Leadership in Sustainable Infrastructure

Leadership en Infrastructures Durables

Vancouver, Canada

May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

QUANTITATIVE STEEP CREEK RISK ASSESSMENT, DISTRICT OF NORTH VANCOUVER, BRITISH COLUMBIA

Kris Holm[1,3], Matthias Jakob[1], and Hamish Weatherly[1] Fiona Dercole[2], Steve Bridger[2]
[1] BGC Engineering Inc., 500-980 Howe Street, Vancouver, British Columbia, Canada
[2] District of North Vancouver, 355 West Queens Road, North Vancouver, British Columbia, Canada
[3] kholm@bgcengineering.ca

Abstract: The District of North Vancouver (DNV) has a long history of managing geohazards. Starting in the 1990s, and updated approximately every 10 years, DNV has retained geotechnical and geoscientist consultants to assess debris geohazard (i.e., debris floods and debris flows) risks and make recommendations for reducing risk to tolerable levels. In 2015-2016, we completed comprehensive flood, debris flood- and debris-flow risk assessments for 35 steep creeks within the District using a variety of custom-tailored methods described in this contribution. While most creeks' headwaters are in forested and largely undeveloped terrain, the lower reaches flow through municipal areas containing over 20,000 buildings and a network of roads, utilities, and stormwater management infrastructure. The objectives of the assessment were to assess debris geohazards including their frequency, magnitude, extent, and potential to result in blockage and overflow of DNV stormwater management infrastructure; estimate the risk posed by these hazards to buildings and persons within buildings, prioritize locations for risk reduction planning; and develop risk control options and costs. Based on the results of the assessment, DNV staff are developing a 10-year work plan that will be integrated with the District's asset management, GIS-based inspection program, climate change adaptation and hazard mitigation plans. The work presented herein is an example of a pro-active science-based creek management program aiming to optimize funds for public safety and economic risk reduction.

1 Introduction

Following a damaging debris flood on Kilmer Creek in November 2014, the DNV requested a district-wide geohazard risk and risk control options assessment of 35 steep creeks that could block stormwater management assets and/or damage buildings and infrastructure (Figure 1). Of these creeks, this paper is focused on risk assessment of 25 "urban" creeks defined as being accessible by road and serviced by DNV's stormwater management infrastructure. The remainder of the creeks are in rural areas in the northeast part of the District, which are accessible by boat only. The objectives of this study were to: (i) assess debris geohazards including their frequency, magnitude, extent, and potential to result in blockage and overflow of DNV stormwater management infrastructure; (ii) numerically model geohazard scenarios and create maps showing the estimated extent and potential severity of impact to buildings and infrastructure; (iii) estimate safety and economic risk posed by these hazards to buildings and persons within buildings; (iv) prioritize locations for risk reduction planning based on results of the risk assessment; and (v) propose risk control measures and costs to reduce these risks to levels considered tolerable by the DNV.

The creeks assessed are defined as "steep creeks" subject to floods, debris floods or debris flows, with the potential to cause economic damages and loss, and/or pose risk to life for persons within buildings. For the purposes of this paper, a channel is considered "steep" when the channel slope is equal to or exceeds approximately 3° (~ 5%). Stormwater management infrastructure assessed on these creeks include culverts and stormwater mains owned by the DNV with potential for debris blockage and/or physical damage. Culverts in upper watershed areas that are not owned by the DNV, but that affect watershed boundaries and associated creek flows into the DNV, were also assessed. However, hazard scenarios and risks associated with blockage of these culverts were not assessed in detail. Of the 25 urban creeks assessed, 14 are classified as having potential to produce debris floods, 2 to debris flows, and 9 that are unlikely to produce either debris flows or debris floods.

Table 1 lists the types of elements at risk and types of risks or impacts assessed. Specifically, “safety risk” considers risk to life for persons within buildings, while “economic risk” considers direct damages to buildings, roads and culverts due to debris impact. Assessment of drainage infrastructure focuses on identifying requirements and costs to upgrade assets as part of debris risk management. Assessment of other types of infrastructure was limited to identifying their location in relation to areas impacted by debris hazard scenarios.

Table 1: Elements at risk

Element at Risk	Type of Risk or Impact Assessed
Persons within Buildings	Quantitative estimation of individual and group risk to life for persons located within buildings.
Buildings	Quantitative estimation of damage to buildings due to debris impact expressed as a proportion of appraised building value and direct damage cost, and as an annualized damage cost. Identification of facilities considered critical by DNV for function during an emergency that are located within areas potentially subject to debris geohazard impact. These include schools, police stations, or fire stations.
Roads	Estimation of spatial extent and intensity of impact by debris geohazard scenarios.
Culverts	Estimation of event return periods likely to result in blockage by debris for a given culvert.

2 Study Area Physiography

The DNV is a 160 km^2 district municipality bounded by Burrard Inlet to the south, Capilano River to the west, and Indian Arm to the east (Figure 1). The developed southern portion of the District is flanked by the North Shore Mountains, which rise up to 1,449 masl and contain steep, mostly forested slopes overlain by colluvium and till. In addition to the larger Capilano, Lynn and Seymour rivers, numerous steep creeks originate in undeveloped, smaller (1-15 km^2) watersheds and flow through stormwater management infrastructure downstream. Figure 1 shows the watershed boundaries for the steep creeks assessed, which are affected in some areas by drainage alterations caused by road construction and logging.

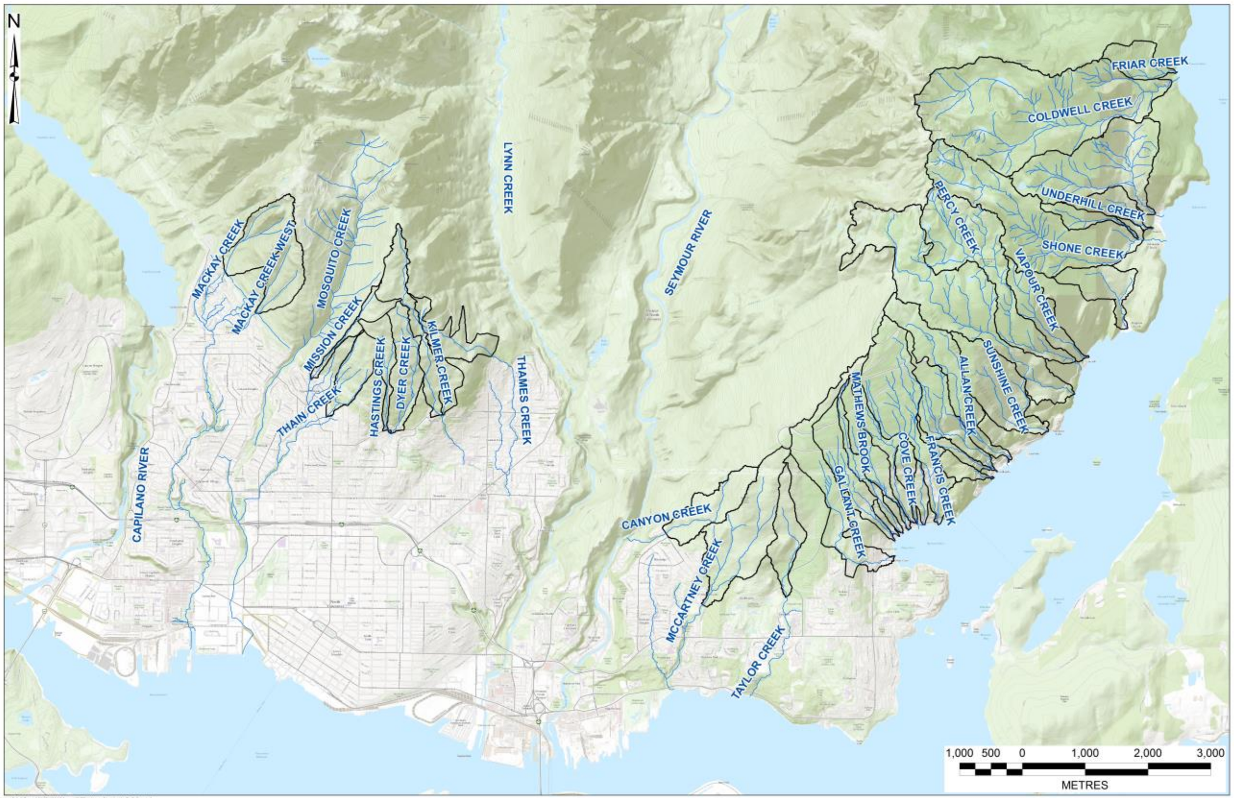

Figure 1: Study area and creek watershed boundaries upstream of development interface

3 Infrastructure

DNV buildings, drainage management works and transportation infrastructure were considered in the assessment of debris geohazard impact. All of these assets are classified by the DNV using a unique identifier (Asset ID). Other types of infrastructure, such as power infrastructure (transmission lines) or oil/gas infrastructure, were not assessed.

The DNV also maintains a geospatial database of building locations and characteristics throughout the District, including building type, assessed value, estimated replacement value, and population. The building inventory was developed from a combination of DNV information and windshield surveys[1] completed by Carlos Ventura and colleagues at the UBC Earthquake Research Facility as part of an earthquake risk assessment (Journeay et al. 2015). All data are associated with a unique Building ID and geospatially related to building footprints in GIS.

Drainage infrastructure within the current DNV asset inventory includes 371 culverts, 7 natural hazard mitigation structures, and approximately 350 kilometres of storm mains with replacement costs totalling $296 million (DNV 2015). An additional 86 culverts also exist within the DNV that are owned by others (e.g., the Province of BC). Of these, a total of 93 culverts and stormwater mains were considered to have credible potential for debris blockage and/or that are located in creek sections subject to debris hazard processes, and were assessed in detail.

Transportation infrastructure within the DNV and applicable to this study includes roadways and pedestrian or vehicle bridges. Pedestrian and vehicle bridges were reviewed where they intersect with a study creek upstream of development or within the area modelled. However, pedestrian bridges were not prioritized for

---

[1] Windshield surveys are systematic observations made from a vehicle.

evaluation of risk reduction alternatives. No vehicle bridges were identified as having credible potential for debris blockage.

4 Methods

During hazard characterization, the creeks are assessed with respect to geographic location, development and local infrastructure, and geomorphic and hydrological characteristics. The process involves compilation and review of previous assessments on the creeks in conjunction with desktop analyses and field investigation. The details of each component are described in the following sections.

4.1 Previous Studies

The initial phase of the assessment included a thorough review of previous studies conducted within the DNV that focused on debris geohazard and risk estimation, stormwater management and culvert hydraulics, infrastructure vulnerability, and that provide records of previous water conveyance failures. The outcomes of the review included a compilation of material that remains current and applicable to the current assessment, identification of data gaps and limitations to be addressed by the current assessment and identification of data gaps and limitations that lie outside the scope of work but affect the methodology or expected results of the study.

The steep creeks around DNV have a documented history of flood, debris flood and debris flow events. Therefore, previous assessments of clear-water flood, debris flood, debris flow, landslide and other slope movement features were reviewed as documented by Kerr Wood Leidal (1995, 2003a-k, 2011), Northwest Hydraulic Consultants (2010), the Ministry of Environment (1995), and BGC Engineering Inc. (2009, 2010, 2011, 2013). DNV records, news reports and field observations, including a detailed description of the November 2014 event on Kilmer Creek, were also reviewed. The November 2014 records were of critical importance in that they were used to calibrate the hazard analysis and debris-flood modelling described here-in. Calibration of event frequency was also provided by a review of information kept by DNV maintenance personnel of culvert inlets that have historically required maintenance for debris blockage during storm events.

4.2 Desktop Study

Terrain analysis formed the initial stage of hazard characterization. The analysis involved delineation of creek and creek tributaries, delineation of watershed boundaries and mapping of geomorphic features as described in the sections below. All terrain analysis was completed using 2013 LiDAR data provided by DNV and 1 m topographic contours.

Initial creek delineations were provided by DNV and modified based on terrain analysis coupled with field observations. Modifications to the creek delineations were completed where the initial version did not extend to the upstream headwaters, where notable tributaries identified during field inspections had not been delineated, or where anthropogenic modification of the landscape had altered the drainage pattern.

Watersheds were delineated within ArcGIS using watershed boundaries calculated using Global Mapper v15.2 and BASINS 4.1 (United States Environmental Protection Agency (EPA) 2013). This work was supplemented by field observations of local and regional drainage patterns and reference to previous investigations of drainage along roadways or other infrastructure. In particular, a drainage assessment was completed in 2007 along Old Grouse Mountain Highway to facilitate culvert sizing (BGC 2007). The delineated drainage patterns identified during the assessment were included in the present assessment.

4.3 Field Investigation

The majority of study creeks visited were traversed from the development interface (e.g., boundary of residential development with the undeveloped upper watersheds) upstream to the point at which the creek had little potential to contribute to sediment transport to development. In many instances, creeks were hiked along the full length to the headwaters in order to delineate the entire creek. Select creeks were traversed through development in order to characterize the potential for blockage of culverts and attendant flooding potential.

The primary objective of field investigation for the hazard component of this study was to collect parameters supporting debris volume and frequency estimation, as well as hydraulic analyses at culvert crossings and observations on infrastructure maintenance. These parameters included channel hydraulic characteristics (gradient, width, and bankfull height), channel bed characteristics (grainsize distribution, sediment availability and bedrock exposure), cross sections where high water marks could be reconstructed, sediment sources (bank erosion, rockfall, localized slope instability), culvert properties (dimensions, gradient, freeboard and condition), debris control structure dimensions, and pedestrian footbridge channel geometry.

In addition to the creeks, major roadways affecting regional drainage patterns were visited to check and refine the local watershed boundaries. This includes Mt. Seymour Road, Indian River Drive and Old Grouse Mountain Hwy. On Percy Creek, which is subject to debris flows, four test pits were mechanically excavated on the fan to use stratigraphic information for volumetric determination and collect organic samples for radiocarbon dating. Tree core samples were also collected for dendrochronological analysis.

4.4 Hydrogeomorphic Process Assignment

The study 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 processes (Jakob et al. 2015). Identifying the dominant hydrogeomorphic process on a creek is important for detailed assessment of flow magnitude and behaviour, selection of parameters for numerical modelling of flows, selection of criteria to estimate vulnerability, and associated risk and mitigation design. A dominant hydrogeomorphic process type was assigned to each study creek based on fieldwork and desktop study that included review of previous work, the geomorphology of fans (where existing), channel deposits and their associated watersheds, channel gradients, field observations, and records of previous events.

4.5 Frequency-Magnitude Analysis

Frequency-magnitude (F-M) estimations form the core of any hazard assessment because they combine the findings from frequency and magnitude analyses in a format suitable for numerical analysis. Frequency and magnitude of hydrogeomorphic events are inversely related. The higher the event frequency, the lower its magnitude and vice versa. In short, the rarer an event, the larger it will be. Hazard magnitude is expressed as the peak flow and the total volume of sediment mobilized in the specific hazard event.

4.5.1 Frequency Estimation

Frequency analysis determines how often hydrogeomorphic events occur, on average. Frequency can be expressed either as a return period or an annual probability of occurrence. Frequencies of hydrogeomorphic events were established through flood frequency analysis, determination of the critical threshold for full bed mobilization, radiocarbon dating of organics in test trenches (Percy Creek) and dendrochronology (Percy Creek).

4.5.2 Magnitude Estimation

The objective of the magnitude analysis is to estimate debris volumes and peak discharges of past hydrogeomorphic events. The results form inputs to numerical modelling and assessment of debris blockage at culverts and stormwater mains. Table 2 summarizes the approaches used to estimate debris volumes for creeks subject to debris floods and debris flows, which have the potential to carry much higher sediment loads than clear-water floods.

Table 2: Methods employed for estimation of debris magnitudes

Application	Method
Flood and debris flood prone streams with a mobile bed but not steep enough to produce debris flows.	• Determine the shear stress threshold (i.e., critical shear stress) for bed mobilization. • Use average channel dimensions and Manning's equation to determine the discharge that corresponds to the critical shear stress. • Use a hydrograph associated with a specific return period to calculate the amount of time that the flow exceeded the discharge threshold. • Use Rickenmann's (2001) sediment transport equation to calculate sediment discharge based on stream power. • Calculate sediment volume based on the estimated sediment discharge rate multiplied by the duration over which the critical shear stress occurs. • Use of regionally-derived frequency-magnitude curves for debris floods as a comparative tool with previously employed methods.
Percy Creek debris flows	• Excavation of test pits to collect samples of organic material for radiocarbon dating and collection of tree core samples for dendrochronological analysis. • Reconstruct yield rates along the creek to estimate the total volume of erodible sediment available. • Add estimated sediment volumes from point sources along the creek. • Use of regionally-derived frequency-magnitude curves for debris flows.
Debris flood, debris flow hybrids	• Use appropriate combination of methods from above.
Dam outbreak floods	• Determination of peak discharge and outflow hydrographs from the failure of a landslide dam using the model BREACH (Fread 1991).

While based on the best available data, estimates of debris-flow or debris-flood magnitudes contain uncertainties. Older deposits can be eroded or reworked and are therefore often difficult to distinguish unambiguously from one another. Creek-side development also creates practical limits to subsurface investigation of past deposits. Hydromorphic processes also involve hazard mechanisms that cannot be quantified by flow modelling, such as bank erosion.

Frequency and magnitude information was combined to produce frequency-magnitude relationships for each debris-flood and debris-flow prone creek.

4.6 Hazard Scenarios

Hazard scenarios are hypothetical scenarios where flows occur outside the normal creek channel in areas where they can impact development or infrastructure. The scenarios quantify the extent and "intensity", or destructive potential, of a flood, debris flood or debris flow and are used to estimate building damages and risk to life. Hazard scenarios do not encompass every possible flow or avulsion scenario that could occur but define representative events at a range of return periods that are suitable for risk estimation. These return periods are based on the results of frequency-magnitude analysis.

For each creek, we estimated the return period where culverts and stormwater mains are anticipated to overflow either due to capacity exceedance or blockage by sediment or organic material. Judgment was required in some cases where a series of culverts or storm mains were expected to block during a representative hazard event. Flow magnitudes and expected blockage scenarios then formed the inputs for flow modelling. For Percy Creek, representative debris flow hazard scenarios were based on estimated debris-flow frequency-magnitude relationships for return period classes up to 3000 years including avulsion scenarios and estimated representative avulsion scenarios. Debris-flood prone creeks were assessed up to return periods of 200 years, which was considered the upper limit of the flood frequency analysis. Many of the debris-floods creek in the DNV are also supply-limited, placing an upper threshold on sediment mobilization.

4.7 Hazard Scenario Modelling and Mapping

Having established an F-M curve for each creek, numerical flow routing models were then used to estimate the extent, velocity and depth of flow for each hazard scenario on a given creek. For debris flood modeling, the commercially available two-dimensional hydraulic model FLO-2D (2007) was used to estimate debris-flood velocity, depth and the extent of inundation for each debris-flood hazard scenario. Culverts or stormwater mains were blocked in the model for each scenario. Estimated capacities of culverts or stormwater mains not assumed to be blocked were also input into the model. For debris flow modeling on Percy Creek, the three-dimensional numerical model *DAN3D* was used (McDougall and Hungr 2004). The model grid cell outputs were then imported into GIS, overlaid on base maps, and used to interpret hazard intensity maps.

Hazard intensity maps were developed for each scenario from the modeling that show the destructive potential, of a flood, debris flood or debris flow. Model results were displayed using a “flow intensity index” (I_{DF}) and flow depth. The flow intensity index is calculated as flow depth multiplied by the square of flow velocity (Jakob et al. 2012). It is not appropriate for estimating damages associated with low velocity flooding (e.g., approximately < 1 m/s), where values of I_{DF} will approach zero irrespective of flood depth. Below an intensity threshold of $I_{DF}<1$, flood vulnerabilities for buildings were estimated based on assumed flood depths.

5 Risk Assessment

Risk assessment involves estimation of the likelihood that a debris flood or debris flow scenario will occur, impact elements at risk, and cause particular types and severities of consequences. We estimated individual and group safety risk (loss of life risk) for persons within buildings, and economic risk associated with building damages due to debris impact. The primary objective of the safety risk assessment is to identify cases where the estimated risk level exceeds risk tolerance thresholds defined by the DNV. Following consideration of safety risk, the economic risk assessment can support further prioritization of risk reduction options.

Both quantitative risk assessment (QRA) and semi-quantitative risk assessment (semi-QRA) methods were used to estimate risk. QRA methods were used to estimate safety and economic risk for each creek system as a whole, considering all hazard scenarios and culvert blockages modelled for a given creek. The results support risk reduction prioritization for each creek (e.g., should creek “X” be higher priority, from a risk perspective, than creek “Y”). Semi-QRA methods were used to assign relative risk ratings to individual culverts or storm water mains. The economic risk rating for individual culverts addressed the question, “what is the probability that a particular culvert blocks and results in some level of economic consequences?”. The results of semi-QRA support risk reduction prioritization for individual culverts (e.g., should culvert “X” be higher priority, from a risk perspective, than culvert “Y”).

5.1 Safety Risk

Safety risk was quantitatively estimated for each creek from two perspectives: risk to individuals and groups. Individual safety risk considered the risk to a particular individual exposed to a hazard, and is independent of the number of persons exposed to risk. Group safety considered the collective risk to all individuals exposed to hazard, and is proportional to the number of persons exposed to risk. In both cases, safety risk estimates considered the spectrum of hazard scenarios assessed for a given creek. Hazard scenarios were considered as having a credible (non-negligible) risk to life only where flows exceeded a minimum intensity threshold (I_{DF} > 1), or where buildings were identified as particularly vulnerable to impact.

Individual risk estimate results were compared to geohazard tolerance criteria adopted by the DNV in 2009. For risk to groups, estimated risks were compared to group risk tolerance criteria formally adopted in Hong Kong (GEO 1998) and informally applied in Australia (AGS 2007) and DNV. Group risk tolerance thresholds based on criteria adopted in Hong Kong (GEO 1998) are shown on an F-N Curve in Figure 1.

5.2 Economic Risk – Creek Systems

Economic risk estimates for each creek were based on the hazard scenarios and considered direct damages to buildings. The results were reported as a direct damage cost for each scenario and as an annualized figure. The annualized cost was calculated by multiplying the hazard scenario probability by the estimated damage cost for a given scenario, and then summing the results for all scenarios.

Building damage cost estimates were based on vulnerability criteria relating damage levels to flows with a certain level of intensity or destructive power. Damage was measured as a proportion of the building replacement cost or as an absolute cost. Annualized damage cost was calculated by interpolating a damage curve from cost estimates for individual events at a given probability of occurrence.

Building damages associated with low intensity flows ($I_{DF} < 1$) were assumed to include inundation by water and sediment. Damages for such flows were estimated using flood stage-damage curves developed for Alberta Environment and Parks (AEP) following the damaging floods in southwestern Alberta in June 2013 (IBI Group 2015).

Building damages associated with higher intensity flows ($I_{DF} > 1$) have the potential to cause structural building damage due to dynamic impact pressure, and were considered to have credible potential to cause loss of life. Building damages levels for higher intensity flows were assigned using intensity-damage criteria developed from judgement with reference to Jakob et al. (2011).

5.3 Economic Risk – Culverts

Table 3 displays the matrix used to determine relative economic risk ratings for individual culverts. The hazard rating in the matrix corresponds to the culvert blockage rating, and the consequence rating to estimated direct building damage costs downstream of the culvert.

Table 3: Economic risk matrix

Hazard Rating (Probability Hazard Scenario Occurs and Impacts Elements at Risk)			Economic Risk Rating				
Classification	Hazard Scenario Probability	Culvert Overflow Rating (Years)					
Very Low	0.001-0.0003	n/a	1	1	2	3	4
Low	0.003-0.001	>200	1	2	3	4	5
Moderate	0.01-0.003	200	2	3	4	5	6
High	0.03-0.01	50	3	4	5	6	7
Very High	0.1-0.03	20	4	5	6	7	7
Consequence Rating	Indices		Very Low	Low	Moderate	High	Very High
	Direct Damage Cost ($M)		<0.1	<0.5	0.5-1	1-10	>10

6 Results

6.1 Safety Risk

Of the 25 creeks assessed in detail, a total of 5 single family residential buildings on three creeks were subject to estimated risk levels exceeding DNV's individual safety risk tolerance standard for existing development (>1x10^{-4} risk of fatality per year). An additional 13 single family residential buildings on various creeks were estimated as subject to risk levels exceeding DNV's individual safety risk tolerance standard for proposed development (>1x10^{-5} risk of fatality per year). Figure 1 displays estimated group risk for Percy Creek on an F-N curve, the only urban creek where the best-estimate of group risk falls in the unacceptable range. The lower, upper and best-estimates shown on the graph (where the dashed line represents the bounds) reflect the range used to estimate vulnerability.

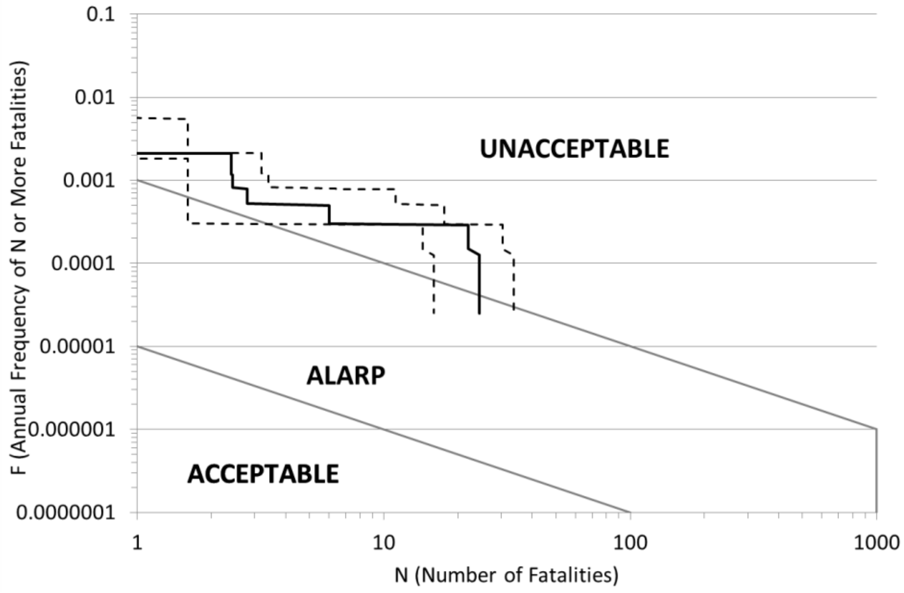

Figure 1: F-N Curve for Percy Creek

6.2 Economic Risk

Estimated damage costs for each hazard scenario and creek ranged from $10,000 on Francis Creek to over $3M on Mackay Creek, with annualized damage costs ranging from negligible to about $100,000. Because the annualized cost is proportional to event frequency, highly damaging but rare events may have a lower annualized cost than more frequent but less damaging events. Semi-quantitative risk ratings assigned to each stormwater drainage asset ranged from 2 to 7 and support prioritization of risk control measures along a given creek.

7 Conclusions

This study provided debris geohazard risk assessment and conceptual debris risk control options for creeks within the DNV. The study includes 35 "steep" creeks (creeks with channel gradients >5%) prone to flood, debris-flood or debris-flow processes that could cause economic damages or pose risk to life for persons within buildings.

For stormwater drainage assets with credible potential for debris blockage, we estimated the return period where culverts and stormwater mains are anticipated to overflow either due to capacity exceedance or blockage by sediment or organic material. We developed and modelled representative hazard scenarios and estimated safety and economic risk associated with these scenarios. An interactive geohazard asset management application, the “Debris Hazard Info Tool” (DNVHIT), was developed to display the results and supporting data for this work.

Based on the results of the hazard assessment, we assessed safety and economic risk at both a creek and individual asset level of detail. Risk estimates for each creek support prioritization of overall risk reduction planning. Relative risk ratings at the asset level support risk reduction prioritization for each stormwater management asset, and quantify the level of risk reduction achieved by implementing the risk control measures. Based on the results of the assessment, DNV staff are developing a 10-year work plan that will be integrated with the District’s asset management, GIS-based inspection program, climate change adaptation and hazard mitigation plans.

Acknowledgements

This work was motivated and funded by the District of North Vancouver. The authors would like to thank Michael Porter for his detailed review of the original assessment.

References

Australian Geomechanics Society (AGS). 2007. A national landslide risk management framework for Australia, 42(1).

BGC Engineering Inc. 2007. Old Grouse Mountain Highway – Culvert Sizing. *Memo prepared for* Hedberg and Associates Consulting Ltd.

BGC Engineering Inc. 2009. North Vancouver Debris Flow and Debris Flood Quantitative Risk Assessment: Update. Report prepared for District of North Vancouver, September 22, 2009.

BGC Engineering. 2010. Mosquito Creek Debris Flood Hazard Assessment. Final report prepared for Natural Resources Canada dated March 31, 2010.

BGC Engineering. 2011. Quantitative Risk and Mitigation Option Assessment. Final report prepared for District of North Vancouver dated January 6, 2011.

BGC Engineering Inc. 2013. Mosquito Creek Post-Mitigation Quantitative Risk Assessment. Report prepared for District of North Vancouver, dated October 2, 2013.

DNV 2015. Asset Management Plan, Drainage. Prepared by the District of North Vancouver, 27 pp.

Fread DL (1985, revised 1991) BREACH: An Erosion Model for Earthen Dam Failures. NWS Report, National Oceanic and Atmospheric Administration, Silver Spring, Maryland.

Hong Kong Geotechnical Engineering Office (GEO) 1998. Guide to Slope Maintenance (Geoguide 5). Geotechnical Engineering Office, Hong Kong.

IBI Group 2015. Provincial Flood Damage Assessment. Prepared for Government of Alberta ESRD - Resilience and Mitigation, dated February 2015.Intergovernmental Panel on Climate Change (IPCC). 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Jakob, M., Stein, D. and Ulmi, M. 2012. Vulnerability of buildings to debris flow impact. Natural Hazards 60:241–261.

Journeay, J.M., Dercole, F., Mason, D., Weston, M., Prieto, J.A., Wagner, C.L., Hastings, N.L., Chang, S.E., Lotze, A., and Ventura, C.E. 2015. A profile of earthquake risk for the District of North Vancouver, British Columbia. Geological Survey of Canada Open File 7677, 223 pp.

McDougall S, Hungr O. 2004. A model for the analysis of rapid landlside motion across three-dimensional terrain. Can Geotech J 41(6):1084–1097 doi:10.1139/t04-052

Ministry of Environment, Lands and Parks. 1995. Design Brief on the Floodplain Mapping Study. *Prepared for the* Water Management Branch, Province of British Columbia. January, 1995.

Northwest Hydraulic Consultants (NHC). 2010. Flood Assessment Study, North Vancouver. *Prepared for* Natural Resources Canada and the District of North Vancouver.

Natural Resources Canada (NRCAN), 2015. A profile of earthquake risk for the District of North Vancouver, British Columbia; by Journeay, J M; Dercole, F; Mason, D; Westin, M; Prieto, J A; Wagner, C L; Hastings, N L; Chang, S E; Lotze, A; Ventura, C E; Geological Survey of Canada, Open File 7677, 2015; p. 145-150.

Rickenmann D. 2001. Comparison of bed load transport in torrents and gravel bed streams. *Water Resources Research* **37**(12): 3295-3305.

United States Environmental Protection Agency. 2013. BASINS [computer program]. Version 4.1. US EPA, Washington, DC.