BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

TOWN OF CANMORE

STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT

FINAL

PROJECT NO.: 1261009-09 DATE: September 30, 2016

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September 30, 2016
Project No.: 1261009-09

Mr. Andy Esarte, P.Eng.
Town of Canmore
Canmore Civic Centre
Canmore, Alberta T1Q 3K1

Dear Andy,

Re: Stoneworks Creek Debris-Flood Risk Assessment – FINAL

We trust the above 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:

Matthias Jakob, Ph.D., P.Geo.
Senior Geoscientist

EXECUTIVE SUMMARY

On June 19 and 20, 2013, extreme rainfall events in southeastern Alberta initiated flooding, debris floods and debris flows in the Bow River valley between Seebe and Banff National Park, resulting in extensive damage to houses, watercourses, roads, the Trans-Canada Highway, railways and other infrastructure in Canmore and surrounding areas.

In response to these events, Canmore retained BGC Engineering Inc. (BGC) to complete forensic studies for 9 creeks, a study describing the hydroclimate of the June 2013 event, and a detailed debris-flood hazard and risk assessment for Stoneworks Creek. This work was organized into three steps:

1. Forensic assessment
2. Hazard assessment
3. Risk assessment.

This report presents methods and results of the third phase, risk assessment, which involves estimation of the likelihood that a debris flood will occur, impact elements at risk, and cause particular types and severities of consequences.

The principal objective of this work is to support decisions and expenditures to reduce debris-flood life loss risk on Stoneworks Creek fan to levels considered tolerable by Canmore. 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 (safety risk) due to impact by different debris-flood scenarios for persons located within buildings
3. Compare estimated safety risk to international risk tolerance standards.

BGC assessed risk associated with seven debris-flood scenarios representing a range in debris-flood return periods classes from 10 to 30 years to 1000 to 3000 years in accordance with the Draft Alberta Guidelines for Steep Creek Risk Assessments. 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. These were selected as the key elements that can be systematically assessed and compared to risk tolerance standards.

[1] E.g. international standards for safety risk (Section 3.23.2) and/or standards set by Canmore.

Estimated direct damage costs to buildings for individual scenarios ranged from $7.2 million (M) to $29.2 M depending on the scenario. BGC's estimate of annualized building damage cost for all scenarios is about $790,000/year. The relatively high estimate of direct damage costs compared to those recorded in 2013 event reflects differences in the types of damages assessed (building damages) versus those recorded (primarily related to emergency response). The relatively high annualized cost compared to estimates for other Canmore creeks mainly reflects the higher frequency of damaging events and the close proximity of Stoneworks Creek to high value improvements.

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. As such, they should be considered a minimum loss potential cost. These factors, if considered, would increase annualized damage costs.

Annual business revenues in impacted areas range from $30.4 M to $32.6 M (or 36% to 38% of the total revenues of all business in the study area) depending on the scenario. Note that this should be considered a proxy for the level of business revenue in impacted areas, not an estimate of total economic loss, since revenue data was not available for all business, and the duration and severity of business loss is unknown and very challenging to quantify in detail.

BGC did not identify any occupied 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 extends into the "As Low As Reasonably Practical (ALARP)" range when compared to international risk tolerance standards.

These results suggest while life loss risk on Stoneworks Creek can be regarded as tolerable compared to existing risk tolerance standards, economic risk is high. Thus, mitigation efforts would largely target reduction of economic risk.

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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 Town of Canmore (Canmore). This rainfall event resulted in extensive damage to houses, watercourses, roads, the Trans-Canada Highway, railways and other infrastructure in Canmore and surrounding areas.

In response to these events, Canmore retained BGC Engineering Inc. (BGC) to complete a number of forensic studies of creeks subject to geomorphic events during the extreme rainfall, a hydroclimate study, and a debris-flood hazard and risk assessment for Stoneworks Creek (Drawing 1).

The work was based on BGC's proposal and work plan dated November 8, 2013 and discussions with the Town of Canmore. The work was completed under the Town of Canmore/BGC Master Consulting Agreement dated July 15, 2013.

The work for Stoneworks Creek was organized into the following phases:

1. Forensic assessment of the June 2013 debris flood
2. Hazard assessment
3. Risk assessment
4. Risk-based evaluation of mitigation options.

The first two phases of work are described in BGC (2013, 2014, 2015).

The first two phases identified and characterized debris-flood scenarios across a wide range of frequencies and magnitudes. The reader should refer to these reports for background description of the physical and hydroclimatic setting of Stoneworks Creek and the hazard assessment methodology and results. Two detailed studies (Liu et al., 2016, Pomeroy et al, 2016) summarize the hydroclimate and meteorology of the June 2013 events.

At the request of the Town of Canmore, the risk assessment phase was postponed until Canmore had advanced its land use planning for future development at Stoneworks Creek. This report presents methods and results of the third phase, debris-flood risk assessment. The primary objective of this work is to support decisions and expenditures to reduce debris-flood risk within the Stoneworks Creek study area to levels considered tolerable by Canmore and its stakeholders. Table 1-1 summarizes the scope of work.

This 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 results of this assessment should be considered as a snapshot in time, subject to periodic review in light of future changes (e.g. new development, debris flood mitigation, geohazard events, and climate change).

The major steps in this assessment are to:

1. Assess direct or potential consequences to buildings and infrastructure from impact by debris floods expressed as debris-flood scenarios
2. Assess risk to life (safety risk) due to impact for persons located within buildings
3. Compare the results of safety risk estimation to international risk tolerance thresholds.

The report is organized as follows:

- Section 1.0 summarizes background, objectives and work scope
- Section 2.0 describes the data compiled for the assessment
- Section 3.0 summarizes the framework and steps of risk analysis, with results presented and discussed in Section 4.0. For estimated risk to life, the results are also compared to international criteria for life loss risk tolerance
- Conclusions and recommendations are provided in Section 5.0.
- Appendix A describes hazard events occurring elsewhere, for comparison to Stoneworks Creek.

Table 1-1. Work tasks.

Task	Work Component	Description and Method
1	Project Management	• Project management, contract administration, client liaison; • Budget tracking, communications, etc.
2	Data Collection	• Compile results from Phases 1 and 2 (forensic and 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)	• Describe methodology and results; • Compare estimates of risk to life to international risk tolerance thresholds; • Present results in tabular and map format; • Describe steps required to optimization the risk reduction strategy • Integrate draft review comments into Final report.

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 for 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 entire fan plus areas where modelled debris floods extended past the geomorphic fan boundary, and includes the elements at risk listed in Section 2.1 (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 forensic and hazard assessments (BGC 2013, 2014a, 2015) document the results of the first two phases of the risk management framework for Stoneworks Creek. This report documents the results of the third and part of the fourth phases of the risk management framework for Stoneworks Creek.

Risk Communication and Consultation	Risk Management Steps	Land Management Planning and Regulation
By way of maps, reports, signage, warning systems, public meetings, and educational materials	1. Project Initiation a. Recognize the potential hazard b. Define the consultation zone (study area) and level of effort c. Define roles of the client, regulator, stakeholders, and QRP d. Determine 'key' risks to be considered in the assessment	Ongoing review of the risk management process for land use and development permitting
	2. Hazard Assessment a. Identify and characterize the hazard b. Develop a hazard frequency-magnitude relationship c. Identify hazard scenarios to be considered in risk estimation d. Estimate hazard extent and intensity parameters for each scenario	
	3. Risk Assessment a. Characterize elements at risk and determine vulnerability criteria b. Estimate risk: the probability that hazard scenarios will occur, impact elements at risk, and cause particular consequences.	
	4. Risk Evaluation a. Compare the estimated risk against tolerance criteria b. Prioritize risks for risk control and monitoring	
	5. Risk Control a. Identify options to reduce risks to levels considered tolerable. b. Select option(s) providing the greatest risk reduction at least cost	
	6. Action a. Implement chosen risk control options b. Define ongoing monitoring and maintenance requirements	

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

For this assessment, BGC and Canmore 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 Stoneworks 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. Previous Assessments

BGC (2016a) developed an inventory and risk-based prioritization of steep-creek fans, encroachment, flood inundation and clear-water culvert avulsion hazards along Alberta highways within the Rocky Mountain Foothills on behalf of Alberta Transportation. A total of 247 fans were characterized in the study, including Stoneworks Creek fan. While life loss risk was not considered in this study, BGC notes that Stoneworks Creek fan was identified as the highest priority fan in the entire study. Key factors contributing to the high priority include:

- The location of the highway in the central portion of the fan
- The observation that a debris flood event could avulse and intersect the highway at multiple locations.

2.0 DATA COMPILATION

Data required to assess the risk of debris floods on Stoneworks Creek 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 Canmore, and debris-flood scenarios were based on BGC's Stoneworks Creek hazard assessment (2015). 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 Canmore and the external reviewer[2]. Table 2-1 does not include all elements that could suffer direct or indirect consequences due to a debris flood.

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 or the railway are not included. 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 Stoneworks Creek debris-flood risk assessment.

Element at Risk[1]	Description
Building Structures	Commercial, institutional, recreational, residential, transportation.
Persons	Persons located within buildings.
Roads	Local roads, Highway 1.
Utilities	Sewerage, stormwater management, gas distribution, electrical power and telephone line distribution.
Critical facilities	Medical facilities
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.

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

A description of each of these elements located on Stoneworks Creek fan is provided below.

2 Dr. Norbert Morgenstern

2.1.1. Buildings

Information on buildings within the study area was obtained from Alberta's Department of Municipal Affairs via Alberta Ministry of Environment and Sustainable Resource Development (ESRD) within data compiled for each parcel (property boundary). The assessment data used for this study has an "effective date" of Dec. 31, 2013 (e.g. reflects 2013 municipal assessments). The use of 2013 assessment data was confirmed by Canmore and is similar to that used by BGC on the other risk assessments provided to Canmore following the June 2013 event. The locations of buildings (building footprints) were provided by Canmore (2013). These data were used in the risk analysis to identify location(s) of buildings within parcels that could be impacted by debris-flow scenarios.

Building types on the fan include single family, wood construction dwellings and multi-family, commercial, or industrial buildings, also wood construction. Single family dwellings are typically constructed from wood rafters or joists on wood stud walls (Canmore assessor, pers. com. October 9, 2013). The multifamily, commercial or industrial buildings are typically larger and framed from beams or major horizontal members spanning between columns supporting lighter floor joists or rafters. A church occupies a converted bungalow (Canmore assessor, pers. comm. May 16, 2014).

Each land parcel contains a unique identification number ("PID") and unique lookup code identifying the primary use and type of building within the parcel. In the case of single buildings (e.g. residential houses), each parcel contains only one assessed land and building value. Parcels with multiple units (e.g. condominiums or mixed residential/commercial) contain multiple assessed values, all with the same PID but with different tax roll numbers. In these cases, the total assessed value of units(s) within a parcel was calculated by summing the assessed values for all roll numbers with the same PID. Data on building structure type or contents were not available. In the case of some multiple residential units, building and land values were not separated in the data[3]. Based on discussion with Canmore, BGC understands that building values in these cases can be estimated as 80% of the combined land and building value.

In total, about $286 million (M) of assessed buildings infrastructure is located within 225 parcels in the Stoneworks Creek study area, with assessed land values totaling about $170M[4]. This corresponds to 7% of the assessed building value and 4% of the assessed land value within Canmore. All buildings are less than 20 years old and, are wood frame and less than 3 stories high. Basements are typically 8 to 10 feet (2.4 to 3.0 m) high (pers. comm., Frank Watson, Canmore Assessor). 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. Assessment of proposed development in the future is outside BGC's scope of work.

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[3] Cases where the "Linc Number" (tax code) = 12, 20, 21, or 21A and no building value was assigned.

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

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

Table 2-2. Building data uncertainties.

Type	Description
Building Value	Assessed parcel land and building values were not separated for some roll numbers. Building values were assigned as 80% of total assessed parcel value for these lookup types.
Building Structure	No site-specific information describing building structure (e.g. wood frame or concrete construction) were available. Building use (predominant actual use codes from Municipal Affairs data, related lookup codes from Canmore data), and general comments by the Canmore Assessor were used to define building structure type for the purpose of vulnerability assessment (see Section 3.7.1).
Parcel Lookup Code (Building Use)	Based on communication with Canmore, the vast majority of the parcel lookup codes are correctly assigned, but some errors may exist. BGC assumed the accuracy of parcels data provided by Canmore to be correct for the purpose of this assessment.
Building Location	Information on exact building types within parcels was not directly available, and ambiguities exist where multiple buildings exist within parcels and where building footprints overlap parcel boundaries.

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.

Table 2-3 summarizes the types of critical facilities described in Alberta Infrastructure (2013). The table also shows the design flood levels cited by Alberta Infrastructure that should be protected against for such facilities.

Canmore General Hospital was identified as a critical facility in the Stoneworks Creek study area.

Table 2-3. Critical Facilities (modified after Alberta Infrastructure 2013).

Class	Importance of Avoiding Major Damage During a Flood Emergency	Design Flood Level	Examples of Facilities
1	Critical to the ability to save and avoid loss of human life.	1:1000	Legislative buildings Communication centres
2	Critical to the ability to rescue and treat the injured and to prevent secondary hazards.	1:1000	Hospitals and medical facilities Extended care facilities
3	Critical urban linkages important to the maintenance and welfare of public order and welfare.	1:500	Courthouses Provincial Buildings
4	Critical to the ongoing housing of substantial populations.	1:500	Schools Post-secondary educational facilities Seniors Residences High-rise buildings Correctional facilities Rehabilitation treatment centres
5	Critical to the orderly return to long term social and economic welfare.	1:500	Airports
6	Important to the ability to avoid endangering human life and environment.	1:1000	Hazardous waste disposal and treatment facilities High risk research facilities
7	Important to retention of documented historical data and artifacts.	1:1000	Museums, archives, cultural centres

2.1.3. Persons

Population estimates used in this assessment are based on 2014 Census summaries (Canmore 2015), dwelling counts from tax roll classification data (Canmore 2013), and business data (Hoovers 2013).

The Stoneworks Creek study area intersects a portion of Municipal Census District nos. 0B, 11, 12B and 19A. With the exception of Cross Zee Ranch, the Stoneworks Creek study area does not intersect a developed portion of District No. 0B and therefore, is not considered in the population totals. Census data for municipal districts within the Stoneworks Creek study area is summarized in Table 2-4.

Table 2-4. 2014 census data for municipal districts within the Stoneworks Creek study area.

Municipal District	Permanent population	Non-permanent population[1]	Approximate proportion in study area (%)	Permanent Population in Study Area	Non-permanent population in Study Area
6	243	85	40	97	85
7B	111	3	10	11	3
11	85	17	40	34	17
12B	456	71	90	410	71
19A	439	119	25	110	119

1) Non-Permanent Residents are defined as "persons with permanent address elsewhere and usually occupy the household on a non-permanent basis" (Canmore 2011). It does **not** include persons staying in hotels.

Based on 2014 Census data, the Stoneworks Creek study area is home to a permanent population of approximately 662 people, plus approximately 295 non-permanent residents which corresponds to a total estimated population of 957. Based on Approximately 1211 persons also work in private businesses in the study area (Hoovers 2013).

Assessment of risk at a parcel level of detail requires estimation of the number of persons in each parcel on the fan. However, Census data does not provide estimates at this resolution. As such, individual parcel populations were estimated based on the number of building units of a given type, in each parcel, and the estimated number of persons in a given unit type. Steps to complete this estimate are described below.

First, BGC estimated the number of building units based on a combination of parcel land usage and tax roll codes. For detached residential homes, there is only one roll number per parcel. For multiple units, unique tax roll numbers exist for each taxable entity (e.g. apartment, business, stratified hotel room), each with a tax code number and category description. Descriptions for ambiguous tax codes (which do not distinguish commercial use types) were clarified by referencing parcel land use codes (e.g. to distinguish a hotel room from an office[5]).

Second, BGC estimated the number of occupants per building unit. Permanent residential occupancy rates were based on 2014 Census data and corresponded to 2.2 persons per dwelling unit. These occupancy rates were multiplied by the number of units in a given parcel (based on number of rolls) to provide a total for the parcel.

Finally, the estimated number of workers (if any) within a given parcel (Section 2.1.6) was added to give the total estimate for the parcel.

Table 2-5 summarizes calculated populations used in the risk analysis. Note that the population totals shown in the table should not be summed because some population types overlap (e.g.

[5] E.g. "COM1" (Commercial – Service/Retail/Office) versus "COM2" (Commercial – Hotel/Visitor Accommodation)

workers might also live on the fan). The population estimates are somewhat higher than Census estimates. This is attributed to the large number of hotels and businesses in the Stoneworks Creek study area (which are not accounted for in Census totals). Moreover, the Census data itself also contains uncertainties and should not be considered an exact reference.

Table 2-5. Summary of calculated population estimates used in risk analysis.

Population Type	Population Total
Residents	555
Tourists[1]	424
Hotel Rooms	758
Employees	1211
Total	**2947**

1. The tourist population is an annual estimate and does not consider variations in tourist activity throughout the year.

Additional uncertainties are listed in Table 2-6. Implications of the uncertainties listed in Table 2-6 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.

Table 2-6. Uncertainties associated with estimating the number of occupants of a building.

Uncertainty	Implication
Average occupancy rates may not correspond to actual occupancy rates for a given dwelling unit.	Over- or underestimation of occupant numbers
Seasonal population fluctuations (including tourists) exist that were not accounted for.	
Errors in employee data sourced from Dunn and Bradstreet (D&B) (Hoovers 2013) may exist. These data were not verified by BGC.	
Errors in assignment of D&B employee data to specific parcels may exist, due to inconsistencies in building address data.	
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.	Uncertainty in estimation of human vulnerability to debris-flood impact
Seasonal visitors may occupy private residences, and additional temporary visitors occupy restaurants, shops, and professional services.	Underestimation of occupant numbers

2.1.4. Roads

Roads considered in the assessment include municipal roads in the Stoneworks Creek study area (including Palliser Trail, Palliser Lane, Ray McBride Street, Bow Valley Trail, Mountain Avenue, Hospital Place, 1st Avenue, 2nd Avenue, William Street, Sydney Street), and Highway 1

(Drawing 2). Hiking/biking trails (Johnny's Trail and Montane Traverse) were not directly considered in the risk assessment.

2.1.5. Utility Systems

Utility systems considered in this study are shown on Drawings 2 and 3 include the following:

- Gas distribution infrastructure controlled by Alta Gas
- Sanitary, water and storm systems managed by Canmore
- Electrical transmission managed by Altalink[6].

2.1.6. Business Activity

Business activity considered in this assessment includes public and private employers with their primary address located in the Stoneworks Creek study area. Employer data are based on information compiled by the commercial information provider Dunn and Bradstreet (D&B) (Hoovers 2013)[7], as well as communication with Canmore (2013).

In summary, 167 employers are located in the Stoneworks Creek study area, representing a wide range of economic sectors generating about $86 CAD[8] M/year and employing approximately 1211 people. These figures represent approximately 11% of Canmore's workforce, generating 8% of Canmore's annual revenue.

Business locations were identified by linking business data sourced from D&B (Hoovers 2013) to individual roll numbers provided by Canmore.

The business data used in the assessment are subject to uncertainties associated with both the data itself and how it is assigned to particular parcels. Table 2-7 summarizes uncertainties associated with the data. Business activity impacts listed in this report are likely underestimated due to the uncertainties in the business data.

In addition to the uncertainties listed in Table 2-7, business activity estimates do not include individuals working at home for businesses located elsewhere or businesses that are located elsewhere but that depend on transportation corridors. Inclusion of these figures would substantially increase the level of business activity that could be affected by a debris-flood event. Such estimates are outside of BGC's scope.

[6] Assumed to also carry telephone cables

[7] This assessment considers 2013 business data on file at BGC that was used for risk assessments at other Canmore Creek (e.g. Cougar Creek, Three Sisters Creek, Stone Creek). 2016 data could be obtained upon request.

[8] D&B revenue data provided in USD and was converted at 1 USD = 1.28 CAD.

Table 2-7. Business data uncertainties.

Type	Description
Date	Business data used for this study is from 2013, as such information may have changed.
Revenue data	Missing for 70 workplaces (not available from D&B).
D&B data quality	BGC has not reviewed the accuracy of business data obtained for this assessment.
Worker location	Whether the employee primarily works at the office or some other location is not known. The estimates also do not include individuals working at home for businesses located elsewhere.
Source of revenue	Whether a business' source of revenue is geographically tied to its physical location (e.g. a retail store with inventory, versus an office space with revenue generated elsewhere) is not known and is outside the scope of this assessment.
Geocoding	Some ambiguity existed in linking business data to parcels. Cases where more than one street address existed for a parcel were combined and summed.

2.2. Debris-flood Scenarios

This section describes the different debris-flood scenarios that fed into the consequence and thus, 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 forensic report (BGC 2013) described the storm and resulting debris flood that occurred on Stoneworks Creek between June 19 and 21, 2013. No fatalities occurred on Stoneworks Creek as a result of the June 2013 debris flood. Table 2-8 summarizes damages recorded, with costs summarized in Table 2-9 based on data provided December 30, 2013 by Canmore.

The costs summarized in Table 2-9 include work to complete emergency assessments and reconstruction. They do not include many additional costs, such as services provided by the fire department (e.g. time, food, or equipment), other workers (e.g. overtime, benefits, food, clothes, equipment, etc.), or any costs associated with flood relief accommodations. Importantly, they also do not include estimates of direct damage costs to impacted development and infrastructure (e.g. roads, buildings, property, water/sewer system, gas, or power transmission), costs of professional services to assess hazard and risk (e.g. this assessment), or costs of long-term risk reduction measures. As such, actual costs of the June 2013 event were higher than those summarized below.

Table 2-8. Summary of damage to Stoneworks Creek fan during the 2013 debris flood.

Area	Damage
Lower Fan	• Sediment deposition above Palliser Trail resulting in flows following the ditch of Palliser Trail to the southeast and ponding above Highway 1 • Flooding to a depth of about 1 m on the southeast sector of the fan resulting in damage to the Palliser Village condominium complex • Flooding at the off-ramp/on-ramp intersection of Palliser Trail and Highway 1 on the northwest sector of the fan • Blockage of the 1200 mm diameter culverts under Palliser Trail and Highway 1
Engineered Channel Diversion Works	• “Significant” damage to the 2012 Engineering works. • Destruction of diversion system comprised of sheet piling panels wall where it crossed the main channel • Outflanked the protection on the left bank • Aggradation buried a portion of the constructed channel • Complete blockage and subsequent exposure of the 1400 mm culvert at the access road crossing • Complete blockage of the 1400 mm diameter culvert at the upstream road crossing.

On the southeast sector of the fan, channel incision to a depth of about 6 m occurred over a distance of about 80 m, starting at the abandoned gravel pit. The erosion narrowly missed the transmission line towers. On the northwest edge of the fan, minor flows were diverted towards Cross Zee Ranch but no damage occurred to the buildings. Culverts located on the fire access road and the upstream road crossing were blocked by sediment.

Table 2-9. Reported cleanup costs for Stoneworks Creek fan following the 2013 debris flood. Source: Town of Canmore

Work	Cost
Palliser Trail closed	n/a
Palliser[1] condo building	$25,000
Palliser[1] and Hector[2] condos evacuated	n/a
Damage to Ranch	$25,000
Flood infrastructure damage	$750,000
Cleanup of flood debris	$500,000
Damage to hospital, and businesses on Bow Valley Trail	$500,000 - $1,000,000
Several businesses interrupted, one permanently	n/a
Emergency response	$250,000
TOTAL	**$2,050,000 to 2,550,000**

Notes:

1. Palliser condo is located at 300 Palliser Lane.
2. Hector at Palliser Village is comprised of 3 buildings located at 200A, 200B and 200C Palliser Lane.

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 intensities and likelihoods of occurrence. BGC (2015) developed debris-flood scenarios that are considered representative across the range of return periods considered. These are listed in Table 2-10 and are the debris-flood scenarios considered in this report. For description of methods to develop these scenarios and further discussion of uncertainties and limitations, see BGC (2015).

Drawings 4-7 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), (Jakob et al., 2011).

Scenarios 1 to 5B correspond to 1:10 to 1:30, 1:30 to 1:100, 1:100 to 1:300, 1:300 to 1:1000, and 1:1000 to 1:3000 year frequency intervals[9]. The bounds of a given range are exceedance probabilities. For example, the 1:100 to 1:300 year range should be interpreted as to the probability of events at least as large as a 1:100 year event, but not as large as a 1:300 year event, with the “best” estimate falling towards the middle of the range.

Table 2-10. Summary of debris-flood scenarios for events on Stoneworks Creek. Greyed-out cells indicate that debris flows from the Stoneworks Creek tributary were not considered (BGC 2015).

		Stoneworks Creek input parameters (debris flood)[1]		Tributary input parameters (debris flow)[2]	
Scenario	**Return Period Class (years)**	**Peak Flow (m^3/s)**	**Sediment Volume (m^3)**	**Peak Flow (m^3/s)**	**Sediment Volume (m^3)**
1	10 to 30	12	7,000		
2	30 to 100	18	10,000		
3	100 to 300	23	12,000		
4A	300 to 1000	30	23,000		
4B	300 to 1000	30	23,000	200	9,000
5A	1000 to 3000	36	27,000		
5B	1000 to 3000	36	27,000	260	13,000

Notes:
1. Debris floods are modelled with 20-25% sediment concentration.
2. Debris flows are modelled with 50% sediment concentration.

Elements at risk data were managed within Excel and a Microsoft SQL Server database[10], and linked to geospatial data (e.g. parcel boundaries) in ArcGIS. Debris-flood model grids produced

[9] 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.
[10] Relational database management system produced by Microsoft.

as part of the hazard assessment (BGC 2015) 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 Canmore without major changes to the data management structure.

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.

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 prior to or during an event. This approach provides a baseline estimation of risk to facilitate comparison of different debris-flood risk reduction options.

Following presentation of results, Section 4.5 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:

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

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. 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 1-5B (Table 2-10).

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 3-2. 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] above.

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-flood 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 areas 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, Canmore 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 illustration purposes, these tolerance criteria are shown on Figure 3-1 compared with Canadian mortality rates for the year 2008 (Statistics Canada 2013). Figure 3-1 shows that the DNV risk tolerance threshold of 10^{-4} (1/10,000) for existing development is comparable to the lowest background risks that Canadians face throughout their lives. This tolerance threshold is also similar to the average Canadian's annual risk of death due to motor vehicle accidents, 1/12,500, for the year 2008 (Statistics Canada 2013).

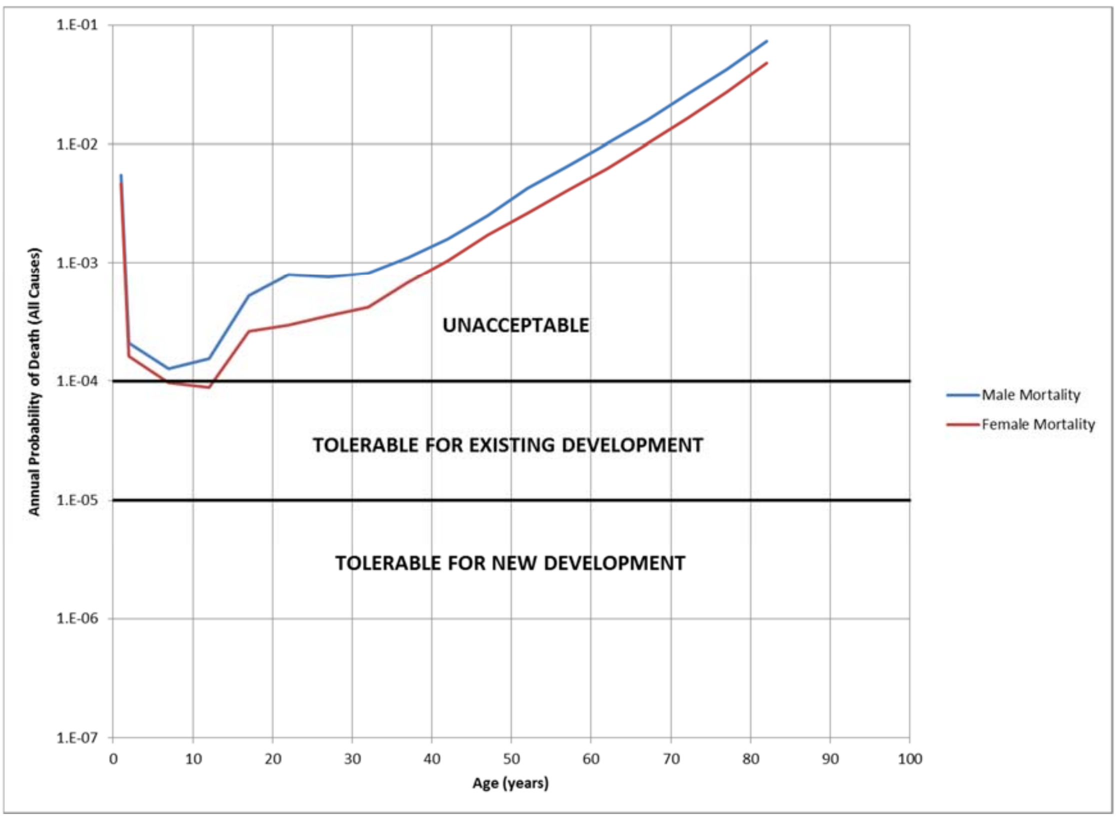


Figure 3-1. DNV individual risk tolerance criteria for landslides compared with Canadian mortality rates in 2008.

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 3-2. Three zones can be defined as follows:

- Unacceptable – where risks are generally considered unacceptable by society and require mitigation

- 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)
- Acceptable – where risks are broadly considered acceptable by society and do not require mitigation.

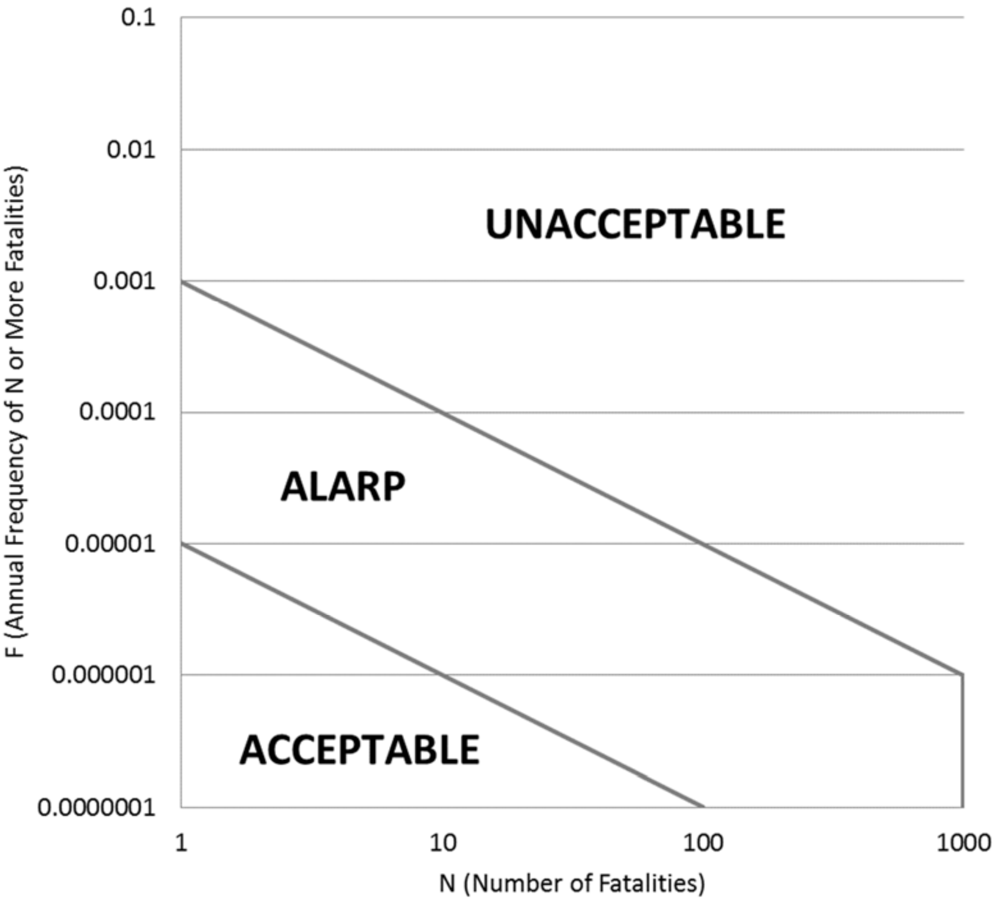


Figure 3-2. Group risk tolerance criteria as defined by GEO (1998).

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 2-10 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 1:30 to 1:100 year range, this would correspond to:

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

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. Cases where modeled debris-floods impacted (intersected) these elements were considered certain ($P(S:H)$=1) to be impacted. Those elements outside the modeled flow extent were not considered subject to impact by the scenario ($P(S:H)$=0).

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 case of a parcel containing a detached home and an out-building, no data existed to automatically distinguish the home from the out-building. With >220 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.

For workers in non-residential buildings, a value of 0.25 was assigned for analysis of risk to both groups and individual workers, corresponding to 8-9 hours per day, 5 days per week, 50 weeks per year. Hotel rooms were also assigned a value of 0.25, corresponding to 0.5 x 50% average annual occupancy (pers. comm., Canmore, Nov. 4, 2013).

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 buildings and persons within buildings, based on estimated levels of destructive power and resistance to impact. Vulnerability levels were not quantified for roads and utility systems.

This section refers to debris flood "intensity", I_{DF} as a measure of destructive power, calculated as follows:

$$I_{DF} = (d)(v^2) \quad [6]$$

where:

I_{DF} is the intensity index.

d is the modelled flow depth.

v is the modelled flow velocity.

3.7.1. Low intensity flows (I_{DF} < 1)

Lower intensity flows are defined as flows where intensity index (I_{DF}) was less than one. Damages associated with these low intensity flows are typically limited to flood damage. While the possibility of fatalities cannot be entirely ruled out, it is considered to be too low to be measurable given that high flood depths (e.g. > 2 m) were not estimated for any hazard scenario.

BGC used depth-damage functions to estimate flood damages as a proportion of building assessment value. These functions are based on flood depth at a particular building location and are expressed as a proportion of building cost for different building types (e.g. Figure 3-3). They do not consider flow velocity and apply where flood inundation is the primary factor for damage (e.g. areas downstream of the highway).

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.

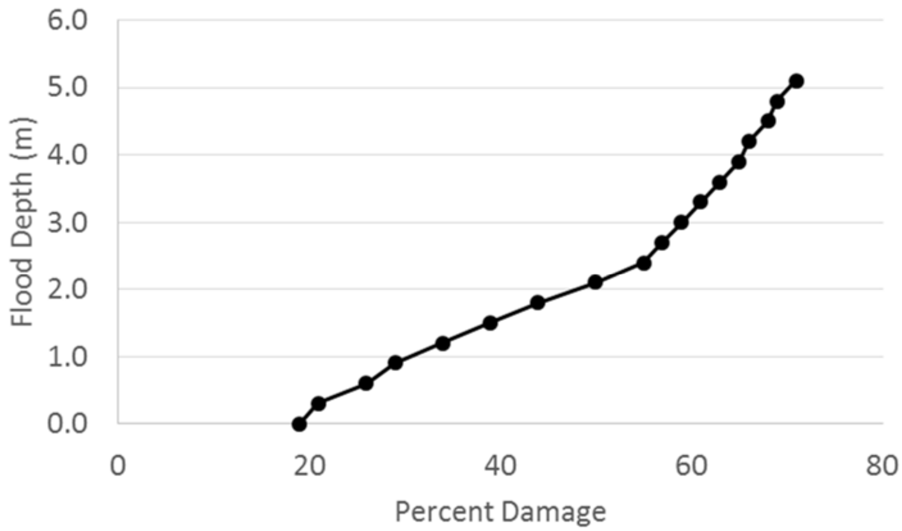


Figure 3-3. Example of a flood depth-damage function (residential homes).

Given the large number of depth damage curves and the requirement to associate these curves with Canmore'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).

Note that on a depth-damage curve, "zero" flood depth corresponds to the first floor elevation. In the absence of site-specific data, these were assigned based on default Hazus criteria. For residential homes assumed to have full basements (Land Use Code = Res1), the first floor elevation is assumed to be 1.2 m. Flood depths shallower than 1.2 m were assumed to result in basement damage only. For simplicity, BGC assumed that all other buildings contained a concrete slab foundation with first floors 30 cm higher than the surrounding ground surface. The depth-damage curves applied to non-residential buildings did not consider basement damage and will underestimate such damage if existing.

3.7.2. High intensity flows (IDF >1)

Higher intensity flows are defined as modelled flows where I_{DF} was greater than 1. These flows have potential to result in structural building damage due to dynamic and static impact pressure, and are considered to have credible potential to cause loss of life. Vulnerability ratings for these flows consider the likelihood of fatalities as an indirect consequence of building damage or collapse.

Table 3-1 shows the vulnerability ratings used for flows where I_{DF} >1. These values are based on judgement with reference to Jakob et al. (2011). They contain uncertainty due to factors that cannot be captured at the scale of assessment, such as variations in the structure and contents of a given building and the location of persons within the building at the time of impact.

Table 3-1. Summary of estimated vulnerabilities as a function of hazard intensity.

Hazard Intensity Index (Range)	Building Damage Description		Building Vulnerability[1]	Human Vulnerability[2]	
	Category	Description	Best Estimate	Estimated Safety Vulnerability, Individual Risk (V)	Estimated Safety Vulnerability, Group Risk (V)
<1	Slight	Low likelihood of building structure damage due to impact pressure. High likelihood of flood damage.	n/a[4]	~0[3]	~0[3]
1-10	Moderate	High likelihood of moderate to major building structure damage due to impact pressure. Certain severe sediment and water damage. Building repairs required, possibly including some structural elements.	>25% - 75% (50%)	0.01	0.005
10-100	Major	High likelihood of major to severe building structure damage due to impact pressure. Certain severe sediment and water damage. Major building repairs required including to structural elements.	>75% - 90% (83%)	0.1	0.05
100-400	Complete	Very high likelihood of severe building structure damage or collapse. Complete building replacement required.	>90% (95%)	0.5	0.5

Notes:
1. Proportion of building assessment value
2. Probability of loss of life given impact
3. Approximated in the risk analysis as 0.000001
4. Depth-damage curves were used to assess low intensity flood damage.

3.7.3. Business Activity

As described in Section 2.1.6, BGC mapped the distribution of business activity in Stoneworks Creek study area by estimating the total annual revenue for each parcel identified as containing businesses.

Based on the data available, it is not possible to determine the vulnerability of businesses to complete loss of function, and associated economic cost, due to debris-flood impact. For example, a retail store could suffer loss of inventory and business function, whereas a business generating revenue elsewhere could suffer office-related damages without necessarily losing their source of revenue.

As a proxy for level of business impact, BGC summed the annual revenue estimated for parcels impacted by a debris-flood scenario. Additional factors such as indirect losses, damages to business equipment or inventory, interruption of transportation corridors, or effects of prolonged outage, were not estimated.

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

Assessment of roads and utilities was limited to identification of the location of infrastructure in relation to the extent and intensity of modelled debris-flow scenarios. Drawings 4 and 5 show modelled debris-flood intensity in relation to surface infrastructure including roads and utilities, for the various debris-flood scenarios, and Drawings 6 and 7 show modelled debris-flood intensity in relation to subsurface infrastructure. Table 4-1 qualitatively describes potential impacts, which were previously described in BGC (2015).

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

Scenario	Results
1 10 to 30 years	• In the confined reach directly below the fan apex, the majority of flows are conveyed within the channel. Shallow overland flows also occur on the floodplain within this reach (<0.2 m). • A minor avulsion occurs towards the southeast, onto the golf course. This is expected to be shallow (< 0.3 m) overland flow. • The majority of flows are routed through the gravel pit towards the south east. There is potential for further gullying at the south end of the gravel pit. These flows flood the area southeast of the Palliser condo development. This may include shallow flooding on the highway access ramps. • For the 10 to 30-year return period scenario, it is assumed that the culverts under the highway at the southeast and northwest ends of the fan function effectively (this is based on BGC's judgement). No highway flooding is expected to occur. • Flows pass under the culverts at the southeast end of the fan and flood the area around the hospital and surrounding retail and industrial properties to a depth of up to 1.5 m in local depressions. • Flows directed to the northwest exceed the capacity of the 2012 diversion channel and are directed into ditches on either side of Palliser Trail. Flows are directed into culverts under the highway, where shallow flooding (< 0.5 m) occurs around the visitor's centre. • A minor avulsion occurs down the middle of the fan, from the north end of the gravel pit. Flows from this avulsion reach Palliser Trail, but do not flood the road or travel significant distances along the ditches.

Scenario	Results
2 30 to 100 years	• In the confined reach directly below the fan apex, the majority of flows are conveyed within the channel. Shallow overland flows also occur on the floodplain (<0.2 m), over a larger area compared to Scenario 1. • The minor golf course avulsion travels slightly farther, compared to Scenario 1. • For the 30 to 100-year return period scenario, it is assumed that the culverts under the highway at the southeast and northwest ends of the fan function effectively (this is based on BGC's judgement). No highway flooding is expected to occur. • Similar flow conditions are present to the southeast towards the Palliser condos, and on the other side of the highway around the hospital. • Similar flow conditions are present to the northwest. Flow depths of up to 2 m in the ditches along Palliser Trail and the highway. Increased overland flow occurs around the visitor's center, but the flow remains shallow (<0.5 m). • Flow directed to the middle fan avulsion has increased when compared to Scenario 1.
3 100 to 300 years	• Flow paths are similar to previous scenarios; however, there is slightly more flooding potential southeast of the Palliser condos, around the hospital and around the visitor's center. • For the 100 to 300-year return period scenario, it is assumed that the culverts under the highway to the southeast will either become blocked, or will not have sufficient capacity to route the flow. Shallow highway flooding is expected in this area. It is assumed that culverts to the northwest of the model domain will continue to function as designed. • Flow directed to the middle fan avulsion has increased when compared to Scenario 2. Flow from the avulsion is directed to the southeast and northwest along the ditch on the northeast side of Palliser Trail.
4A 300 to 1000 years	• Flow paths are similar to previous scenarios; however, there is slightly more flooding potential southeast of the Palliser condos, around the hospital and around the visitor's center. • For the 300 to 1000-year return period scenario, it is assumed that the culverts under the highway to the southeast will either become blocked, or will not have sufficient capacity to route the flow. Shallow highway flooding is expected in this area. It is assumed that culverts to the northwest of the model domain will continue to function as designed, since less flow is directed to the northwest.

Scenario	Results
4B 300 to 1000 years with debris flow	• Flow paths, depths and extents are effectively identical to Scenario 4A on the lower portions on the fan. For example, flow depths around the hospital and the Palliser condos vary only by a few centimeters between 4A and 4B. • The majority of impact from the debris flow is limited to the debris flow tributary, where flow depths up to 2.5 m are predicted (no flow depths greater than 2 m impacted any homes).
5A 1000 to 3000 years	• Flow paths are similar to previous scenarios; however, there is more flooding potential southeast of the Palliser condos, around the hospital and around the visitor's center. • For the 1000 to 3000-year scenario, it is assumed that the culverts under the highway to the southeast will either become blocked, or will not have sufficient capacity to route the flow. Shallow highway flooding is expected in this area. It is assumed that culverts to the northwest of the model domain will continue to function as designed, since less flow is directed to the northwest.
5B 1000 to 3000 years with debris flow	• Flow paths, depths and extents are effectively identical to Scenario 5A on the lower portions on the fan. For example, flow depths around the hospital and the Palliser condos vary only by a few centimeters between 5A and 5B. • The majority of impact from the debris flow is limited to the debris flow tributary, where flow depths up to 3 m are predicted (no flow depths greater than 2 m impacted any homes).

4.2. Buildings and Business Activity

Drawings 8 and Drawing 9 show estimated building damage proportions for individual parcels (i.e.Table 3-1), while Drawings 10 and 11 show estimated building damage costs. Review of the hazard intensity maps (Drawings 4 to 7) indicates that, even for the largest events, the high intensity flows (I_{DF}>1) are blocked by Highway 1. As such, building damage estimates downstream of the highway are based on flood depth-damage criteria (Section 3.7.1).

Table 4-2 summarizes parcel consequence estimates for each scenario, including total building damage costs and annual business revenues affected.

Table 4-2. Summary of consequence estimates.

Debris-flood Scenario	Frequency (1:years)	Number of Parcels Affected	Building Damage Cost ($M)	Average Cost/Parcel ($)	Annual Business Revenue of Impacted Parcels ($M) [1]
1	1:10 to 1:30	44	$7.2	$160,000	$30.4
2	1:30 to 1:100	46	$7.8	$170,000	$30.4
3	1:100 to 1:300	46	$8.7	$190,000	$30.4
4A	1:300 to 1:1000	52	$13.6	$260,000	$32.5
4B		53	$16.8	$320,000	$32.5
5A	1:1000 to 1:3000	56	$25.8	$460,000	$32.6
5B		57	$29.2	$510,000	$32.5

Note:

1. D&B revenue data provided in USD and was converted at 1 USD = 1.28 CAD.

The estimated direct building damage costs range from $7.2 M for the 10 to 30 year return period and 30 to 100 year return period scenarios to about $29.2 M for the 1000 to 3000 year return period unmitigated scenario. For comparison, estimated direct damage costs to buildings for individual scenarios ranged from $4 M to $134 M at Cougar Creek depending on the scenario (BGC 2015). Considering all scenarios together, the annualized cost is estimated as $790,000/year, which reflects the relatively high frequency of damaging debris floods. For comparison, total assessed building value for the entire Stoneworks Creek study area corresponds to about $286 M.

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 2-9 for the June 2013 event, are not included. If these were considered, actual damage costs would increase.

4.3. Critical Facilities

As described in Section 2.1.2, the only critical facility located in the Stoneworks Creek study area is Canmore General Hospital. Canmore General Hospital was impacted by all debris-flood scenarios considered in this assessment.

4.4. 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.

4.4.1. Individual Risk

No occupied parcels exceeded the individual risk tolerance standard for existing buildings of 1:10,000 ($1x10^{-4}$) risk of fatality. Drawing 12 shows eight parcels that exceed 1:100,000 ($1x10^{-5}$) individual risk of fatality per year. BGC notes that higher intensity flows are impacting outbuildings at Cross Zee Ranch adjacent to Stoneworks Creek channel. These outbuildings were assumed to be vacant for the purposes of this assessment.

4.4.2. Group Risk

Figure 4-1 presents the results of group risk analysis on an F-N curve, and Table 4-3 lists the estimated numbers of fatalities (N) for each debris-flood scenario.

Estimated overall group debris-flood risk for Stoneworks Creek study area extends into the "ALARP" range when compared to the international risk tolerance standards described in Section 3.3.

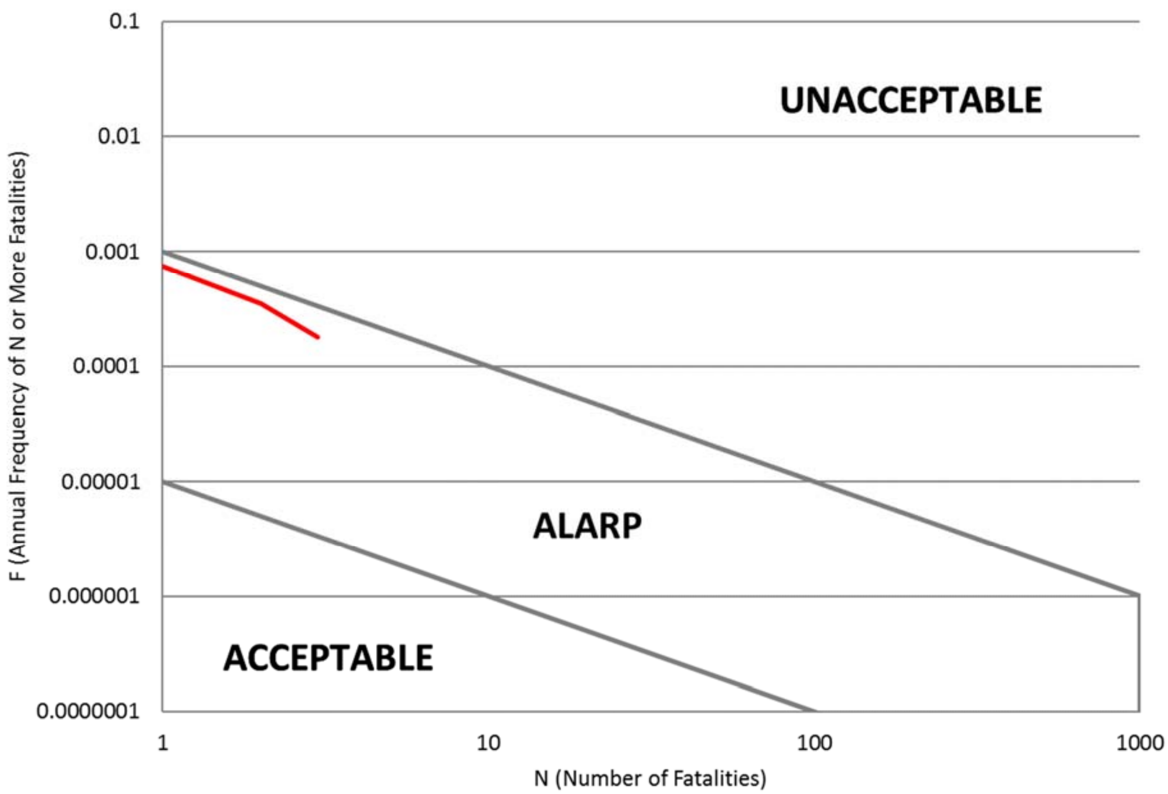


Figure 4-1. F-N curve (in red) showing the results of the Stoneworks Creek risk analysis for groups.

Table 4-3. Estimated number of fatalities (N) for each debris-flood scenario and with the assumptions made in this report.

ID	Frequency (1:years)	Estimated Number of Fatalities (N)[1]
1	1:10 to 1:30	0
2	1:30 to 1:100	0
3	1:100 to 1:300	0
4A	1:300 to 1:1000	0
4B		1
5A	1:1000 to 1:3000	2
5B		3

Note: [1]N values in the table are rounded to the nearest 1 fatality.

4.5. Discussion

This section compares BGC's estimates of safety risk to recorded events. 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 Stoneworks 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.

4.5.1. Comparison to Case Studies

Appendix A describes hazard events occurring elsewhere, for comparison purposes. The events described in Appendix A 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 Stoneworks 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 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 for Stoneworks Creek is at the low end of this range, at 0% to 0.8%. This is considered reasonable given that much of impact is limited to low velocity flood inundation downstream of Highway 1.

4.5.2. 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 Stoneworks Creek debris-flood scenarios for comparison purposes.

The mortality functions of Jonkman *et al.* (2008) consider about 165 historic flood locations in the Japan, Netherlands, UK, USA, and South Africa, but are mainly validated using a single 1953 flood disaster on Canvey Island, Netherlands. The functions were calibrated for large scale flooding of low-lying areas. 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 3 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. The mortality function relates mortality to flood depth using a best-fit trendline for a lognormal distribution:

$$F_D(h) = \emptyset_N\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right) \quad [7]$$

$$\mu_N = 1.46 \qquad \sigma_N = 0.28$$

where F_D is flood depth (m), $\emptyset_N$ is the cumulative normal distribution; σ_N is the average of the normal distribution; and μ_N is the standard deviation of the normal distribution.

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. It is defined similarly to equation [7], but where $\mu_N = 7.6 \qquad \sigma_N = 2.75$.

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. Table 4-4 compares BGC's estimated N values to estimates based on Jonkman et. al. (2008) criteria developed for large-scale flooding of low-lying areas. For higher probability scenarios, BGC's estimate of the expected number of fatalities is lower than would be estimated using mortality functions of Jonkman et. al. (2008), but agrees more closely for lower probability events. The difference reflects slightly higher vulnerability estimates at shallow flood depths with the Dutch Mortality Model, which may reflect its calibration to the 1953 flood disaster on Canvey Island. BGC's estimate is more consistent with the lack of fatalities in June 2013.

Table 4-4. Comparison of the number of estimated N values for Stoneworks Creek.

Debris Flood Scenario	Frequency (1:years)	BGC Estimate	Jonkman et. al. (2008) Criteria
1	1:10 to 1:30	0	2
2	1:30 to 1:100	0	3
3	1:100 to 1:300	0	3
4A	1:300 to 1:1000	0	3
4B		1	3
5A	1:1000 to 1:3000	2	3
5B		3	3

4.5.3. Comparison to 2013 Event

As described in Section 2.2, it is difficult to exactly simulate the consequences of the June 2013 event because some aspects of debris flood processes (e.g. sediment deposition or scour) are difficult to model reliably. The $2 M to 2.5 M recorded costs for the June 2013 event (Table 2-9) are approximate, and are also not the same as those quantified in this assessment (direct building damage costs), making direct comparison difficult. The 100 to 300 year return period debris flood (Table 2-10, Scenario 3) represents a similar magnitude debris flood to the June 2013 event. While the extent of sediment deposition and flooding for the June 2013 event is consistent with the model results for this scenario (BGC 2015), BGC's direct building damage estimates for the 100 to 300 return period year event (Table 4-2, Scenario 3) are approximately 4 times greater than costs recorded for the June 2013 event. A more comprehensive figure of the total damages (direct building damages and cleanup costs), if compiled, would help calibration for future economic loss assessments.

The annualized building damage cost for Stoneworks Creek is higher than any of the other Canmore creeks where risk assessments have been completed (Table 4-5). BGC believes there are multiple contributing factors to the discrepancy between the recorded and predicted damage costs and the high estimate of annualized damage cost. These include:

- The two cost estimates are not comparable because the types of damage are not the same. The recorded damage costs are an approximate estimate that includes emergency response and recovery, but that does not systematically account for building damages. To BGC's knowledge, no such estimate exists. Some damages may have been assessed by individual insurance agents, but these data were not available and are unlikely to contain estimates of uninsured damages. In contrast, the damage costs considered in this assessment exclusively consider building damages and do not include the cost of emergency response or recovery.
- More frequent damaging events result in higher annualized damage costs. Debris-flood scenarios at Stoneworks Creek (and Pigeon Creek) include relatively higher frequency (i.e. 10 to 30 year return period) damaging events than other Canmore creeks (Table 4-5).
- The FLO 2D model used to simulate debris-flood scenarios does not consider runoff infiltration on the fan. The model is calibrated by high water marks in the upper channel which is underlain by bedrock and where groundwater likely interconnected with surface water flow during the June 2013 debris floods. It is plausible that a portion of flows from low magnitude, high frequency events infiltrate the ground surface on the largely coarse-grained permeable alluvial fan leading to a reduction in the amount of overland flow and subsequent building damage.
- The close proximity of Stoneworks Creek to high value building improvements located on the fan (i.e. Palliser condominiums) and flooding at the southeast end of the fan around the hospital contribute to higher annualized building damage estimates. This is consistent with the high annualized building damage costs estimated for Cougar Creek which is directly proximal to high value homes. As expected, lower building damage costs are recorded for Stone and Pigeon creeks, which have comparatively fewer building improvements and lower improvement values and for Three Sisters Creek where development is in the lower reaches of the fan.

While there is some uncertainty in the accuracy of the predicted damage costs, the overall conclusion of the risk assessment does not change. Furthermore, future evaluation of mitigation options will focus on the percentage reduction in the building damage cost, not the absolute value. Therefore, the accuracy of the annualized damage losses is considered to be of lesser importance.

Table 4-5. Comparison of Annualized Building Damage Cost and Highest Frequency Return Period Event for Canmore Creeks.

Creek Name	Annualized Building Damage Cost ($)	Highest Frequency Return Period Event Considered (1:years)	Reference
Stoneworks Creek	790,000	1:10 to 1:30	This document
Cougar Creek	630,000	1:30 to 1:100	BGC 2015b; discussion with Canmore[1]
Stone Creek	450,000	1:30 to 1:100	BGC 2015d; discussion with Canmore[1]
Pigeon Creek	440,000	1:10 to 1:30	BGC, 2016b
Three Sisters Creek	370,000	1:30 to 1:100	BGC 2015c

Note: 1. J. Eisl, Town of Canmore, personal communication, May 20, 2016

No fatalities were estimated for the 100 to 300 year return period scenario considered in the group risk assessment (Table 4-3, Scenario 3). This is consistent with the June 2013 event, where no fatalities occurred.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

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

BGC assessed risk associated with five debris-flood scenarios representing a range in debris-flood return periods 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 primarily on estimation of direct building damage and safety risk (i.e. loss of life). 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 $7.2 M for the 10 to 30 year return period scenario to $29.2 M for the 1000 to 3000 year return period scenario. Estimated annualized building damage cost is $790,000/year. 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 increase annualized damage costs. As noted in Section 4.5.3, estimated annualized building damage costs for Stoneworks Creek are high when compared to other Canmore creeks and to recorded events for multiple reasons (i.e. estimated and recorded costs are not comparable, more frequent damaging events, limitations of the FLO 2D model, and the close proximity of Stoneworks Creek to high value improvements).

Annual business revenues in impacted areas range from $23.8 M for the 10-30 year return period scenario to $25.5 M for the 1000-3000 year scenario. For reference, revenues of all businesses in the Stoneworks Creek study area correspond to about $67 M/year. As noted in Section 4.2, 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 did not identify any occupied 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 also fell into the "ALARP" range when compared to international risk tolerance standards.

5.2. Recommendations

Following this risk assessment, a number of steps will lead to optimization of the risk reduction strategy:

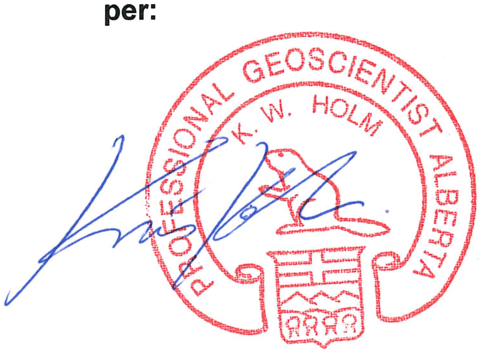
1. Building damage cost estimates and vulnerability ratings should be reviewed for calibration purposes if detailed building damage cost information becomes available for the June 2013 debris flood.
2. For the purpose of risk estimation, BGC assumed that the outbuildings at Cross Zee Ranch were vacant. This assumption should be confirmed given that the area (PID 432036) is subject to debris flood hazard.
3. Canmore will need to define risk tolerance levels primarily in terms of loss of life for individual and group risk, and annualized economic loss potential.
4. Debris-flood risk reduction options should be identified including both structural and non-structural measures. Structural measures, such as containment of debris through barriers upstream of the populated channel sections, channel armouring as well as concrete check dams, are some of the components of a comprehensive risk reduction strategy. Moreover, debris-flood risk could also be lowered by reducing the following:
    - Probability of the debris flood occurring (e.g. watershed stability). This option is not considered feasible due to lack of watershed access, the fact that most of the watershed is within park lands, and because of the abundance of potential sediment sources.
    - Debris-flood magnitude (e.g. volume or peak discharge). Volume reduction can be achieved through debris containment and reduction of potential channel bank erosion through armoring (e.g. measures currently being completed).
    - Debris-flood intensity (e.g. runout extent, velocity, impact forces). This can be achieved through containment (reduction of flow velocities and runout extent) and thus, reduction of impact forces.
    - Spatial probability of impact (likelihood that the debris flood will reach or impact elements at risk). This can also be reduced by containing debris floods upstream of the developed area.
    - Number of persons exposed to hazard. This could be achieved through evacuations tied to an early warning system, or by property acquisitions.
5. Risk evaluation should be completed for each risk reduction option, once identified, to support selection of preferred options that reduce debris flood risk to levels considered tolerable by Canmore.

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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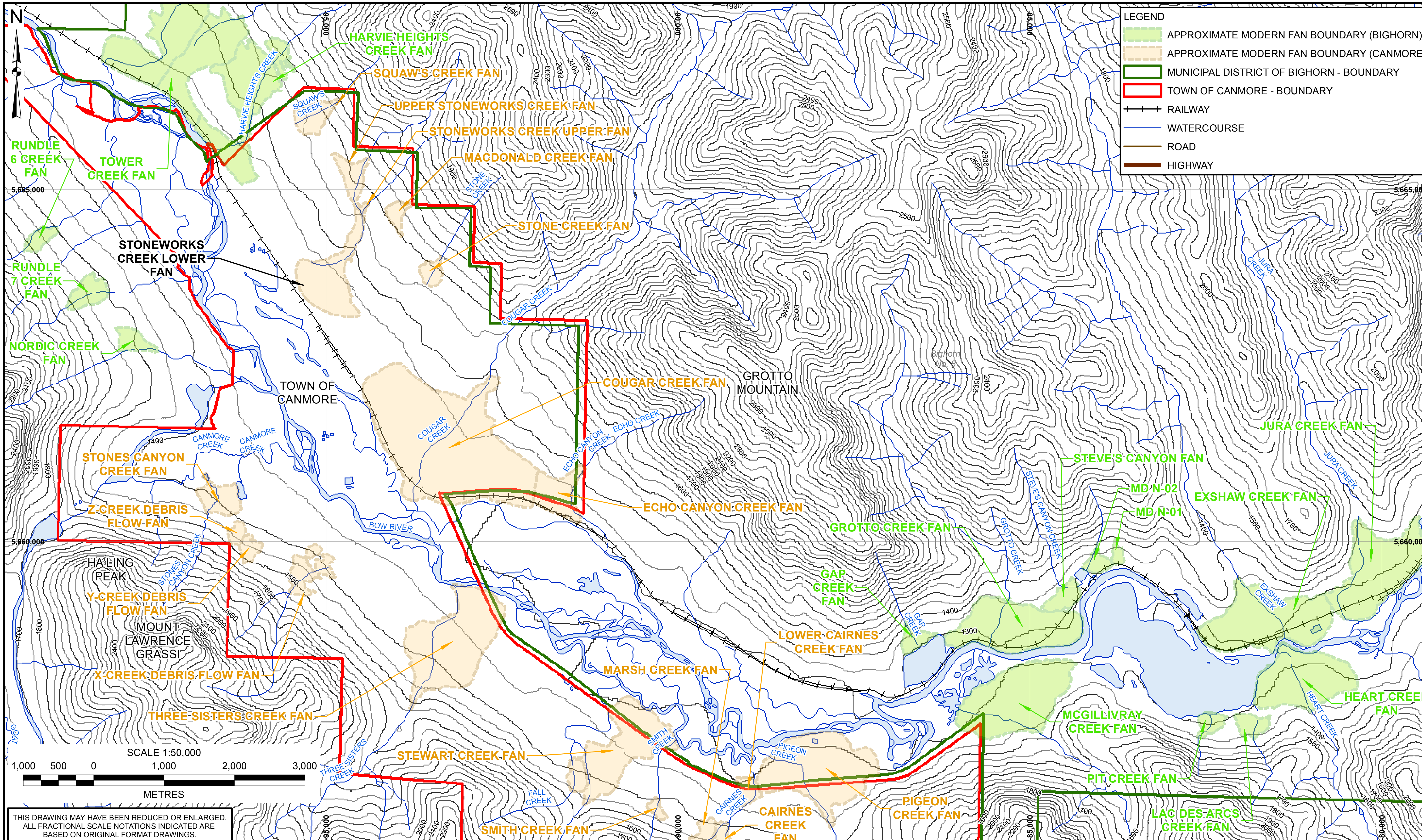
DRAWINGS



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CLIENT: Town of CANMORE

PROJECT: STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT

TITLE: LOCATION MAP

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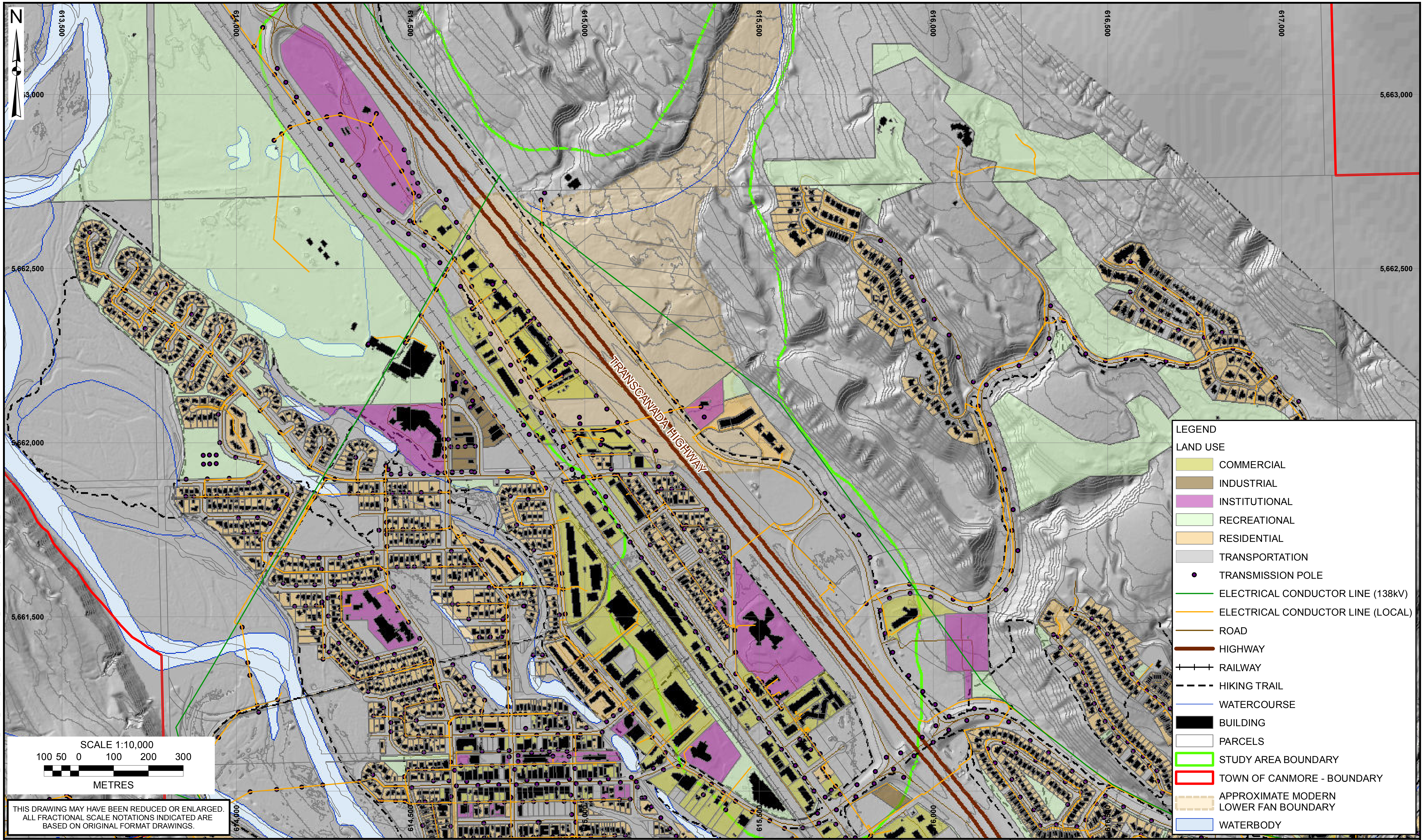

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BASEMAP: BUILDINGS AND SURFACE INFRASTRUCTURE

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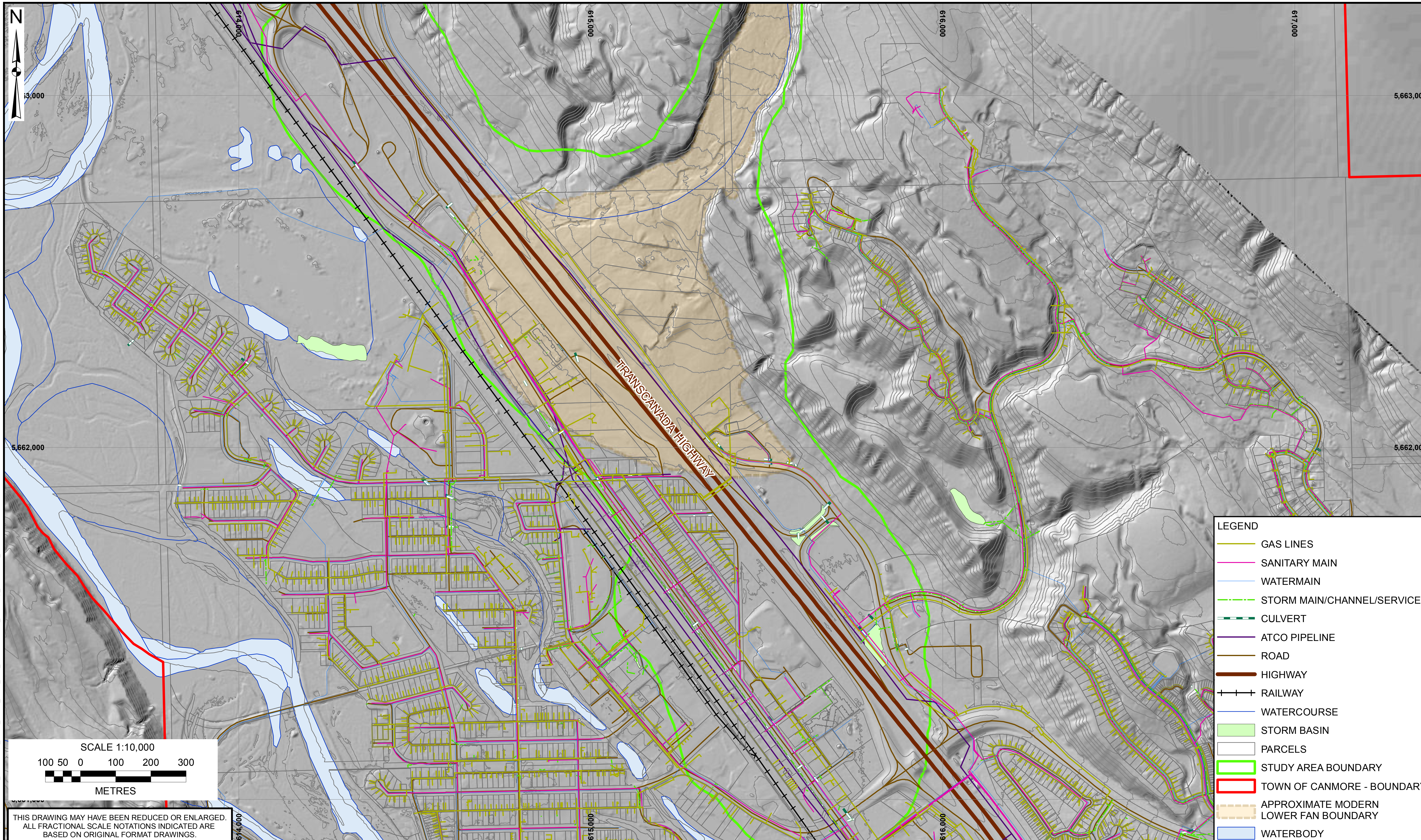

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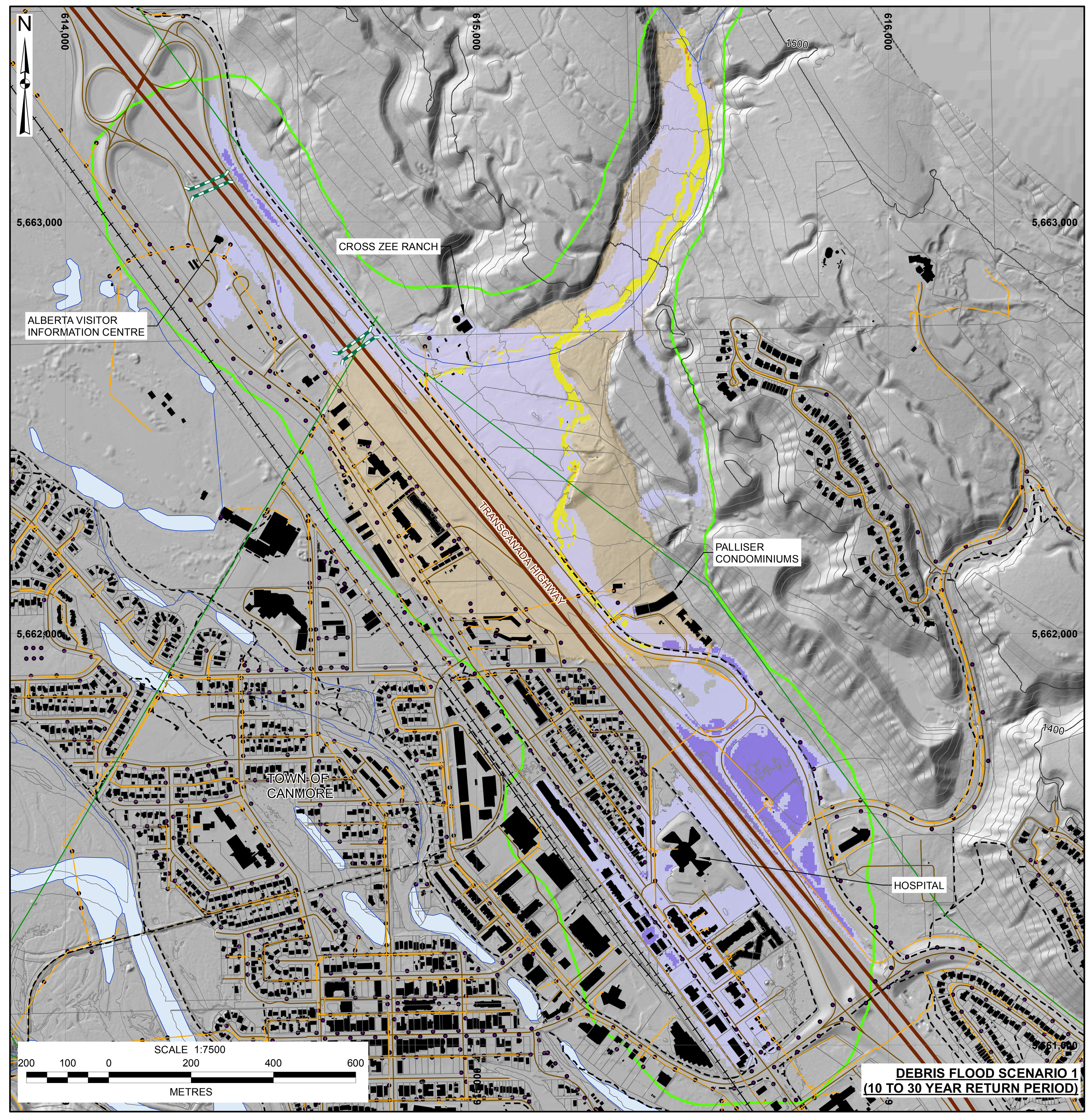

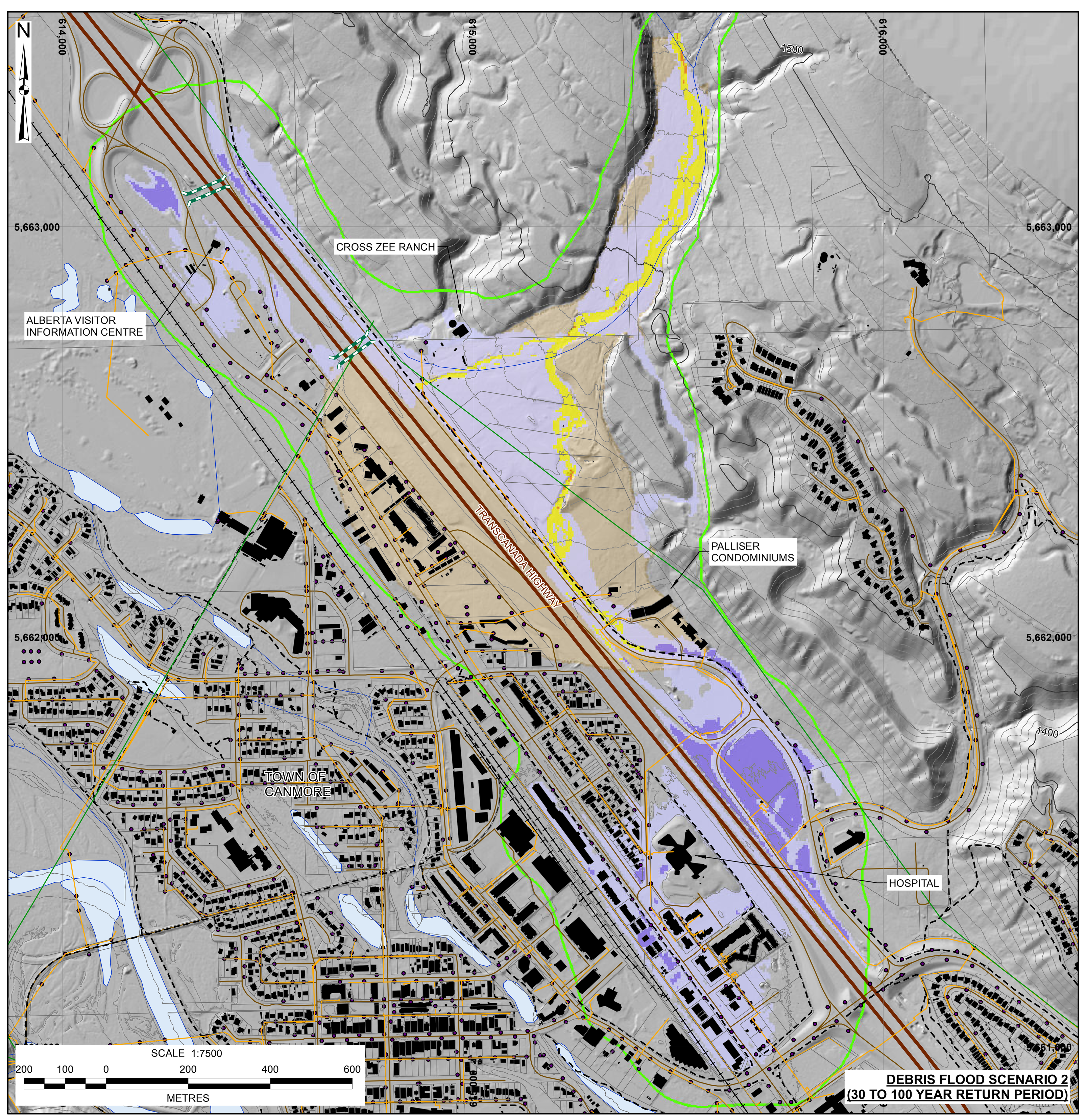

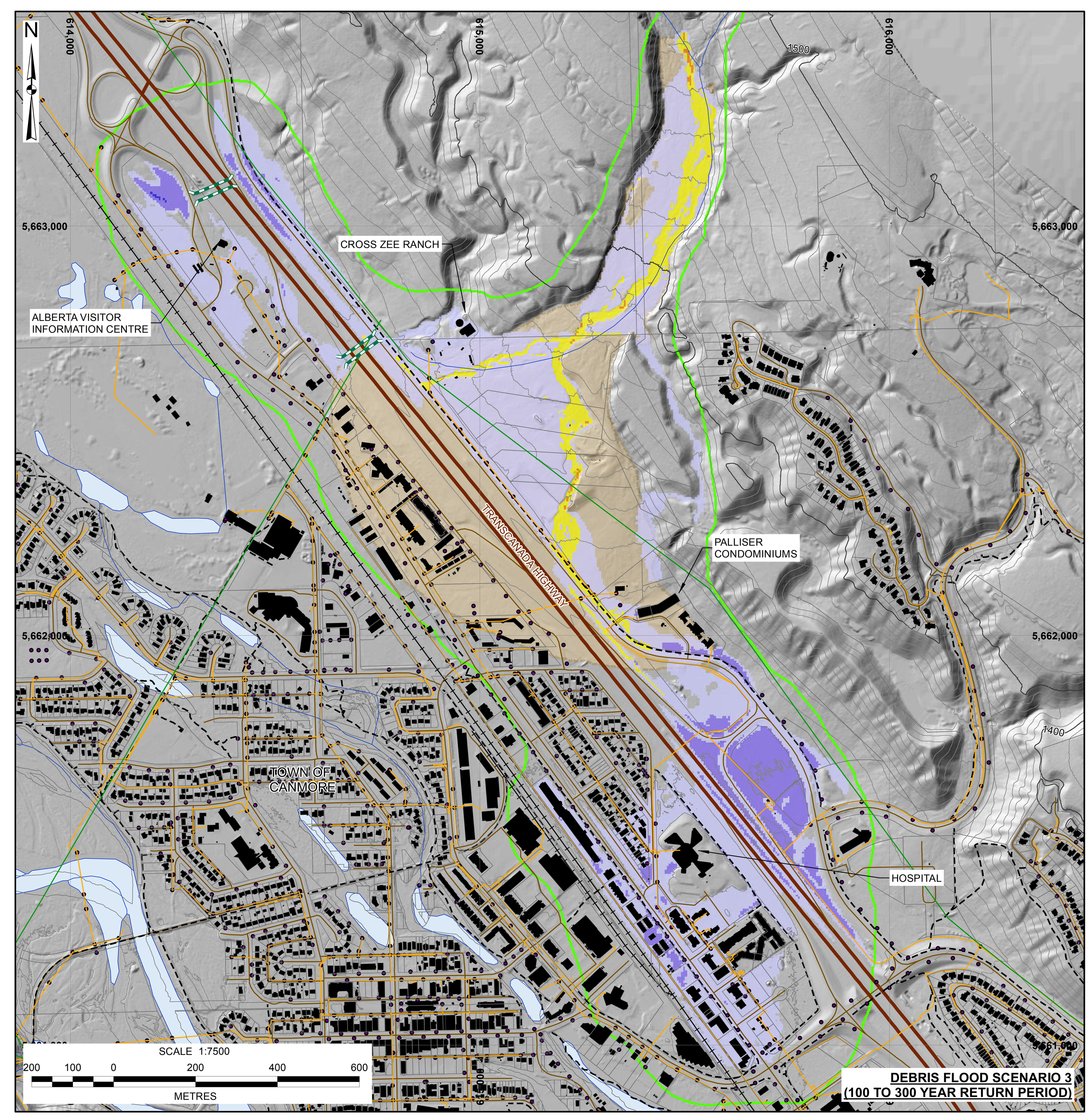

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LEGEND

FLOW DEPTH (m) (v < 1 m/s)
- < 1
- 1 to 2.5
- > 2.5

IMPACT INTENSITY INDEX (v > 1 m/s)
- < 10
- 10 to 100
- > 100

- TRANSMISSION POLE
- APPROXIMATE LOCATION OF MODELLED CULVERT
- ELECTRICAL CONDUCTOR LINE (138kV)
- ELECTRICAL CONDUCTOR LINE (LOCAL)
- ROAD
- HIGHWAY
- RAILWAY
- HIKING TRAIL
- WATERCOURSE
- BUILDING
- PARCELS
- STUDY AREA BOUNDARY
- TOWN OF CANMORE - BOUNDARY
- APPROXIMATE MODERN LOWER FAN BOUNDARY
- WATERBODY

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PROJECT: STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT

TITLE: DEBRIS-FLOOD INTENSITY, SURFACE INFRASTRUCTURE: DEBRIS-FLOOD SCENARIOS 1-3

PROJECT No.:	DWG No.:
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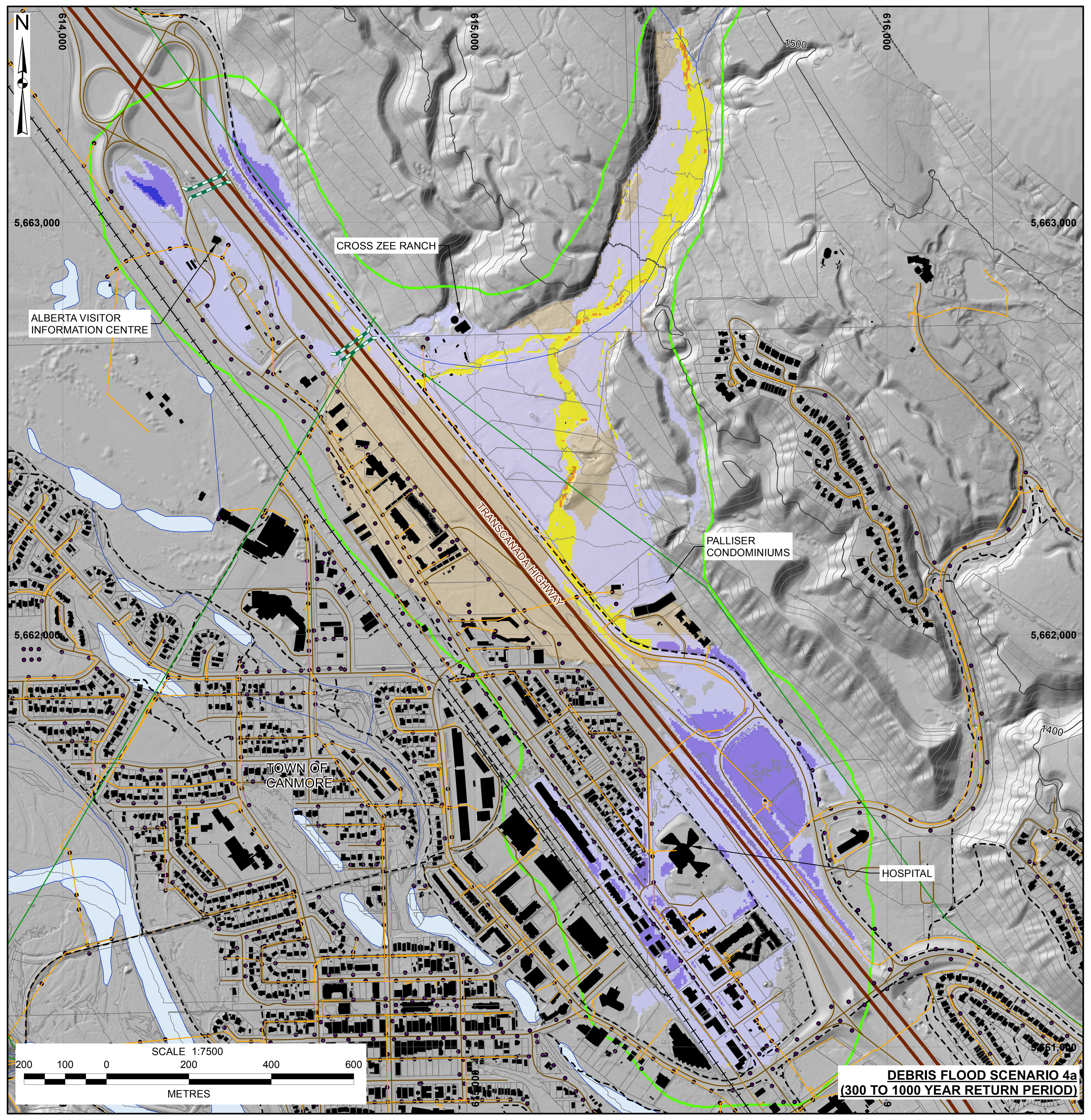
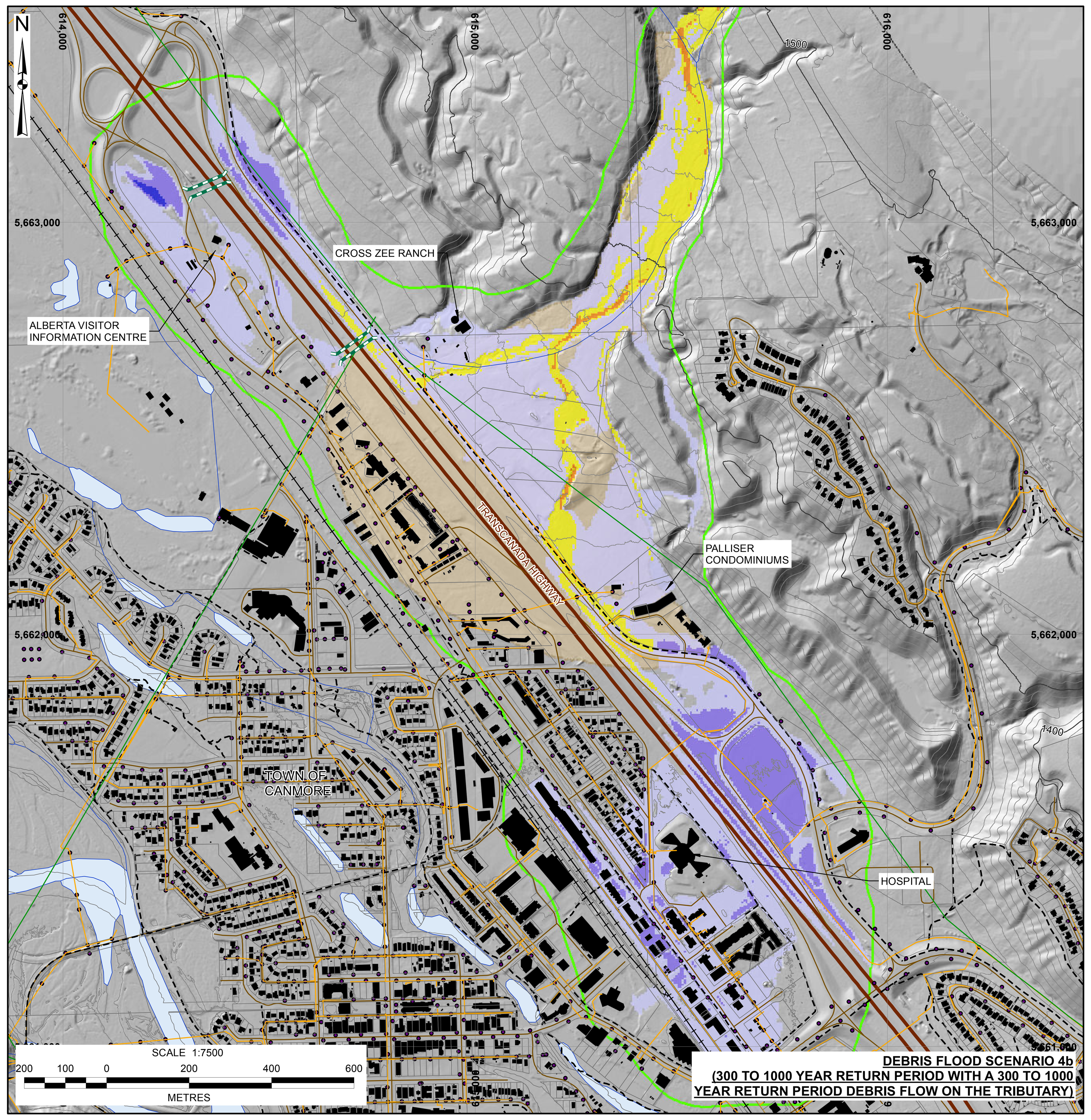
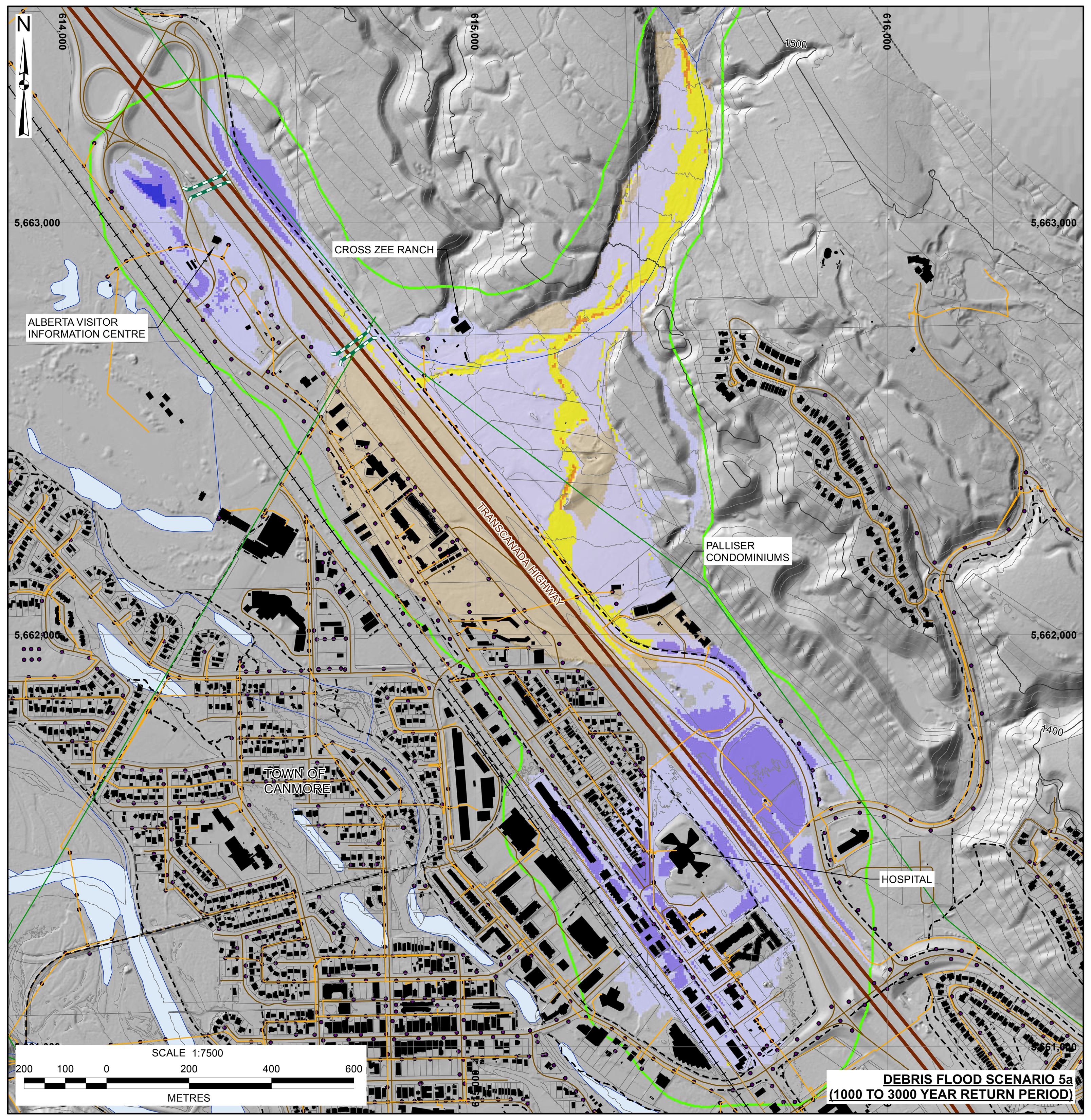
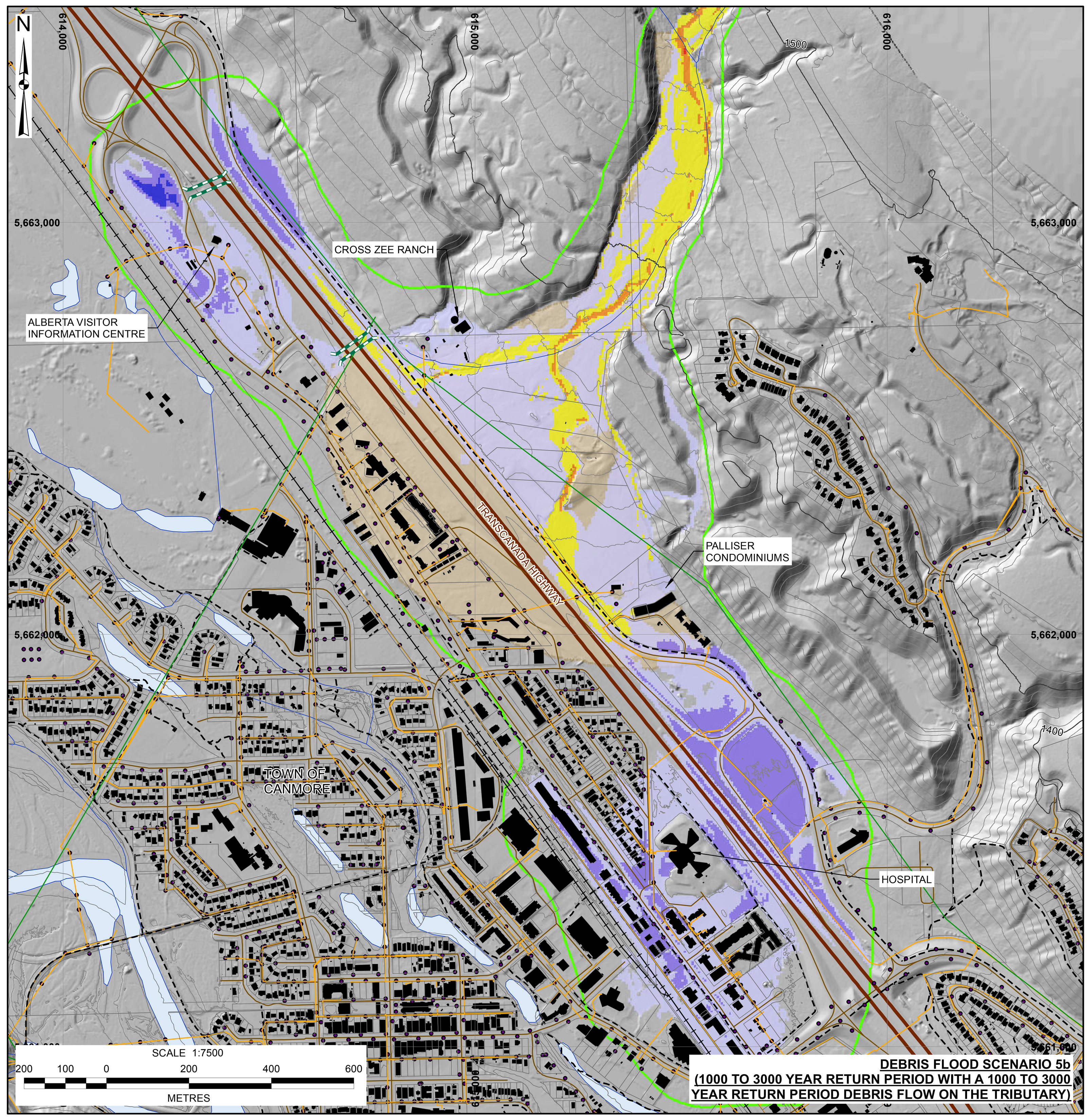








THIS DRAWING MAY HAVE BEEN REDUCED OR ENLARGED. ALL FRACTIONAL SCALE NOTATIONS INDICATED ARE BASED ON ORIGINAL FORMAT DRAWINGS.

THIS BAR MEASURES 100 mm AT FULL SIZE. ALL SCALES REFERENCED TO FULL SIZE

LEGEND

FLOW DEPTH (m) (v < 1 m/s)
- < 1
- 1 to 2.5
- > 2.5

IMPACT INTENSITY INDEX (v > 1 m/s)
- < 10
- 10 to 100
- > 100

- TRANSMISSION POLE
- APPROXIMATE LOCATION OF MODELLED CULVERT
- ELECTRICAL CONDUCTOR LINE (138kV)
- ELECTRICAL CONDUCTOR LINE (LOCAL)
- ROAD
- HIGHWAY
- RAILWAY
- HIKING TRAIL
- WATERCOURSE
- BUILDING
- PARCELS
- STUDY AREA BOUNDARY
- TOWN OF CANMORE - BOUNDARY
- APPROXIMATE MODERN LOWER FAN BOUNDARY
- WATERBODY

NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT" AND DATED SEPTEMBER 2016.
3. PROJECTION IS NAD 83 UTM ZONE 11N.
4. BUILDINGS, PARCELS, AND UTILITIES WERE OBTAINED FROM TOWN OF CANMORE.
5. WATERCOURSES, WATERBODIES, ROADS AND RAILWAY WERE OBTAINED FROM CANVEC.
6. HILLSHADE WAS DERIVED FROM LIDAR PROVIDED BY LIDAR SERVICES IN C. (LSI), DATED JUNE 28, 2013. CONTOUR INTERVAL IS 5 m.
7. MODEL RUNS (DEBRIS FLOOD SCENARIOS) ARE LABELLED IN THE LOWER RIGHT HAND CORNER OF EACH MAP INSET.
8. THIS MAP SHOULD NOT BE RELIED UPON AT A SCALE LARGER THAN (MORE DETAILED) THAN SHOWN ON THIS MAP.
9. THIS MAP REPRESENTS A SNAPSHOT IN TIME. FUTURE CHANGES (DEVELOPMENT, DEBRIS FLOOD MITIGATION, GEOHAZARD EVENTS) MAY WARRANT THE RE-DRAWING OF CERTAIN AREAS.
10. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

SCALE:	1:7,500
DATE:	SEP 2016
DRAWN:	JDC
CHECKED:	JBM
APPROVED:	MJ

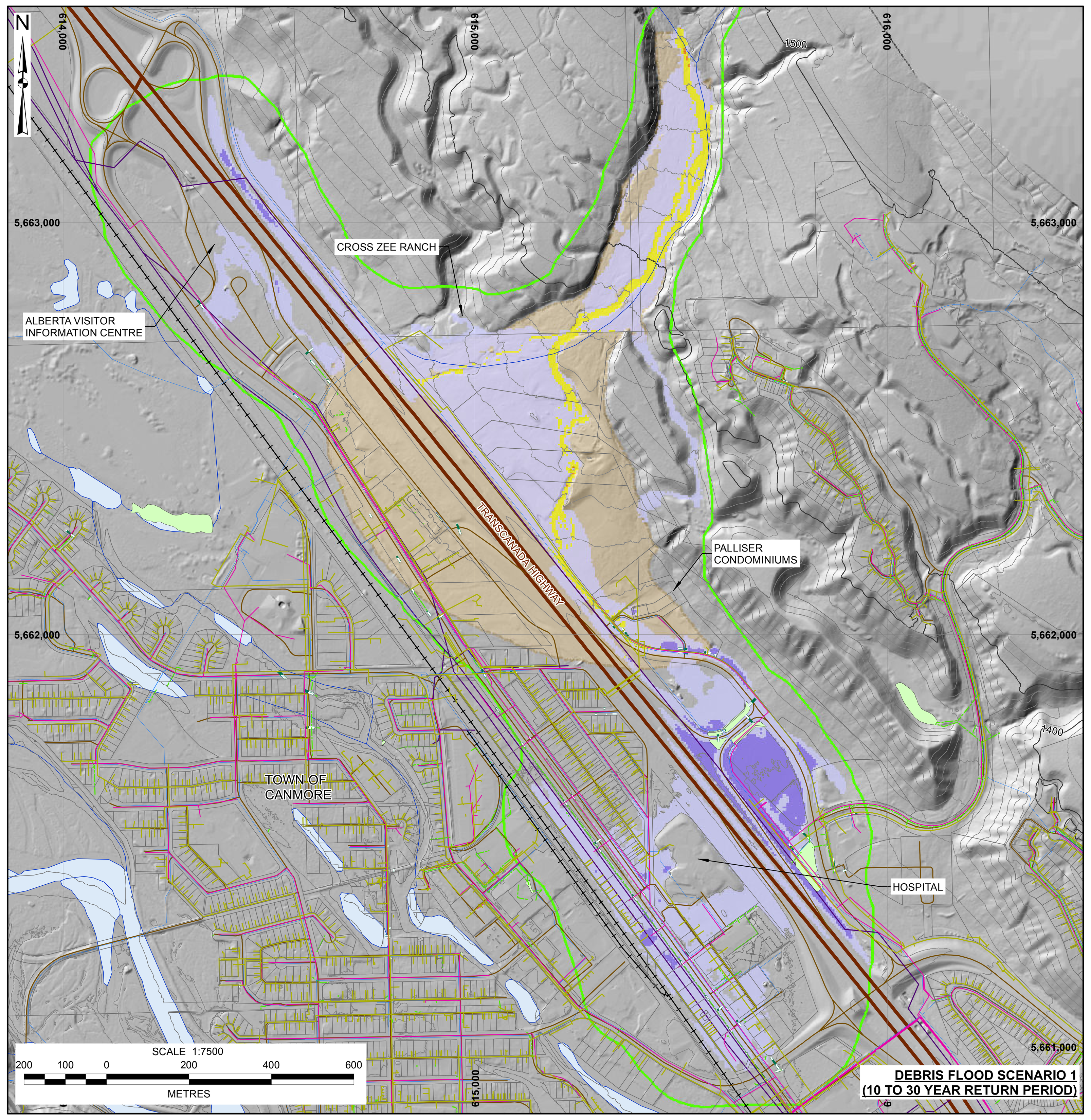
BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

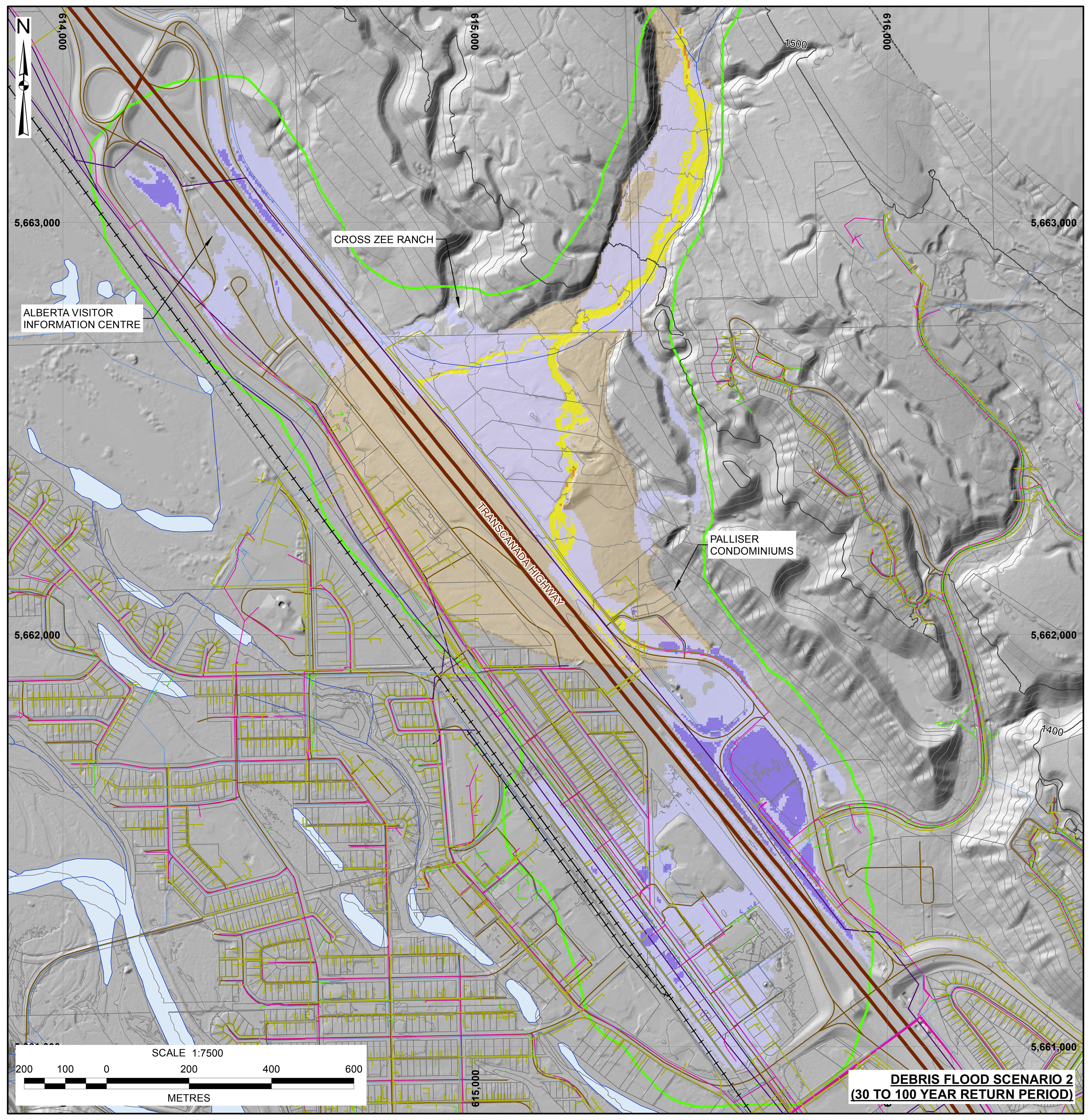
CLIENT: Town of CANMORE

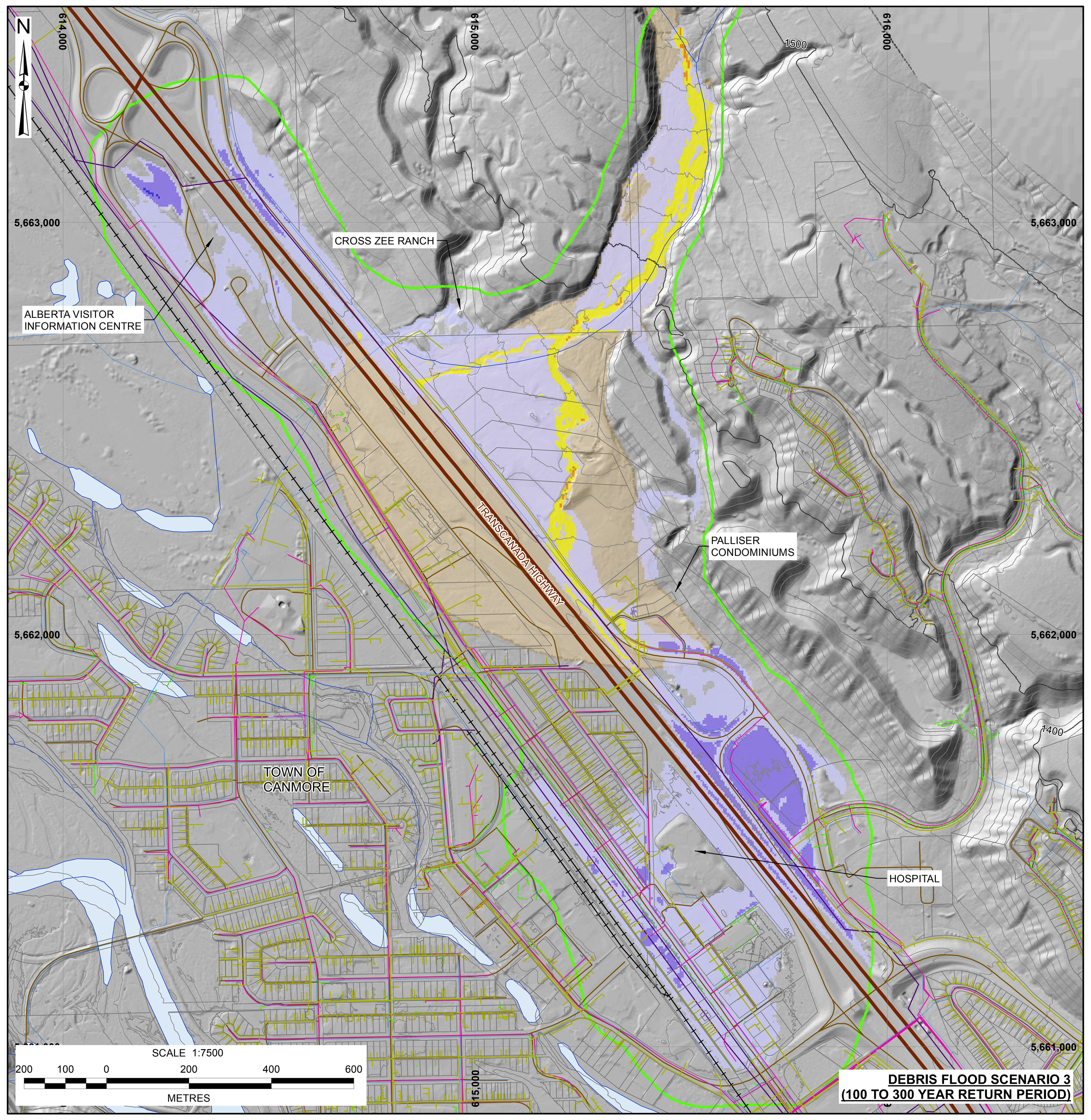
PROJECT: STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT

TITLE: DEBRIS-FLOOD INTENSITY, SURFACE INFRASTRUCTURE: DEBRIS-FLOOD SCENARIOS 4a-5b

PROJECT No.:	DWG No.:
1261009	05







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THIS BAR MEASURES 100 mm AT FULL SIZE. ALL SCALES REFERENCED TO FULL SIZE

LEGEND

FLOW DEPTH (m) (v < 1 m/s)
- < 1
- 1 to 2.5
- > 2.5

IMPACT INTENSITY (m³/s²) (v > 1 m/s)
- < 10
- 10 to 100
- > 100

- GAS LINES
- ATCO PIPELINE
- STORM MAIN
- WATERMAIN
- STORM MAIN/CHANNEL/SERVICE
- CULVERT
- ROAD
- HIGHWAY
- RAILWAY
- WATERCOURSES
- STORM BASIN
- PARCELS
- STUDY AREA BOUNDARY
- APPROXIMATE MODERN LOWER FAN BOUNDARY
- WATERBODY

NOTES:
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SCALE:	1:7,500
DATE:	SEP 2016
DRAWN:	JDC
CHECKED:	JBM
APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

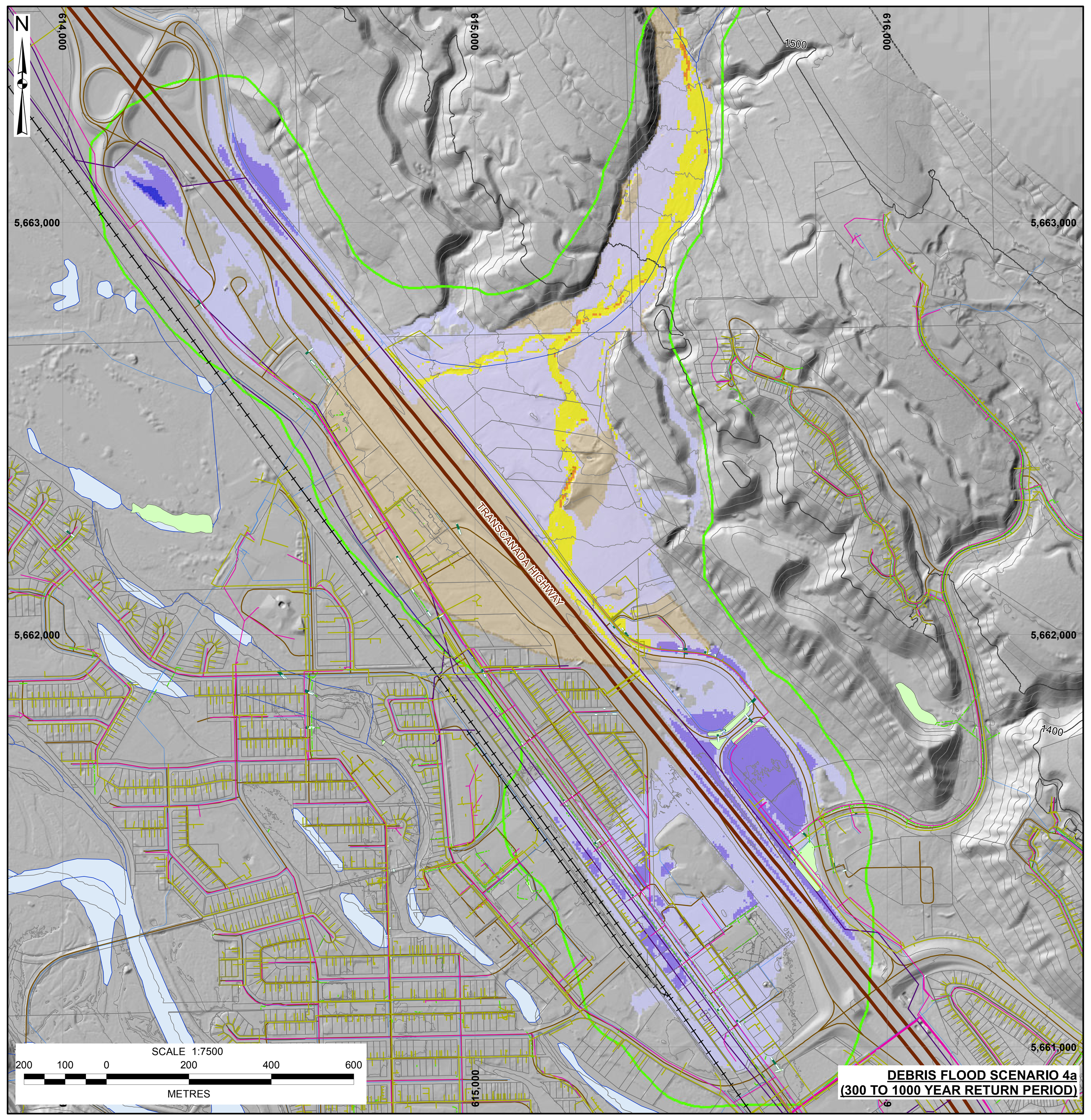
CLIENT: Town of CANMORE

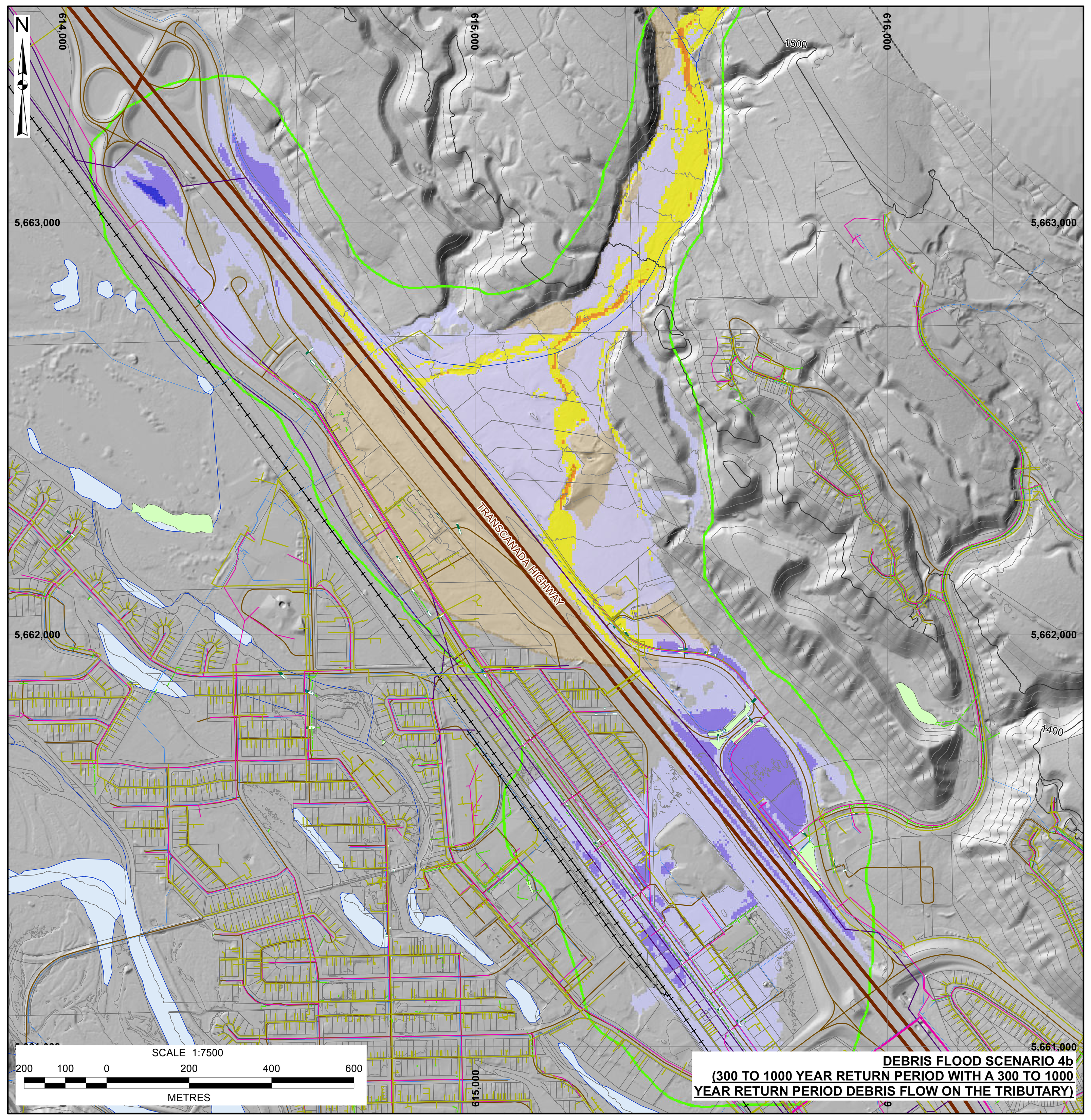
PROJECT: STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT

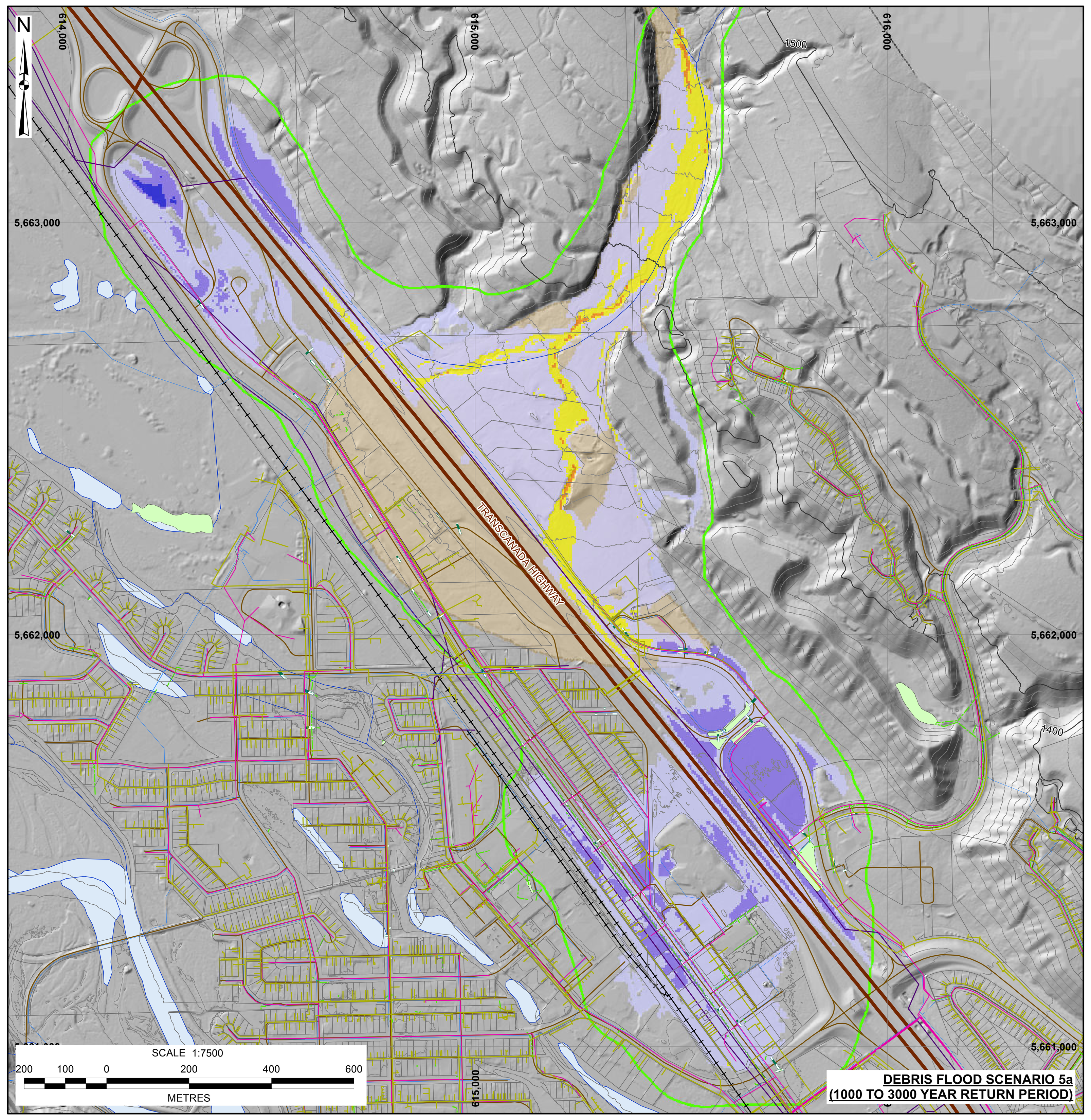
TITLE: DEBRIS-FLOOD INTENSITY, SUBSURFACE UTILITIES: DEBRIS-FLOOD SCENARIOS 1-3

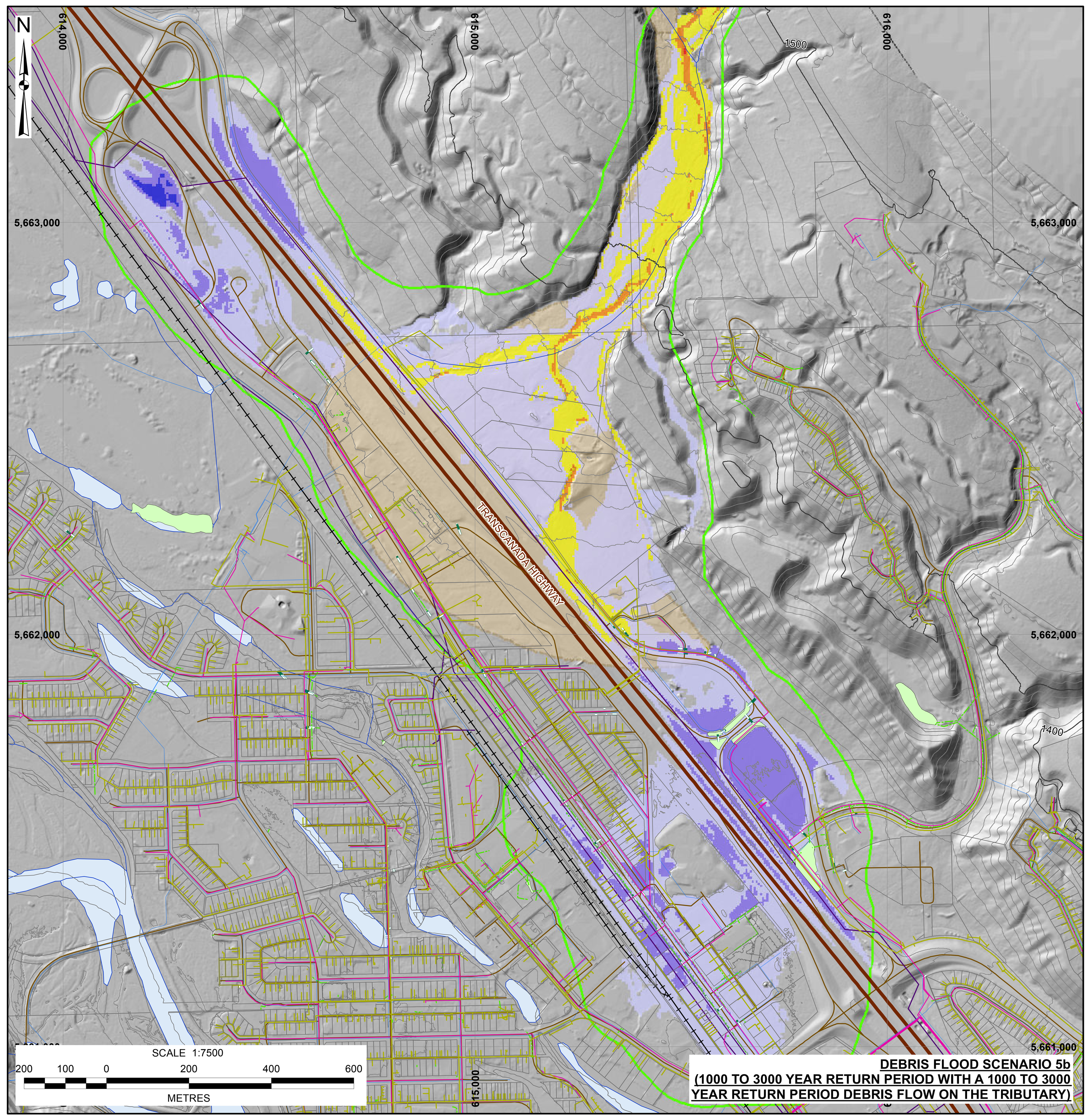
PROJECT No.: 1261009

DWG No.: 06









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LEGEND

FLOW DEPTH (m) (v < 1 m/s)
- < 1
- 1 to 2.5
- > 2.5

IMPACT INTENSITY (m^3/s^2) (v > 1 m/s)
- < 10
- 10 to 100
- > 100

- GAS LINES
- ATCO PIPELINE
- STORM MAIN
- WATERMAIN
- STORM MAIN/CHANNEL/SERVICE
- CULVERT
- ROAD
- HIGHWAY
- RAILWAY
- WATERCOURSES
- PARCELS
- STORM BASIN
- STUDY AREA BOUNDARY
- APPROXIMATE MODERN LOWER FAN BOUNDARY
- WATERBODY

NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT" AND DATED SEPTEMBER 2016.
3. PROJECTION IS NAD 83 UTM ZONE 11N.
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5. WATERCOURSES, WATERBODIES, ROADS AND RAILWAY WERE OBTAINED FROM CANVEC.
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SCALE:	1:7,500
DATE:	SEP 2016
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CHECKED:	JBM
APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

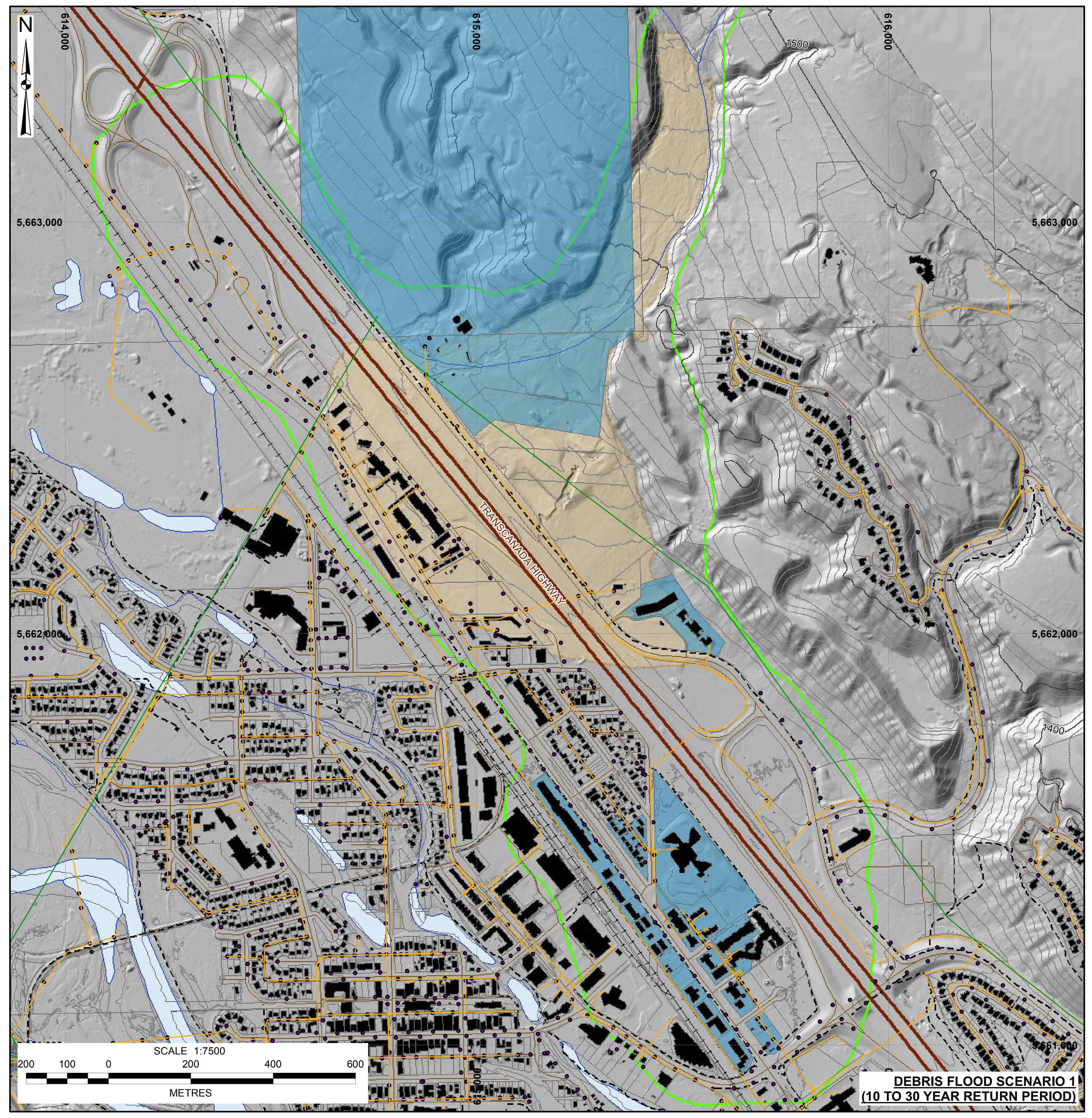
CLIENT: Town of CANMORE

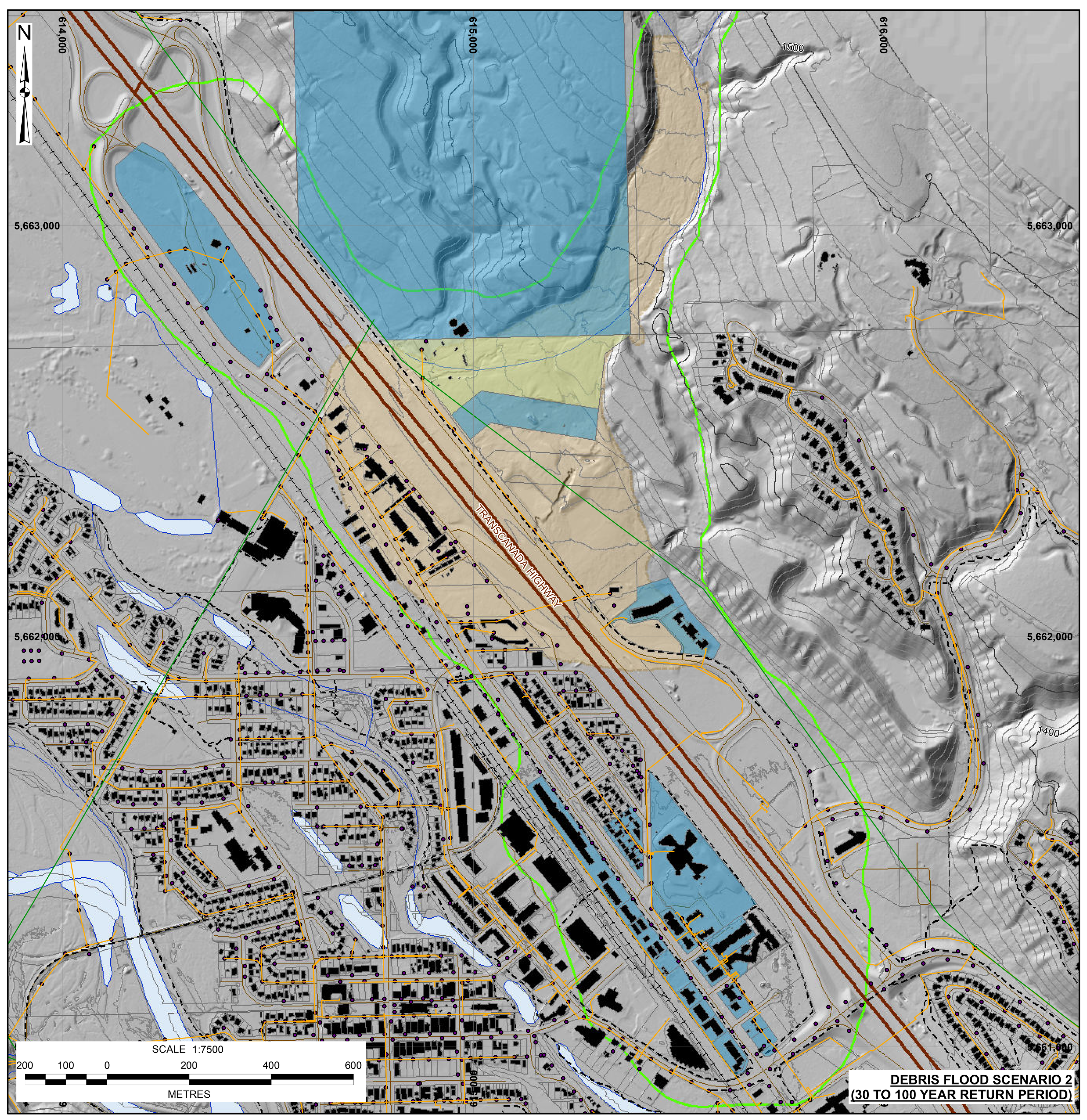
PROJECT: STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT

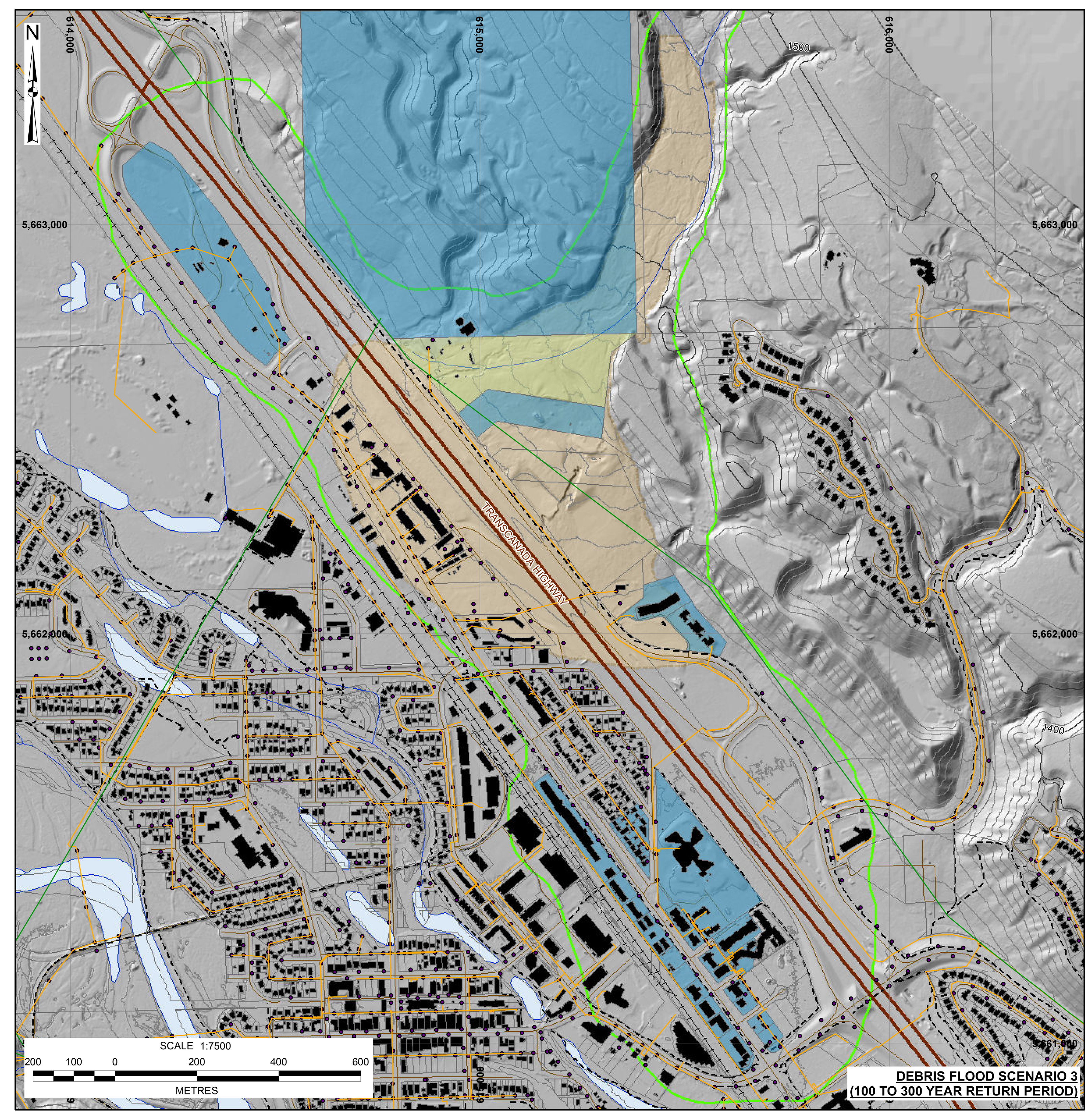
TITLE: DEBRIS-FLOOD INTENSITY, SUBSURFACE UTILITIES: DEBRIS-FLOOD SCENARIOS 4a-5b

PROJECT No.: 1261009

DWG No.: 07







THIS DRAWING MAY HAVE BEEN REDUCED OR ENLARGED. ALL FRACTIONAL SCALE NOTATIONS INDICATED ARE BASED ON ORIGINAL FORMAT DRAWINGS.

LEGEND

BUILDING DAMAGE
- MODERATE DAMAGE (>0-25%)
- MAJOR DAMAGE (>25%-75%)
- SEVERE DAMAGE (>75%-90%)
- DESTRUCTION (>90%)
- BUILDING
- PARCELS
- TRANSMISSION POLE
- ELECTRICAL CONDUCTOR LINE (138kV)
- ELECTRICAL CONDUCTOR LINE (LOCAL)
- ROAD
- HIGHWAY
- RAILWAY
- WATERCOURSE
- STUDY AREA BOUNDARY
- APPROXIMATE MODERN LOWER FAN BOUNDARY
- WATERBODY

NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
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SCALE:	1:7,500
DATE:	SEP 2016
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CHECKED:	JBM
APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: Town of CANMORE

PROJECT: STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT

TITLE: DIRECT DAMAGE LEVELS, BUILDINGS: DEBRIS FLOOD SCENARIOS 1-3

PROJECT No.: 1261009

DWG No.: 08

THIS BAR MEASURES 100 mm AT FULL SIZE. ALL SCALES REFERENCED TO FULL SIZE

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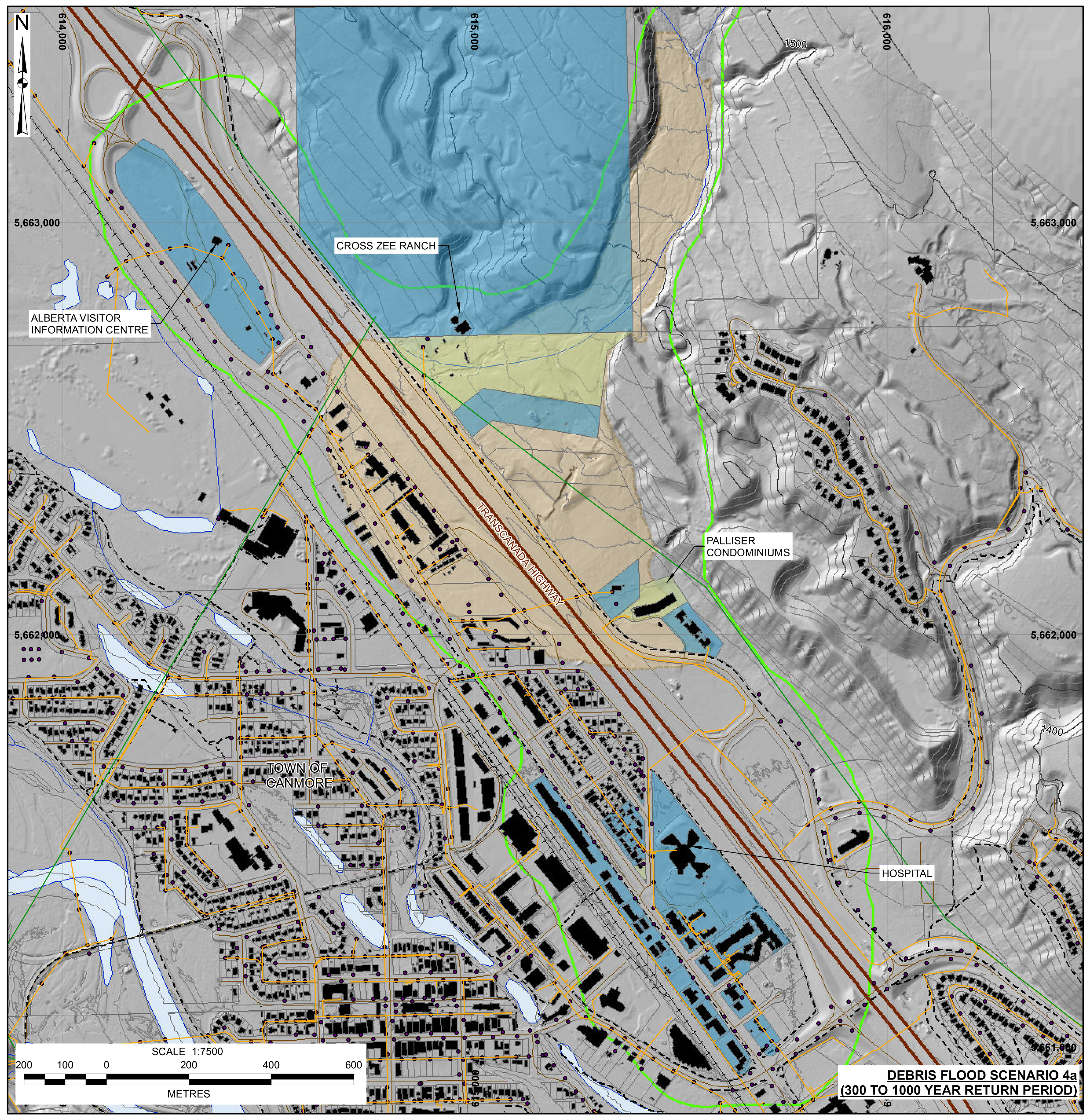

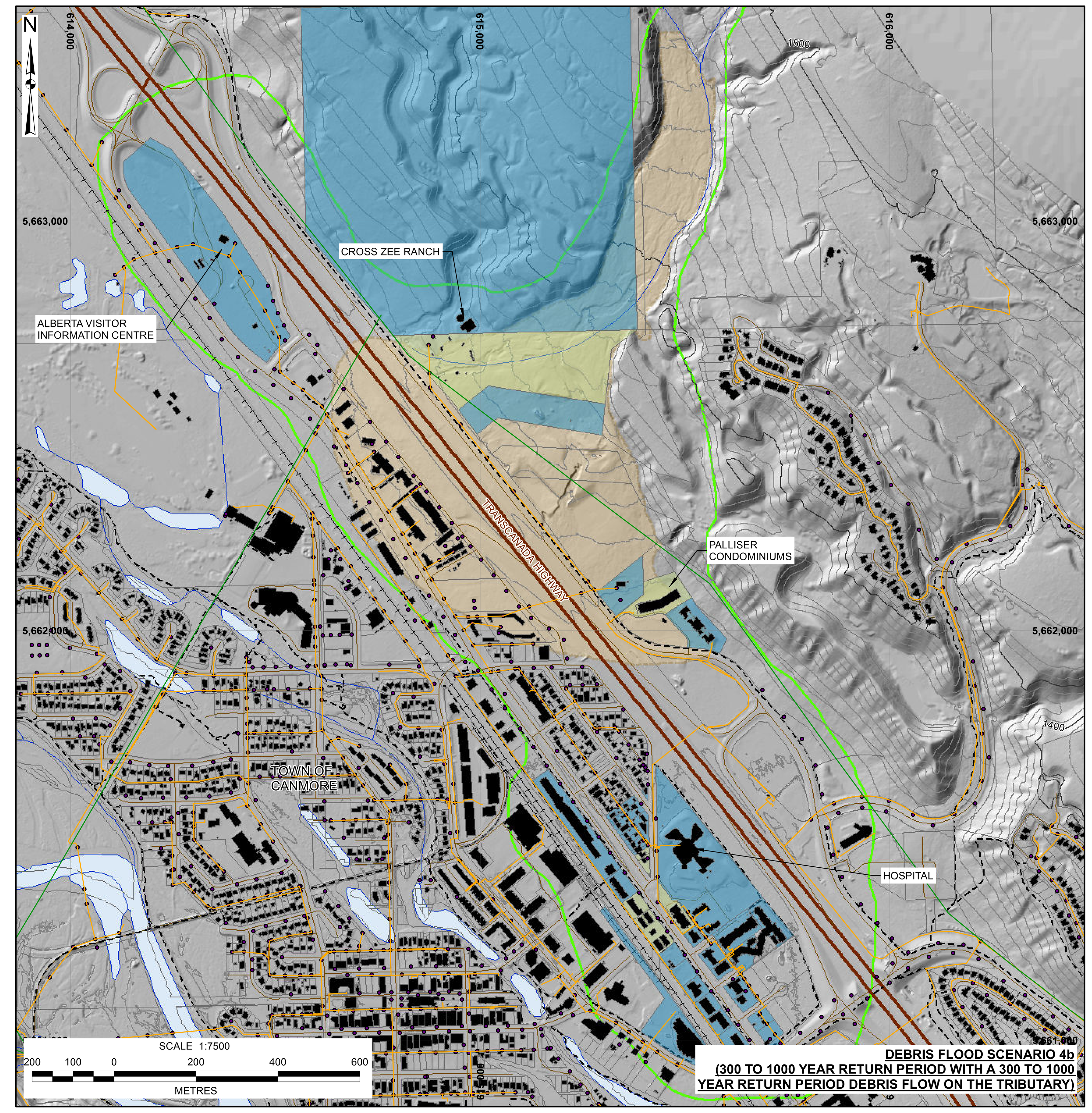

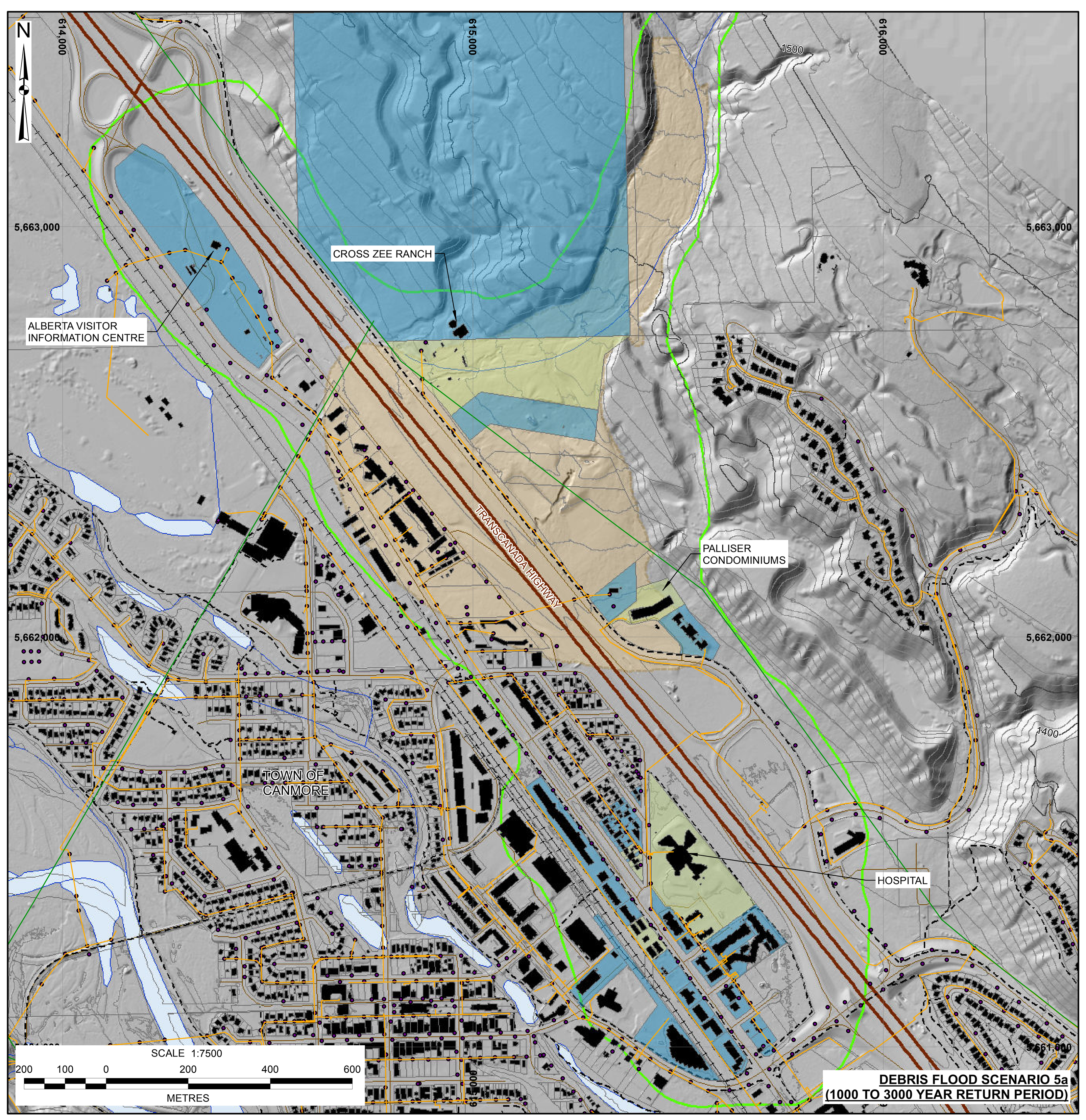

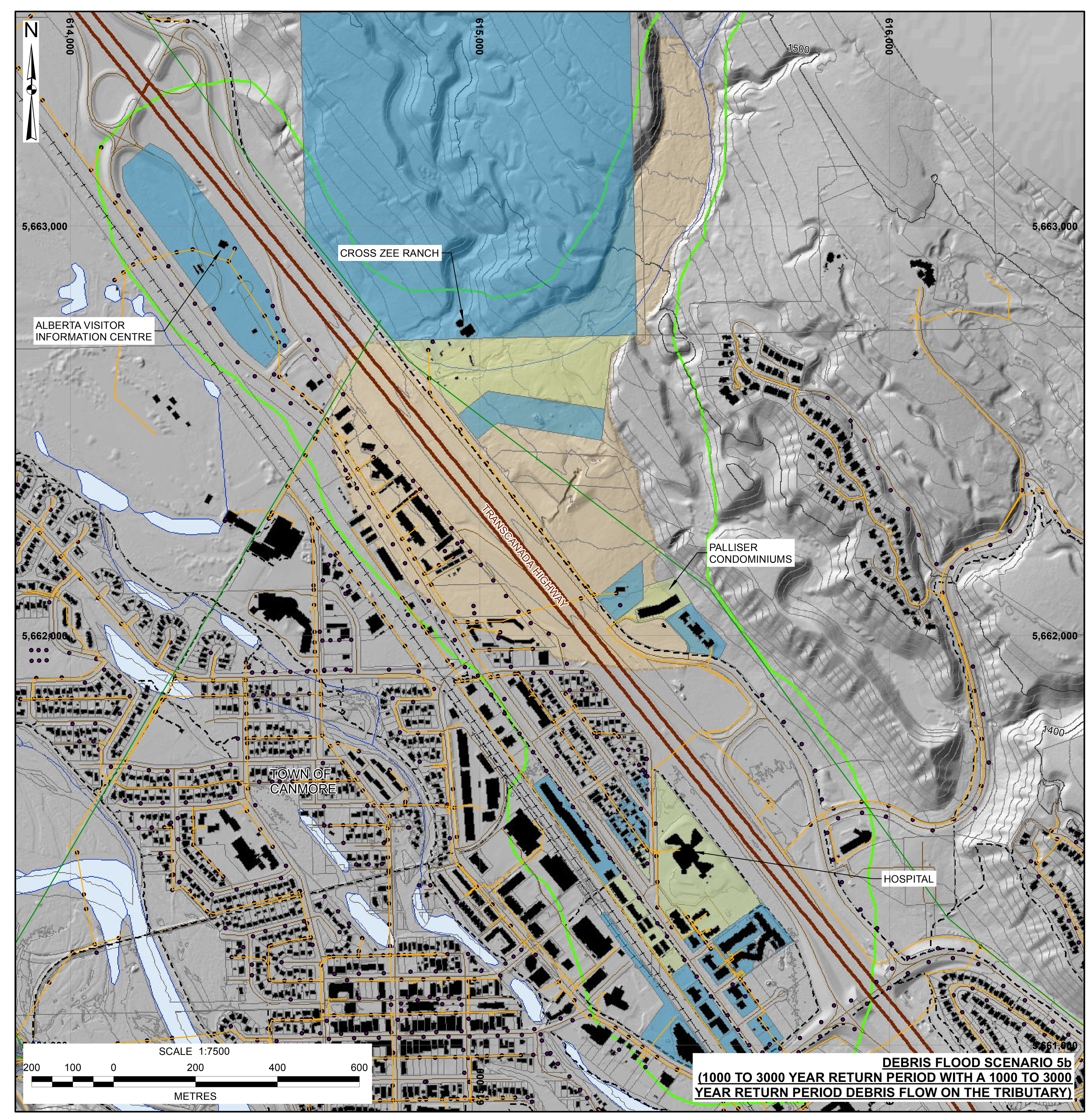

THIS BAR MEASURES 100 mm AT FULL SIZE. ALL SCALES REFERENCED TO FULL SIZE

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LEGEND

BUILDING DAMAGE
- MODERATE DAMAGE (>0-25%)
- MAJOR DAMAGE (>25%-75%)
- SEVERE DAMAGE (>75%-90%)
- DESTRUCTION (>90%)
- BUILDING
- PARCELS
- TRANSMISSION POLE
- ELECTRICAL CONDUCTOR LINE (138kV)
- ELECTRICAL CONDUCTOR LINE (LOCAL)
- ROAD
- HIGHWAY
- RAILWAY
- WATERCOURSE
- STUDY AREA BOUNDARY
- APPROXIMATE MODERN LOWER FAN BOUNDARY
- WATERBODY

NOTES:
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2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT" AND DATED SEPTEMBER 2016.
3. PROJECTION IS NAD 83 UTM ZONE 11N.
4. BUILDINGS, PARCELS, AND UTILITIES WERE OBTAINED FROM TOWN OF CANMORE.
5. WATERCOURSES, WATERBODIES, ROADS AND RAILWAY WERE OBTAINED FROM CANVEC.
6. HILLSHADE WAS DERIVED FROM LIDAR PROVIDED BY LIDAR SERVICES IN C. (LSI), DATED JUNE 28, 2013. CONTOUR INTERVAL IS 5 m.
7. MODEL RUNS (DEBRIS FLOOD SCENARIOS) ARE LABELLED IN THE LOWER RIGHT HAND CORNER OF EACH MAP INSET.
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SCALE:	1:7,500
DATE:	SEP 2016
DRAWN:	JDC
CHECKED:	JBM
APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

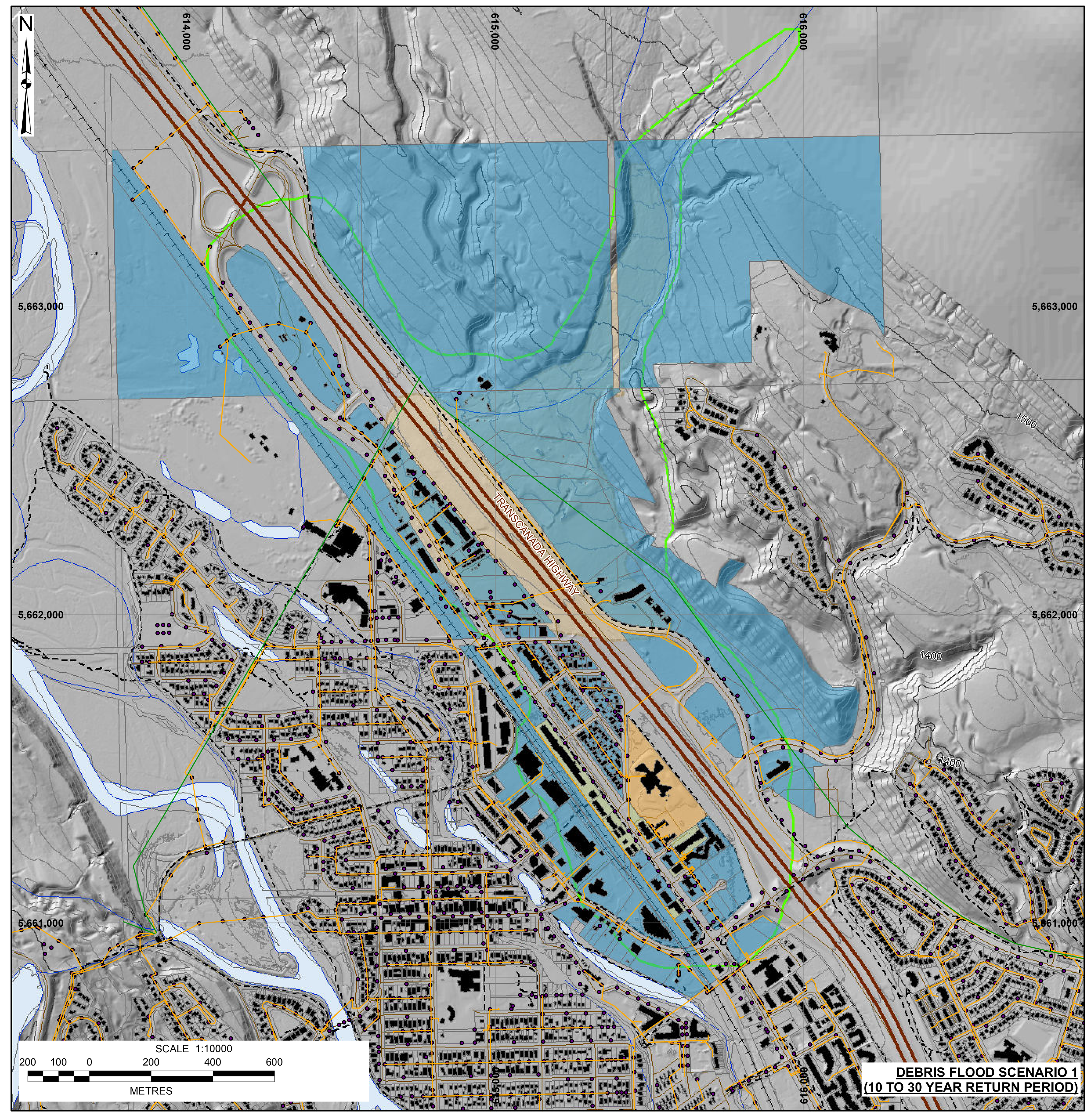
CLIENT: Town of CANMORE

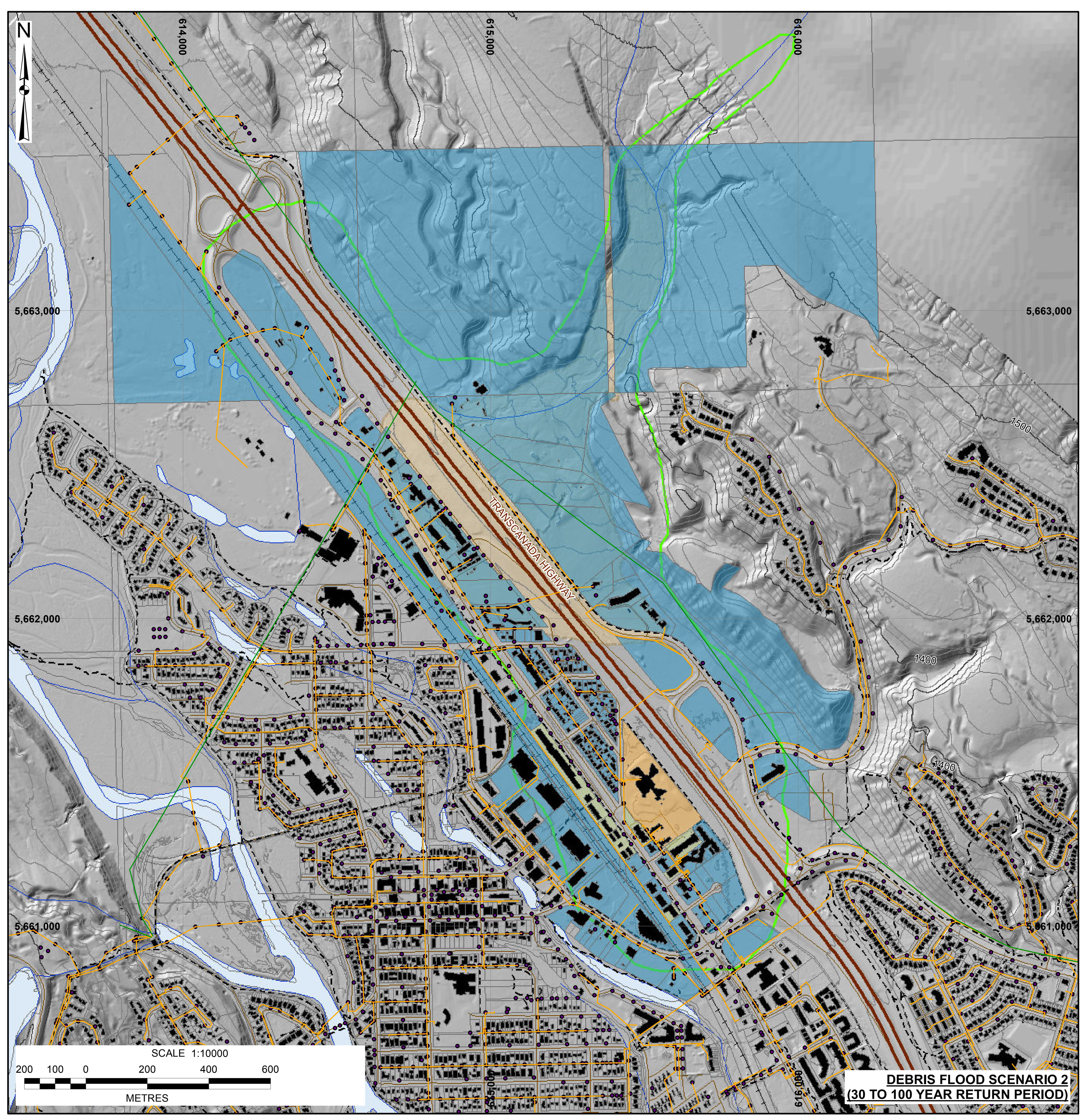
PROJECT: STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT

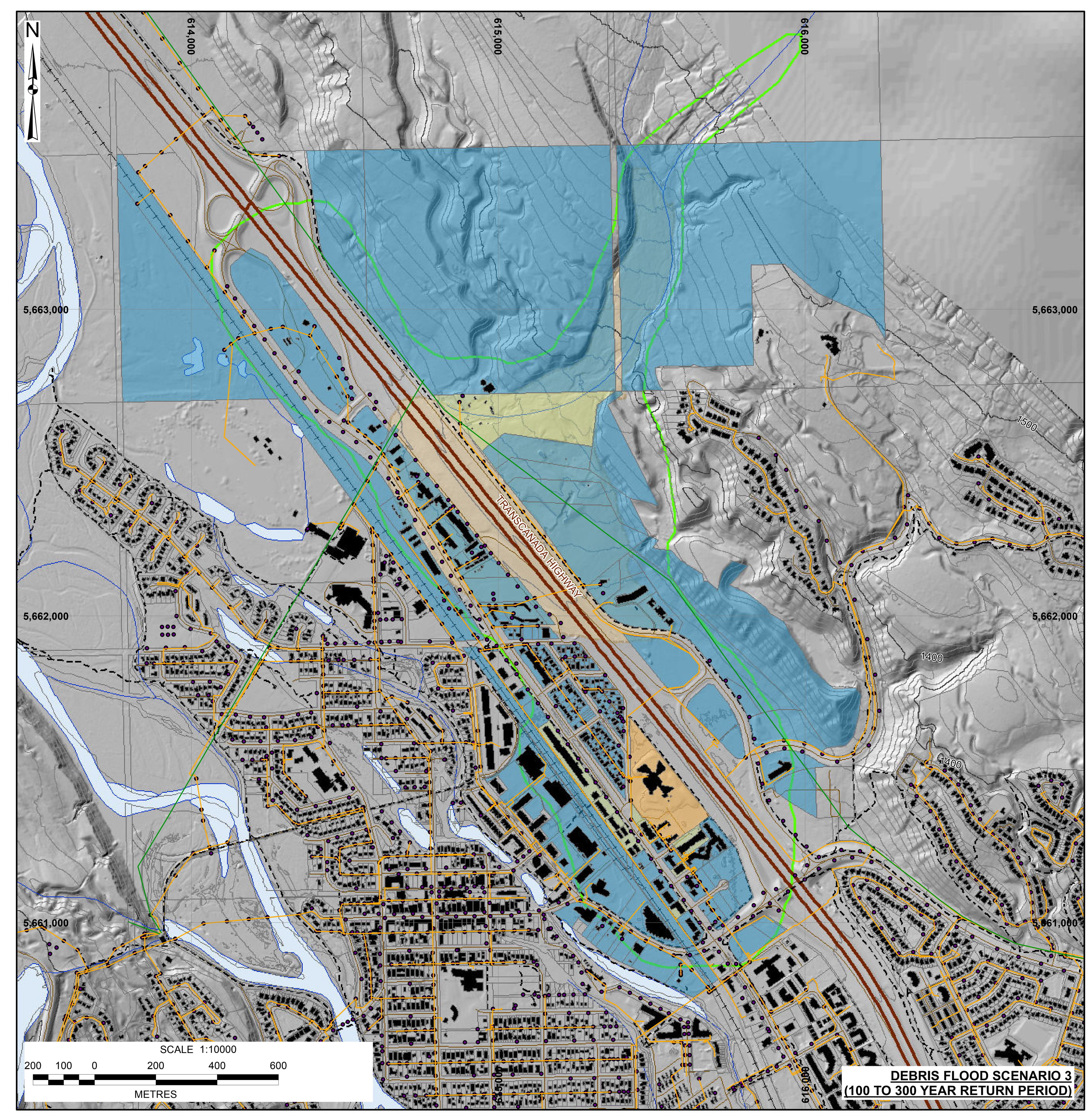
TITLE: DIRECT DAMAGE LEVELS, BUILDINGS: DEBRIS-FLOOD SCENARIOS 4a-5b

PROJECT No.: 1261009

DWG No.: 09







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LEGEND

BUILDING DAMAGE COST
- ≤$0.1M Damage
- >$0.1M to $1M Damage
- >$1M to $10M Damage
- >$10M Damage
- BUILDING
- PARCELS

- TRANSMISSION POLE
- ELECTRICAL CONDUCTOR LINE (138kV)
- ELECTRICAL CONDUCTOR LINE (LOCAL)
- ROAD
- HIGHWAY
- RAILWAY
- WATERCOURSE

- STUDY AREA BOUNDARY
- APPROXIMATE MODERN LOWER FAN BOUNDARY
- WATERBODY

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SCALE:	1:10,000
DATE:	SEP 2016
DRAWN:	JDC
CHECKED:	JBM
APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: Town of CANMORE

PROJECT: STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT

TITLE: DIRECT DAMAGE COSTS, BUILDINGS: DEBRIS FLOOD SCENARIOS 1-3

PROJECT No.:	DWG No.:
1261009	10

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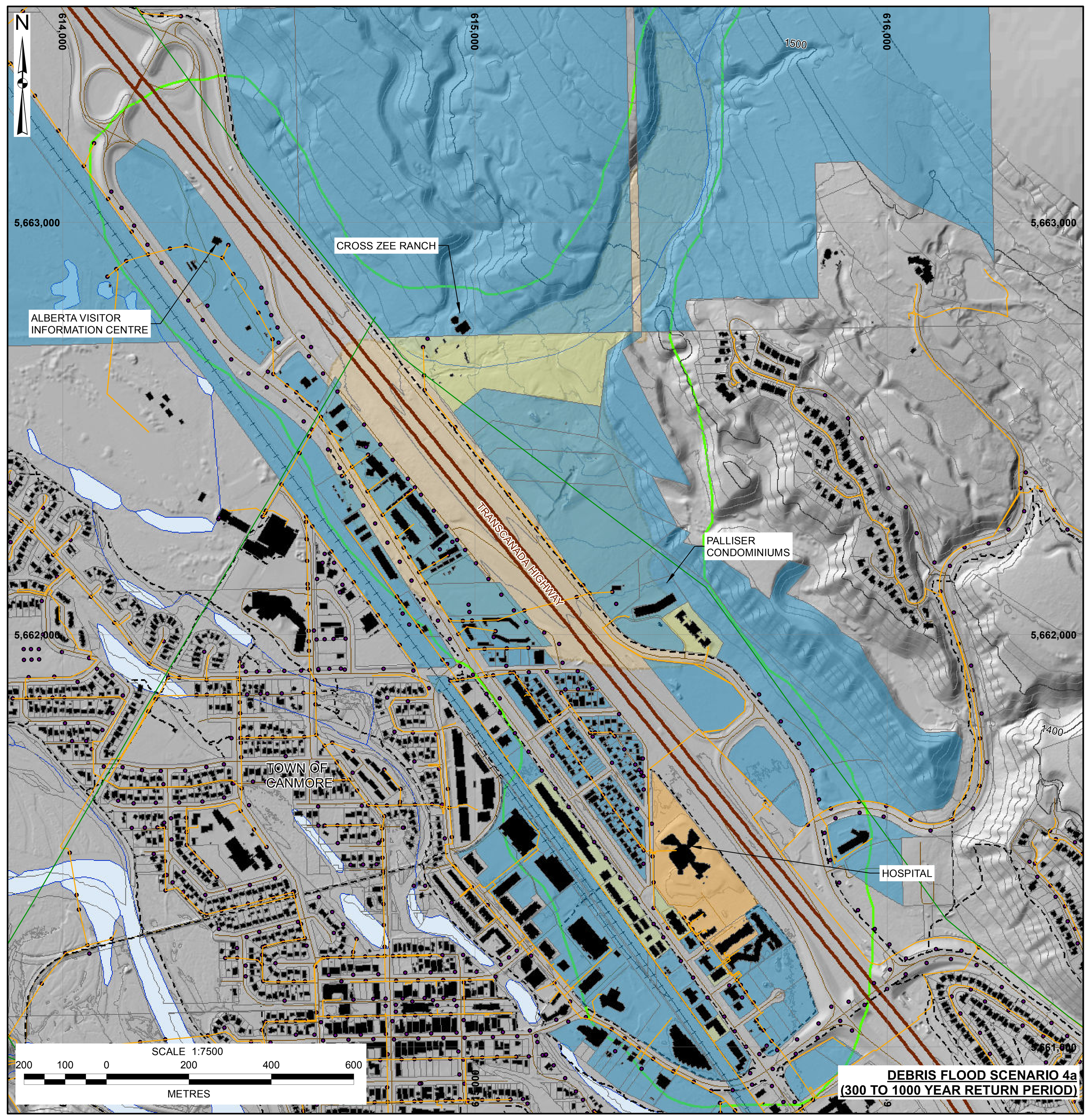

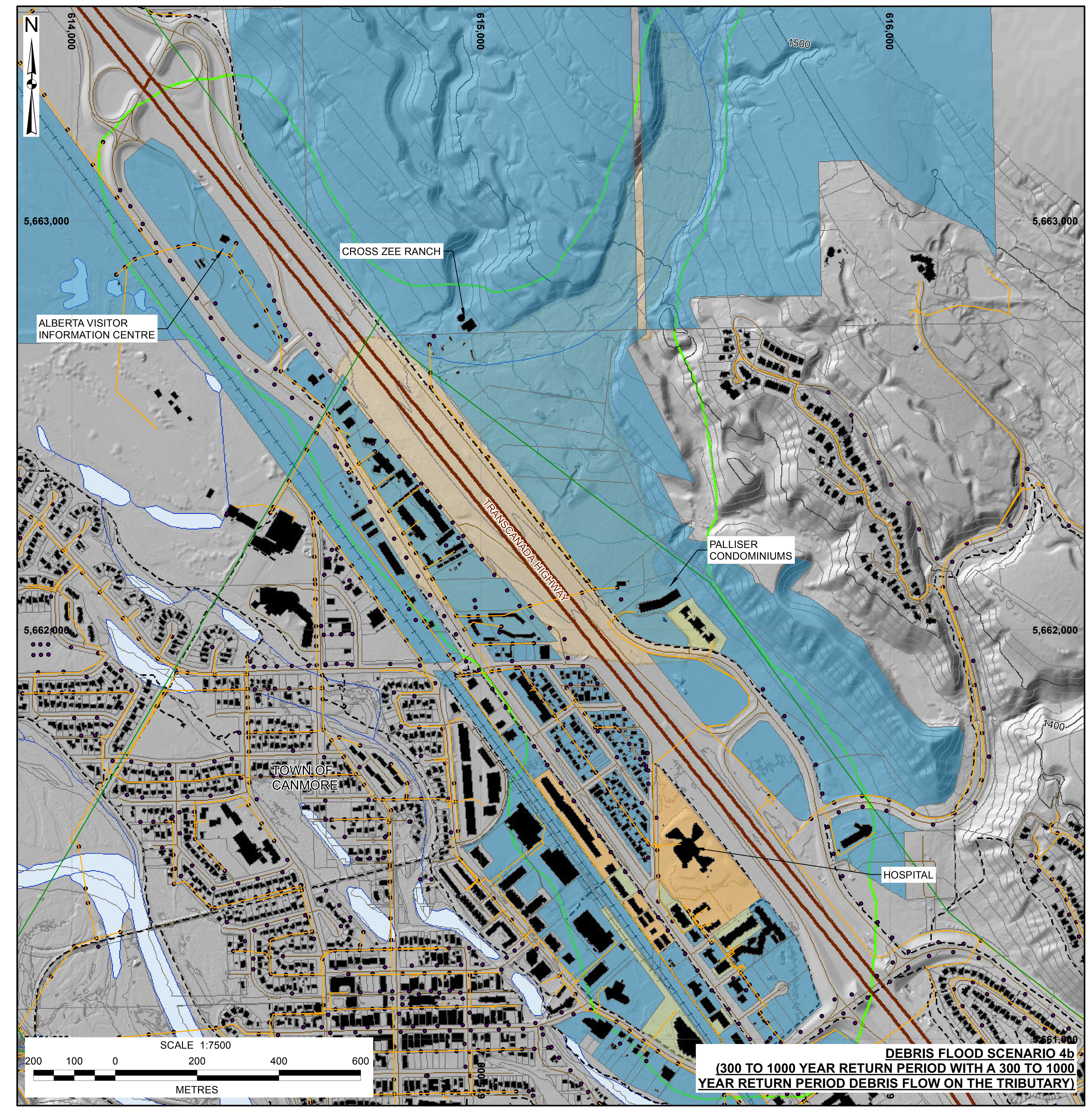

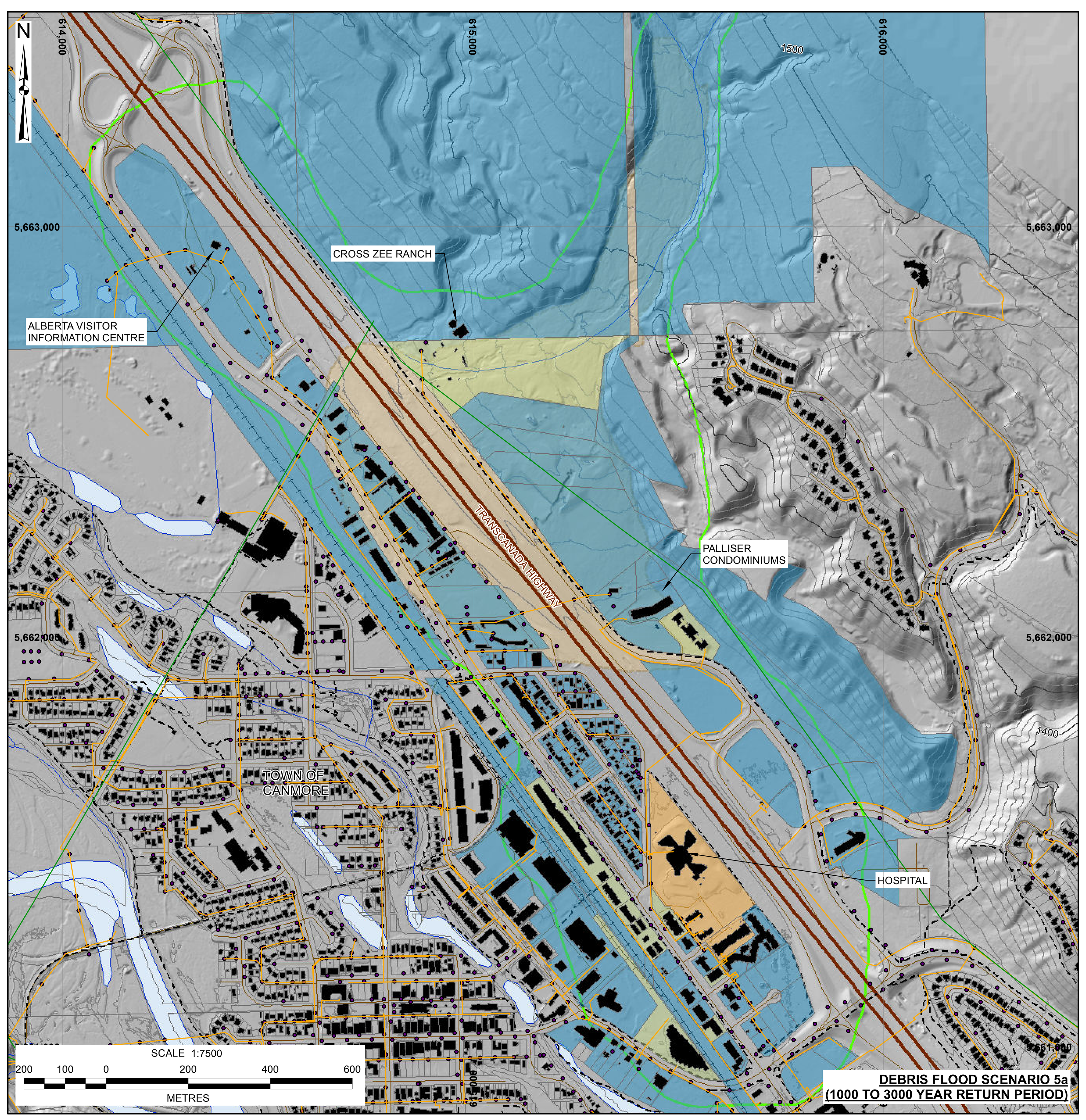

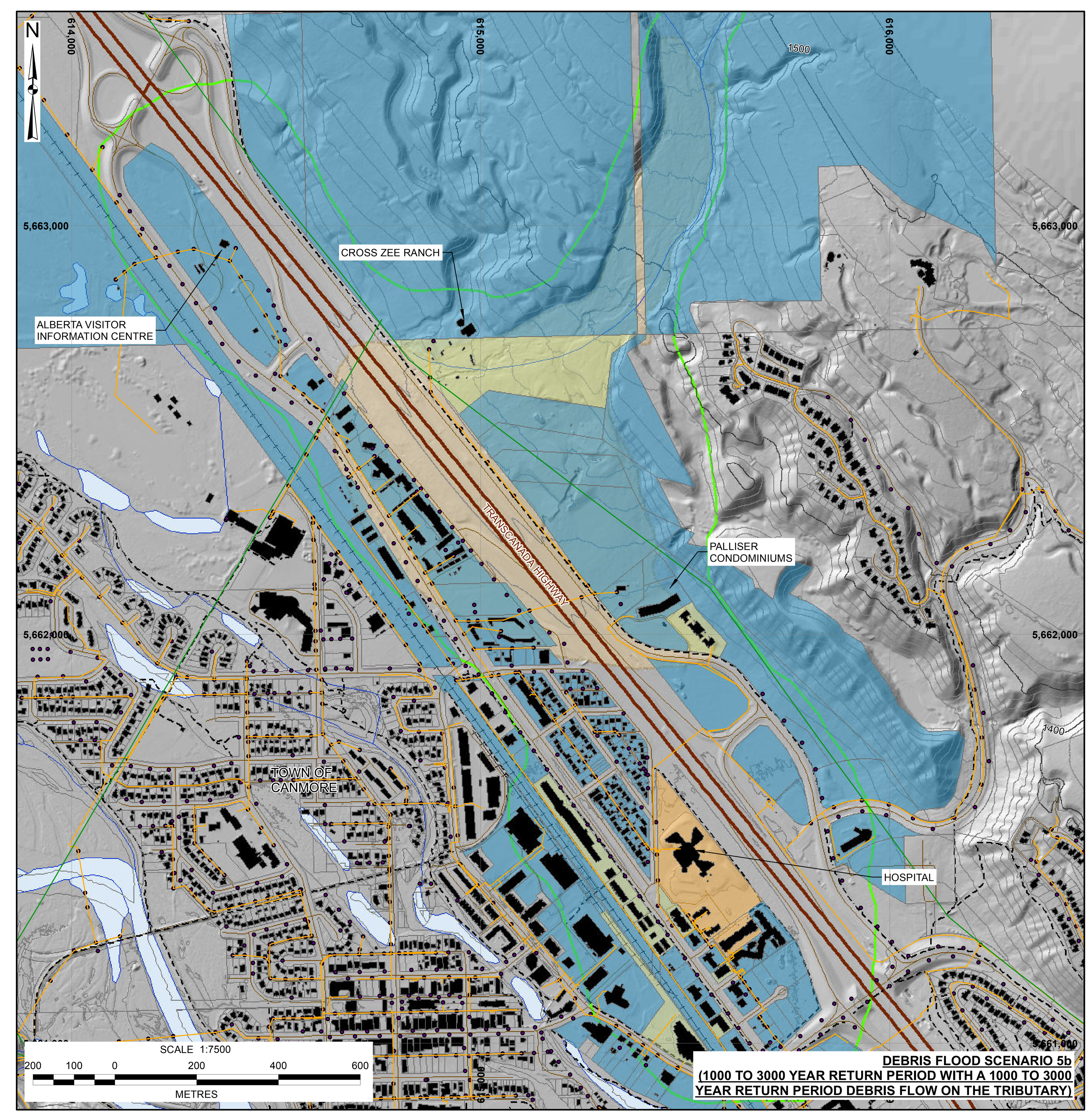

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LEGEND

BUILDING DAMAGE COST
- ≤$0.1M Damage
- >$0.1M to $1M Damage
- >$1M to $10M Damage
- >$10M Damage
- BUILDING
- PARCELS

- TRANSMISSION POLE
- ELECTRICAL CONDUCTOR LINE (138kV)
- ELECTRICAL CONDUCTOR LINE (LOCAL)
- ROAD
- HIGHWAY
- RAILWAY
- WATERCOURSE

- STUDY AREA BOUNDARY
- APPROXIMATE MODERN LOWER FAN BOUNDARY
- WATERBODY

NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT" AND DATED SEPTEMBER 2016.
3. PROJECTION IS NAD 83 UTM ZONE 11N.
4. BUILDINGS, PARCELS, AND UTILITIES WERE OBTAINED FROM TOWN OF CANMORE.
5. WATERCOURSES, WATERBODIES, ROADS AND RAILWAY WERE OBTAINED FROM CANVEC.
6. HILLSHADE WAS DERIVED FROM LIDAR PROVIDED BY LIDAR SERVICES IN C. (LSI), DATED JUNE 28, 2013. CONTOUR INTERVAL IS 5 m.
7. MODEL RUNS (DEBRIS FLOOD SCENARIOS) ARE LABELLED IN THE LOWER RIGHT HAND CORNER OF EACH MAP INSET.
8. THIS MAP SHOULD NOT BE RELIED UPON AT A SCALE LARGER THAN (MORE DETAILED) THAN SHOWN ON THIS MAP.
9. THIS MAP REPRESENTS A SNAPSHOT IN TIME. FUTURE CHANGES (DEVELOPMENT, DEBRIS FLOOD MITIGATION, GEOHAZARD EVENTS) MAY WARRANT THE RE-DRAWING OF CERTAIN AREAS.
10. THIS DRAWING SHOWS ESTIMATED BUILDING STRUCTURE DAMAGE COSTS FOR INDIVIDUAL PARCELS.
11. UNLESS BGC AGREES OTHERWISE IN WRITING, THIS DRAWING SHALL NOT BE MODIFIED OR USED FOR ANY PURPOSE OTHER THAN THE PURPOSE FOR WHICH BGC GENERATED IT. BGC SHALL HAVE NO LIABILITY FOR ANY DAMAGES OR LOSS ARISING IN ANY WAY FROM ANY USE OR MODIFICATION OF THIS DOCUMENT NOT AUTHORIZED BY BGC. ANY USE OF OR RELIANCE UPON THIS DOCUMENT OR ITS CONTENT BY THIRD PARTIES SHALL BE AT SUCH THIRD PARTIES' SOLE RISK.

SCALE:	1:7,500
DATE:	SEP 2016
DRAWN:	JDC
CHECKED:	JBM
APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:
Town of CANMORE

PROJECT:
STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT

TITLE:
DIRECT DAMAGE COSTS, BUILDINGS:
DEBRIS-FLOOD SCENARIOS 4a-5b

PROJECT No.:	DWG No.:
1261009	11

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NOTES:

1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT," AND DATED SEPTEMBER 2016.
3. BUILDINGS, PARCELS, AND UTILITIES WERE OBTAINED FROM TOWN OF CANMORE.
4. WATERCOURSE, WATERBODY, AND RAILWAY WERE OBTAINED FROM CANVEC.
5. HILLSHADE WAS DERIVED FROM LIDAR PROVIDED BY LIDAR SERVICES INC. (LSI), DATED JUNE 28, 2013. CONTOUR INTERVAL IS 5 m.
6. PROJECTION IS NAD 83 UTM ZONE 11N.
7. SEE THE REPORT FOR METHODS AND LIMITATIONS OF INDIVIDUAL RISK ESTIMATES.
8. "PDI" CORRESPONDS TO "PROBABILITY OF DEATH OF AN INDIVIDUAL".
9. RESULTS ARE SHOWN AT A PARCEL LEVEL OF DETAIL AND CONSIDER ONLY PERSONS INSIDE BUILDINGS.
10. THIS MAP SHOULD NOT BE RELIED UPON AT A SCALE LARGER THAN (MORE DETAILED) THAN SHOWN ON THIS MAP.
11. THIS MAP REPRESENTS A SNAPSHOT IN TIME. FUTURE CHANGES (DEVELOPMENT, DEBRIS FLOOD MITIGATION, GEOHAZARD EVENTS) MAY WARRANT THE RE-DRAWING OF CERTAIN AREAS.
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SCALE:	1:5,000
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APPROVED:	KH

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:
Town of CANMORE

PROJECT:
STONEWORKS CREEK DEBRIS-FLOOD RISK ASSESSMENT

TITLE:
RESULTS:
RISK TO INDIVIDUALS: DEBRIS-FLOOD SCENARIOS 1 - 5b

PROJECT No.:	DWG No.:
1261009	12

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APPENDIX A
CASE STUDY COMPARISONS

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 associated with hurricane Katrina amounted to 1464. Of the 746 fatalities that were recovered in

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

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%).