BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

MUNICIPAL DISTRICT OF BIGHORN NO. 8

HEART CREEK DEBRIS-FLOOD RISK ASSESSMENT

FINAL

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April 27, 2015
Project No.: 1286005

Mr. Dale Mather
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No. 2 Heart Mountain Drive, P.O. Box 310
Exshaw, Alberta
T0L 2C0

Dear Dale,

Re: Heart Creek Debris-Flood Risk Assessment - FINAL

Please find enclosed our draft report for your review and comment.

We trust this report satisfies your requirements at this time. Should you have any questions or comments, please do not hesitate to contact the undersigned. We appreciate the opportunity to continue working on such an interesting and challenging project.

Yours sincerely,

BGC ENGINEERING INC.
per:

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WITH BGC ENGINEERING INC.

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EXECUTIVE SUMMARY

On June 19 and 20, 2013, extreme rainfall events in southeastern Alberta initiated flooding, debris floods and debris flows in the area encompassing the Municipal District of Bighorn (MD of Bighorn), resulting in extensive damage to houses, watercourses, roads, the Trans-Canada Highway, railways and other infrastructure in MD of Bighorn and surrounding areas.

In response to these events, MD of Bighorn retained BGC Engineering Inc. (BGC) to complete detailed hazard assessments for Jura, Exshaw, Heart, Harvie Heights, Grotto and Steve's Canyon creeks. BGC was also asked to complete risk assessments and develop conceptual mitigation for those creeks with potentially high consequences for residential development (Exshaw, Heart and Harvie Heights Creek). This report summarizes the methods and results of the debris-flood risk assessment for Heart Creek.

The principal objective of this work is to support decisions and a funding submission to Alberta's Community Resiliency Program to reduce debris-flood life loss risk on Heart Creek fan to levels considered tolerable by MD of Bighorn. This assessment does not consider all conceivable risks associated with debris floods. Rather, it considers a representative subset of risks that can be systematically estimated, compared to risk tolerance standards[1], and then used to optimize mitigation strategies. These mitigation strategies, once implemented, would also reduce relative levels of risk for a broader spectrum of elements at risk than those explicitly considered in this report.

The major steps in this assessment are to:

1. Assess direct consequences or potential consequences to buildings and infrastructure due to impact by different debris-flood scenarios.
2. Assess risk to life due to impact by different debris-flood scenarios for persons located within buildings.

BGC assessed risk associated with seven debris-flood scenarios representing a range in debris-flood return period classes from 10-30 to 1000-3000 years. Elements impacted by these scenarios and considered in the risk assessment included buildings, roads, utilities, critical facilities, and persons within buildings. Of these, the risk analysis focused on estimation of direct building damage and safety risk. Risk mitigation decisions based on the elements assessed will also reduce relative levels of risk for a broader spectrum of elements than those explicitly considered.

Estimated direct damage costs to buildings for individual scenarios ranged from $0.9 million (M) to $2 M depending on the scenario. BGC's "best estimate" of annualized building damage cost, is approximately $110,000/year.

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[1] E.g. international standards for safety risk (Section 3.2) and/or standards set by MD of Bighorn

The estimated building damage costs are based only on assessed building values. They do not include damage to contents or inventory, costs of cleanup and recovery, indirect costs of business interruption, loss of power transmission, or highway or rail transportation interruption. These factors, if considered, would likely increase annualized damage costs by a factor of 2 or more. No business activity was identified within the impacted areas.

BGC identified two parcels where estimated average safety risk for individuals exceeded 1:10,000 probability of death per annum. This risk tolerance threshold has been adopted internationally by several jurisdictions as well as by the District of North Vancouver, British Columbia, for existing developments. Estimated group safety risk fell into the “ALARP” range when compared to international risk tolerance standards.

It is noteworthy that mitigation, while primarily reducing risk to the development of Lac Des Arcs would also reduce risk to closure of Highway 1, which traverses Heart Creek near its fan apex where it is particularly vulnerable to debris flood impact. Even though highway risks were not part of BGC’s scope of work, it is clear that Highway 1 closures can have significant economic impacts especially since Highway 1A on the north side of the valley would likely be closed due to debris flood inundation during the same storm.

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LIMITATIONS

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1.0 INTRODUCTION

1.1. General

On June 19 and 20, 2013, extreme rainfall events in southeastern Alberta initiated flooding, debris floods and debris flows in the area encompassing the Municipal District of Bighorn No. 8 (MD of Bighorn). This rainfall event resulted in extensive damage to houses, watercourses, roads, the Trans-Canada Highway, railways and other infrastructure in MD of Bighorn and surrounding areas.

In response to these events, MD of Bighorn retained BGC Engineering Inc. (BGC) to complete a debris-flood hazard and risk assessment for Heart Creek (Drawing 1), located on the south side of the Bow River flowing through the Hamlet of Lac des Arcs, across from the Hamlet of Exshaw. This work for Heart Creek has been organized into the following phases: 1) hazard assessment; 2) risk assessment; and 3) risk-based evaluation of mitigation options.

The hazard assessment identified and characterized debris-flood scenarios across a wide range of frequencies and magnitudes. This work is described in BGC (2015b). The reader should refer to this report for background description of the physical and hydroclimatic setting of Heart Creek and the hazard assessment methodology and results.

This report presents methods and results of the debris-flood risk assessment phase. The primary objective of this work is to support decisions and expenditures to reduce debris-flood risk on Heart Creek fan to levels considered tolerable by MD of Bighorn and its stakeholders; a decision that has not been made at the time of this draft report. To complete this objective, the assessment considers key debris-flood risks that can be systematically estimated, compared to risk tolerance standards, and then used to select and optimize mitigation strategies.

The major steps in this assessment are as follows:

1. Assess direct or potential consequences to buildings and infrastructure from impact by debris floods.
2. Assess risk to life due to impact for persons located within buildings.

The report is organized as follows:

- Section 1 summarizes objectives and work scope.
- Section 2 describes the data compiled for the assessment.
- Section 3 summarizes the framework and steps of risk analysis, with results presented and discussed in Section 4. For estimated risk to life, the results are also compared to international criteria for life loss risk tolerance.
- Conclusions are provided in Section 5.

1.2. Risk Assessment Framework

Risk is a measure of the probability and severity of an adverse effect to health, property or the environment, and is estimated by the product of hazard probability (or likelihood) and consequences (Australian Geotechnical Society (AGS) 2007).

Debris-flood risk assessment involves estimation of the likelihood that a debris flood will occur, impact elements at risk, and cause particular types and severities of consequences.

Each of these components are estimated separately and then combined. The objective is to provide a systematic, repeatable assessment with an appropriate level of detail given the information available.

The geographic area considered for a geohazard risk assessment is known as the "consultation zone" (Hong Kong Geotechnical Engineering Office (GEO) 1998), defined in Porter et al. (2009) to include "*all proposed and existing development in a zone defined by the approving authority that contains the largest credible area affected by landslides, and where fatalities arising from one or more concurrent landslides would be viewed as a single catastrophic loss".* Definition of this zone is particularly important to assess group safety risk, which is proportional to the number of persons exposed to a hazard. The consultation zone in this assessment spans the geomorphic extent of Heart Creek fan and includes the elements at risk listed in Section 2.1 within the geomorphic extent of Heart Creek fan (Drawing 1).

Geohazard risk assessment is part of the larger framework of geohazard risk management, which encompasses initial hazard identification through risk analysis and optimization of risk reduction and monitoring measures.

Figure 1-1 provides an overview of a risk management framework, after Canadian Standards Association (CSA 1997), AGS (2007), and ISO 31000:2009. BGC's hazard assessment (BGC 2015b) documents the results of the first phase of the risk management framework for Heart Creek, plus the hazard basis for the second phase, which is the subject of this report.

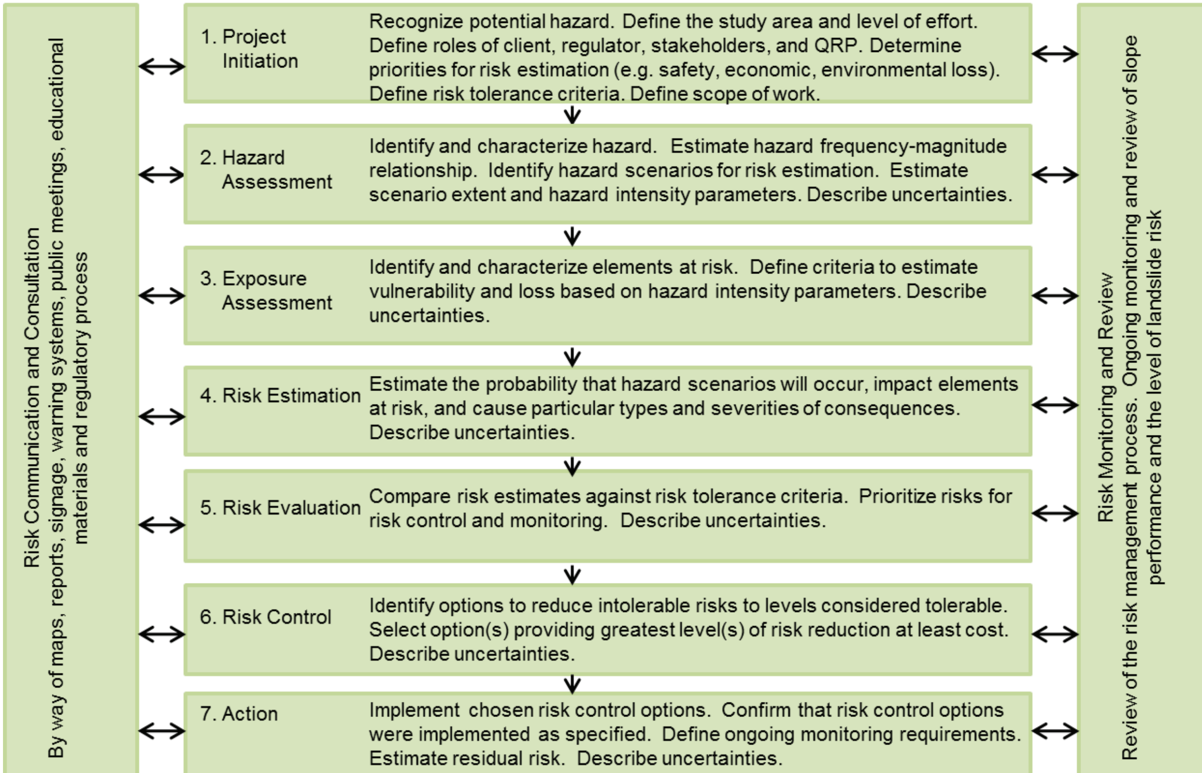

Figure 1-1. Risk management framework (adapted from CSA 1997, AGS 2007, and ISO 31000:2009).

For this assessment, BGC and MD of Bighorn have chosen a quantitative risk assessment (QRA) approach. This is compatible with Canadian and international guidelines for risk management as it provides a systematic method to assess risk based on estimated likelihoods of occurrence and consequences of an event. Using a QRA approach facilitates definition of thresholds for risk tolerance, evaluation of potential debris-flood mitigation alternatives, and transparent description of uncertainties. It also enables a more quantitative approach to characterize the high number of different elements at risk within the consultation zone. Other jurisdictions where risk assessment is a more established standard of practice, such as the District of North Vancouver, Hong Kong and Australia, use a similar approach.

While based on the best data available, it is important to note that each step in this risk assessment is subject to uncertainties. These uncertainties are noted where relevant in the report and should be considered when making risk management decisions. Additional description of risk assessment methodology is provided in Section 3.0.

1.3. Terminology

The appropriate use of this assessment requires some understanding of hazard and risk terminology. In particular, the following key terms are used in this assessment:

Hazard:	Process with the potential to result in some type of undesirable outcome. For example, the hazard could include a debris-flood runout area intersecting the footprint of a building. The term hazard refers to the specific nature of the process (type, frequency, magnitude), but not the consequences. Hazards are described in terms of *scenarios*, which are specific debris-flood events of a particular frequency and magnitude. The debris-flood hazard scenarios considered in this assessment are based on the results of BGC's Heart Creek hazard assessment (BGC 2015).
Element at Risk:	Anything considered of value in the area potentially affected by hazards.
Consequence:	The outcomes for elements at risk, given impact by a debris flood. In this report, consequences considered include potential loss of life, damage to buildings and infrastructure, loss of usage of critical facilities, and direct interruption of business activity.
Mortality:	The number of potential fatalities divided by the number of persons exposed to a hazard, should the hazard occur.
Risk:	Likelihood of a debris-flood hazard scenario occurring and resulting in a particular severity of consequence. In this report, risk is defined in terms of safety or damage level. For example, this could include the likelihood of debris-flood impact to a building resulting in destruction of the building.

1.4. Scope of Work

Table 1-1 describes the work required to meet the objectives described in Section 1.1. The work was approved in an award letter from MD of Bighorn dated March 19, 2014, based on BGC's proposal dated January 8, 2014 and discussions with the MD of Bighorn. BGC was retained by the MD of Bighorn under the terms of a Master Consulting Agreement, dated March 28, 2014.

Table 1-1. Work tasks.

Task	Work Component	Description and Method
1	Project Management	• Project management, contract administration, client liaison • Budget tracking, communications
2	Data Collection	• Compile results from hazard assessment into a format suitable for risk analyses • Obtain and organize buildings infrastructure data into a format suitable for analyses • Create database linked to GIS containing spatial and buildings infrastructure information
3	Data Processing	• Process hazard analysis results into GIS grid layers indicating debris-flood intensities (destructive power) for different debris-flood scenarios • Complete spatial analysis assigning estimated debris-flood intensities to buildings or parcels in impact zones
4	Risk Analysis	• Estimate risk based on estimated hazard probability, spatial and temporal probability of impact, and vulnerability of elements at risk, for different debris-flood scenarios and types of elements at risk
5	Reporting (Draft/Final)	• Description of methodology and results • Comparison of estimates of risk to life to international risk tolerance thresholds • Presentation of results in tabular and map format • Integration of draft review comments into Final report

2.0 DATA COMPILATION

Data required to assess the risk of debris floods on Heart Creek fan includes an inventory of elements at risk, modeled debris-flood scenarios (maximum water depth and velocity), and algorithms for the estimation of losses. Data showing elements at risk were provided by MD of Bighorn, and debris-flood scenarios were based on BGC's Heart Creek hazard assessment (2015b). Methods to compile and manage these data are described in this section. Methods to develop the loss estimation algorithms are described in Section 3.0.

2.1. Elements at Risk

Table 2-1 lists the "elements at risk" considered in this assessment. These elements were defined through discussions with MD of Bighorn. Table 2-1 does not include all possible elements that could suffer direct or indirect consequences due to a debris flood on Heart Creek.

The elements at risk listed in Table 2-1 are limited to those that could be reasonably assessed, based on the information available. For example, indirect economic consequences due to highway interruption are not included, even though those could amount to very significant losses, especially if Highway 1A were to be closed at the same time which was the case in the mid June 2013 flood event. The assessment also focuses on risk associated with direct debris-flood impact. Additional risk associated with, for example, loss of access to the elements listed in Table 2-1, is not considered.

Risk mitigation decisions based on the elements assessed will also reduce risk for a broader spectrum of elements in protected areas than those explicitly considered.

Table 2-1. List of elements at risk considered in the Heart Creek debris-flood risk assessment.

Element at Risk[1]	Description
Building Structures	Residential properties.
Persons	Persons located within buildings.
Roads	Local roads, Highway 1.
Utilities	Electrical power and telephone line distribution.
Business activity	Businesses located on the fan that have the potential to be directly impacted by debris floods, either due to building damage or interruption of business activity due to loss of access.

Note:

1 The location and characteristics of buildings, roads, and utilities were provided by Challenger Geomatics.

A description of each of these elements is provided below.

2.1.1. Buildings

Information on buildings within the study area was provided by MD of Bighorn[2] within data compiled for each parcel (property boundary). The locations of buildings (building centroids) were digitized by Challenger Geomatics from Bing imagery dated May 2013. These data were used in the risk analysis to identify location(s) of buildings within parcels that could be impacted by debris-flood scenarios.

Building types on the fan include residential (full-time and summer cabins), wood construction dwellings. Dwellings are typically constructed from wood rafters or joists on wood stud walls (MD of Bighorn assessor, pers. com. May 16, 2014). Most buildings are 30 to 40 years old and are 1 to 2 stories high. Basements are typically 2.4 m high.

Each land parcel contains a unique identification number ("PID") and unique property class code identifying the primary use and type of building within the parcel. Four building types (Commercial, School, Residence, Garage) were also assigned by Challenger Geomatics. In the case of single buildings (e.g. residential houses), each parcel contains an assessed land and improvement (i.e. building) value.

In total, about $15 million (M) of assessed buildings infrastructure[3] is located within 118 parcels on the Heart Creek fan. This corresponds to about 8% of the assessed buildings value within MD of Bighorn. For comparison, the sum of the assessed buildings infrastructure and the calculated improvement value estimated by BGC is about $71 M within the Exshaw Creek and Jura Creek study area, which corresponds to 33% of the assessed and estimated building value within MD of Bighorn. The values listed above do not include building contents or inventory and do not necessarily correspond to replacement cost, which may be higher. As such, they should be regarded as minimum costs.

Table 2-2 summarizes the main uncertainties associated with the buildings attributes data provided.

Table 2-2. Building data uncertainties.

Type	Description
Building Value	Several parcels did not include improvement values. For these PIDs, the improvement value was estimated by BGC based on the average of the improvement value for the specific building type.
Property Class Code (Building Use)	Based on communication with the MD of Bighorn, the vast majority of the property class codes are correctly assigned, but some errors may exist. BGC has not reviewed the accuracy of parcels data provided by the MD of Bighorn and they were assumed to be correct for the purpose of this assessment.
Building Location	Building footprints were not available. Information on exact building types within parcels was not directly available, and ambiguities exist where multiple buildings exist within parcels and where building centroids overlap parcel boundaries.

[2] Cadastral and land title data was provided by Altalis via MD Bighorn

[3] Note that impacts on land values were not considered in this assessment.

Building Type	BGC has not reviewed the accuracy of building location and building type data provided by Challenger Geomatics and they were assumed to be correct for the purpose of this assessment.

2.1.2. Critical Facilities

Critical facilities are defined in guidelines developed for new facilities funded by Alberta Infrastructure (Alberta Infrastructure, 2013) as those that:

- Provide vital services in saving and avoiding loss of human life
- Accommodate and support activities important to rescue and treatment operations
- Are required for the maintenance of public order
- House substantial populations
- Confine activities that, if disturbed or damaged, could be hazardous to the region (Alberta Infrastructure 2013)
- Contain hazardous products or irreplaceable artifacts and historical documents.

Buildings defined as “critical” were not identified on Heart Creek. As such, this category of elements of risk was not considered further in the risk assessment.

2.1.3. Persons

Population estimates used in this assessment are based on 2011 Census summaries (MD of Bighorn 2011), dwelling counts from tax roll classification data (MD of Bighorn 2013), business data (Hoovers 2014), and direct communication with key facilities are noted below.

According to 2011 Census data, the Hamlet of Lac Des Arcs has a population of 144. These include 64 full-time private dwellings and 47 private dwellings that are unoccupied or occupied by part-time residents. All buildings are within the Heart Creek fan boundary (Drawing 2), which suggests approximately 1.3 to 2.3 persons occupy an average residential dwelling unit.

Assessment of risk at a parcel level of detail requires estimation of the number of persons in each parcel on the fan. These data are not directly available and were estimated based on the number of building units of a given type or property class code, in each parcel, and the estimated number of persons in a given building type or property class code. Results were then compared to Census totals to ensure they fell within a reasonable range. Steps to complete this estimate are described below.

First, BGC estimated the number of building units based on a combination of building type and property class codes. Second, BGC estimated the number of occupants per building unit. Individual unit occupancy rates were calibrated so that the total population estimate for Heart Creek fan corresponded approximately to 2011 Census totals for the same area.

Table 2-3 summarizes calculated populations used in the risk analysis. Note that these values should not be summed without consideration that some population types overlap (e.g. workers might also live on the fan).

Table 2-3. Summary of calculated population estimates used in risk analysis.

Population Type	Population Total
Residents	156
Commercial Employees	2

These calculated population estimates, while systematically compiled from the best available data, are subject to uncertainties. In the case of the permanent population, calculated values were calibrated to Census (2011) with an average dwelling occupancy rate of 1.8 per dwelling unit. Additional uncertainties are listed in Table 2-4.

Implications of the uncertainties listed in Table 2-4 include possible over- or underestimation of group safety risk for particular parcels depending on whether the number of persons was over- or underestimated, respectively. BGC believes that the accuracy of population estimates is sufficient to allow risk management decisions. However, the estimates should not be used for detailed assessment of individual parcels (e.g. for building permit applications) without being manually checked. Furthermore, re-development will increase the number of people at risk which implies changes for individual risk for the properties that witness densification as well as a potential increase in the overall (group) risk.

Table 2-4. Uncertainties associated with estimating the number of occupants of a building.

<table>
<tr><th>Uncertainty</th><th>Implication</th></tr>
<tr><td>Average occupancy rates may not correspond to actual occupancy rates for a given dwelling unit.</td><td rowspan="4">Over- or underestimation of occupant numbers</td></tr>
<tr><td>Seasonal population fluctuations exist that were not accounted for.</td></tr>
<tr><td>Errors in employee data sourced from Dunn and Bradstreet (D&B) (Hoovers 2014) may exist. These data were not verified by BGC.</td></tr>
<tr><td>Errors in assignment of D&B employee data to specific parcels may exist, due to inconsistencies in building address data.</td></tr>
<tr><td>Distribution of persons within a building are unknown. As such, the number of persons most vulnerable to debris-flood impact on the first floor or basement is unknown.</td><td>Uncertainty in estimation of human vulnerability to debris-flood impact</td></tr>
<tr><td>Seasonal visitors may occupy private residences.</td><td>Underestimation of occupant numbers</td></tr>
</table>

2.1.4. Roads

Roads considered in the assessment include municipal roads on Heart Creek fan, and Highway 1 (Drawing 2).

2.1.5. Utility Systems

Utility systems considered in this study are shown on Drawings 2 and include the following:

- Electrical transmission managed by Altalink[4]
- ATCO Pipeline.

2.1.6. Business Activity

Business activity considered in this assessment includes public and private employers with their primary address located on Heart Creek fan. Employer data are based on information compiled by the commercial information provider Dunn and Bradstreet (D&B) (Hoovers 2014).

One business located on the fan of Heart Creek was identified, generating about $220,000/year (USD) and employing approximately two people. Note that this estimate is subject to some uncertainty, as described at the end of this section.

Business locations were identified manually by linking business data (addresses) sourced from D&B (Hoovers 2014) to individual roll numbers provided by MD of Bighorn.

The business data used in the assessment are subject to uncertainties. In particular, BGC's experience with D&B data suggests it is not always complete, which would mean that total business activity within the study area is underestimated. In addition, business activity estimates do not include individuals working at home for businesses located elsewhere or businesses that are located elsewhere but depend on transportation corridors. Inclusion of these figures could increase the level of business activity that could be affected by a debris-flood event. This has not been quantified as part of this study.

2.2. Debris-flood Scenarios

This section describes the different debris-flood scenarios considered in the risk assessment. The 2013 debris flood has been used as a basis to calibrate the risk model with observed damages and life loss.

2.2.1. June 2013 Debris Flood

BGC's hazard report (BGC 2015b) described the storm and resulting debris flood that occurred on Heart Creek between June 19 and 21, 2013. Table 2-5 summarizes damages and costs recorded, based on data provided August 28, 2014 by MD of Bighorn.

The costs summarized in Table 2-5 include work to complete emergency assessments and reconstruction and estimates of direct damage costs to impacted development and infrastructure. Costs not incurred directly by the MD of Bighorn (e.g. private and industrial infrastructure) are best estimates provided by the MD of Bighorn. Costs do not include services

[4] Assumed to also carry telephone cables

provided by the fire department (e.g. time, food, or equipment), other workers (e.g. overtime, benefits, food, clothes, equipment, etc.), or flood relief accommodations[5]. Importantly, they also do not include professional services to assess hazard and risk (e.g. this assessment), or long-term risk reduction measures. As such, actual costs of the June 2013 event were higher than those summarized below.

No fatalities occurred on Heart Creek as a result of the June 2013 debris flood.

Table 2-5. Reported damage and repair costs for Heart Creek fan following the 2013 debris flood (MD of Bighorn, 2014).

Item	Description	Cost
Municipal Infrastructure		
Roads/sidewalks/bridges	Repairs and resurfacing of bridge over Heart Creek	$50,000
Recreational Facilities	Repairs to Heart Creek trail ($25,000) and Trans-Canada trail ($50,000) and bench replacement.	$75,000
Subtotal		$125,000
Private Infrastructure		
Homes	Damage to 10 homes @ $10,000 average each; 6 homes purchased on Bow River bank ($5,562,000)	$5,662,000
Industrial Infrastructure		
Alberta Transportation	Repairs to Hwy 1	$1,000,000
ATCO Gas	Re-routing and restoration of gas service to hamlet	$500,000
Subtotal		$1,500,000
Other Expenses		
Other Expenses	Repairs to Heart Creek	$300,000
Total		**$7,587,000**

2.2.2. Debris-flood Scenarios used in the Risk Assessment

The risk analysis described in Section 3.0 is based on modeled debris-flood scenarios, which are defined as debris-flood events with particular characteristics and likelihoods of occurrence. BGC (2015b) developed debris-flood scenarios that are considered representative across the range of return periods considered. These are listed in Table 2-6 and are the debris-flood

[5] General costs incurred by the MD of Bighorn (not fan specific), include: $69,977 for operating the Emergency Operations Center, and $26,650 for crucial 'volunteers' working during the state of local emergency.

scenarios considered in this report. For description of methods to develop these scenarios and further discussion of uncertainties and limitations, see BGC (2015b).

Drawings 3-4 show estimated debris-flood intensities at each model grid cell location, for each scenario. Debris-flood intensity is defined as the destructive power of a debris-flood, measured in this assessment as flow depth multiplied by the square of flow velocity (see Section 3.7.1) (Jakob et al., 2011).

Scenarios 1 to 5 correspond to 10 to 30 year, 30 to 100 year, 100 to 300 year, 300 to 1000 year, and 1000 to 3000 year frequency intervals[6]. The bounds of a given range are exceedance probabilities. For example, the 100 to 300 year range should be interpreted as to the probability of events at least as large as a 100 year event, but not as large as a 300 year event, with the "best" estimate falling towards the middle of the range.

Table 2-6. Summary of debris-flood scenarios (BGC 2015).

Scenario ID	Frequency (years)	Sediment Volume Estimate (m^3)	Peak[1] Flow (m^3/s)	Hydro-Geomorphic Processes	Probability	Model Runs and Assumptions
1	10 to 30	14,000	25	Debris Flood	100%	
2a	30 to 100	19,000	40	Debris Flood	25%	Al LeSann Bridge is blocked
2b					75%	Al LeSann Bridge and Hwy 1 culvert are blocked
3a	100 to 300	23,000	50	Debris Flood	25%	Al LeSann Bridge is blocked
3b					75%	Al LeSann Bridge and Hwy 1 culvert are blocked
4	300 to 1000	27,000	65	Debris Flood	100%	Al LeSann Bridge and Hwy 1 culvert are blocked
5	1000 to 3000	32,000	80	Debris Flood	100%	Al LeSann Bridge and Hwy 1 culvert are blocked

[1]Peak flow as reported here is the total discharge including the sediment in transport.

2.3. Data Management

Elements at risk data were managed within Excel and a Microsoft SQL Server database[7], and linked to geospatial data (e.g. parcel boundaries) in ArcGIS. Debris-flood model grids produced as part of the hazard assessment (BGC 2015b) were also imported to ArcGIS. This approach allows updating of any data component (e.g. new development, new flood loss algorithms, or new flood scenarios) and expansion of the analysis to different fans or floodplains within MD of Bighorn without major changes to the data management structure.

[6] Note that the inverse of return period is event frequency, and that the bounds of the interval are cumulative frequencies; e.g. the frequency of an event of at least a certain magnitude.

[7] Relational database management system produced by Microsoft.

3.0 RISK ASSESSMENT

3.1. General

Risk assessment involves estimation of the likelihood that a debris-flood scenario will occur, impact elements at risk, and cause particular types and severities of consequences.

The primary objective of the risk assessment is to support risk management decision making. Importantly, the assessment does not consider all possible risks that could be associated with a debris flood. Rather, the risk assessment considers key risks that can be systematically estimated, compared to risk tolerance standards, and then used to optimize mitigation strategies. These mitigation strategies, once implemented, would also reduce relative levels of risk for a broader spectrum of elements than those explicitly considered in this report. Debris-flood impact and resulting consequences are determined by relating the characteristics of debris-flood scenarios (flow velocity and depth) to impacted elements at risk at a given location.

This assessment considers direct impact to the elements at risk listed in Section 2.1, and focuses on direct structural building damage and risk to life. It excludes emergency response and reconstruction costs (e.g. the costs of the June 2013 event summarized in Section 2.2.1). This approach represents a practical way to achieve the assessment objectives given the data available. However, such auxiliary costs would have to be added to assess the total costs of a destructive debris flood, as these costs could exceed the direct damages that have been systematically considered in this assessment.

This risk assessment does not consider structural debris-flood mitigation or evacuation of persons in affected areas. This approach provides a baseline estimation of risk to facilitate comparison of different debris-flood risk reduction options. No other risk reduction measures are considered.

Following presentation of results, Section 4.4 compares BGC's estimates of safety risk to alternative analysis methodologies and previously recorded events, to calibrate estimates where possible and check that the results are within a reasonable range.

3.2. Quantitative Risk Assessment (QRA)

Risk (P_E) was estimated using the following equation:

$$P_E = \sum_{i=1}^{n} P(H)_i P(S{:}H)_i P(T{:}S)_i \, N \quad [1]$$

where:

$P(H)_i$ is the annual hazard probability of debris-flood scenario i of n

$P(S{:}H)_i$ is the spatial probability that the event would reach the element at risk

$P(T{:}S)_i$ is the temporal probability that the element at risk would be in the impact zone at the time of impact

$N = V_i E_i$ describes the consequences. [2]

where:

V_i is vulnerability, the probability elements at risk will suffer consequences given debris-flood impact with a certain severity of destructive power

E_i is a measure of the element at risk, quantifying the severity of potential consequences (e.g. number of persons, building value).

In the case of safety risk (risk to life), risk is estimated separately for individuals and groups (societal) risk (see Section 3.2). Estimated risk for combined debris-flood scenarios is calculated by summing the risk quantified for each individual debris-flood scenario. The analysis considers debris-flood Scenarios 2-5 (Table 2-6).

Individual risk considers the probability that a hazard scenario result in loss of life for a particular individual, referred to as Probability of Death of an Individual (PDI). Individual risk levels are independent of the number of persons exposed to risk.

In contrast, group risk considers the probability of a certain number of fatalities. Unlike individual risk, a greater number of persons exposed to the same hazard corresponds to increased risk. For this reason, it is possible to have a situation where individual risk is considered tolerable, but group risk is not tolerable due to the large number of people affected.

Group risk is typically represented graphically on an F-N curve, as shown in Figure 3-1. The Y-axis shows the annual cumulative frequency, f_i, of each hazard scenario, and the X-axis shows the estimated number of fatalities, N_i, where:

$$f_i = \sum_{i=1}^{n} P(H)_i P(S{:}H)_i P(T{:}S)_i \quad [3]$$

and N_i is represented by equation [2] (see Section 3.2).

Group risk was calculated according to Equation 3. However, results in this report were not shown on an F-N curve as no fatalities were estimated (see Section 4.3.2).

Direct building damages were calculated as total annualized damage considering all scenarios, as well as direct damage costs for individual scenarios. Assessment of loss of function for critical facilities and impact to business activity were completed for individual scenarios.

Assessment of roads and utilities included identification of the location of infrastructure in relation to the extent and intensity of modelled debris-flow scenarios, but did not include estimation of damage levels. An estimate of damage level would be very difficult in such cases, given uncertainties in any estimation of erosion severity for flows avulsing out of the channel and flowing over the fan surface, a significant portion of which is paved. In all cases, the assessment considers area directly impacted by modelled flows. It does not include assessment of consequences associated with, for example, areas rendered inaccessible due to impact elsewhere.

Methods used to estimate each variable in equation [1] are described in Sections 3.4 to 3.7.

3.3. Risk Tolerance Criteria

Currently, MD of Bighorn has not yet adopted criteria to assess whether safety risk for individuals or groups exceed tolerable levels. However, to help guide decisions regarding levels of risk tolerance, results of this assessment were compared to criteria adopted elsewhere.

Estimated safety risk to individuals was compared to tolerance criteria adopted by the District of North Vancouver (DNV), British Columbia in 2009, following guidelines developed in Hong Kong (Hong Kong Geotechnical Engineering Office (GEO) 1998). The DNV criteria for individual geohazard risk tolerance are as follows:

- Maximum 1:10,000 ($1x10^{-4}$) risk of fatality per year for existing developments
- Maximum 1:100,000 ($1x10^{-5}$) risk of fatality per year for new developments.

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 the DNV. Group risk tolerance criteria reflect society's general intolerance of incidents that cause higher numbers of fatalities. Group risk tolerance thresholds based on criteria adopted in Hong Kong (GEO 1998) are shown on an F-N Curve in Figure 3-1. Three zones can be defined as follows:

1. Unacceptable – where risks are generally considered unacceptable by society and require mitigation.
2. As Low as Reasonably Practicable (ALARP) – where risks are generally considered tolerable by society only if risk reduction is not feasible or if costs are grossly disproportionate to the improvement gained (this is referred to as the ALARP principle).
3. Acceptable – where risks are broadly considered acceptable by society and do not require mitigation.

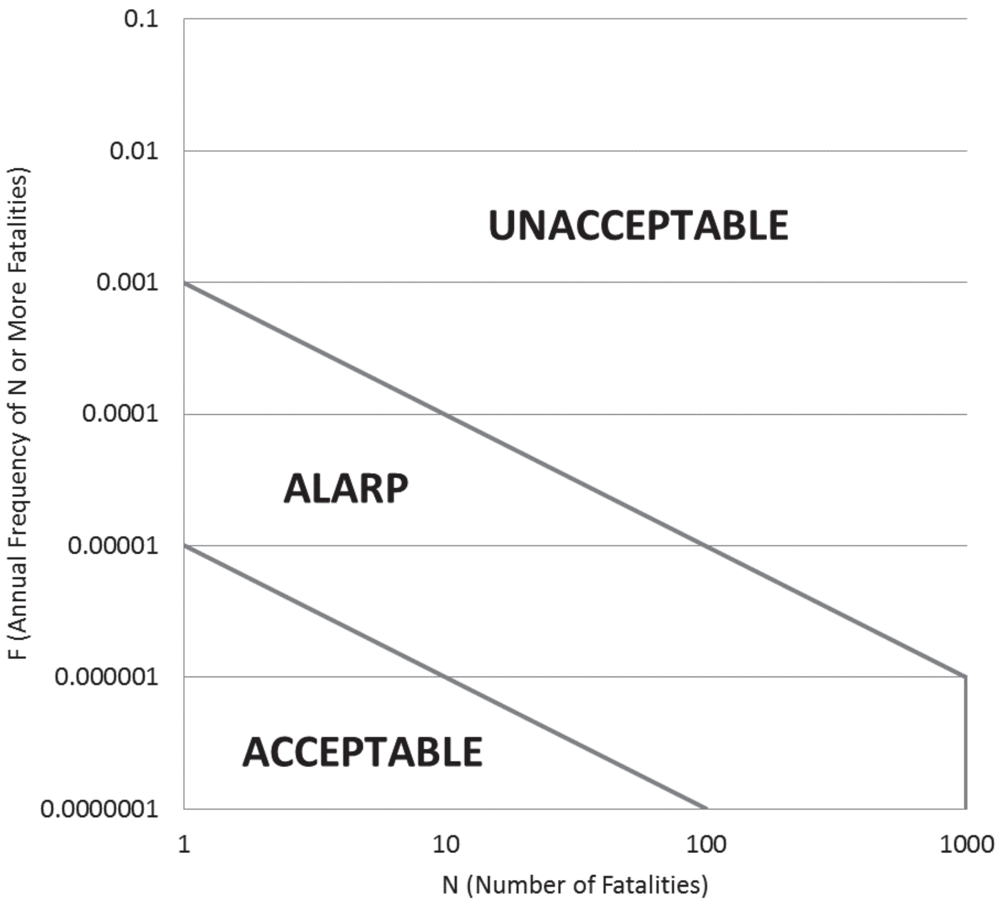

Figure 3-1. Group risk tolerance criteria as defined by GEO (1998).

3.4. Hazard Probability, $P(H)$

Hazard probability, $P(H)_i$, corresponds to the annual probability of occurrence of each hazard scenario, which are defined in Table 2-6 as annual frequency ranges. The bounds of a given range are exceedance probabilities. As such, for a scenario with the annual probability range P_{min} to P_{max}, the probability of events within this range corresponds to:

$$P(H)_i = P_{max} - P_{min} \quad [4]$$

For example, for the 30 to 100 year range, this would correspond to:

$$P(H)_i = \frac{1}{30} - \frac{1}{100} = \frac{1}{43} \quad [5]$$

The upper and lower bounds of each range were used in the risk analysis as approximate upper and lower uncertainty bounds for each frequency range.

3.5. Spatial Probability, $P(S:H)$

Spatial probability, $P(S:H)$ of debris-flood impact considers modelled debris-flood extents in relation to the location of elements at risk. $P(S:H)$ was calculated as:

$$P(S:H)_i = P_A P_I \quad [6]$$

where:

P_A is the probability of a particular debris-flood avulsion scenario. Avulsion scenarios were assigned as equal probability of occurrence (e.g. two possible avulsion scenarios would each be assigned a 50% chance of occurring).

P_I is the spatial probability of building impact given an avulsion scenario. Cases where modeled debris-floods impacted (intersected) these elements were considered certain $P_I = 1$ to be impacted. Those elements outside the modeled flow extent were not considered subject to impact by the scenario.

In the case of buildings, ambiguities exist where there are multiple buildings within parcels or parcel boundaries overlap, because data on these buildings is only available at the parcels level of detail (the building footprints themselves do not have data associated with them). For example, in the case of a parcel containing a detached home and an out-building, no data existed to automatically distinguish every home from an out-building. With >315 parcels in the assessment, manually reviewing such cases was not possible.

To account for these uncertainties, buildings in a parcel were assumed as impacted if a debris-flood scenario impacted any building footprint within the given parcel. In cases where a building footprint intersects more than one modelled debris-flood intensity level, the maximum (most conservative) value was used.

3.6. Temporal Probability, $P(T:S)$

For assessment of risk to buildings, temporal probability, $P(T:S)$, was assigned as 1 (certain) based on the assumption that all buildings considered are permanent structures.

For assessment of safety risk, the value of $P(T:S)$ corresponds to the proportion of time spent by persons within a building.

For persons in residential buildings, an average value of 0.5 was assigned for analysis of risk to groups implying that about half of the residents will be in their homes during a debris flood. A more conservative value of 0.9 was used for estimation of individual risk, corresponding to a person spending the greatest proportion of time at home, such as a young child, stay-at-home person, or an elderly person.

3.7. Vulnerability

Vulnerability is defined in this report as the degree of loss of a given element at risk that results from debris-flood impact with a certain level of destructive power. For human life loss, it addresses the question, "what is the chance of fatality for persons within buildings, should the building be impacted by a debris flood?" For buildings, it addresses the question, "what level of direct damage will occur if the building is impacted by a debris flood?" This section describes how vulnerability ratings were assigned to different elements at risk based on estimated levels of destructive power and resistance to impact. Section 3.7.1 first describes methods to estimate destructive power in terms of debris-flood "intensity" and flow depth. Sections 3.7.1 to 3.7.3 then describe criteria used to estimate vulnerability for different elements at risk.

3.7.1. Buildings

Vulnerability of buildings to damage was assessed in terms of four damage categories, as shown in Table 3-1. These categories were derived from an international review of the literature and reported in Jakob et al. (2011). These classes represent a spectrum of potential damages ranging from flooding and sedimentation to building collapse.

Building damage costs were estimated by multiplying the average percent damage listed in Table 3-1 by the assessed improvement value for the affected parcel. Estimated damage costs for individual parcels were then summed to give the total estimated damage cost for each scenario. Damage costs were also reported as an annualized figure. This was calculated by multiplying the total damage cost for a given scenario by its estimated likelihood of occurrence, and then summing the results across the scenarios.

Table 3-1. Damage categories for buildings.

Damage Class	Damage Level	Percent Damage[1] (% Range, Average)	Description
1	Moderate	>0 - 25% (12.5%)	Moderate likelihood of building structure damage and high likelihood of major sediment and/or water damage. Building repairs required but primarily to non-structural elements.
2	Major	>25% - 75% (50%)	High likelihood of moderate to major building structure damage and severe sediment and water damage. Building repairs required, possibly including some structural elements.
3	Severe	>75% - 90% (83%)	High likelihood of major to severe building structure damage and sediment and water damage. Major building repairs required including to structural elements.
4	Destruction	>90% (95%)	Very high likelihood of severe building structure damage or collapse. Complete building replacement required.

Note:

1. Percent damage in terms of assessed building value.

Vulnerability estimates were based on the maximum modelled flow depth and velocity at a given building location. Two different criteria, depth-damage functions and a flow "intensity index", were used to consider factors for building vulnerability: low-velocity flood inundation (e.g. in areas of backwater flooding) and higher velocity debris-flood impact. Both criteria were applied to each parcel and the maximum estimated damage level was used. These criteria are described below.

Depth-Damage Functions (Flood Vulnerability)

Depth-damage functions are empirical relations between flood depth and average damage for particular building types. These functions are based on flood depth at a particular building location and are expressed as a proportion of building cost (e.g. Figure 3-2). They do not directly consider flow velocity and apply where flood inundation is the primary factor for damage (e.g. areas with backwater flooding).

Depth-damage functions used in this analysis were obtained from the U.S. Federal Emergency Management Agency (FEMA) software program Hazus-MH, which is a multi-hazard loss estimation tool developed by FEMA. The functions were compiled by FEMA from a variety of sources including the Federal Insurance and Mitigation Administration (FIMA), U.S. Army Corps of Engineers (USACE), and the USACE Institute for Water Resources (USACE IWR), and include damage functions for building structure, contents, and inventory for 457 different classified building types.

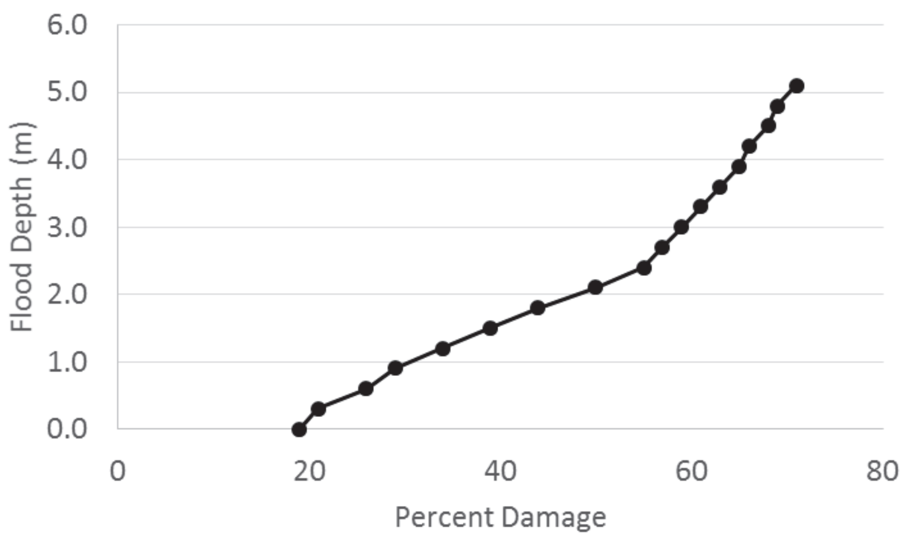

Figure 3-2. Example of a flood depth-damage function (residential homes).

Given the large number of depth damage curves and the requirement to associate these curves with MD of Bighorn's assessment building types, building type data were generalized. Depth-damage curves used as "default" in Hazus-MH are available for 44 average building types. These curves represent the mean of curves for 44 simplified building categories (e.g.

the default depth-damage curve for retail stores is the average of curves for 144 retail store types).

Default Hazus-MH depth-damage functions were cross-tabulated with MD of Bighorn's building use codes. For simplicity, damage functions for building structure only were used, and parcel "improvement" assessment values were used as a proxy for building replacement costs. Applied to assessed building values, the damage costs estimated based on these functions should be regarded as a minimum.

Intensity Damage Function (I_{DF}) (Debris-flood Vulnerability)

The "intensity index" is based on Jakob et al. (2011), who documented sixty-six case studies where characteristics related to flow intensity, such as flow depth and velocity, were recorded or could be estimated and related to recorded building damage. These criteria were chosen for this study because it is based on the largest available case study survey relating damage to parameters that can be estimated by modelled debris-flood scenarios.

Debris flow intensity was represented by Jakob et al. (2011) as follows:

$$I_{DF} = d \times v^2 \quad [7]$$

where: d is flow depth (m) and v is flow velocity (m/s).

Values of I_{DF} were plotted on a log scale against recorded building damage to estimate probabilities of a certain proportion of building damage, categorized similarly to Table 3-1. These criteria apply where debris-flood impact is the primary factor for damage and are less applicable for low velocity areas (e.g. v < 1 m/s), where I_{DF} will approach zero for any flow depth.

Figure 3-3 shows building damage cases reported by Jakob et al. (2011), plotted as a function of reported flow depth and velocity. Figure 3-3 displays a general trend towards higher building damage cases at higher flow intensities, as would be expected, but with some overlap between damage levels at a given flow velocity and depth. This overlap may be associated with uncertainties in estimating flow characteristics, differences in vulnerability between different buildings, or variations in how damage levels were estimated.

Figure 3-3 also shows I_{DF} thresholds (I_{DF} = 1, 10, 100) that were used to estimate the building damage categories listed in Table 3-1. Buildings on the fan include wood construction dwellings ("Res1" land use category).

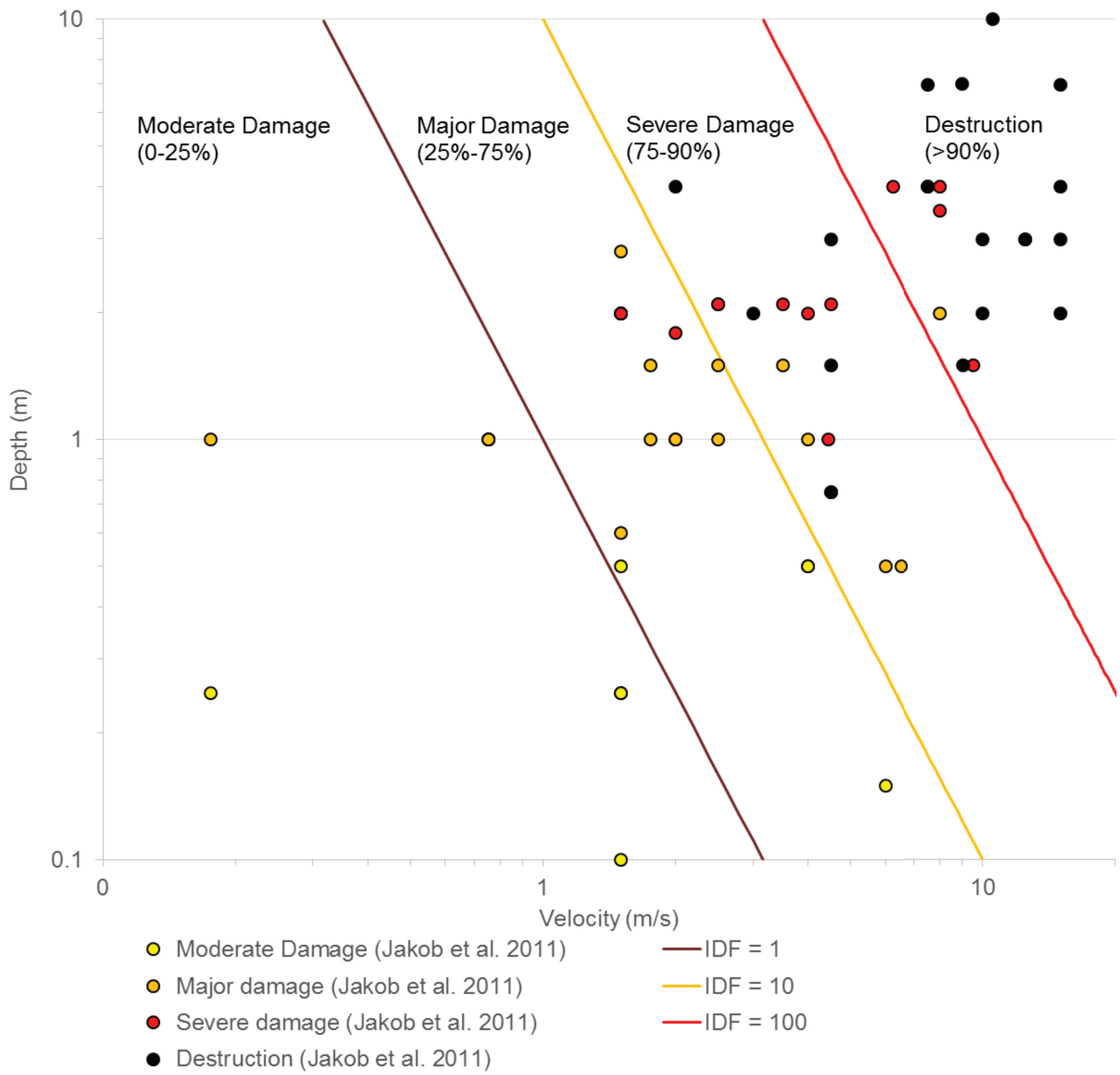

Figure 3-3. Building damage cases reported by Jakob et al. (2011), plotted as a function of flow depth and velocity. Damage thresholds are plotted according to Equation [7].

3.7.2. Roads and Utility Systems

Roads and utility systems were considered as potentially subject to damage if impacted by a modelled debris-flood scenario. Vulnerability levels associated with modelled debris-flood intensities at a given location were not assessed.

3.7.3. Persons

Within buildings, human vulnerability was estimated as an indirect outcome of building damage or collapse. Outside buildings, estimates of risk to life were not attempted because the position of persons in relation to debris flooding is unknown and unpredictable during a debris flood. Within buildings, human vulnerability criteria is also subject to uncertainties because of limited information on factors influencing vulnerability. These include the specific nature of damage, the position of persons within a building, and the ability of persons to escape impact.

Table 3-2 shows estimated average probability of life loss assigned for a certain level of building damage. Vulnerability to injury is not considered. The criteria shown in Table 3-2 were calibrated based on known events and comparison to results calculated from published mortality functions for large scale river floods (see Section 4.5). Building impact by flow depths < 30 cm or flow intensities of less than one were assumed to pose negligible risk to life for persons within buildings and were thus excluded from the analysis.

Two different vulnerability classes are shown. Estimates for individual risk correspond to an individual most at risk, who may be located on the building ground floor. Estimates used for group risk are 50% lower, with the exception of the highest damage category. This reflects an average estimate for the parcel, recognizing that persons on upper floors will have a relatively lower vulnerability to debris flood impact except in the case of building destruction.

Table 3-2. Vulnerability categories for persons within buildings.

Building Damage Level			Estimated Safety Vulnerability, Individual Risk (V)	Estimated Safety Vulnerability, Group Risk (V)
Class	Percent Damage1 (% Range, Average)	Damage Level		
1	<0 to 25%	Moderate	1:1000	1:2000
2	>25% to 75%	Major	1:100	1:200
3	>75% to 90%	Severe	1:10	1:20
4	>90 to 100%	Destruction	1:2	1:2

Note:

1. Percent damage in terms of assessed building value.

4.0 RESULTS

This section summarizes results of the risk analysis based on the methods described in Section 3.0.

4.1. Surface and Subsurface Infrastructure

As noted in Section 1.4, assessment of roads and utilities was limited to identification of the location of infrastructure in relation to the extent and intensity of modelled debris-flood scenarios. Drawings 3 and 4 show modelled debris-flood intensity in relation to surface and subsurface infrastructure, including roads and utilities, for the various debris-flood scenarios. Table 4-1 provides an overview of potential impacts, which were previously described in BGC (2015b).

Table 4-1. Description of potential debris-flood scenario impacts (BGC 2015).

Return Period (years)	Scenario	Sediment Volume (m^3)	Results
10-30	1	14,000	• Flow along south Hwy 1 ditch to the west. Hwy 1 is overtopped and there is potential for gullying along south west edge of fan towards the Bow River. Flow velocities are less than 1 m/s and flow depths are less than 1 m. • Majority of flow is conveyed through the Hwy 1 culvert. • Properties are flooded with less than 1 m of water to the east of the main channel along Heart Rise, Heart Crescent, Lac Des Arcs Drive, and Mountaineer Close. Flow velocities are less than 1 m/s. • Majority of flow is conveyed through the Al LeSann Bridge. • An avulsion occurs downstream of the Al LeSann Bridge to the east and an avulsion channel runs through properties along Heart Crescent. • A zone of potential gullying is identified along Mountaineer Close. • The two properties to the north of the main channel where the creek turns northwest are flooded with impact intensity less than 10. The low lying park area to the south of the bend is flooded with water depths up to 2.5 m. • The north edge of the fan is susceptible to erosion from the Bow River.
30-100	2a	19,000	• Same flow conditions to the west along Hwy 1. There is some flow along the south ditch to the east. • Channel widening and more properties are flooded east of Heart Rise. • An avulsion occurs upstream of the Al LeSann Bridge and an avulsion channel runs through properties to the west of Heart Crescent. • Similar conditions along Mountaineer Close and the main channel bend as observed in Scenario 1.

Return Period (years)	Scenario	Sediment Volume (m^3)	Results
30-100	2b	19,000	• Hwy 1 is overtopped to the west and east of the Hwy 1 culvert and flow paths with intensity indices less than 10 form along the north and south highway ditches to the west. • Water flows down the Hwy 1 access ramp into the Lac Des Arcs community and floods the Lac Des Arcs Campground. Gullying occurs south of Des Arcs Road and a channel with impact intensity of less than 10 runs to the Bow, affecting surrounding properties. • The south west sector of the fan is flooded from flows running east along Hwy 1. Flow velocities are less than 1 m/s and flow depths are less than 1 m. The southernmost properties along Heart Road and Heart Place are flooded and there is potential for gullying through the eastern fan deposits. • Similar flow paths downstream of Hwy 1, as seen in Scenario 2a.
100-300	3a	23,000	• Some flow is diverted to the west and east along the Hwy 1 south and north ditches and down the Hwy 1 access road. • Flow paths downstream of the Hwy 1 culvert are similar to Scenario 2a.
100-300	3b	23,000	• Flow paths are similar to Scenario 2b, however more flooding and gullying potential is interpreted for the Lac Des Arc Campground and more properties are flooded in the south east fan sector along Heart Road and Heart Place. Several properties are located within the potential gullying zone along the eastern fan boundary.
300-1000	4	27,000	• Flow conditions are similar to Scenario 3b, however, more homes are flooded in the east fan sector along Lac Des Arcs Drive and more properties are in the potential gullying zone.
1000-3000	5	32,000	• Similar flow paths ad Scenario 4, however more severe. • Majority of properties in the east fan sector are flooded and more properties along Lac Des Arcs Drive are in the potential gullying zone. • Potential for gullying increases in the Lac Des Arcs campground.

4.2. Buildings and Business Activity

Drawings 5 and 6 show estimated building damage proportions for individual parcels (i.e., Table 3-1), while Drawing 7 and 8 show estimated building damage costs. No business activity was recorded in the impacted areas.

Table 4-2 summarizes parcel consequence estimates for each scenario, including total building damage costs.

Table 4-2. Summary of consequence estimates.

Debris-flood Scenario	Frequency (years)	Number of Parcels Affected	Building Damage Cost ($M)	Average Cost/Parcel ($)
1	10 to 30	18	0.9	50,000
2a	30 to 100	19	1.1	60,000
2b		31	1.3	40,000
3a	100 to 300	20	1.1	60,000
3b		35	1.5	40,000
4	300 to 1000	42	2.0	50,000
5	1000 to 3000	43	2.0	50,000

Note: See Section 4.4.3

The estimated direct building damage costs range from $0.9 M for the 10-30 year return period scenario to about $2.0 M for the 1000-3000 year return period unmitigated scenario. For comparison, total assessed building value for the entire fan corresponds to about $15 M.

BGC's best-estimate of annualized building damage cost is $110,000, based on the scenario damage costs listed in Table 4-2. It should be emphasized that the estimated building damage costs are based only on a portion of assessed building values and do not include damage to contents or inventory. In addition, costs of cleanup and recovery, such as those listed in Table 2-5 for the June 2013 event, are not included. If these were considered, actual damage costs could increase by a factor of 2 or more. It is also important to note that this assessment does not include Bow River damages. For comparison, Table 4-3 below shows the annualized building damage for other creeks in the Municipal District of Bighorn, reported in BGC's risk assessments for these creeks (BGC 2015a, 2015c).

Table 4-3. Annualized building damage costs for M.D. Bighorn creeks.

Creek	Annualized Building Damage Cost
Heart	$110,000
Exshaw and Jura	$210,000
Harvie Heights	$80,000

4.3. Safety Risk

As described in Section 3.2, safety risk is estimated separately for individuals and groups (societal risk). The results presented are the combined annual risk from all debris-flood scenarios, given that some parcels may be impacted by more than one scenario.

To account for uncertainty, the results are reported as a range. BGC's "best estimate" is based on the annual probability of occurrence of each hazard scenario, as defined in Section 3.4.

The lower and upper risk estimate bounds are based on the lower and upper bounds of debris-flood hazard probability, respectively, for each scenario.

4.3.1. Individual Risk

BGC's best-estimate of individual risk exceeded the tolerance standard of 1:10,000 ($1x10^{-4}$) risk of fatality per year for two parcels. A complete list of parcel IDs is available upon request.

Drawing 9 shows zones where BGC's best-estimate of individual risk (PDI) exceeds 1:10,000 ($1x10^{-4}$) and 1:100,000 ($1x10^{-5}$) risk of fatality per year. Drawing 9 is based on the spatial distribution of individual parcels exceeding the above two thresholds, but the results have been interpreted (generalized) into zones to reflect uncertainties in the assessment. Parcels exceeding the 1:10,000 ($1x10^{-4}$) and 1:100,000 ($1x10^{-5}$) threshold are concentrated along the east side of Heart Creek main channel. These estimates are associated with increased modelled flow depths through this section and include the residences along Heart Creek that were damaged during the June 2013 event.

4.3.2. Group Risk

The number of fatalities estimated for a given scenario was negligible (less than 1 fatality[8]). As such, results were not presented on an F-N plot such as Figure 3-2.

4.4. Discussion

This section compares BGC's estimates of safety risk to recorded flood, debris flood or debris flow events observed elsewhere. The objective is to verify that vulnerability criteria and results of the safety risk estimation are reasonable when compared to documented events and to results based on published mortality functions for large river floods (where there is more recorded data than mountain creeks).

This section uses the term *mortality*, defined as the number of potential fatalities divided by the number of persons exposed to hazard. For example, a mortality rate of 1 indicates that the entire exposed population will likely perish or that there is a 100% chance of death of the entire population at risk. A mortality rate of 0.01 indicates that 1% of the affected population will likely perish.

For Heart Creek, the number of persons exposed to debris-flood hazard was calculated for each debris-flood scenario as the total number of persons within the area impacted by a scenario multiplied by their temporal probability of being in the hazard zone. Estimated mortality rate ranged from 0.1% to 0.3% for all scenarios, consistent with BGC's estimation of negligible fatalities for a single event scenario (Section 4.3.2).

[8] Because the value of N is a product of the number of elements at risk (E) and vulnerability (V), calculated results are not necessarily round numbers. Estimated fatalities for a single scenario were less than 0.1, which BGC considered as "negligible".

4.4.1. Comparison to Case Studies

Appendix A describes hazard events occurring elsewhere, for comparison purposes. The events described in this section include some cases where loss of life and the population that was exposed to hazard are both known, and other cases where loss of life did not occur but are relevant for comparison to Heart Creek. The examples chosen include cases where evacuation was either not possible due to the event's suddenness, or evacuations were resisted or not executed to their fullest extent.

The above case studies have yielded mortalities ranging over one order of magnitude from about 0.01 (1%) to 0.12 (12%). BGC's estimated mortality rate of 0.1% to 0.3% lies below the lower bound for all scenarios. This estimate reflects the relatively lower flow intensities expected at Heart Creek in comparison to the case studies examined.

4.4.2. Comparison to Flood Mortality Models

Unlike debris floods on mountain creeks, much more research has been focused on estimating mortalities from flooding in lowland areas (Di Mauro 2012). These include complex models focusing on the behavior of single individuals, such as the Life Safety Model (Johnstone et al. 2006) and the US LifeSim Model (Aboelata and Bowles 2005), and relatively simpler "mortality functions" based on statistical relations between measurable flood variables and fatalities (De Bruijn and Klijn 2009). Of the latter, one of the most commonly applied models is that of Jonkman *et al.* (2008), which is currently included in the Standard Dutch Damage and Casualty Model (De Bruijn and Klijn 2009). Mortality functions of this model were applied to Heart Creek debris-flood scenarios for comparison purposes.

The mortality functions of Jonkman *et al.* (2008) are based on investigation of about 165 historic flood locations in the Japan, Netherlands, UK, USA, and South Africa. The functions were calibrated for large scale flooding of low-lying areas following a dike breach and do not account for the higher sediment concentrations and sustained higher flow velocities typical of debris floods. However, they are still useful for comparison purposes because they are based on much more data than is available for debris-flood events.

Jonkman *et al*. (2008) propose mortality functions for three zones:

1. *Breach Zone:* This zone was defined for the vicinity of a dike breach, where high flow velocities lead to collapse of buildings and instability of people standing in the flow. Due to lack of data to develop a mortality function for this zone, mortality is arbitrarily assumed as 1 (certain) where flow intensity exceeds a threshold defined as velocity exceeding 2 m/s, flow depth rising by more than 0.5 m/hr, and where velocity multiplied by depth exceeds 7.
2. *Rapidly Rising Water Zone*: This zone corresponds to areas where water depths exceed 2 m and rise at more than 0.5 m/hr.

3. *Remaining Zone:* This zone corresponds to areas with shallower water depths and/or slower rates of water rise, where it is easier to escape and find shelter. The mortality function is defined for areas not included in the Breach or Rapidly Rising Water zones.

Rather than pre-defining geographic zones, the appropriate mortality function was selected for each parcel based on modelled flow velocities and depths at that location.

The estimated mortality rate based on the mortality functions of Jonkman et al. (2008) is less than 1 for all considered scenarios, consistent with BGC's mortality estimate for Heart Creek.

4.4.3. Scour

Flow velocities and flow depth influence erosion susceptibility along the channel and on the fan surface. All other things being equal, higher flow velocities and higher flow depths will result in more intensive erosion. Erosion will be concentrated in the channel and along its banks. On the fan surface, erosion will be confined where surface vegetation is absent or sparse or the flow channelized (for example in paleochannels or in ditches). Sheet flow (unchannelized flow) at low velocities (less than approximately 2 m/s) and low flow depths (< 0.3 m) is unlikely to result in significant erosion. FLO 2D does not simulate erosion and sediment re-deposition along existing channels and some judgment is required in the interpretation of the final modeling result.

Drawings 3 and 4 show potential scour zones as red-patterned polygons ("Zone of Potential Gullying"). Due to the above-described limitations, it is extremely difficult to predict the level of scour, associated building damage, and associated risk to life that could occur within these zones during an event. As such, BGC has not quantified additional risk that might be associated with scour during a scenario, and risk estimates within zones of potential gullying shown on the drawings should be regarded as minimums. However, risk reduction decisions based on the types of risk assessed will reduce risk for a broader spectrum of elements and outcomes than those explicitly considered, including scour.

5.0 CONCLUSIONS

This assessment estimated debris-flood risk for Heart Creek fan based on the results of BGC's hazard assessment (BGC 2015b). The primary objective of the assessment was to support decision making and expenditures to reduce debris-flood risk to levels considered tolerable by MD of Bighorn.

BGC assessed risk associated with four debris-flood scenarios representing a range in debris-flood return periods from 30-100 to 1000-3000 years. Elements impacted by these scenarios and considered in the risk assessment included buildings, roads, utilities, critical facilities, and persons within buildings. Of these, the risk analysis focused primarily on estimation of direct building damage and safety risk (i.e. loss of life), but excluded risks that could be associated with sudden gully erosion as those cannot be systematically quantified. These were selected as the key elements that can be systematically assessed and compared to risk tolerance standards. Risk mitigation decisions based on the elements assessed will also reduce relative levels risk for a broader spectrum of elements than those explicitly considered.

Estimated direct damage costs to buildings for individual scenarios ranged from $0.9 M for the 10-30 year return period scenario to $2.0 M for the 1000-3000 year return period scenario. BGC's best-estimate of annualized building damage cost is $110,000, based on the scenario damage costs listed in Table 4-2. The estimated building damage costs are based only on assessed building values. They do not include damage to contents or inventory, costs of cleanup and recovery, indirect costs of business interruption, loss of power transmission, or highway or rail transportation interruption. These factors, if considered, would likely increase annualized damage costs by a factor of 2 or more.

No business activity was recorded within the impacted area for any scenario. For reference, revenues of all businesses on Heart Creek Fan correspond to about $200,000/year. As noted in Section Table 4-2, the impact to business revenue should be interpreted as a proxy for the level of business activity in impacted areas, not an estimate of economic loss.

BGC identified 2 parcels where estimated average safety risk for individuals exceeded 1:10,000 probability of death per annum. This risk tolerance threshold has been adopted internationally by several jurisdictions as well as by the District of North Vancouver, British Columbia, for existing developments. Estimated group safety risk fell into the "ALARP" range when compared to international risk tolerance standards.

The decision on funding for mitigation measures, apart from economic losses to fan properties and loss of life, ought to consider interruptions to traffic on Highway 1. This also calls for mitigation to be implemented upstream of Highway 1 which will be included in BGC's forthcoming risk report (BGC, 2015b).

6.0 CLOSURE

We trust the above satisfies your requirements at this time. Should you have any questions or comments, please do not hesitate to contact us.

Yours sincerely,

BGC ENGINEERING INC.
per:

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APEGA Permit to Practice: 5366

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APPENDIX A
COMPARISON TO CASE STUDIES

October 1921 Debris Flood at Britannia Beach, BC

On October 28, 1921, after a full day of torrential rain, a massive flood destroyed much of the community and mine operations on the lower beach area. Fifty of 110 homes were destroyed and thirty-seven people lost their lives. Construction activities had led to a landslide that dammed a portion of the creek, and when this dam collapsed the town below was flooded.

BGC reviewed historical documents to estimate the flow velocities and flow depths associated with the Britannia Creek debris flood. Eye witness accounts talking about a "20 m high wave of water" are likely misinterpreted from "20 feet of water", since the imperial system prevailed in those days. Even 20 feet (~7 m) appears unlikely given the photographic evidence from the flood[1]. The photographs suggest that an area alongside and south of the current creek was overwhelmed by debris and water with flow depth to perhaps 3 m near the fan apex and 1 m near the fan fringe. Because the loss of confinement on the fan decreased flow velocities, it is expected that velocities ranged between 4 m/s just downstream of the fan apex to perhaps 2 m/s at the fan margins.

In summary:

- Of 300 people living in the community on the Britannia Creek fan, 37 were killed, resulting in a mortality of 0.12 (12%). For a single person, the chance of death was 37/300 = 0.124.
- Of the 300 people living on the fan, 15 suffered severe injuries (5% injury rate).
- Per home destroyed, there was on average, one (0.74) fatality.
- 45% of all buildings on the fan were destroyed.

December 1981 Debris Flow at Charles Creek, BC

On December 4, 1981, a 30,000 to 40,000 m^3 debris flow travelled down Charles Creek, approximately 4 km north of Horseshoe Bay, following a period of heavy rain and snowmelt. Initial surges blocked a bridge under a residential road, resulting in further deposition upstream, blockage of the highway bridge and deposits of up to 6 m high on the surface of the highway.

Two houses were inundated by water and gravel, although no structural damage occurred. Of the 40 residents who attempted to evacuate from the houses below Charles Creek, 1 woman was swept away by flood water. This corresponds to a 0.025 (2.5%) mortality rate for this event.

Hummingbird Creek near Salmon Arm, British Columbia

On July 11, 1997 a large debris flow occurred at Hummingbird Creek on Mara Lake. A 25,000 m^3 debris avalanche was initiated downstream of a forest road culvert that drained a small catchment. The debris avalanche evolved into a debris flow that reached between 600 and 1000 m^3/s and deposited 92,000 m^3 of sediment on the fan (Jakob et al. 1997). There were no impact-related fatalities recorded, but one heart attack related to the trauma of seeing the debris flow.

[1] http://www.seatoskycommunity.org/archived/britanniabeach/disaster/1921flood.html

Deposition depths ranged between 3.5 and 1 m upstream of Highway 97A and between 0.1 and 0.5 m downstream of the highway. Flow velocities upstream of the Highway ranged between 6 m/s and perhaps 12 m/s. Downstream of Highway 97A flow velocities ranged between an estimated 1 and 3 m/s. Of the five cabins upstream of the highway, 2 were destroyed. There were no people present in these cabins at the time of impact. Lower Hummingbird Creek fan is largely settled with private residences, mostly for weekend use. The total number of cabins on the fan that were affected by the event is approximately 20.

Assuming a potential occupancy of two people per cabin, mortality for the upper fan could have ranged from 0.1 to 3. For the lower fan, mortality could have ranged between 0.2 and 0.8. The fact that no one died through impact is clearly associated with the absence of many property owners at the time of impact, which underlines the necessity to include temporal probabilities in risk calculations.

Testalinden Creek near Oliver, British Columbia

On June 13, 2010, a debris flow was triggered by the overtopping and subsequent incision of an earth fill dam at Testalinden Lake. The debris flow destroyed five houses, severely damaged two, obliterated several orchards and vineyards, and deposited debris on a major highway. This event was highly publicized and photographed, allowing estimation of flow depths that appeared to have ranged between 1 and 2 m at impact with homes.

Although seven homes were destroyed or severely damaged, no deaths occurred. However, the event occurred in the afternoon on a Sunday during summer, and it is not known how many homes were occupied (if any) at the time of impact. Furthermore, it is reported that some residents heard the approaching debris flow and ran away from their homes.

February 2010 Debris Floods in Funchal, Madeira

On February 26, 2010, 108 mm of rain were recorded within a 5 hour period (average intensity of 22 mm/hr) at Funchal (pop. approx. 100,000), the capital of the Portuguese Island of Madeira in the North Atlantic. This event triggered landslides and debris floods that caused the loss of 50 lives[2]. Based on Google Earth imagery showing houses along the flooded corridors, an estimated 1000 to 5000 people were exposed to the debris-flood hazards, corresponding to a mortality rate of 0.01 to 0.05 (1 to 5 %).

August 2005 Flooding, New Orleans, USA

During landfall on August 29, 2005, Hurricane Katrina caused massive flooding and devastation along a 270 km stretch of the US Gulf Coast. The storm surge caused overtopping and breaching of levees around New Orleans. An area of 260 km^2 of the city flooded at some locations up to 4 m deep. It took over 40 days to dewater the city. Flow depths reached up to 3 m. The rate of water level rise over the first 1.5 m reached up to 50 m/hr or roughly one cm/min. The total death toll

[2] See the Youtube video of debris floods: (http://www.youtube.com/watch?v=nXjb5QBb9TA).

associated with hurricane Katrina amounted to 1464. Of the 746 fatalities that were recovered in their location of death, 54% died in their residence, 20% in medical facilities and 10% in nursing homes and 7% perished in the open. The typical causes of death were drowning or physical trauma due to debris impacts and collapsing buildings.

Mortalities were calculated for various neighborhoods in New Orleans that could reasonably be homogenized. Mortalities range between 0 and 0.15 (15%). For the whole of New Orleans (including Orleans, St. Bernard and New Orleans East), a mortality of 1.2% was calculated. For the Lower 9th Ward, which was one of the worst affected areas and suffered the direct impact of a wave due to dike breach, mortalities ranged between 0.03 (3%) and 0.07 (7%).