

Identification, Prioritization, and Risk Reduction: Steep Creek Fans Crossed by Highways in Alberta

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ABSTRACT

Heavy rainfall in Alberta, Canada, in June 2013 led to one of Canada's most expensive natural disasters, with estimated damage costs exceeding CDN \$6 Billion. Debris flows and debris floods caused highway closures and extensive damages to development on alluvial fans along the eastern slopes of the Canadian Rocky Mountains.

Alberta Transportation retained BGC Engineering Inc. (BGC) to inventory debris flow, debris flood, and/or flood hazards sites for provincially-managed highways, prioritize sites for mitigation, and describe typical mitigation options. This paper describes the component of work involving steep creek alluvial fans associated with about 3,400 km of highways, associated roadside facilities and ramps in southwestern Alberta.

BGC mapped and assigned hazard ratings to 247 alluvial fans crossed by highways. Statistical analysis of watershed attributes was completed to predict hydrogeomorphic or flood processes on alluvial fans. The fans were rated by risk considering the relative likelihood that an event will occur, impact the highway, and result in highway closure. Site-specific risk control design considerations, options, and approximate costs were also provided for high-priority fans, the results of which were presented on an interactive, searchable web application. This application can be used to support decisions for further assessment and risk reduction planning.

RÉSUMÉ

Les fortes pluies du mois de juin 2013 en Alberta ont provoqué une des catastrophes naturelle les plus coûteuses de l'histoire du Canada avec des dommages évalués à plus de 6 milliards de \$CAN. Les coulées de débris et inondations boueuses ont causé la fermeture d'autoroutes et des dommages importants aux infrastructures bâties sur les cônes alluviaux situés le long du flanc est des Rocheuses canadiennes.

Alberta Transportation a retenu BGC Engineering Inc. (BGC) pour dresser un inventaire des coulées de débris, inondation de débris, et aléas d'inondation le long des autoroutes gérées par le gouvernement provincial afin de sélectionner les sites prioritaires pour l'atténuation de l'aléa lié à ces événements et décrire les options typiques d'atténuation du risque. Ce document présente l'étude des cônes alluviaux provenant de cours d'eau à fort gradient associés aux 3,400 km d'autoroute, installations routières, et bretelles d'accès du sud-ouest de l'Alberta.

BGC a identifié et cartographié 247 cônes alluviaux interceptés par le réseau autoroutier. Des analyses statistiques de caractéristiques de bassins versants ont été menées afin de prédire les processus hydrogeomorphiques et hydrologiques sur ces cônes alluviaux. Ces cônes alluviaux ont ensuite été classés suivant leur niveau de risque en tenant compte de l'éventualité qu'un événement se produise, impacte l'autoroute, et entraîne sa fermeture. Les différentes options de réduction du risque propre à chaque site, les mesures à prendre pour chacune de ces options ainsi que leur coût approximatif sont détaillés pour les cônes alluviaux de haute priorité. Ces résultats ont été présentés sous forme d'une application web interactive comprenant une fonction de recherche. Cette application peut servir à justifier la reprise d'évaluations futures ainsi que la planification d'un programme de réduction du risque.

1 INTRODUCTION

In June 2013, three consecutive days of heavy rain in southwestern Alberta triggered the most expensive natural disaster in Canadian history. A low-pressure system, blocked by a high-pressure system to the north, caused 48-hour precipitation to exceed 200 mm in many places along the eastern Rocky Mountains. Flooding occurred along all major river systems and hundreds of debris flows and debris floods were triggered on steeper tributaries (e.g., Figure 1). Province-wide, four lives were lost, 100,000 people were displaced, and transportation corridors were

severed including closure of the Trans-Canada Highway for one week. Direct damage costs exceeded \$6 billion (CDN) and recovery is ongoing (Wood, 2013).

Following immediate response and recovery efforts, the Government of Alberta commissioned studies to improve the understanding and management of flood, debris flood and debris-flow hazard and risk within the province. No systematic, region-wide assessment had been completed of streams that cross, encroach upon, occupy floodplains or drain to alluvial fans intersecting Alberta's highways. Alberta also lacked a province-wide inventory of developed "steep creek" fans subject to debris flow, debris flood or flood hazards (herein referred to as

hydrogeomorphic hazards). Steep creeks are defined as those containing channel gradients equal to or exceeding approximately 5% (Church, 2013).



Figure 1. Trans-Canada Highway at the Town of Canmore on June 20, 2013. Photo: Town of Canmore

This paper focuses on assessment of steep creek alluvial fans crossed by Alberta highways, including hazard characterization, risk-based prioritization and development of typical risk reduction options for the high priority sites. All identified alluvial fans are located within or along the eastern slopes of the Rocky Mountain Region, a 51,000 km² area bordering the western edge of the province (Figure 2).

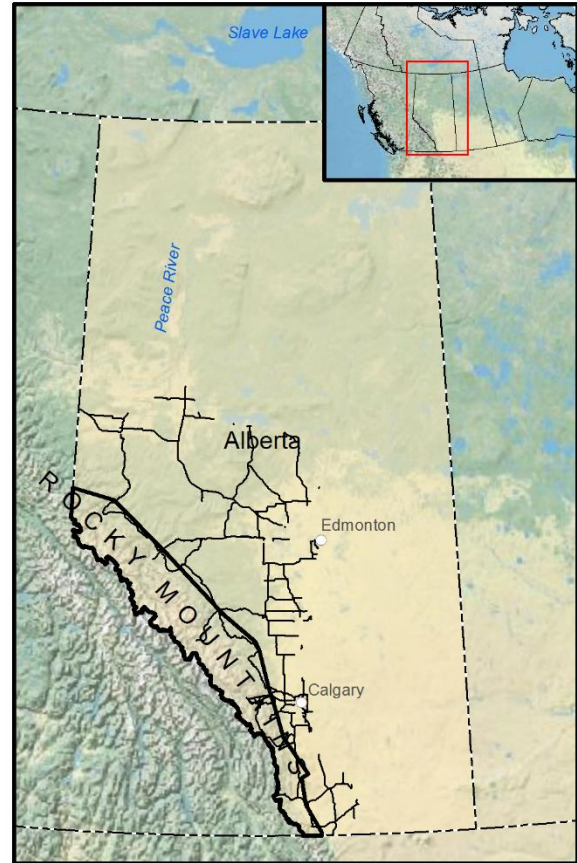


Figure 2. Alberta steep creek fan study area (black outline) intersecting provincial highways (black lines)

1.1 Study Area

The study area is underlain by faulted and folded sedimentary rocks and contains four major river basins, with some glaciation in their headwaters. Furthest north, the Peace/Slave and Athabasca basins drain northeastward to the Arctic Ocean. In the mid and southern Rockies, the North and South Saskatchewan basins drain eastward towards Hudson's Bay. The South Saskatchewan River Basin contains the Red Deer, Bow River and Oldman River sub-basins. These sub-basins, particularly the Bow River watershed, contain most of the developed fans within the study area. Most of these fans originated during the transition from glaciation to deglaciation at the end of the late Pleistocene (approx. 11,700 years BP), as geomorphic processes supplied sediment to the channel system and conveyed to the fans. Sediment yields were highest immediately following deglaciation (Jordan and Slaymaker, 1991; Friele and Clague, 2002; Dadson and Church, 2005), and declined since. Despite this reduction, periodic hydrogeomorphic events still occur, threatening development. An observed increase in the frequency of high intensity rainfall events (BGC, 2013) may suggest a climate-change related trend. The Rocky Mountains have a continental climate with warm summers and cold winters. The majority of heavy storms occur in the month of June, which is also the month with

the highest precipitation amount. Most regional floods are caused by rainfall, secondarily by snow melt, although rain-on-snow is considered a contributing factor to flooding in June 2013 (BGC, 2014a).

1.2 Previous Work

BGC Engineering Inc. (BGC) completed quantitative debris-flow and debris-flood hazard assessments for 15 steep creek fans in the Town of Canmore and Municipal District of Bighorn, located about 100 km west of Calgary. Risk assessments and conceptual mitigation designs were completed for 10 fans (BGC, 2013, 2014c-e, 2015a-q).

These assessments are the most detailed steep creek risk assessments in Alberta and were the primary data source for these fans. Previous studies also delineated fans through portions of the central study area (Jackson, 1987; de Scally, 1999), which we refined based on 2013 Light Detection and Ranging (LiDAR) imagery. A geohazard review was completed of fans along Highways 40 and 541 south of Canmore (AMEC, 2006). Highway channel crossings were inspected following the June 2013 floods (AMEC, 2013) and allowed identification of channels subject to debris flow or debris flood events that occurred during the 2013 event.

2 HAZARD CHARACTERIZATION

Hazard ratings were assigned to all steep creek fans in the study area. The sections below describe classifications of process types (debris flow, debris flood, or flood), estimates of flow statistics, and assignment of relative ratings for hazard frequency, avulsion and bank erosion susceptibility, as well as landslide dam outbreak flood potential.

2.1 Fan Mapping

Fan extents were interpreted based on 2013, 1.5 m resolution SPOT satellite imagery and hillshade images built from 2013, 1-m resolution LiDAR Digital Elevation Models (DEM) (Figure 3.). LiDAR coverage is available for approximately two thirds of the study area, and hillshade images from a 25 m resolution GeoBase DEM¹ are used for the remainder. Fan boundaries and hazard ratings are less accurate for areas without LiDAR coverage.

A total of 710 fans were mapped for the Rockies-wide inventory, of which 247 are crossed by provincially managed highways. A total of 105 fans were field checked to calibrate remote-sensed interpretations and identify channels with evidence for recent (e.g., June 2013) events. Subsurface investigations, channel hikes, or upper basin inspections were not completed except for those fans investigated in detail by BGC.

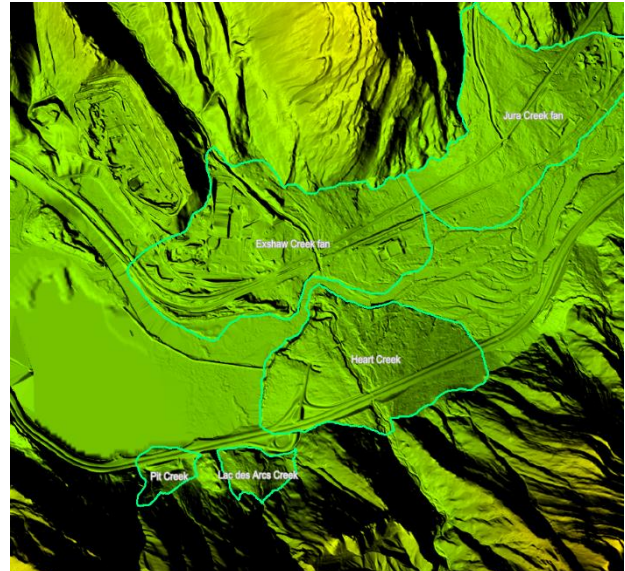


Figure 3. LiDAR hillshade showing Exshaw, Jura, Heart, Pit, and Lac des Arcs fans

2.2 Hydrological Analyses

Channels used for hydrological analysis are based on the Alberta Hydro Network (AEP, 2015) except where uppermost basins extended into British Columbia. The National Hydro Network is used for watershed areas within British Columbia, with channels manually joined to the Alberta Hydro Network to ensure channel connectivity.

A total of 170 fans inventoried within the study area do not intersect a mapped stream. Because a defined channel is required for flood frequency analysis (FFA), flow and watershed statistics were not computed for these fans. A hydrogeomorphic process type is assigned to these fans based on terrain interpretation, fieldwork, and our review of previous work.

2.3 Flood Frequency Analysis

Various studies (Jakob and Jordan, 2001; Jakob et al. 2015; AMEC, 2007) show that steep creeks, defined as those with average gradients greater than 5% (Church, 2013), produce flows that can be up to two orders of magnitude higher than flows for comparable return periods as determined by traditional FFA.

FFA can, however, provide a basis to compare flows between creeks and can be completed remotely at a regional scale. Flood quantiles for 100-year flood return periods are estimated at the fan apex using regional analysis based on publicly available maximum annual peak instantaneous streamflow (Q_{IMAX}) data from Water Survey of Canada (WSC) hydrometric stations (WSC, 2010). Peak flows are estimated for various return periods by first fitting a Generalized Extreme Value (GEV) distribution to the Q_{IMAX} data from the selected gauge station(s) and extrapolating the results to the location of interest using a linear regression analysis based on drainage area.

¹ Technically, GeoBase grid cell resolution is 3/4 arc-second, or about 20 m north-south and 23 m east-west in southern Canada.

2.4 Hydrogeomorphic Process Type Assignment

Steep creeks are subject to hydrogeomorphic processes whose dominant driver is water with varying sediment concentrations; these include clear water flood, debris flood, and debris flow process types (Jakob et al., 2015). The process type assignment does not contribute to the fan prioritization rating. However, it is important for more detailed assessment of flow magnitude and behaviour, the choice of parameters for numerical modelling, criteria used to estimate vulnerability and associated risk, and design of risk reduction measures.

We use two methods to assign hydrogeomorphic processes: terrain interpretations and morphometric statistics. The statistically predicted process type is applied to every stream segment in the entire study area, which totals about 77,000 km in length. These process types are displayed as colour-coded stream segments on a searchable web application termed the “Alberta Hydro Hazard Info Tool” (AHHIT) (Figure 4).



Figure 4. Statistically predicted debris flow (brown), debris flood (green) and flood (blue) stream process types near Kananaskis Village.

2.4.1 Terrain-Interpreted Process Type

We interpret the dominant process types for each fan from the following information sources:

- The geomorphology of fans and their associated watersheds observed in the available imagery
- Field observations
- Records of previous events
- Review of statistically predicted process type for channel(s) intersecting the fan

While a single process type is assigned to a given fan, many fans are subject to more than one. Fans classified as subject to debris flows are sometimes also subject to floods and debris floods. Those classified as debris flood fans may be subject to floods, but will generally not be subject to debris flows as those fans and watersheds

are steeper. Those classified as subject to floods were interpreted as not subject to debris floods or debris flows.

2.4.2 Statistically Predicted Process Type

Debris flow fans in the Canadian Rocky Mountain are steeper than 4 degrees and have steep, first or second Strahler order drainage basins with Melton ratios greater than 0.25 to 0.3 (Strahler, 1952; Melton, 1957; Jackson et al. 1987; Wilford et al. 2004). Melton ratio is defined as watershed relief divided by the square root of watershed area.

A previous study combined Melton ratio with straight-line watershed length to differentiate between fans subject to debris flow, debris flood, or flood processes (Wilford et al. 2004), where watershed length is considered the longest planimetric straight-line distance from the fan apex to the most distant point on the watershed boundary. Table 1 summarizes the class limits described in their study.

Table 1. Class limits for debris flows, debris floods, and floods as adapted from (Wilford et al. 2004).

Process	Melton Ratio	Watershed Length (km)
Floods	< 0.3	All
Debris Floods	0.3 to 0.6	All
	> 0.6	≥ 2.7
Debris Flows	> 0.6	< 2.7

We use a similar approach to predict potential geomorphic process types for every channel within the study area (irrespective of whether it contained a fan). However, we refine the approach to leverage the higher spatial data resolution, greater number of channels for statistical analyses, and modern GIS processing capabilities available to our study; and to consider major changes in valley orientation as shown in Figure 5. Specifically, we apply *total stream network length*, the total channel length upstream of a given stream segment to the stream segment farthest from the fan apex, instead of the watershed length (Wilford, 2014).

The major steps of the analysis are:

1. Collect statistics on watershed length and Melton ratios for stream segment(s) intersecting the upstream edge of each fan.
2. Analysis of Variance (ANOVA) to determine class boundaries that best predict process types for fans that have been previously studied in detail. Following analyses of these streams, results were compared to process types interpreted for fans during the desktop study.
3. Updated class boundaries to predict process types for all stream segments in the study area, regardless of whether they intersected fans.

Class boundaries for channels that do not intersect a mapped fan are presented in Table 2 and are based on Melton ratio and total network stream length. Class boundaries for channels with a mapped fan at the outlet are presented in Table 3; these use fan gradient in addition to Melton ratio and stream network length. Process-type

predictions are more reliable for channels with a mapped fan. The classification describes the *potential* process type, but does not consider the geomorphic conditions needed to actually generate events. For example, channels may be classified as “debris flow” or “debris flood” without evidence for previous events or where there is limited sediment supply. Watershed conditions that affect hydrogeomorphic process types cannot be considered using a purely statistical approach (Wilford et al., 2004).

Table 2. Class boundaries using total stream network length for watersheds without a mapped fan.

Process	Melton Ratio	Watershed Length (km)
Floods	< 0.2	All
Debris Floods	0.2 to 0.5	All
	> 0.5	≥ 3
Debris Flows	> 0.5	< 0.3

Table 3. Class boundaries using total stream network length for watersheds with a mapped fan.

Process	Melton Ratio	Watershed Length (km)	Fan Gradient (degrees)
Floods	< 0.2	All	< 3
Debris Floods	< 0.2	All	≥ 3
	0.2 to 0.5	All	All
	≥ 0.5	≤ 3	≤ 5
Debris Flows	> 0.5	> 3	all
	> 0.5	< 3	> 5

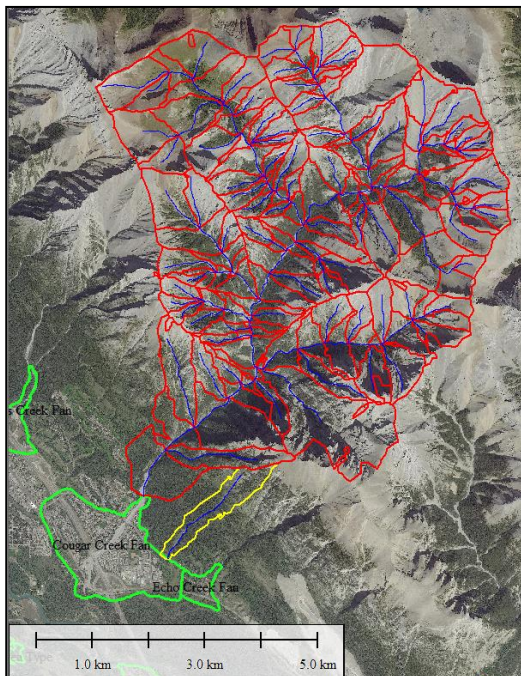


Figure 5. Cougar Creek Debris Fan (green line) and catchments (red line) for individual channel segments within the upstream watershed (blue line), and a second smaller watershed with connectivity to Cougar Creek fan (yellow line).

2.5 Hazard Frequency

Table 4 lists the relative hazard frequency ratings and corresponding annual return period ranges assigned to each fan.

Table 4. Relative Frequency and Return Period Categories.

Relative Frequency	Approximate Return Period Range (years)
High	< 30
Moderate	30 – 100
Low	> 100

Hazard frequency estimates are based on surface evidence for geomorphic activity within the basin and fan, as shown by the examples in Figure 6 and Figure 7 and apply to events large enough to produce visible surface evidence. Accordingly, the ratings are relative measures. However, hazard and risk are dominated by large events and neglecting smaller ones is of lesser consequence.



Figure 6. Example of evidence for recent landslide activity within the basin of Fan No. 197.

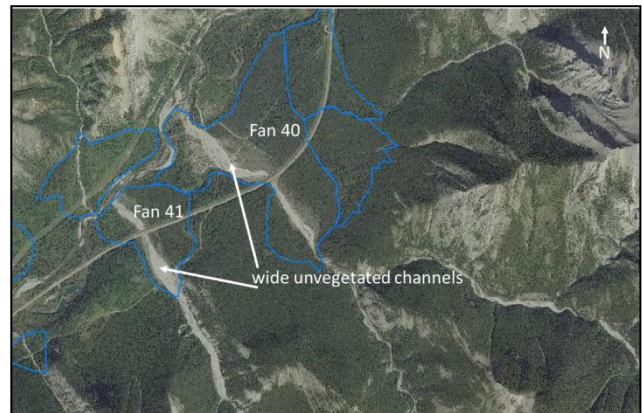


Figure 7. Example of vegetation evidence for recent debris floods on Fan Nos. 40 and 41.

Geomorphic evidence for “activity” within each basin (e.g., erosion, landslides, and sediment transport) is rated as Low, Moderate, or High, based on the freshness of channel deposits and whether basin sediment supply is limited or unlimited.

Geomorphic evidence for activity on each fan (e.g., evidence for recent events) is rated as Low, Moderate or High based on freshness and visibility of recent sediment deposits and the estimated age of vegetation: pioneer (<2 year), young (<50 year), or mature (> 50 year). The rating considered evidence for geomorphic activity anywhere on the fan surface.

2.6 Avulsion Susceptibility

During an event, flows may avulse entirely or partially into a different portion of the fan. We assign avulsion susceptibility categories as High, Moderate, or Low, based on the level of channel confinement and surface evidence for previous avulsions. Fans with previously recorded avulsions were assigned a High rating. Channel confinement levels are based on estimated bank height and the presence of locations where confinement could be reduced during an event (e.g., channel bends, changes in channel gradient, channel constrictions at road crossings).

Surface evidence for previous avulsions are based on vegetation evidence and the presence of relict channels, lobes, and deposits on the fan surface (e.g., Figure 8). These features can be detected, if present, on LiDAR hillshades; interpretations are less certain for areas without LiDAR coverage.

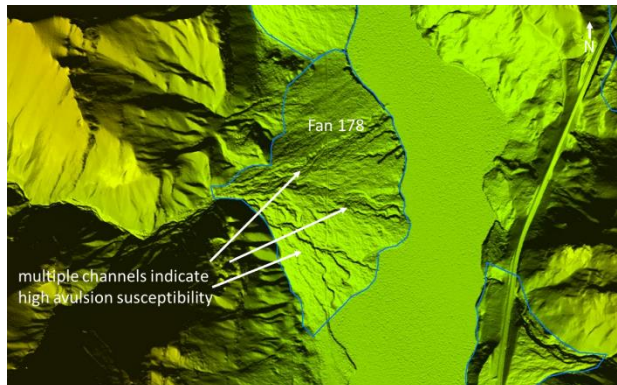


Figure 8. Example of evidence for High avulsion susceptibility on fan no. 178.

2.7 Bank Erosion Susceptibility

Bank erosion refers to widening of the existing channel during an event. We assign bank erosion susceptibility categories as High, Moderate, or Low, based on surface signs of previous channel widening (e.g., Figure 9). In general, the higher ratings apply to channels with moderate or lower levels of confinement. Because the remote-sensed imagery represents a snapshot in time, estimating channel widening in relation to some “equilibrium” channel width is difficult. Bank erosion susceptibility is also controlled by factors not possible to determine remotely, such as channel bank vegetation and sediment grain size distribution as well as sediment apparent cohesion. As such, this rating is subject to more uncertainty than other hazard factors.

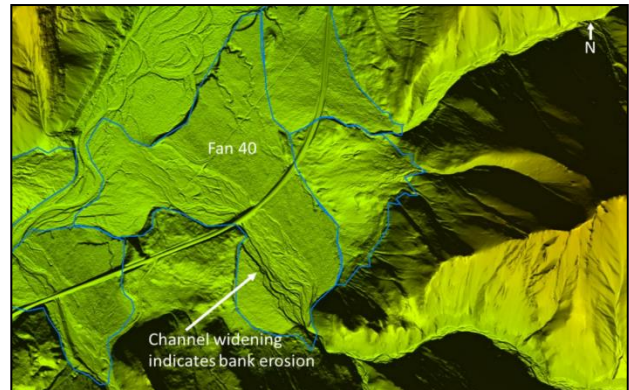


Figure 9. Example of evidence for high susceptibility to bank erosion on Fan no. 40.

2.8 Landslide Dam Outbreak Potential

We assign landslide dam outbreak flood potential ratings as High, Moderate, or Low based on evidence of past landslide dams, presence of large landslide scars with the potential to travel to the valley floor, and presence of channel sections potentially susceptible to blockage (e.g., channel constrictions). Figure 10 shows an example of landslide dam locations in Cougar Creek basin. Note that actual landslide dams are not visible at the resolution of the figure; the interpretations are based on the combination of characteristics noted above and were field checked during 2013.



Figure 10. Example of evidence for landslide dam outbreak flood potential in Cougar Creek basin.

3 HIGHWAYS INVENTORY

The entire project study area included 3,400 linear km of provincially managed highways in Alberta, of which about 1,100 km are located in the Rocky Mountains (e.g. areas with steep creek fans). The assessment considered both the highways and associated roadside facilities (e.g. pullouts and rest stops) and ramps. It excluded highways within national parks, as those are operated by the federal government.

4 FAN PRIORITIZATION

We prioritized hazard sites based on the relative likelihood that an event will occur, impact the highway and result in some level of undesirable consequence. The primary objective of prioritization was to identify sites for further site-specific assessment and long term monitoring.

Priority scores were calculated as follows:

$$P_F = P_{H,S_i} \times C_i \quad [1]$$

where

P_F is the numerical priority score,

P_{H,S_i} are the weightings for encounter probability, the estimated probability that a hazard event will occur and impact the highway. C_i are weightings for consequence given highway impact.

Encounter probability on a fan was calculated as the hazard frequency (P_H) multiplied by proxies for spatial probability of road impact (S_i):

$$P_{H,S_i} = P_H \times \sum S_i \quad [2]$$

P_H are the weightings for the hazard rating assigned to a given fan. Possible weightings are 1, 2, or 3 for Low, Moderate, or High hazard ratings, respectively.

Values of S_i are weightings for avulsion susceptibility, bank erosion susceptibility and landslide outbreak flood potential. We chose these as proxies for the relative likelihood that flows would exit the normal stream channel, increasing the potential for highway impact. Quantitative estimates of spatial probability of impact, as would be completed for a detailed risk assessment, were not considered feasible given the regional scale of study. Low, Moderate or High ratings for these factors are assigned weightings of 1, 2, or 3, respectively, and summed to give a total rating.

We calculated consequence as the product of proxies for the "importance" of a highway (E) and the estimated likelihood of a >1 day closure given impact (V):

$$C = E \times V \quad [3]$$

where

E is the summer daily traffic volume (number of cars per day), with an additional 1000 cars/day added to more highly weigh the importance of fans containing roadside facilities such as ramps, safety rest areas, or vehicle inspection stations.

V is the estimated potential for a major (e.g., >1 day) closure given impact by a debris hazard event.

We assigned closure likelihoods based on terrain analysis and judgement, with reference to recorded closures and previous damage assessments (Thurber 2013, Klohn Crippen Berger 2013, Golder 2013).

Table 5 provides highway closure criteria. While a single rating is applied to each fan, a spectrum of closure durations is possible at any given site depending on the magnitude of the event. Given that event frequency-

magnitude relationships have not been developed for each fan, we chose a "high magnitude" event (e.g., comparable to June 2013) as a benchmark for estimates. As events can have multiple possible outcomes, the ratings are considered relative for the purpose of fan prioritization.

Table 5. Likelihood of "major" (e.g. >1 day) highway closure given impact by a debris hazard event.

Process	Likelihood	Description
Low	0.01	Low likelihood of debris deposition on road. Low likelihood of partial or complete highway closure.
Moderate	0.5	Debris flow or debris flood deposition onto roadway removable by maintenance crews in several hours. Possible road surface damage or damage to crossing. Partial or complete highway closure unlikely to exceed 1 day.
High	0.9	Debris flow or debris flood onto roadway requiring heavy equipment to clear debris and restore road surface. Possible road bed damage or damage to crossing. Possible partial or complete highway closure likely to exceed 1 day.

Table 6 shows the percentile ranks used to define Low, Moderate, and High priority categories for each hazard site.

Table 6. Hazard site priority categories.

Priority Category	Percentile Rank
High	≥ 90
Moderate	≥ 50 to < 90
Low	< 50

5 RISK PRIORITIZATION RESULTS

The study results are presented on a searchable web application (Figure 11). The application allows the user to view all fans, search or navigate to a fan of interest, and display the priority rating, detailed characteristics of the hazard and elements at risk, and risk control options for high priority rated fans. It also displays a morphometric-based prediction of potential hydro-geomorphic hazard type for all stream channels across the study area.

Figure 12 shows the distribution of High, Moderate, and Low priority fans across the study area. A total of 24 fans were rated as High priority, 227 as Moderate priority, and 247 as Low priority. Most of the highest priority fans in the study area were located along Highway 1 and 1A, and Highway 40. Most notably, Cougar Creek fan contains over \$1B in assets and is traversed by Canadian Railways and the Trans-Canada Highway. The design and construction of risk reduction measures including channel erosion protection works and a debris barrier upstream of the fan

apex are presently underway on this fan. More detailed hazard and risk assessments have also been completed for 15 fans in Canmore and the neighbouring Municipal District of Bighorn. These are the only jurisdictions, to BGC's knowledge, where detailed hydrogeomorphic risk assessments have been completed in Alberta to date.

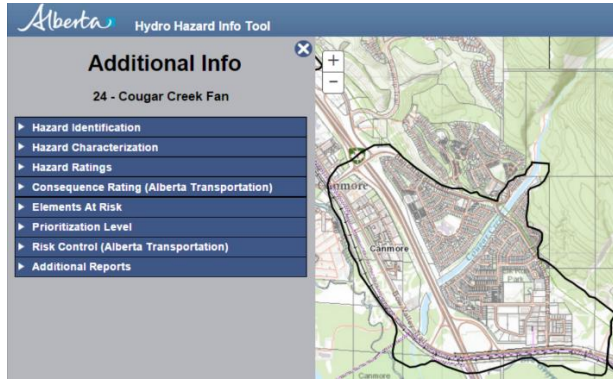


Figure 11. Screen-capture of the Alberta Hydro Hazard Info Tool (AHHIT), centered on Cougar Creek fan in Canmore.

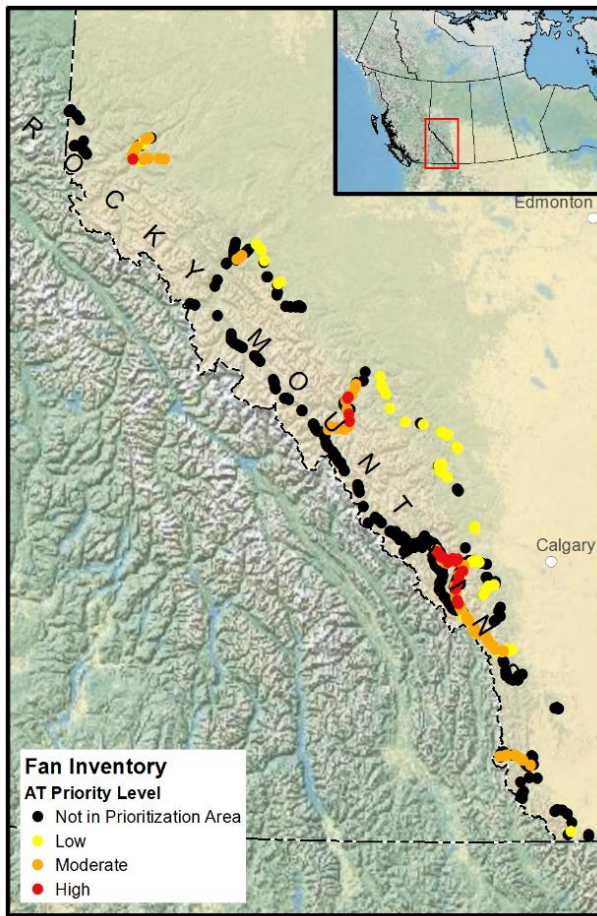


Figure 12. Point locations and priorities of steep creek fans crossed by Alberta Highways. Black dots show fans that were inventoried for the larger study, but that did not cross highways managed by the Province of Alberta.

6 RISK REDUCTION ASSESSMENT

In this section we describe risk reduction design considerations and typical risk reduction options recommended for different hazard sites.

6.1 Site Factors

Factors considered for each site included:

Design Goals. Risk control designs address the specific key risk(s) that are intolerable at a given site such as reduction of highway closure time, damage costs, and/or safety risks. Risk control designs intended to reduce one key risk may not be effective at reducing other key risks. For example, highway closure during periods of elevated hazard to reduce safety risk would increase highway closure time.

Site Geometry and Access. Risk control options are often influenced by the position of the highway relative to the fan apex or watercourse and the available land, as well as access to areas of the fan, watercourse, or watershed, due to property boundaries or topography.

Contributions to Risk. The most effective risk control measures are those that target the item, element, or phenomenon which most contributes to risk. For example, at some sites the high risk rating may be caused by very frequent, relatively low consequence events and at other sites the high risk rating may be caused by infrequent, but very high consequence events.

Other Elements at Risk. Risk reduction design at a highway should consider how the design affects the risk to adjacent buildings and infrastructure.

Risk Transfer. Modifications to the fan, watercourse, or watershed (including modifications to elements in the study area) can change the risk to other elements on the fan. For example, a highway embankment across a fan may contribute to flooding on the upstream side of the road, or may protect elements that are located on the downstream side of the road from flooding.

Vulnerability. Vulnerability describes the scale of damage that the hazard is likely to cause. It could be described in terms of destruction level or duration of highway closure. Vulnerability should be assessed for the highway and other elements at risk that are identified. It is related to assessment of relative contributions to risk and risk transfer.

Hazard Type. Hydrogeomorphic process type (flood, debris flood, debris flow) affects peak discharge and sediment volumes, as well as scour and deposition. It influences mitigation type selection and is critical for sizing of structures. Failure to identify the hazard type can contribute to poor performance and losses. Site-specific review is needed to confirm the hazard type, peak discharge, flow velocity, and transported sediment volume.

6.2 Risk Reduction Options

Typical risk reduction options recommended for different hazard sites included:

Source Zone Stabilization. The objective of source zone stabilization is to prevent slide initiation and debris entrainment through slope stabilization and erosion control measures. This may include vegetation, channel armour, debris barriers, and grade control structures at upper reaches of the watershed. It is generally not feasible to stabilize most watersheds due to size, although it may be applicable following wildfires, or where the sediment source is localized. Access to the watershed area is required.

Channel Armouring. Channel armouring reduces the volume of sediment entrained from the channel. It is typically installed in accessible areas upstream of the highway (e.g., upper fan, lower reach of watershed) and includes grade control structures, riprap lining, or articulated concrete mats. It reduces event magnitude and associated consequences. Armouring is typically used downstream of debris barriers to prevent re-entrainment of debris and in combination with debris flood/flow conveyance channels. Channel armouring at any given location may increase erosion potential downstream of the armoured section.

Conveyance. Conveyance describes directing a debris flood or flow beneath the highway in adequately sized and protected culverts or bridge openings. Opening sizes are designed based on site-specific analysis of expected peak discharge and sediment load. This option may include training berms along the channel upstream of the highway to prevent avulsion from the active channel, which are typically armoured to avoid erosion. Increasing conveyance beneath a highway may increase risk to elements downstream.

Designated Overflow. This option allows hazardous flows to overtop the highway. Hazardous flows are directed to a designated overflow area that is designed to resist overtopping with minimal damage. A 'ford' crossing or 'low water' crossing design functions as a bridge or culvert during typical flow conditions, but is designed to be overtopped by high flow conditions. This option may reduce economic risks and damage costs, but would not reduce safety risks to motorists, and results in periodic road closures during and following events. Traffic interruption can be reduced by staging maintenance equipment for rapid response.

Diversion. Diversion elements direct hazardous flows away from the highway and other elements at risk, and ideally limits the spatial impact of the flow to an area that does not contain elements at risk. This typically requires a diversion barrier constructed across the natural channel. Outlet structures that become blocked by debris can be used to divert flow during hazardous events. This requires consideration of risk transfer and is only applicable when other elements at risk on the fan are well understood. Typically the clear-water component of the diverted flow needs to be conveyed across the highway beyond the point of sediment deposition.

Sediment Capture. Sediment retention structures can be installed upstream of the highway to capture coarse sediment and allow water to pass. Flexible net barriers can be used in small sediment load channels. Large earthworks or concrete barriers can be used for larger sediment load channels. Sediment basins may also be applicable. This is typically only practical where the natural topography can be used to contain sediment and act as abutments for the barrier. Highway crossing structures need to be designed to pass the peak water flow.

Attenuation Barrier. Attenuation barriers retain sediment and debris and temporarily store water to limit flood peak discharge downstream of the barrier to a value that can be conveyed through existing culvert and bridge openings. This is typically a very expensive option that is only feasible at highly developed fans (e.g. Cougar Creek). It may be appropriate where existing highway bridges or culverts do not have capacity to convey peak water discharge and replacement of the bridge or culvert is not feasible.

Road Realignment. The objective of highway or road realignment is to avoid the debris hazard or to reduce the hazard intensity at the road position. It is not often a feasible option due to high costs and conflicts with property boundaries, and it may require property acquisition.

No Stopping Zones. No stopping zones warn motorists of the debris hazard and prohibits motorists from stopping within the hazard zone. It may be effective to reduce safety risks to motorists, but does not address traffic disruption or economic risks. This measure is broadly applicable to reduce safety risk to as low as reasonably practicable and can be combined with other risk control methods.

Precautionary Closure. A precautionary closure is a temporary highway closure before an event occurs based on warning systems such as rainfall threshold protocols or debris-flow alarms. This limits motorist exposure to the hazard zone during periods of elevated debris flow hazard. It may be effective at reducing safety risks to motorists, but does not address traffic disruption or economic risks. It requires a large, site-specific dataset for accurate calibration, which is not typically available. It may result in frequent traffic disruptions when no hazardous event occurs.

Emergency Response. Preparation of emergency response plans that are implemented during forecasted high flow events can reduce the duration of highway disruption or closure. Emergency response often includes staging equipment that can remove sediment from critical culverts and flow paths during or immediately after an event.

7 CONCLUSION

This study provides the Government of Alberta with an inventory and risk-based prioritization of steep-creek fans intersecting municipal development and major roads and highways in Alberta. We characterized 710 fans across the entire study and prioritized 247 fans crossed by provincially managed highways, based on the relative likelihood that an event will occur, impact the highway and result in some

level of undesirable consequence. We provide conceptual risk control options for High Priority-Rated fans.

The study results are presented on a geospatial web application that allows the user to review fan hazards, identify development at risk, and prioritize fans for further assessment and risk reduction planning. Future upgrades to the application could include the ability to manage periodic geohazard inspections and reporting, and tools to support emergency planning.

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