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GENERAL INFORMATION PRODUCT 159e

**Geomorphic considerations in flood
mapping**

Natural Resources Canada

2025

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2025

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Environment and Climate Change Canada

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The documents in the Federal Flood Mapping Technical Bulletins Series are intended as a resource to support municipal, provincial, and territorial agencies and Indigenous communities working on flood hazard mapping. It is acknowledged that flood management in Canada is regulated at the provincial and territorial level of government, and that provinces and territories reserve the right to create their own guidelines specific to their jurisdictions.

NOTICE

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CONTEXT

A community achieves an elevated level of resilience when its risks are proactively managed, it is adequately prepared for known and potential disaster events, and it demonstrates an ability to recover after such events have taken place. To become resilient, a community's mitigation planners must first understand risks and ensure their capacity to manage those risks.

Floods are the most commonly occurring natural hazard in Canada and account for the largest portion of disaster recovery costs on an annual basis (Public Safety, 2022). Mitigating flood risks is therefore key to increasing the resilience of affected communities. By proactively investing in flood risk mitigation activities, a community may improve its future growth and prosperity, reducing the risk of significant disaster recovery costs, productivity losses, economic losses, destruction of non-monetary cultural assets, environmental damage, injuries, and deaths.

Flooding is the temporary inundation by water of normally dry land and can occur on marine and lake coasts, along rivers, and in low-lying areas. Flooding is caused by extreme rainfall, rapid snow/ice/glacier melt, strong winds (storm surge and waves), stream blockages from ice jams or debris, failure of engineering works including dams, poor drainage characteristics, high groundwater levels, and other sources. Mapping that accurately depicts flood hazards, including those impacted by future conditions due to anticipated development or projected changes in climate, serves as the precondition for mitigation activities and is therefore the first step to increasing community resilience regarding flooding.

FEDERAL FLOOD MAPPING GUIDELINES SERIES

The *Federal Flood Mapping Guidelines Series* are resources to advance and standardize flood mapping projects and activities in Canada. These guidelines address each step of the flood mapping process and provide advice to individuals and organizations in Canada that need to understand and manage flood hazards and their consequences to communities.

FEDERAL FLOOD MAPPING TECHNICAL BULLETINS SERIES

The *Federal Flood Mapping Technical Bulletins Series* are intended to complement the documents in the *Federal Flood Mapping Guidelines Series*. These bulletins cover specialized subjects that may be discussed only briefly in the guideline series.

This technical bulletin, *Geomorphic Considerations in Flood Hazard Mapping*, describes hydrogeomorphic processes. The document discusses the conditions under which

hydrogeomorphic processes are applicable, and how they should be considered during the flood hazard mapping process.

1.0 INTRODUCTION

1.1 Objective

Flood maps are an integral resource for decision-makers tasked with the identification, characterization, and management of flood-related hazards. Typical flood maps show the potential inundation area during high flow events and may also show the intensity of flooding using a combination of flow depths and velocities, indicating the potential damage to infrastructure and threat to public safety. Flood maps are generally produced using hydraulic models with varying resolution of topographic data depending on the size of the study area. For steep creeks on alluvial fans, flood mapping may also include composite hazard maps that show the combined probability of flood intensity across a range of event frequencies (e.g., EGBC, 2023).

Existing flood mapping approaches often neglect the interactions between water and sediment in the characterization of flood hazards. To bridge this gap, hydrogeomorphology has emerged as an interdisciplinary science that focuses on the interaction of hydrologic processes with landforms (Scheidegger, 1973; Sidle & Onda, 2004). Floods with sufficient magnitude to cause local landscape changes are referred to as hydrogeomorphic floods, or hydrogeomorphic processes, because water (“hydro”) and sediment (“geo”) are transported. Hydrogeomorphic processes can be broadly characterized as clearwater floods, debris floods, or debris flows.

The amount of geomorphic change occurring during a single event varies with process type, with the most geomorphic change typically occurring on steep creeks subject to debris floods or debris flows, and the least on low-gradient meandering rivers subject to clearwater floods. That is not to say that low-gradient rivers are static, but rather that change in low-gradient rivers tends to occur progressively over time and in more predictable locations. The way in which hydrogeomorphic considerations should be incorporated into flood mapping therefore varies based on the geographic setting and the dominant hydrogeomorphic processes within the watershed.

This technical bulletin provides guidance on when and how to consider geomorphology in flood mapping. Hydrogeomorphic processes affect flood inundation and intensity through changes to the flow density, blocking of river channels or culverts, and increases or decreases in the riverbed elevation through deposition and scour. They can also change the spatial distribution of flooding through changes in river size and planform due to bank erosion or avulsion (the creation of a new channel) and reduce the stability of hillslopes through slope undercutting.

1.2 Document Structure

This technical bulletin is targeted at decision-makers commissioning and applying flood mapping studies and technical practitioners carrying out the work. The document is structured as follows:

- [Section 2.0](#) introduces the terminology discussed throughout the technical bulletin and is recommended reading for anyone using this document.
- [Section 3.0](#) introduces hydrogeomorphic processes (i.e., clearwater floods, debris floods, and debris flows) and describes ways to identify the dominant process based on desktop and field assessments. It also discusses the broad, generalized geographic distribution of these process types in Canada and the ways they can affect flood mapping. This section is intended to support both technical practitioners and decision-makers.
- [Section 4.0](#) provides a more detailed description of each hydrogeomorphic process type, as well as guidance for technical practitioners about how to consider these processes in flood mapping. The potential approaches are presented at a high-level and practitioners can reference the cited references for more detailed descriptions of appropriate methods.
- [Section 5.0](#) discusses the validity of flood maps and when mapping studies should be updated. It also presents additional considerations related to future changes in geomorphic processes related to climate change. This section is intended for both decision-makers and technical practitioners.

1.3 Limitations

This technical bulletin is intended to highlight the importance of hydrogeomorphic considerations in riverine flood mapping and to provide avenues for incorporating the relevant processes. The following limitations should be considered when reading this document:

- The focus of this technical bulletin is on hydrogeomorphic processes as they relate to flood mapping in a riverine setting.
- The technical bulletin focuses on channelized flows and does not consider hazards occurring on hillslopes (e.g., landslides), though it is recognized that these hillslope processes often transition into channelized debris flows and debris floods.

- Debris flow considerations are also included in landslide mapping guidelines in some provinces and territories. Readers should familiarize themselves with all relevant guidelines for debris flow hazard mapping.
- The flood mapping guidelines do not address risk, which requires also quantifying the vulnerability of infrastructure or the public.
- Different jurisdictions may use different terms for flood maps or for levels of mapping. The terms defined in this document reflect generalized map products and study scales.

Flood mapping and geomorphic analyses should be completed by qualified professionals.

2.0 TERMINOLOGY

This section introduces key terms that are used throughout the remainder of this technical bulletin and are not currently defined within the *Federal Flood Mapping Guidelines Series* documents:

Aggradation: Raising of the stream bed due to an excess of sediment supply relative to sediment transport capacity. Aggradation occurs through deposition of sediment on the riverbed.

Alluvial Fan: A fan-shaped landform deposited by a river where gradient and/or confinement decreases leading to decreased sediment transport capacity. This landform is more correctly called a colluvial fan or colluvial cone when formed by debris flows, but for simplicity the term alluvial fan is used throughout this document irrespective of process type.

Avulsion: Formation of a new channel outside of the existing channel boundaries through a cutoff between meander bends, reoccupation of a previously abandoned channel on the floodplain, or incision of a new channel on the floodplain or fan surface.

Bank Erosion: The removal of material along the channel banks leading to widening of the river or a shift in the river location.

Clearwater Flood: Riverine flooding due to an excess of clearwater discharge from rainfall, snowmelt, or other sources (e.g., dam release) that does not entrain sufficient sediment to 'bulk' the flow.

Debris Flood: Floods involving exceptionally high rates of coarse bedload transport in steep channels (typically 5% to 27% gradient). Debris floods are transitional between clearwater floods and debris flows.

Debris Flow: A rapid, channelized flow of saturated debris containing fine-grained sediment (i.e., sand and finer fractions). Due to their high sediment concentrations, debris flows are similar in consistency to wet concrete. They are typically faster than debris floods and have substantially higher peak discharges and impact forces than either clearwater floods or debris floods.

Degradation: Lowering of the stream bed due to an excess of sediment transport capacity relative to sediment supply.

Flood Intensity: A measure of the force associated with a clearwater flood, debris flood, or debris flow. It is a proxy for the potential damage to infrastructure or threat to safety and can be quantified based on the flow depth (d) and velocity (v) (e.g., $I = d \times v^2$ from Jakob, Stein, & Ulmi, 2011).

Flow Bulking: The process by which rapidly flowing water entrains bed and bank materials either through erosion or preferential “plucking.” In the case of debris flows, bulking may entail entrainment of the entire loose channel debris.

Geomorphic Change: Changes to the landscape through the erosion, transport, and deposition of sediment. In rivers this occurs through lateral changes (bank erosion and avulsion) and/or vertical bed changes (aggradation and degradation).

Geomorphology: The study of landforms and landscapes and the processes that create and change them.

Hydrogeomorphic Process: General term used to describe interactions between water and sediment in a stream channel that result in geomorphic change. The main hydrogeomorphic process types are clearwater floods, debris floods, and debris flows.

Reach: A section of a river with relatively consistent stream flow, gradient, bed material size, confinement, floodplain characteristics, and morphology.

3.0 HYDROGEOMORPHIC PROCESSES IN CANADA

Rivers alter landscapes through the erosion and deposition of sediment. These changes can occur dramatically during a single flood event or progressively over time. Prior to evaluating the impacts of geomorphology in a flood mapping study it is first necessary to identify the dominant hydrogeomorphic process(es) as each process may be associated with different magnitudes and timescales of geomorphic change. This section outlines the three primary hydrogeomorphic process types, provides guidance on how to determine the dominant process at a site, explores the geographic distribution of each process in Canada, and outlines the main flood mapping considerations.

3.1 Hydrogeomorphic Process Types

Hydrogeomorphic processes can be divided into three main types: clearwater floods, debris floods, and debris flows. Different hydrogeomorphic processes can occur within the same system at different times. Clearwater floods can transition into debris floods, for example, when the flow becomes powerful enough to transport all of the material on the riverbed. Debris flows typically originate as landslides on steep slopes (>27%) with high sediment concentrations but can become diluted as they travel downstream, transitioning to debris floods or clearwater floods. This can occur through injections of water by tributaries or as sediment is deposited leading to a decrease in sediment concentration.

Most steep creeks (>5%) also experience different hydrogeomorphic processes during different high flow events. For example, rivers classified as debris-flow prone may also be subject to clearwater floods and debris floods during smaller, more commonly occurring floods. In systems prone to debris floods or debris flows, these rarer, larger magnitude events typically produce greater damage than more commonly occurring clearwater floods.

Clearwater Floods

Clearwater floods are high flow events that have a low sediment concentration by volume; although bedload may be transported, it is present in insufficient quantities to 'bulk' the flow. In low-gradient rivers, clearwater flooding can induce significant changes in bed elevation through aggradation or degradation and contribute to bank erosion and avulsion hazards. River stability is inversely related to gradient and sediment supply, so the likelihood (and magnitude) of geomorphic change varies with both properties (Church, 2006; [Figure 3.1](#)).

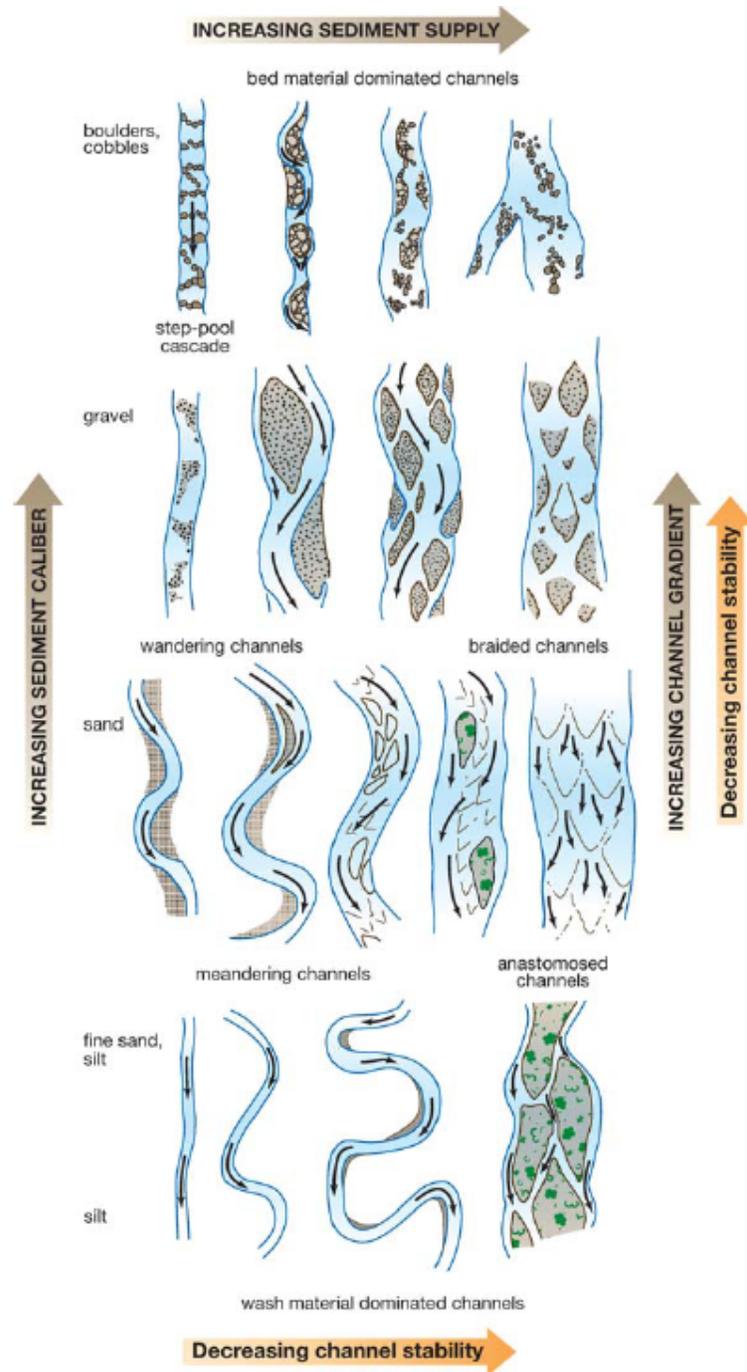


Figure 3.1: Stream classification from Church, 2006.

Clearwater flooding can cause substantial inundation, as well as major geomorphic changes and damage to infrastructure. The flooding on the Nicola River, Coldwater River, and Coquihalla Rivers in British Columbia in November 2021 provides an illustrative example. Clearwater floods resulting from an atmospheric river-related

rainfall event washed out Highway 8 along the Nicola River in more than 25 locations, requiring nearly a full year to re-open. Highway 5 (the 'Coquihalla Highway') was also damaged in numerous locations, including seven bridge collapses ([Figure 3.2](#)), and Highway 1 was closed for over a week due to inundation.



Figure 3.2: Bridge collapse on Highway 5 due to erosion and scour on the Coldwater River in November 2021. Photo credit: BGC Engineering Inc.

Debris Floods and Debris Flows

In mountainous terrain, rivers typically have higher gradients and more sediment supply than in lowland rivers. These rivers are less stable ([Figure 3.1](#)) and incorporate increasing amounts of sediment into the flow during large events, resulting in increased sediment concentration (i.e., flow bulking). Depending on the watershed conditions, these steep creeks may be subject to a spectrum of processes ranging, with increasing sediment concentration, from clearwater floods to debris floods to debris flows ([Figure 3.3](#)).

Debris floods most commonly occur in confined channels or on alluvial fans with gradients exceeding 5% but can also occur on lower gradient gravel-bed rivers with watershed areas up to several thousand square kilometers (Church & Jakob, 2020).

Debris flows dominate in steeper channels (>27%) with smaller watershed areas (typically <10 km²). Due to high sediment concentrations, debris flows can approach consistencies similar to wet concrete. They are typically faster than debris floods and have substantially higher peak discharges and impact forces. They are particularly threatening to life and properties due to these characteristics. The peak discharge of a debris flow can be one to two orders of magnitude higher than a 200-year clearwater flood in the same river system (Jakob, 2005).

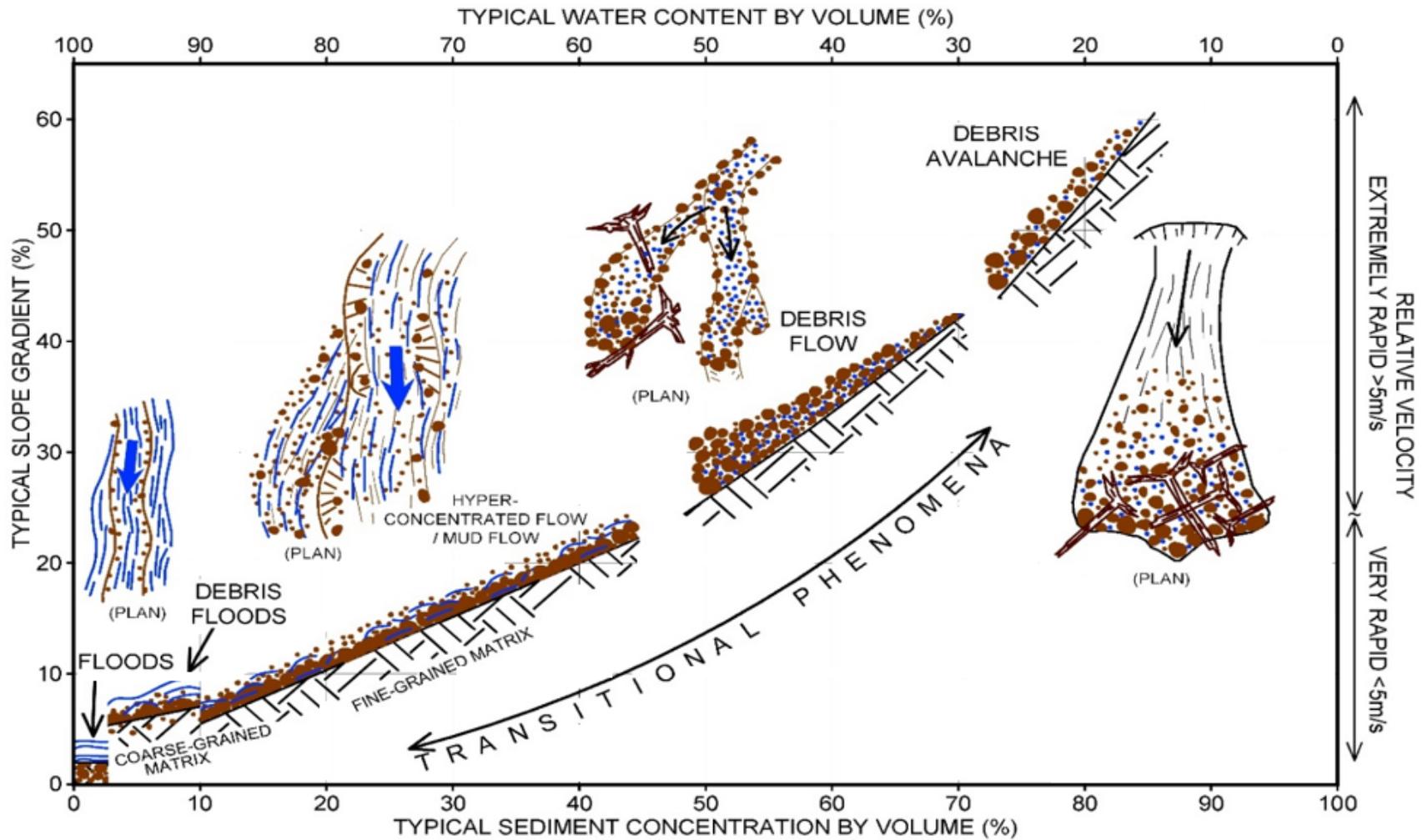


Figure 3.3: Hydrogeomorphic process classification by sediment concentration, gradient, velocity, and morphology.

Cougar Creek in the town of Canmore, Alberta provides an example of the potentially damaging effects of debris floods (Jakob & Church, 2020). A debris flood initiated on Cougar Creek during a multi-day rainfall event in June 2013. The peak discharge of the event was estimated at 100 m³/s and approximately 90,000 m³ of sediment was deposited on the alluvial fan. The channel widened from approximately 6 m to 30 m (or more) in a single day as riprap armouring was undermined and failed throughout the fan ([Figure 3.4](#)). Numerous streamside buildings were damaged by foundation exposure and undercutting.

Channel widening reduced the flow depth within Cougar Creek, thereby reducing the force associated with the flow. As a result, several metres of sediment deposited on the channel bed causing substantial aggradation. The high sediment yield blocked culverts, redirecting streamflow along the Trans-Canada Highway. This led to undercutting and failure of the highway ([Figure 3.4](#)).



Figure 3.4: Cougar Creek on (a) 19 and (b) 20 June 2013, taken approximately a day apart at the same location on the mid to upper fan, looking downstream (south). The average width of the channel in the upper (a) photograph is approximately 6 m; in the lower (b) image it has widened to approximately 30 to 60 m. c) The channel of Cougar Creek after the debris flood downstream of the location of (a/b) with the blocked Highway 1 ('Trans-Canada Highway') crossing the lower fan. In this section, the active channel widened up to 90 m. Photo credits: Town of Canmore.

3.2 Steep Creek Watersheds and Fans

Prior to characterizing the effects of hydrogeomorphic processes in a flood mapping study it is necessary to determine which process types are possible within a watershed. Steep creek watersheds that experience debris floods and debris flows have distinct landforms that aid in their identification. These watersheds typically consist of hillslopes,

small feeder channels, a main channel, and an alluvial fan composed of deposited sediments at the lower end of the watershed ([Figure 3.5](#)).

At the watershed scale, distinct zones of sediment production, transfer, erosion, deposition, and avulsion may be identified ([Figure 3.5](#)). In mid- to upper-reaches, steep mountain slopes deliver sediment and debris to the main channel through various mass movement mechanisms (i.e., rock fall, rock slides, debris avalanches, debris flows, slumps, and raveling). These sediments are then transferred downstream by clearwater floods, debris floods, and debris flows during high flow events. Debris floods and debris flows characteristically gain momentum and sediment as they move downstream until they spread across an alluvial fan where the channel enters the main valley floor. Here, momentum is lost through a decrease in confinement and reduced channel gradients, resulting in sediment deposition.

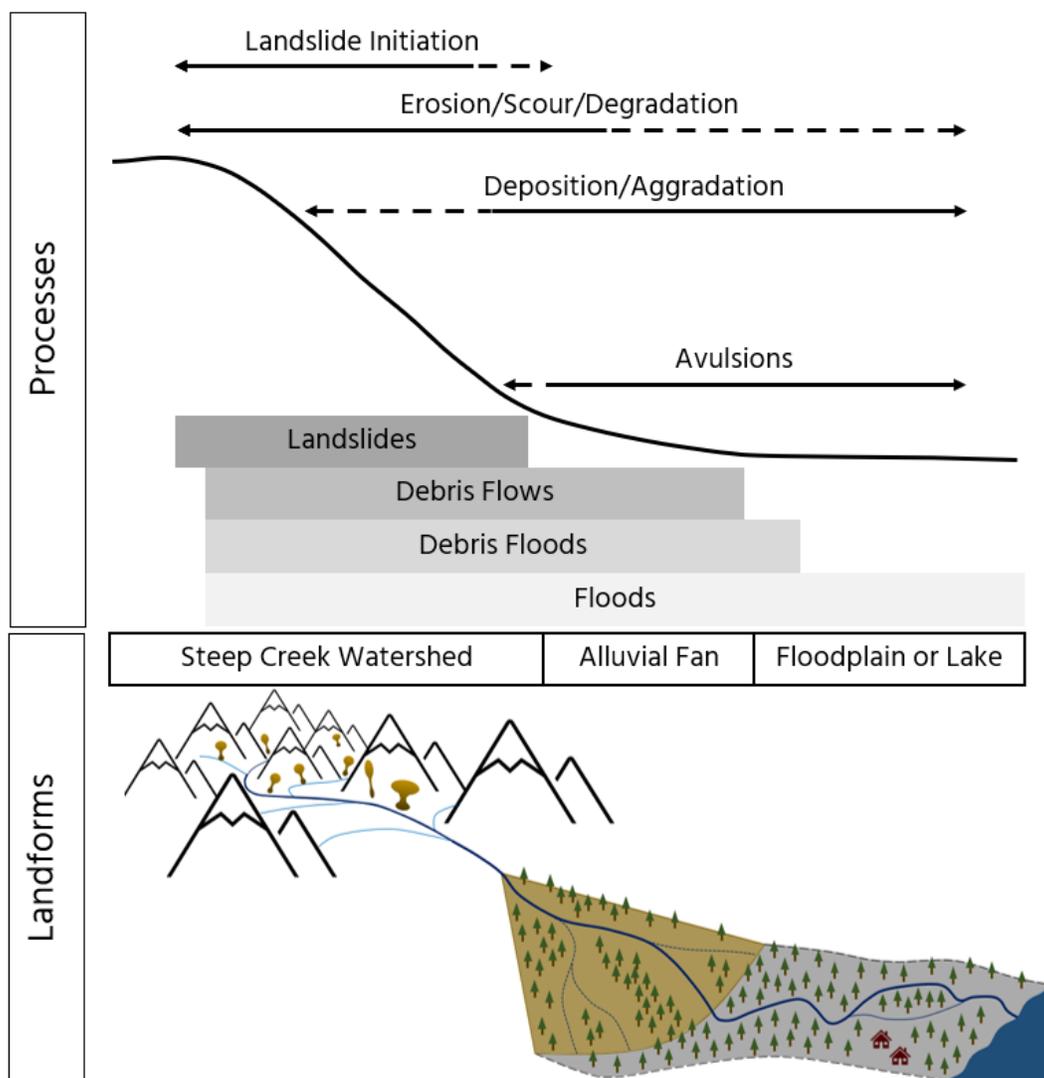


Figure 3.5: Schematic diagram of geomorphic processes in a steep river watershed. The alluvial fan provides sediment storage over a time scale of thousands of years. Sketch developed based on Schumm (1977), Montgomery and Buffington (1997), and Church (2013).

An alluvial fan is a depositional landform at the outlet of a mountainous watershed. As alluvial fans are formed through deposition, they are dynamic and potentially very dangerous (hazardous) landforms that show the approximate extent of past and future hydrogeomorphic processes. The episodic nature and relative rarity of large events on some alluvial fans contributes to their danger, as infrastructure and residences are often constructed on alluvial fans in the interval between large events.

Stream channels on a fan are prone to avulsions, which are rapid changes in channel location, due to natural cycles in alluvial fan development and from the loss of channel confinement during debris floods and debris flows (e.g., Kellerhals & Church, 1990; van Dijk et al., 2009; 2012; de Haas et al., 2018) ([Figure 3.6](#)). If the alluvial fan is formed at

the edge of a still water body (lake, reservoir, ocean), the alluvial fan is termed a fan-delta. These landforms differ from alluvial fans in that sediment deposition at the margin of the landform occurs in still water, which promotes the deposition of sediment due to a backwater effect (i.e., the ponded water downstream reduces the river gradient and sediment transport capacity of the flow). The magnitude of the backwater effect is sensitive to the water elevation in the downstream water body; when water level is high the backwater effect is magnified and the frequency and possibly severity of upstream aggradation (and avulsions) increases (van Dijk et al., 2009; 2012).

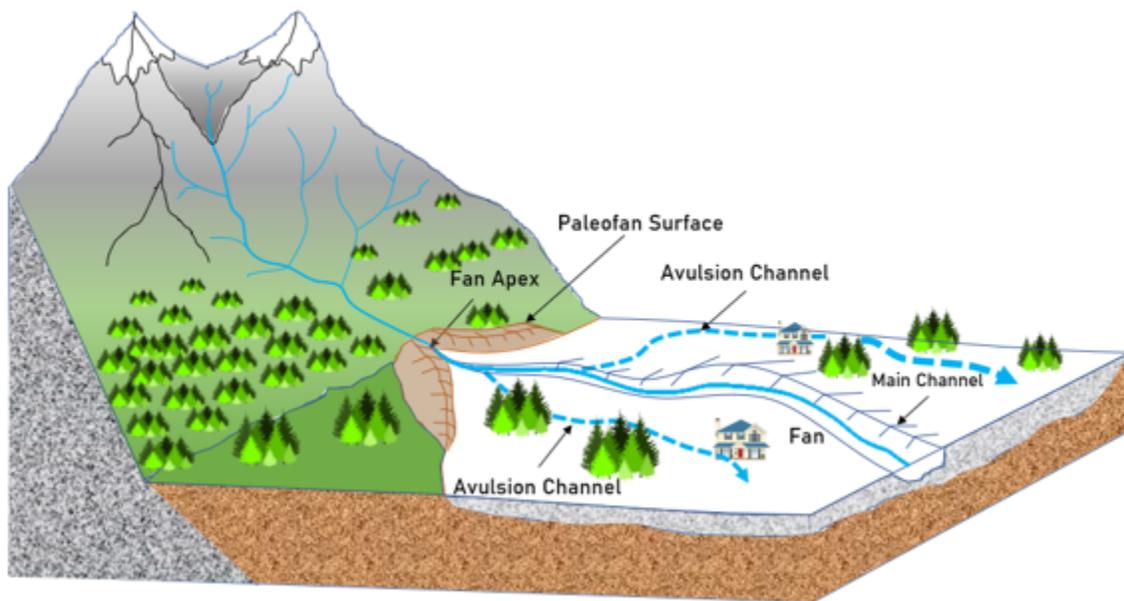


Figure 3.6: Schematic of a steep creek channel with avulsions downstream of the fan apex. The paleofan surface represents the portion of the fan that was deposited in the distant past and is no longer accessible to the present-day river.

3.3 Hazard Process Identification

If the watershed under consideration in a flood mapping study contains mountainous terrain and landforms indicative of debris floods or debris flows, differentiating between the dominant hydrogeomorphic processes is a critical next step. The dominant hydrogeomorphic process type can be evaluated based on two factors: (1) the characteristics of the watershed, and (2) the nature of the sediment deposits.

Watershed Characteristics

Wilford et al. (2004) presented a diagram for distinguishing between hydrogeomorphic processes based on the stream length and 'Melton Ratio' of the drainage basin.

[Figure 3.7](#) shows a version that has been subsequently refined with larger datasets by Holm et al. (2016), Lau (2017), and unpublished data at BGC Engineering Inc. The

Melton Ratio is related to the total relief (H), or difference in elevation between the highest and lowest points in the watershed, and the watershed area (A) (i.e., $M = H/\sqrt{A}$). It essentially provides a measure of the steepness of the watershed.

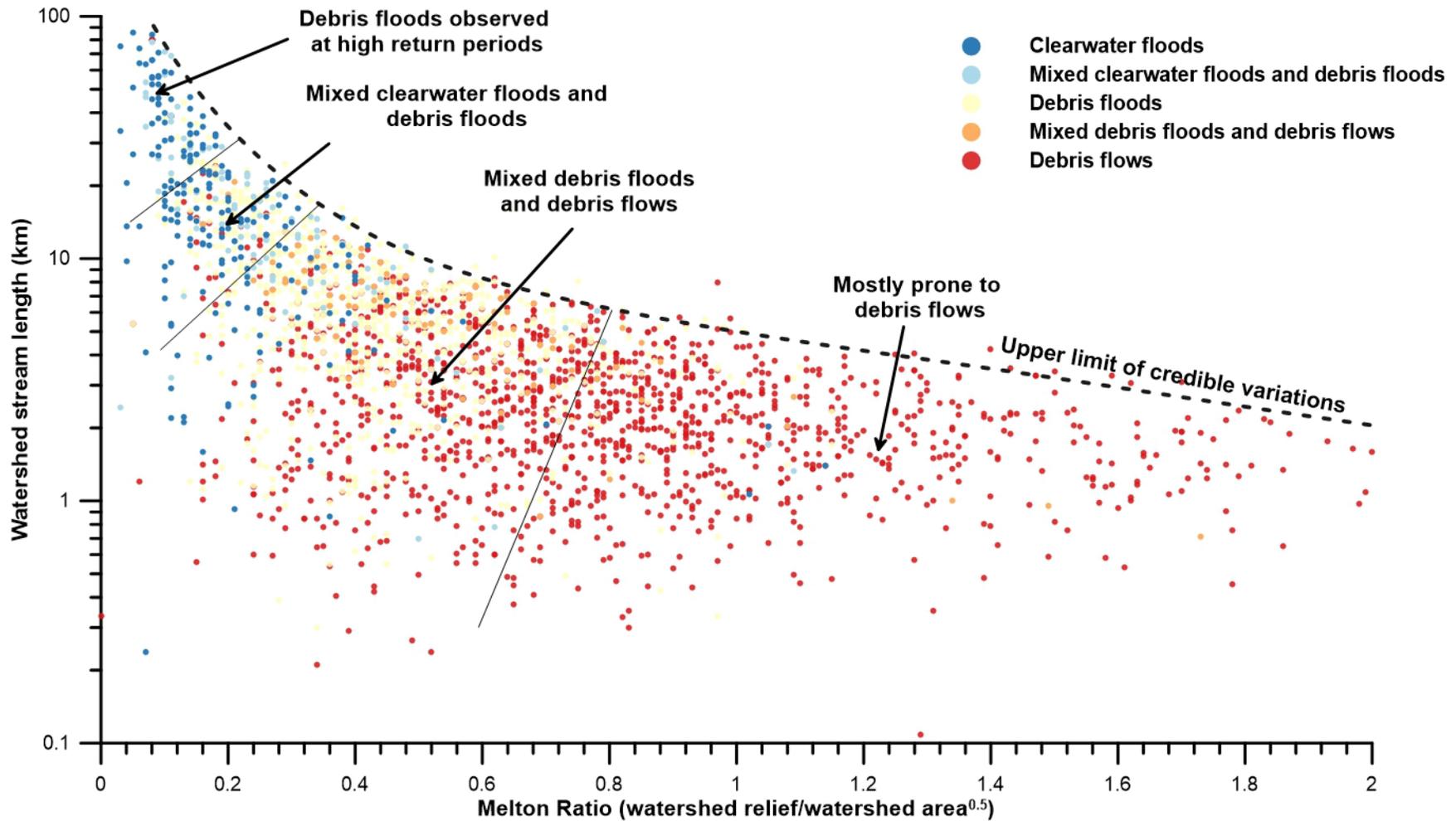


Figure 3.7: Dominant hydrogeomorphic processes as a function of Melton Ratio and stream length. The grouping of classes as shown in the shaded polygons is based on judgement. Many creeks/ivers are also subject to more than one process.

Although there is significant overlap between processes in [Figure 3.7](#), the diagram provides a preliminary method for assessing whether a process has the potential to occur within a watershed. In a steep watershed with a Melton Ratio of 0.8, for example, a river with a relatively short upstream length of 0.2 km is likely to be primarily susceptible to debris flows while a river with an upstream length of 5 km may be susceptible to debris flows and debris floods.

Sediment Deposits

Follow-up field work is often needed to confirm the active hydrogeomorphic processes at a given location. [Table 3.1](#) provides a summary of characteristics that can be observed in the field and used to identify debris flows, debris floods, and clearwater floods.

While debris flow deposits may either remain entirely unsorted or exhibit inverse grading (i.e., increasing grain size toward the top of the deposit), debris flood deposits are sorted and imbricated, or aligned in the direction of the flow, like 'normal' clearwater flood deposits. Debris flows are also distinctive in that they are matrix-supported (i.e., dominated by finer-grained material containing clasts) and often deposit levées along their margins and boulder lobes at the front of their deposits.

Debris floods are transitional between clearwater floods and debris flows, and it can therefore be challenging to differentiate different debris flood events from other process types. Although debris flood deposits resemble flood deposits in some ways (e.g., clast-supported sediments with normal grading), the sand content in debris flood deposits is usually much higher than in clearwater flood because of how fast these sediments are deposited, resulting in less effective sorting (Blair & McPherson, 1994). Like debris flows they may also contain paired terraces and buried or impact-scarred vegetation, but they typically do not have well-defined boulder deposits or inverse grading.

Table 3.1: Sedimentary and geomorphic characteristics for different hydrogeomorphic process types.

Sediment or Geomorphic Characteristic	Clearwater Floods	Debris Floods	Debris Flows
Matrix-supported deposit stratigraphy	No	Rarely	Yes
Clast-supported deposit stratigraphy	Yes	Often	Rarely
Inverse grading of deposit	No	No	Yes
Clast imbrication (i.e., grains aligned in the direction of the flow)	Usually	Sometimes	No
Defined boulder deposits at front of deposited lobe	No	Sometimes, but with less sharp boundaries than for debris flows	Yes
Boulder levées at edges of deposit	No	No	Yes
Terraces on both sides of the channel at the same elevation (“paired terraces”)	Only if stream is incising into alluvial bed	Often	Rarely
Buried vegetation	Sometimes	Yes	Yes
Impact-scarred riparian vegetation	Rarely	Often	Yes
Fine-grained overbank deposits	Usually	Sometimes	Rarely
Channel gradient (watershed)	Typically <27%	Typically <27%	Typically >27%
Channel gradient (fan)	<5%	5 to 9%	> 9%

3.4 Geographic Distribution of Process Types

As the dominant hydrogeomorphic process type varies with river and fan gradient, as well as other factors like sediment supply, it is possible to broadly characterize susceptible areas based on topography alone. [Figure 3.8](#) shows the high-level distribution of areas susceptible to debris floods and debris flows in Canada based simply on gradient. Given that clearwater floods can occur on any river gradient, they occur throughout Canada. As [Figure 3.8](#) only shows broad geographic trends, it is important to complete a more detailed assessment to identify all relevant hydrogeomorphic processes upon initiation of a flood mapping study using the methods described in [Section 3.3](#).

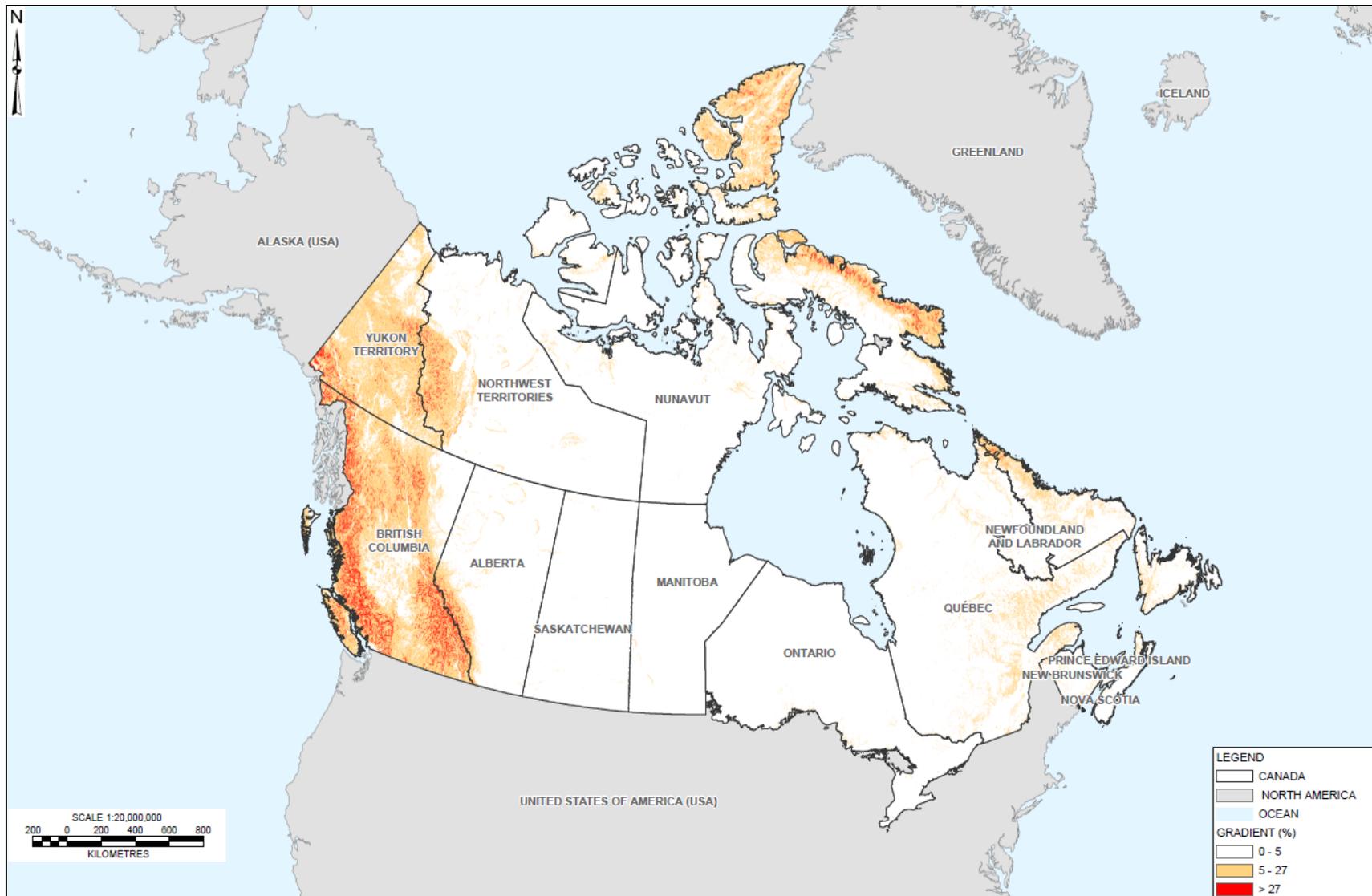


Figure 3.8: High-level overview of geographic distribution of debris flood- and debris flow-prone areas in Canada based on topographic gradient from a 1 km resolution digital elevation model.

3.5 Mapping Considerations

Once the dominant hydrogeomorphic process has been identified within a study area, it is necessary to consider the ways in which the related geomorphic processes can impact a flood mapping study. Sediment erosion, transport, and deposition can influence flood mapping in three broad ways: by increasing the density of the flood water, by blocking flow paths with sediment or large woody debris, and by changing the landscape over which the water flows. [Table 3.2](#) summarizes the relevant mapping considerations for each hydrogeomorphic process.

Table 3.2: Overview of geomorphic considerations in flood mapping for each hydrogeomorphic process. The '+' symbols represent the relative importance of each mapping consideration.

Dominant Hydrogeomorphic Process	Location	Mapping Consideration
Clearwater Floods 	Low-Gradient Floodplains and Alluvial Fans	Sediment/large woody debris blockage (+) Aggradation (+) Degradation (+) Bank Erosion (+) Avulsion (+)
Debris Floods 	Moderate Gradient Floodplains and Alluvial Fans	Flow bulking (+) Sediment/large woody debris blockage (++) Aggradation (+++) Degradation (++) Bank Erosion (+++) Avulsion (++)
Debris Flows 	Steep Alluvial Fans	Flow bulking (++) Sediment/large woody debris blockage (+++) Aggradation (+++) Degradation (++) Bank Erosion (++) Avulsion (+++)

4.0 GUIDELINES FOR HYDROGEOMORPHIC HAZARD MAPPING

4.1 Clearwater Floods

4.1.1 Process Description

Clearwater flooding occurs on low-gradient alluvial fans and floodplains (e.g., channel gradient <5%) where the mobilized sediment does not significantly bulk the flow. Clearwater floods can also occur in higher gradient rivers prone to debris floods or debris flows in the time between larger events, when sediment is recharging after being scoured and transported away. However, as these clearwater floods have smaller discharges and are less erosive than their bulked counterparts, they typically do not govern flood hazard magnitude (or risk) in steeper settings.

Clearwater floods can cause lateral changes (i.e., bank erosion and avulsion) or vertical changes (i.e., aggradation and degradation). The distribution of change depends on the relative erodibility of the riverbed and banks (e.g., Millar, 2005; Eaton, Millar, & Davidson, 2010), as well the balance between sediment supply and transport capacity within the reach. A gravel-bed river with non-cohesive banks may preferentially erode its banks, as they are more erodible than the armoured bed, whereas a sand-bed river with cohesive clay banks may be more likely to erode vertically. Each process can have important considerations in mapping, as described below.

Bank Erosion

Floods exert high shear stresses on the riverbed and banks, often leading to erosion of the banks and a change in the river size or position. Bank erosion occurs through two main mechanisms: (1) erosion at the outside of a meander bend leading to its outward growth over time, and (2) sudden widening during a flood event ([Figure 4.1](#)). The 'type' of erosion a river experiences varies primarily based on its morphology and setting but may also be influenced by flood magnitude.

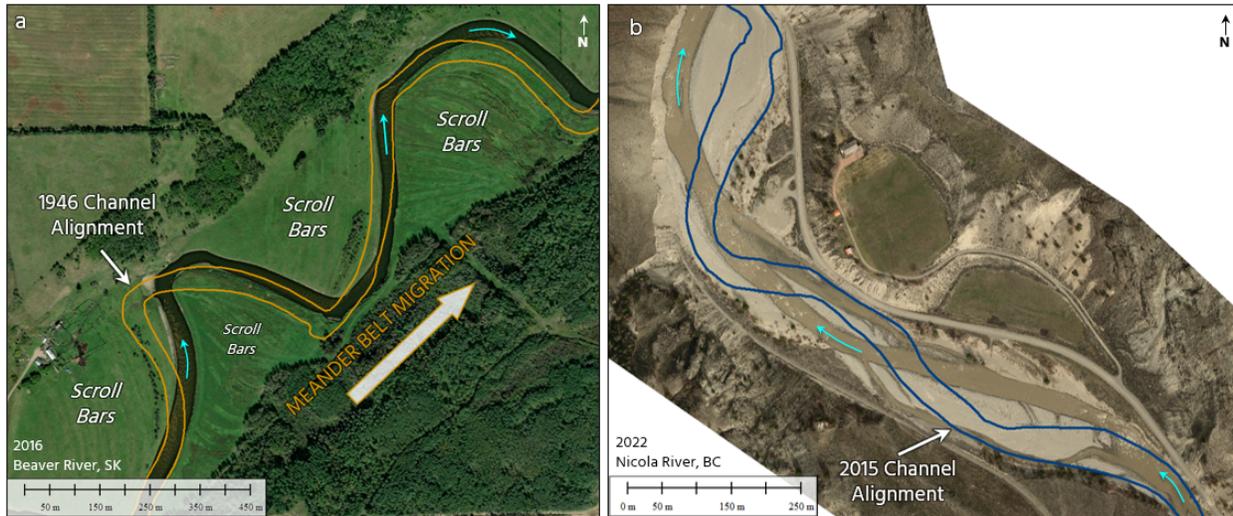


Figure 4.1: Overview of (a) progressive erosion and meander migration on a meandering sand/silt-bed reach of the Beaver River in Saskatchewan, contrasted with (b) channel widening in a meandering gravel-bed reach of the Nicola River in British Columbia following an extreme flood in November 2021. Over time the exposed bars will re-vegetate, narrowing the Nicola River back toward the pre-flood width. Photo credit: (a) ESRI world imagery, (b) Urban Systems

Low-gradient meandering rivers typically transport fine bedload material (e.g., sand) with much of their sediment transported in suspension (Church, 2006). During floods, the fine suspended sediment (i.e., silt and clay) accretes onto the riverbanks, providing bank cohesion and allowing fine-bed rivers to develop a highly sinuous planform with a deep and narrow geometry. Bank erosion in these low-gradient rivers is concentrated at the outside of meander bends as the toe of the bank is undercut where shear stresses are highest, leading eventually to failure of the cohesive material above (Eaton, 2006; Darby et al., 2010). Erosion is roughly balanced by deposition of eroded material in point bars along the inside bank of downstream bends, enabling the river to maintain a consistent width while migrating across the floodplain (Church, 2006; Fuller, 2007; Olson, Legg, Abbe, & Reinhardt, 2014).

In low-gradient rivers, meander bends typically extend outward and migrate downstream (e.g., [Figure 4.1a](#)) within a meander belt defined by the outermost points of existing meander bends (Olson et al., 2014). This process of meander extension and migration is often progressive over years or decades but can also be punctuated in time during large flood events through mass failure when a slab of bank material is undercut by erosion of the bank toe (Darby et al., 2010). In general, these low-gradient fine-grained rivers tend to be more laterally stable than their coarser counterparts ([Figure 3.1](#)), with erosion occurring in predictable locations.

Higher gradient rivers typically transport coarser bedload and often have gravel- or cobble-sized bed material. These systems have lower bank cohesion as they do not

deposit fine clays and silts during floods and therefore adopt a wider and shallower channel geometry (Church, 2006). Large flood events may also cause sudden widening as the channel adjusts to convey additional flow through entrainment and erosion of the non-cohesive bank material ([Figure 4.1b](#)). This geomorphic change is often realized during a single flood as the resisting force of the bed material is exceeded, leading to large-scale bed mobilization and destabilization (Langendoen & Simon, 2008; Pitlick, Marr, & Pizzuto, 2013; Eaton, Mackenzie, Jakob, & Weatherly, 2017).

Channel Bed Aggradation & Degradation

Channel aggradation and degradation reflect a general raising or lowering of the channel bed due to an imbalance between the transport capacity of the river and the amount of sediment supplied (Church, 2015) ([Figure 4.2](#)). Aggradation and degradation can be triggered by a variety of natural and human-caused disturbances to a watershed ([Figure 4-3](#)). Obstructions such as dams are a common cause of downstream degradation, as they reduce sediment supply to downstream reaches (Brandt, 2000; Williams & Wolman, 1984). Conversely, reaches upstream of a dam may aggrade because of an increase in base-level at a reservoir inlet (Evans, Huxley, & Vincent, 2007).

The severity of the channel response to a fluctuation in sediment supply and/or transport capacity generally decreases with distance from the initial disturbance but can propagate for hundreds of kilometers upstream or downstream (e.g., Andrews, 1986). Degradation and aggradation may persist for decades or longer (e.g., Weatherly & Jakob, 2014); many major rivers in Canada are still degrading into thick deposits of glacially-deposited material in response to isostatic rebound associated with the removal of the ice sheets following the last glaciation 11,000 years ago (Ashmore, 1993; Church, Ham, Hassan, & Slaymaker, 1999). Despite the potentially long time scale for adjustment, the rate of bed change is typically fastest immediately after the perturbation and decreases over time.

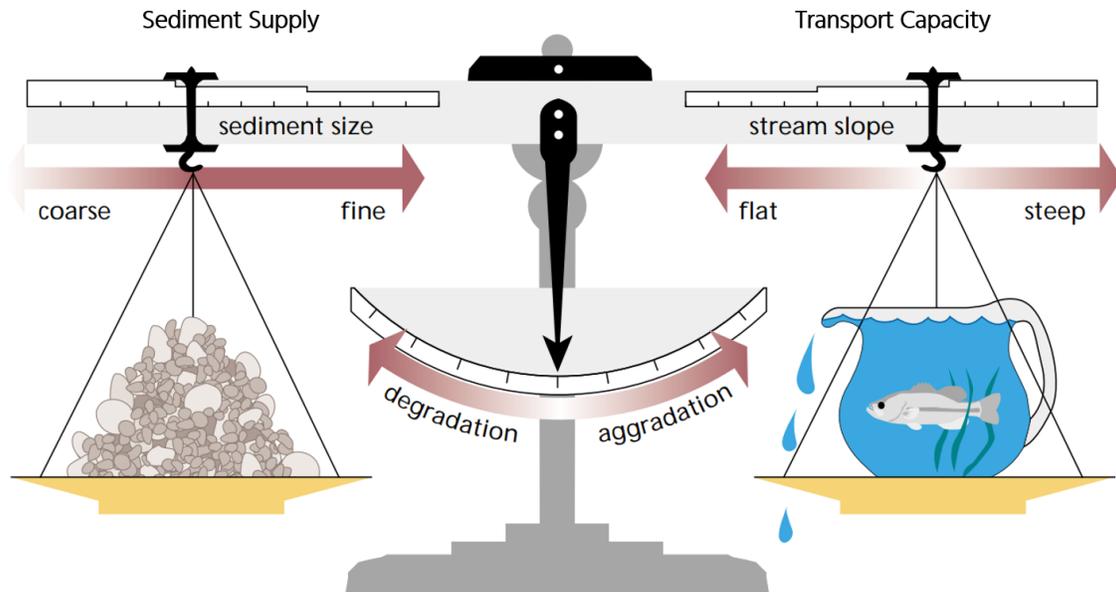


Figure 4.2: Diagram demonstrating the balance between sediment supply and transport capacity in a river. Schematic adapted from Stein et al. (2012) based on concepts from Lane (1954), Rosgen (1996) and Federal Interagency Stream Restoration Working Group (1998).

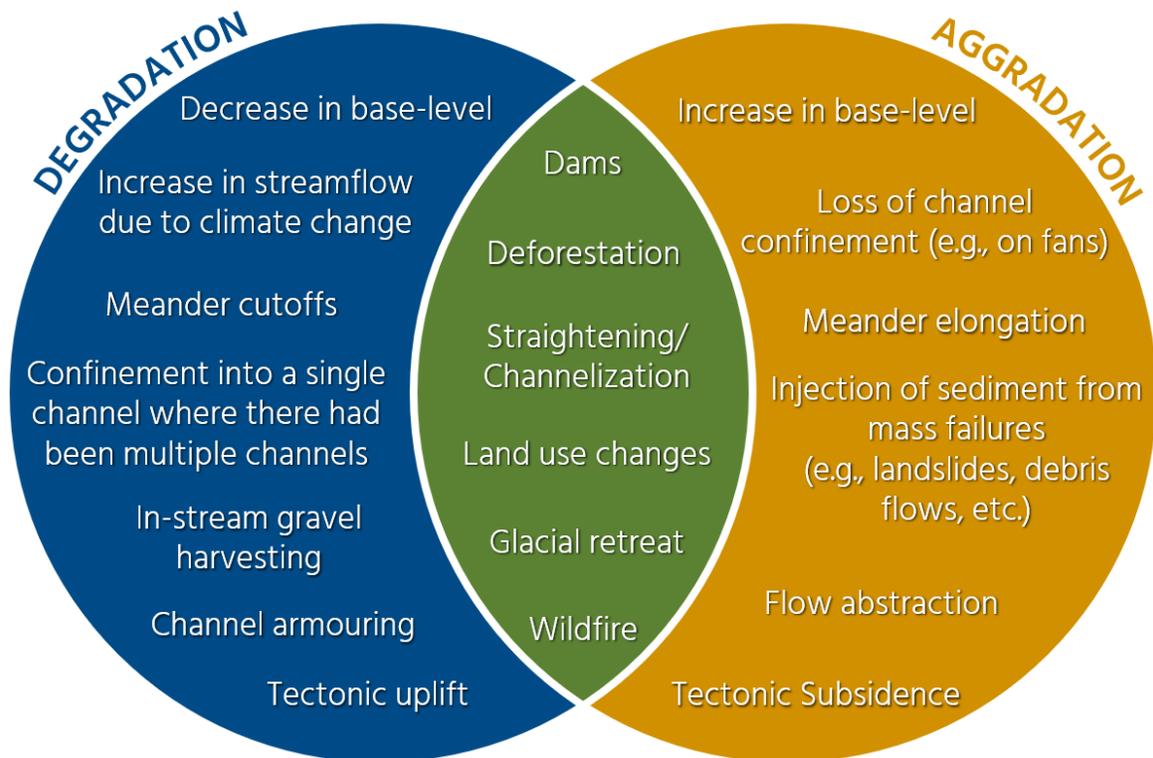


Figure 4-3. Example trigger mechanisms driving degradation and aggradation in rivers.

Avulsion

Rivers can change their course during floods, carving a new flow path or occupying an active or abandoned side channel in the floodplain. This process, termed avulsion, involves a combination of flood inundation and vertical erosion. Avulsions occur mainly through cutoffs between meander bends in high-sinuosity, low-gradient meandering rivers, and through side channel creation or reoccupation in wandering or braided rivers (Konrad, 2012) ([Figure 4.4](#)). Regardless of the mechanism, avulsions tend to occur within the limits of historical river migration (Olson et al., 2014).

Meander cutoffs in low-gradient rivers occur in response to gradual bank erosion at the outer bank of meander bends ([Figure 4.4](#)). Over time the outward growth of meanders leads to an increase in channel sinuosity. As the river length increases relative to the valley length, the channel gradient and erosive capacity of the flow both decline. When the gradient of the potential cutoff path becomes high enough relative to the gradient of the meander bend, an avulsion will occur as the river abandons the parent channel and follows a new, shorter and steeper path between meander bends (Slingerland & Smith, 2004). Meander bend cutoffs can occur as either neck cutoffs or chute cutoffs. Neck cutoffs occur when two meander bends intersect because of erosion on successive bends, while chute cutoffs involve the formation of a new channel on the floodplain between two meander bends ([Figure 4.4](#)).

Channel switching in steeper gradient rivers involves the same processes as a chute cutoff between meander bends: the river carves a new path on the floodplain or occupies an active or abandoned side channel. However, this process can also occur in the absence of meander bends, especially in laterally active wandering or braided reaches. The large sediment deposits present in wandering and braided reaches, as well as the shallow and wide geometry associated with these morphologies, promote overbank flow and the formation of new channel paths (Desloges & Church, 1989) ([Figure 4.4](#)). Channel avulsions are therefore common in aggrading environments characterized by high sediment supply such as alluvial fans.

Ice Effects

Geomorphic change can also occur through mechanical scouring of the riverbed and banks by ice or through fluvial erosion during releases of ice-dammed flow. Ice jams are relatively common on Canadian rivers, with the eastern and northern regions of the country being generally more prone to ice jam events than western provinces (Rokaya, Budhathoki, & Lindenschmidt, 2018). Ice jams can impact river morphology both during the passage of the ice jam release wave during breakup of the jam and associated ice run (Beltaos, 2007, 2008). During a release, abrupt drops in upstream water levels can also lead to bank failures resulting from a sudden decrease in pore pressures (Beltaos,

2008). The factors involved in the formation of ice jams and the magnitude of flood events associated with their breakup are often extremely variable (Pawlowski, 2020). These complexities indicate that changes to river morphology as a result of a breakup event are generally unpredictable.

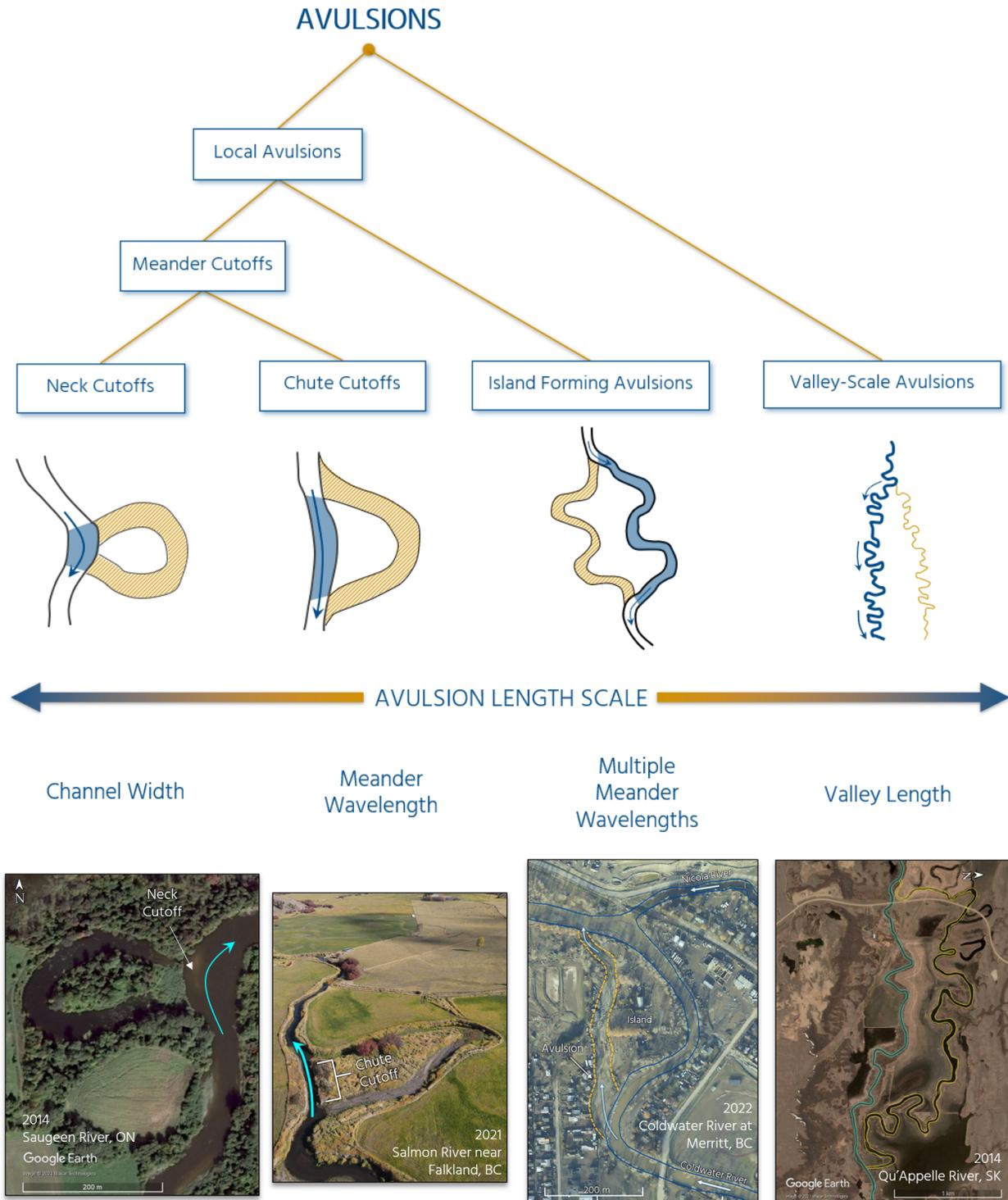


Figure 4.4: Typical avulsion types at various length scales, after Olson et al., 2014. Photo credits: (a) Google Earth, September 24, 2014; (b) Ecoscape Environmental Consultants Ltd, October 18, 2021; (c) Google Earth, December 12, 2021; (d) Google Earth, May 6, 2014.

4.1.2 Geomorphic Characterization

The nature and intensity of clearwater geomorphic processes occurring within a study watershed or reach govern both the analysis methods that should be used and mapping products that should be developed. The first step when incorporating geomorphic considerations into flood mapping is to identify the relevant geomorphic processes within the study area. Air photos, satellite imagery, or other high-quality imagery can be used to assess changes in the watershed and study area over time. At the coarsest scale, this may involve simply looking at historical imagery to identify changes in the river location or channel pattern, as well as sources of sediment supply within the watershed. In a more detailed study, or in cases where significant river change is identified, a practitioner may wish to map and quantify changes over time by georeferencing historical air photos and delineating the location of the riverbanks in each imagery year.

Given the subjectivity inherent in a historical assessment, it is recommended to develop standard protocols to be used in the study to ensure consistency between practitioners, or to have a single practitioner complete the historical data review. Protocols may include standardizing the number of control points to use for georectifying, the scale of air photos to include, and the process for delineating the riverbanks (e.g., at the edge of vegetation at a defined scale). The required scale of the imagery will vary based on the river size, but in general the river should be clearly visible in the imagery. Photos with poor resolution or shadows should be avoided to reduce the error associated with the analysis. It is recommended that practitioners use as long a record as possible; air photos are available from at least the 1950s onward in most parts of Canada. In some locations air photos can also be supplemented with earlier maps that show river locations or land parcel boundaries.

Lidar data is becoming increasingly available and affordable and can also be used to identify landforms that indicate past river migration (e.g., oxbow lakes or abandoned channels) as well as sediment sources (e.g., landslides). Digital elevation models (DEMs) generated from lidar data can be used to create relative elevation models (REMs) that show the floodplain elevation relative to the river elevation, as shown in [Figure 4.5](#), and provide evidence of the lateral extent of historical migration (see Olson et al., 2014 for detailed methods).

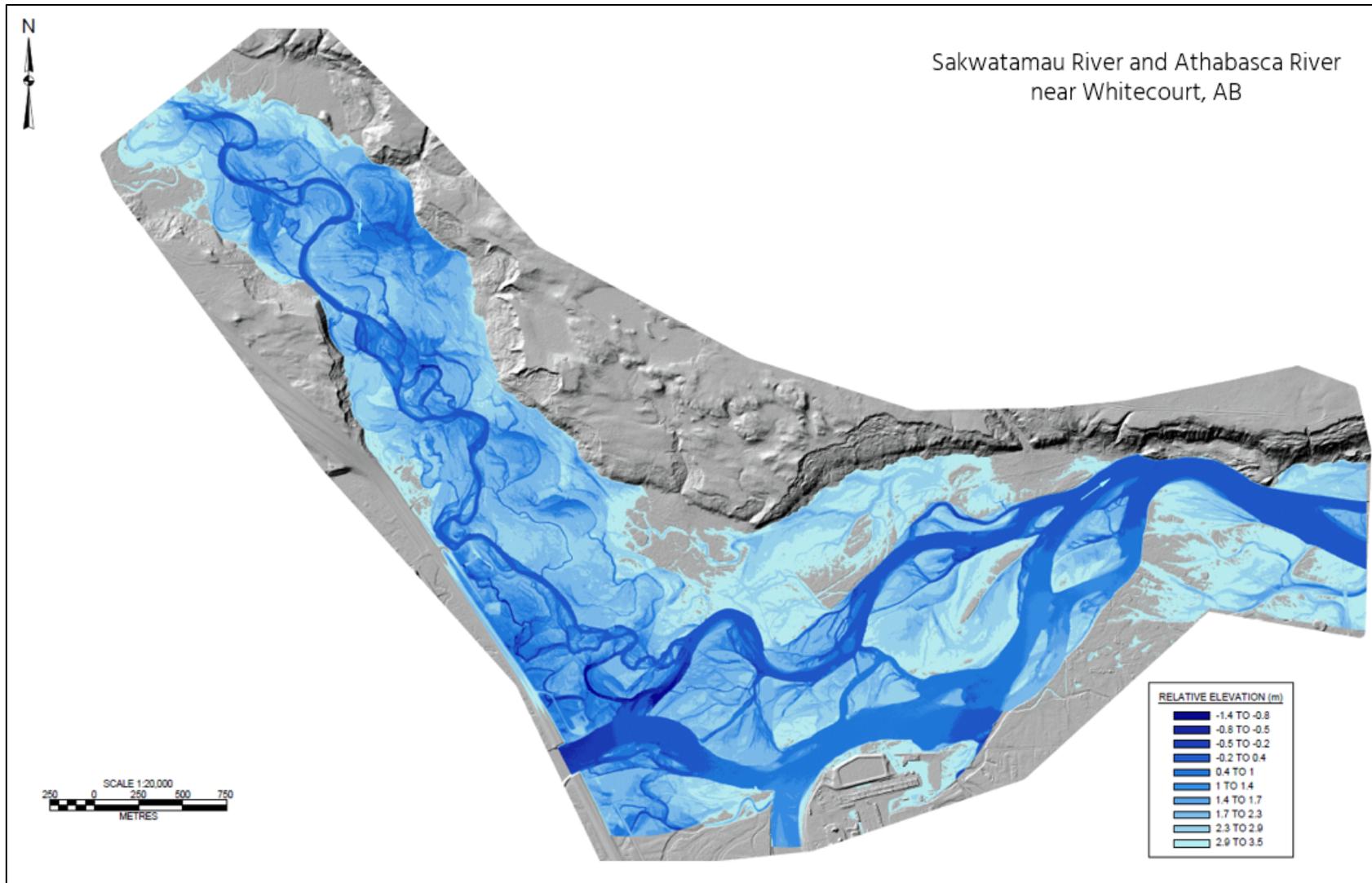


Figure 4.5: REM showing the elevation of the valley bottom relative to the Athabasca River and Sakwatamau River elevations.

Landforms visible in lidar can be used to indicate whether a reach is aggrading or degrading. The presence of river terraces in a valley, for example, indicates that the river has or is currently undergoing a period of degradation. Some channels may have published aggradation or degradation rates due to the impacts they may have on existing infrastructure, such as bridges, and can be used to characterize the rate of the observed vertical change. Similarly, data from hydrometric station rating curves can be leveraged to quantify trends in bed elevation (e.g., Stover & Montgomery, 2001).

Where multiple lidar datasets are available, change detection can also be used to quantify changes in the riverbed elevation through aggradation or degradation, to monitor the upstream progression of knickpoints, and to identify bank erosion, avulsion, or hillslope failures occurring between the lidar datasets ([Figure 4.6](#)). Bathymetric surveys from two or more years can also be compared to quantify channel changes.

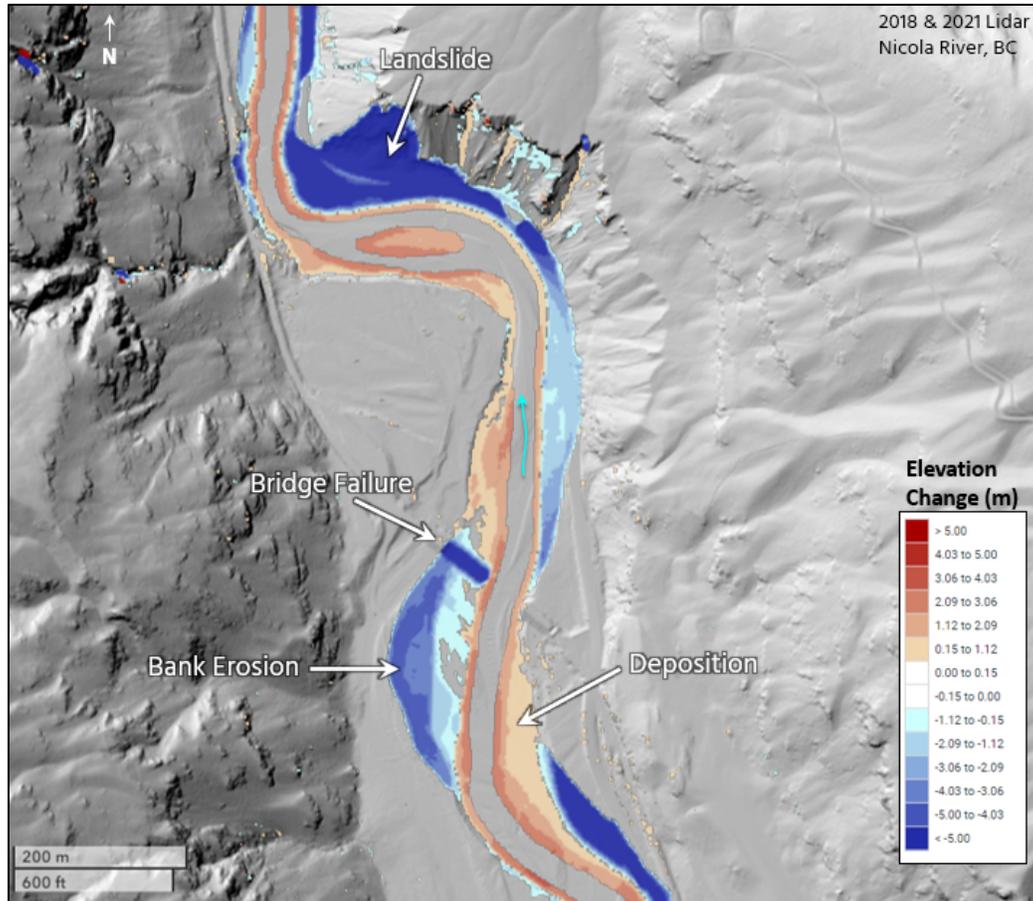


Figure 4.6: Lidar change detection between datasets from April 2018 and December 2021 on the Nicola River in BC. Blue colours indicate negative vertical change and red colours indicate positive change.

4.1.3 Modelling and Mapping Methods

Flood mapping typically relies on hydraulic modelling, completed using hydraulic software packages such as HEC-RAS (Brunner & CEIWR-HEC, 2021), to simulate flood inundation extent, flow depths, and velocities. Although flow bulking is not a concern during clearwater floods, sediment deposition may warrant consideration; sediment, large woody debris, and other debris can block flood infrastructure (e.g., culverts, bridges) or river channels, increasing flood depth through a backwater effect or raising the riverbed elevation. Erosion and avulsion can also shift the location or size of the river, changing the hydraulics in a floodplain.

Depending on the objectives of the mapping study and the relevant hydrogeomorphic processes in the reach, it may be warranted to model multiple flood scenarios for each flood discharge. Examples of potential scenarios include:

- Culvert blockage: this can be modelled by simply removing culverts from a hydraulic model, which is effectively equivalent to full blockage as a backwater will develop and the flow will adopt a new path.
- Aggradation: this can be simulated by raising the riverbed elevation throughout the study area or in local areas where aggradation is anticipated during a single flood event or gradually over time (e.g., based on historical aggradation rates). In the case of clearwater floods, this can be especially important in locations where protective works are present (e.g., dikes) as progressive aggradation reduces freeboard, potentially resulting in overtopping or breaching of flood infrastructure.
- Degradation: similar to aggradation, this can be simulated by lowering the riverbed elevation. Although degradation will likely reduce flooding extents, it may increase the erosive capacity of the flow due to increased confinement, potentially increasing bank erosion and slope failures. These processes should be considered separately as they are not adequately captured by hydraulic models.
- Avulsion: if a potential avulsion path has been identified based on existing side channel locations or a REM, the model terrain can be adjusted to reflect the predicted future alignment (e.g., by ‘burning in’ a new main channel into the terrain and/or infilling the existing main channel).
- Bank erosion/widening: this can be modelled by adjusting the terrain to reflect the predicted widened geometry of the river.

The model adjustments presented above should be used to compare hypothetical future scenarios, not to predict exact hydraulics, as avulsion locations and erosion extents are difficult to predict based on flood magnitude alone. In studies where hazard probabilities are quantified, a probability of occurrence can be assigned to each modelled scenario; the probability will likely vary with flood magnitude in most cases (e.g., the probability of culvert/bridge blockage increases in larger floods while the probability of the unblocked flow scenario decreases). Sensitivity testing is also recommended to assess the sensitivity output to the scenario values (e.g., aggradation depth) and the scenario probabilities.

In cases where erosion or avulsion pose a hazard they may warrant consideration in separate hazard maps. Erosion or avulsion hazard mapping involves identifying areas in a valley or on a fan that are susceptible to river migration (i.e., avulsion or bank erosion). This should be considered where there is potential for significant lateral change in a single event, or where there is potential for substantial cumulative, progressive changes over the time horizon considered in the mapping study.

Most erosion and avulsion mapping methods employ some combination of the following approaches: (1) identifying the active area around the river, (2) characterizing erosion magnitude to define a setback distance or hazard severity, and (3) adding an additional setback to account for uncertainty or access requirements. Which components a study should include, as well as the preferred approach and level of detail, will depend on the study objectives and geomorphic setting. Simpler approaches like defining a standard setback distance or defining the setback distance based on some characteristic discharge have been used in the past (e.g., Simons, Li, & Associates, 1996 in FEMA, 1999) but are not recommended in laterally-active rivers as they do not account for differences in sediment supply or lateral stability between different settings (e.g., [Figure 3.1](#)).

The active area around a river can be delineated most simply by defining the meander belt, a corridor that includes the full extent of all meander bends within a reach ([Figure 4.7](#)) (e.g., Parish Geomorphic, September 27, 2001; Rapp & Abbe, 2003). Other more robust methods involve defining the historical migration zone (HMZ) of the river, also sometimes called the modern valley bottom (MVB) (e.g., Piégay et al., 2005; Olson et al., 2014). The HMZ (or MVB) includes all areas that have been historically occupied by the river based on an air photo analysis or landforms visible in lidar and can most easily be identified by creating an REM of the valley bottom or fan (especially in wandering or braided rivers). Olson et al. (2014) provide detailed methods for creating REMs and delineating the HMZ.



Figure 4.7: Example of a meander belt on the Annapolis River in Nova Scotia. Belt width varies with meander amplitude and Reach 1 has a wider meander belt than Reach 2. Photo credit: ESRI World Imagery, October 12, 2019.

The approach used to characterize the future erosion magnitude (and/or erosion setback) will depend on the channel pattern – and lateral stability – of the river within the study area. In the case of some low-gradient meandering rivers that are subject to slow progressive erosion, it may be sufficient to define the potential erosion zone based on the width of the meander belt or the bankfull width. For example, some guidelines have recommended defining a ‘meander belt allowance’ based on a set number of bankfull widths from the centre of the meander belt, or by adding a single meander belt width to the outside of the existing meander belt (e.g., Ontario Ministry of Natural Resources [OMNR], 2002). These approaches do not explicitly consider the historical rate of lateral migration and should therefore be used with caution.

In laterally active rivers it is recommended to use more robust methods to predict the location and extent of erosion. Future erosion can be estimated by projecting forward the observed historical rate of erosion over a defined time horizon, while avulsion hazard areas can be defined based on REMs or hydraulic modelling (e.g., Olson et al.,

2014). This approach is most appropriate in meandering rivers experiencing progressive erosion. Cellular-based approaches have also been proposed that predict the location of future erosion based on the relationship between river characteristics and past erosion locations (Graf, 2000; Le Cozannet et al., 2020).

In some cases, an event-based erosion magnitude may be needed to account for the probability of erosion within an area during a given flood. In rivers with cohesive banks, event-based meander bend erosion can be modelled using the Bank Stability and Toe Erosion Model (BSTEM), which simulates fluvial entrainment of the bank toe followed by slab failure over the overlying cohesive bank material and can be run through HEC-RAS (1D only) or independently in Excel© (see Simon, Pollen-Bankhead, & Thomas, 2011 for a detailed explanation of the model).

In gravel-bed rivers the bed and bank stability are believed to be governed by the stability of the coarse fraction of the bed material; when the coarse tail of the bed material (e.g., D_{84}) is mobilized the river becomes unstable and widening progresses until the coarse material re-deposits (Eaton, Mackenzie, & Booker, 2020). Widening in gravel- or cobble-bedded rivers with non-cohesive banks can therefore be estimated based on flood hydraulics and grain size using the methods presented in Jakob et al. (2022).

When predicting the location or magnitude of future erosion it is important to consider the soils and geology within the erosion hazard area. Erosion is unlikely to progress into areas containing bedrock and will be slowed by less erodible surficial material such as basal till or colluvial fan deposits, relative to the historical erosion observed in areas containing floodplain or glaciofluvial deposits. High terraces of typically erodible material may also experience less erosion than anticipated because of the larger volume of material present (Bufe et al., 2019).

When determining setback distances or erosion allowances, it may be necessary to add an additional allowance for slope failure and/or other considerations such as access requirements. While high terraces may limit the progression of erosion at the observed historical rate, undercutting of the toe may cause hillslope failures that have the potential to impact infrastructure at the top of the slope. In such cases a geotechnical setback should be considered and will vary based on the slope geometry, soil composition, and failure mechanism (e.g., Olson et al., 2014). An additional setback may also be needed for emergency or construction access (e.g., 6 m according to OMNR, 2002).

Erosion and flood protection measures should also be considered, where present. Although these measures (e.g., riprapped dikes) may limit or prevent erosion during most flows, they can also fail during flood events, especially if armouring is undersized

or poorly placed or if the flood magnitude exceeds the design event. In detailed studies where flood protection infrastructure is present it may be warranted to evaluate the stability of the works during a range of floods (e.g., by comparing modelled velocities to riprap sizing) or to simulate breaches in the protective works.

4.2 Debris Floods

4.2.1 Process Description

Within the past 20 years (Hungar et al., 2001; Wilford et al., 2004), the English term 'debris flood' has come into use to describe severe floods involving exceptionally high rates of coarse bedload transport in steep channels, relative to the rates observed during clearwater floods. Debris floods typically occur on rivers with channel gradients between 5% and 27% but can also occur on lower gradient gravel-bed rivers.

Bedload transport in gravel-bed rivers has been characterized in three stages (Carling, 1988; Ashworth & Ferguson, 1989). In stage 1, fine material (typically sand) overpasses a static (i.e., stable) bed or is mobilized by winnowing from an otherwise static bed. Streamflows are insufficient to mobilize the bed material at this stage. In stage 2, bedload transport occurs at low rates with individual clasts mobilized from the bed surface. This state is defined as "partial transport" by Wilcock and McArdeil (1993) and most of the bed remains stable. In stage 3, the entire streambed becomes mobile, and activity may extend to a depth of several median grain sizes below the surface as the result of momentum transfer by grain-grain collisions. A debris flood is then a case of stage 3 transport. Debris floods are two-phase flows, with 'clear water' or water with substantial suspended sediment load, overlying a slurry-like flow containing a high concentration of bed material, the finest fractions of which may be suspended (Manville & White, 2003). Debris floods are relatively rare because stage 3 transport is rare in gravel-bed channels.

Church and Jakob (2020) developed a three-fold typology for debris floods, which had previously not been well defined. The three types hinge upon the triggering mechanisms, but in all cases full bed mobilization is triggered by the exceedance of a critical force acting on the bed:

- Type 1: a debris flood occurs gradually in association with a storm hydrograph and the concomitant increase in flow depth and shear stress (i.e., stage 3 sediment transport).
- Type 2: a debris flood develops abruptly through dilution from a debris flow in which the flow mechanics switch from visco-plastic to Newtonian.

- Type 3: a debris flood initiates through the collapse of a moraine, ice, landslide, beaver or artificial dam. Additional details of Type 3 debris floods are provided in Jakob, Clague, and Church (2015).

While large-scale bed mobilization and bank erosion are all expected outcomes, each debris flood process type will result in different volumes of debris being generated, different discharges, sediment concentrations, and scale of bank erosion ([Table 4.1](#)).

Table 4.1: Debris flood typology and associated characteristics (after Church and Jakob, 2020).

Term	Typical Sediment Concentration (% by volume)	Typical Q_{\max} Factor (i.e., maximum discharge relative to clearwater discharge)	Typical Return Period (years)
Type 1 (meteorologically generated debris flood)	<5	1.05	>2 (>50% AEP)
Type 2 (debris flow to debris flood dilution)	<50	2 to 5 (but possibly larger)	>50 (>2% AEP)
Type 3 (outbreak floods)	<10	2 to 100 (dependent on size of dam and distance to dam failure)	>100 (>1% AEP)

Hyperconcentrated flows are a special case of debris flood that can occur as Type 1, 2 or 3 debris floods. The term hyperconcentrated flow was defined by Pierson (2005) as “a type of two-phase, non-Newtonian flow of sediment and water that operates between normal discharge (water flow) and debris flow”. However, the use of the term hyperconcentrated flow should be reserved for volcanic or weak sedimentary fine-grained slurries, where the concentration of suspended fine sediments is sufficient to impart yield strength to the fluid and maintain high fluid viscosity (Pierson, 2005). In such flows, sands and gravels are kept in suspension by turbulence and dynamic grain interactions.

4.2.2 Geomorphic Characterization

A general goal of debris flood characterization is the development of a frequency-magnitude

(F-M) relation. The relation addresses the question “how often do events of different magnitudes occur?”. The ultimate objective of an F-M analysis is to develop a graph that relates the return period of the hazard to its magnitude (e.g., peak discharge or sediment volume). The resulting F-M curve then forms the key input to modelling-based hazard mapping.

Jakob et al. (2022) provides a comprehensive methodology to assess debris-flood hazards and is a recommended resource for practitioners. These methods include desktop studies and field investigations. The latter includes air photo and satellite image interpretation and analysis, review of lidar data, and historical accounts (see the recommended methods in Section [4.1.2](#)). Field investigations include dendrogeomorphology, test trenching for stratigraphic logging and radiocarbon dating of organics deposited within debris-flood deposits, and bed material sampling. These techniques can be supplemented by an empirical relation between net sediment deposited on fan surfaces and the effective runoff, and sometimes average river gradient, as identified by Rickenmann and Koschni (2010) and validated by work in the Bow Valley, Alberta (Jakob et al., 2022).

Engineers & Geoscientists British Columbia (EGBC, 2018) have published guidelines that specifically address debris flood hazard assessments. Those guidelines are intended for new developments and include the suggested level of effort, typical deliverables, and return periods to be considered. The required level of effort and return periods considered vary according to the type of development application.

4.2.3 Modelling and Mapping Methods

Debris-flood hazard assessment typically involves the use of hydrodynamic models to simulate potential inundation areas and flow intensities. Hydraulic software packages such as HEC-RAS (Brunner & CEIWR-HEC, 2021), FLO-2D (FLO-2D Software Inc., 2017), and BASEMENT (Vetsch et al., 2020) can identify inundation area and predict flow depth and flow velocity with reasonable accuracy, given credible input hydrographs. Sediment transport algorithms can also be used in these models with varying degrees of success to simulate zones of aggradation and degradation.

Erosion and avulsion generally cause most of the damage associated with debris floods (Jakob, Clague, & Church, 2015) and are therefore vital to consider in debris flood-prone systems. Due to their higher volumetric water concentration, debris floods are typically more erosive along alluvial channel banks than debris flows. Bank erosion and excessive amounts of bedload introduce substantial sediment to the river system. This sediment accumulates (aggrades) in reaches with decreased gradient, often leading to avulsions. Because storm hydrographs typically fluctuate several times during a given storm, several cycles of aggradation and remobilization of deposited sediments on channel and fan reaches can be expected.

Given the high rate of sediment transport and avulsion potential in a debris flood event, it is recommended to model various scenarios. Example model scenarios include:

- Bridge or channel blockage: this can be modelled by removing bridge openings to produce full blockage of the flow or by simulating an impediment to the flow within the channel (e.g., landslide dam).
- Aggradation: this can be simulated by raising the riverbed elevation throughout the study area or in local areas where aggradation is anticipated during a single flood event as aggradation has the potential to cause avulsion, including in reaches with flood protection (e.g., dikes) by increasing the likelihood of overtopping. Some hydraulic models are capable of modelling sediment transport with the user able to choose from a range of empirical equations. However, many of these bedload transport equations tend to overpredict transport rates in debris-flood prone creeks and rivers, as they were developed for lower gradient rivers.
- Avulsion: similarly, if a potential avulsion path has been identified based on existing side channel locations or a REM, the model terrain can be adjusted to reflect the predicted future alignment (e.g., by ‘burning in’ a new main channel and/or infilling the existing main channel).
- Flow bulking: in simulating debris flood events it is typically necessary to bulk the flow to account for the high sediment concentration (as described in Section [4.1.3](#)). Given the uncertainty in bulking values, it can be prudent to model the same event with multiple bulking values (i.e., sensitivity testing).
- Bank erosion/widening: this can be modelled by adjusting the terrain to reflect the predicted widened geometry of the river.
- Protective works: the high stream power associated with debris floods can destabilize armouring (e.g., riprap), which is typically designed for clearwater floods, through erosion and undermining. The effects of the failure of flood protection works can be modelled by artificially breaching or removing structures such as dikes.

[Figure 4.8](#) provides an example of debris flood intensity mapping for scenarios with the same debris flood magnitude. The more extensive aggradation modelled in [Figure 4.8b](#) produces more widespread inundation across the fan while reducing flood intensity in the main channel.

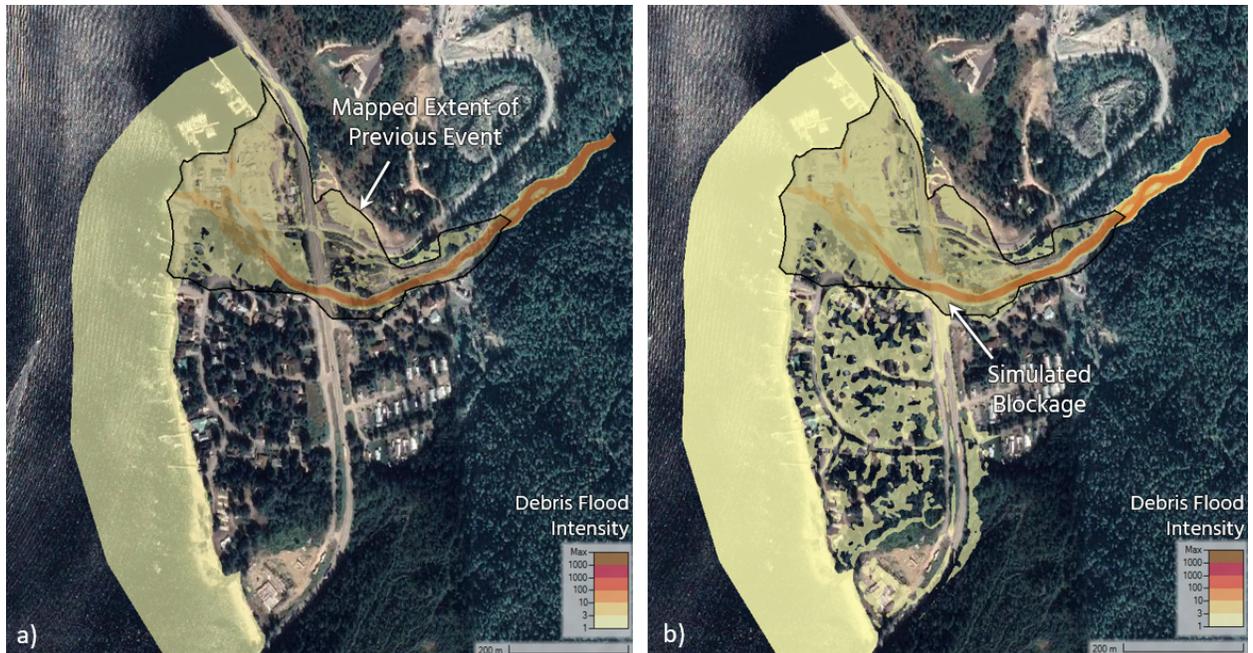


Figure 4.8: Modelled debris flood intensity (where $I = dxv^2$) for the same event magnitude under two different scenarios: a) following aggradation on the lower fan, downstream from the highway bridge, and b) following more severe aggradation extending to the upper fan and blocking the highway bridge. Photo credit: Google Earth, August 12, 2020.

Bank erosion poses a major hazard in debris flood-prone systems and the potential damage due to bank erosion may warrant separate consideration. Bank erosion is a complex process that depends on many factors, including the bank material, bank height and gradient, channel geometry, bed and bank grain size distributions, amount and type of vegetation, and flood duration (Church & Jakob, 2020).

Hydrodynamic models are not yet capable of simulating bank erosion during a debris flood event, and it should therefore be considered separately from the hydrodynamic modelling described above. Debris flood-prone channels typically have coarse bed material and non-cohesive banks; erosion in these settings therefore typically occurs through rapid channel widening and can be estimated using the approach described in Jakob et al. (2022). This method can be used to predict the erosion extent for a range of return periods throughout the length of a river and therefore lends itself to mapping erosion hazard zones.

Where possible the erosion modelling should be calibrated to observed erosion from a historical assessment. In cases where armouring is present, the modelled hydraulics can be used to evaluate the potential stability of the bank protection under a range of flows. If there is potential for destabilization of the armouring, this can be simulated by modelling the potential erosion without armouring.

4.3 Debris Flows

4.3.1 Process Description

Debris flows were first recognized in Canada in the 1940s; however, most studies of the topic have been carried out since the early 1980s. A bibliography of Canadian debris flows is provided in VanDine and Bovis (2002). That bibliography contains 295 citations which are categorized into various subjects and geographical areas.

A 'debris flow', as defined by Hungr, Leroueil and Picarelli (2014), is a very rapid, channelized flow of saturated material containing fine-grained sediment (i.e., sand and finer fractions) with a plasticity index of less than 5%. Debris flows are typically initiated by a sideslope debris avalanche that impacts the main channel at an oblique angle and transfers its momentum to the channel. Liquefaction occurs shortly after the onset of landsliding due to turbulent mixing of water and sediment, and the slurry begins to flow downstream, 'bulking' by entraining additional water and sediment until saturation is reached (often at 6,070% sediment concentration by volume). Bulking may entail entrainment of the entire loose channel substrate, often leading to scour to bedrock in the transport zone. Coarse granular debris flows require a channel gradient of at least 27% for transport over significant distances (Takahashi, 1991). Transport is possible at lower gradients, with the silt-clay fraction being the most important control on debris-flow mobility (Jakob et al., 2015).

Post-fire debris flows are a special case where the lack of vegetation and root strength can lead to abundant rilling and gullying. These processes deliver sediment to the main channel where it mixes with water, leading to the formation of debris flows. In those cases, no single source or sudden liquefaction is required to initiate or maintain debris-flow mechanics.

Unlike debris avalanches, which travel on unconfined slopes, debris flows travel in confined channels bordered by steep slopes. The front of the rapidly advancing flow is steep and commonly followed by several secondary surges that form due to particle segregation and upwards or outwards migration of boulders. 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 along the channel that become part of the debris-flow depositional legacy. Similarly, depositional lobes are formed where frictional resistance from unsaturated coarse-grained or wood-rich fronts is high enough to slow and eventually stop the motion of the trailing liquefied debris.

4.3.2 Geomorphic Characterization

As with debris floods, a general goal of debris flow characterization is the development of an F-M relation, which relates debris flow frequency to a range of magnitudes. Debris flow frequencies and magnitudes can be reconstructed through application of many of the same methods used for debris floods. Additionally: (1) Griswold and Iverson (2014) developed empirical relations between area inundated by debris flow and volume, (2) correlation of dated deposits between test trenches can provide three-dimensional resolution of the fan's architecture and estimates of event volumes (Jakob, 2005; 2013), (3) Jakob et al. (2020) developed regional frequency-magnitude relationships for southwest British Columbia and southern Alberta, and (4) where only peak discharges or debris flow volumes can be measured, empirical relations between these two parameters can be used (Mizuyama, Kobashi, & Ou, 1992; Jakob & Bovis, 1996; Rickenmann, 1999). Additional Canadian guidance is provided by Hungr et al. (1984), VanDine (1985), Bovis and Dagg (1992), and Bovis and Jakob (1999), amongst others.

The resulting F-M curve forms the key input to modelling-based hazard mapping. Similar to debris floods, EGBC (2023) have published guidelines that specifically address debris flow hazard assessments.

4.3.3 Modelling and Mapping Methods

There are numerous software packages that can model the non-Newtonian rheology of debris flows, including the afore-mentioned HEC-RAS and FLO-2D. Other debris-flow models include RAMMS (Frank et al., 2017), D-Claw (George & Iverson, 2014; Iverson & George, 2014), and ProDF (Gorr et al., 2022). An overview of the current state of debris flow modelling is provided in Trujillo-Vela et al. (2022).

Sudden loss of confinement and decrease in channel gradient cause debris flows to decelerate, drain their inter-granular water, and increase shearing resistance, which slow the advancing bouldery flow front and block the channel. The more fluid afterflow (hyperconcentrated flow) is then often deflected by the slowing front, leading to secondary avulsions. Because debris flows often display surging behaviour, in which bouldery fronts alternate with hyperconcentrated afterflows, the cycle of coarse bouldery lobe and levee formation and afterflow deflection can be repeated several times during a single event. These flow aberrations and varying rheological characteristics pose a challenge to numerical modelers seeking to create an equivalent fluid (Iverson, 1997, 2014).

Despite these challenges, researchers have increasingly had success in using non-Newtonian hydrodynamic models to model the extent of debris flow inundation (e.g., Jakob et al., 2013; Gibson et al., 2022; Yilmaz et al., 2022). Researchers have found

that model performance is most sensitive to debris flow volume and less sensitive to flow properties (e.g., Barnhart et al., 2021), illustrating the importance of accurately characterizing the hazard.

As with clearwater floods and debris floods, it is recommended that practitioners consider various scenarios when conducting modelling. These scenarios could include:

- Bridge or channel blockage: this can be modelled by removing bridge openings to produce full blockage of the flow or by simulating an impediment to the flow within the channel (e.g., landslide dam).
- Aggradation: this can be simulated by raising the riverbed elevation throughout the study area or in local areas where aggradation is anticipated during a single flood event. Given the surging behaviour of debris flows, aggradation during earlier stages of the event may increase the likelihood of avulsion during subsequent stages.
- Avulsion: if a potential avulsion path has been identified based on flow paths shown in the debris flow modelling or known historical avulsion locations, the model terrain can be adjusted to reflect the predicted future alignment (e.g., by 'burning in' a new main channel and/or infilling the existing main channel).
- Flow rheology: sediment concentration is high in debris flow events and the flow rheology varies both as function of sediment concentration and percentage of fines. There is typically significant uncertainty in the flow rheology and modelling should be conducted with a range of values.
- Protective works: the high stream power and impact forces associated with debris flows can destabilize armouring (e.g., riprap) and other protective works, which are typically designed for much lower magnitude clearwater floods. The effects of the failure of flood protection works can be modelled by artificially breaching or removing structures such as dikes.

Channel banks can be severely eroded during debris flows, though lateral erosion is often associated with the trailing hyperconcentrated flow phase that is characterized by lower volumetric sediment concentrations. The most severe damage results from direct impact of large boulders or transported wood against structures that are not designed for the impact forces. It is nevertheless important to consider potential avulsion paths and erosion extents based on the observed flow paths from hydraulic models and the predicted erosion from a physically-based bank erosion model (e.g., Eaton et al., 2017; Jakob et al., 2022), combined with geoscience judgement (e.g., [Figure 4.9](#)).

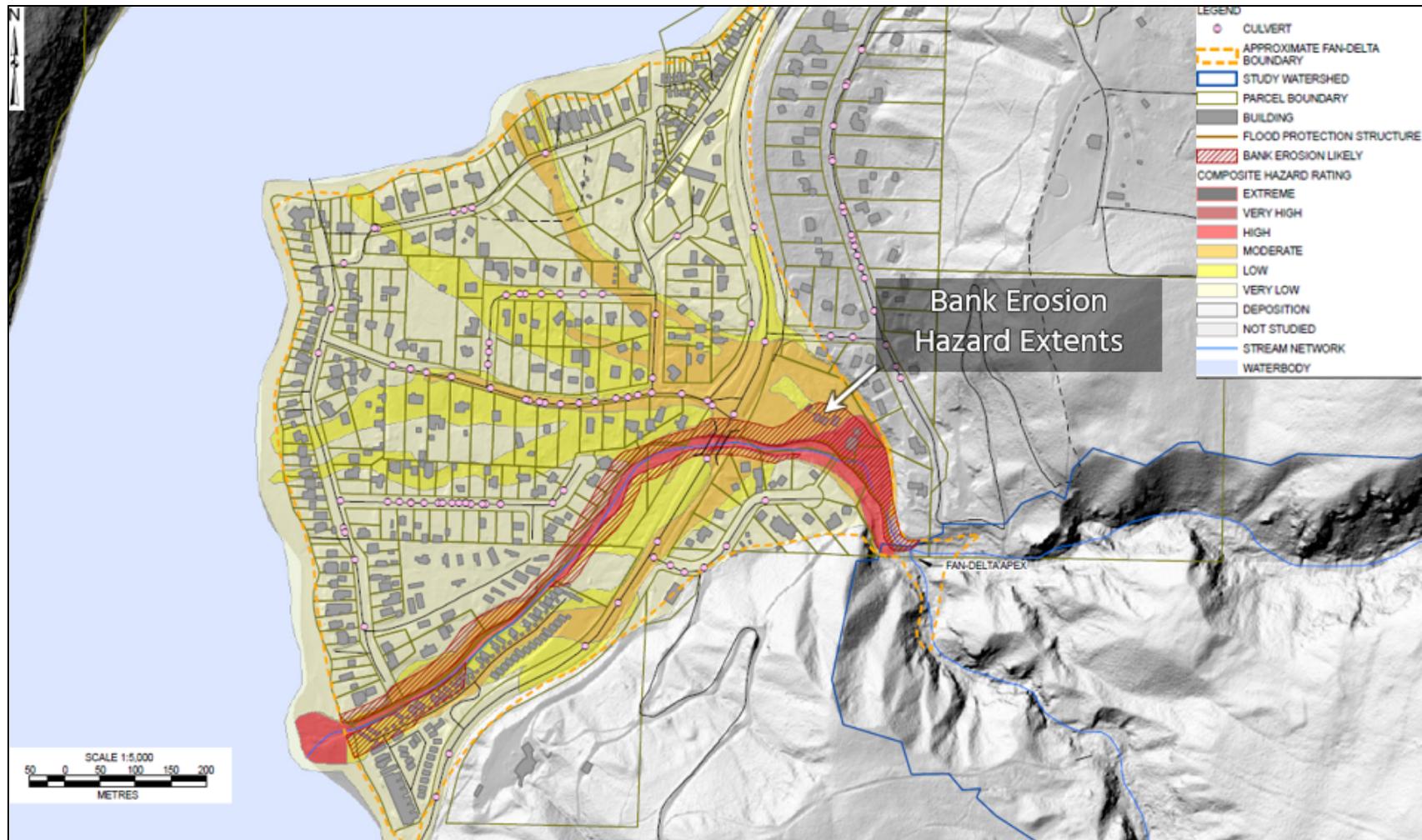


Figure 4.9: Composite hazard map showing combined debris flow hazard for all modelled event magnitudes. The potential bank erosion extent is also shown for the largest modelled debris flow event and was estimated using the methods described in Jakob et al. (2022).

5.0 ADDITIONAL CONSIDERATIONS

5.1 Map Validity

Flood maps reflect the watershed, floodplain, and river conditions at the time that the mapping study was completed. In general, maps should be updated when there are significant changes to the watershed hydrology, sediment supply, or river morphology or location. Where possible, practitioners should provide detailed recommendations to decision-makers about when maps should be updated, including monitoring to identify changes that will trigger requirements for map updates.

Practitioners should consider what landscape changes affect the relevancy of flood maps at a given study location. Depending on the location and dominant hydrogeomorphic process type the following circumstances may impact map validity:

- Occurrence of rare (i.e., high magnitude) clearwater flood, debris flood, or debris flow events
- Wildfire
- Pest infestation (e.g., mountain pine beetle)
- Change in sediment supply (e.g., construction of sediment retention basin or cumulative aggradation)
- Shift in channel pattern (e.g., from meandering to braided)
- Change in the channel location through bank erosion or avulsion
- Change in flood or erosion protection structures (e.g., dikes)
- Culvert addition, replacement, or removal.

Changes to vegetation within the watershed alter the flow of water and the provision of sediment to the river and may be an important consideration, especially in mountain settings. Wildfire, for example, affects both hydrology and sediment supply in the first 3-5 years after a fire, increasing debris flow frequency and magnitude in affected watersheds. The impact is dependent on both burn severity and coverage, and a practitioner may therefore recommend repeating a mapping study if more than a certain proportion (e.g., 20%) of the upstream watershed area is burned.

Given the availability of satellite imagery, observed changes in the river and surrounding hillslopes can also be used to trigger updates to flood maps. A practitioner could recommend that mapping be repeated if the river avulses or shifts outside of the historical migration zone or meander belt. A change in the channel pattern may also

warrant a map update as it indicates changes in the sediment supply and future river behaviour; a transition from a meandering to braided planform, for example, may indicate an increase in sediment supply and aggradation, and may in turn increase flood extent as well as erosion and avulsion potential.

Changes to the flood and drainage infrastructure can also affect the validity of flood maps, especially in urban settings where there are likely to be the most elements at risk. A practitioner may therefore recommend a mapping update if there are any changes to the drainage infrastructure or flood protection (e.g., dike length) within a study area.

5.2 Climate Change

Climate change is impacting temperatures and precipitation worldwide and is changing the timing and magnitude of peak flows in parts of Canada. The impacts of climate change on geomorphic processes are inherently complex as geomorphic response is fairly far removed from changes in temperature, increasing the uncertainty in future behaviour. However, research suggests that some geomorphic processes are likely to occur more frequently, or with greater magnitude, as climate change progresses due to increased rainfall intensity and duration, shifts in hydrological regimes, as well as other factors such as the thawing of permafrost.

The hazards posed by clearwater flooding are likely to increase with climate change in some parts of Canada. Areas with a mixed hydrologic regime – where the largest floods in the year can result from either snowmelt or rainfall – are likely to be the most sensitive to climate change (e.g., Schnorbus, Werner, & Bennett, 2014). This mixed regime is most common in coastal watersheds in BC, where flooding results from both the spring freshet (i.e., snowmelt) and intense rain-on-snow events often caused by atmospheric rivers in the fall and winter.

Climate change is anticipated to produce an increase in the frequency of a given flood magnitude (e.g., shifting a '200-year' flood event to a '50-year' event) and may potentially increase flood magnitudes in affected watersheds (Curry, Islam, Zwiers, & Déry, 2019). These shifts are likely to increase the frequency and/or magnitude of bank erosion associated with clearwater floods and debris floods. Climate change may also impact ice jam dynamics; for example, periodic mild temperatures in the winter may lead to multiple cycles of freezing and break-up in a single winter with the potential for increased scouring and erosion (e.g., Turcotte, Burrell, & Beltaos, 2019).

Climate change also has the potential to impact the frequency of debris flow events through changes in hillslope processes, as debris flows typically initiate from landslides on steep valley sides. Research in southwestern BC found that the frequency of landslides exceeding 10,000 m³ had increased since the early 2000s and projected a

300% increase in shallow landslides by 2100 (Jakob & Owen, 2021). Debris flow volumes were also observed to have increased over the same historical time period. Overall, the increased frequency of intense rainfall and upslope transition of the freezing line is expected to produce more frequent small debris flows as the threshold for full bed mobilisation is exceeded more frequently.

Research on debris avalanches, which can produce very large debris flows, also suggests that their frequency may shift with climate change. The frequency of debris avalanches has been declining over time since glaciation as the effects of glacial debuitressing wane and the landscape stabilizes. However, several recent failures in southwestern BC (at Mount Meager in 2010, James Turner Mountain in 2015, Mount Currie in 2017, and Joffre Peak in 2019) suggest that the frequency of debris avalanches (and very large debris flows) may be increasing as permafrost thaws.

Given the potential impacts of climate change on hydrology, it is now typical in many studies to use projected future streamflow values in hydraulic modelling and flood mapping. However, the potential geomorphic impacts of climate change should also be considered (e.g., increased potential for blockage by landslide dams). This can be accomplished through modelling a range of scenarios, as described in Sections [4.1.3](#), [4.2.3](#), and [4.3.3](#). Climate change is also likely to produce emergent impacts that are not yet well understood or quantified, and practitioners and decision-makers should be prepared to update mapping studies when watershed conditions change (see Section [5.1](#)).

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