root strength that helps hold soil in place. This destabilisation can make slopes more vulnerable to landslides and debris flows.

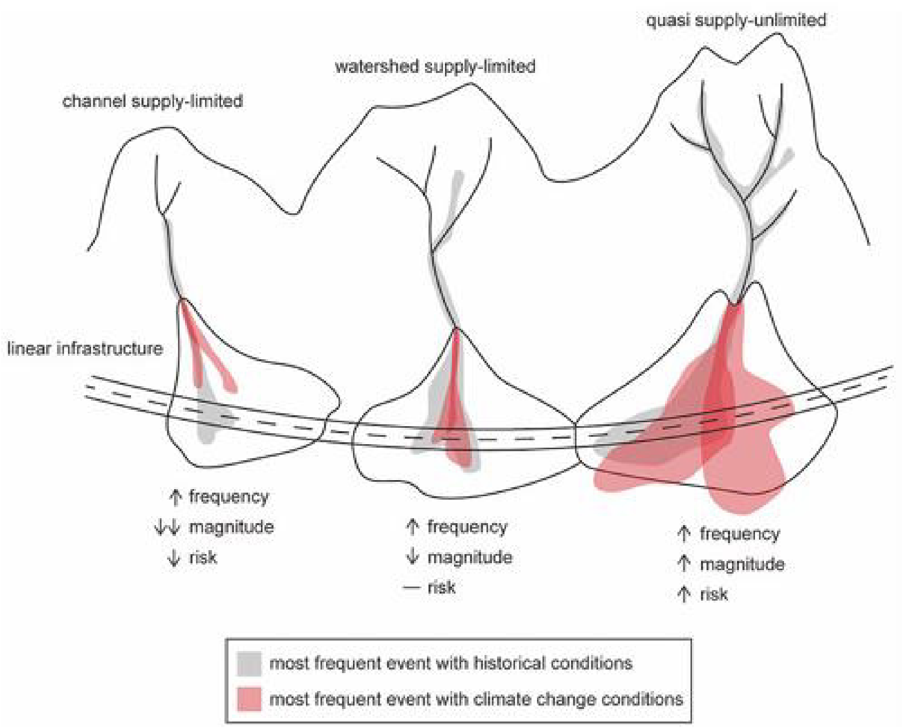


FIGURE 22: Hypothetical example of three different debris-flow producing watershed types and their changes in risk profiles to a highway (Stoffel et al 2024).

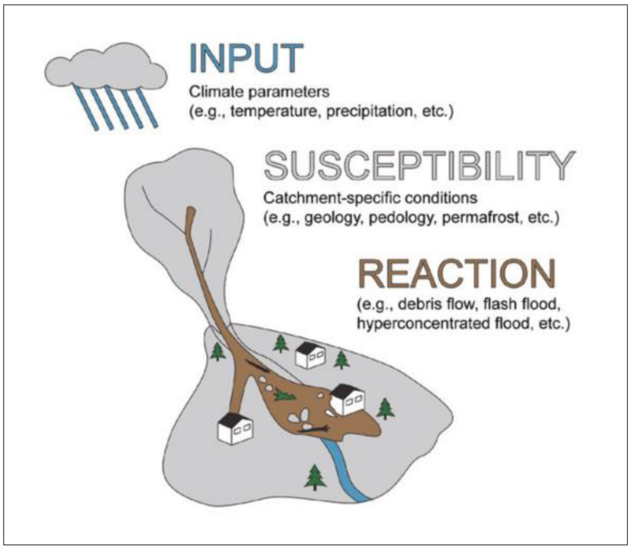


FIGURE 23: Process overview - changing climate parameters affecting catchment susceptibility and consequences in a steep stream watershed (from Stoffel et al. 2024).

In addition, parts of New Zealand are exposed to climatic events caused by tropical cyclones. Although research has shown declining trends in the annual number of tropical cyclones at global and regional scales, it is likely that cyclones are becoming more intense with global warming (increased moisture capacity). Research has also shown an existing trend in poleward migration of tropical cyClone tracks at a rate of about one degree of latitude per decade (Kossin et al. 2014).

4 ENGINEERING GEOLOGICAL ASSESSMENT

The dynamic nature of debris flow fans poses a significant hazard to people and infrastructure located on them. This is not only applicable to currently active fans – fan areas that have been inactive (and have since been built on) can reactivate and start actively eroding or receiving sediments as a result of an extreme event or, in the longer term, climate change. It is the responsibility of the practitioner to not only describe or quantify uncertainties (natural uncertainty, knowledge-source uncertainty and analysis uncertainty) that are associated with predicting the effects of debris flows at a site, but also the possible effects of climate change on those assessments (Stoffel et al 2024).

Evaluation of debris flow / flood hazards for risk assessment or mitigation design purposes must consider:

- The characteristics of the steep creek catchment where the flow is most likely to be initiated.
- Evidence from the confined channel where debris is transported and where sediment entrainment can occur.
- The characteristics of the alluvial fan, where most of the debris flow material is deposited. It is crucial to assess whether locations exist on the fan surface where avulsion is most likely or has happened in the past.

In the upcoming sections, observations and analyses essential for hazard quantification within the catchment, transportation zone, and depositional fan area are outlined. Additionally, methods for presenting the collected data are listed.

Two worked examples that represent common debris flow assessment scenarios geoprofessionals are exposed to are presented in Appendices B and C.

4.1 CATCHMENT ASSESSMENT

Table 5 summarises the elements that should be assessed in the steep creek catchment to understand the geographical, geological and geomorphological setup and history of the catchment, current sediment availability and history of extreme rainfall events to contribute to the assessment of whether the catchment is susceptible to debris flow processes.

4.2 MAIN CHANNEL ASSESSMENT

Elements that should be assessed in the main confined channel and its tributaries to inform potential flow velocity, flow depth, preferential flow paths and sediment/debris composition and availability are summarised in Table 6. Elements include geometrical parameters as well as evidence of areas that could contribute to sediment/debris supply (mass movements and vegetation) in a future event as well as evidence (features of debris transport and partial deposition) of past events.

4.3 DEBRIS FAN ASSESSMENT

Table 7 summarises assessment elements on the debris fan that are critical to understand the hazard at the site (i.e. spatial variability of debris runout, depositional history, susceptibility to avulsion, vegetation history and susceptibility to entrainment, geological subsurface profile and sediment structure) depending on the project scope and site configuration. In addition, infrastructure at risk of debris flow impact must be mapped and characterised. If recent debris flow debris deposits are present on-site, detailed documentation (volume, depth, grain size, extent, associated rainfall event, etc.) will provide a dataset to inform future hazard assessments.

The assessment of subsurface conditions (e.g. through excavation of test pits across a representative area) can inform the assessment of the history and type of hydrogeomorphic hazard the site has experienced in the past as well as inform potential frequency / magnitude relationships and flow depth.

Table 5. Assessment Elements - Catchment

Item	Information to be collected or prepared	Source or Reference	Data Presentation
Catchment geometry and slope characteristics	• Catchment morphometry, (geometry, relief, drainage characteristics, Melton Ratio) • Slope angles, slope aspect	• LIDAR, • DEM, • GIS analyses	• Tabulated data, • Engineering geological model, • GIS / Engineering geological maps
Catchment geology	• Geological composition (rock and associated debris, rock strength, erodibility, debris grainsize, volume of readily erodible debris) incl. geological history • Recognition and identification of mass movement processes[1] (failure type, size, volume, activity, etc.)	• Geological maps, • Historical aerial imagery, • Site walkover assessment, • UAV survey, • GIS analyses (e.g. source area susceptibility assessment, etc.)	• Engineering geological model, • Engineering geological maps, • Historical imagery, • Site photos
Historical data	• Rainfall records, in particular during known high intensity rainfall events (cyclones, storms etc.), which can be assessed against historical debris flow initiations • Records of previous debris flows in this area: do they commonly occur in the area or not?	• Regional/ local council rain gauge records, • HIRDS	• Tabulated data, • Site photos (historic records)
Hydrology	• Analysis of baseline flow characteristics (clear-water peak flows) • Verification of hydraulic capacity of existing infrastructure (e.g. culverts, channels, road crossings)	• Streamflow data (if available)	• Hydrological assessment, • Tabulated data
Land use and vegetation	• Identification of current and historic land use / type and age of vegetation (e.g. native vegetation, pasture, forestry, etc.) • Areas of human modification that may influence sediment/debris supply or/and surface water runoff during an event (e.g. clear-felled forestry, etc.)	• Historical aerial imagery, • Site walkover assessment, • UAV survey, Historical verbal evidence (has to be taken with neutral judgement)	• Historical imagery, • Engineering geological maps, • Site photos

[3] Refer to NZGS Slope Stability Geotechnical Practice Unit 2 - Landslide recognition, Identification and field investigations (NZGS, in preparation).

Table 6. Assessment Elements – Main Channel

Information to be collected or prepared	Source or Reference	Data Presentation
• Channel length, width, channel geometry and gradient • Assessment of erodible debris source areas (type, area, volume, grain size), including partially deposited debris within channel, bed material sampling (Wolman counts), and yield rates • Evidence of erosion along channel banks • Sediment at the base and depth of incision • Evidence of particle jamming, superelevation • Levees, strandlines, mudlines, trim line; debris impact scars on trees well above the clear-water flood limit, loss of branches from trees to equivalent height might give indication of occurrence of previous events • Vegetation density, type and age of vegetation within the channel stream bed and along channel banks • Areas of human modification that may influence sediment/debris supply or/and surface water runoff during an event (e.g. culverts, etc.)	• LiDAR, • DEM, • GIS analyses, • Historic aerial imagery, • Site walkover assessment, • UAV survey, • Dendrogeomorphology	• Historical imagery, • Engineering geological model, • Geomorphological maps, • Engineering geological maps, • Site photos, • UAV imagery

Table 7: Assessment Elements – Alluvial Fan

Item	Information to be collected or prepared	Source or Reference	Data Presentation
Fan morphology	• Dimensions and location of depositional lobes and levees • Fan gradient • Depth of incision of current channel at fan apex and along length of fan • Evidence of deposition and avulsion (history and variability) • Records and changes in deposited clast sizes and sediment structure (clast supported vs matrix supported) • Notes of which channel(s) are active vs inactive • Areas of erosion, presence of abandoned channels • Identification of hotspots on the fan surface where avulsion is most likely or has happened in the past (e.g. culverts, channel bends, low lateral channel banks; evidence can be well obscured by vegetation or removed by human activity; verification through numerical modelling)	• LiDAR (potential to identify paleo-channels and depositional features that are obscured by vegetation; verification during site walkover assessment) • DEM • Historic aerial imagery • Site walkover assessment • UAV survey	• Tabulated data • Historical aerial imagery • Engineering geological model • Engineering geological maps • Site photos • Numerical debris flow runout assessment
Vegetation	• Type of vegetation and establishment history • Evidence of special features, i.e. debris impact scars and their height above current channel bed level • Proximity to active and historic channels	• Aerial imagery • Site walkover assessment • UAV survey • Dendrogeomorphology	• Site observations • Site photos
Subsurface Profile	• Grain size, angularity • Lack of stratification and particle sorting. Possible inverse particle grading • Clast orientation (typically random in debris flow deposits) • Presence of matrix supported angular to sub-angular cobbles and boulders; • Presence of buried topsoil, vegetation horizons and timber logs (radiocarbon sampling)	• Site walkover assessment: Logging of natural exposures (channel sections, road cuts etc.) • Excavation of test pits (hand augers are likely to be of limited use) potentially including radiocarbon dating • PQ machine boreholes (likely to be of limited use except in thick fans)	• Site photographs • Test pit logs incl. photos • Engineering geological model incl. cross-sections (if sufficient data was collected)
Elements at risk (Population / Infrastructure)	• Identification of elements at risk (i.e. population at risk, type residential/ industrial facilities, utilities, roads and railways, critical infrastructure) • Comprehensive mapping of elements at risk (such as buildings, culverts, bunds, bridges, etc), including their dimensions • Assessment of clear-water flow capacity of road crossings (i.e. culverts, bridge freeboard etc.)	• Site walkover assessment • Regional/ local council information • Engineering survey • Hydrological assessment • Risk assessment	• Engineering geological maps • Risk assessment tabulated data and hazard maps • Technical drawings • Numerical debris flow runout assessment

5 HYDROLOGICAL ASSESSMENT

5.1 CATCHMENT HYDROLOGY

An assessment of the catchment hydrology allows for the characterisation of the runoff response within a catchment area. This process requires evaluating rainfall, runoff, and the interaction of water with the land surface and subsurface. Debris flow volumes for a range of annual exceedance probabilities (AEP's) can be estimated at screening level through the assessment of potential clearwater runoff, multiplied by a debris bulking factor. However, it is important to note that

1. Debris flows can be initiated by factors other than rainfall.
2. Simply because a certain return period rainfall event occurs in a catchment, it does not necessarily mean that a debris flow will be initiated, as other precursors (for example sufficient sediment supply) are also required.
3. If it does occur, a debris flow may have a volume smaller, or larger, than that expected for clear water.

A clear-water peak flow assessment can range from simple methods for small (< 0.65 km^2) catchments (such as The Rational method, which estimates peak discharge from a catchment based on rainfall intensity, catchment area, and runoff coefficient; refer Section 5.2) through to detailed modelling of catchment runoff response using the Curve Number method or other empirical loss methodology where streamflow data is available. These simulations can model the interaction of various hydrological processes, including rainfall, infiltration and surface runoff. They can also account for the spatial and temporal variability of these processes if required, providing a more comprehensive understanding of the catchment's hydrological behaviour.

5.2 SMALL CATCHMENT PEAK FLOW ESTIMATION – RATIONAL METHOD

The Rational Method is a simple empirical procedure for estimating runoff from small catchments, and uses a simple equation to calculate peak flow using rainfall intensity, catchment area and a runoff coefficient:

$$Q = 2.78 * C * I * A$$

Where:

Q = peak flow (m^3/s)
C = runoff coefficient
I = average rainfall intensity (mm/hr) during the design storm of duration (D) for the appropriate design annual exceedance probability (AEP)
A = catchment area (ha)

In this method, the design storm duration is defined as the time of concentration (Tc), which is the time required for surface water runoff to travel from the furthest point of the catchment to the design point. This means that the entire catchment area contributes to the peak discharge at the design point for any given probability of occurrence. The critical storm duration (D) is equal to Tc. Various methodologies exist for calculating Tc, however the Kirpich Formula is particularly suitable for small, steep catchments that may typically be assessed for debris flow potential, calculated as follows:

$$Tc = 0.0195 * L^{0.77} * S^{-0.385}$$

Where:

Tc is the time of concentration (hr)
L is the length of the longest watercourse (m)
S is the slope of the catchment (dimensionless)

The average rainfall intensity for the design storm duration can be estimated using the NIWA High Intensity Rainfall Depth System tool, available online at: https://hirds.niwa.co.nz/ .

In the Rational Method, runoff coefficients are used as a percentage of loss. Typical values range from 0.95 for impervious surfaces such as bare rock, to 0.25 for low cropped grass.

This method is relatively straightforward and provides a quick estimation and typically provides a conservative approach to peak-flow estimation, making it useful for preliminary assessments. However, it was developed originally for small agricultural catchments and typically oversimplifies catchment response at a larger scale (> 0.65 km^2) and so should not be used for any detailed assessment at scales greater than this as it will often overestimate peak discharge.

5.3 LARGER CATCHMENT SCALE PEAK FLOW ESTIMATION

For larger catchments, a number of methods exist for peak flow estimation. Where defined streams and rivers exist, the Henderson Collins (2018) NZ river flood statistics tool, available online at www.niwa.maps.arcgis.com, allows users to extract flood statistics from a regional flood model that can provide indicative peak flow estimates at each confluence point within a mapped catchment or at-site flood statistics where available. Where historical flow data is available, typically through NIWA or Regional Council's science teams, flood frequency analysis can be completed on streamflow data instead. It is important to note that these values will be based on historical flow records and will not incorporate potential increases or decreases in flows resulting from climate change.

Where modelling is required, the Curve Number Method, as detailed in TP108 (ARC, 1999), is a widely used approach in New Zealand for estimating direct runoff from a rainfall event. It incorporates factors such as soil type, land use, and antecedent moisture conditions. The curve number (CN), which ranges from 30 to 100, is a key parameter in this method with higher values indicating greater runoff potential relating to land cover and underlying soil conditions.

This method is particularly useful in regions with variable land cover and can provide more accurate runoff predictions compared to simpler methods.

5.4 BULKING FACTORS

Converting a clear water peak flow estimate into a debris flow estimate can be carried out using bulking factors, which increases the water discharge to account for a high concentration of sediment in the flow. Note that in this instance, bulking factors are for streamflow across the hydrograph, so are different to bulking factors applied to peak rate only. Based on the bulking factor (i.e. sediment concentration), sediment / water flow ranges from normal clear water flows to hyperconcentrated flow to debris or mud flows.

A typical range of bulking factor values is outlined in Table 8. It is important to note that these types of flows are on a continuum and the boundaries between them are not always clearly defined, with a single debris event able to produce different flow types at different points of the event. It is recommended that any assessment using bulking factors completes a sensitivity analysis: evaluating multiple scenarios with different bulking factors to understand the potential range of debris flow volumes, rather than selecting a single value.

Table 8: Bulking Factor Ranges for Total Flood Hydrograph (West Consultants, 2011)

Clear-water flow	Hyperconcentrated flow	Debris or mud flow
1.00-1.25	1.25 – 1.67	1.67-2.5

5.5 HYDRAULIC ASSESSMENT

An assessment of existing structures (such as a bridge or culverts ability to convey debris flows) is often required. A typical approach might involve a first-pass hydraulic capacity check of the structure in question. For example, for a given culvert diameter and surveyed slope, a preliminary theoretical maximum clear water conveyance limit can be estimated using software such as the U.S Governments Federal Highway Administrations HY-8 program, which is a free hydraulic design software for culverts. This information can then be used to determine the ability for a structure to convey an estimated debris flow volume using bulking factors (as a preliminary assessment of risk, bridge structures could be assessed as a concrete open bottomed arch culvert). The effect of vegetation (often termed 'woody debris') carried with the flow also needs to be considered as discussed in Section 8.6.

For a more detailed assessment of debris flow runout and attenuation behind structures, more detailed modelling is required, as outlined within Section 6.

6 NUMERICAL DEBRIS FLOW MODELLING – AN OVERVIEW

6.1 MODELLING SCENARIOS

Geoprofessionals utilising numerical runout analysis for a debris flow assessment typically encounter two common situations:

1) A debris flow event has recently occurred, and field data (source area, debris volume, runout length, flow depth, see Figure 24) is available to be used for back analysis to tune and calibrate of a hydrodynamic model so it can be used in the development and design of mitigation options.
2) The debris flow runout assessment is required to assess a greenfield site on or near a debris fan that is due for development and may have shown debris flow activity in the past, but field data is limited. This challenging scenario requires in depth local knowledge of the catchment, hydrogeomorphic watershed processes, and sound geomorphological interpretation of the fan, all of which are combined into a frequency-magnitude analysis (see Section 7). Modelling simulation and results must consider a larger amount of uncertainty (e.g. identification of source areas, flow volumes, velocities and depths, complex flow mechanics).

6.2 MODELLING SOFTWARE OPTIONS

Numerical debris flow runout modelling has advanced rapidly over the last decades due to the increase in computational power, availability of high resolution DEMs, and increased sophistication of numerical solution methods (Iverson & George, 2024).

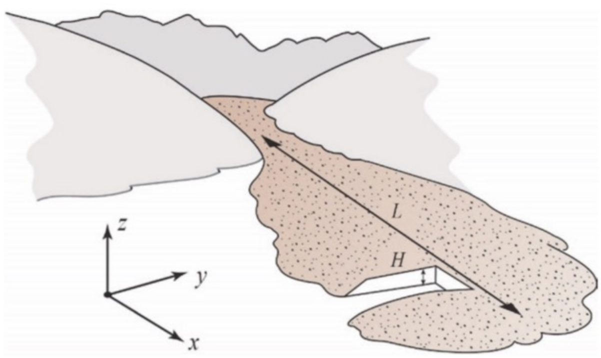


FIGURE 24: Schematic illustration of characteristic debris flow parameters flow depth H in the z direction and runout length L in the x and y directions (adapted from Iverson, 2005) that can be used for back analysis of a debris flow scenario.

There are several software packages available that may be used to model debris flow / debris flood behaviour, in particular the potential extent of runout, velocity and flow depth. Commonly used software for debris flow runout modelling includes RAMMS debris flow (Figure 25), Flow-R and FLO-2D, HEC-RAS. Some of the benefits and limitations of each package are summarised in Table 9 (partly based on Cesca & D'Agostino, 2008, Horton et al, 2013). This is not an exhaustive list, and geoprofessionals may wish to consider alternatives (e.g. DAN3D, ProDF, Debris flow predictor, Grfin tools) that may be more suitable for their project needs as technologies advance.

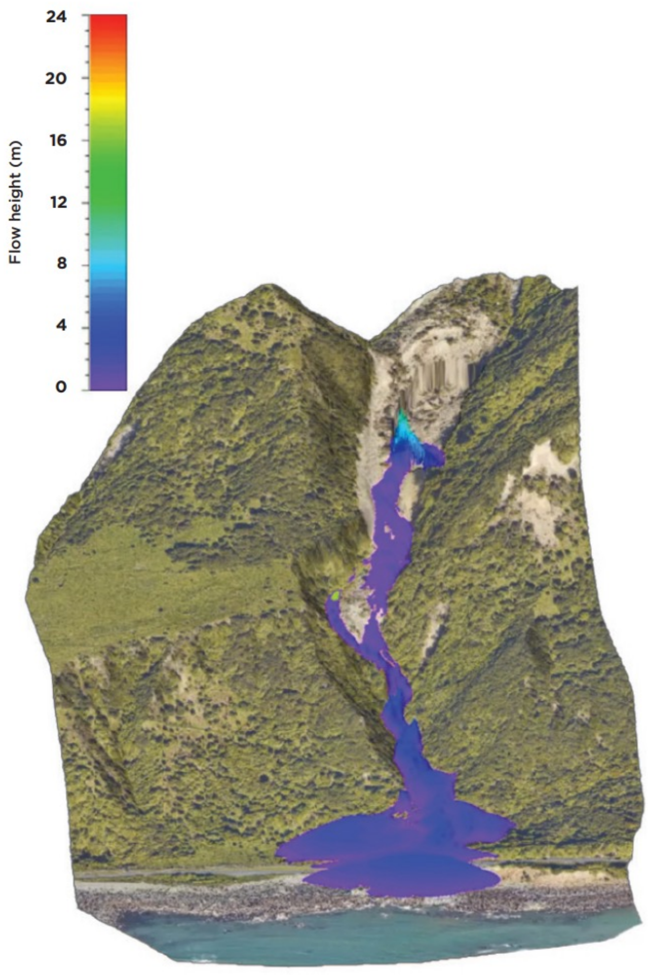


FIGURE 25: Example of a RAMMS debris flow back analysis output for the February 2018 debris flow at Jacobs Ladder, New Zealand; Darafshi & Borella (2020).

Table 9: Benefits and limitations of some commonly used debris flow software packages.

Software Package	Benefits	Limitations / Remarks
RAMMS Debris Flow	• Developed specifically to simulate the runout of muddy and debris-laden flows in complex terrain • Widely used • Combines state-of-the-art numerical solution methods (Voellmy-fluid friction model) with helpful input features and user-friendly visualization tools • Can be used for modelling small and extremely large debris flows • Many of the input and output features have been optimized to allow geoprofessionals to – define event scenarios, – evaluate simulation results, and – predict the influence of proposed structural mitigation measures on the runout of debris flows.	• Debris flow simulation using the RAMMS model requires a number of input data including a DEM (resolution has significant effect on runout results), peak runoffs, and sediment volume • Model calibration using debris-flow post-event survey field data is an essential step (and should be done before application of the model)
Flow-R	• A distributed empirical model for assessing regional susceptibility to debris flows • Successfully applied to different case studies in various countries. • Allows for automatic source area delineation and for the assessment of the propagation extent. • Choices of the datasets and the algorithms are open to the user. • Also suitable for assessing other natural hazards such as rockfall or snow avalanches.	• Only allows identification, at a preliminary level of detail, of potential debris-flow or debris-flood hazard and modelling of their runout susceptibility at a regional scale • Cannot model avulsions that are likely at culverts and bridges and which could redirect flow out of the channel
FLO-2D	• FLO-2D is a flood routing model that combines hydrology and hydraulics • Developed in 1987 to predict mudflow hydraulics • Since adapted to conduct any sort of overland and channel modelling type (e.g. urban flood mapping, alluvial fans, coastal flooding). • Uses QGIS and the FLO-2D Plugin to build models. • Ability to integrate different types of geospatial data e.g., LiDAR, aerial images, shape files, contour maps and DEM • Can import HEC-RAS geometry cross-sections	• Primarily a flood routing model • Grid element represents single elevation, Manning's n value, and flow depth • Modelling mesh is fixed size • Hydraulic structures and rating table are developed outside of the model • Rapidly variable flow (i.e. a dam breach) is not simulated • 1D channel flow (no secondary currents, or vertical velocity distributions).
HEC-RAS	• HEC-RAS 2D is a hydraulic modelling software, developed by the U.S. Army Corps of Engineers for clear-water hydraulic analysis, with recent integration of non-Newtonian modelling and hydrological loss processes. • Uses implicit finite volume solution algorithms, providing stability and robust simulation • It is a free to use, even for commercial use • Allows for a flexible mesh size to be used, so finer grids can be employed in areas of particular interest • Has an in-built GIS platform for modifying terrain, adding features and visualisation of model inputs and outputs. • Ability to accurately model structures such as bridges and culverts, in addition to modelling porous media and sub-grid features such as debris flow barriers (Version 6.6+) • Can model spatially variable Manning's n value • Can model 1D, 2D or combined 1D/2D • Can simulate subgrid erosion and deposition to represent bank erosion, channel scour and aggradation.	• Non-Newtonian simulation options limited to bulking factors, and the following equations; Bingham, O'Brien (quadratic), Clastic Grain Flow and Herschley-Bulkley • Debris flow modelling capabilities are relatively new, with limited case studies outside of the United States. Users would be prudent to ensure some form of calibration is completed and then using debris-flow post-event survey field data. • Cannot simulate other natural hazards such as rockfall or snow avalanches • Sediment erosion/deposition subject to accurate parameterisation. Likely only useful for high level sensitive analysis. • Costs: Free

6.3 TRANSPARENCY, MODEL INPUT, CALIBRATION, DATA INTERPRETATION, AND PRESENTATION

All of the currently available modelling packages simplify flow behaviour and properties to some extent and should only be considered a tool to support the overall engineering geological and hydrogeomorphological understanding of the site. When judiciously formulated and applied with healthy skepticism, these models can provide useful information about anticipated flow depths, velocities, and extents of debris flow inundation as well as debris interactions with structures such as levees and dams. Model simulation scenarios should be thoroughly documented, tested, and available for scrutiny (Iverson & George, 2024).

In addition, model results are dependent on high resolution digital elevation models, which are not always available and can often not be obtained within the project budget. DEMs can be constructed by digitising analog topographic contour data but this DEM construction can be labour intensive. The resolution of DEM data is an important consideration in debris flow modelling and considerable care is required in selecting the numerical grid resolution for a given problem. Adequate resolution using LiDAR may be necessary to portray accurately high value / high consequence features such as buildings, levees, or dams in debris flow runout zones, whereas the use of coarser DEM resolution might be practical in other areas along the debris flow path to reduce computation time of the simulation (Iverson & George, 2024). Low resolution (e.g. 8 m) DEMs are generally insufficiently detailed to define important topographical features such as channels.

As with other software packages used in geotechnical engineering, the quality of the output cannot be better than the input and, therefore, careful selection of initial and boundary conditions (e.g. hydrograph parameters; Mitchell et al, 2022) as well as calibration of the model by geomorphic observations and ground truthing, such as selection of debris volumes, source areas, spatial distribution of downstream debris flow deposits, as well as statistical analysis remains critical. The evaluation of model performance and sensitivity is key, and multiple evaluation concepts are available to compare model results, independent of simulation platform (e.g. Heiser et al., 2017).

Numerical modelling still faces challenges to simulate sediment entrainment, grain-size segregation, deposition along the flow path, lateral levee formation and flow path avulsion (Iverson & George 2024). Visual display of numerical modelling results is a beneficial way of discussing the complex mechanisms behind debris flows and their impact at a certain site. Geoprofessionals are required to provide as much high-quality input data and reduce as many uncertainties as possible while thoroughly documenting (be as transparent as possible and share simulation processes) and critically interpreting simulation results.

7 DEBRIS FLOW HAZARD AND RISK ASSESSMENT

FIGURE 26: Debris Flow Damage, Awataraiki Stream, Matata, New Zealand, following the 18 May 2005 debris flow event. McSaveney, et al (2005).

As has been described previously in this document, debris flows have the potential to do significant harm owing to the potentially large volume, high velocity, and the ability of debris flows to transport large, entrained boulders and other debris (Figure 26).

As outlined in Section 6.1 of Unit 1 of the Slope Stability Guidance, Risk assessment is the key process in determining how likely a hazard (in this case, debris flow) is to damage infrastructure, buildings, or result in injury or death of people. 'Risk' can be defined (de Vilder et al, 2020) as:

A measure of the probability and severity of an adverse effect to life, health, property or the environment. Quantitatively, Risk = Hazard × Potential Worth of Loss. This can be also expressed as 'Probability of an adverse event times the consequences, if the event occurs'

A widely used approach for risk assessment has been developed by the Australian Geomechanics Society (AGS 2007a-d) which considers the likelihood and magnitude of landslides (including debris flows) and potential consequences. Following the general approach of AGS (2007) the life risk associated with debris flows can be calculated using the following equation:

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

Where:

- $P_{(LOL)}$ is the annual probability of a fatality as a result of the debris flow occurring.
- $P_{(H)}$ is the annual probability of a debris flow of a certain magnitude occurring.
- $P_{(S:H)}$ is the spatial probability of impact on an element at risk from the defined hazard. For debris flows, this relates to the runout or inundation extent.
- $P_{(T:S)}$ is the temporal probability of a person being present at the site at the time of impact.
- $V_{(D:T)}$ is the vulnerability or probability of loss of life if the hazard impacts the site.

A number of other hazard and risk assessment frameworks exist other than that could be utilised as alternatives to AGS (2007), depending on the situation and stakeholder requirements. Further information is available in Slope Stability Guidance Unit 1 amongst other publications.

Geoprofessionals should make sure that a clear framework is established to transparently convey the hazards and their level of risk, ensuring the client can make well-informed decisions. The geoprofessional must understand the purpose and intended use of the framework, provide the analysis in the format appropriate to inform decisions, and appropriately document recommendations and limitations.

A suggested approach to assess hazards and risks associated with debris flow and related events is provided in Sections 7.1 to 7.4.

7.1 WORKFLOW TO ESTIMATE DEBRIS FLOW HAZARD AND RISK

Figure 27 provides a summary of the suggested workflow for assessing debris flow hazards and their associated levels of risk.

The workflow includes an initial screening to determine the 'relative hazard level'. This consists of a desktop study and a high level, qualitative geomorphological assessment, to identify whether a debris flow hazard exists at the given site (including characterisation). This initial screening process is outlined in Section 7.2. More detailed analysis will be required in many cases, the details of which are described 7.3.

As is common with natural hazard risk assessments, the likelihood of a hazard (in this case, a given magnitude of debris flow) occurring is often difficult to accurately estimate, while the potential consequences of the hazard occurring are often more easily assessed. It is important in a risk assessment to recognise and communicate the uncertainty in each of the characteristic's terms in the risk assessment, particularly where the uncertainty is large. Further information is provided in, for example, Paul and Miner (2025).

All debris flow hazard and risk assessments require consideration of climate change, which can be incorporated in the hydrology assessment stage of the analysis (refer to Section 3.5 and Section 5).

7.2 DETERMINATION OF RELATIVE HAZARD LEVEL

As an initial screening tool, an assessment of the relative hazard posed by a debris flow system may be useful. This is a desktop assessment to qualitatively describe the activity level of the debris flow hazard, based on the characteristics of the catchment and alluvial fan. It is intended to provide an initial assessment of the hazard to inform whether further, more detailed assessment is required. This initial hazard activity assessment is broadly similar to the Level A Susceptibility analysis outlined in de Vilder et al (2024) and is shown on Table 10. The hazard level criteria are based on surface evidence for geomorphic activity within the catchment and fan. As such, they do not consider the timing of events and is based on events large enough to produce visible surface evidence. Dense tree cover, for example, could obscure small events which would not be detected at the scale of study (BGC, 2020).

Some examples of initial hazard level assessment for a range of New Zealand catchments are provided in Figures 28 to 31.

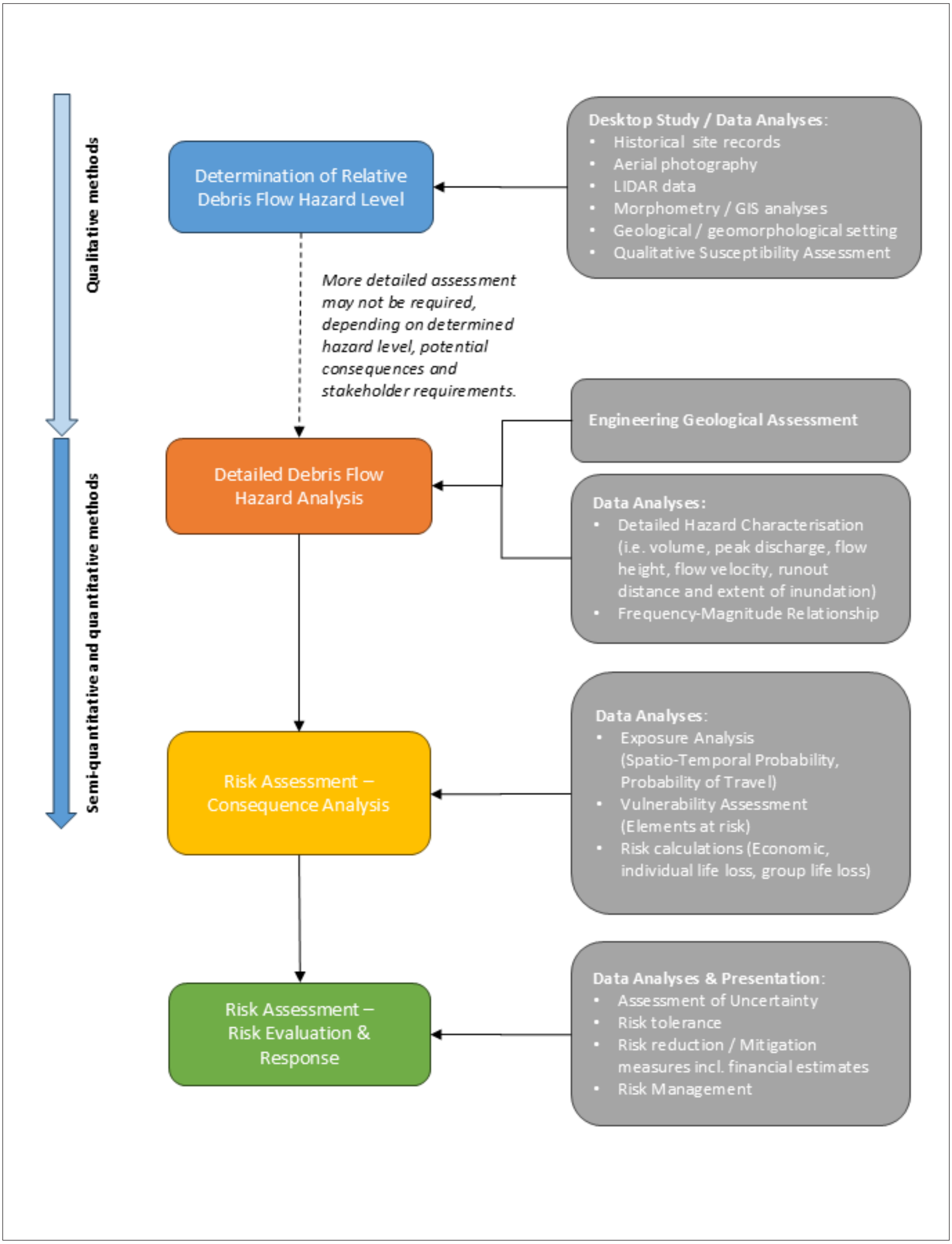


Figure 27: Suggested Workflow for hazard and risk assessment for debris flow hazards.

Table 10: Relative Hazard Level Criteria for Mountainous Watersheds. Modified from BGC, 2020. Examples of Catchment and Fan Activity Characteristics are provided in Figures 28 to 31.

		Catchment Activity Characteristics				
		No identifiable source areas; absence of fresh or recently active landslide scars or channel deposits; supply limited catchment	Poorly defined source areas absence of fresh landslide scars, but evidence of inactive slope instability; supply limited catchment	Well defined source areas, presence of some fresh landslide scars and some reworked deposits; usually supply limited catchment	Numerous, well defined, actively producing source areas in tributaries along main channel, channel choked with debris, abundant fresh landslide scars, supply unlimited catchment	Numerous, well defined, actively producing source areas in tributaries along main channel; easily entrained materials along incised channels, channel choked with debris (high yield rate), abundant fresh landslide scars, supply unlimited catchment
Fan Activity Characteristics		Very Low	Low	Moderate	High	Very High
Obvious fresh deposits in main channel; lobes and/or levees of previous deposits easily recognisable; swaths of bare sediment or pioneer vegetation, multiple active channels	Very High	NA	NA	High	Very High	Very High
Obvious fresh deposits in main channel; lobes and/or levees of previous deposits easily recognisable; swaths of pioneer vegetation, some active channels	High	NA	NA	High	High	Very High
Partly vegetated mainstem, lobes, channels and/or levees of previous events clearly descendible, but overgrown in part; swaths of young vegetation (<50 years)	Moderate	Low	Moderate	Moderate	High	High
Vegetated mainstem channels, relict lobes and levees of previous events observable; mature vegetation (>50 years) on fan	Low	Low	Low	Moderate	Moderate	High
Raised paleo fans. Vegetated fans with no clear relict channels	Very Low	Very Low	Low	Low	Moderate	Moderate

Catchment systems with very low or low hazard activity are unlikely to pose a significant level of risk in most cases, unless there is an increase in consequence (for example, development of a subdivision on the fan) and in these cases, more detailed assessment may not be necessary. However, where this initial assessment produces relative hazard levels of Moderate or higher, or there is potential for a significant increase in consequence, more detailed hazard and risk analyses requiring detailed hazard process quantification, numerical modelling, as well as exposure and vulnerability analysis of the elements at risk is required, corresponding to Levels B to E of de Vilder et al (2024) and would involve the steps lower in the work flow outlined on Figure 27.

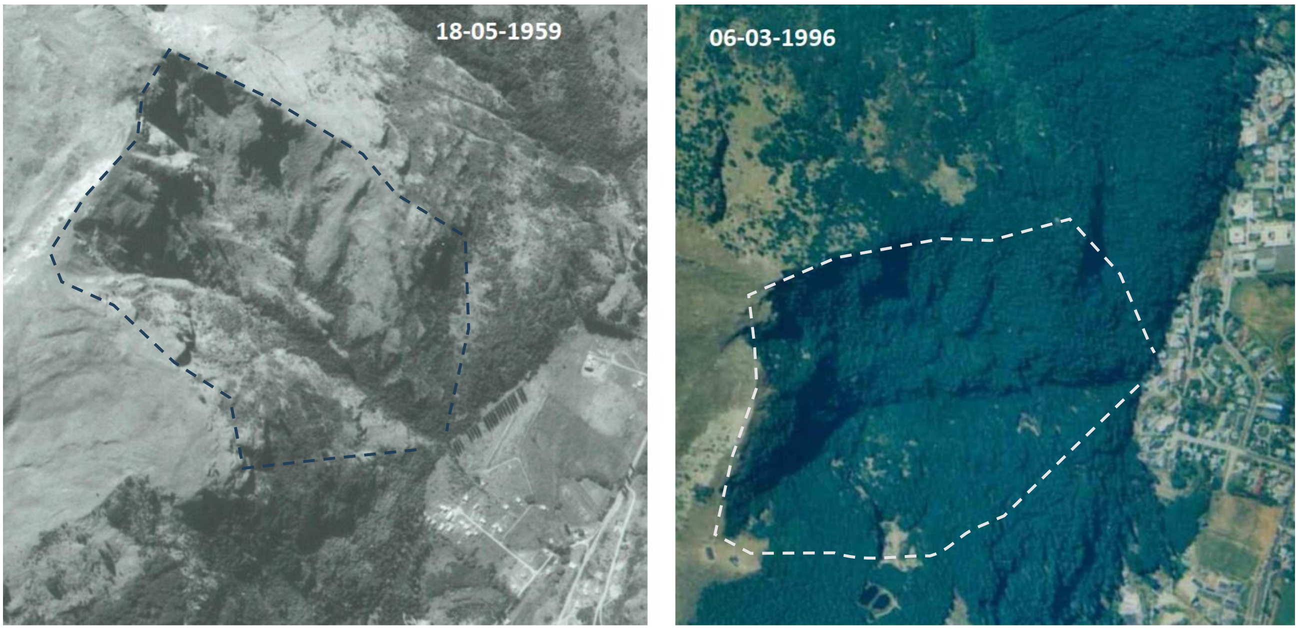


FIGURE 28: Historical Aerial Photographs of the Reavers Lane Catchment, Queenstown (approximately outlined). No clear evidence of landslides in the catchment over the approximately 40 years between the photographs and extensive vegetation growth in this period would suggest a Low Catchment Activity. Figure modified from ORC (2011).

FIGURE 29: Matata Catchment Activity – Aerial imagery review: The large majority of the catchment is well vegetated (right), but there is evidence for a number of active or recent landslides within the catchment (left), possibly suggesting a Moderate Catchment Activity.

FIGURE 30: Boundary Creek watershed and alluvial fan, eastern side of Lake Hawea. Numerous, well defined, actively producing source areas are apparent in the catchment, suggesting a Very High activity characteristic (as per Table 10.). The Alluvial fan appears to have active deposition in the main channel, and several inactive channels to the true right (looking downstream) of the main channel, suggesting a Moderate or High activity characteristic. An overall hazard level of High to Very High results for the entirety of the fan. Image from Google Earth.

FIGURE 31: Coalescing Alluvial Fans, Matukituki Valley, West of Wanaka. Various fan activity states are apparent, ranging from active avulsed channels (Very High, VH) to partly vegetated areas with inactive channels (Moderate, M) to areas of quite mature vegetation (Low, L). Image from Google Earth.

7.3 HAZARD ASSESSMENT

Where the high-level assessment described in Section 7.2 indicates that relative debris flow hazard levels are likely to be Moderate or higher, or the consequences of a debris flow may be Significant or more severe, a more detailed assessment of the hazard and risk may be required. This typically would involve assessment of the following:

- **Detailed characterisation of the debris flow hazard** (i.e. volume, peak discharge, flow depth, flow velocity, runout distance and extent of inundation) **Section 7.3.1**
- **Estimating debris flow frequency / magnitude relationship** (via the establishment of debris flow scenarios). Larger flood or debris flow events will, in general, inundate a greater area of the alluvial fan but occur less frequently. Estimating the frequency / magnitude relationship for a debris flow catchment can require significant investigation, analysis and associated cost. **Section 7.3.2**
- Assessing the **Probability of Travel / Spatial Probability of Impact** reaching the element at risk. This is typically assessed using numerical modelling, supported by observation of the distribution of debris flow deposits and geomorphic features on a debris fan. **Section 7.3.3**
- Assessing **Spatio-Temporal Probability** requires an understanding of the elements at risk such as current or future development, infrastructure, and importantly the population at risk (e.g. Strouth et al, 2024); i.e. Identify, characterise, and map the elements at risk. **Section 7.4.4**
- Assessing **Vulnerability**, based on debris flow intensity, which in turn is potential debris flow depth, velocity, and density at the point of impact on the various elements at risk. **Section 7.4.5**

The following section provides further details to assess parameters that are part of semi-quantitative and quantitative risk assessment process. Our strong recommendation is to estimate volume and peak discharge based on field evidence where possible. Where this is not possible, the volume assessment and empirical relationships as provided in the following sections could be used as proxies.

7.3.1 DEBRIS FLOW HAZARD CHARACTERISATION

The following sections provide selected references and empirical relationships to further characterise the debris flow hazard. Jakob et al. (2022) provides provide a comprehensive methodology to assess debris-flood hazards with the goal of developing a consistent approach, allowing for better input to quantitative risk assessments and the selection of appropriate mitigation measures.

7.3.1.1 Flow Volume

As defined by Jakob (2005) debris flow volume is defined as the total amount of inorganic and organic material and water transported past a specific point of reference (usually the fan apex). It is a combination of the three components:

1. The volume of the initiating failure or failures;
2. The volumes entrained along the zone of transportation by bank scour and erosion; and
3. The volumes deposited along the zone of transportation as lateral levees and avulsion flows. This volume is usually much less that the volume entrained.

Estimates of Initiating Volumes

Debris flow volume can be estimated from:

a. recent events where the dimensions of the deposit are measured in the field
b. if debris flow deposits on a fan are visible on historic air photographs, the debris area can be related to debris flow volume (Griswold and Iverson, 2008).
c. if test trenching and C14 dating has been completed at various locations on the fan, volume ranges can be estimated of past debris flow events.

Landslide scar areas can be measured on air photos, orthoimagery, or remote sensing data, or in the field, and average depth can be estimated. One problem associated with the use of aerial photos is the inability to capture small failures hidden under a dense tree canopy; numerous small failures can contribute greatly to sediment recharge in steep watersheds. LiDAR is very helpful in these situations.

A challenge in estimating the volume of individual landslides is to determine which failures occurred in a specific event. Multiple failures are common in large rainstorms and may be able to be gauged based on historical records, airphotos and satellite imagery to help constrain the dates of occurrence. This also becomes very helpful to review the climatic conditions at the time of failure.

Entrainment of debris and yield rate

Debris flows incorporate (entrain) sediment and other materials from their surroundings as they move. Entrainment can significantly increase the flow's volume, density, and therefore destructive potential. Debris entrainment involves a combination of:

- Bed destabilisation and erosion.
- Instability of stream banks undercut by bed erosion. As described by Hungr et al (2005) steep stream and gully channels are actively incised, leading to banks in a state of marginal equilibrium easily disturbed by bed lowering, often during debris flow surges. This can cause immediate shallow landslides into the surge or delayed releases that contribute material for subsequent surges.

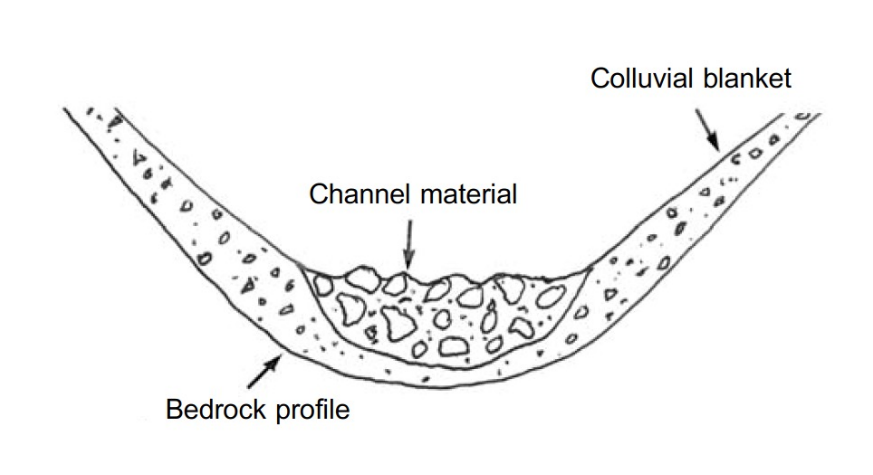


FIGURE 32: Schematic diagram of an eroded vertical cross section of a debris-flow channel (Hungr et al, 2005)

The yield rate (Y_i) is defined as the volume per metre of channel length (Hungr et al, 2005). The channel system of a debris flow watershed is divided into channel 'reaches' that are approximately constant in terms of the following parameters:

- Channel slope angle;
- Existing channel dimensions (width and depth);
- Bed material;
- Bank slope angle and height;
- Bank slope material; and
- Tributary drainage area or discharge.

Once the applicable yield rates are estimated, the debris flow magnitude V can be estimated by:

$$V = V_{initial} + \sum V_{point} + \sum_{i=1}^{n} Y_i L_i$$

Where:
$V_{initial}$ is the initial volume of the debris flow released from the main source areas
V_{point} are the volumes from other point sources (tributary channels, secondary failures etc)
L_i and Y_i are the length and yield rate of *n*-channel reaches

While the concept represented by the formula above is simple, several problems need to be resolved, as follows:

1. The optimal number of tributaries to include in the debris flow channel summation varies. Some debris flows impact only one branch, while major storms can mobilise nearly all tributaries in the drainage system (although this rarely happens).
2. The angle at which substantial erosion ends and the slope at which deposition begins needs to be determined (they may not be the same point). Depending on the magnitude of the debris flow, the material within the flow and water content, the depositional slope may be as low as 2° to over 30°. What the appropriate angle is will need be assessed based on site observations.
3. Estimation of the yield rate itself. Some channels and gullies form in low-erodibility substrates like bedrock or compacted soil. In these channels, bedload material and colluvial wedges at stable banks are temporary and likely to be eroded by strong debris flow surges. The volume of debris in low-erodibility channels can be estimated visually, but assessing yield rates is more challenging and subjective in channels with erodible bases due to difficulties in judging sediment depth and changes in particle size.

For all these reasons, a comprehensive site walkover (fan and channel) should be completed to gather this data. Where a full channel walk is not possible or practical, representative measurements in lower reaches should be estimated based on field observations and used to correlate estimates for all channel reaches in a catchment.

Table 11 provides some yield rates for various channel types which are defined in terms of bed gradients, channel bed and side slope materials. The table was developed for British Columbia but is expected to remain relevant to New Zealand conditions.

Table 11. Typical yield rates in relation to channel types developed for British Columbia (Lo, 2000; originally presented in Hungr et al, 1984).

Channel Type	Channel Gradient	Channel Bed Material	Side Slope	Stability Condition[1]	Channel Debris Yield Rate[2+] (m^3/m)	Erodibility Coefficient ($m^3/m/km$)
A	20°-35°	Bedrock	Non-erodible	Stable, practically bare of soil cover	0-5	0-5
B	10°-20°	Thin debris or loose soil over bedrock	Non-erodible (bedrock)	Stable	5-10	5-10
C	10°-20°	Deep talus or moraine	Less than 5m high	Stable	10-15	10-15
D	10°-20°	Deep talus or moraine	Talus, over 5m high	Side slopes at repose	15-30	15-30
E	10°-20°	Deep talus or moraine	Talus, over 20m high	Side slopes practically unstable (landslide area)	Up to 200 (considered as point source)	Not applicable

Legend:
*Prior to the expected debris flow event
+For catchment areas of 1-3 km^2. For larger catchment areas, refer Section 4.3.2 of Lo (2000).

Empirical Estimates

Figure 33 provides a summary of a number of empirical relationships that have been developed relating catchment area to debris flow volume for granular debris flows. As can be seen in the relationships shown by Marchi et al (2019), significant variation is apparent between the 50th percentile and 99th percentile volume estimate, with all other relationships located between these two. Which relationship is more appropriate to adopt depends on the intended analysis:

- For risk assessment purposes, volumes closer to the 50th percentile may be appropriate.
- For design purposes, it is suggested volumes towards the upper end of the range (closer to the Marchi et al 98th or 99th percentile relationships) are adopted.

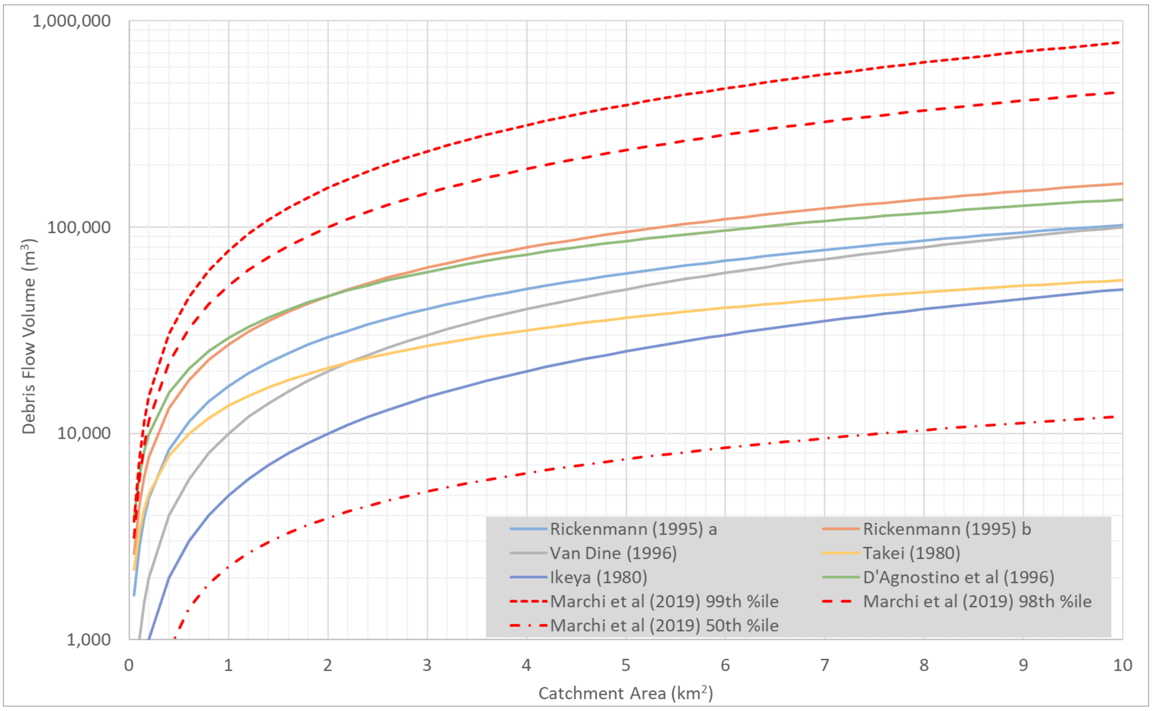


FIGURE 33: Empirical Relationships between Catchment Area and Debris Flow Volume

Gartner (2014) provides a predictive model used to estimate volume of debris flow with independent variables for rainfall intensity, watershed morphology (area and relief), as well as increased erosion due to loss of vegetation. This model was specifically developed to model loss of vegetation due to wildfire and therefore is useful where there has been a change in vegetation within the catchment.

$$\ln V = 6.07 + 0.71\ln(i60) + 0.22\ln(Bt) - 0.24\ln T + 0.49\ln A + 0.03\sqrt{R}$$

Where
V= mean volume of sediment (m^3)
*i*60 = peak 60-minute rainfall intensity (mm/h) for a given return period
Bt = the total area of watershed burned by most recent fire (km^2)
T = the time since the most recent fire (years)
A = the watershed area (km^2)
R = the relief (m) (maximum change in elevation upstream of the watershed outlet (i.e. the fan apex).

The model does not have a limit for the time since the most recent wildfire, and the effect of this variable can be minimised by selecting a small area affected (Bt) and a long period since the fire (T). Note the equation presented by Gartner is calibrated to Southern California. Scaling factors may be required to apply in other regions. For example, in British Columbia a scaling factor of 0.25 to 0.5 is applied for coastal, granular debris flows (BGC, pers comm.)

7.3.1.2 Peak Discharge

Knowledge of the peak discharge and the associated flow velocity is important when evaluating the conveyance capacity of stream channel reaches or critical cross-sections, such as those under bridges. This information is also crucial for sizing conveyance, inlet and outlet structures, culverts, and similar infrastructure. Figure 34 from Ikeda et al. (2019), plots debris flow peak discharge versus debris flow volume from a predominantly Japanese dataset.

The data in Figure 34 can be generalised using the following formula (Ikeda et al., 2019)

$$Q_p = \alpha \cdot M^{0.833}$$

Where
Q_p = the debris-flow peak discharge [m^3 /s],
M = Debris flow volume [m^3], and
α = tends to approximate 0.01 if the debris flows are muddy but approximate 0.1 if the flows are granular.

Mizuyama et al (1992) provide similar formulae as follows.

For granular debris flows:

$$Q_p = 0.135 \cdot M^{0.78}$$

For muddy debris flows:

$$Q_p = 0.0188 \cdot M^{0.79}$$

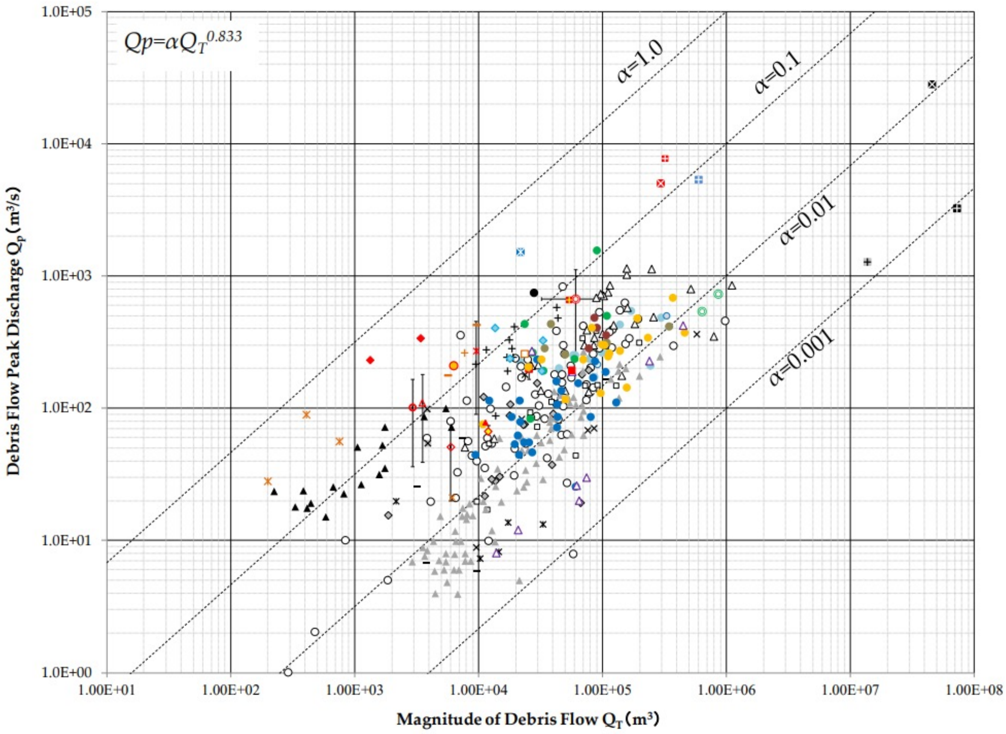


FIGURE 34: Peak discharge (Q_p) of debris flows vs debris-flow volume (Q_T: equivalent to M); (Ikeda et al., 2019).

7.3.1.3 Flow Depth

The flow depth is considered to be the vertical thickness a debris flow as it moves down a slope or through a channel. In general terms, the flow depth is dependent on the discharge and confinement, meaning flow depths are typically greater for debris flows that are confined by steep gullies or incised channels.

For design of debris flow barriers described by Volkwein et al. (2011), the flow depth h is calculated as a function of the channel width and the peak discharge.

$$h_{fl} = \frac{Q_p}{v \cdot b_u}$$

$$(h_{fl\,d} = 0.1\,m - 3\,m)$$

Where:
Q_p = Design debris flow discharge
b_u = bottom width of barrier section
v = velocity
h_{fl} = flow depth (h_{fld} = design flow depth)

For estimation of flow depth for debris flows that are not confined by topography or have avulsed from their channel, b_u should be considered based on previous channel widths evident from a morphological assessment of the debris fan.

Flow depth can also be back-calculated from the equations of, for example, Van Dine or Volkwein (Section 7.5.1.4).

7.3.1.4 Flow Velocity

The velocities of debris flows vary widely, due to differences not only in the character of the debris such as grain concentration and grain size distribution, but also in the shape of the channel such as its width, slope, etc. Most of these equations apply to the channelised section of the debris flow system: velocities when the flow becomes unconfined will be less.

A number of empirical relationships have been developed relating velocity to peak discharge as follows:

Rickenmann's (1999) general equation:

$$v = 2.1 Q^{0.33} S^{0.33}$$

Where Q is debris flow discharge (peak or otherwise) S is the channel slope.

Volkwein et al., (2011) suggests a very similar equation:

$$v = 2.1 \cdot {Q_p}^{0.34} \cdot {I_s}^{0.2}$$

Where:
v = velocity at the front of the flow
Q_p = peak discharge
I_s = tangent of the slope inclination in degrees

Moase (2017) provides a number of empirical formulae as provided in Figure 35 to calculate velocity and notes that calculation of channel dimensions is an iterative process, because the channel capacity depends on the velocity, and vice versa.

$v = \frac{1}{n} R^{2/3} S^{1/2}$	Manning's equation
$v = \frac{1}{n} h^{2/3} S^{1/2}$	PWRI, 1988
$v = 2.1 Q^{1/3} S^{1/3}$	Rickenmann, 1999
$v = \frac{2}{3} \xi h^{3/2} S^{1/2}$	Hungr et al., 1984
$v = 0.35 h^2 S + 5.36$	Prochaska et al., 2008

where

n is the pseudo-Manning's coefficient ($s/m^{1/3}$)[2]

R is the hydraulic radius ($R = A/P$) (m)

P is the wetted perimeter (m)

S is the slope of the bed (m/m)

h is the maximum flow depth (m) and

ξ is a coefficient that depends on grain size and grain concentration ($s^{-1}m^{-1/2}$)[3]

[2] From Rickenmann (1999), $n = 0.077 Q^{1/15}$. Considered a pseudo-Manning's coefficient in debris-flow hydraulics, because it depends on the flow properties, in addition to the channel roughness.

[3] From Rickenmann (1999), $\xi = 150 Q^{-2/5}$.

FIGURE 35: Empirical Methods to Calculate Velocity (Moase 2017)

Manning's roughness coefficient reflects the roughness of the channel surface, which affects how smoothly water flows. The rougher the surface, the higher the resistance to flow, leading to a higher value of (n). As indicated by Volkwein et al (2011), the pseudo-Manning values typically lie between 0.05 s/m$^{1/3}$ and 0.18 s/m$^{1/3}$, while the values for granular debris flows lie between 0.1 s/m$^{1/3}$ and 0.18 s/m$^{1/3}$

Alternatively, VanDine (1996) suggests the following relationship which considers the shape of the channel. This is a useful equation as the effect of widening the channel, or altering the channel gradient, can be estimated (Refer Section 8.6).

$$v = \frac{\gamma \sin\theta \, h^2}{l \, V}$$

Where:
θ = channel gradient
h = flow depth (m)
ϒ = unit weight of debris mass (kN/m^3)
V = dynamic viscosity of debris mass (k-Pa.s.; values as outlined in Table 1)
l = a constant based on the cross-sectional shape of the channel (3 for a broad channel, 8 for a semi-circular channel)

Estimating Velocity based on Superelevation and Bend Geometry

Superelevation refers to the difference in surface elevation, or banking, of a debris flow as it travels around a bend. Higher velocities result in increased banking. If the bend geometry is known, flow velocity can be estimated from superelevation or vice versa (Prochaska et al., 2008).

Based on the results of large-scale flume experiments, back-calculation using superelevation measured in the field for a recent debris flow event may presently be the most accurate way to estimate debris flow velocity (Iverson et al. 1994). Having stated this in natural environments, there is significant uncertainty in estimating superelevation and radius of curvature, which makes the application of this methodology more difficult. The most commonly referenced method for making this estimation is the forced vortex equation (from Prochaska et al., 2008).

$$v = \sqrt{\frac{R_c g}{k} \frac{\Delta h}{b}}$$

Where:
v = mean flow velocity (m/s),
R_c = the channel's radius of curvature,
g = acceleration of gravity (m/s^2),
Δ*h* = superelevation height (m) (Figure 39),
k = correction factor for viscosity and vertical sorting, and
b = flow width (m) (Figure 39).

Prochaska et al. (2008) indicates "The vortex equation was originally derived for water, and thus, the correction factor k is sometimes applied to account for the viscosity and vertical sorting of particles within debris flows (Hungr et al. 1984). Different studies suggest different values for k in order to match experimental superelevations to theoretical values. Suwa and Yamakoshi (2000) mention that k is usually greater than or equal to 1. VanDine (1996) stated that k may vary between 1 and 5. Hungr et al. (1984) reported that k may vary between 2.5 and 5.

It is therefore suggested that it this equation is used, the sensitivity of velocity to k is assessed for values of k between 1 and 5 and checked for sensibility against other empirical relationships.

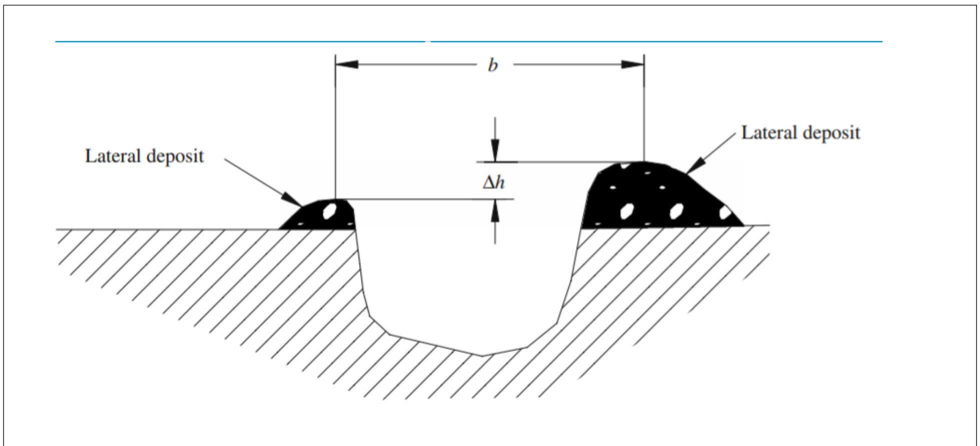


FIGURE 36: Measurements of Flow Width and superelevation height (Prochaska et al, 2008)

7.3.2 ESTIMATING DEBRIS FLOW FREQUENCY / MAGNITUDE RELATIONSHIP

Catchments may produce a range of magnitudes with associated probabilities of occurrence. Frequency / Magnitude (FM) estimation relates the volumes of mass movements (in this case, debris flows or floods) to specific return periods (or probabilities) for the range of events that are likely to occur; from the smallest events that can cause damage or injury to the Maximum Credible Event. Here, the Maximum Credible Event (or MCE) refers to the largest occurrence that can reasonably be expected, based on historical data, geological assessments, and modelling.

The probability of occurrence refers to single debris flow of a certain size; on other words, at one point on the FM curve. Estimating the probability of occurrence of a debris flow in a particular catchment requires consideration of a range of information, including:

- Historical evidence or reports of debris flows affecting the site.
- Geological or geomorphological evidence of debris flow deposits or geomorphic features typical of debris flows. Geological evidence can include an estimate of the rate of catchment erosion or alluvial fan deposition relative to geomorphic features of a known age (such as glacial features, alluvial terraces, or volcanic deposits).
- Subsurface records of debris flow units within an alluvial fan with or without dating information available.
- Surface dating of debris flow units or lobes on an alluvial fan surface.

Based on the available information frequency of debris flow occurrence can be estimated. The uncertainty in the resulting estimate can be large so the adequacy of the available information will need to be evaluated to determine whether the level of uncertainty is acceptable given the potential consequences of debris flows in the catchment / fan.

Establishing a reliable FM relationship is a core element of any hazard assessment but is subject to many uncertainties and may be difficult to assess as detailed records of debris flow events and their magnitude are rarely available. If the existing or proposed development on the fan or along a transport corridor is substantial, significant effort needs to be expended to obtain data from the deep past, which may extend to the beginning of the Holocene era (Jakob & Friele, 2009).

The frequency of smaller events may be able to be assessed via historical records, assessment of debris flow stratigraphy combined with dating processes, vegetation growth, etc. Where information is required

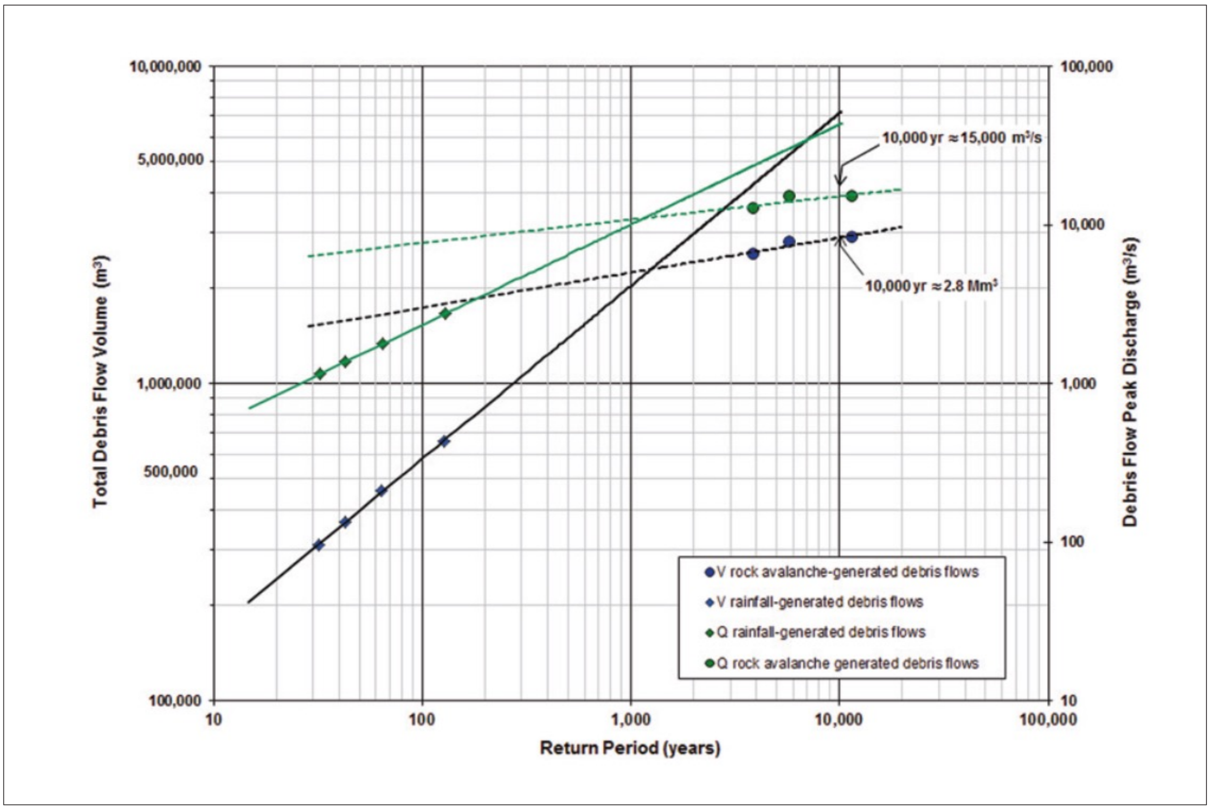


FIGURE 37: Example of Frequency/Magnitude (in terms of volume and peak discharge) relationships for debris flows on the Cheekye Fan, Canada (Jakob & Nolde, 2024).

from more than around 50 – 100 years ago, as will be the case most, if not all, of the time, several judgement-based assumptions will be required to develop the Frequency / Magnitude model. Care should also be taken where empirical and statistical predictive equations are used as a number of geological, geomorphological, hydrological, and land use factors may affect landslide initiation and magnitude which these equations might not take into account.

The total fan volume can be employed to constrain the Frequency-Magnitude (F-M) relationship in within the last ~15,000 years (ie post the last glacial maximum).

Debris Flow Scenarios

For risk assessment purposes, the spectrum of possibilities determined in the Frequency / Magnitude assessment can be divided into scenarios, each with a specific probability and corresponding flow intensity and flow distribution across the fan (Strouth et al, 2024). This variability can be incorporated into a risk assessment by breaking down the debris flow hazard into a set of scenarios that encompass the range of possible outcomes, as shown on Table 12.

The various scenarios outline the likelihood of different flow intensities at a specific element. The risk is calculated for each scenario and then summed to determine the total risk for the range of potential debris flow behaviours.

The scenario set should cover a representative set of credible and relevant cases that could occur across a range of debris-flow frequencies and magnitudes, but fewer scenarios are generally preferable to more (Strouth et al, 2024). The steps outlined in Table 12 can be followed to define scenarios. These are based on the Frequency / Magnitude assessment.

7.3.2.1 Dating Methods

Dating debris flows can either involve relative or absolute methods. Relative methods provide a qualitative sequence of ages of debris flow deposits without defining specific dates, while the latter estimate a fixed age or date range. Relative dating methods include

- Lichenometry. This technique utilises the fact that certain lichen species are slow growing and long-lived and grow outwards in a radial manner to form crust-like, circular patches (termed thalli) on rocks (Davies, 2022).
- Measurement of weathering rinds on surface boulders, on the assumption that the deeper the rind, the longer the boulder has been in place.

Absolute methods include:

- Radiometric dating techniques (e.g. radiocarbon, luminescence, Caesium-137).
- Dating of Tephra horizons (tephrochronology), where these exist.
- Biological dating techniques (dendrogeomorphology, lichenometry).

Table 12: Steps to Define Debris Flow Scenarios (modified from Strouth et al, 2024)

Step	Description	Considerations
1. Lowest Event (LE)	Identify the smallest debris-flow depth and velocity that could result in a loss to elements at risk. This is the smallest event that needs to be considered in the risk estimate	Based on Frequency / Magnitude assessment
2. LE Exceedance Probability	Estimate the probability of initiation of the smallest debris flow that could result in loss. This describes the probability of the smallest (most frequent) debris flow or any larger (less frequent) debris flow occurring	
3. Upper-Event: (UE)	Identify the maximum credible debris-flow, in terms of extent and flow intensity at the exposed element(s)	
4. UE Exceedance Probability	Estimate the probability of initiation of the maximum credible event	Avoid using an arbitrary value set by Acts or Standards to define the upper event.
5. Define Magnitude Classes	Divide the lower-event to upper-event range into magnitude classes. Use the fewest number of classes possible	Step changes or inflection points in the runout area and impact intensity value are useful markers for differentiating classes as are changes in triggering mechanism
6. Assign Incremental Probabilities	Calculate the incremental probability of each magnitude class	Addition or subtraction of individual classes must not change the total probability of a debris flow occurring, which is represented by the LE exceedance probability

Special features (scars, traumatic resin ducts etc.) and maturity of vegetation on the alluvial fan can provide important information on debris flow frequency (Kaitna & Huebl, 2013). In simple terms forest succession refers to the gradual replacement of one community of plants by another; from shade-intolerant species to those that tolerate shade. Where inundation has recently occurred, colony species such as Toetoe and bracken fern are the first to appear. These species are gradually replaced by species such as kamahi and rātā, which in turn are replaced with conifers such as Rimu and Totara in old-growth mature forest growth on the alluvial fan, suggesting the last destructive event in that area may have been several hundred years ago. Some further information on forest succession in New Zealand environments is provided in Appendix A, while an example of the differences in vegetation pattern is provided in Figure 38.

Jakob (2005) indicates that there are several areas of uncertainty in all dating methods, as follows:

1. A bias towards a higher frequency in the more recent past will likely exist, due to erosion of older geomorphological evidence
2. Debris flow frequency is not constant over long durations. Debris flow activity was likely much greater in the early part of the Holocene due to glacial retreat where large amounts of unconsolidated and unvegetated material was available for erosion.
3. Wetter conditions due to climate change may increase debris flow frequency in some watersheds.
4. Forest fires and human induced land use change (e.g. deforestation by clear-felling) can have a profound effect on both the frequency and magnitude of debris flows.

7.3.3 ESTIMATING PROBABILITY OF TRAVEL

The probability that a debris flow travels and impacts an element at risk depends on the volume of the debris flow and its probability of avulsion (in general terms, the larger the magnitude of the debris flow the greater the avulsion potential) and the location of the specific element. Initial estimates of the probability of travel can be assessed using the empirical formulae for runout distance and extent of inundation outlined in this Section. More detailed assessment would by necessity be based on geomorphic evidence of the fan (as outlined in Sections 3.3 and 4.3), supported by the results of numerical modelling.

FIGURE 38: Changes in vegetation type at Gunns Camp, Fiordland. The lighter vegetation, generally to the right of the active channel appears to be of similar size, and likely points to regrowth following a very large debris flow event. Darker, and taller vegetation to the left of the active channel is at least partly old-growth forest, suggesting hundreds of years since inundation in this area.

7.3.3.1 Runout Distance and Extent of Inundation

Runout distance varies considerably depending on the:

- Type of movement: fine grained (or muddy) debris flows tend to travel further than granular / bouldery flows
- Movement volume: larger volumes typically travel further, and
- Degree of confinement: confined flows travel further than unconfined flows.

A common empirical method to estimate the travel distance of a flowing landslide according to basic slope cross-sectional geometry is to assess the 'Fahrböschung' Angle (F-Angle; e.g. Mitchell and McDougall, 2019, refer also to Slope Stability Guidance, p.72). As an initial estimate the F-angles provided in Table 13 could be used. As the values provided in Table 13 are 10% passing, there is a 90% probability that the landslide debris travels less distance. These values should therefore be conservative and could be used as an initial 'look up' table to determine the likely furthest runout distances.

As an alternative, Rickenmann (1999), developed the following expression:

$$L_{max} = 1.9V^{0.16}H^{0.83}$$

Where:
L_{max} = the maximum runout distance (measured from the source area horizontally)
H = vertical height (m) from source area
V = Debris Flow Volume (m^3)

Rickenmann (1999) also provides the following relationship between the runout distance on the fan (L_{fan}) and volume:

$$L_{fan} = 15V^{1/3}$$

The area of inundation (*B*) provides a measure of debris flow mobility and potential consequences (Jakob, 2005). Bouldery debris flows will spread a smaller distance compared to muddy debris flows because the latter will spread over larger areas due to their high mobility. Jakob provides the following relationships:

$B_v = 200V^{2/3}$ for volcanic/muddy debris
$B_b = 20V^{2/3}$ for bouldery debris

7.3.4 ESTIMATING TEMPORAL PROBABILITY

When people or vehicles (like cars, buses, and trains) are at risk, or when building occupancy varies (e.g., between day and night, weekdays and weekends, or different seasons), it is important to consider the likelihood of people being in the area affected by debris flow. This is known as Temporal Probability.

For mobile elements at risk, temporal probability is the proportion of the year that a person, car, or bus will be in the affected area when the debris flow occurs. For buildings, it is the proportion of the year that the number of people considered to occupy the building or the area likely to be impacted.

Where appropriate, the temporal probability may account for the possibility that people might receive a warning and evacuate. While prior evacuation is a less likely scenario for debris flows due to their rapid speed, it can occur due to other precursors; in particular, evacuation because of intense rainfall. As an example, no fatalities occurred at Gunns Camp during the 2020 debris flow event. Even though the camp was occupied prior to the debris flow, it was evacuated due to flooding in the Hollyford River before the debris flow occurred.

Table 13. F-angles (°) for channelised flows and open-slope avalanches for different landslide volumes (from de Vilder and Massey, 2020).

Landslide Volume (m^3)	10%-Passing Fahrböschung Angle	
	Channelised Flow	Avalanche
10	22	38
100	18	36
1000	14	34
10,000	11	32
100,000	9	30
1,000,000	7	28

As a general rule of thumb, for a typical family home, a value of 0.67 can be adopted in most cases (Darren Paul, WSP Australia; pers comm). However, it is noted in Massey et al (2012) that a value of 1.0 was adopted for risk assessments associated with cliff collapse and debris avalanching following the Christchurch Earthquake Sequence, based on a 2010 UK study. It is therefore recommended that adopted values are discussed and agreed with relevant stakeholders.

7.3.5 VULNERABILITY ASSESSMENT

7.3.5.1 Assessing Vulnerability to Damage of Property and Infrastructure

As outlined in Part 6 of Unit 1, the degree of physical damage to property and infrastructure can be considered in terms of a 'damage state', which describes the amount of damage in relation to the ability of the building or infrastructure to function normally. In contrast, 'damage ratio' describes economic loss. It is calculated by dividing the cost to repair a damaged asset by the cost of replacing the asset (Massey et al, 2018).

Massey et al (2018) present two figures which compare debris flow velocity (Figure 39) and debris height (Figure 40) to damage state or damage ratio in regard to typical timber framed buildings construction. While Massey et. al. expresses some concern that there appears to be no obvious statistical relationship between the damage state and debris height or velocity for local and international data, these graphs remain very useful in assessing potential building structure vulnerabilities to debris flows and floods. For non-timber constructions, Kappos and Papanikolaou (2016) discuss four damage states ranging from 'DS1 negligible structural damage' to 'DS4 Collapse' for unreinforced masonry structures, while Burland (2012) considers six damage states (0-5) based on visible damage to brickwork or masonry walls (0 – Negligible to 5 – Severe).

Intensity Index
Developed as a method of determining building damage from debris flows, Jakob et al (2012) define Intensity Index (IDF) for building damage, as follows:

$$I_{DF} = dv^2$$

Where:
d = the maximum expected flow depth (m)
v = the maximum flow velocity (m/s).

The I_{DF} surrogates impact force and thus correlates with building damage. Four classes of building damage were considered by Jakob et al (2012), ranging from nuisance flood / sedimentation damage to complete destruction as indicated on Table 14.

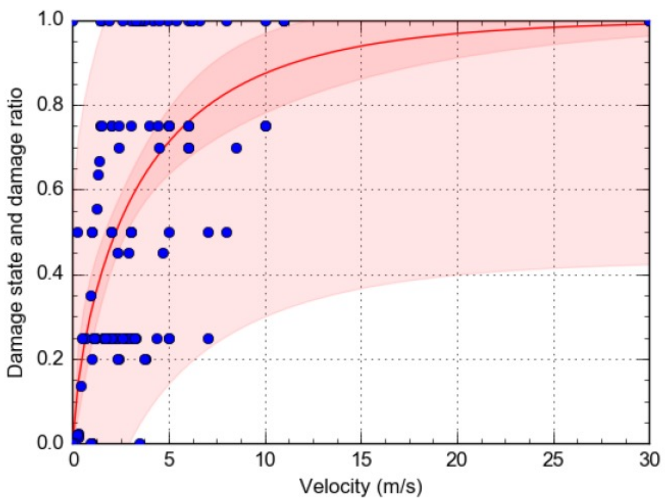


FIGURE 39: Residential Building Damage State v Debris Flow Velocity (Massey et al, 2018). The darker red and lighter red shaded areas represent the 1st standard deviation and 95th% confidence range respectively. Flow Height not considered in this graph.

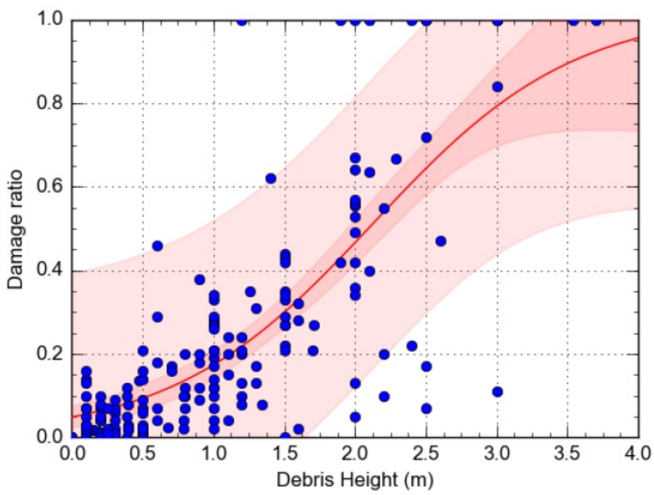


FIGURE 40: Residential Building Damage Ratio v Debris Flow Height (Massey et al, 2018). The darker red and lighter red shaded areas represent the 1st standard deviation and 95th% confidence range respectively. Flow velocity is not considered in this graph.

Table 14: Damage Class and definitions for impacts to residential buildings (modified from Jakob et al, 2012)

Damage Class	Damage Description	Typical I_{DF} (note 1)
Class I – Some Sedimentation	Sediment-laden water ingresses buildings main floor or basement, requiring renovation. Up to 25% insured loss	Less than 1
Class II – Some structural damage	Some supporting elements damaged and could be repaired with major effort; 25 – 75% insured loss	1 - 10
Class III – Major structural damage	Damage to foundation piles, pillars and will likely to require complete building reconstruction >75% insured loss	10 - 100
Class IV – Complete destruction	Structure is completely destroyed and/or physically transported from original location 100% insured loss	>100

Figure 41 show examples of these damage classes experienced during recent debris flows, and other rapid landslides in New Zealand. This is similar to Table 14, however includes a separation between light: non-structural damage and moderate: repairable damage at an I_{DF} of 2.0. Otherwise, values are the same between the figure and the table.

Estimating Probability of Damage from I_{DF}

Jakob et al (2012) provide a statistical distribution of I_{DF} in relation to damage class mostly based on residential buildings, reproduced as Table 15. For example, for very large values of I_{DF} (>1000), there is 100% chance that the impact will result in complete building destruction, whereas values of I_{DF} between 10 and 100 results in a 25% chance of complete destruction, 38% probability of major structural damage, 37% chance of some structural damage and little or no chance of sedimentation only. Note that Table 15 does not specifically consider the type of building construction and is based on limited data. Therefore, some level of judgement will be required with consideration to building type.

Notwithstanding, this distribution is useful as it provides a means of assigning a range of building vulnerability probabilities for risk assessment purposes. Event tree analysis would be particularly suitable should the risk assessment require the level of detail outlined in Table 15. Details of event tree analysis for debris flows are included in Strouth et al (2024) and the 2026 update to AGS (in prep) which should be referred to for additional detail.

Damage States	Description (Massey et al, 2018)	Rapid Landslides (Debris Flow and Rockfall)	Intensity Index (modified from Jakob et al 2012)
0	None: No damage.	Debris Flow/Avalanche stops short of building.	
<0.1	Insignificant: Minor non-structural damage.		Less than 1
0.1 – 0.25	Light: Non-structural damage only.		1 -2
0.25 – 0.6	Moderate: Reparable structural damage.		2-10
0.6 – 1.0	Severe: Irreparable structural damage.		10 – 100
1.0	Critical: Structural integrity fails.		>100

FIGURE 41: Examples of Damage States for Rapid Landslides, including Debris Flows (adapted from Slope Stability Guidance Unit 1)

Table 15. Damage Class Probabilities in research of Jakob et al (2012)

Damage class probabilities given I_{DF} (%) ALL DATA					
Class IV – Complete destruction	0	6	25	67	100
Class III – Major structural damage	0	22	38	28	0
Class II – Some structural damage	30	50	37	5	0
Class I – Some Sedimentation	70	22	0	0	0
I_{DF}	0-1	$1\text{-}10^1$	$10^1\text{-}10^2$	$10^2\text{-}10^3$	$>10^3$

7.3.5.2 Estimating Vulnerability to Life Safety

For life loss estimates, 'Vulnerability' refers to the probability that a person will be killed given that they are impacted by a landslide (in this case, a debris flow). The probability of loss of life is dependent on debris flow volume, velocity, and flow depth. De Vilder and Massey (2020) indicate that, for the small New Zealand data set, fatalities have occurred when the debris height exceeds typical window height (1.0 to 1.4 m) and / or when the load from the debris exceeds the load capacity of a wall of the building. For timber framed houses, de Vilder and Massey suggest this is typically between a debris height of 1.4 to 1.6 m and when the damage ratio to the building is >0.8. In the same document, de Vilder and Massey provide a summary of vulnerability ranges based on Hong Kong data. Pertinent ranges are reproduced in Table 16 for persons in buildings.

Alternatively, Pollock and Wartman (2020) suggest that for rapid landslides (>5 m/s), the probability of a fatality occurring varies greatly between around 0.2 and 0.8 as shown on Figure 42. Pollock and Wartman further indicate that at these flow depths, individual behaviour is the most significant driver: hazard preparation, situational awareness, and informed protective action such as moving to a higher floor or a prepared refuge space can dramatically increase the odds of survival.

7.4 RISK EVALUATION AND RESPONSE

Risk assessment involves evaluating risks and potential remedial options and mitigation measures to make informed decisions on the acceptability or adoption of the risks (de Vilder et al., 2024). General tolerability criteria are discussed in Section 3.1 of Unit 4 of the Slope Stability Guidance Series by de Vilder et al. (2024) and Taig et al. (2011) and thus are not repeated here. Specific asset owners may have tolerability criteria that differ from the values outlined in these references, and the geoprofessional should be aware of these differences. When applying risk-based performance criteria to assets or life safety, the following terms should be considered:

Table 16. Summary of Vulnerability ranges from Hong Kong data (Findlay et al, 1999 in De Vilder and Massey, 2020)

Location	Description	Population Vulnerability (Individuals)		
		Data Range	Recommended	Comments
Open Space	Struck by rockfall	0.1 – 0.7	0.5	May be injured but unlikely to cause death
	Buried by debris	0.8 – 0.1	1	Death by asphyxia
	Not buried but hit by debris	0.1 – 0.5	0.1	High chance of survival
Vehicle	Vehicle is buried/crushed	0.9 – 1	1	Death almost certain
	Vehicle is damaged only	0 – 0.3	0.3	High chance of survival
Building	Building collapse	0.9 – 1	1	Death is almost certain
	Building inundated with debris	0.8 – 1	1	Death is highly likely
	Building inundated with debris but person is not buried	0 – 0.5	0.2	High chance of survival
	Debris strikes building only	0 – 0.1	0.05	Virtually no danger

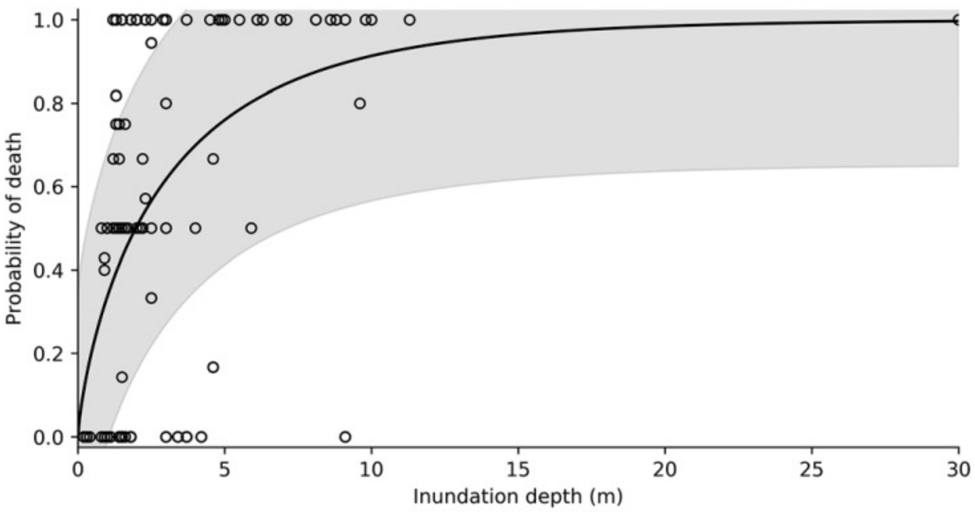


FIGURE 42: Human vulnerability to rapid landslides in relation to inundation depth. The grey shading represents +/- 1 standard deviation from the mean (black line). From Pollock & Wartman (2020).

Tolerable Risk: This is the level of risk that society is willing to accept in exchange for certain benefits. It represents a range of risk regarded as non-negotiable, subject to ongoing review, and should be reduced further where reasonably practicable (AGS, 2007).

Acceptable Risk: This is the level of risk that all affected parties are willing to accept. Typically, no further action is required to reduce the risk at this level (AGS, 2007). The threshold may vary depending on whether the asset is existing or newly proposed, as detailed in the Natural Hazard Risk Tolerance Literature Review published by the Earthquake Commission (2023).

So Far As Is Reasonably Practicable (SFAIRP): This is the extent to which a risk can be reduced As Low As Reasonably Practicable (ALARP) such that the measures (cost, time, effort) relating to the available ways of eliminating or minimising the risk are proportionate to the level of risk (Health and Safety at Work Act 2015). This approach prioritises implementing a risk reduction measure that can achieve a lower residual risk.

When a risk level is deemed unacceptable or falls within a marginally acceptable range, action must be taken to reduce the risks to tolerable levels. Risk management strategies include engineering interventions, community awareness programs, and dynamic monitoring systems designed to prevent or reduce the impact of debris flow events. Some of these mitigation options are outlined in Section 8.

8 DEBRIS FLOW MITIGATION

8.1 GENERAL

This section sets out a general methodology for the design of engineered debris flow mitigation within the context of the New Zealand environment and the New Zealand Building Code. As with all geotechnical engineering, the assessment of the hazard or failure mechanism is the most important aspect, and the better the understanding of the hazard is, the more effective the design will be at mitigating the risk that the hazard presents. It is assumed that in designing the mitigation, the potential geometry and parameters of the debris flow are well understood, including the level of uncertainty associated with those assumptions.

There are a range of mitigation strategies available for debris flows, as shown on Figure 43. In this document the terminology of engineered and non-engineered solutions has been used. These terms are subjective and for the purpose of this document simply provide a differentiator between building a physical structure (engineered) and, for example, avoidance of the debris flow (nonengineered). Non-engineered strategies for landslide hazard mitigation are discussed in Unit 4 and outlined in Figure 43 but are not repeated here in any detail.

In designing the mitigation, the whole debris flow system needs to be assessed, and the best options will likely include a combination of solutions including different structures and avoidance techniques, both upstream and downstream of the fan apex. Figure 44 shows how different mitigation strategies tend to be appropriate at different locations along the debris flow system.

8.2 DESIGN APPROACH

The recommended design process for debris flow mitigation measures is shown in Figure 45. Sections 4 and 5 of Unit 4 of the Slope Stability Guidance Series provide more detail of the general design approach for mitigation strategies for landslides, which should be referred to for more detail.

8.3 ENGINEERED MITIGATION STRATEGIES

As indicated in Figure 44, engineered mitigation measures for debris flows fall into one of two categories, although several types of debris flow control measures could be utilised together to form a 'functional mitigation chain'.

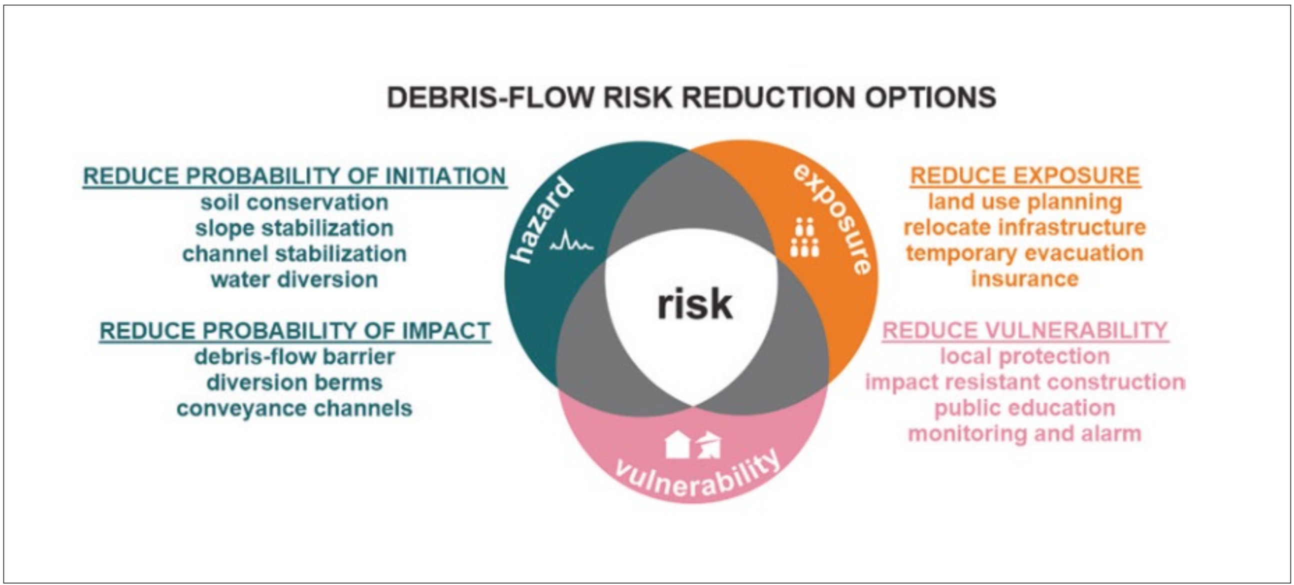


FIGURE 43: Risk reduction options (from Strouth et al. 2024)

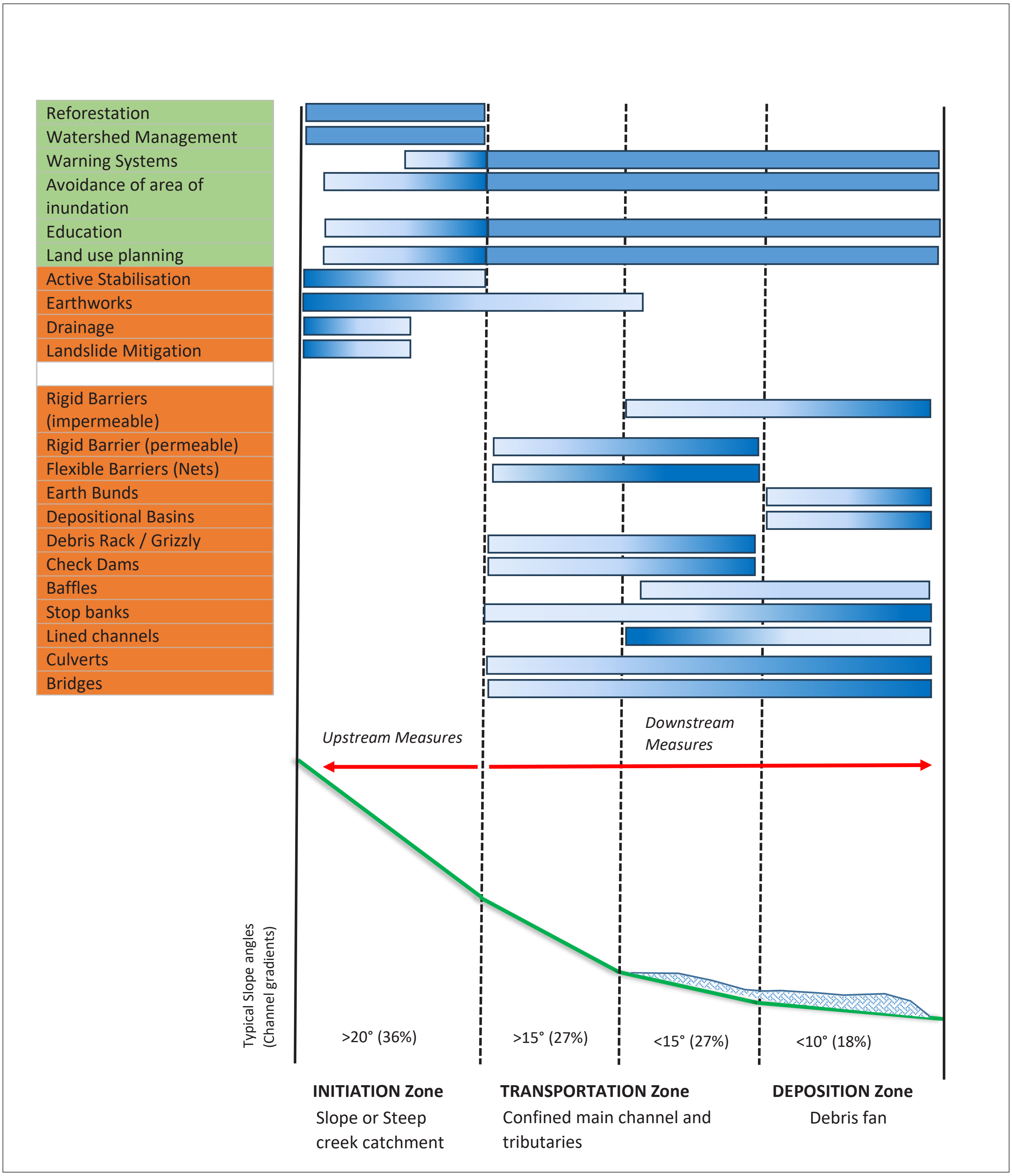


FIGURE 44: Applications of mitigation measures along catchment profile. The degree of shading broadly correlates with the appropriateness of the solution (lightly shaded; less appropriate; darkly shaded; more appropriate). Non-engineered strategies are highlight in green; engineered options in orange.

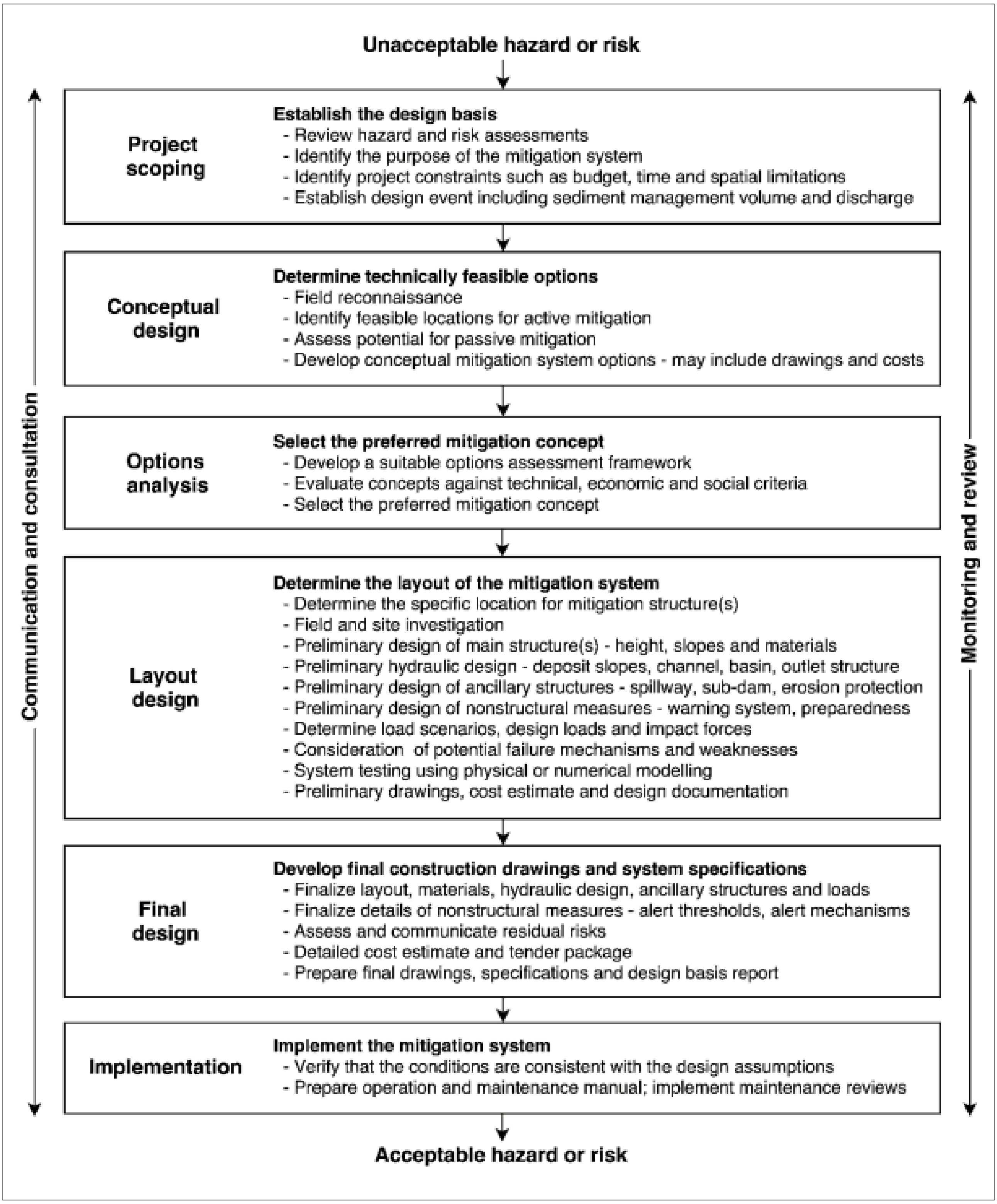


FIGURE 45: Mitigation Design Approach Flow Chart (Moase, 2017)

Upstream (Catchment) Measures mainly involve elements within the catchment that can reduce the potential for debris flows to initiate. This essentially means looking to manage the catchment itself, either by trying to limit the failure of material from the slopes or catching the material before it can be transported downstream.

In a New Zealand context, engineered measures in the catchment are less likely to be considered as they would likely require very extensive works in order to be effective, and as such are not likely to be cost effective. Where catchment measures are considered, such as landslide mitigation, anchored rockfall structures and earthworks, details of their design process can be found in Unit 4.

Downstream Measures (either within the Transportation Zone, on the Debris Fan, or both) seek to reduce the consequences of the debris flow hazard. In essence, downstream measures can be subdivided into:

- *Arresting Structures (Barriers).* These comprise structures built more or less perpendicular to the flow of the debris. The design intent of these structures is to halt (or partially halt) the flow across the span of the barrier. These types of structures can be designed with varying amounts of permeability from Check Dams (solid / rigid barrier) to debris flow nets and can either be installed individually or as part of a series along the transportation zone.
- *Flow Impediment Structures.* These structures are constructed to allow or partially allow the flow to deposit material. Impediment structures include depositional basins and debris training structures, including baffles, grizzly racks etc.
- *Deflection and Conveyance Structures.* These structures are constructed more or less parallel to the debris flow and are intended to deflect or convey the debris flow in a contained manner away from (including downstream of) the element at risk. These structures include lined channels, culverts and deflection berms.

Figure 46 shows an example of the use of multiple downstream measures on a debris fan near Kaikoura crossed by SH1 and the Main North Line railway.

FIGURE 46: Open Control Structures at Jacob's Ladder (a) lateral berm (b) depositional basin (c) large dimension culvert under the transport corridor for conveyance of residual flow. Photo courtesy NCTIR.

8.4 DESIGN CONSIDERATIONS

A debris flow control structure constructed on a debris fan must be specifically tailored to the characteristics of the debris flow, the nature of the debris fan, and the design intent of the mitigation. Consideration also needs to be given to the financial resources, materials, and equipment available for its design, construction, and maintenance requirements.

The design of any debris mitigation is an iterative process as in most instances several of the input parameters will need to be determined as part of the design process. Some of these parameters may also be subject to the budget available and the desired risk profile.

To improve certainty in design, the aspects listed in Table 17 should be considered.

Table 17: Design Considerations for the Design of Engineered Debris Flow Mitigation Structures

Potential Design Consideration	Reasons	Cross References
Frequency of occurrence	Watersheds that experience frequent debris flow are less suited to mitigation measures that require high levels of maintenance.	Section 7.3.2
Design magnitude or volume	Volume estimation is necessary when designing a containment structure as part of the mitigation solution. Van Dine (1996) defines the design magnitude as the reasonable upper limit of the volume of material that is likely [in relation to the design life of the structure] to be involved in an event. This can be considered as equivalent to the Reasonable Worst Case (RWC) rather than the Maximum Credible Event (MCE), Both events can be determined from an F/.M curve	Section 7.3.1.1, 7.3.2
Peak Discharge	Critical to sizing culverts, bridge crossings, and conveyance systems, as well as for designing deflection berms. Required in many empirical assessments to calculate flow velocity and depth.	Section 7.3.1.2
Maximum Discharge Velocity	Required to calculate the impact force of the debris on a structure as well as for the design of erosion protection measures.	Section 7.3.1.4
Flow Height, Runup Distance and Superelevation	Height requirements allowing for runup or pile up behind structure. When a control structure is located in the path of a debris flow its design height should be greater than the height of the potential run-up flow. Assessment of superelevation is important for structures parallel to the flow, where there are changes in direction	Section 7.3.1.3 and 8.4.5.4
Size and Grading of Debris	Estimates of the mean and maximum sediment sizes and timber fragments, and their grading characteristics need to be considered in the design of flow impediment structures.	Section 8.5.3.3
Runout Distance, Flow Paths and Area of Inundation	This is the primary factor to consider when planning development in the runout area of a debris flow. Once a channelised flow path reaches the debris fan, its flow path down the fan becomes difficult to predict.	Section 7.3.3.1
Impact Pressure	The design of many types of debris control structures should consider the potential impact forces, both dynamic thrust and point impact forces.	Section 8.4.5.1 – 8.4.5.3
Depositional (Storage) Angle	The depositional angle of the debris is important factor in both the design of depositional basins, and to dimension the spacing between check structures where these are used in series	Section 8.4.5.5
Topographic and Subsurface Conditions	Understanding surface and subsurface conditions is crucial for effective debris flow mitigation. Key considerations include: 1. Arresting Structures: Narrow, rocky channels for structures like flexible barriers or check dams are preferable. Consider the volume that can be retained. 2. Flow Impediment Structures: Broad areas with easily excavatable materials are ideal. Construct near the topographical apex to prevent outflanking by debris flow avulsion events.	

Sections 8.4, 8.5 and 8.6 outline the design considerations for more common engineered mitigation in New Zealand. This not to say that other mitigation solutions are not appropriate; however, these appear, in the author's experience, to be more used in a New Zealand context.

8.4.1 LEGISLATIVE REQUIREMENTS

The legislative framework governing civil infrastructure works in and around New Zealand's waterways involves national statutes, environmental standards, regional plans, and iwi management strategies. Engagement with a suitably qualified Planner is recommended as specific consenting requirements are likely to differ depending on regional policy statements and district plan requirements. Key legislative instruments include the following.

Resource Management Act 1991 (RMA)

The Resource Management Act 1991 (RMA) is the primary law for managing freshwater environments in New Zealand. It aims to ensure sustainable resource use while protecting air, water, soil, and ecosystems from harm. The Act regulates activities like water use, pollution, and alterations to waterways, with regional councils responsible for its implementation. In general terms, resource consent should be expected to be required as many mitigation solutions could be considered as having significant environmental impacts – particularly if temporary ponding or diversion of the stream, or modification to the stream's flow, bed, or banks is required as part of the mitigation solution.

National Policy Statement for Freshwater Management (2020)

The National Policy Statement for Freshwater Management 2020 (NPS-FM) is the main source of national direction for how councils should manage freshwater. The NPS-FM identifies that in-stream structures and works in waterways can adversely affect ecosystem health impacting fish and other freshwater communities. The NPS-FM sets out requirements to maintain or improve ecosystem health, mahinga kai (traditional foods, their sources and methods of gathering), and threatened species in freshwater ecosystems.

National Environmental Standards for Freshwater

The National Environmental Standards for Freshwater 2020 (NES-F), require regional councils to regulate activities that may impact freshwater and their ecosystems. The standards protect freshwater habitats and species, ensure fish passage, and safeguard mahinga kai for safe harvest and consumption.

8.4.2 BUILDING CODE CONSIDERATIONS AND CONSENT REQUIREMENTS

Whether or not Building Consent is required is subject to the local authority, the type of structure proposed, and the asset that the debris flow mitigation is protecting. It is likely that Building Consent or a Building Consent exemption will be required in most cases as the structures are likely to carry a significant consequence of failure.

Appendix A of the MBIE Guidance for Rockfall (MBIE, 2016) provides a comprehensive assessment of Building Code and Consent considerations for the design and construction of rockfall protection structures. Much of these remain relevant for debris flow protection structures. Particular aspects are summarised as follows.

- The design of a debris barrier would be considered as an alternative solution within the Building Code as it is not specifically covered within B1 Structure. One method to demonstrate compliance with Clause B1 of the Building Code is by adopting accepted design standards. These may include EAD No. 340020-00-0106, summarised in Berger et al (2021) Additionally, specifying a structure that complies with an internationally established quality and load testing system, can also help demonstrate compliance. EAD 340020-00-0106 references the Guideline for European Technical Approval ETAG 27 for rockfall protection kits, in this regard.
- As defined in AS/NZS1170, Serviceability Limit State (SLS) refers to conditions under which the debris flow protection structures remain functional and effective during normal conditions. Considerations here include:
    1. Minor deformations, maintenance of flow paths, and minor damage that does not affect overall performance.
    2. Limits on deflections and movements to ensure the structure continues to perform its intended function without significant maintenance.
    3. Ensuring flexible barriers or check dams do not sag excessively, maintaining clear flow paths, and preventing minor debris accumulation that could impede flow.
    4. Structures designed to SLS may need to withstand multiple impacts of the design event with limited to low repair. This may be applicable where the design event is relatively frequent.
- Conversely, Ultimate Limit State (ULS) pertains to the maximum load-carrying capacity of a structure before it reaches a point of collapse or failure. Considerations include:

1. Ensuring the debris flow protection structures can withstand large debris flow events without catastrophic failure.
2. Addresses the maximum load-carrying capacity and structural integrity under severe conditions.
3. Safety factors as defined in Section 8.3.3 and material strength to prevent collapse or significant damage during extreme events.
4. Designing barriers and check dams to withstand large debris flows, ensuring structures can handle the impact and volume of debris during rare, high-intensity events.
5. Structures designed to the MCE debris flow event correspond approximately to the ULS design load case.

8.4.2.1 Design Life

The design life of the structure should be considered carefully and agreed with the asset owner. Building Code Section B2 specifies the minimum durability periods for building elements, which are based on the building's intended life and how difficult the elements are to access or replace:

50 years: For elements that provide structural stability or for elements that are difficult to access or replace.

15 years: For elements that are moderately difficult to access or replace.

5 years: For elements that are easy to access or replace.

In the instance of a debris flow barrier the structure itself is designed to take impact and therefore the environment is dynamic. Defining a specific design life is therefore difficult as even minor impacts may compromise the durability of impacted elements, requiring replacement.

8.4.3 CONSTRUCTABILITY

Constructability issues for debris flow mitigation structures often revolve around the challenging terrain and environmental conditions where these structures are needed. The steep slopes and unstable ground typical of transportation zones in particular can make it difficult to install mitigations in this area (for example, nets or check dams). Ensuring the structural integrity and durability of mitigation measures under such conditions requires careful planning and design, installation of durable elements and robust maintenance. Access to the construction site can also be limited, necessitating the use of specialised equipment and techniques to safely and effectively build these structures.

8.4.4 SAFETY

As required by the Health and Safety at Work Act (2015), safety considerations must be incorporated into all stages of the design process. While Slope Stability Guidance Unit 4 provides much greater discussion in regard to Health and Safety by Design (HSbD) factors, general considerations for the design of debris flow mitigation structures include:

Location: Solutions which involve construction on the unconfined parts of the fan are likely to be preferable based on their lower construction risk compared to works in the confined stream channel. However, the reverse might be true from a Public Safety perspective, as works in the channel would presumably be harder to access.

Downstream Effects: Solutions which arrest, rather than convey debris flow material are likely to be preferable where there are elements at risk further downstream. Any mitigation must not increase the risk downstream, or to adjacent areas!

Debris Flow Hazard: Mitigation works are by their nature, located in, or in very close proximity to, debris flow hazards. Consideration needs to be given to decreasing the risk to the construction crew and all other involved parties following heavy rainfall or earthquake events. The use of a Trigger Action Response Plan (TARP; see for example Mason et al, 2018) is strongly encouraged.

8.4.5 MAINTENANCE AND CLEARANCE

Regular maintenance and inspection are essential to ensure that the structures remain effective and ready for future debris flow events. Debris flow mitigation structures are expected to be impacted over their design life. Replacement or maintenance of a number of components should be expected over the design life of the structure, depending on the type of mitigation. A maintenance schedule should be developed for each element of the mitigation solution considering:

1. **Routine / Regular assessments.** These are undertaken on a specific time interval (yearly or every second year) and principally focus on aspects such as:
    a. Vegetation clearance
    b. Maintenance of the designed flow path
    c. Inspection and replacement of damaged or corroded elements
2. **Post event assessments.** These events are undertaken following some triggering event. These events would obviously include any occurrence of a debris flow but could include some threshold rainfall or earthquake event. Such assessments would include all the items listed in 1 above but could also include observations of the catchment area to identify any evidence of (for example) landsliding, which may increase the debris flow hazard.

After a debris flow impact, cleaning out the accumulated material is crucial to restore the functionality of mitigation structures. This process typically involves the use of heavy machinery such as excavators and loaders to remove the debris. In some cases, manual labour may be required for more delicate or hard-to-reach areas. The removed material must be properly disposed of, or repurposed, depending on its composition and potential environmental impact. Planning for operations and maintenance from the beginning of the design process is therefore critical.

8.5 ARRESTING STRUCTURES

8.5.1 DESIGN INTENT

The characteristic feature of this type of protection is that the solids (including timber debris) of debris flows are retained while the water flows and finer sediment pass through the structure (Berger et al, 2021). Once the flow has abated, and time allowed for drainage to occur, debris can be physically removed from behind the barrier, and the barrier repaired as necessary.

Arresting structures are best located where the flow is confined such that it cannot be horizontally outflanked (noting that it may be overtopped). As such, these structures are best located within the transportation zone, or neat the apex of the debris flow fan.

8.5.2 DEFLECTION VERSUS LOAD

The impact of a debris flow on a barrier is an impulse load. In order to stop the debris, the barrier needs to have sufficient capacity to absorb the potential energy of the debris flow. Barriers can be designed to be very stiff (rigid) or more flexible. The more a structure can deflect or displace whilst stopping the debris flow, the less load the debris impact will transfer to the structure and its foundations.

8.5.3 FLEXIBLE BARRIERS

Flexible debris flow nets are now typically the most used mitigation for debris flows in New Zealand (see Figure 47). Several proprietary products are available which are sized in relation to impact pressure. Use of proprietary debris flow net systems is highly recommended. It greatly simplifies the design process, systems have been field tested, thereby reducing risk to all stakeholders (including the designer). It is further recommended that any proprietary systems being considered has been certified in accordance with EOTA standard EAD-340020-00-0106 or an equivalent standard.

At the time of writing, 'off the shelf' systems up to 22 m in width, 7 m in height, and able to sustain impact pressures of 180 kN/m^2 are readily available. However, the systems can be custom designed by the manufacturers for site specific conditions.

Flexible barriers have the advantage of having a relatively small footprint and can be installed relatively cheaply and expediently in comparison to rigid barriers. Their main disadvantage is that they may not have sufficient capacity to retain the volume or withstand the impact of the debris flow at larger volumes. Wendeler (2016) suggests ring nets are only suitable for volumes of debris less than 1,000 – 1,500 m3. Multiple nets may be able to work in series provided the channel geometry is suitable but this won't always be the case; for example due to access difficulties or property boundary constraints.

It is also notable that cleaning behind a flexible barrier presents significant challenges not only for access but also to be able to clean without damaging the ring net and many nets will need to be replaced after debris flow impact.

Debris flow volume, channel geometry, flow height, and impact pressure are key considerations when assessing the feasibility of flexible barriers for hazard mitigation.

Channel Geometry

Debris flow nets need to be constructed within an accessible area in which the flow is channelised as the nets are anchored up the walls of the channel. A choke point where the flow is restricted by natural features such as rock outcrops provides a good site as there is likely to be better conditions for anchoring and the length of the net is reduced compared to other parts of the channel. However, this may mean that the retained volume is reduced which should be carefully considered.

Flow Height and Impact Pressure

The expected flow height of the design event relative to the barrier height needs to be understood such that the barrier can be appropriately dimensioned, allowing for sag under load. The impact pressure as the barrier fills up and potentially overtops can be derived via the results of numerical modelling or the empirical formulae outlined in Section 8.4.5.1.

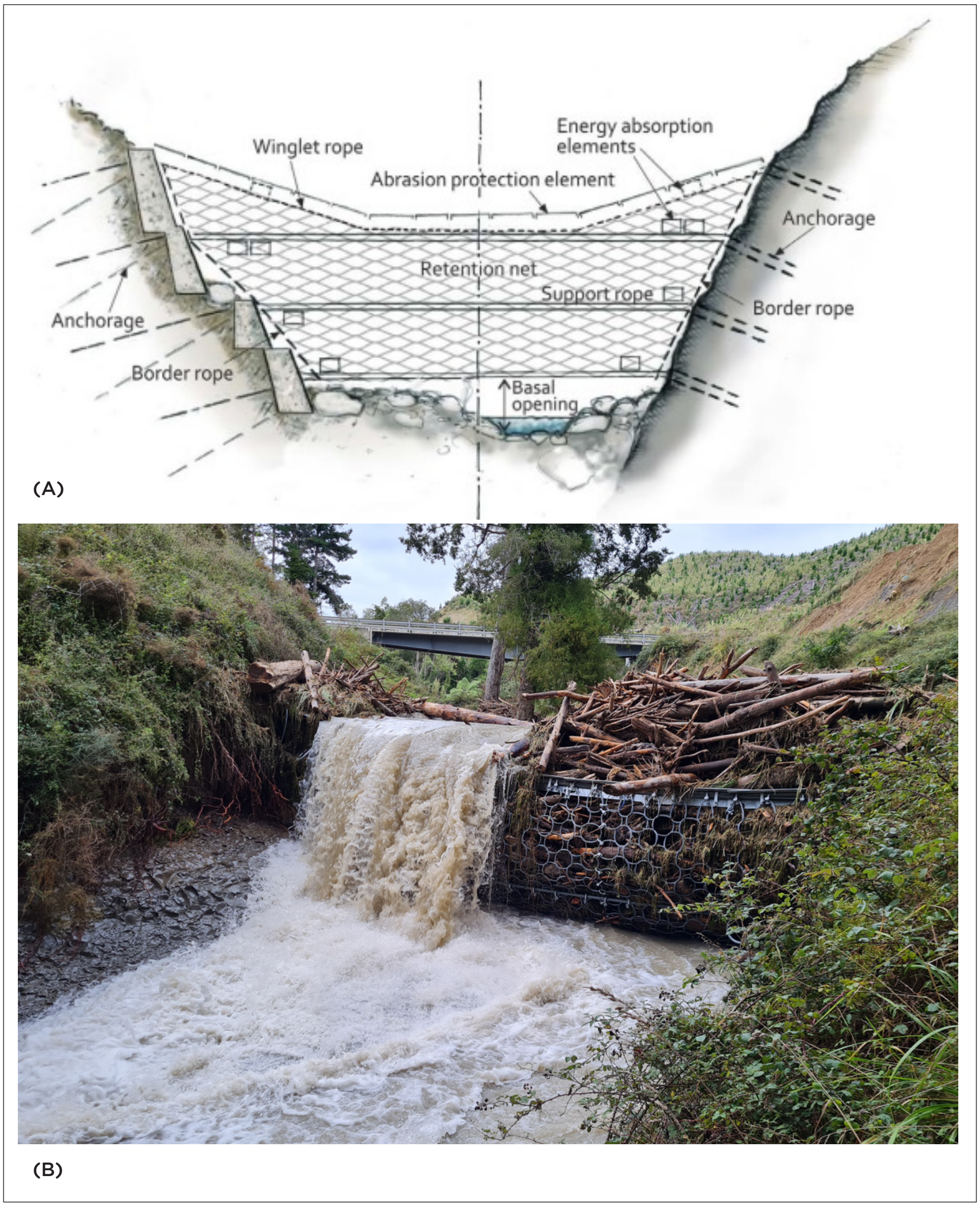


FIGURE 47: (A) Debris Flow Net Componentry (Berger et al, 2021).
(B) Slash / driftwood arrested behind a debris flow net near Napier (photograph courtesy of Geobrugg).

8.5.4 RIGID BARRIERS

Rigid barriers essentially comprise a one, or a series of, dams or check structures constructed in the transportation zone of the debris flow system. The primary design intent of rigid barriers is to either to intercept and retain debris flow material or to reduce flow velocity to minimise impact forces and encourage partial deposition. Rigid barriers are typically designed as **Check Dams** intended to trap sediment and reduce flow energy constructed across channels. Dams can be tiered to manage large volumes of debris and can be designed as either open or closed structures as follows:

- Open structures have openings or grids that allow water and smaller sediments to pass through and are designed to filter and control debris flow by trapping larger boulders and coarse material, but allow finer sediments and water to continue downstream, reducing the volume retention requirements.
- Close structures are built as solid barriers and are designed to block both water and sediment, in a sediment retention basin upstream of the structure.

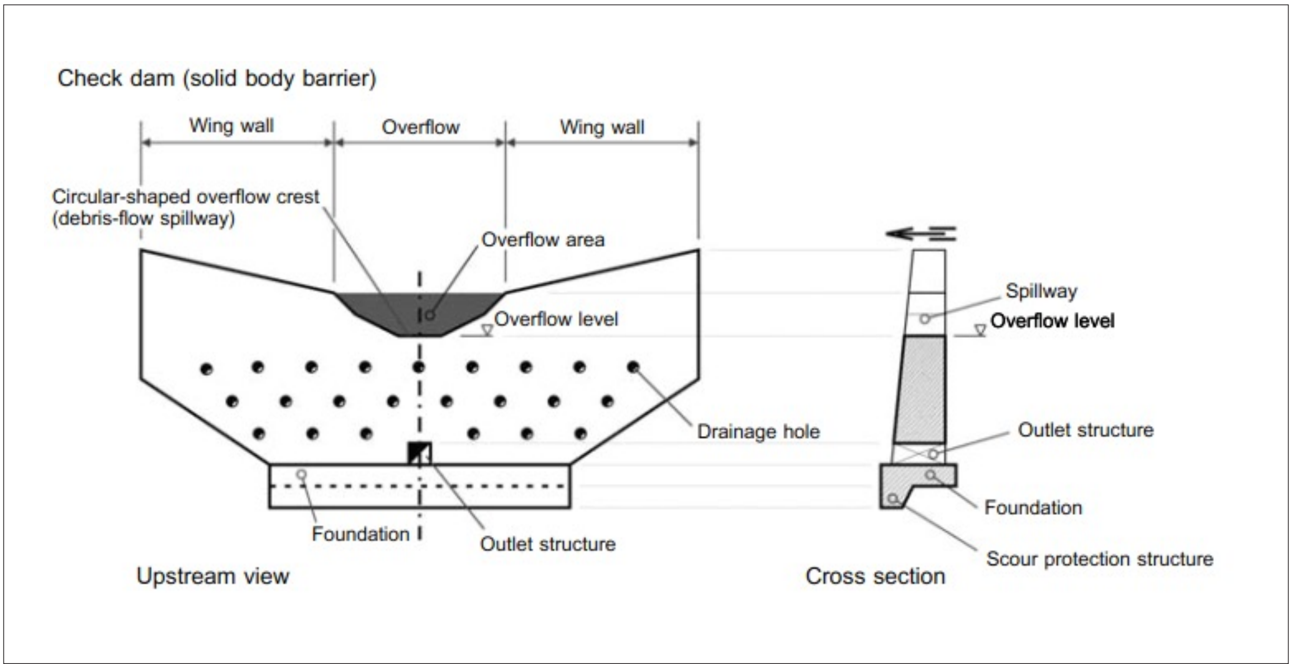


FIGURE 48. Sketch of typical check dam (Heubl and Fieberger, 2005)

Check dams require heavy reinforcement to withstand high impact forces generated on impact by the debris flow. They may include energy-dissipating features upstream like baffles or stepped surfaces

Steel and concrete rigid barriers have historically had relatively limited applicability in New Zealand. More commonly, barriers are formed using earth retention techniques such as earth, or mechanically stabilised earth, to form bund. These structures would likely require a larger footprint for the structure to be formed compared to steel and concrete. A composite structure that uses both earth or MSE bund combined with a traditional rigid barrier is also possible.

Some of the advantages of rigid barriers are their ability to store larger volumes of debris as well as easier cleaning and operations and maintenance compared to flexible barriers. Disadvantages include the high capital cost, large footprint, design time, Consent issues (particularly in regard to the requirements of NPS-FM and NES-F), and aesthetic concerns.

The stability of the debris-resisting barrier, including sliding resistance, overturning resistance and the induced bearing pressures, should be checked for the various design loading conditions, including allowances for debris flow runup against the structure. Downstream erosion protection should also be considered as described in Section 8.6.5.2.

Many of the design considerations for rigid barriers are similar to flexible structures, as described in Section 8.4.5. However, more detailed information on the design of these structures is provided in Piton and Recking (2016a; 2016b), Osanai et al (2010), among others.

8.5.5 DESIGN CONSIDERATIONS

Debris flow barriers, whether flexible or rigid are sized (or 'dimensioned' in European texts) by a consideration of pressure (rather than energy, which is commonly the case for rockfall), volume and flow height.

In general, the guidance within the Kwan & Cheung (2012) design note indicates that a debris flow is a relatively long mass of material being transported down the catchment or channel. Thus, the impact will be spread out over a longer time than just the initial impact which, from a loading perspective, is similar to the debris building up as a series of surges rather than one event as shown on Figure 49. Loading on barriers should therefore consider (i) dynamic impact load due to debris impact, and (ii) static load arising from the debris that have been stopped and deposited behind the barrier. If debris overflow is allowed, the corresponding drag force (iii) induced on the barriers should also be considered.

8.5.5.1 Dynamic Impact Pressure

From Kwan & Cheung (2012) and Sun et al (2005) the dynamic impact pressure of the first, and any subsequent debris surges can be calculated as

$$P_d = \alpha \rho_d v^2 \sin \beta$$

Where:
P_d = dynamic impact pressure (kN/m^2).

α = dynamic pressure coefficient. For flexible barriers, Kwan & Cheung indicate that this value should be taken as 2.0 for granular debris flows; for rigid barriers, 3.0 is suggested by Sun et al (2005). This coefficient is highly dependent on the makeup of the debris and how the debris behaves as a fluid. If the debris contains smaller particles and a lower ratio of debris to water, it is more likely to behave as a Newtonian fluid and the flow will be more laminar, therefore the impact force would be less.

Given the potential range of this value the impact force will be sensitive to this as an input.

ρ_d = debris flow density; suggested by Berger et al (2021) as 1,600 to 2,200 kg/m^3.
v = velocity of moving debris surge at the point of impact with the barrier (m/s). This velocity may differ between surges due to material accumulation behind the barrier. Debris flow modelling will inform this value. Typical values range from 1.0 to 15 m/s. Given the potential range of this value and that it is squared, the impact force will be extremely sensitive to this as an input.

Whilst channel geometry and gradient will affect the velocity it should be noted that, similar to α, the velocity is dependent on the makeup of the debris as this effects how the debris actually flows. However, the velocity and a are somewhat inversely proportional where a lower α value will typically indicate a higher velocity and vice versa. Therefore, it will likely be too conservative to adopt a high α value and a high velocity.

β = angle between the velocity vector of the debris flow and the surface of the barrier. For flexible barriers, this can be ignored as β becomes more or less 90°.

8.5.5.2 Static Pressure

Kwan & Cheung (2012) indicate that the static pressure of deposited debris can be determined as follows:

$$P_s = \frac{Kd\rho_s g}{\sin\beta}$$

Where:
P_s = static pressure of the deposited material (N/m^2)

K = coefficient of at rest earth pressure K0 for the debris material. Kwan & Cheung suggest a value of 1.0, however, this will vary depending on the expected makeup of the debris material and the time since being deposited (i.e. has the water drained from the material or is it overly saturated / entrained within the water).
d = depth of deposited flow (m), allowing for run-up
ρ_s = static debris flow density; suggested by Kwan & Cheung to be taken as 2,200 kg/m^3 as a minimum.
g = acceleration due to gravity (m/s^2)
β = angle between the velocity vector of the debris flow and the surface of the barrier. For flexible barriers, this can be ignored as b becomes more or less 90°. For rigid barriers, β will be 90° or greater.

8.5.5.3 Drag Force

Where overflow of the barrier could occur, drag force should be considered, calculated as

$$\tau = h\rho_d g \tan\phi_e$$

Where:
τ = the shear stress giving rise to the drag force (N/m^2)
h = thickness of the overtopping surge (m)
ρ_d = debris flow density; suggested by Berger et al (2021) as 1,600 to 2,200 kg/m^3.
$\tan\phi_e$ = coefficient of friction along the interface of the overtopping surge and the previously deposited debris
g = acceleration due to gravity (m/s^2)

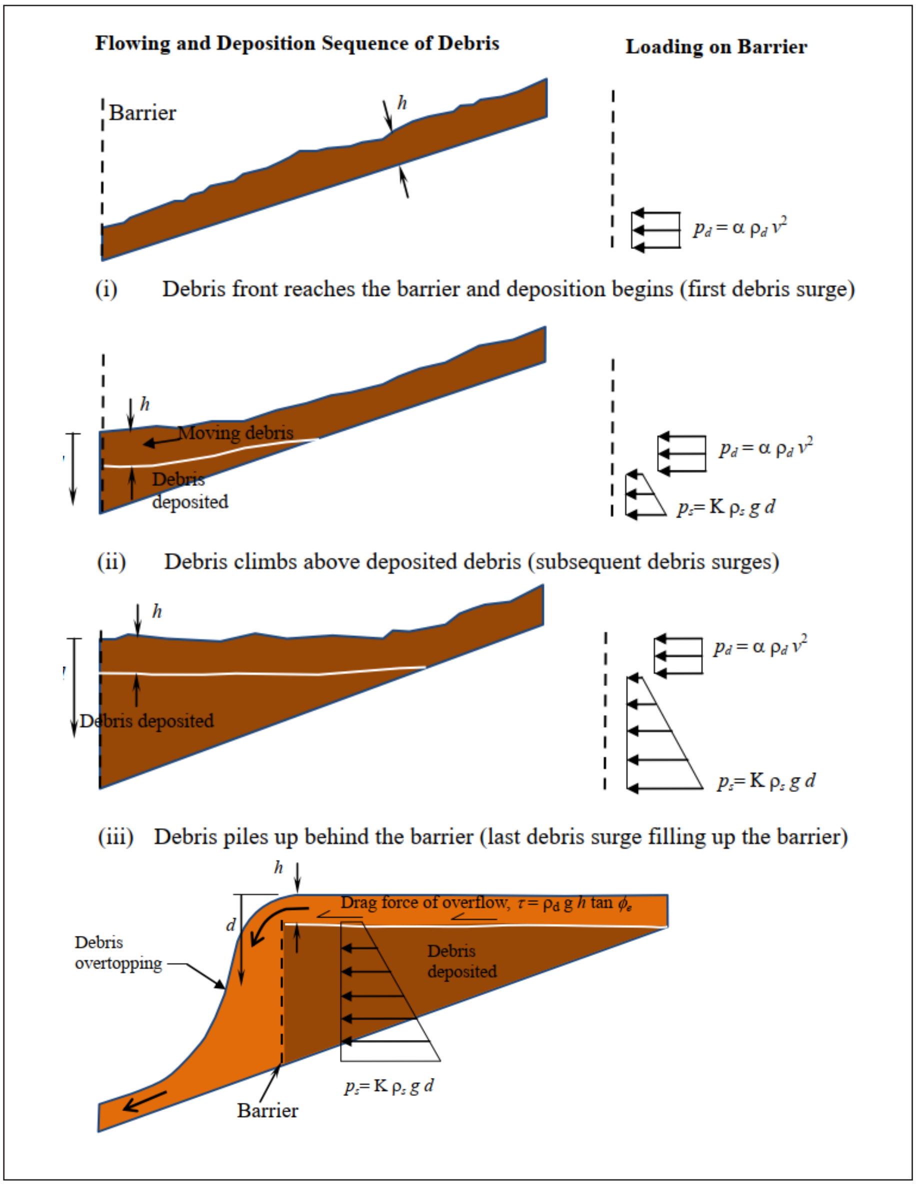


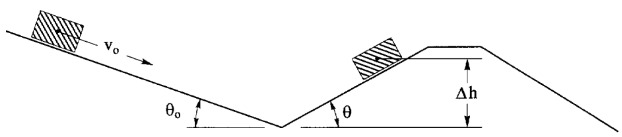
FIGURE 49: Typical debris slide accumulation and forces acting on a flexible barrier (from Kwan & Cheung, 2012)

8.5.5.4 Runup Distance

Run-up occurs where the front of the debris flow surge impacts and moves up the face of the barrier. Lo (2000) offers a number of formulae to assess the change in height of the top of the debris (Δh). The following equation, developed using a 'lumped mass' model is useful:

$$\Delta h = \frac{v_o^2 \tan\theta}{2g(\tan\phi_a + \tan\theta)}$$

Where:
ϕ_e = coefficient of friction of the debris: this considers the energy lost through friction.
θ = runup slope angle as shown on the following diagram (Lo, 2000)



V_o = debris flow velocity at point of impact

Calculating the run-up distance is likely to only be necessary when designing barriers for a single surge of material. It is more likely that the debris will continue to build up behind the barrier as indicated in Figure 50. In this case it is not necessary to account for the run-up distance.

8.5.5.5 Retention Capacity

The maximum retention capacity of a barrier is dependent on the channel slope, deposition angle and the height of the barrier (Volkwein et al., 2011). It is therefore important to carefully select the barrier's location to maximise the retention volume. Where a single structure is unable to provide sufficient volume, then a series of structures may need to be considered, allowing for overtopping.

To determine the storage capacity of a structure, it is necessary to determine the expected gradient of the deposit (Figure 11). The slope of the deposit is usually less than the natural channel slope, although the ratio between the two values depends on the hydraulic conditions. Moase (2017) indicates that it is standard practice in Japan, Europe and Hong Kong to use a design deposit slope between 1/2 and 2/3 of the existing streambed slope. Volkwein et al also indicate that several empirical studies suggest that the deposition angle corresponds to 2/3 of the channel gradient.

The slope angle of the deposited material is also more or less the angle of repose of the material. Observations of material and existing debris fans help inform this value.

8.5.5.6 Single Block Impact Force

Single large boulders entrained in finer grained material have the potential to cause significantly more damage than the matrix that carries it. Considerations vary depending on whether the arresting structure is flexible or rigid, as described in the following sections.

Flexible Barriers

The single impact of a block is usually only significant when the impact occurs directly on a support rope. Most of the kinetic energy of the block is transferred to the rope elongation energy, while a part of the energy is also absorbed by the energy absorption elements (Berger et al, 2021). Where proprietary systems are not used:

- The rope elongation and force on the ropes will need to be assessed as described in Section 1.2.1.2 of Berger et al; and
- If the support ropes are separated further than the design block size, a punching shear test may need be performed separately for the net.

Where proprietary flexible systems are used, these aspects do not need to be separately assessed as they will likely have been included as part of the design and certification process. However, it is recommended that this is checked with the manufacturer.

Rigid Barriers

Boulder impact should be considered on rigid barriers however, some equations (particularly the Hertz equations in Van Dine (1996) in Lo (2000)) produce unrealistically high forces. Kwan et al (2024) proposed an 'enhanced flexural stiffness method' that considers energy loss during an impact and the inertial resistance of the structure. The boulder impact force (F_B) can be expressed as

$$F_B = \sqrt{\lambda\left(\frac{1+COR}{1+\lambda}\right)^2 v_o\sqrt{mk}}$$

Where:
λ = mass ratio between boulder and barrier
COR = Coefficient of Restitution between the boulder and barrier. Kwan et al (2024) indicate that this can be taken as 0.3 between concrete and rock: steel to rock is assumed to be similar.
v_o = boulder impact velocity (m/s)
m = boulder mass (kg)
k = flexural stiffness of the structural member. Kwan et al (2024) indicate that for a cantilevered beam k can be determined as

$$k = \frac{3EI}{L^3}$$

Where:
EI = flexural rigidity (N/m^2) being the product of the modulus of elasticity (E) and moment of inertia (I)
L = Cantilever length to point of boulder impact (m)

8.5.5.7 Safety Factors

Load factors

For flexible barriers, Berger et al (2021) suggest that load factors are calculated based on an assessment of the 'risk' (their term as shown in Table 18) and the expected return period of the design flow event. Recommended load factors are provided in Table 19.

Table 18: Design Risk Classes according to potential consequences of failure and protected elements (adapted from Volkwein et al (2011) and Berger et al (2021)

Risk Class	Description
1	Broadly acceptable risks in terms of loss of life Low economic consequences[4] For protection measures for forests, alluvial zones and pastures
2	Tolerable risk potential in terms of loss of life Significant economic consequences For protection measures in the wide vicinity of settlements, roads and rail lines
3	Unacceptable risk potential in terms of loss of life Serious economic consequences For protection measures in the close vicinity of settlements, roads and industrial zones

Table 19: Load Factors considering risk class (Table 18) and expected return period

	Return Period of Design Flow		
Risk Class	1 – 30 years	30 – 100 years	Over 100 years
1	1.0	1.0	1.0
2	1.3	1.3	1.3
3	1.5	1.3	1.2

Capacity Reduction Factors
Volkwein et al (2021) recommend a safety factor of 1.35 for resistance (hence the capacity reduction factor = 1/1.35 = 0.74); however, when a capacity reduction factor is used in the design of resisting elements (as is the case for anchor design for flexible catch structures, for example) this appears to be a 'double dip' and can be ignored.

8.5.5.8 Other Considerations

Barrier Height
For flexible structures, the height of the barrier reduces during debris flow impact. The residual height h_b' is defined as the smallest distance between the upper support rope and the channel base or the lower support rope after a filling event of a debris flow protection net. Standard values for the residual height can be obtained from the system manufacturer but are typically between 60% and 80% of the undeformed barrier height. Volkwein et al (2011) indicates that the post-event barrier height can be typically assumed at about 3/4 of its pre-event height.

Ground Anchor Design
The pressure imparted on flexible barriers is ultimately resisted by a combination of braking elements and ground anchors. For proprietary systems (which are strongly recommended in this guidance) the manufacturer should be contacted for the design anchor forces. Ground anchors can then be designed based on these forces as outlined in Unit 4 and NZGS Ground Anchors: Design and Construction Guidelines.

Abrasion
For flexible barriers where over-topping is anticipated, appropriate measures to protect the top rope of the barrier against abrasion should be provided and should be discussed with the manufacturer.

Access and Maintenance Requirements
Arresting barriers are by the nature of their design, intended to retain debris flow material. Following an event, the collected material will need to be removed and any damage to the structure repaired. Establishment of suitable access for maintenance and repair is therefore a key part of the design process, regardless of whether the arresting structure is flexible or rigid.

Cleaning behind a flexible barrier following impact presents significant challenges. The net will be under load, particularly in larger events and thus will need to be very carefully released using a hydraulic jack or Tirfor winch. Parts, or the whole of the net will need to be replaced after debris flow impact. The design of the heads of any in-ground anchors should also consider how these would be replaced without needing to replace the anchor completely. Use of a Safety by Design approach is a critical component of the design process and is discussed in more detail in Section 9 of Unit 4 of the Slope Stability Guidance Series.

8.5.6 Drainage Considerations

Debris-resisting barriers to mitigate debris flows are inherently built in stream channels and consequently adequate provisions must be made to allow water flow to take place effectively and safely under normal conditions and after a debris flow event has occurred (Sun et al, 2003). Low level culverts are not recommended as they are subject to blockage (unless they are specifically designed to be oversize as conveyance structures).

[4] Whether an economic consequence is considered 'Low', 'Significant' or 'High' very much depends on the Stakeholder.

8.6 FLOW IMPEDIMENT STRUCTURES

8.6.1 Design Intent

Flow impediment structures are designed to encourage deposition of the debris, by reducing confinement, decreasing channel gradient, increasing impediments to flow, or some combination of these. All lead to a decrease in flow velocity, thereby promoting deposition of the debris.

8.6.2 Types of Structures

Typical flow impediment structures comprise:

1. **Unconfined Depositional Basins** (Figure 50) are sections of the debris fan specifically designed to collect some or all of the debris from a channelised debris flow. To facilitate the settling of coarse-grained debris, the slope of the fan is flattened, and / or the debris channel is widened such that the flow loses confinement. This debris control approach is most effective for larger debris fans that have relatively low gradients and little development. The shape and structure of the debris fan can help determine the optimal placement of the basin. Basins can be formed by channel widening and excavation, but also through building up berms on either side of existing channels and at some point lower on the alluvial fan.
2. **Baffles** (Figure 52) are mainly used to slow down debris flows, encouraging the material to settle. They can also redirect the flow when needed. These impediments can be natural or man-made, such as earth berms, timber, or steel, and work similarly to structures that slow down snow avalanches. They can be arranged individually, in lines, or staggered. While they can function on their own, they are often used alongside other control methods, particularly in areas designed for unconfined deposition. While they are typically intended to be sacrificial and replaced or rebuilt after use, their design should ensure that they do not contribute to the mass of the debris flow.
3. **Debris Straining Structures** Debris racks, grizzlies, or other forms of debris-straining structures are used to separate the coarse-grained debris from the fine-grained debris and water of the debris flow, promoting the deposition of the coarser material. They are often used to prevent culvert openings and bridge clearances from becoming blocked with debris (Figure 50). To remain effective, the coarse-grained debris must be removed from behind the straining structure on a regular basis (van Dine, 1996).

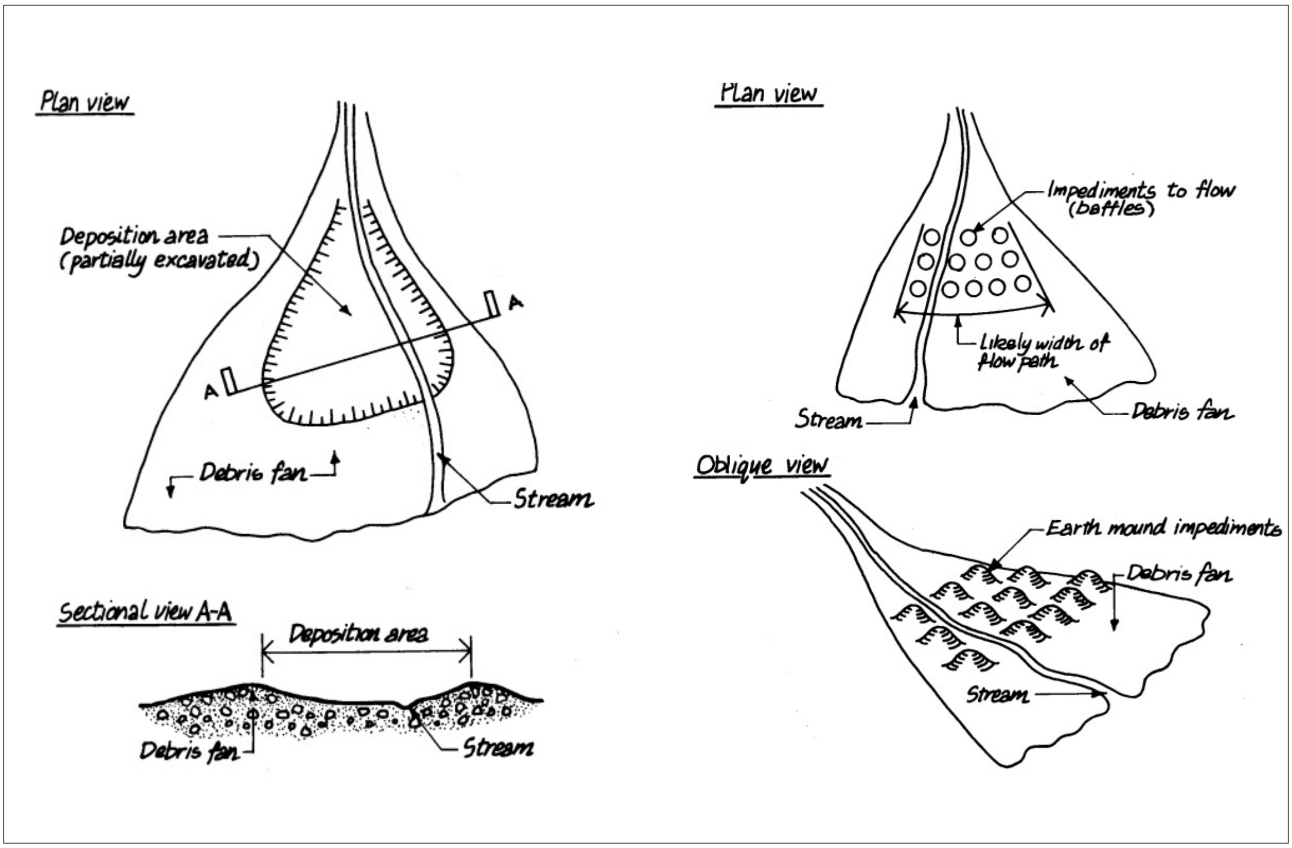


FIGURE 50: Conceptual details for a Depositional Basin (left) and Baffles (soil mounds) to impede flow. Both images from Van Dine (1996)

8.6.3 DESIGN CONSIDERATIONS

Design considerations for basins include the magnitude or volume of the debris flow; the likely flow paths, including length to width ratio of the flow on the fan; the potential runout distance and the probable storage angle.

8.6.3.1 Channel Gradient

As outlined in Section 3.2.2, partial deposition, in the form of lateral levees, generally occurs at a gradient of less than 15° (27%); while deposition on the debris fan usually begins once the gradient flattens to less than a 10° (18%) gradient. However, the angle of deposition varies depending on the source material and needs to be evaluated based on specific observations at the site. In general terms, the flatter the angle of the channel, the greater the degree of deposition. However, to construct a flatter section, part of the channel may need to be steepened; and the effect of this steepened section needs to be considered, and appropriate erosion protection planned.

Empirical studies suggest that the deposition angle corresponds to 2/3 of the original stream gradient (Volkwein et al, 2011).

Importantly, Hungr et al. (1987) indicated that confinement is more critical to maintaining flow (and, therefore, avoiding deposition) than gradient, when the gradient is less than 18° (32%). From an earthworks perspective, it is also easier to combine a reduction in the channel gradient with some widening of the channel, which leads to a loss of confinement of the debris flow, as discussed in the following section.

8.6.3.2 Effect of Loss of Channel Confinement

Van Dine (1996) indicates that previous Japanese work found that with no change in the channel gradient, deposition could occur where there is a widening of the channel expressed as:

$$B_d = \alpha Q^{\frac{1}{2}}$$

Where:
B_d = width of deposition (m)
Q = discharge (m^3/s)
α = a dimensionless variable that can ranges between 1.5 and 3 for catchments smaller than 1 km^2 but is around 4 for catchments larger than 1 km^2.

Ikeya (1976) made the approximation that where the gradient of the debris fan is less than 10° (18%), deposition will occur when the flow widens out to two to three times its flow width. In general terms, Ikeya suggests that an increase of between five and six times the flow width would cause deposition.

The size of the depositional basin needs to be considered in relation to the expected volume of the design debris flow. In sizing any basin, consideration should given to what 'Sabo' professionals in Japan consider a sediment management volume target. As a general range, it is suggested that the management volume target could be 60 to 80% of the design volume, however this will depend on various factors such as the expected sediment load, its composition, watershed characteristics, and the specific design objectives of the basin. This volume may be managed through storage, but can also be achieved through source zone stabilisation, channel stabilisation, or other methods (Moase, 2017). In other words, a design event volume of 10,000 m^3 does not automatically require a 10,000 m^3 basin. In essence, this reduction allows for the fact that some proportion of the water and fine sediment can be allowed to flow downstream out of the depositional basin.

8.6.3.3 Debris Straining Structures

The overall intent of the debris straining structures is to capture the larger particles (including large woody debris) within future debris flows, while allowing smaller material and water to pass. As indicated in Figure 51, they are often used upstream of culverts that are undersized for debris flow[5] material, such that they reduce the likelihood of blockage.

The spacing between bars in these structures depends on the expected grain-size distribution of sediment during a debris flow event, as well as the presence of large timber fragments (Moase, 2017). The spacing can be considered as the 'relative opening' in accordance with the following formula

$$Relative\ Opening = \frac{Opening\ Size}{Material\ Size}$$

Here, opening size is the spacing between bars (horizontally and / or vertically). Material size for the expected flowing sediment should be taken as the maximum particle size or close to this (D'Agnostino, 2013). Piton et al (2024) suggest the D_{95} could be taken as the typical size of boulders found in jammed structures. Where significant amounts of woody debris are expected, the material size can be taken as the average length of wood particles, as the largest dimension is typically orientated at 90° to the flow direction.

[5] They may well have sufficient capacity for clear-water flow however!

FIGURE 51: Debris Straining Structure, Rosy Morn Stream, Kaikoura Coast. Photo courtesy NCTIR

For sediment blocking and capture, it is generally accepted that the relative opening size should be between 1.0 and 2.0 to allow for the bedload to pass through the screen under "normal" stream flow conditions. Osanai et al (2010) suggest that the relative openings should be adopted as 1.0 as a baseline but could be up to 1.5 if there is confidence that blockage will occur. Whether the constraint is related to the width or to the height has an influence on the values of relative openings leading to possible, probable and very probable jamming (Piton et al, 2024; see Figure 52).

Where significant amounts of large timber fragments are expected, the timber contributes significantly to the blocking potential. Values of between 1/3 and 2/3 of the average length of the timber fragments are recommended in Moase (2017). However, the particle size distribution of the sediment in the flow normally controls the design spacing.

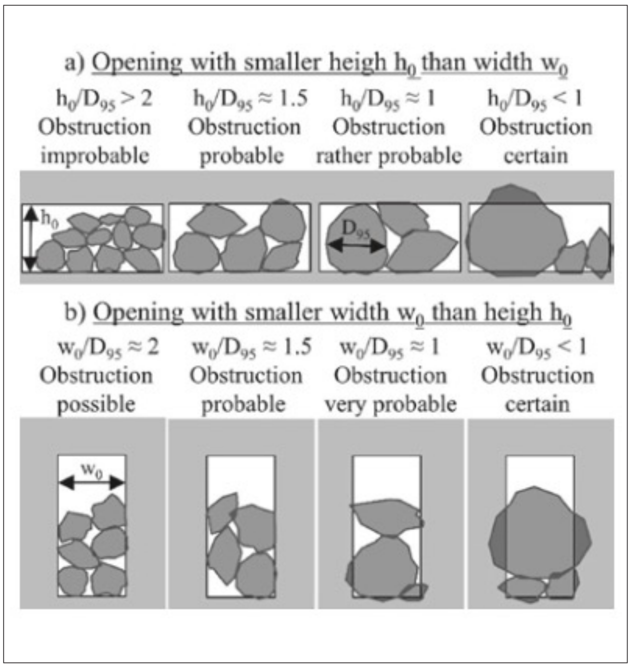


Figure 52: Effect of opening size (w_o) compared to Sediment D95 for various opening geometries (Piton et al, 2024)

8.6.3.4 Single Block Impact Force

Single block impact forces may need to be considered in the design of impediment structures. This is as described in Section 8.5.5.6 which should be referred to for further details

8.7 DEFLECTION AND CONVEYANCE STRUCTURES

8.7.1 DESIGN INTENT

Deflection and conveyance structures are designed to encourage deposition of the flow, by removing confinement, decreasing channel gradient, or increasing impediments to flow, or some combination of these. Any and all of these lead to a decrease in flow velocity, thereby promoting deposition of the debris flow.

8.7.2 DEFLECTION STRUCTURES

Deflection structures are intended to redirect the debris flow into an uninhabited or unused portion of the fan, away from elements at risk, as shown in Figure 53. Deflection walls or berms are constructed from riprap, concrete, reinforced concrete, gabions or other materials, depending on the available project budget and hazard severity (VanDine, 1996).

8.7.3 LATERAL WALLS OR BERMS

Lateral walls or berms are constructed parallel to the desired path of the debris flow. They are used to constrain the lateral movement of a debris flow, encourage the debris to travel in a straight path, and thereby protect an area of – or a structure on – the debris fan. These structures are more or less the same as deflection walls, where the intent is to deflect flows to less vulnerable areas.

8.7.4 CONVEYANCE STRUCTURES

If space on the fan is very constrained due to development or other issues, a “schussrinne”, or shooting channel, is an option (Moase, 2017). In this option, conveyance through the main channel is improved to decrease the risk of avulsion at sharp bends or due to stalling debris lobes. Standard improved conveyance measures include installing larger culverts, adding additional culverts, installing larger or wider bridges, and straightening the channel. Channel confinement and a minimum channel gradient are required to avoid debris deposition. The exact channel geometry required is site dependent.

Moase (2017) notes that channels are designed to maintain confinement to promote conveyance. However, this also promotes erosion, requiring stabilisation measures. Rock or concrete lining of the conveyance channel is therefore also required should conveyance structures be considered, as shown in Figure 54.

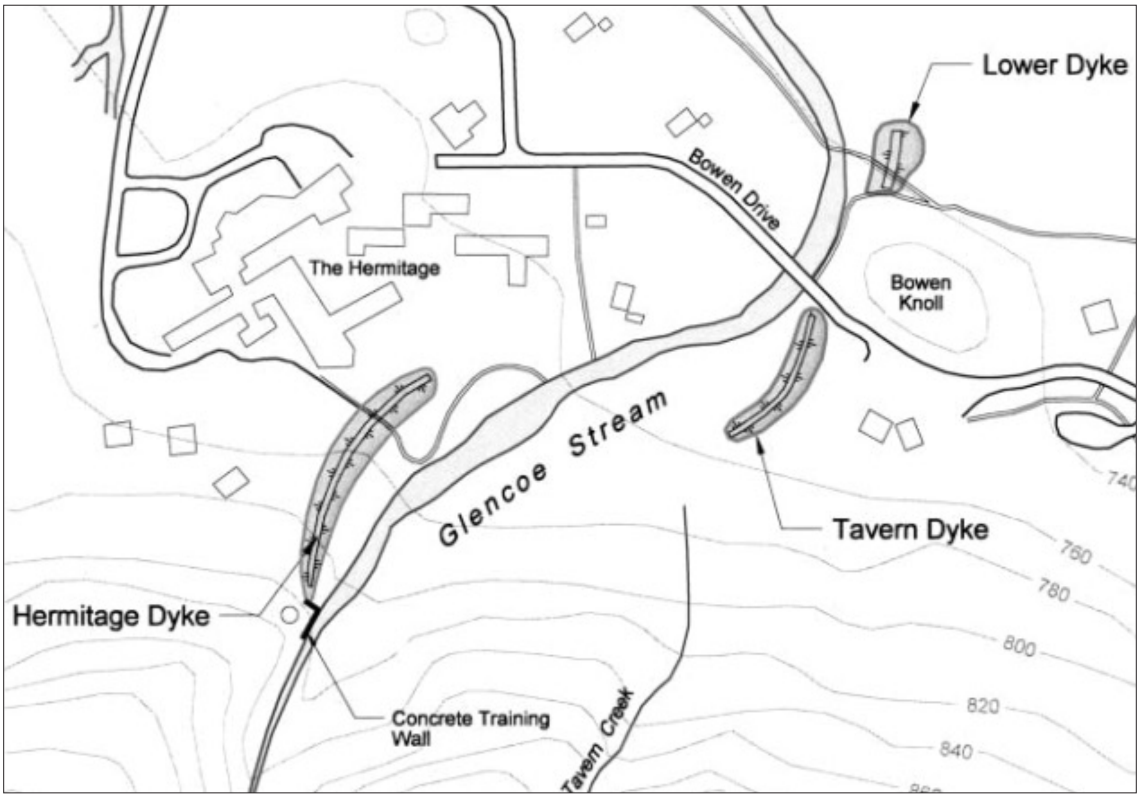


FIGURE 53: Location of lateral berms constructed at Mount Cook Village (Skermer et al, 2002)

FIGURE 54: Rock and concrete lined conveyance channel, Roxburgh (Golder, 2019)

8.7.5 DESIGN CONSIDERATIONS

8.7.5.1 Channel Dimensions

As indicated by Moase (2017) the selection of channel dimensions depends on several factors, including peak discharge, flow velocity, channel slope and channel roughness. Discharge, velocity and channel capacity are related through the following equation:

$$Q = vA$$

Where:
Q = discharge (m^3/s)
v = flow velocity (m/s) and
A = cross sectional channel area (m^2)

Equations that can be used to calculate velocity are described in Section 7.3.1.4.

For conveyance channels, the design velocity should equal or exceed the incoming velocity of the debris flow, such that flow continues. For channels and structures that are designed to promote deposition of debris flow material, design velocities much lower than the incoming debris flow velocity should be considered. Q remains constant under both considerations.

It is advisable to include consideration of potential blockages, whether partial or complete, caused by both organic and inorganic debris in addition to assessing the hydraulic capacity of the structure. For instance, the installation of a debris rack can help reduce the likelihood of blockages, even in cases where there is otherwise sufficient hydraulic capacity. Evaluating whether a structure can convey debris flows safely is also closely related to the potential for flow avulsion, which occurs when flow is redirected from its original channel. Depending on the gradient and degree of confinement at a given structure, the behaviour of the debris flow in response to an undersized or blocked channel may differ significantly from that observed in shallow, unconfined areas. Site-specific analysis to ensure that conveyance structures are both effective and resilient under a variety of flow conditions is therefore a critical design aspect.

8.7.5.2 Erosion Protection

In unlined conveyance channels, erosion protection measures may be required to prevent erosion of the channel side walls and unwanted entrainment of debris. Minimum riprap sizes can be determined from the following equation, provided by Moase (2017), modified from the US Army Corps of Engineers)

$$D_{max} = \frac{4S^{0.555}q^{2/3}}{g^{1/3}}$$

Where:
D_{max} = maximum riprap size (m)
S = slope of the bed (m/m)
q = unit discharge (equal to Q/b, where b is the channel width in m)
g = gravitational acceleration (m/s^2)

This equation is intended for uniform flow down a regular chute with channel slopes between 2 and 20%, assuming riprap density between 2400 and 2800 kg/m^3.

ONE LAST WORD

As Piton et al (2024) note: "It is finally worth stressing that an enlightened risk mitigation should not be based only on structural mitigation measures. It should find the right balance between relocation (in essence the safest solution), hazard mapping and land use planning, and alert and crisis management and preparation."

Rip rap sizing may lead to very large boulder dimensions, which may be difficult to achieve, but can be mitigated by increasing the hydraulic radius of the channel to some degree (but not so wide that deposition is allowed to occur). If this is not possible, consideration should be given to alternative scour protection measures, such as concrete lining the structure or grouted rip rap. Alternatively, if some entrainment can be allowed, it would be possible to design the conveyance channel with an oversize width to allow some sacrificial thickness to be eroded without breaching the bund or undermining any elements at risk.

8.8 NON-ENGINEERED MITIGATION

Non-engineered debris flow mitigation measures utilise natural processes and materials to manage debris flow risks and stabilise affected areas. These approaches are particularly effective in environmentally sensitive regions as they reduce landscape disruption and foster ecological harmony. By integrating the natural terrain and vegetation, these methods aim to reduce risk against debris flows, erosion, and further destabilisation, providing a sustainable alternative where conventional engineering solutions may be impractical or overly costly.

Section 8 of Unit 4 provides a detailed summary of non-engineered mitigations for landslides in general, which should be referred to for greater detail. In relation to debris flow and associated phenomena, non-intervention measures could include:

1. **Avoidance and Retreat:**
   - Relocating road users temporarily to pre-existing alternative routes.
   - Relocating asset to a safer location, such as moving coastal roads inland or evacuating residents from debris flow prone areas during heavy rainfall events.
   - Bridging flow paths areas using structures like bridges or viaducts to span the instability.
   - Tunnelling beneath the debris flow such that the road or rail asset is unaffected by debris flow impact.
2. **Land Use Planning:**
   Land use planning measures aim to prevent debris flows by setting constraints for new developments. These tools include regional policy statements, regional plans, and district plans, which provide guidance and rules for managing landslide risks. Resource and Building consents also play supporting roles, addressing landslide hazards during the development process. Further information can be found within the MBIE Landslide Planning Guidance (de Vilder et al., 2024).
3. **Monitoring and Early Warning Systems:**
   As outlined by Marchi et al (2024), Debris-flow warning systems can be categorised into two types: advance warning systems and event warning systems.

Advance warning systems predict debris flows based on meteorological factors like rainfall thresholds determined from historical data. Event warning systems, on the other hand, detect debris flows during or after initiation using various devices such as radar and ultrasonic sensors for flow-level detection, impact sensors like tripwires and pendulums, seismic and infrasound sensors for detecting ground vibrations and air pressure waves, and video cameras.

Regardless of the type of system, for early warning devices to be effective, a robust protocol must be established that all stakeholders are aware of and understand. Additionally, as debris flows often coincide with other meteorological hazards, particularly flooding, early warning systems may need to adopt a unified approach addressing multiple risks.

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APPENDIX A. REVEGETATION

The following notes are substantially taken from Maggy Wassilieff, '*Forest succession and regeneration - Forest succession*', Te Ara - the Encyclopedia of New Zealand, http://www.TeAra.govt.nz/en/forest-succession-and-regeneration/page-1 (accessed 1 May 2020). It is included to provide practitioners with some background information to inform frequency – magnitude estimates as it allows some estimation of the period since the last destructive event (in this case, debris flow) based on the vegetation present in the area being assessed.

A.1 FOREST SUCCESSION

Forest Succession refers to the change in plant species that occur over time as vegetation re-establishes in an area, ultimately leading to the establishment of mature forests. Many plants are adapted to just one phase of a forest succession. They suit either the first (pioneer) phase, or the mature forest phase, or somewhere in between. As a succession proceeds, some plant and soil trends are fairly universal.

During a succession, plant height increases, soil builds up and soil nutrients increase. Plants change:

- from species that regularly produce many small, light seeds, to those that produce a few large seeds, or occasionally produce many seeds.
- from species with short life cycles to long-lived trees.
- from shade-intolerant species to those that tolerate shade.

This process can be observed in both primary and secondary successions, each characterised by distinct stages and species. **Primary succession** occurs on newly formed or exposed surfaces, such as volcanic ash or glacial moraine. **Secondary succession** occurs on soil that has been disturbed but previously supported vegetation, such as after fires or landslides.

Throughout both primary and secondary successions, the initial colonizers play a crucial role in improving soil conditions, thereby enabling the establishment of more diverse and resilient plant communities over time

The following sections provide examples of observed primary succession following (a) volcanic eruption and (b) glacial retreat.

A.1.1 PRIMARY SUCCESSION AFTER AN ERUPTION

When Mt Tarawera erupted in 1886, it buried vegetation under a thick layer of ash and scoria. For about 10 years the area was bare. Then Toetoe (Cortaderia fulvida), Bracken fern (Pteridium esculentum) and Tree tutu (Coriaria arborea) appeared on the lower slopes. Above 600 metres, the first plants were Racomitrium moss, lichens and mat-forming daisies (Raoulia species).

Toetoe (*Cortaderia fulvida*)

Tree Tutu (*Coriaria arborea*)

Thirty years after the eruption, there was a young forest of pōhutukawa (Metrosideros excelsa), Rewarewa (Knightia excelsa) and Kāmahi (Weinmannia racemosa) on the lower slopes. Tree tutu was spreading up the volcano's sides.

Rewarewa (*Knightia excelsa*)

Kāmahi (*Weinmannia racemosa*)

By the 1990s, around 100 years after eruption, Kāmahi forest clothed the lower slopes. Some Kāmahi was growing in Tree tutu shrublands on the upper slopes. Tree tutu had spread upwards onto the flat area of the summit and was becoming a closed canopy over the low-growing mats of mosses, lichens and daisies.

A.1.2 PRIMARY SUCCESSION IN GLACIAL AREAS

At the end of the last glacial period (around 20,000 to 18,000 years bp), glaciers retreated up their valleys and left moraines behind. On the West Coast, at Franz Josef, various plant communities can be seen growing on moraines of different ages. These have developed over more than 10,000 years. They show the different stages of a succession on moraine (which may be analogus to a debris fan).

The first plants to grow on the fine gravels of moraine are similar to those on volcanic surfaces – mat-forming daisies, willow herbs (Epilobium species), lichens, and Racomitrium moss. Within 10–20 years a shrubland develops, dominated by Tree tutu and tree broom (Carmichaelia arborea).

Willow herbs (*Epilobium parviflorum*)

Tree Broom (*Carmichaelia arborea*)

Seedlings of Kāmahi and Southern Rātā (Metrosideros umbellata) establish themselves early, but in their first years, faster-growing shrubs overtop them. In time, the kāmahi and southern rātā – longer-lived and taller than shrubs – overtake the shrubs. They then dominate the forest for 300–400 years.

Southern rātā (*Metrosideros umbellata*)

These first-generation Kāmahi and Rātā eventually die. After this, Rātā are unable to germinate in the shade of the forest that has emerged. They are replaced by conifers: Rimu (Dacrydium cupressinum), Miro (Prumnopitys ferruginea) and Hall's Tōtara (Podocarpus laetus). Kāmahi is shade-tolerant, so it establishes a second generation. Rimu–kāmahi forest has lasted for at least 11,500 years on the oldest moraines.

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