COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION

FINAL

PROJECT No: 1261-001
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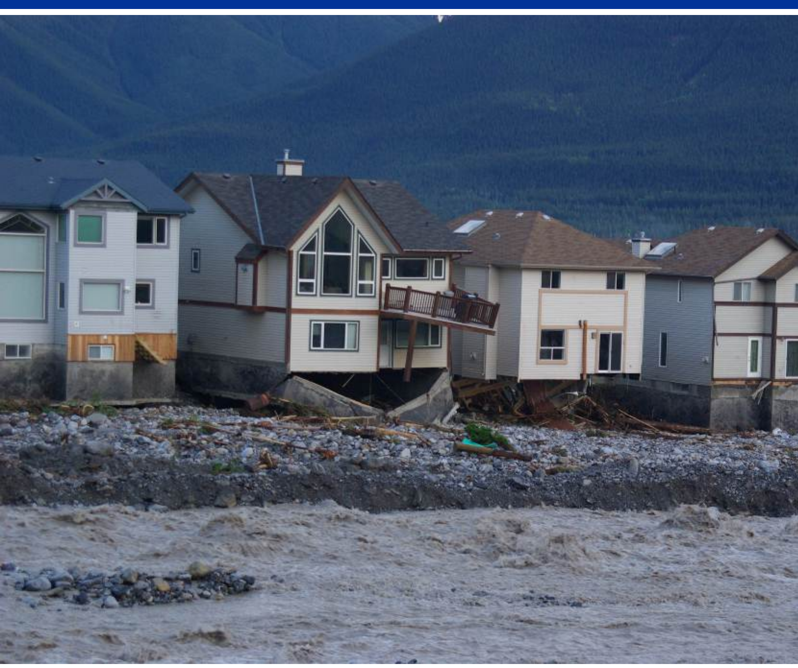

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

TOWN OF CANMORE

COUGAR CREEK

2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION

FINAL

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December 11, 2013
Project No.: 1261-001

Andy Esarte, P.Eng.
Engineering Services, Town of Canmore
902 7th Avenue
Canmore, Alberta T1W 3K1

Dear Mr. Esarte

Re: Submission of Cougar Creek, Forensic Analysis and Short Term Debris Flood Mitigation – FINAL

Please find attached the above quoted report. It has been a pleasure assembling this information.

Yours sincerely,

BGC ENGINEERING INC.
per:

Matthias Jakob, Ph.D., P.Geo.
Senior Geoscientist and Project Manager

EXECUTIVE SUMMARY

This report provides a forensic analysis and assessment of conceptual short-term mitigation measures for Cougar Creek as it pertains to the June 19 to 21, 2013 debris flood. This report will be followed by a detailed hazard assessment that will be submitted in October 2013 by BGC.

An intensive and persistent rainstorm combined with snowmelt from June 19 to 21, 2013 in southeastern Alberta initiated hundreds of debris flows and debris floods on tributaries of the Bow and Ghost Rivers and other larger streams draining the southeastern Rocky Mountains. Bow River reached its highest recorded discharge at Banff with 439 m^3/s exceeding the previous record of 1923 (399 m^3/s). Some 9 million m^3 of rain (220 mm) fell on the 43 km^2 watershed of Cougar Creek over the course of 3 days, a total that was augmented by snowmelt. This storm event led to extensive sediment aggradation along Cougar Creek both upstream of the fan apex and on the fan reaches, which was accompanied by lateral instability on the fan as the channel lost confinement.

The channel aggradation allowed the streamflow to overtop the confines of the previously confined channel which led to flood waters eroding banks past property lines, undermining buildings foundations and destroying the support of decks and supported balconies. The peak flow of the debris flood appeared to have exceeded at least three times the estimated 100-year return period flood (16 m^3/s, AMEC, 2007). Due to significant effort by the Town of Canmore and its contractors, no creek avulsion occurred until the creek reached Highway 1, where the existing box culverts were blocked by sediment and woody debris. Such an avulsion further upstream would have led to significantly more damage to buildings and infrastructure than was observed. Nonetheless, a number of buildings suffered major damage. None of the buildings on Cougar Creek fan was completely destroyed by the event. The 9.5 m wide, elliptical culvert under Elk Run Boulevard sustained damage, but survived thanks to continuous excavation of debris during the event which threatened to block the culvert.

Additional major damage was recorded at Highway 1, where the blocked culverts resulted in flows avulsing over the highway and down the median to the east. These overflows resulted in portions of the highway being undermined and collapsing. The box culverts at Highway 1A and CP Rail were also blocked by sediment and debris, the latter of which was out of commission for approximately three days until it was repaired by CP Rail staff and contractors.

A review of historical air photographs and reports indicates that large debris floods possibly occurred in 1923, 1948, 1974 and 2013 indicating a preliminary return period of approximately 30 years for the last century. Smaller events (floods or debris floods) did occur during the 1948-2013 period and have been recorded as having occurred in 1956, 1967, 1980, 1990, 2005 and 2012, indicating a return period of approximately 8 years. These smaller events have largely been confined to the channel and thus are not obvious on air photographs. The respective volumes of these previous events will be estimated in detail in BGC's forthcoming comprehensive hazard assessment of Cougar Creek. The most striking changes on the fan in the past 30 years is residential, commercial and industrial development, which now occupies some 90% of the fan.

The June 2013 debris flood has left many hundreds of thousands of cubic metres of loose and thus readily mobilized sediment in the mainstem channel of Cougar Creek upstream of the fan apex. A storm of similar magnitude to the 2013 event could mobilize this material and lead to renewed aggradation and erosion issues on Cougar Creek fan. This realization demonstrates the need for short and long-term mitigation measures on the fan, which is densely developed with homes, an elementary school, industry and urban infrastructure such as telecommunication and sewerage.

The Town of Canmore has indicated that they have a low risk tolerance for further damages on the fan of Cougar Creek. The Town therefore wishes to implement short-term mitigation options in the fall and winter of 2013/2014 that would provide protection against an event of similar magnitude to that experienced in June 2013. The short-term mitigation works would then be followed by the design and construction of long-term mitigation works in 2014. A more detailed hazard and risk analysis of Cougar Creek is ongoing and will provide critical inputs to the design of the long-term mitigation works.

The short and long-term mitigation strategy needs to be two-fold. The backbone of any mitigation strategy must avoid excessive fan reach aggradation, which could lead to culvert blockage and possible avulsions into developed areas. Second, bank erosion will have to be reduced to avoid repeat erosion of house foundations along the creek corridor.

In the short-term, BGC recommends a combination of debris retention at the previous site of the 1982 rockfill dam, as well as erosion protection downstream. Specifically, the recommended measures include:

- A debris flow net spanning some 40 m at the site of the 1982 rockfill dam supported by several posts. This structure would have an appropriately sized outlet structure to allow Cougar Creek streamflows to pass and to drain the debris that would be impounded by the barrier in case of a major debris flood. Ideally the debris net would also allow for the passage of people and wildlife;
- Erosion protection through gabion mattresses placed on both banks between Highway 1 and the uppermost extent of the existing development; and
- Eight (8) grade control structures (Class IV riprap) to minimize the potential for channel degradation and scour within the channelized reach.

The channel erosion protection would remain until the end of its design life (unless damaged in the interim), while the debris net would be disassembled and reused at an appropriate location in lieu of a permanent reinforced concrete structure at the site of the 1982 rockfill dam.

It is of paramount importance to emphasize that these short-term measures will only reduce risk to loss of life and property damage for events with sediment volumes on the order of several tens of thousands cubic meters. It is unlikely that these measures will be sufficient to reduce risk to tolerable levels for larger events that will occur with statistical certainty. Ultimately, Cougar Creek will require a long-term solution that will reduce total risk of loss of life and excessive property damage to levels considered tolerable by the Town of Canmore and other stakeholders. The type and scale of long-term risk reduction measures will be determined through the forthcoming quantitative risk assessment that will determine debris flood risks for the entire spectrum of events that are being reconstructed in BGC's detailed hazard assessment, which will follow this forensic analysis. Under no circumstances should the short-term mitigation measures proposed herein be viewed as a viable long-term solution as this assumption would invariably lead to renewed property loss or possibly loss of life in a future extreme event.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF DRAWINGS

LIST OF APPENDICES

LIMITATIONS

BGC Engineering Inc. (BGC) prepared this document for the account of Town of Canmore. The material in it reflects the judgment of BGC staff in light of the information available to BGC at the time of document preparation. Any use which a third party makes of this document or any reliance on decisions to be based on it is the responsibility of such third parties. BGC accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this document.

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1.0 INTRODUCTION

1.1. Background

The southwestern Alberta mountain front was affected by a high intensity/duration rainstorm between June 19 and 21, 2013. Direct runoff coupled with meltwater released from rain-on-snow caused sudden and prolonged high flows in the Bow, High, and Ghost Rivers and their tributaries originating in the Rocky Mountains. These flows resulted in high rates and volumes of sediment transport, bank erosion and avulsions on alluvial fans.

Almost all of the steep gradient tributaries to Bow River within the municipal boundary of the Town of Canmore were affected by the combined storm and snowmelt runoff, including Cougar Creek, the focus of this report (Drawing 1). The Town of Canmore has requested that BGC Engineering Inc. (BGC) conduct a forensic analysis of the June 2013 flood event on Cougar Creek and provide short-term conceptual mitigation options in the event of a similar flood occurring in 2014.

1.2. SCOPE OF WORK

BCG is retained by the Town of Canmore under the terms of a Master Consulting Agreement dated July 15, 2013 (the Contract). The BGC scope of work for Cougar Creek includes the following tasks:

1. Review of previous work completed by various consulting and engineering firms.
2. Visual inspection of the watershed and fan by helicopter and a foot traverse of the fan and main channel of Cougar Creek upstream from the fan apex.
3. Location, documentation and categorization of the damage sites.
4. Provide a preliminary estimate debris flood frequency using historical air photographs.
5. Provide conceptual options for short-term debris flood mitigation in case of a large flood event in 2014, and long-term mitigation options to reduce the risk of incurring property damage and/or loss of life in the event of future debris floods.

The observations reported here are assumed to be factual and it is on this basis that preliminary recommendations on conceptual mitigation measures are provided herein. However, it must be understood by the Town of Canmore that further information gathering and assessment are required and that the conceptual options provided herein may be modified on the basis of new information through the remainder of 2013 and 2014. This report will be superseded by a comprehensive hazard assessment projected for submission in October 2013, which will be authored by BGC.

1.3. Terminology

Steep mountain creeks are typically subject to a spectrum of mass movement processes that range from clear water floods to debris floods to debris flows in order of increasing sediment concentration. There is a continuum between these processes in space and time with floods transitioning into debris floods and eventually debris flows through progressive sediment entrainment. Conversely dilution of a debris flow through partial sediment deposition and tributary injection of water can lead to a transition towards debris floods and eventually floods.

Debris flows typically require a channel gradient in excess of some 30% for transport over long distances and have volumetric sediment concentrations typically in excess of 50-60%. The distinction between floods, debris floods and debris flows is important, as they differ in flow mechanics and potential consequences.

A debris flood can be defined as: "a very rapid surging flow of water heavily charged with debris in a steep channel" (Hungr et al., 2001). In North America, the term debris flood is not widely accepted and has been challenged, especially by researchers from the USGS, who prefer to use the term hyperconcentrated flow because it can be defined on the basis of sediment concentration (Pierson, 2005). Pierson defines a hyperconcentrated flow as "a type of two-phase, non-Newtonian flow of sediment and water that operates between normal streamflow (water flow) and debris flow (or mudflow)". Transitions from water flow to debris flood / hyperconcentrated flow and vice versa occur at minimum volumetric sediment concentrations of 3 to 10%, but this range depends on the overall grain size distribution and the ability to acquire yield strength[1]. Debris floods typically occur on creeks with channel gradients between 3 and 30%.

It appears at this time that the June 2013 event that impacted Cougar Creek is best described as a debris flood rather than a flood or debris flow. Given that there is a continuum between these processes, this division is somewhat arbitrary. In the case of Cougar Creek, however, two types of debris floods can be distinguished. The June 2013 event on Cougar Creek transported a major volume of sediment onto the fan, presumably as bedload. The stream power was sufficient to move gravel in a layer several grains deep. On the other hand, debris floods on Cougar Creek also likely occur as a consequence of landslide dam outbursts. Those are believed to have higher fines contents as they mobilize the landslide dam during the incision process and are thus characterized by largely matrix-supported deposits on the fan.

[1] The yield strength is the internal resistance of the sediment mixture to shear stress deformation; it is the result of friction between grains and cohesion (Pierson, 2005).

Cougar Creek has developed an extensive alluvial fan since deglaciation of the area in the order of 10,000 years ago. An alluvial fan is a fan shaped deposit of sediment crossed and built up by streams where they flow from a steep mountain channel onto the dramatically reduced gradient of a valley floor, in this case the valley floor that is occupied by the Bow River. Exact process attribution to fan formation is often difficult to achieve since multiple processes (rock fall, debris flows and debris floods) may have contributed to its evolution. In this case, the term “composite fan” is more appropriate. Steeper accumulations of debris as found below steep bedrock gullies are referred to as colluvial cones and are largely produced by rockfall.

Streamflows and associated transported sediment come from a single point source at the apex of the fan. As the stream loses confinement and the channel gradient decreases, it drops coarse-grained material. This aggradation reduces the capacity of the channel and forces it to change direction, thereby gradually building up a shallow conical fan shape. Over time, the creek moves to occupy many positions on the fan surface. When significant settlement occurs on a fan, there is an implicit need to inhibit this process. Continuous vigilance and periodic works, even if only maintenance of successful works, are therefore required on developed fans.

In general, the grain size of fan materials diminishes downstream with the distal fan portions often characterized by sandy fine gravels or coarse to medium sands where they interfinger with floodplain deposits. However, this downstream fining is not continuous because principal fan channels can convey larger grain sizes even to the more distal fan portions. In test trenches, those paleochannels are identified as “lag deposits”.

The alluvial fan of Cougar Creek is described in more detail in Section 2.2.

2.0 PHYSICAL SETTING

2.1. Watershed Description

Cougar Creek is a tributary of Bow River, located on the north side of the river approximately 1.5 km east of downtown Canmore. Drawing 2 shows the watershed and fan boundary. Watershed characteristics are summarized in Table 2-1 below

Table 2-1. Watershed Characteristics of Cougar Creek

Characteristic	Value
Watershed area[1] (km^2)	43.5
Fan area (km^2)	3.1
Maximum elevation (m)	2820
Minimum elevation[2] (m)	1404
Mean elevation (m)	2150
Average gradient mainstem (%)[3]	5.5
Average gradient on fan (%)	4.2

1 As measured to the fan apex.
2 As observed at the fan apex.
3 For a distance of 3 km upstream of the fan apex.

The Cougar Creek watershed is characterized by multiple tributary basins with watershed areas between 0.1 and approximately 5 km^2. The hypsometric curve shown in Figure 2-1 illustrates that approximately 50 % of the watershed lies above 2000 m and that there do not appear any plateaus at high elevation. Between approximately 1700 m and 2400 m elevations, the distribution of area with elevation is roughly linear.

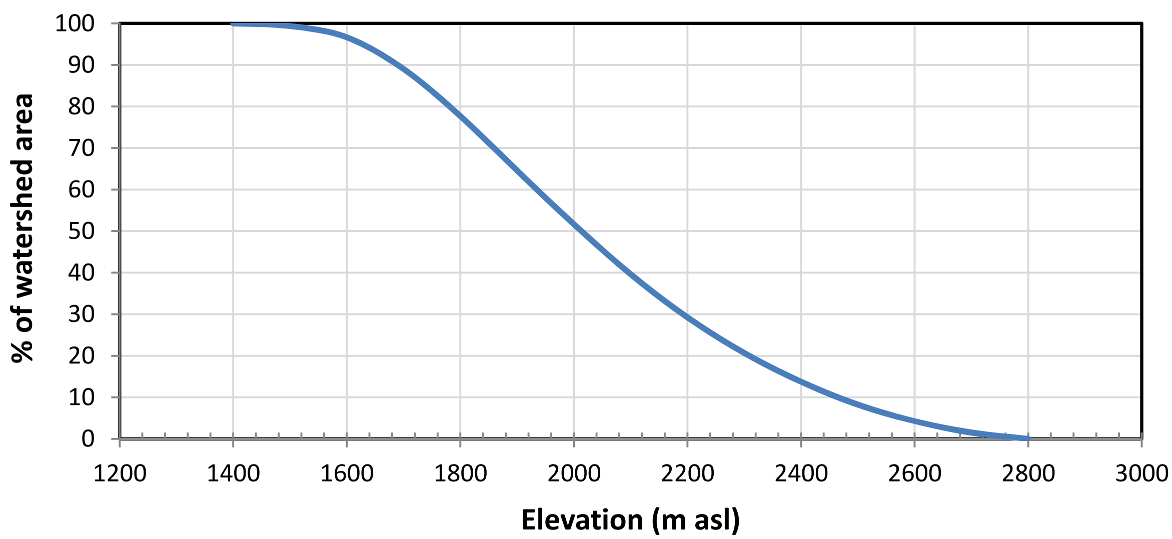

Figure 2-1. Hypsometric Curve for Cougar Creek

The average channel gradient of the mainstem channel is only 5.5% for 3 km upstream of the fan apex. This low gradient indicates that Cougar Creek is not susceptible to debris flows along its main channel. However, all tributaries of Cougar Creek are capable of producing debris flows that feed sediment into the Cougar Creek mainstem channel. The watershed is covered by Engelmann spruce and Douglas firs as well as birches and various shrubs up to an elevation of a maximum of 2400 m. Above that elevation, the alpine region is characterized by krummholz and low shrubs. There are no glaciers in the Cougar Creek watershed. Additional details of the watershed are provided in Section 5.2.

2.2. Fan Description

The fan area is shown in two separate drawings. Drawing 3 is a shaded, bare earth Digital Elevation Model (DEM) of the fan and surrounding terrain, while Drawing 4 is an orthophoto of the area with the DEM contours overlain. The DEM was generated from a LiDAR survey conducted by LiDAR Services International Inc. (LSI) on June 28, 2013. LSI post-processed the LiDAR data and provided BGC with a 1 m x 1 m post spacing XYZ file, which was then used to generate the hillshade DEM and contours shown on Drawings 3 and 4. The fan area delineated on these drawings has been interpreted by BGC based on the LiDAR data.

The alluvial fan of Cougar Creek has an area of 3.1 km^2. Almost the entire fan is developed including the following:

- approximately 1417 residential homes;
- a number of lodges/resorts between Highway 1 and Highway 1A;
- a light industrial area in the southeast corner of the fan;
- one elementary school (Elizabeth Rummel);
- a recreational area that includes an off-leash dog park and three baseball fields;
- a heliport (Alpine Helicopter);
- numerous roads including a crossing of the creek at Elk Run Boulevard;
- Highways 1 and 1A;
- the Canadian Pacific (CP) Rail line;
- various municipal infrastructure (telecommunication lines, sewers, etc.); and
- powerlines.

Drawing 5 shows the various building types located on the fan, while Table 2-2 summarizes the number of buildings on the fan by type.

Table 2-2. Summary of Building Type on Cougar Creek Fan

Building Type	Number
Commercial	96
Industrial	83
Institutional	26
Recreational	1
Residential	1417
Transportation/Utilities	15
Unknown	5
Total	**1643**

Drawing 6 is a profile of Cougar Creek from the upstream extent of the 2013 LiDAR data to the confluence with the Bow River. Average channel gradients are as follows:

- ~ 3.7% for 1 km upstream of the fan apex;
- ~ 3.0% between the fan apex and Elk Run Boulevard (550 m);
- ~ 5.1% between Elk Run Boulevard and Highway 1 (850 m); and
- ~ 4.3% between Highway 1 and Highway 1A (500 m).

Four creek crossings are located on the fan. From upstream to downstream these crossings are as follows:

Table 2-3. Cougar Creek Road Crossings

Crossing	Description
Elk Run Boulevard (Photo 2-1)	• elliptical, multi-plated steel culvert • design drawings by Engineering Associates Canada (1982) show the culvert is approximately 6.45 m high, 9.5 m wide and 29 m long with a gradient of 5% • capacity = 160 m^3/s (CH2M HILL, 1993a) • concrete wingwalls at 45^o are located at both the inlet and outlet, and extend out about 5 m • concrete cutoff wall extends about 1.4 m below the culvert invert. • The culvert was rehabilitated in 2012. Design drawings by Associated Engineering (2012) show the installation of an invert protection plate, repairs to the cutoff wall and placement of a concrete liner at the base of the culvert.
Highway 1 (Photo 2-2)	• three concrete box culverts: 2.44 m wide x 2.75 m high x 64 m long • constructed in 1967 • capacity = 64 m^3/s (CH2M HILL, 1993a) • culverts installed with a concrete apron and wingwalls
Highway 1A (Photo 2-3)	• three concrete box culverts: 2.44 m wide x 2.75 m high x 20 m long • constructed in 1967 • capacity = 64 m^3/s (CH2M HILL, 1993a) • culverts installed with a concrete apron and wingwalls
CP Railway	• three concrete box culverts: 3 m wide x 1.55 m high x 5.8 m long (Hydroconsult, 1999) • 2 x 900 mm CSP culverts[1]

[1] The culverts were installed following the May 1990 flood event, which was the result of the failure of the upstream rockfill dam (see Section 3.3).

Photos 2-1, 2-2 and 2-3 show the culvert inlet at Elk River Boulevard, Highway 1 and Highway 1A, respectively. Additional detail on these engineering works is provided in the following section.

Photo 2-1. Culvert inlet at Elk Run Boulevard. BGC photograph of July 23, 2013.

Photo 2-2. Downstream view of the culvert inlet at Highway 1. BGC photograph of July 23, 2013.

Photo 2-3. Culvert inlet at Highway 1A. The culvert was full of debris at the time of the site visit. BGC photograph of August 8, 2013.

3.0 PREVIOUS STUDIES AND ENGINEERING WORKS

This section provides a chronological summary of previous studies and flood protection works on Cougar Creek. This summary is based on the information and reports provided to and reviewed by BGC. If additional studies or design drawings are available, they should be forwarded to BGC for review. The intent of this section is to provide historical context to previous engineering efforts along the creek corridor and to illustrate that the extent of creek hazards along Cougar Creek was never fully realized.

3.1. 1925 to 1981

The historical background for this period has been reproduced from CH2M HILL Engineering Ltd. (CH2M HILL, 1993a). BGC has not obtained any of the reports or information provided by CH2M HILL in that report. Table 3-1 below is a reproduction of Table 1 in the 1993 CH2M HILL report.

Table 3-1. Historical Background of Cougar Creek Flood Protection Works 1925–1982 (after CH2M HILL, 1993a)

Year	Description
1925	A 40 ft (12.2 m) concrete bridge was constructed at the location of the present day Highway 1A (at the time of construction the highway was known as the Trans-Canada Highway).
1967	A large flood washed out the Highway 1A abutments. Reports of 70,000 yd^3 to 80,000 yd^3 (53,500 m^3 to 61,200 m^3) of sediment pushed through the span. The highway was rebuilt and renamed Highway 1A. The bridge crossing was replaced with 3 concrete box culverts: 2.44 m wide x 2.75 m high x 20 m long. The new Trans-Canada Highway (Highway 1) was constructed upstream of Highway 1A. Cougar Creek flows are conveyed through 3 concrete box culverts: 2.44 m wide x 2.75 m high x 64 m long. Channelization of the creek was completed following the flood. This channelization started in the upper reaches of the fan complex. The design concept was to allow for some bedload deposition before reaching the highways. BGC Note: a 1967 Alberta Government Department of Highways As-Built Profile (as shown in Figure 10, AMEC, 2012) shows a variable channel profile with steep sections on the order of 100 m to 200 m in length separated by gentle sections of similar length. Presumably, the flatter sections were designed to promote sediment deposition.
1969	Alberta Environment reported that the 1969 channel improvements were successful.
1967 - 1980	The only reported maintenance during this period was the placement of riprap downstream of culverts and repairing a gabion drop structure in the same area.

Year	Description
Jan 1980	An Alberta Environment River Engineering report evaluated Cougar Creek and the following conclusions were made: • Historical evidence indicates flash floods occur every 8 to 10 years (1948, 1956, 1967, and 1974). • The fan is not ideally suitable for development due to the catastrophic flood potential of Cougar Creek. • The danger of erosive forces not as serious as high flood levels.
Jan 1981	Alberta Environment River Engineering report made the following conclusions: • The creek has been channelized by excavation in 1957, 1966, and 1967. • The channel had adjusted so that the “stepped” profile constructed in 1967 had reverted to a constant bed slope of approximately 5%. • The channel on the alluvial fan is subject to lateral movement. • The report recommended that the creek be trained through armouring to prevent lateral movement.
1982	Elk Run Boulevard was constructed. A multi-structural, elliptical steel culvert was used for the crossing. Design drawings by EAC (1982) show the culvert is approximately 6.45 m high and 9.5 m wide.

Of note is that BGC tracked down the original newspaper article of the 1967 event noted in the table above. The Calgary Herald reported that an estimated 70,000 to 80,000 cubic feet of sediment was deposited under the bridge, not cubic yards as referenced in the 1993 CH2M HILL report.

3.2. 1981

With the imminent development of the Cougar Creek subdivision in 1980, Alberta Housing Corporation (AHC) and Alberta Environment initiated studies of Cougar Creek to assess the need and extent of creek stabilization works. These studies were led by Engineering Canada Associates (ECA) with Hydrocon Engineering Ltd. as a sub-consultant. Hydrocon (1981a) proposed that an overtoppable, permeable rockfill dam be constructed at a bedrock constriction above the fan apex. The dam was to function as a sediment trap to minimize downstream deposition, as there were concerns that long-term aggradation would ultimately fill the creek and cause overbank flooding on the fan. The design of the dam was based on a benchmark yield of the sediment volume reportedly transported onto the fan during the 1967 flood (~ 61,000 m^3). This volume was then increased to 80,000 m^3 for an additional factor of safety. This volume was considered adequate to trap the expected 100-year return period bedload volume. These calculations were based on an infinite sediment supply and sediment transport rates calculated using the Meyer-Peter-Müller formula. The capacity of the trap was also felt to be adequate to contain at least 5 years of accumulated sediment based on a mean annual bedload transport rate of 19,000 m^3.

The Hydrocon (1981b) design drawing for the dam shows the following:

- a dam crest elevation of 1423.8 m;
- a dam crest width of 4 m;
- a minimum elevation of 1415.0 m (8.8 m high dam);
- 2H:1V sideslopes on the downstream side of the dam;
- 1.5H:1V on the upstream side of the dam;
- a coarse rock drain constructed of Class II riprap (1 m thick, 4 m wide and 46 m long) through the foundation of the dam along the original water course to prevent permanent ponding;
- a storage volume of 80,000 m^3 assuming a deposition angle of ½ the creek bed slope;
- a 1 m thick layer of Class II riprap on the dam crest that extends to the downstream toe;
- a 10 m long riprap apron that consists of Class II riprap for the initial 5 m and Class I riprap thereafter;
- the riprap apron varies in thickness from 1.5 m to 2.0 m (allowing for a 0.5 m deep stilling basin that extends 5 m beyond the downstream toe);
- the core of the dam consists of unclassified rockfill of Class I (less than 15% smaller than 75 mm and an average diameter of 200 mm); and
- the core material was to be covered with a 0.5 m thick layer of Class III filter on its crest and both upstream and downstream slopes.

Drawing 7 shows the location of the rockfill dam. The structure was intended to be pervious enough to prevent permanent ponding in the reservoir and able to withstand overtopping by a 100-year flood event, with 0.67 m of water over the crest (Alberta Environment, 1991). An inspection of the dam by Alberta Environment (1991) in May 1982 noted the following modifications to the design:

- the top width was reduced to 2.0 to 2.5 m;
- an apron of Class II riprap 1 m wide and 2 m deep was constructed along the upstream toe; and
- the downstream toe apron was constructed of Class II riprap with a layer of Class III riprap.

Following construction of the dam in 1982, ownership was transferred to the Town of Canmore and licence to operate was issued to the Town (CHM2 HILL, 1993a). In addition, both sides of the creek between Highway 1 and Elk Run Boulevard were to be shaped and armoured with riprap. As built drawings by ECA (1982) show that the original design was a 25 m wide, v-shaped channel at the base with 2H:1V sideslopes. Class II riprap was to extend up the sideslopes about 2 m and into the channel by 3 m. According to the as-built drawings, it does not appear that the v-shaped portion of the designed channel was constructed. These works were completed in the summer of 1981 as development of the Cougar Creek subdivision commenced.

Downstream of Highway 1, Cougar Creek was regraded and shaped and native material was pushed to the side to form dikes (CHM2 HILL, 1993a). Riprap was placed around the highway culverts.

3.3. 1990 – Dam Break

On May 25, 1990, the Cougar Creek dam breached. Details of the events leading up to the failure and possible causes were summarized by the Dam Safety Branch of Alberta Environment (1991). Observations and conclusions from that report are summarized below.

Cougar Creek flows were high prior to the dam failure. The peak flow in the hour before the failure was estimated at 13 m^3/s. This peak flow was the result of rainfall and coincident snowmelt. Rainfall totals of 22 mm and 30 mm were recorded on May 24 and 25, 1990 at Banff. In addition, snowpillow data indicate that rapid snowmelt was occurring at higher elevations (> 2000 m). Alberta Environment staff witnessed and photographed the failure, and provided the following observations:

- The rock drain through the foundation of the dam did not appear to have been clogged prior to the dam failure.
- The dam contained approximately 35,000 m^3 of water at the time of failure.
- Approximately 1 hour before failure, water was exiting from half way up the downstream slope and across its entire width and cascading down (Photo 3-1). The water seemed to be coming through and around the dam rather than under or over it.
- The reservoir rose 1 m in the hour before the failure and 0.15 m in the hour previous to that.
- As the water level approached the crest, it began to flow through the Class II riprap armouring and cascade down the downstream slope. At no time did water flow over the dam crest (Photo 3-2).
- The failure occurred shortly after the water began flowing through the crest amouring. For about 30 seconds before the failure onset, there was a distinctive sound of rocks grinding against one another.
- The failure began on the downstream edge of the crest, forming a V-shaped breach that grew quickly and reached bedrock underlying the dam. The time of dam failure was approximately 5:20 PM (Photo 3-3).
- The entire failure and reservoir purging took only 3 minutes and resulted in a 3 m high flood wave moving downstream.

Photo 3-1. Upstream view of Cougar Creek Dam 1 hour before the failure. May 25, 1990 (Alberta Environment, 1991).

Photo 3-2. Upstream view of Cougar Creek Dam 10 minutes before the failure. May 25, 1990 (Alberta Environment, 1991).

Photo 3-3. Upstream view of Cougar Creek Dam shortly after the breach initiated. May 25, 1990 (Alberta Environment, 1991).

It is not known how much sediment filled the dam prior to its failure. The town manager for Canmore indicated that there had never been the need to clean out the dam since its construction. Based on gravel terraces observed during the site visit, Alberta Environment (1991) estimated the sediment volume at 15% (or 5,250 m^3) of the water storage capacity of 35,000 m^3. Alberta Environment (1991) attributed failure of the dam to instability of the downstream slope induced by erosion of the Class I unclassified core material (i.e. a piping failure).

The dam failure caused major erosion downstream. The channel bed was scoured to bedrock in the middle of the breach and most of the dam material was mobilized downstream, except for a portion on the left abutment (Photo 3-4). Remnants of the rockfill dam are still present, as shown on Photo 3-5. The culverts under Highway 1, Highway 1A and the CP Rail tracks were either partly or completely filled with sediment, resulting in a partial washout of the CP Rail tracks. Minor damage also occurred to the shoulders of Highway 1 when the backed up flood waters partially overtopped the road. Damage to the rail tracks was repaired within two hours, although the track remained closed until the next morning while the culverts were unplugged. Photos 3-6 through 3-9 illustrate some of the downstream damage caused by the dam failure.

Photo 3-4. Upstream view of Cougar Creek Dam about 2 hours after the dam failure. May 25, 1990 (Alberta Environment, 1991).

Photo 3-5. On right bank looking to left bank of Cougar Creek at the site of the 1982 rockfill dam. The rockfill remnants of that dam are visible on the left bank. BGC photograph of July 23, 2013.

Photo 3-6. Downstream view of Cougar Creek looking toward Elk Run Boulevard. Photo courtesy of Kent Berg, Alberta Environment and Sustainable Resource Development. May 26, 1990.

Photo 3-7. Downstream view of Cougar Creek looking toward Elk Run Boulevard. Photo courtesy of Kent Berg, Alberta Environment and Sustainable Resource Development. May 26, 1990.

Photo 3-7. Aggradation at the CP Railway following the 1990 dam failure. Photo courtesy of Kent Berg, Alberta Environment and Sustainable Resource Development. May 26, 1990.

Photo 3-8. Excavation activities at Highway 1A following the dam failure. Photo courtesy of Kent Berg, Alberta Environment and Sustainable Resource Development. May 26, 1990.

Alberta Environment concluded that the use of overflow structures of this design should be discouraged, and that others methods of sediment collection and storage should be investigated. This occurrence is of relevance to the proposed mitigation strategy discussed in further detail in Section 8.0.

3.4. 1990's

Following the 1990 failure of the rockfill dam and with additional residential development being proposed for the fan, the Town of Canmore and Alberta Environment re-evaluated the channel stabilization requirements along the creek corridor. CH2M HILL was retained for this work and a number of reports were prepared, including the following:

- The "Cougar Creek Flood Protection Study" (CH2M HILL, 1992a) provided a review of previous information, recommended rehabilitation measures, prescribed bank armouring design, estimated a bedload transport volume of 11,000 m^3 for the 100-year return period event, and identified the locations for three sediment traps. Drawings (CH2M HILL, 1992b) were subsequently prepared for Phase 1 of the work.
- Technical Memorandum No.1 (CH2M HILL, 1992c) revised the 100-year bedload transport volume to 6,900 m^3.
- Technical Memorandum No. 2 (CH2M HILL, 1992d) presented the design for a sediment trap consisting of six basins in series.
- The "Cougar Creek Flood Protection Study" was finalized by CH2M HILL in March 1993.
- Contract documents (CH2M HILL, 1993b) and drawings (CH2M HILL, 1993c) were prepared for Phase 2 of the flood protection works.
- Technical Memorandum No. 3 (CH2M HILL, 1993d) reviewed the sediment transport volume and determined that the storage capacity within the channel was sufficient to allow sediment to deposit in the channel; hence it was determined that no traps were necessary.
- A flood risk mapping study (Technical Memorandum No. 2 (CH2M HILL, 1994) was prepared for Alberta Environmental Protection, River Engineering Branch. The purpose of this study was to compute water surface profiles for the 100-year, 50-year and 10-year floods, and to prepare a flood hazard map based on the 100-year flood profile.
- A monitoring report (Technical Memorandum No. 2 (CH2M HILL, 1995)) was issued in October 1995 following a high flow event on Cougar Creek in June.

The above summary has been taken from AMEC (2003), as to date BGC has only received copies of the flood protection study and flood risk mapping study (CH2M HILL, 1993a, 1994). The 1993 report outlines three proposed alternatives for rehabilitation of Cougar Creek. Common measures to all three alternatives include:

- regrading and reshaping the creek channel;
- placing riprap at various locations to prevent bank erosion; and

- constructing training berms to train the flow into the creek channel.

The sediment control measures are different for each option and include:

1. Construct a sediment control dam
2. Construct sediment traps
3. No sediment control.

CH2M HILL (1993a) recommended that Option 2 be adopted. The second option included constructing four sediment traps: one large trap (8,000 m^3) downstream of the old dam site and three smaller basins: one upstream of Elk Run Boulevard, one upstream of Highway 1, and one upstream of Highway 1A. The objective of the sediment traps was to provide sufficient storage capacity for bedload transported by the 100-year flood (11,000 m^3). However, it was noted that Option 3 may be a viable option, considering the available storage capacity of the channel itself.

The 1994 report indicates that the remedial measures designed by CH2M HILL and implemented included the following:

- 425 m of riprap on the right bank upstream of Elk Run Boulevard;
- 425 m of riprap on the left bank upstream of Elk Run Boulevard;
- Repair of riprap between Elk Run Boulevard and Highway 1 that was damaged during the 1990 dam break flood;
- Construction of a berm between Highway 1 and Highway 1A to protect the heliport;
- 150 m of riprap on the right bank downstream of Highway 1 that tied into existing riprap; and
- Placement of 10 m of riprap in the creek bed downstream of Elk Run Boulevard, upstream of Highway 1, and upstream and downstream of Highway 1A.

As BGC has not reviewed the design drawings, the extent or size of riprap placed in the channel and on the banks is not known. However, the 1993 report shows a typical cross-section with 2H:1V sideslopes, a base width of 25 m, and Class II riprap extending 3 m into the channel and up the sideslopes for a height of 2 m. The 1993 report also references the use of Class III riprap on the creek bed upstream and downstream of the culverts.

Presumably a decision was made that there was sufficient storage capacity available in the regraded channel, so there was no need for construction of the proposed sediment traps.

Given that the above channel protection is no longer functioning, a similar design in isolation should not be contemplated moving forward.

3.5. 1999

In 1999, Hydroconsult investigated culvert replacement options for the CP Rail crossing of Cougar Creek. Hydroconsult (1999) estimated the 100-year peak instantaneous flow at 15.9 m^3/s and concluded that the existing box culverts had sufficient hydraulic capacity for this peak flow. However, they also concluded that the crossing did not have sufficient capacity to convey the sediment flow and potential deposition that would likely accompany the event. Hydroconsult noted that the flow area of the culverts was only 40% of the upstream bankfull channel area. Therefore, Hydroconsult recommended that should CP Rail decide to upgrade and/or replace the existing culvert crossing, that it be replaced with a single span bridge 10 m wide. It was also recommended that CP Rail, in cooperation with the Town of Canmore and Alberta Transportation, examine sediment control measures upstream of the Highway 1 crossing. Preliminary consideration of possible alternatives indicated that a sediment trap excavated into the bed of the channel would be a viable measure.

3.6. 2000's

3.6.1. Potential Remedial Measures – 2003

In 2003 the Town of Canmore retained AMEC Earth & Environmental Ltd. (AMEC) to provide technical advice regarding the control of erosion and sedimentation on the Cougar Creek fan. That report provides a review of: available information; an assessment of sediment sources, volumes and probability of occurrence; results of a detailed on-site inspection; and a preliminary assessment of potential remedial measures.

AMEC (2003) made the following conclusions:

- Based on a review of previous report, bedload transport volumes for a 100-year event were estimated to be in the range of 6,900 to 11,000 m^3. Given the uncertainty associated with the bedload estimates, AMEC recommended that a volume of 7,000 m^3 be used for evaluating sedimentation control options.
- Comparative cross-sections were available for 1993 and 1995, and AMEC attempted to compare these sections to ones surveyed in 1982. However, the lack of precise horizontal controls between the two surveys made direct comparison difficult. There was no discernible trend towards increasing or decreasing channel bed levels over this period based on the limited data.
- AMEC (2003) proposed that the preferred alternative for sediment control was a sediment trap located in the upper fan area below the 1982 sediment dam location. A trap with an approximate volume of 2,900 m^3 was recommended – 4 m bottom width, 2 m deep and 180 m long. The storage represented 40% of the 100-year bedload volume estimate of 7,000 m^3. While it was anticipated that the trap would fill during a 100-year event, AMEC (2003) noted that "the volume stored would provide a reasonable reduction to the volume of material deposited downstream".
- An assessment of riprap stability indicated that Class II riprap is not stable on 2H:1V sideslopes or channel bed between Elk Run Boulevard and the Highway 1 for the 0.8 m flow depth (100-year return period) and 4.3% channel gradient reported in the CH2M HILL (1994) flood study.

- Class II riprap is stable at a bank angle of 2H:1V for a flow depth of 1 m and a channel gradient of 1.1%.

Based on the observations and conclusions, AMEC (2003) developed the following list of prioritized recommendations:

As Soon As Possible

1. Highway 1A culverts should be cleared out.
2. Existing armouring upstream of Elk Run Boulevard should be repaired.
3. A sediment trap should be excavated between the upstream end of development and the 1982 dam.
4. Cross-section monitoring sections should be established.
5. A reconnaissance of the watershed should be undertaken to determine if there are areas of significant sediment storage and/or debris available for transport during future extreme runoff events.
6. The Town of Canmore should initiate discussions with CP Rail regarding the capacity of the existing culverts at the rail crossing and replacement options.

Within the Next 3 to 4 Years

7. Thirteen drop structures should be constructed between Elk Run Boulevard and Highway 1. A design incorporating concrete lock blocks (or large riprap) keyed into the banks was developed, using Class II riprap to provide scour control downstream of the 2 m high drop structures. A structure spacing of 50 to 60 m was established to provide gradients of approximately 1.1% between structures.
8. Riprap downstream of Elk Run Boulevard should be placed in conjunction with drop structure installation.
9. The downstream concrete apron and the flood of the culvert barrels should be repaired at Highway 1A.

Within the Next 5 Years

10. Cleaning of deposited sediment within the channel should be conducted on an as-needed basis.
11. Additional armouring should be added on the right and left banks upstream of Highway 1A. This armouring may include drop structures, if the performance of works upstream of Highway 1 indicates that the design concept works well.

3.6.2. Highway 1 to Highway 1A Proposed Works – 2006

Between Highway 1 and Highway 1A, riprap had previously been installed on both banks. Class II riprap was installed on both banks for approximately 25 m downstream of the Highway 1 culvert and for 20 m upstream of the Highway 1A culvert. Partial bank armouring (Class II riprap) was also installed along a 170 m length of the right bank During the spring runoff of May 2003, erosion damage occurred to both banks of Cougar Creek in this reach.

Subsequent to the damage, the Town of Canmore conducted emergency repairs to the eroded channel banks, which consisted of reshaping and compaction of the banks.

The Town of Canmore retained AMEC to provide a design for more permanent channel works, including the installation of erosion protection along sections of unprotected bank. Partial construction of riprap armouring was conducted in June 2005; however, unseasonably high rainfall and the resulting flood on Cougar Creek rendered the incomplete armouring ineffective (AMEC, 2006). Using indirect methods, AMEC (2007) estimated that the 2005 flood had a return period of 30 years. The Town of Canmore further retained AMEC to provide an updated design for the works in 2006.

Tractive force analysis indicated that riprap of 1600 mm diameter was required for a stable bank in the study reach. Because the costs of installing riprap of this size was judged to be cost-prohibitive, AMEC (2006) recommended that the banks be protected with Class II riprap on sideslopes of 2H:1V. However, for this class of riprap to meet design criteria, a maximum channel gradient of 1.1% needs to be attained. Therefore, AMEC (2006) also recommended that six grade control structures, with a nominal 2 m high drop, be constructed along the channel. While the detailed design of these control structures was outside the scope of work, AMEC (2006) noted that "it should be understood that installation of Class 2 riprap armouring without the installation of grade control structures is only an interim erosion protection step in this reach of Cougar Creek".

The 2006 report includes construction drawings for the proposed bank armouring, but not for the grade control structures. Because of concerns that budgetary constraints could limit the length of channel bank protection that could be constructed in 2006, the works were prioritized as follows:

1. Regrade the channel bed;
2. Install riprap along the right (west) bank;
3. Reshape Highway 1A approach channel banks;
4. Install riprap along the left (east) bank; and
5. Install the grade control structures.

Items 1 to 3 were completed in 2006. Item 4 was partially finished. Grade control structures were not yet constructed.

3.6.3. Sediment Transport – 2007

In 2007, AMEC was retained by the Town of Canmore to: determine the origin of sediment being deposited on the Cougar Creek fan; conduct channel survey comparisons; conduct a regional flood frequency analysis; and assess peak and average bedload transport volumes. Conclusions from that study are as follows:

1. The sediment being transported downstream to and deposited at the Highway 1A and CP Rail crossings is originating from two sources: the upper watershed (11 to 27%)

and bed and bank erosion within the upstream, channelized portion of Cougar Creek (73 to 89% of the total).

2. There are limited data for assessing the frequency and severity of flood events on Cougar Creek. Based on regional flood hydrology, the 1995 flood is estimated to have had a return period of approximately 30 years, while the 2005 flood is estimated to have a return period of approximately 10 years.
3. Comparative cross-sections indicated that Cougar Creek was generally enlarging its cross-section through lateral erosion and some degradation in the reach upstream of Highway 1. The channel downstream is generally an area of deposition. The volume of sediment supplied by the upper watershed was estimated at 255 to 650 m^3/yr, while the average annual bedload transported to Highway 1 was estimated to range from 2000 to 2,850 m^3, with the majority being generated by bed and bank erosion above the highway.

3.6.4. Sediment Control Options – 2008

Following the 2007 report, AMEC met with representatives of the Town of Canmore, CP Rail and Alberta Infrastructure and Transportation (AIT) to discuss the results of the 2007 work and plan further investigative work. A 2008 report presented the results of AMEC's investigation of channel stabilization and sediment control options for Cougar Creek. The AMEC (2008) report investigated five options:

- Option A – 5 riprap grade control structures between Highways 1 and 1A;
- Option B – 3 riprap grade control structures between Highways 1 and 1A;
- Option C – 11 concrete block grade control structures between Highways 1 and 1A;
- Option D – riprap channel armouring between Elk Run Boulevard and Highway 1;
- Option E – concrete mat channel armouring between Elk Run Boulevard and Highway 1; and
- Option F – do nothing.

All options included completion of the left (east) bank armouring between Highway 1 and 1A (255 m), as well as construction of a sediment trap north of Elk Run Boulevard. For conceptual design, a trap volume of twice the greater estimated bedload transport volume (225 to 650 m^3/year), or 1,300 m^3, was used.

Based on preliminary engineering and general economic analyses, Option D was selected as the preferred single option. It was further noted that ultimately a combination of upstream (Option D or E) and downstream (Options A, B and C) would provide the most comprehensive and robust solution to sediment management issues on Cougar Creek.

3.6.5. 2012 Flood

From June 5 to 9, 2012, a large storm system moved into the Canmore area resulting in high rainfall. The total rainfall over the five day period ranged from 101 mm at the Bow Valley

Provincial Park climate station to 124 mm at the South Ghost Headwaters stations, which were the only two stations with complete records over that period (AMEC, 2013). Flows in Cougar Creek began to increase on June 5 and peaked around 03:00 on June 6. During the flood event, the creek shifted laterally at several locations and the following damage was documented by AMEC (2012):

- Erosion of the banks was most severe upstream of the pedestrian bridge crossing, where three sections of the pathway collapsed. The armour that had previously been placed along the creek failed due to undercutting, outflanking (bank erosion upstream of the bank erosion), or from being under-sized relative to hydraulic conditions.
- The left bank downstream of the pedestrian bridge was similarly undermined.
- Existing riprap was also damaged at three locations upstream of Elk Run Boulevard. Temporary post-flood repairs included filling these sections with larger rock salvaged from the channel.
- Degradation of the channel bed was observed downstream of Highway 1 and the concrete sheet piling on the downstream of the culvert structure was exposed. Lateral erosion on the left (east) bank was temporarily repaired using salvaged material following the flood.

Following the flood, the Town of Canmore had eight cross-sections surveyed by Alpine Land Surveys Ltd (Alpine). These cross-sections were positioned at the same location as 2006 surveys for a previous study by AMEC (2007). The cross-section comparison indicated a net increase in channel area both upstream of Highway 1 and between Highway 1 and 1A, totaling approximately 20,000 m^3 and 2,500 m^3, respectively. AMEC (2012) estimated that greater than 35% of the sediment loss in this reach between 2006 and 2013 was a result of the 2012 flood, with the remainder occurring in the 2007 to 2011 period or was carried further downstream. AMEC (2013) concluded that these volumes supported previous conclusions that the majority of sediment transported toward the Highway 1A and CP Rail crossings originates locally between Highway 1 and Elk Run Boulevard.

The AMEC (2012) report provides design drawings for recommended channel works to repair damages incurred during the 2012 flood. The drawings focus on bank restoration and improvement in two areas: surrounding the pedestrian bridge and upstream of Elk Run Boulevard. As before, Class II riprap was recommended to be placed on 2H:1V sideslopes with a top of riprap elevation of 2 m above the channel bed. A 3 m launching apron with a thickness of 1 m provided for a depth of scour of approximately 1 m below the design channel bed level. Again AMEC (2013) noted that the future consideration of grade control structures (presented as Option D in AMEC, 2008) was required for the stability of the Class II riprap under the design flood conditions.

AMEC (2012) estimated the total cost of the recommended repairs at approximately $1.3 million. The proposed repairs were constructed in 2012/2013.

3.7. Summary

This section illustrates that considerable engineering effort has been expended on the Cougar Creek fan in the past 40 to 50 years. Despite these efforts, the engineering works to date have largely been ineffective against high magnitude floods, including the 2012 bank protection, which was destroyed by the 2013 flood (see next section). This can be attributed largely to the insufficient characterization and quantification of the debris flood hazard which requires a detailed understanding of geomorphic processes in the watershed, especially the interaction of hillslope and fluvial processes. These statements are by no means intended to belittle previous efforts, as increased awareness regarding the potential magnitude and frequency of debris floods only dates back about 10 to 15 years. Furthermore, most of that increased knowledge has emerged and been applied in British Columbia, rather than Alberta. For example, Jakob and Jordan (2001) in a paper in the Canadian Journal of Civil Engineering estimated that peak flows associated with debris floods can be 2 to 5 times greater than the 200-year peak flow estimate for clear water floods. Moreover, there is no legislative framework, nor detailed guidelines in Alberta that mandate geomorphological-based geohazard assessments that go well beyond traditional hydrological analyses for mountain creeks.

Moving forward, it is thus important that future short-term and long-term mitigation options at Cougar Creek reconcile this increased knowledge-base and understanding of debris floods and their triggering mechanisms, and that detailed hazard assessments focus on the geomorphic and hydraulic elements of such events.

4.0 EVENT CHRONOLOGY AND INCURRED DAMAGES

This section details the succession of events of the storm that occurred between June 19 and 21 in Canmore and the damage incurred. This information is important as it helps the reconstruction of the event in terms of the physical consequences of the event as well as their timing. Much of the description of the event below is derived from a chronology of events published in the Rocky Mountain Outlook on June 27, 2013 and accounts provided by Andy Esarte, P.Eng., engineering manager for the Town of Canmore and Ben Gadd, a resident of the Cougar Creek fan.

This section should be read in association with Appendix A, which contains a number of photos taken during and after the 2013 debris flood.

4.1. Event Sequence

Wednesday June 19, 2013

Rain began in the morning hours and continued all day.

4:00 P.M. The first flows from Cougar Creek observed at Highway 1A.

7:00 P.M. Town of Canmore began to evaluate creek levels.

9:00 P.M. Canmore Fire Rescue called out to monitor water levels. Some bank erosion in unprotected areas was occurring.

10:30 P.M. Residents observe that the riprap placed in 2012 was holding up, but unprotected sections begin to fail. Rain continues all night, with the roaring sound of the creek clearly audible several blocks away from the creek.

11:00 P.M. A strong flood surge at Highway 1a carried woody debris, blocking the culvert and causing flows to overtop the road. The surge overtopped the CP Rail tracks and washed them out. Shortly after the flow slowed giving the impression that the storm was subsiding. This was not the case. Water began flowing along Bow Valley Trail from the west (area around Alpine Helicopters and the Ford dealership) indicating that Highway 1 had been overtopped. With no equipment in position at Highway 1 and access cut off, flow within the culvert would not be restored until the following week.

Thursday June 20, 2013

1:00 A.M. Peak flows had scoured a substantial portion of the bank armour both upstream and downstream of Elk Run Boulevard. Lateral bank erosion was rapidly occurring. At this point channel aggradation had not yet started in a meaningful way.

1:54 A.M. The RCMP advise that both the eastbound and westbound lanes of Highway 1 be closed, as well as Highway 1A from the Cougar Creek crossing east to Exshaw.

2 A.M. A large section of the Elk Run culvert inlet armouring sloughed into the channel and was washed away. This was the initiation of outflanking of the wingwalls that would continue for the next 12 hours. RCMP begins knocking on doors on the Cougar Creek fan to warn residents to be prepared to evacuate.

3 A.M. Town of Canmore initiates its Emergency Operations Centre.

3:45 A.M. Local state of emergency declared in Canmore, Lac Des Arcs and Exshaw.

4 A.M. Fan residents south of the pedestrian bridge over Cougar Creek evacuated.

At some point between 03:00 and dawn, aggradation started while lateral erosion of the banks continued. The channel widened significantly both upstream and downstream of Elk Run Boulevard. Construction crews worked to slow outflanking of the wingwalls and erosion of the roadway at Elk Run by depositing granular material to start, and later large riprap. Their efforts prevented avulsion onto Elk Run Boulevard and / or Benchlands Trail. At the closest point the creek was within approximately 0.5 m of overtopping the roadway at Elk Run Boulevard. Reports of exposed foundations of homes started before day break. Bank erosion and aggradation in the channel continued for probably the next day until the Town could re-establish a channel with equipment.

6 A.M. Mandatory evacuation orders begin for homes along Cougar Creek, voluntary evacuation order for other areas.

6:30 A.M. The power has been interrupted to many residents on the fan and rain is continuing. Cougar Creek is now flowing bankfull. Both sides of the creek have eroded more than 10 m outside the previous channel edge. Trees are toppling into the creek as their banks are undercut. The culvert at Elk Run Boulevard is now two-thirds full.

7 A.M. First load of fill arrives at Elk Run Bolulevard to counteract erosion behind the culvert wingwalls.

8:45 A.M. The Trans-Canada Highway closed east and west of Banff, closing Canmore off from other communities.

10 A.M. The entire east side of Cougar Creek on an evacuation order and Elk Run Boulevard closed to traffic.

1:30 PM A section of Benchlands Drive near the culvert had washed out and the home at 16 Canyon Road has water flowing directly against it. The Winter residence upslope of Canyon Road has now been eroded to an extent that the majority of the concrete deck has failed into the creek. Water is pooling at the lowest section of Grizzly Crescent. At this time, the east-bound lanes of Highway 1 are washed out and streamflow had turned southeastward running between the Cougar Creek subdivision and the west-bound lanes of Highway 1.

3 P.M. By mid-afternoon the weather was improving somewhat. At this time, the creek discharge had dropped somewhat exposing the sediment and debris that had aggraded during the event. Rain continued all night.

5:20 P.M. A boil water advisory issued for east Cougar Creek.

8:30 P.M. Last bus out of the evacuated east Cougar Creek

Friday June 21, 2013

The creek has eroded most backyards along the eastern portions of Grizzly Crescent. At Grotto Road and Lady MacDonald Crescent the creek bank had eroded right to the foundations of homes along the creek corridor and exposed the concrete basements. The foundations of some decks that were projecting onto backyards have been eroded and have failed or had been severely damaged. Some slab foundations have been undermined by water erosion and are now threatening to break which had caused sagging of the entire home (for example at 446 Grotto Road). By late afternoon on Friday, Environment Canada lifted the heavy rainfall warning for Banff.

Saturday June 22, 2013

Rain had stopped overnight. Excavators worked on creating a new channel of Cougar Creek. In the afternoon there was a minor thunderstorm with little rain.

Train travel resumed along CP Rail tracks on Monday June 24, while the Trans-Canada Highway re-opened to traffic on Wednesday June 26 at 3 P.M.

4.2. Damages

The damages incurred along the creek corridor during the 2013 debris flood were severe. Drawing 8 shows lot lines superimposed on the 2013 orthophoto, while Drawing 9 is a comparison of the 2008 and 2013 Cougar Creek channel on the fan. In addition, channel changes at two cross-section locations are shown on Drawing 10: RS-2 is located about 250 m upstream of Elk Run Boulevard, while RS-5 is located about 400 m upstream of Highway 1. This last drawing compares cross-sections from: a 2012 survey by Alpine[2], the LiDAR survey of June 28, 2013; and a post-flood survey of August 12, 2013 that was conducted following re-establishment of the creek channel. This last survey was conducted by McElhanney Surveys and extends from Highway 1A to about 500 m upstream of Elk Run Boulevard.

All three drawings demonstrate that significant bank erosion and aggradation occurred during the debris flood to the point where the creek was undermining the foundations of several houses. BGC has not yet calculated the sediment volume associated with the 2013 debris flood. However, the Town of Canmore is in the process of obtaining LiDAR of the fan area, which was flown by McElhanney several years ago. Comparison of the two LiDAR surveys will provide an accurate estimate of bedload transported onto the fan, while recognizing that some sediment would have been transported beyond the fan perimeter into the Bow River during the event.

[2] Alpine surveyed eight creek cross-sections on the fan in 2012. Three above Elk Run Boulevard, four between Elk Run Boulevard and Highway 1, and two between Highway 1 and 1A. Additional details and survey locations are provided in AMEC (2012).

4.2.1. Above Elk Run Boulevard

Above Elk Run Boulevard, aggradation and channel widening resulted in the creek eroding a section of Benchlands Trail and the backyards of a number of homes along Canyon Road and Eagle Landing. Cougar Creek eroded up to the foundation of the Winter residence above Canyon Road and a concrete deck at the front of the house almost collapsed completely. An outdoor hockey rink on the left bank of the creek at Elk Run Boulevard was completely destroyed. A major concern during the flood was Elk Run Boulevard becoming outflanked, resulting in the creek overtopping the road and potentially heading into the subdivision. Emergency crews were present throughout the storm at the road crossing to keep the culvert inlet as free of debris and sediment as possible and to minimize the amount of outflanking that did occur (major erosion occurred behind both concrete wingwalls). Existing riprap on either bank was completely destroyed during the flood, presumably due to initial undermining followed by channel aggradation.

Photos A-1 to A-7 show Cougar Creek during the flood event, while Photos A-8 to A-12 show some of the damage that occurred.

4.2.2. Elk Run Boulevard to Highway 1

Between Elk Run Boulevard and Highway 1, the creek also significantly widened. Damages to homes were severe in this reach. Walking paths on either side of the creek were completely eroded and the pedestrian bridge was outflanked on either bank, although it was not washed away. The pedestrian bridge did sustain structural damage to its left (east) abutment. Riprap placed on the banks and in the channel during 2012 was completely destroyed, initial undermining followed by channel aggradation.

Photos A-13 to A-18 show this reach of Cougar Creek during the flood event, while Photos A-19 to A-28 show some of the damage that occurred.

4.2.3. Highway 1 to CP Railway

Some of the worst damage occurred at Highway 1, as the box culverts underneath the highway became blocked with sediment and debris, forcing flows over the highway. These overflows went in several directions:

- A portion of the overflows turned to the southeast, running between the Cougar Creek subdivision and the west-bound lanes of Highway 1. These flows deposited sediment in the ditch, as well as on to Highway 1A.
- Some of the overflows travelled down the median of Highway 1, eroding the median fill and leading to partial road surface collapse as the driving lanes were severely undercut.
- Some of the overflows avulsed toward Alpine Helicopters, resulting in major damage to this facility and to a Ford dealership located to the immediate west.

As with upstream reaches, riprap placed on the banks and in the channel in 2006 was completely destroyed. A berm located on the right bank, and originally constructed to prevent avulsions to the heliport, was also almost completely eroded. Major aggradation occurred in this reach. The culverts at Highway 1A and the CP Railway also became blocked during the event resulting in flows over the highway and railway. The railway had to be shut down for a period of three days while the track was repaired.

Photos A-29 to A-34 document the damage in this reach.

4.2.4. Damage Costs

At the time of this report, damage costs had yet to be finalized for all stakeholders on the fan. A preliminary estimate by the Town of Canmore is that the debris flood resulted in $8 to $10 million in damage to municipal infrastructure alone (A. Esarte, pers. comm.). Total costs for emergency work, traffic control, culvert clean out and repair of the Cougar Creek crossing of Highway 1 are in the order of $2 million (Roger Skirrow, Alberta Transportation, pers. comm.). The highway was closed from June 20 to 26. Other damages not yet tallied include building and property damages sustained by residents and businesses (e.g. Alpine Helicopters), and the recovery efforts at the railway (CP Rail).

Indirect damages would also have been sustained due to the severing of major transportation corridors and the associated disruption of business.

4.3. Channel Reconstruction

Following the debris flood, the Town of Canmore hired a local contractor (Bremner Engineering) to reconstruct the Cougar Creek channel. Bremner re-established the channel to its pre-flood condition to the extent possible. The channel reconstruction was conducted between the fan apex and Highway 1A, and this work occurred from about late June to late July. When larger riprap was encountered by the excavators, this material was segregated and used to line some of the channel banks and the culvert inlet at Elk Run Boulevard. Photos A-35 to A-40 illustrate the reconstruction efforts.

5.0 BGC SITE OBSERVATIONS

5.1. Introduction

BGC visited Cougar Creek on July 23 and 24, 2013 approximately one month after the debris flood event. A helicopter overflight of the watershed was conducted on July 23, while sections of the fan were traversed on July 24. Between August 6 and 9, 2013, BGC conducted test trenching on the fan and helicoptered up the main channel of Cougar Creek and descended by foot.

BGC personnel present during the July site visits included Dr. Matthias Jakob, Ph.D., P.Geo., and Hamish Weatherly, M.Sc., P.Geo. Soe Moe Kyaw Win, Ph.D., P.Eng., P.Geol., of BGC and Andy Esarte, P.Eng., and Blair Birch, P.Eng., engineers with the Town of Canmore, were also present on the July 23 helicopter flight. During the August 6 to 9 visit, Matthias Jakob and Stephanie Bale of BGC and Brent MacDonald, a local geologist hired as a sub-consultant to BGC, worked on the trenching and completed the traverse of the Cougar Creek mainstem channel.

5.2. Site Observations – Watershed

5.2.1. Overview

During the site visit, BGC personnel flew the watershed by helicopter and also traversed Cougar Creek by foot from Highway 1A to approximately 1 km upstream of the fan apex and from approximately 7 km upstream of the fan apex back to Elk View Boulevard.

The helicopter flight over the Cougar Creek watershed and the subsequent channel traverse of the upper mainstem channel provided the following observations:

- The 2013 event led to widespread debris flow activity in Cougar Creek tributaries, all of which contributed sediment to the mainstem channel ranging from hundreds to thousands of cubic meters for individual events.
- Numerous side slopes were undercut and provided additional sediment to the main channel.
- Both of the above points provide a quasi-unlimited sediment supply to the channel system of Cougar Creek, which implies that an exceedance of a critical hydro-climatic threshold will always result in debris floods. Cougar Creek channel is thus not dependent on long-term sediment recharge for repeated debris floods to occur.
- This very intensive sediment input led to a debris flood that moved large quantities of bedload through rolling and saltation onto the fan reaches. However, only a small proportion of all the materials mobilized upstream of the fan apex arrived on the fan reaches of Cougar Creek.

- The main channel of Cougar Creek apparently underwent cycles of aggradation and degradation during the 2013 flood, but before and after photographs demonstrate net aggradation in some places on the order of 1 to 2 m.
- During the main channel traverse, BGC observed deposits of at least 13 landslides that had previously crossed the creek and likely impounded water, leading to later outbreak floods. Some of these landslides are tributary debris flows, while others are rock slides from adjacent cliffs. Combinations, where debris flows were triggered by rock slides, are also a possibility, but have not been investigated in detail to date.

5.2.2. Detailed Observations

The Quaternary geology of the watershed has not yet been described to BGC's knowledge and is only given a cursory examination herein. Along the main channel of Cougar Creek, Quaternary deposits are rare which is likely due to repeated erosion by landslide processes, floods and debris floods that, over time, will have removed much of these deposits. However, some pockets have survived as shown in Photo 5-1. This photograph shows upstream dipping, massive glaciofluvial sediments between two units of colluvium. The section is interpreted as follows:

At the end of the last Ice Age the Bow Glacier likely occupied the Bow River Valley when tributary watersheds had lost their valley glaciers and glaciation was perhaps confined to the upper watershed. This arrangement likely led to damming of tributaries. Evidence of this damming process was observed by BGC along the mainstem channel where up to 0.5 m thick dense lacustrine sediments were encountered (Photo 5-2). These deposits are unlikely to be remnants of downstream landslide damming given that the sediments underlie large debris flow fans and other massive colluvial deposits and are very stiff without any interbedded organic materials such as conifer needles (Photo 5-3). Moreover, the lacustrine deposits show distinct varves (annual bedding layers) which suggests that they persisted for more than a century. Varve formation is very unlikely for landslide dams, as 90% fail within one year (Costa and Schuster, 1988).

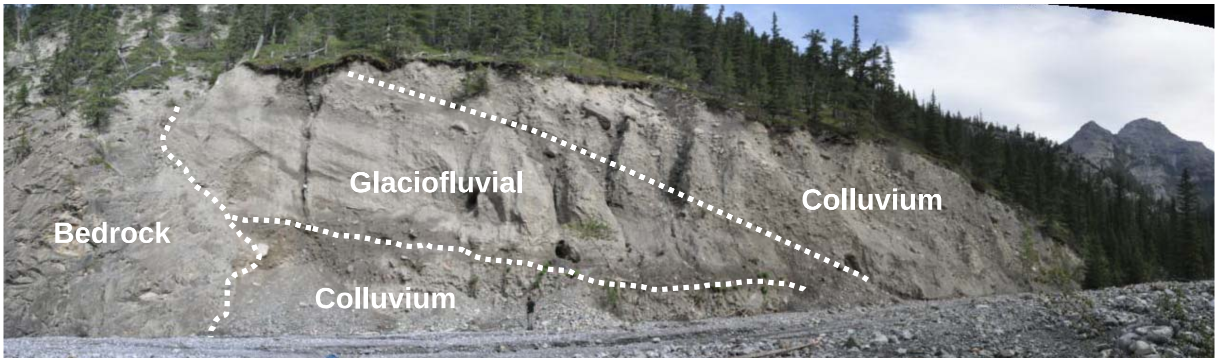

Photo 5-1. A section of the right (west) bank of Cougar Creek approximately 2.3 km upstream of the fan apex. The exposed section is approximately 20 m high.

Photo 5-2. Glaciolacustrine deposits underlying a large debris flow fan deposit approximately 2.8 km upstream of the fan apex. The deposit is locally interrupted by a former creek channel. Photo 5-3 shows a detail of this exposure. BGC photograph of August 29, 2013.

Photo 5-3. Detail of varved (layered) glaciolacustrine deposits at the same location as Photo 5-2. Each layer may present one year of cyclical deposition of fine sediments (later summer and fall) and coarser sediments (spring and early summer). BGC photograph of August 29, 2013.

The glaciolacustrine deposits flanking the lower channel of Cougar Creek consist of clayey silt and have locally formed a perched water table with numerous springs discharging into the channel from the east side of the valley.

The Cougar Creek watershed is no longer occupied by any glaciers. However, one rock glacier has been identified in a west sub-watershed (Photo 5-4) indicating the presence of alpine permafrost at elevations in excess of approximately 2200 m, at least on north-facing slopes. This rock glacier may have originated from a rock slide onto remnant glacial ice which slowly transformed it into a rock glacier. At the present time, the rock glacier is still actively creeping and shedding material from its front into the Cougar Creek channel. During the June 2013 storm, a portion of the rock glacier's active layer (seasonally unfrozen layer) detached and evolved into a small (< 100 m^3) debris flow that discharged into a tributary of Cougar Creek (Photo 5-5).

Photo 5-4. The front of an active rock glacier in the upper Cougar Creek watershed, approximately 7.2 km upstream of the fan apex. Photo 5-5 shows a detail of the active layer detachment on the left flank of the rock glacier. BGC photograph of July 24, 2013.

Photo 5-5. A recent (presumed to occur in June 2013) failure in the active layer of the rock glacier shown in Photo 5-4. The grey line is interpreted as the transition between the active layer and the permafrost body below. BGC photograph of July 24, 2013.

Also of note are debris flows from tributaries that have left high terraces and which are likely to have evolved into debris floods as they diluted during their downstream descent. A good example is "Fork Creek" (informal name by BGC) (Photo 5-6). Here multiple terraces signal previous debris flow activity of a magnitude likely exceeding the event of June 19-21, 2013. The exact magnitude of these events cannot be determined accurately because the amount of channel fill at the time of the event cannot be reconstituted with any degree of certainty.

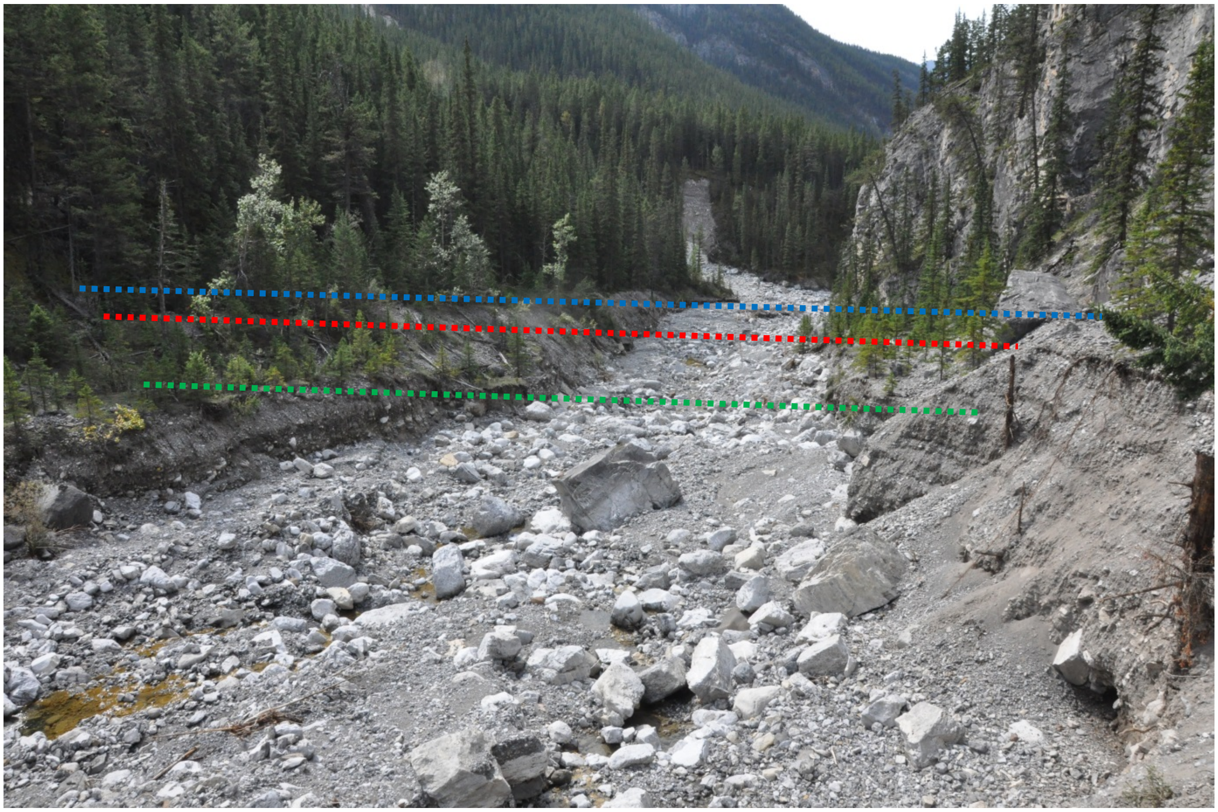

Photo 5-6. Downstream view of the "Forks Creek" tributary to Cougar Creek, located about 3.5 km upstream of the fan apex. The three lines indicate previous debris-flow surfaces of unknown age. The tree on the far right side of the image has been inundated by multiple events over time.

Apart from debris flows, numerous other mass movements were observed by BGC in the Cougar Creek watershed, such as rock slides, gully erosion and raveling, rock avalanches and rock fall. Photo 5-7 provides an example of a landslide (translational bedrock slide along the dominant bedrock dip) in a tributary of Cougar Creek. Given the confinement of the main channel, such landslides have likely dammed the creek on multiple occasions; creating temporary impoundments which failed at some point in time (see Photos 5-8 and 5-9). The presumed high rates of weathering and debris production have created a supply-unlimited condition in the main channel, where the exceedance of a critical hydro-climatic threshold will invariably lead to sediment movement and debris flooding on the fan.

Photo 5-7. A large rock slide in a tributary of Cougar Creek. This event may have temporarily dammed this tributary. BGC photograph of July 24, 2013.

The detailed hazard assessment, which will follow this initial report, will map all landslides in the Cougar Creek watershed.

Photo 5-8. Large landslide deposit overlying fluvial sediments approximately 1.1 km upstream of the fan apex. Photo 5-9 shows the detail delineated here as a red box The height of the landslide deposit above the current channel bed is approximately 25 m. BGC photograph of August 29, 2013.

Photo 5-9. Fluvial sediments underlying coarse, angular landslide debris at the location of Photo 5-8. BGC photograph of August 29, 2013.

Ample source areas remain to produce renewed landslide activity of any of the above-listed processes. This is an important aspect as it forms an additional failure mode to normal bedload mobilization through exceedance of a critical discharge.

A particular concern for the existing and any future development on Cougar Creek fan is the potential for future landslide dams from either tributary debris flows or rock slides and rock avalanches. Ample opportunity for such landslides prevails in the watershed. Photo 5-10 shows a potentially unstable rock face in the lower watershed that is unconfined on three sides. The volume of this rock mass has not been estimated to date.

Photo 5-10. Large, potentially unstable rock mass in the lower (western) Cougar Creek watershed in steeply dipping limestones. BGC photograph of August 7, 2013.

The mainstem channel of Cougar Creek and its tributaries were charged with very high sediment loads and it is possible that the channel has aggraded by 1 m or more in some areas following the 2013 event. Evidence for such aggradation is anecdotal. Rock climbers have noted that in some cases climbing bolts that were at chest height or higher are now at shin height (pers. comm. Patrick LaMontagne). Mr. LaMontagne also provided BGC with a number of repeat photographs along the mainstem channel. An example is provided in Photo 5-11.

Photo 5-11. An upstream view of Cougar Creek: before (upper image) and after (lower image) the 2013 debris flood. The lower image clearly shows that the smaller conifers on the left side of the image have been completely eroded by the 2013 debris flood, suggesting on the order of 1 to 2 m of aggradation. Image provide by Patrick LaMontagne.

5.3. Site Observations – Fan Reaches

For the fan reaches, the helicopter flight and channel traverse allow the following observations:

- The fan of Cougar Creek is very extensive, which suggests a large history of Holocene debris floods and floods as normal streamflows are not capable of creating such a large landform.
- While a significant (probably tens of thousands of cubic metres) volume of sediment was likely transported to the fan of Cougar Creek during the 2013 event, a large volume of additional material was recruited from bank erosion on both sides of the creek.
- Major damage on the lower Cougar Creek fan ensued due to the box culverts underneath Highway 1 being undersized. These culverts are likely correctly sized for a 200-year return period clear water flood without sediment aggradation, but inadequate for the high sediment loads that resulted from the June 2013 event.

The 2013 debris flood exposed cut banks (2 to 4 m high) along Cougar Creek for most of its length. These cut banks show pronounced layering of sediments with variable characteristics, and indicate that numerous debris flood and flood events have previously occurred. An example is shown in Photo 5-12 below. This cut bank shows what appears to be two separate massive and matrix-supported (i.e. individual clasts are rarely in contact) deposits overlying a fluvial deposit that shows sorting, imbrication and is clast-supported (i.e. a majority of the clasts are in contact). The massive nature of the matrix-supported deposits is consistent with the hypothesis of landslide dam outbreak floods, while the underlying fluvial deposit is more suggestive of a flow similar to the June 2013 event.

Photo 5-12. Exposed cut bank along the left bank of Cougar Creek between the pedestrian bridge and Elk Run Boulevard. The dashed red lines separate two massive and matrix-supported debris flood deposits overlying a fluvial deposit. The top dark layer is likely construction fill. BGC photograph of July 23, 2013.

6.0 HYDROCLIMATIC CONDITIONS OF THE JUNE 19-21, 2013 STORM

6.1. Introduction

This section provides a preliminary analysis of regional climate and streamflow data to characterize the June 19-23, 2013 rainstorm in the Canmore area. This section will be expanded upon in a stand-alone report by BGC titled “Hydroclimatic Analysis of the June 2013 Storm”, which is expected to be finalized by December 2013. The objective of this preliminary analysis is to determine the severity of the June 19-23, 2013 storm.

6.2. Rainfall

Rainfall was recorded in the region between June 17 and 23, 2013; however, the storm was concentrated between June 19 and 21, 2013. Rainfall records have been analyzed to date from the various data sources listed in Table 6-1. This list is incomplete, as BGC has not yet had the opportunity to investigate provincial climate stations. The locations of these regional climate stations are delineated on Drawing 11.

Table 6-1. Regional Rainfall Data Sources

Data Source	Station Name	Location (Lat / Long)	Elevation (m asl)	Measurement Frequency
University of Saskatchewan, Marmot Creek Research Basin	Fisera Ridge	50° 57' 24.6" N / 115° 12' 15.8" W	2325	15 min
	Upper Clearing	50° 57' 23.5" N / 115° 10' 31.4" W	1437	15 min
	Hay Meadow	50° 56' 38.8" N / 115° 8' 20.04" W	1845	15 min
Gadd Residence, Cougar Creek Fan	n/a	private	1355 approx.	Hourly*
Meteorological Service of Canada	Kananaskis	51°01'39.080" N / 115°02'05.060" W	1391	Daily
	Banff CS	51°11'36.090" N / 115°33'08.050" W	1396	Daily
	Bow Valley	51°05'00" N / 115°04'00" W	1298	Daily

* Only the totals were recorded as well as the peak one hour precipitation amount

The maximum hourly rainfall intensity and maximum daily rainfall total occurred on June 20, 2013 at all stations except at Kananaskis and on the fan of Cougar Creek (Mr. Gadd's station), which recorded the maximum daily rainfall on June 19. Table 6-2 gives the 1-day maximum and 3-day rainfall totals measured at the regional stations, as well as the maximum hourly rainfall intensity where currently available.

Table 6-2. Maximum Rainfall June 19 to 21, 2013

Station Name	1-Day Rainfall (mm)	3-Day Rainfall (mm)	Maximum 1-hr Rainfall Intensity (mm/hr)
Kananaskis	157	265	n/a
Bow Valley	111	219	n/a
Mr. Gadd	91	147	17.4
Banff	60*	90	n/a
Fisera Ridge	111	224	11.8
Hay Meadow	122	246	13.0
Upper Clearing	126)	225	13.3

* Missing total rainfall data, thus total precipitation is reported.

Comparison of the maximum hourly rainfall intensities recorded at the Marmot Creek stations with a published Intensity-Duration-Frequency (IDF) curve for Kananaskis indicates that the storm had approximately a 2- to 5-year return period frequency for short duration rainfall. This result indicates that the storm intensity was not rare for short durations. In contrast, the recorded long duration rainfall was rare.

Rainfall frequency analyses were conducted for the Kananaskis climate station using the Annual Maximum Series (AMS) approach and the Generalized Extreme Value (GEV) distribution. The Extremes package in the online statistical software *R* was used for the analysis. One-day and three-day maximum rainfalls were analyzed, with the 2013 event included in the input dataset. Results are presented in Table 6-3 and show that with increasing storm duration the return period increases.

Table 6-3. Frequency Analysis Results for Rainfall During the June 2013 Storm at the Kananaskis Climate Station

Duration	Rainfall (mm)	Return Period (years)
1 day	157	235
2 days	224	360
3 days	265	750

Alberta Environment and Sustainable Resource Development (AESRD) regularly generate precipitation maps following notable storm events. The precipitation map for the June 2013 event spans a 72-hour duration and was prepared using 477 weather stations across Alberta. By overlaying the Cougar Creek watershed area over the precipitation map, rainfall totals during this time amounted to approximately 220 mm between 06:00 June 19, 2013 to 06:00 June 22, 2013. This total is consistent with that recorded at the Kananaskis and Bow Valley stations. Rainfall volume for the entire Cougar Creek watershed was then estimated to be 9.1 Mm^3 during this time. Of interest is that the storm was much less severe in Banff, which is only located about 20 km to the northwest of Canmore.

6.3. Streamflow

The Water Survey of Canada operates two real-time hydrometric stations in the vicinity of Canmore: *Bow River at Banff* (05BB001) and *Waiparous Creek* (05BG006). Stations locations are shown on Drawing 11. The peak flows recorded at these two stations during the June 2013 are the largest on record. Estimated peak flows of 439 m^3/s and 306 m^3/s were recorded at *Bow River at Banff* and at *Waiparous Creek*, respectively. The Waiparous Creek discharge is expected to be less than the actual peak instantaneous discharge during the flood as the gauge was destroyed by high water: 306 m^3/s was the last value reported by AESRD before the gauge went offline. This reading may also be inaccurate due to potential damage to the gauge having already been sustained. The WSC did measure a high water mark from the 2013 event and it is expected that a revised peak flow estimate will be published sometime in 2014.

To determine the return period of flooding measured at these two stations, frequency analyses were prepared using the AMS approach. The real-time peak discharge estimates for the June 2013 event were obtained from AESRD, and are considered preliminary at the time of writing. It is expected that the estimates will be refined in the future, at which point the frequency analysis should be repeated. In the case where the maximum peak instantaneous flow was missing for a given year, regression equations were developed to estimate peak instantaneous annual discharge from maximum annual discharge.

The frequency analysis was conducted with the 2013 peak flow included in the input dataset. This procedure comes from a long-time discussion in the hydrological field regarding the inclusion of the highest event (which the 2013 flood was at both stations) in frequency analyses. An argument for the exclusion of the highest event is that one doesn't have any basis to estimate the true return period of the largest one or two events recorded in the arbitrary time window of observations. Conversely, for engineering design, inclusion of the largest events typically results in more conservative input design parameters.

Results of the frequency analysis are provided below. Two results are presented for the *Bow River at Banff* station. The first return period estimate of 175 years is based on the streamflow record of 1909-2013. The second estimate of 15-20 years is based on three known extreme floods that affected the Bow River before discharge was recorded at the present-day location of the *Bow River at Calgary* WSC gauge (05BH004). These floods occurred in 1879, 1897, and 1902, and had estimated discharges of 2265 m^3/s, 2265 m^3/s, and 1550 m^3/s, respectively (Neill and Watt, 2001). It is assumed that these flood events were also experienced at Banff. Linear egression equations for the period of time before the Glenmore Dam began operation were used to relate these three floods to the *Bow River at Banff* peak flow record. The resulting peak flow estimates of 1082 m^3/s, 1082 m^3/s, and 740 m^3/s are all in excess of the 2013 peak flow. As a result, the return period of the 2013 event is much lower using the historical dataset than using the recorded peak flow data only.

Table 6-4. Frequency estimates for regional real-time peak flow records during the June 2013 event.

Station	Drainage Area (km^2)	Peak Discharge (m^3/s)	Time of Peak	Return Period (years)	
				WSC Dataset	Historical Dataset
Bow River at Banff [05BB001]	2210	439	June 21, 2013, 16:00	175	15-20
Waiparous Creek [05BG006]	332	306	June 20, 2013, 11:00	38	-

The Marmot Creek streamflow gauge (Drawing 11) is considered to be the most appropriate analog for Cougar Creek in the area (AMEC, 2007). However, this gauge was damaged during the June 2013 rainfall event by a debris flow. As a result, data were not recorded that could have been used to characterize the event (pers. comm., J. Pomeroy, 2013).

6.4. Snowpack

Snowpack has not yet been analysed by BGC in detail. A snow gauge maintained by the University of Saskatchewan at Fisera Ridge demonstrates that only minimal snow remained at an elevation of 2325 m on June 8 (Figure 6-1). However, Dr. Pomeroy reported significant snow in a nearby treed area which persisted until the storm of June 19 (pers. comm.). At this stage, it is not possible to say how much snow existed in the Cougar Creek watershed prior to the event of June 19. Additional analyses of snowpack distribution and thickness are underway by BGC and will appear in the forthcoming detailed hydroclimatic report.

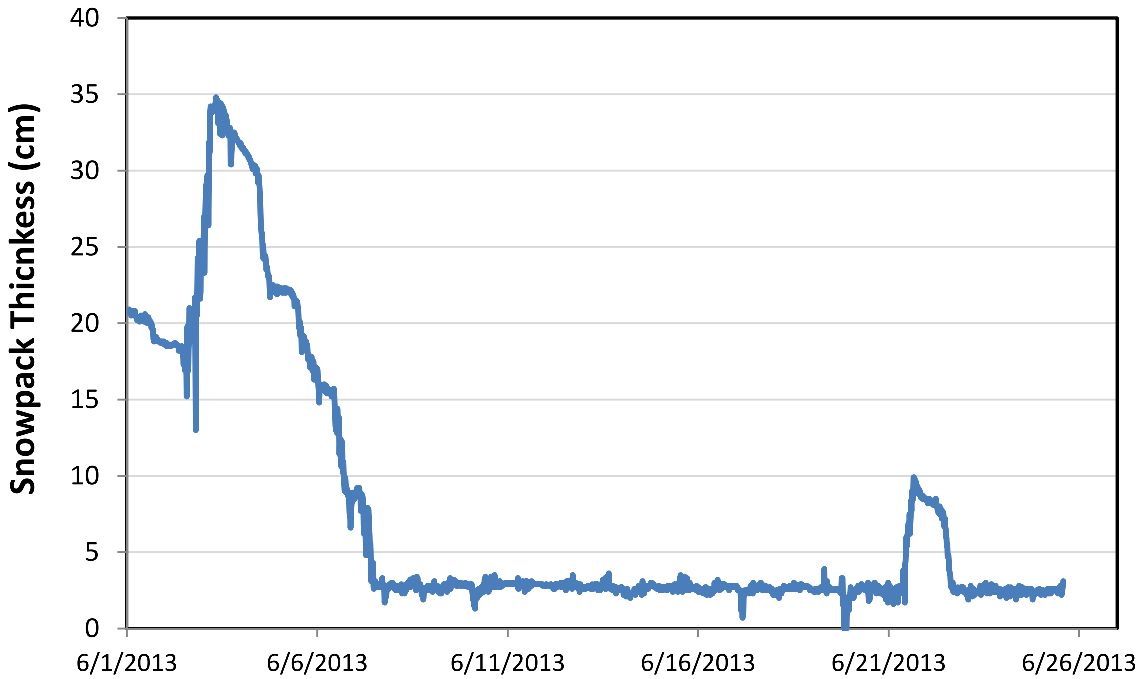

Figure 6-1. Development of Snowpack Thickness at the Fisera Ridge Station

6.5. Conclusions

The June 19 – 21 storm was a rare event because of its long duration and high average intensities. The end result was that the storm: (a) triggered numerous debris flows in tributaries of Cougar Creek and (b) quickly exceeded a threshold for significant bedload movement in the mainstem and principal tributaries of Cougar Creek, which led to prolonged transportation of bedload into the fan reaches of the creek. Due to aggradation of the pre-existing channel, the creek lost confinement and began to erode the elevated banks on either side of the creek. The return period of the rainfall event, as estimated for the Kananaskis climate station, ranges between approximately 200 years for the 1-day duration to approximately 750 years for the 3-day duration. It should be cautioned that these return periods are based on the notion of data stationarity and are not valid if long-term trends are identified and verified. In that case, the return periods would be proportionally lower.

7.0 FREQUENCY ANALYSIS

The BGC field observations of past debris-flood activity on Cougar Creek is also supported by a review of historic aerial photographs. Aerial photos reviewed by BGC are summarized in Table 7-1, while Drawing 12 provides a chronosequence of the listed air photographs.

Table 7-1. Cougar Creek Historic Aerial Photographs

Year	Roll	Photo #	Scale	Date
1925 (oblique)	unknown	unknown	unknown	unknown
1947	A11101	6-8	1:40,000	September 23
1950	AS 167 5101/5102	14, 15 43, 44	1:40,000	September 23
1958	AS 744 5103	54	1:16,000	August 14
1962	AS 830	51-52, 112-114	1:32,000	September 18
1975	AS 1383 3	80-81	1:12,000	June 1
1984	AS 3085	73, 105	1:20,000	August 22
1991	AS 4238	107, 108	1:10,000	September 17
1997	AS 4824	79, 80	1:15,000	July 19
2008	AS 5450	240, 241	1:30,000	August 18

The aerial photograph review indicates that Cougar Creek has been subject to several large historic debris floods and floods. The 1947 air photographs show that Cougar Creek used to occupy a much larger area on the fan than today and consisted of two major channels and a minor channel (Drawing 13). The current development has been superimposed on Drawing 13, indicating the extent of the former channels. One channel avulsed on the right bank at the location of the current Elk Run Boulevard and deposited in the area of Pioneer Road, Coyote Way, Kodiak Road, and Cougar Creek Drive. Also a number of homes along Lady Macdonald Crescent and Grotto Road are located along the major channel further to the east. This east channel had begun to revegetate by 1950 (Drawing 12). It is not known whether either of these major channels represent an extreme debris flood event or were formed by a series of small events. However, a suspected date for a major debris flood event may be June 14, 1923 which demarks the date of the second highest (highest June 21, 2013) flow recorded at the *Bow River at Banff* hydrometric station. The peak flow on that date was 399 m^3/s compared to 439 m^3/s for the June 2013 event. Such high runoff would most likely been attributed to a very heavy rainfall event over the region, perhaps combined with snowmelt. A date of 1923 is consistent with an oblique air photograph of the area taken in 1925. The oblique image looks up (west) the Bow River valley, but it is apparent that there are two major active channels on the Cougar Creek fan (Figure 7-1).

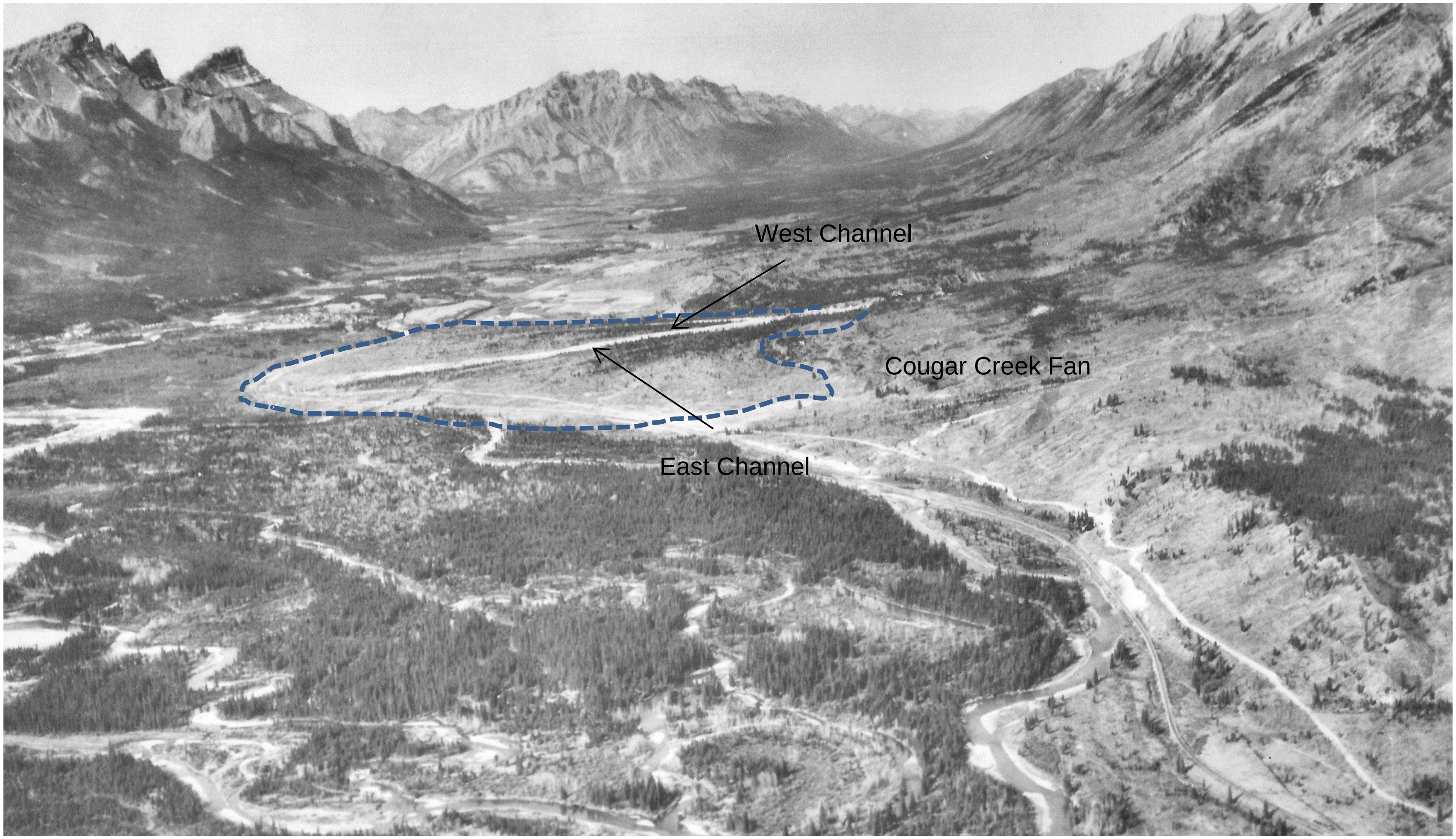

Figure 7-1. 1925 oblique air photograph looking west along the Bow River Valley toward the Cougar Creek fan.

Review of the air photographs indicates that a large debris flood event occurred between 1947 and 1950. During a BGC interview with 94-year old Ms. Straw (August 7, 2013), a local resident of the fan, Ms. Straw remembered a large event occurred on May 24, 1948. Between May 21 and May 24 of that year, only 37 mm of rain fell at Kananaskis Village, which is located some 22 km east of Cougar Creek fan. In comparison, the recorded rainfall of June 19, 2013 at this station was 157 mm and had a return period of approximately 240 years, while the two day precipitation of June 19 and 20 had a return period of approximately 360 years. If the date of the 1948 event was indeed May 24, then the recorded rainfall appears inadequate to trigger a debris flood of the magnitude observed on the aerial photographs (although extreme convectional rainfall in the mountains can be very local). However, analysis of the 1950 air photographs shows a fresh (date unknown) debris avalanche some 2 km upstream of the fan apex, which may have led to a temporary impoundment and a landslide dam outbreak flood (Figure 7-2).

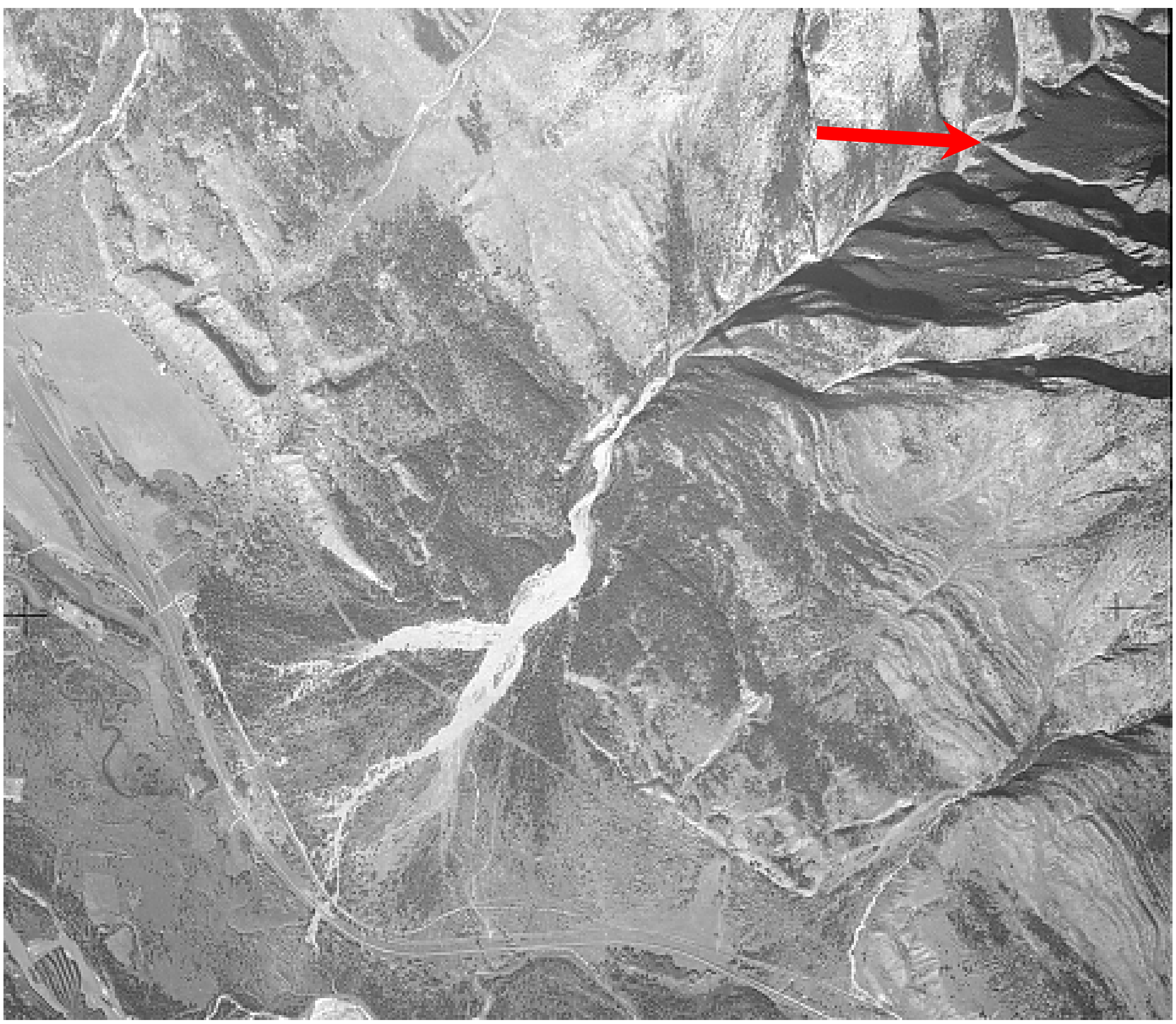

Figure 7-2. 1950 air photograph of the lower reaches of Cougar Creek and the fan. The red arrow indicates a relatively fresh debris avalanche that may have dammed Cougar Creek leading to a landslide dam outbreak flood.

The major channels visible on the 1947 air photograph were still prominent on the 1958 and 1962 air photographs. There does not appear to have been a major event between 1950 and 1962, or at least one of sufficient magnitude to create a new avulsion. The 1958 air photographs show that an area has been cleared for a garbage dump in the present industrial area north of Boulder Crescent and south of Glacier Drive, as well as a pronounced clearing along the Highway 1 corridor.

On the 1975 air photograph (Drawing 12), some widening of the main channel appears to have occurred compared to the 1962 air photographs. This event likely occurred in 1974, as this was a reported flood year (CH2M HILL, 1994).

By 1984 significant changes had taken place on the Cougar Creek fan, including the following:

- The creek has been channelized between the fan apex and Highway 1.
- The first major residential development has been constructed on the western fan sectors and Elk Run Boulevard has been constructed.
- Additional industrial activity has taken place with approximately one third of the eastern fan having been developed.

However, no signs of a major debris flood event can be discerned on the air photographs.

By 1991, most of the western fan sector has been developed with residences north of Highway 1. No major changes have taken place on the eastern fan sector between 1984 and 1991. There are no signs of a major debris flood having occurred on the fan.

Between 1991 and 1997, more residences were added on the eastern fan sector with homes now occupying a larger area than industrial activities. Development has also encroached to the lower lying areas east of Elk Run Boulevard and in the area between Highway 1 and Highway 1A. By 1997, approximately 80% of the fan is densely developed.

By 2008, additional development had been created north of the fan, but also on the easternmost fan fringe. Development on the western fan between Highway 1 and Highway 1A has densified, and Alpine Helicopters started operations just west of Cougar Creek between the two highways. Once again, there are no signs on the air photographs of major debris floods in the previous decade. The 2005 flood, which caused erosion issues on the fan, is hardly visible on this air photograph, demonstrating that events have to be of substantial magnitude to be detected by air photograph analysis.

In summary, large debris floods possibly occurred in 1923, 1948, 1974 and 2013 indicating a preliminary return period of approximately 30 years for the last century. Their respective volumes will be estimated in detail in BGC's forthcoming comprehensive hazard assessment of Cougar Creek. Smaller events (floods or debris floods) did occur during the 1948-2013 period and have been recorded by CH2M HILL (1994) and AMEC (2012) as having occurred in 1956, 1967, 1980, 1990, 2005 and 2012, indicating a return period of approximately 8 years. The event magnitudes for these smaller events have not been determined with high confidence but they are believed to be in the order of 10,000 m^3 to several 10,000 m^3 in volume. These smaller events have largely been confined to the channel and thus are not obvious on air photographs.

The most striking changes on the fan in the past 30 years is residential, commercial and industrial development, which now occupies some 90% of the fan.

8.0 CONCEPTUAL DESIGN OPTIONS

This section provides conceptual design options for Cougar Creek for both the short and long-term. The Town of Canmore has indicated to BGC that they have a low risk tolerance for further damages on the fan of Cougar Creek. The Town therefore wishes to implement short-term mitigation options in the fall and winter of 2013/2014 that would provide protection against an event of similar magnitude to that experienced in June 2013. The short-term mitigation works would then be followed by the design and construction of long-term mitigation works in 2014. A more detailed hazard and risk analysis of Cougar Creek is ongoing and will provide critical inputs to the design of the long-term mitigation works.

The principal design philosophy for both short-term and long-term mitigation options is to address the following:

- reduce the amount of sediment and debris being transported onto the fan; and
- protect the channel banks from lateral instability within the developed portion of the fan.

Any future works at Cougar Creek will include a variety of stakeholders because of the existing development on the fan and the interaction of specific flood mitigation measures with different elements at risk on the fan. Stakeholders for Cougar Creek include:

- Town of Canmore;
- local residents;
- local industries and businesses on the fan;
- Canadian Pacific Railways; and
- Alberta Transportation.

8.1. Short-Term Mitigation Options

As noted above, The Town of Canmore wishes to implement short-term mitigation options in the fall and winter of 2013/2014 that would provide protection against an event of similar magnitude (peak flow and total sediment volume) to that experienced in June 2013. This design criterion is difficult to translate into design since the data have not been completely processed that would allow an accurate estimation of the 2013 debris volumes.

The 100-year return period peak flow of Cougar Creek has been previously been estimated at about 16 m^3/s by AMEC (2003, 2007). Photographs and videos suggest that the peak discharge of the 2013 debris flood was much greater than 16 m^3/s. The best evidence is provided by photographs of the inlet of the Elk Run Boulevard culvert, which show the culvert at about two-thirds capacity (see Photos A-3 to A-6, Appendix A). CH2M HILL (1993a) indicate that this culvert has a capacity of 160 m^3/s, suggesting that the 2013 peak flow may have been in excess of 100 m^3/s. However, the extent of aggradation at the culvert inlet during the peak of the flood is not known and the wingwalls had been outflanked, reducing the hydraulic efficiency of the culvert. It is more than likely that the peak flow was coincident with a reduced culvert capacity. Therefore, for the purposes of the short-term mitigation design, BGC has tentatively assigned a peak flow of 64 m^3/s to the 2013 event which is four times the previous Q_{100} estimate. Debris flood peak flows exceeding the 200-year hydrological estimate by several times have been noted in the past by Jakob and Jordan (2001). BGC is currently conducting hydraulic modelling of the culvert inlet, with various assumed channel geometries, to develop a range of potential peak flows. Results of that sensitivity analysis were not available at the time of writing, but will be available for the upcoming detailed hazard assessment report.

Comparison of a 2010 LiDAR survey with the 2013 LiDAR survey is in progress and will provide an accurate estimate of bedload transported onto the fan. In the meantime, it can be stated with reasonable confidence that several tens of thousands of m^3 of sediment was transported onto the fan of Cougar Creek during the event. The amount of sediment eroded from the channel banks and re-distributed within the fan is also estimated in the order of at least thousands of cubic metres, although these numbers are subject to change pending the detailed LiDAR image comparisons.

Using these design parameters and design philosophy, the following design elements are recommended for short-term mitigation:

<u>Debris Net</u>

One of the principal design elements is the installation of an approximately 6 m high debris net at the site of the 1982 rockfill dam. Here the channel is about 40 m wide and bedrock outcrops on both banks. Debris nets are a cost-effective means to trap sediment and woody debris and are capable of storing several tens of thousands of m^3 of sediment. Two examples of such nets are shown in Photo 8-1 and 8-2.

Photo 8-1. Downstream view of 14 m high debris flow net. Photograph courtesy of Geobrugg North America, LLC.

Photo 8-2. Debris flow net barrier with lambda-shaped frames and the possibility for structure opening for debris clearing in the centre of the structure

Figure 8-1 shows a storage curve for this location that assumes a deposition slope equal to half the channel gradient. A 6 m high net would be capable of storing approximately 23,000 m^3 of debris. Alternatively, a debris basin (excavation into alluvial sediments) could be considered for this location, assuming that the groundwater table would be low enough to allow for some significant excavation.

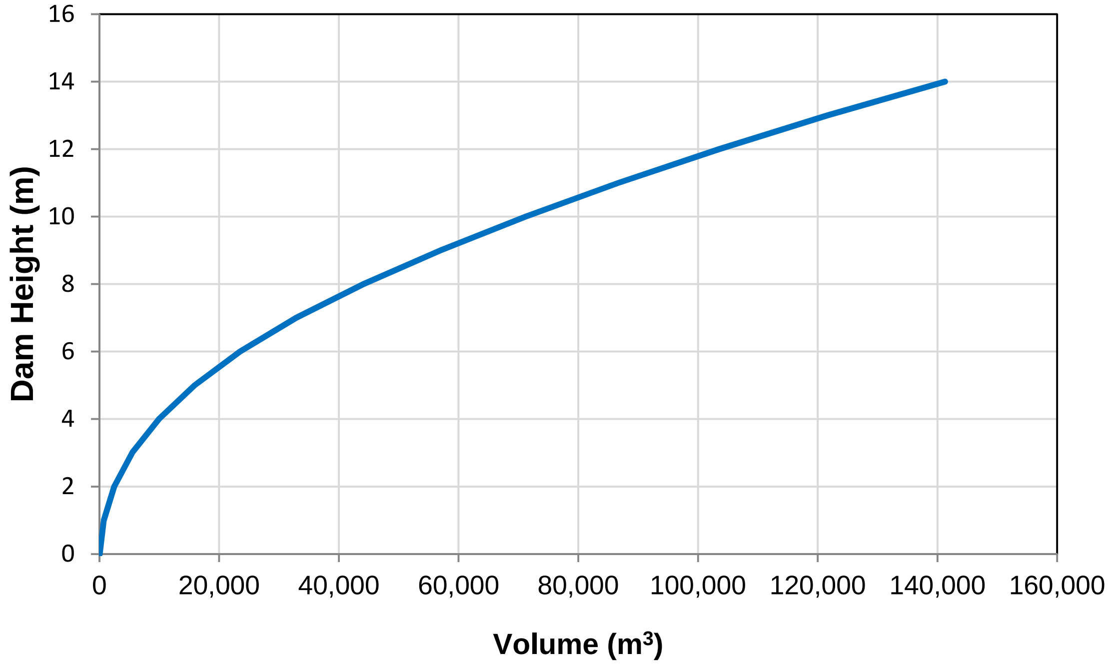

Figure 8-1. Storage Curve at Proposed Barrier Location on Cougar Creek (based on 2013 LiDAR).

A debris net or debris basin would reduce sediment volumes being transported beyond the fan apex significantly, and would require some form of annual sediment removal. However, in previous flood events in 2005 and 2012, AMEC (2007, 2012) noted that approximately 75% to 90% of the sediment being transported to and deposited at the Highway 1A and CP Rail crossings originated from bed and bank erosion within the upstream, channelized portion of Cougar Creek. Therefore, the debris net or basin above the fan apex needs to be considered in conjunction with in-channel works downstream. These recommended works consist of the following elements:

- excavations to enlarge the existing channel that was reconstructed following the 2013 debris flood;
- the placement of gabion mattresses (or articulated cable concrete mats) on both banks from the upstream end of development down to Highway 1;
- the installation of approximately eight grade control structures (Class IV riprap);
- placement of Class IV riprap on the sideslopes and channel bed at the culvert inlets for Elk Run Boulevard and Highway 1; and
- the placement of Class III riprap on the right bank for a short distance below Highway 1.

These design elements are discussed in more detail below.

Channel Excavations

The second design element is to enlarge the reconstructed channel between the upstream end of development and Highway 1. Above Elk Run Boulevard, the channel would be 40 m wide from top of bank to top of bank with 2H:1V sideslopes. At an average depth of 4 m, the channel would be about 25 m wide at its base. Below Elk Run Boulevard, the channel would be 50 m wide from top of bank to top of bank with 2.5H:1V sideslopes. The channel is slightly narrower above Elk Run Boulevard, as sufficient room needs to be maintained on both banks for tree planting and a walking path/access road. Above Elk Run Boulevard, the Town right-of-way is only sufficient for a 40 m wide channel, while further downstream a wider channel can be accommodated.

The objective of the channel enlargement is as follows:

- Remove some of the sediment transported by the 2013 debris flood and thus reduce the volume of sediment that could be mobilized by future events; and
- Provide for as shallow a flow as possible during a flood event, which reduces the propensity for scour and lateral instability. Hydraulic calculations show that the maximum flow depth is on the order of 0.7 m for a flow of 64 m^3/s and the channel dimensions noted above.

Gabion Mattresses

Following channel excavations, gabion mattresses (0.5 m thick) or articulated cable concrete mats would be placed on the sideslopes of the excavated channel. A geotextile would be used for a filter between the gabion mattress and parent material. The mattresses would start from just beyond the top of bank and extend 4 m (length) below the base of the channel at the sideslope angle of 2:1. This extension would provide protection against a depth of scour of approximately 1.5 m to 2.0 m below the design channel bed level. With the increasing gradient down fan and removal of the incoming bedload, scour can be expected in the future. At the two culvert inlets, the gabion mattresses would tie in behind the concrete wingwalls.

The extent of the bank protection is shown on Drawing 14. The bank protection is shown extending upstream of the existing development and tying into high ground on the right bank and into a vegetated area on the left bank. The objective of the gabion extension is to minimize the potential for the creek to outflank the bank protection and erode it from the back side. The flared extension of the bank protection would be buried into the existing bank and thus would not be visible following construction. Some channel reworking will also be required in the vicinity of the flared bank protection to guide the channel towards the protected channel to the extent possible.

Should an event similar to the one in June 2013 occur without the long-term mitigation measures in place, the gabion mattresses would likely be damaged and thus should be considered sacrificial. However, they would greatly reduce erosion of the adjacent banks.

Once long-term mitigation measures have been designed and implemented, the longevity of the gabion mattresses would be greatly increased.

Grade Control Structures

Eight (8) grade control structures are proposed at the locations shown on Drawing 14. The grade control structures would be composed of Class IV riprap and be approximately 2.5 m high, 4 m long, and extend across the entire bottom channel width. The grade control structures would be constructed flush with the bed and lie on top of the gabion mattresses. The approximate spacing of the grade control structures would be 125 m.

The grade control structures are proposed, as it is expected that the creek will tend to downcut and mobilize channel bed sediment, given that the upstream sediment supply will be cut-off by the debris net/barrier (must be done in combination). The most critical of the grade control structures is the furthest upstream one. At this location, the proposed short-term mitigation plan is most vulnerable given that the channel widens significantly beyond this point and the upstream creek alignment cannot be controlled during a major flood. It is of paramount importance that the creek not undermine the gabion mattresses at this location.

It is recognized that the number of grade control structures proposed in the short-term are inadequate for long-term protection. For example, AMEC (2006) proposed that six grade control structures be constructed between Highway 1 and Highway 1A, when evaluating channel stability in that reach. The long-term plan is to potentially construct concrete grade control structures all the way down the channel from the upstream end of development to Highway 1A (see next section). The Class IV riprap proposed in the short-term could be integrated into the long-term design, as the concrete grade control structures (conceptually 2 m high above the bed) would require scour protection of the plunge pool on the downstream side.

Additional Culvert Protection

A major problem during the 2013 debris flood was that the concrete wingwalls at Elk Run Boulevard were outflanked and erosion occurred of the road embankment. This occurrence was not only an issue for equipment access to the culvert inlet, but the stability of the road embankment itself. As noted above, the gabion mattresses will tie in behind the concrete wingwalls at Elk Run Boulevard and Highway 1. For additional erosion protection at Elk Run Boulevard, Class IV riprap will be placed on both banks and on the channel substrate for a distance of about 10 m upstream of the inlet. Class IV riprap will also be placed at the Elk Run Boulevard culvert outlet for a distance of 20 m for scour protection. The recommended thickness of this riprap blanket is 2.5 m.

The excavated channel width will also flare out gradually in a straight line from the concrete wingwalls so that there is not a sudden hydraulic constriction from the wider upstream channel. A lateral convergence ratio of about 4.5:1 (angle of 12.5^{o}) will be adopted at the two culvert inlets, while a lateral divergence ratio of about 6:1 (9.5^{o}) will be adopted at the culvert outlet for Elk Run Boulevard.

Downstream of Highway 1

Downstream of Highway 1, only minimal works are recommended in the short-term. Class III riprap protection of the right bank is recommended for a distance of about 100 m. Riprap is recommended at this location given the moderate left-bend curvature of the channel at the culvert outlet which would concentrate flow velocities and thus shear forces on the outside portions of the channel bend. The riprap protection would extend to the top of bank and into the channel for a distance of 4 m, for additional scour protection.

8.2. Long-Term Mitigation Options

The long-term mitigation options are to build upon the short-term measures to avoid excessive re-construction. Unlike the short-term mitigation options, the long-term options will be dimensioned to reduce total debris flood risk to levels considered tolerable by the Town of Canmore and the stakeholders. The risk assessment will build on the forthcoming geohazard analysis and entail the following aspects:

- Quantification of risk to loss of life for individuals and groups, which is based on the combination of a number of hazard scenarios (debris floods of different return periods and different generation mechanisms) and associated consequences; and
- Quantification of potential direct and perhaps indirect economic losses associated with the different hazard scenarios.

This assessment will be followed by a risk evaluation process in which the Town and its stakeholders decide upon the threshold of tolerable risk in terms of loss of life potential and economic risk. This approach is greatly superior to a hazard-based approach in which a single return period is specified which then becomes the design event. In such cases, a larger event could still result in unacceptable risk.

As noted above, the mitigation efforts will need to reduce: the amount of debris that can arrive at the fan apex from upstream and the amount of bank erosion that could occur on the fan reaches. Based on this premise, three principal additions to the short-term mitigation measures are proposed:

- A concrete dam and basin, likely at the same location of the proposed debris net. Following the detailed hazard and risk assessment, it is possible that the required storage volume could be well in excess of 100,000 m^3. Because the debris net proposed for the short-term is modular, it would be disassembled at the site for later use elsewhere.
    - o Care must be taken in the design, as complete entrapment of sediment in the basin will likely lead to significant scour on the fan, with eventual bank

collapse. The ideal arrangement would be the creation of a stable channel that will entail some (currently unknown) sediment feed and throughput.

- Reinforced concrete check dams along the reaches of Cougar Creek that aim to:
    - Further reduce bank erosion as they tie into the banks on either side;
    - Act as grade control structures below erosion is not possible; and
    - Provide some additional debris storage upstream
- Depending on the magnitude of the design debris flood, modifications may be required at some or all of the road crossings. For example, it would be best to replace the Elk Run Boulevard culvert with a bridge so that there is no channel constriction.

The concrete check dams would be designed so that the stored debris wedge would reach close to the toe of the next upstream dam (see Figure 8-2). The height of each check dam above present grade would need to be optimized with respect to the spacing between the individual structures and their respective costs. A critical output of this assessment is the final slope between the check dams so that water and sediment input can be passed through with no net erosion and minimal deposition. Otherwise there will be a continuing need to reconstruct the channel bed.

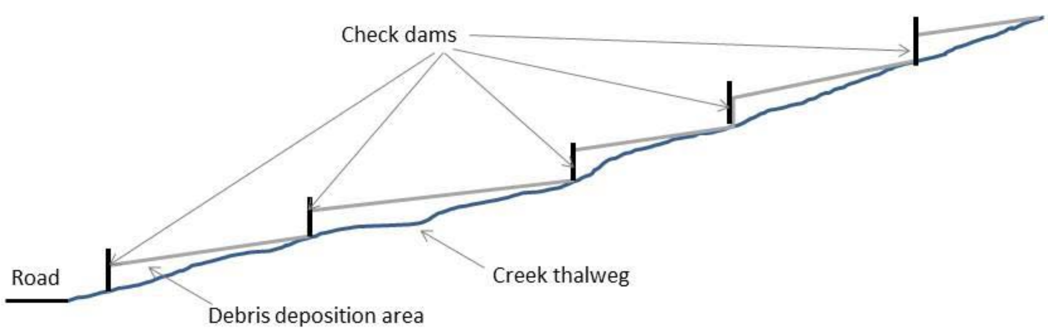

Figure 8-2. Hypothetical creek profile with sequenced concrete check dams and upstream debris deposition areas. The deposition would begin from the overflow sill of the check dams which will be at a lower elevation than the maximum elevation of the check dams as shown.

Furthermore, they would be designed sloping towards the centre of the channel, where an overflow sill would ascertain that the flow returns to the centre of the channel during and following a debris flood. Photo 8-3 shows an example of a sequence of such check dams.

Photo 8-3. Example of a series of stepped concrete check dams. Location unknown.

The type of construction of the debris barrier as well as the number, geometry and dimensions of the check dams have not yet been determined, but will be developed once the detailed hazard and risk assessment is complete. All of these structures would require episodic removal of accumulated sediment and operational costs should be considered within that requirement.

9.0 CONCLUSIONS

Cougar Creek has a long history of floods and debris floods. The fan is one of the largest in the Bow River valley encompassing some 3.1 km^2 and has an estimated volume of approximately 91 million m^3. Given its presumed age of 10,000 years, this volume translates into an average annual bedload transport volume of 9,000 m^3. This average, however, is misleading as in most years the bedload transport will be much lower, while some years will have orders of magnitude higher bedload. Furthermore, during the early Holocene (approximately 10,000 to perhaps 8,000 years before present) rates of sediment delivery to the fan were likely significantly higher because of the abundance of unconsolidated glacial sediments and no or only sparse vegetation.

Cougar Creek fan is particularly dangerous because debris floods are generated by at least two processes. One is bedload mobilization by exceedance of a critical discharge as a function of the intensity and duration of a rainstorm, which at times can combine with snowmelt. The other debris-flood generator is a landslide (debris flow or rock slide/rock avalanche) dam outbreak flood of which there is ample evidence along the main channel of Cougar Creek. In particular a high landslide dam close to the fan apex could result in peak flow rates far exceeding those by rainfall-generated floods and debris floods. These potential peak flows will be quantified in BGC's forthcoming comprehensive debris-flood hazard assessment.

The combination of the severe hazard on Cougar Creek fan and the dense development (that does not allow allocating a portion of the fan for harmless debris deposition) translates into a high, though to date unquantified, risk to people and infrastructure. This risk has previously been recognized by consultants and government alike, and has led to numerous prescribed and implemented mitigation measures. However, the debris flood hazard has been underestimated in the past and funding has not been able to address the full spectrum of conceivable events nor its associated risks.

The June 2013 debris flood was likely the largest event in the last 65 years. The 2013 event was severe because of the total volume of rain that fell on the Cougar Creek watershed. The three day rainfall total for this storm at the nearest long-term climate station (Kananaskis) was the highest on record since observations began in 1939. A tentative return period of 750 years has been estimated for the 3-day rainfall, but may not remain valid due to a changing climate.

The event mobilized tens of thousands of cubic metres sediment that arrived from upstream of the fan apex and from bank erosion on the fan. Prior to fan development, bank erosion was likely much less pronounced, since in absence of an excavated channel, debris avulsed and spread freely on the fan. Because development has progressed on both sides of the creek and a number of linear infrastructures cross the fan (Highways 1 and 1A and CP Rail), the creek must be maintained in its present location and cannot be allowed to avulse.

An examination of the sequence of events of the June 2013 debris flood showed that initial channel erosion was followed by major aggradation on the fan reaches which meant loss of channel confinement and erosion of the fan surface on which homes had been built on either side of the channel. This process is responsible for almost all damage to homes along the creek corridor. Aggradation in the lower fan reaches then led to blockages of the box culverts at Highway 1, Highway 1A and the CP Railway. Redirected drainage by the Highway 1 embankment also scoured the median fill leading to partial collapse of the highway road surface.

This event chronology demonstrates that any short-term or long-term debris flood mitigation must be two-pronged. First, the total amount of debris arriving at the fan apex must be significantly reduced to avoid channel aggradation downstream. Second, bank erosion on the fan reaches must be reduced to avoid renewed undercutting of home foundations and to reduce the amount of debris that can be recruited on the fan reaches and thus be deposited further downstream potentially leading to blockage of the downstream box culverts. In combination, this strategy will greatly reduce the amount of sediment available for transport, and the creek will tend toward degradation and scour of its bed. This process is undesirable because it would lead to oversteepening of the lower creek banks which could jeopardize the integrity of the bank protection. Therefore, additional grade control structures are required to counteract potential degradation and scour in an environment where the channel has been starved of debris.

It is of paramount importance to emphasize that these measures will only reduce risk to loss of life and property damage for events on the order of several tens of thousands cubic meters. It is unlikely that these measures will be sufficient to reduce risk to tolerable levels for larger events that will occur with statistical certainty. Ultimately, Cougar Creek will require a long-term solution that will reduce total risk of loss of life and excessive property damage to levels considered tolerable by the Town of Canmore and other stakeholders. The type and scale of long-term risk reduction measures will be determined through the forthcoming quantitative risk assessment that will determine debris flood risks for the entire spectrum of events that are being reconstructed in BGC's detailed hazard assessment, which will follow this forensic analysis. Under no circumstances should the short-term mitigation measures proposed herein be viewed as a viable long-term solution as this would invariably lead to renewed property loss or possibly loss of life in a future extreme event.

10.0 CLOSURE

The report provided herein provides a forensic review of the debris flood of June 2013 and its impact along the Cougar Creek corridor. As noted earlier, preliminary short-term mitigation measures have been proposed herein and these may evolve or change as additional information is compiled and assessments (e.g. magnitude of the June 2013 debris flood) are undertaken. The detailed hazard assessment work will be documented under separate cover, taking the recommendations in here to a further stage.

Yours sincerely,

BGC ENGINEERING INC.
per:

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APPENDIX A
Photographs

Photo A-1. Upstream view of Cougar Creek from Elk Run Boulevard on June 19, 2013. Note the bank protection and vegetated banks. Photograph courtesy of the Town of Canmore.

Photo A-2. On right bank of Cougar Creek looking to left bank at the Elk Run Boulevard culvert. Emergency efforts to protect the outflanking of the culvert are u7nderway. Photograph courtesy of the Town of Canmore.

Photo A-3. Downstream view of Cougar Creek to Elk Run Boulevard culvert. Photograph courtesy of the Town of Canmore.

Photo A-4. Downstream view of Cougar Creek from right bank looking to Elk Run Boulevard culvert. Photograph courtesy of the Town of Canmore.

Photo A-5. **Side view of inlet to Elk Run Boulevard culvert. Note the outflanking of the culvert that has occurred. Photograph courtesy of the Town of Canmore.**

Photo A-6. **Downstream view to Elk Run Boulevard culvert from Benchlands Trail, which has partially eroded. Photograph courtesy of the Town of Canmore.**

Photo A-7. Upstream view of Cougar Creek from Elk Run looking over to the right bank and the eroded Benchlands Trail. A severely damaged outdoor hockey rink is visible in the foreground. Photograph courtesy of the Town of Canmore.

Photo A-8. Erosion that occurred adjacent to the Winter residence above Canyon Road. Photograph courtesy of the Town of Canmore.

Photo A-9. View from right bank looking over to homes located on Canyon Road. Photograph courtesy of the Town of Canmore.

Photo A-10. Structural damage sustained to home along Eagle Landing. Photograph courtesy of the Town of Canmore.

Photo A-11. Aerial view of restoration efforts along Cougar Creek upstream of Elk Run Boulevard following the 2013 debris flood. Photograph courtesy of the Town of Canmore.

Photo A-12. Aerial view of restoration efforts along Cougar Creek at Elk Run Boulevard following the 2013 debris flood. Photograph courtesy of the Town of Canmore.

Photo A-13. Downstream view of Cougar Creek at Elk Run Boulevard during the early onset of the storm. Some bank erosion has occurred by this time. Photograph courtesy of the Town of Canmore.

Photo A-14. Upstream view Cougar Creek and Elk Run Boulevard. Photograph courtesy of the Town of Canmore.

Photo A-15. Downstream view of Cougar Creek from Elk Run Boulevard. Note the left bank erosion adjacent to Lady Macdonald Crescent. Photograph courtesy of the Town of Canmore.

Photo A-16. Downstream view of the right bank of Cougar Creek from Elk Run Boulevard. Photograph courtesy of the Town of Canmore.

Photo A-17. Upstream view of Cougar Creek looking to the pedestrian bridge. Photograph courtesy of the Town of Canmore.

Photo A-18. Upstream view of the pedestrian bridge from the left bank. Photograph courtesy of the Town of Canmore.

Photo A-19. Damage sustained to home along the left (east) bank of Cougar Creek along Grotto Road. BGC photograph of July 23, 2013.

Photo A-20. Damage sustained to home along the left (east) bank of Cougar Creek along Grotto Road. BGC photograph of July 23, 2013.

Photo A-21. Downstream view of Cougar Creek looking to homes on the left (east) bank along Grotto Road. Photograph courtesy of the Town of Canmore.

Photo A-22. Damage sustained to house along the right (west) bank of Cougar Creek along Coyote Way. Photograph courtesy of the Town of Canmore.

Photo A-23. Downstream view of pedestrian crossing of Cougar Creek from right (west) bank. Photograph courtesy of the Town of Canmore.

Photo A-24. Damage sustained to homes along the left (east) bank of Cougar Creek along Grotto Road. Photograph courtesy of the Town of Canmore.

Photo A-25. Damage sustained to homes along the left (east) bank of Cougar Creek along Grotto Road. Photograph courtesy of the Town of Canmore.

Photo A-26. View from right (west) bank of Cougar Creek at the pedestrian crossing. Photograph courtesy of the Town of Canmore.

Photo A-27. Aerial view of restoration efforts along Cougar Creek between Elk Run Boulevard and Highway 1 following the 2013 debris flood. Photograph courtesy of the Town of Canmore.

Photo A-28. Aerial view of restoration efforts along Cougar Creek at Highway 1 following the 2013 debris flood. Photograph courtesy of the Town of Canmore.

Photo A-29. Aerial view (looking east) of Cougar Creek at Highway 1 following the 2013 debris flood. Photograph courtesy of the Town of Canmore.

Photo A-30. Aerial view (looking northeast) of Highway 1 following the 2013 debris flood. Photograph courtesy of the Town of Canmore.

Photo A-31. Damage to Highway 1 as a result of the 2013 debris flood. View is looking east. Photograph courtesy of the Town of Canmore.

Photo A-32. Aerial view looking upstream (north) of Cougar Creek at Highway 1 during the 2013 debris flood. Photograph courtesy of Alpine Helicopters.

Photo A-33. Aerial view looking east of Alpine Helicopters during the 2013 debris flood. Photograph courtesy of Alpine Helicopters.

Photo A-34. Aerial view looking east of Alpine Helicopters during the 2013 debris flood. Photograph courtesy of Alpine Helicopters.

Photo A-35. Downstream view of reconstructed Cougar Creek channel from the pedestrian bridge. BGC photograph of July 23, 2013.

Photo A-36. Upstream view of reconstructed Cougar Creek channel from the pedestrian bridge. BGC photograph of July 23, 2013.

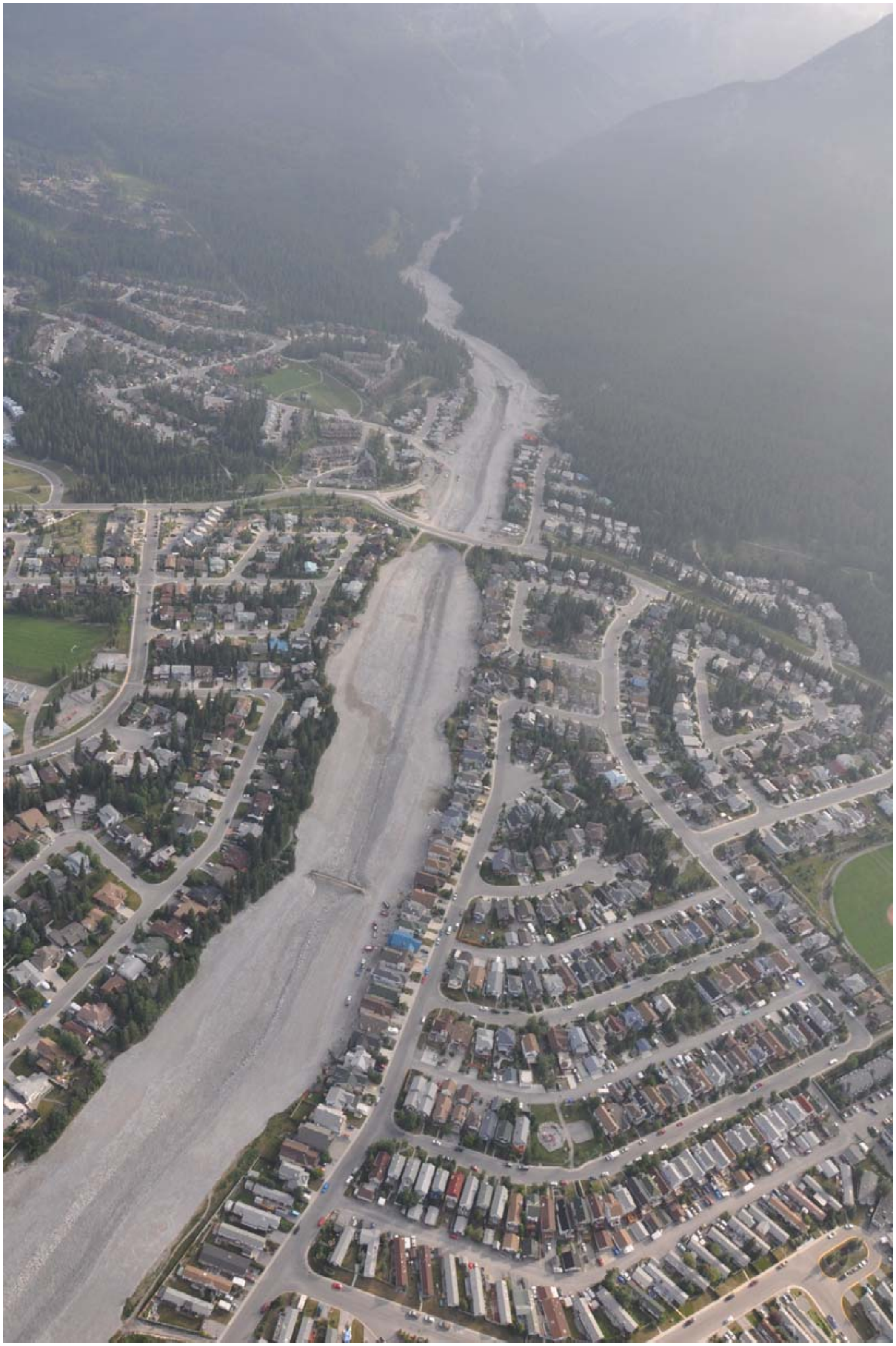


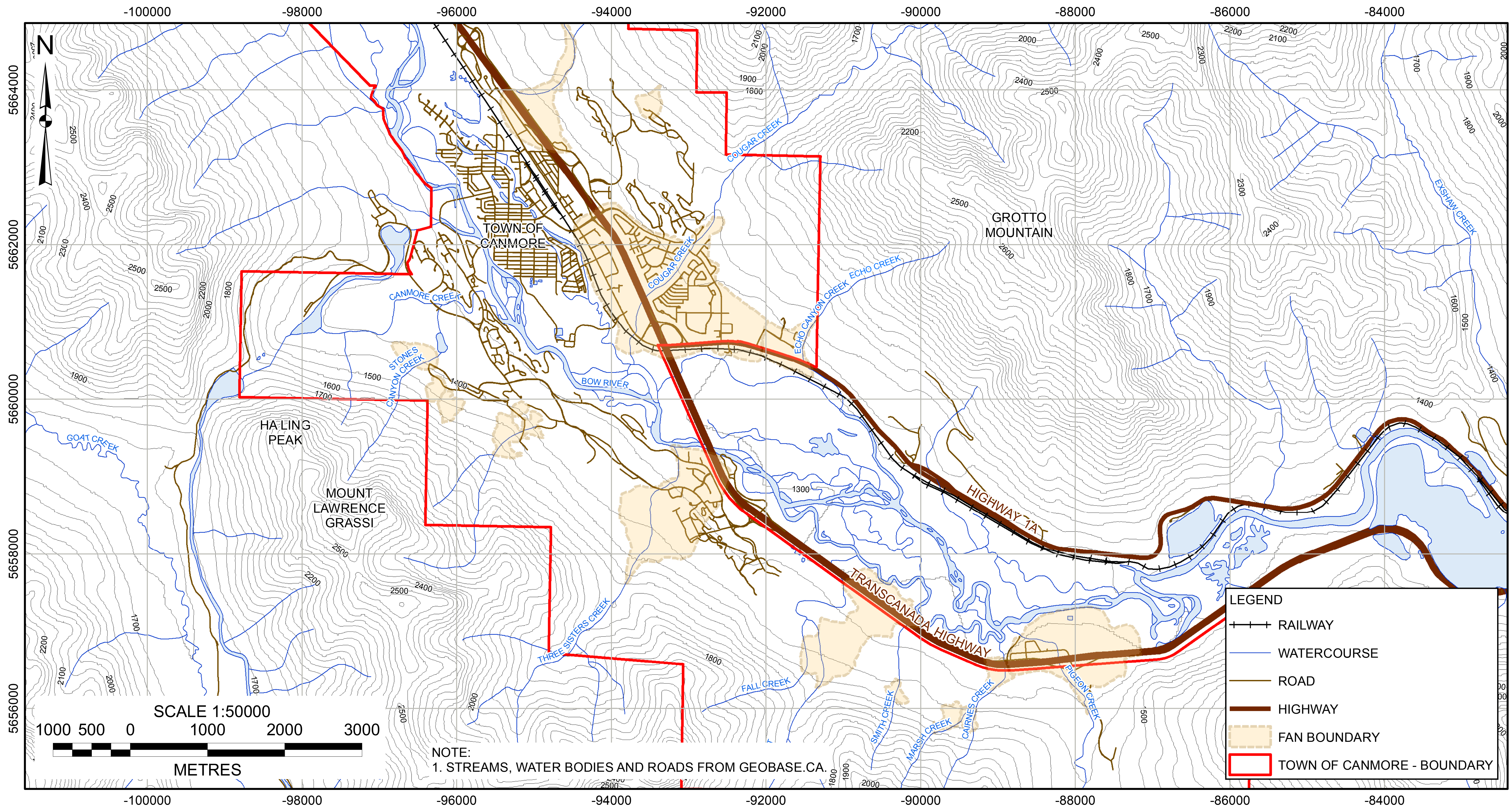
Photo A-37. Aerial view of reconstructed Cougar Creek looking upstream from about Highway 1. BGC photograph of July 23, 2013.

Photo A-38. Aerial view of reconstructed Cougar Creek looking downstream from about the fan apex. BGC photograph of July 23, 2013.

Photo A-39. Aerial view of reconstructed Cougar Creek looking downstream from about the fan apex. BGC photograph of July 23, 2013.

Photo A-40. Aerial view of reconstructed Cougar Creek looking downstream from about the fan apex. BGC photograph of July 23, 2013.

DRAWINGS



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APPROVED:	JC

PROFESSIONAL SEAL:

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: CANMORE

PROJECT: COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION

TITLE: LOCATION MAP

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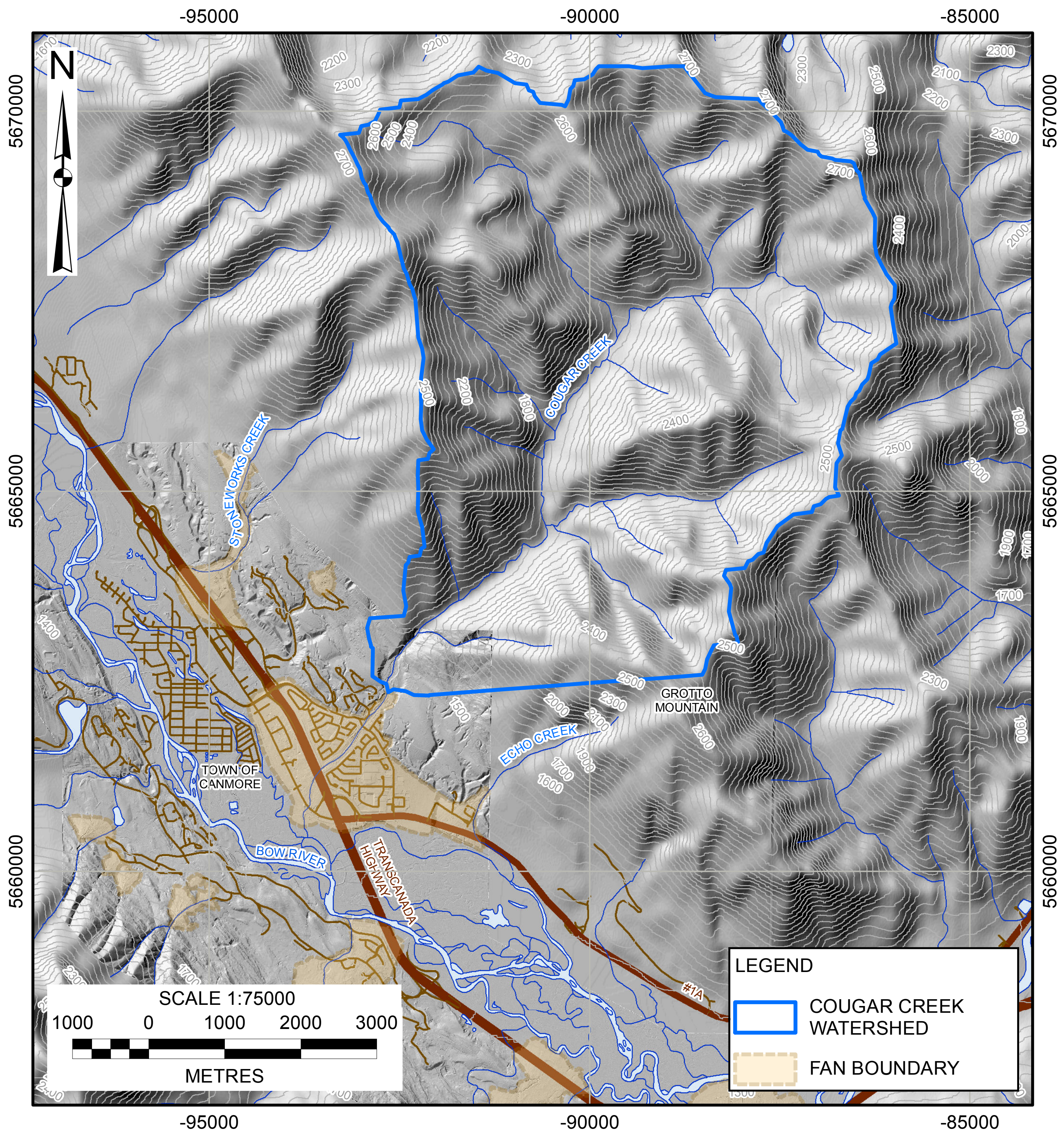

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BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

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COUGAR CREEK, 2013 FORENSIC ANALYSIS
AND SHORT-TERM DEBRIS FLOOD MITIGATION

TITLE:
COUGAR CREEK
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CLIENT:
Town of CANMORE

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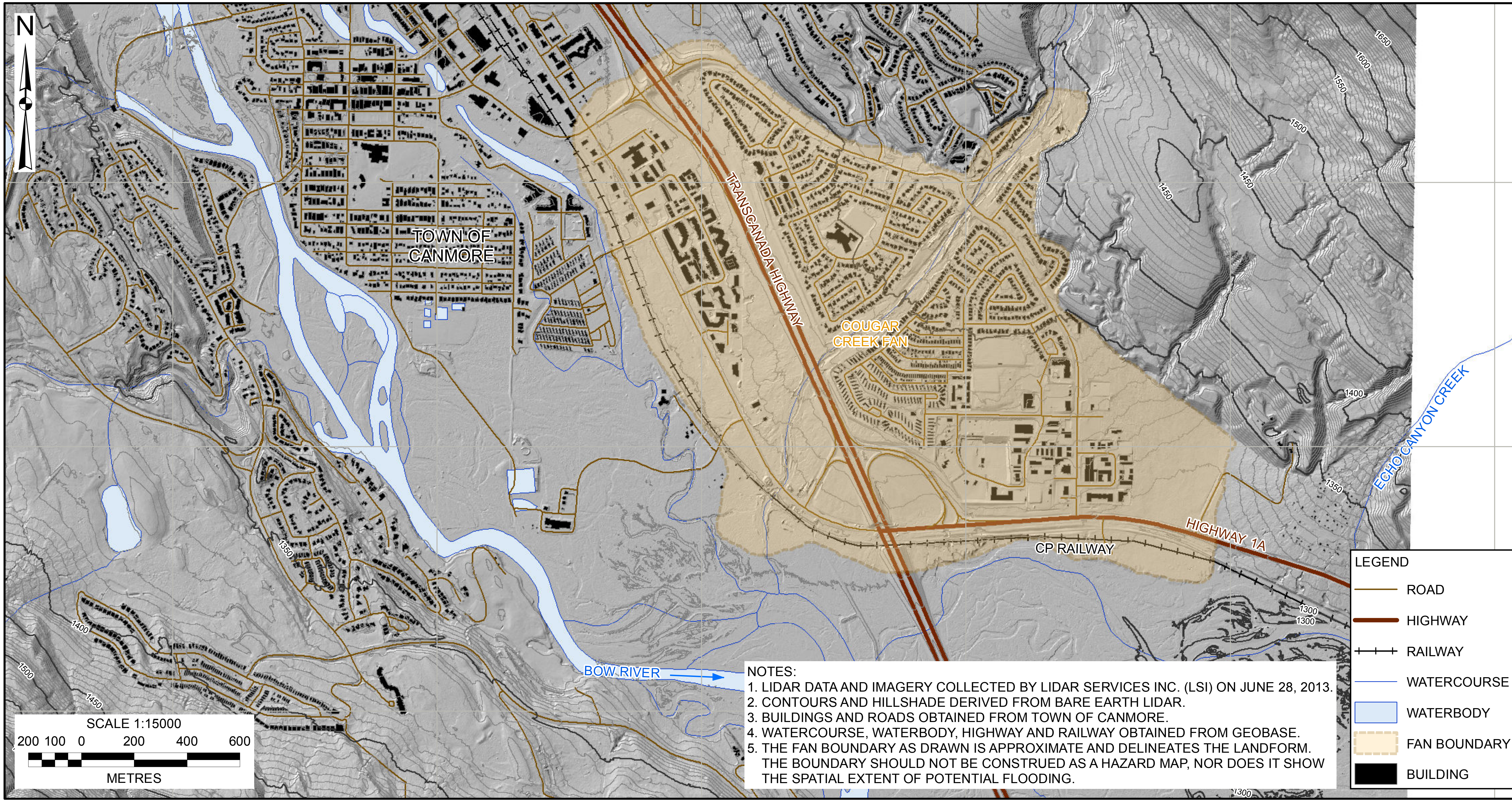

NOTES:
1. LIDAR DATA AND IMAGERY COLLECTED BY LIDAR SERVICES INC. (LSI) ON JUNE 28, 2013.
2. CONTOURS AND HILLSHADE DERIVED FROM BARE EARTH LIDAR.
3. BUILDINGS AND ROADS OBTAINED FROM TOWN OF CANMORE.
4. WATERCOURSE, WATERBODY, HIGHWAY AND RAILWAY OBTAINED FROM GEOBASE.
5. THE FAN BOUNDARY AS DRAWN IS APPROXIMATE AND DELINEATES THE LANDFORM. THE BOUNDARY SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DOES IT SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.

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APPROVED:	JC

PROFESSIONAL SEAL:

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: Town of CANMORE

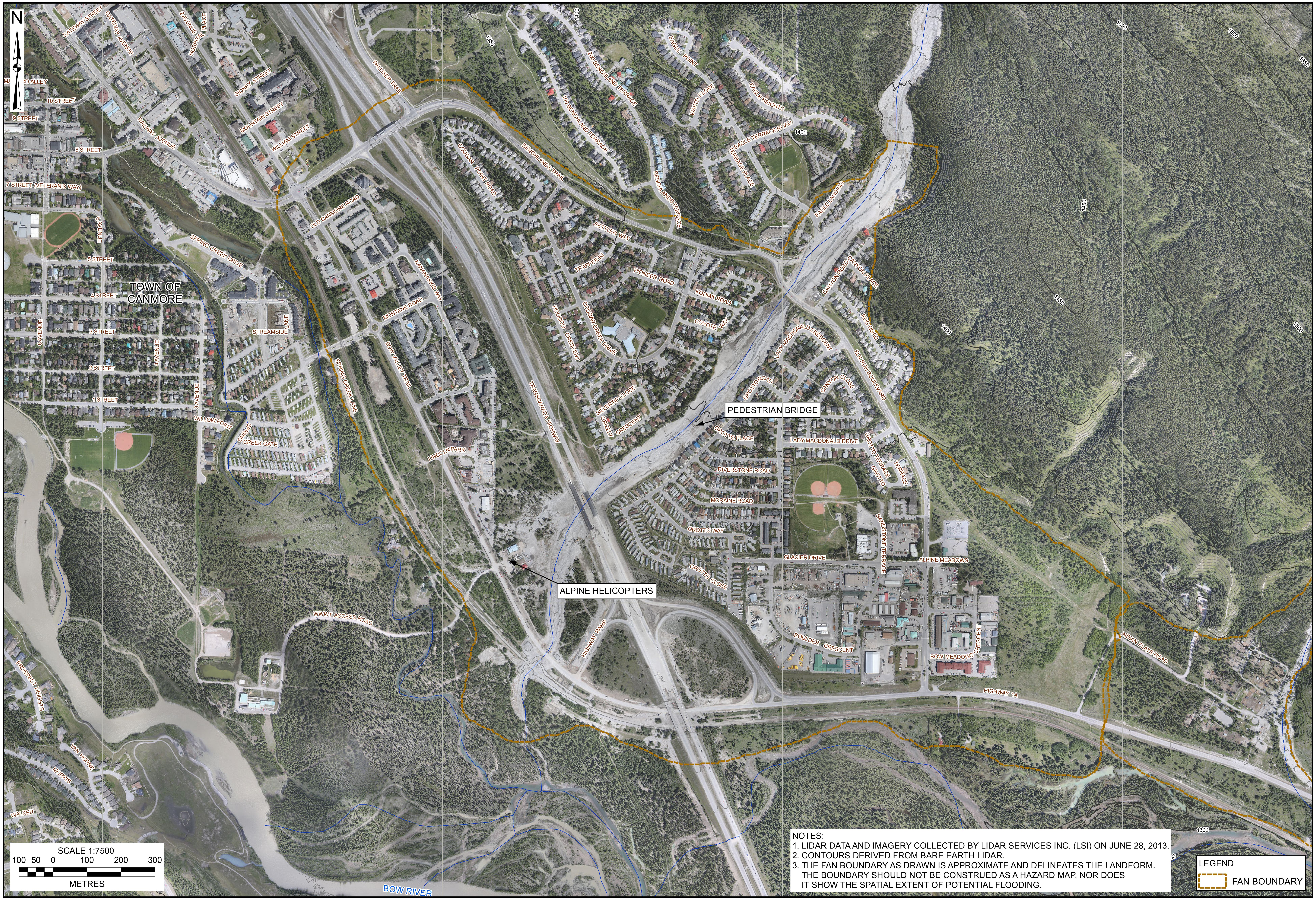
PROJECT: COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION

TITLE: COUGAR CREEK FAN HILLSHADE

PROJECT No.:	DWG No.:	REV.:
1261001	03	

DWG TO BE READ WITH BGC REPORT TITLED "COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION" DATED DECEMBER 2013

X:\Projects\1261001\Workspace\20130828_Report_Cougar_Creek_2013_Forensic_Analysis_And_Short_term_Debris_Flow_Mitigation\03_Hillshade_Cougar_Creek_Fan.mxd



5 m CONTOUR INTERVAL (LIDAR 2013)
3TM

REV.	DATE	REVISION NOTES	DRAWN	CHECK	APPR.

SCALE:	1:7500
DATE:	DEC 2013
DRAWN:	JS
DESIGNED:	HW
CHECKED:	MJ
APPROVED:	JC

PROFESSIONAL SEAL:

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

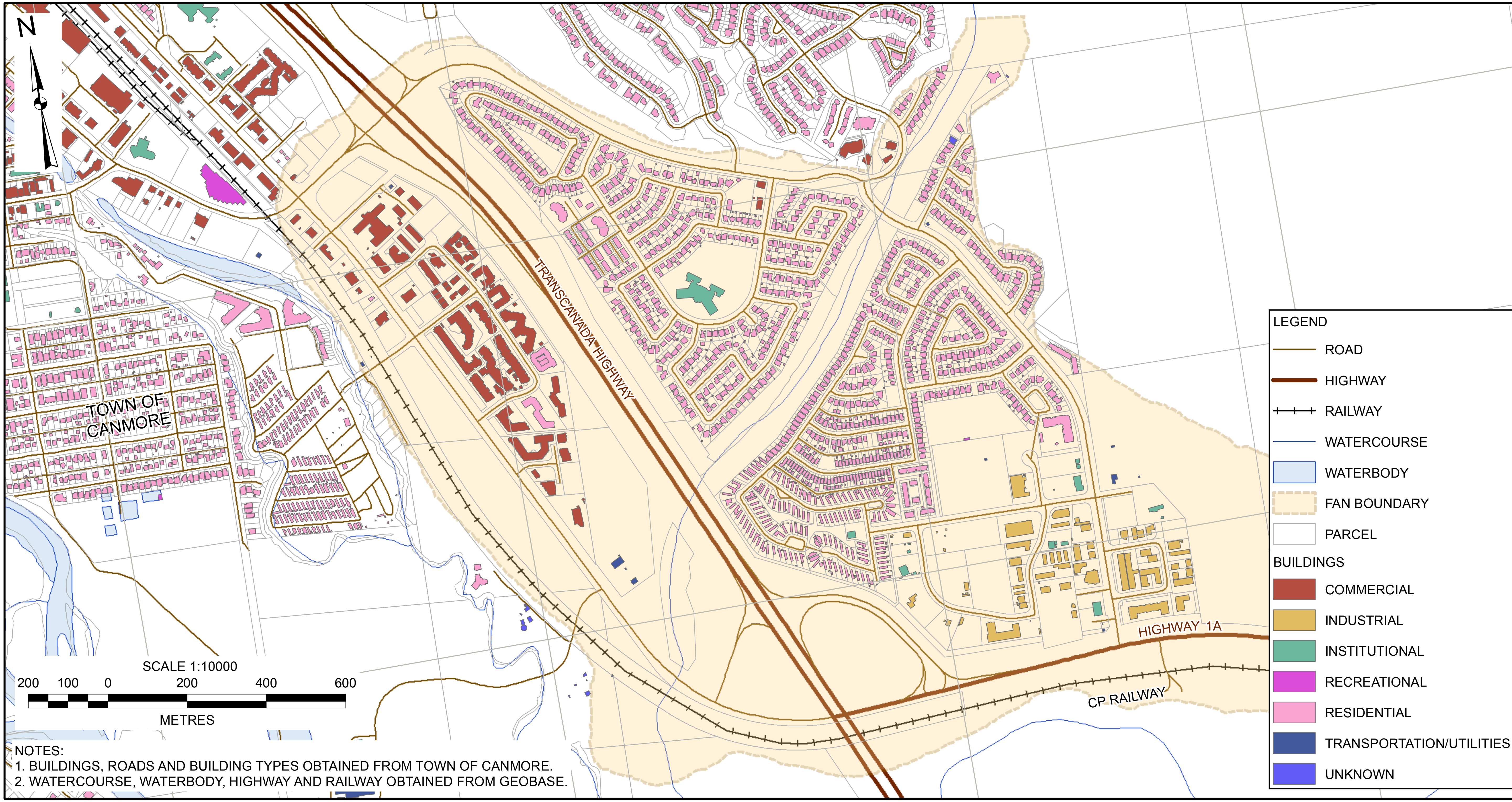
CLIENT: Town of CANMORE

PROJECT: COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION

TITLE: COUGAR CREEK FAN ORTHOPHOTO

PROJECT No.:	DWG No.:	REV.:
1261001	04	

DWG TO BE READ WITH BGC REPORT TITLED "COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION" DATED DECEMBER 2013



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REV.	DATE	REVISION NOTES	DRAWN	CHECK	APPR.

SCALE:	1:10000
DATE:	DEC 2013
DRAWN:	JS
DESIGNED:	HW
CHECKED:	MJ
APPROVED:	JC

PROFESSIONAL SEAL:

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: Town of CANMORE

PROJECT: COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION

TITLE: COUGAR CREEK FAN PROPERTY OWNERSHIP

PROJECT No.:	DWG No.:	REV.:
1261001	05	

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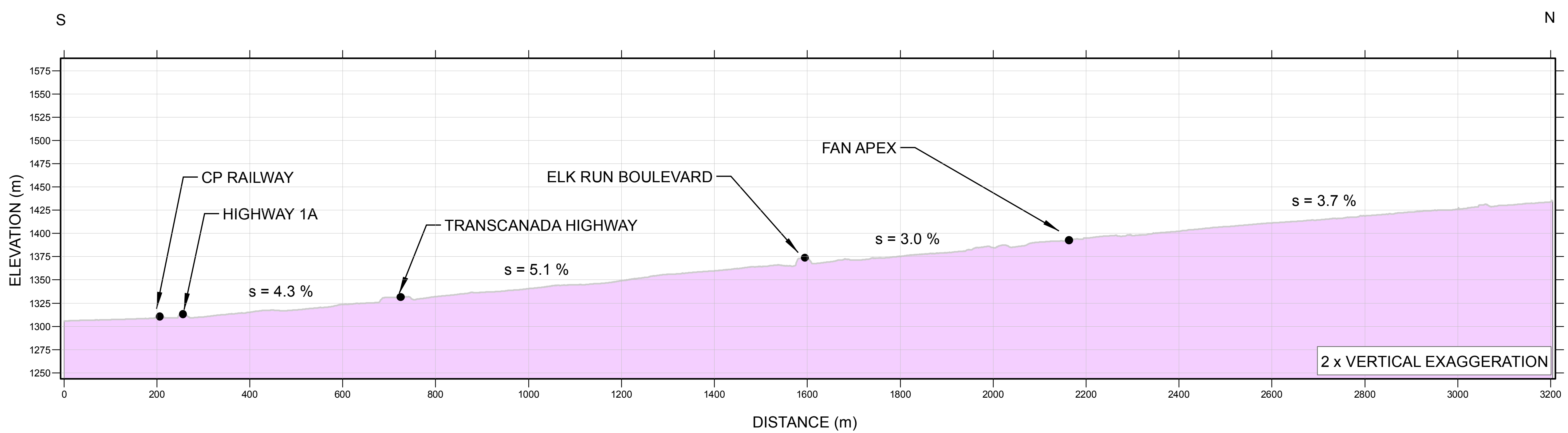
DWG TO BE READ WITH BGC REPORT TITLED "COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION" DATED DECEMBER 2013



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METRES

NOTES:
1. LIDAR DATA COLLECTED BY LIDAR SERVICES INC. (LSI) ON JUNE 28, 2013.
2. STREAM COURSE FROM CANVEC.

REV.	DATE	REVISION NOTES	DRAWN	CHECK	APPR.

SCALE:	1:7000
DATE:	DEC 2013
DRAWN:	JS
DESIGNED:	HW
CHECKED:	MJ
APPROVED:	JC

PROFESSIONAL SEAL:

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: CANMORE

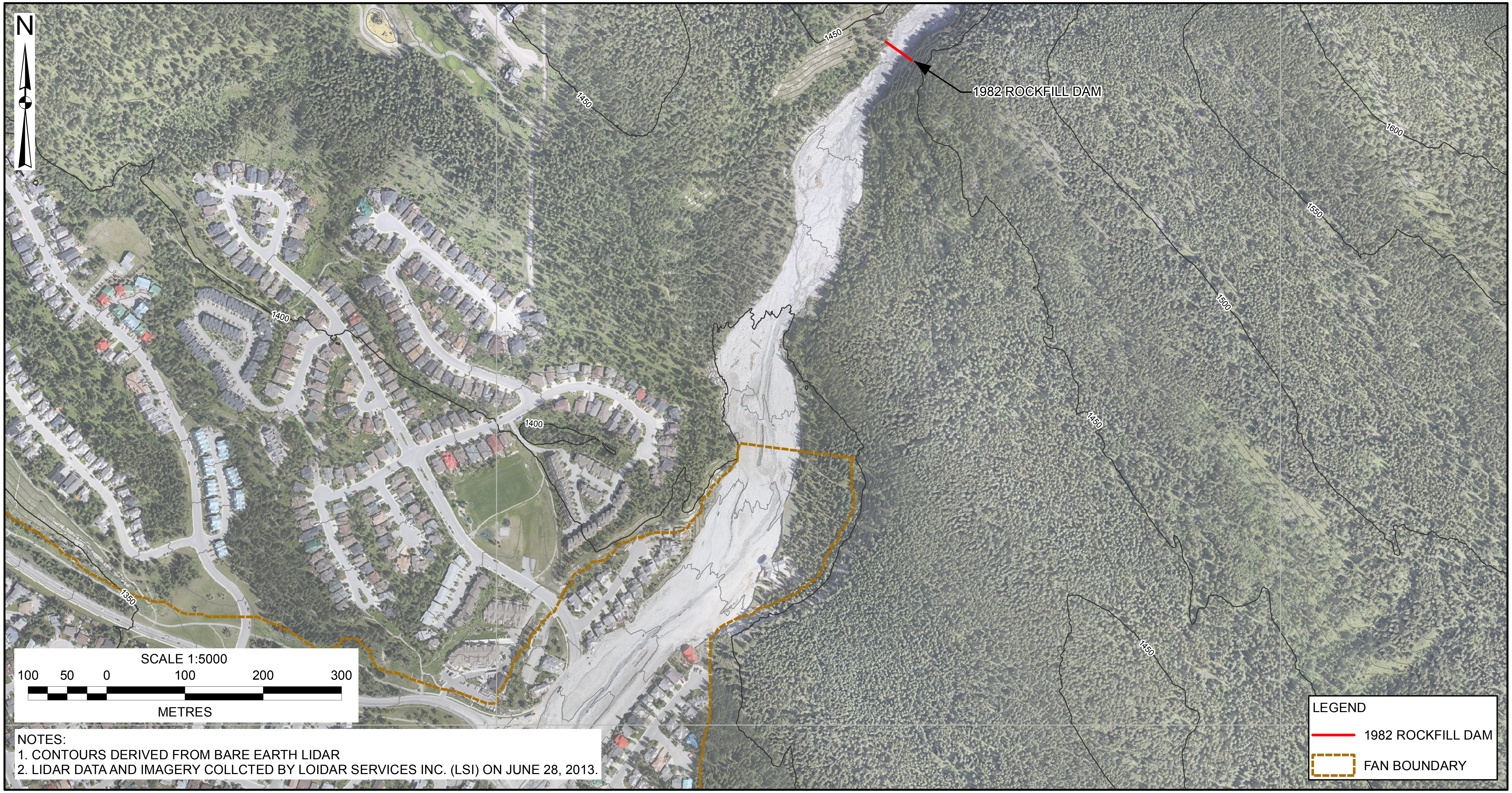
PROJECT: COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION

TITLE: COUGAR CREEK FAN PROFILE

PROJECT No.:	DWG No.:	REV.:
1261001	06	

X:\Projects\1261\001\Workspace\20130828_Report_Cougar_Creek_2013_Forensic_Analysis_And_Short_term_Debris_Flow_Mitigation\06_Profile_Cougar_Creek.mxd

DWG TO BE READ WITH BGC REPORT TITLED "COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION" DATED DECEMBER 2013



5 m CONTOUR INTERVAL (LIDAR 2013)
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REV.	DATE	REVISION NOTES	DRAWN	CHECK	APPR.

SCALE:	1:5000
DATE:	DEC 2013
DRAWN:	JS
DESIGNED:	HW
CHECKED:	MJ
APPROVED:	JC

PROFESSIONAL SEAL:

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

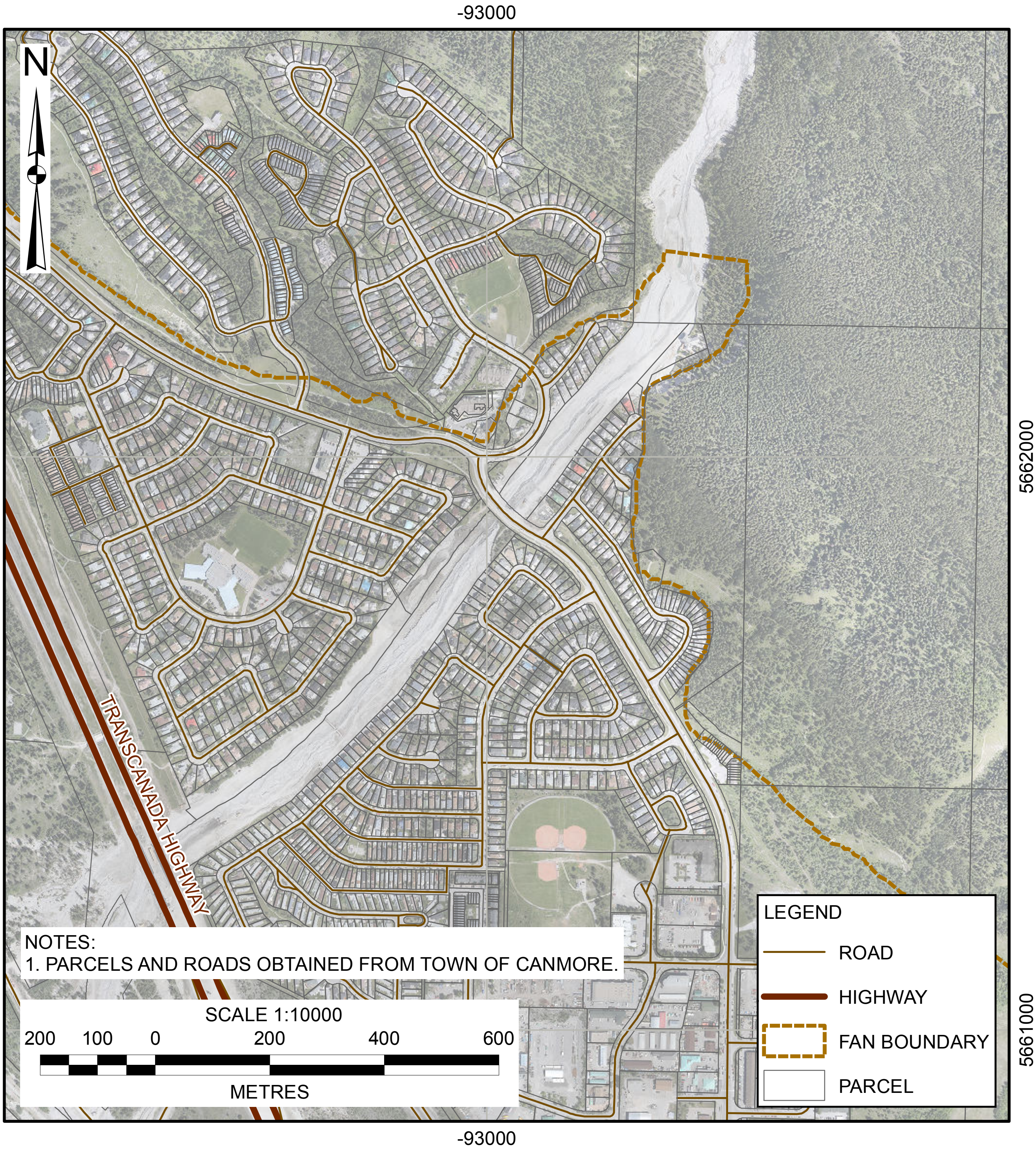
CLIENT: Town of CANMORE

PROJECT: COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION

TITLE: LOCATION OF THE 1982 ROCKFILL DAM

PROJECT No.:	DWG No.:	REV.:
1261001	07	

DWG TO BE READ WITH BGC REPORT TITLED "COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION" DATED DECEMBER 2013



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DATE:	DEC 2013	CHECKED:	MJ
DRAWN:	JS	APPROVED:	JC

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

PROJECT:
COUGAR CREEK, 2013 FORENSIC ANALYSIS
AND SHORT-TERM DEBRIS FLOOD MITIGATION

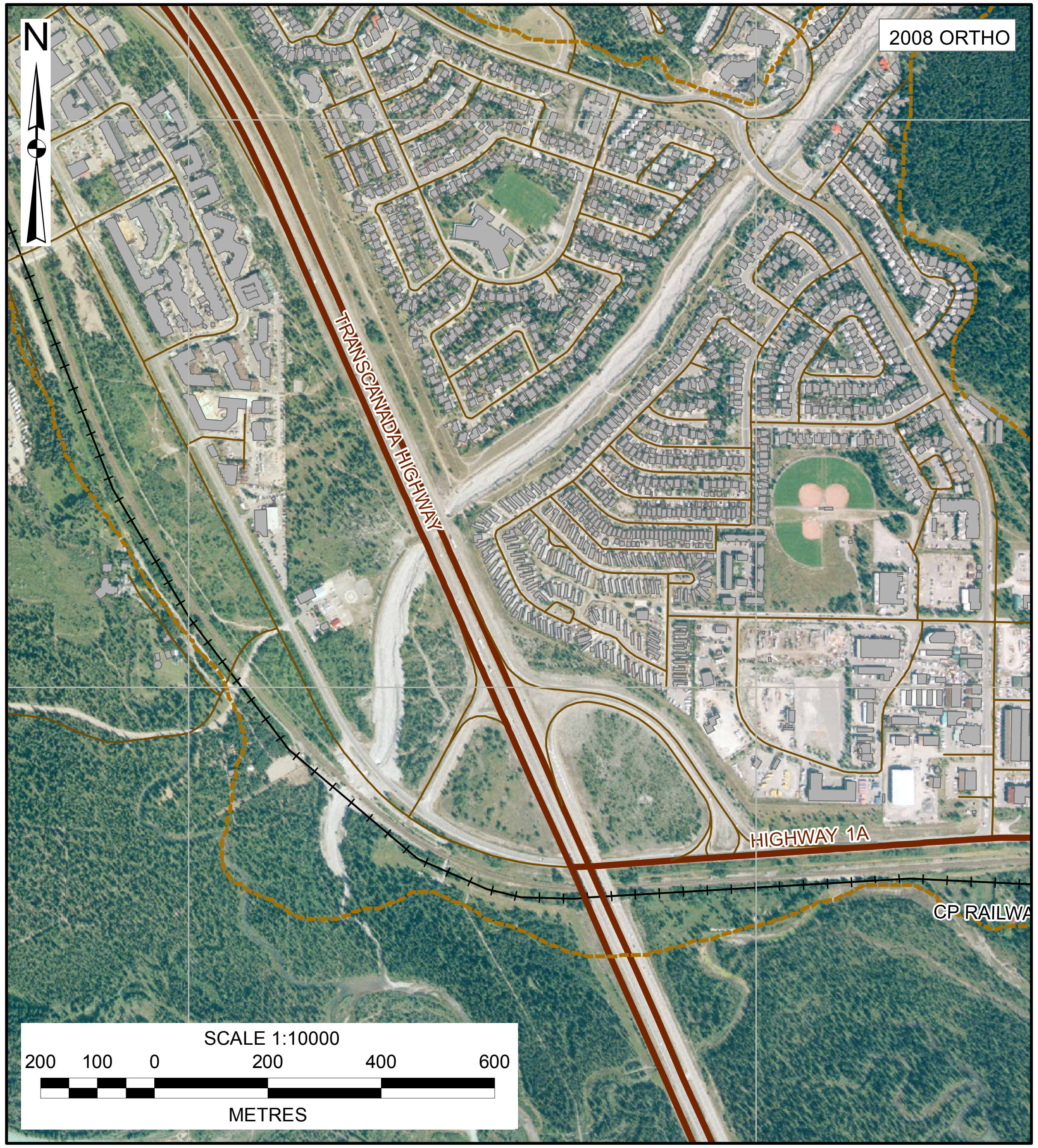
TITLE:
2013 COUGAR CREEK ENCROACHMENT

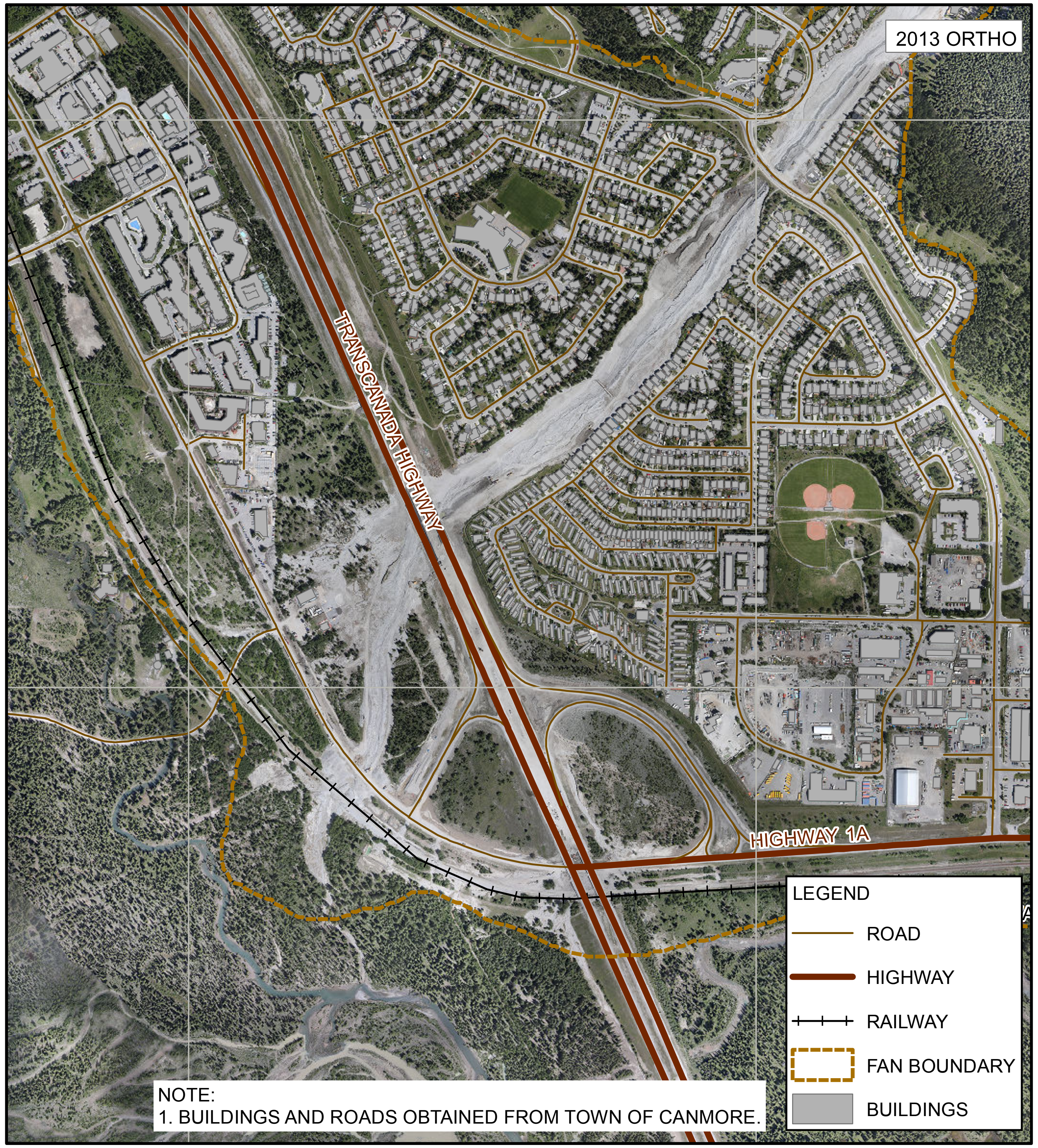
CLIENT: Town of CANMORE

PROJECT No.:	DWG No.:	REV.:
1261001	08	

X:\Projects\1261001\Workspace\20130828_Report_Cougar_Creek_2013_Forensic_Analysis_And_Short_term_Debris_Flow_Mitigation\08_2013_Cougar_Creek_Encroachment.mxd

DWG TO BE READ WITH BGC REPORT TITLED "COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION" DATED DECEMBER 2013





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REV.	DATE	REVISION NOTES	DRAWN	CHECK	APPR.

SCALE:	1:10000
DATE:	DEC 2013
DRAWN:	JS
DESIGNED:	HW
CHECKED:	MJ
APPROVED:	JC

PROFESSIONAL SEAL:

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: Town of CANMORE

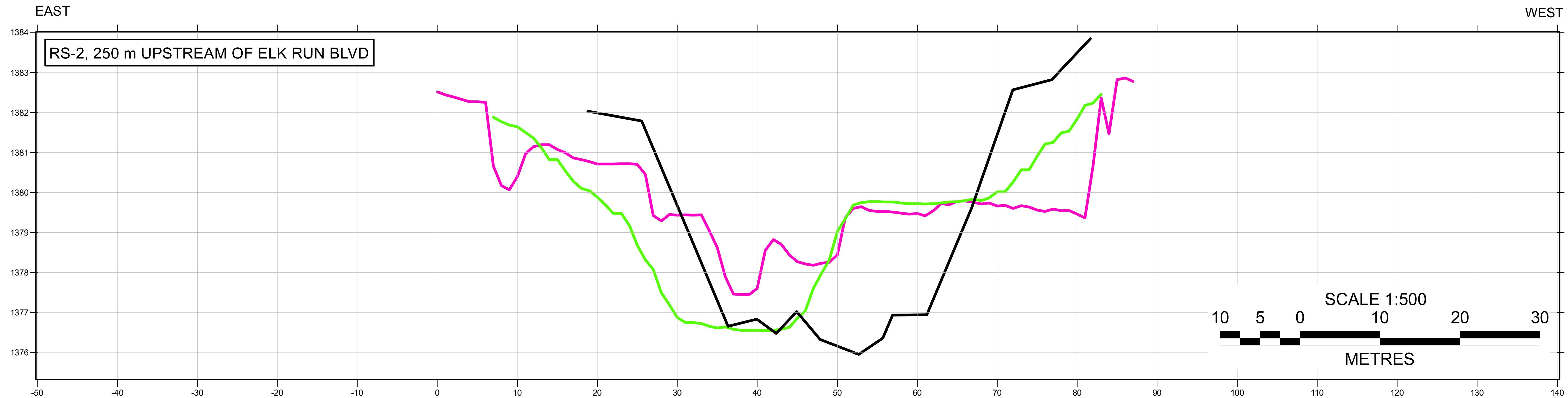
PROJECT: COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION

TITLE: 2008-2013 COMPARISON OF COUGAR CREEK

PROJECT No.:	DWG No.:	REV.:
1261001	09	

X:\Projects\1261001\Workspace\20130828_Report_Cougar_Creek_2013_Forensic_Analysis_And_Short_term_Debris_Flow_Mitigation\09_2008_2013_Comparison_Of_Cougar_Creek.mxd

DWG TO BE READ WITH BGC REPORT TITLED "COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION" DATED DECEMBER 2013

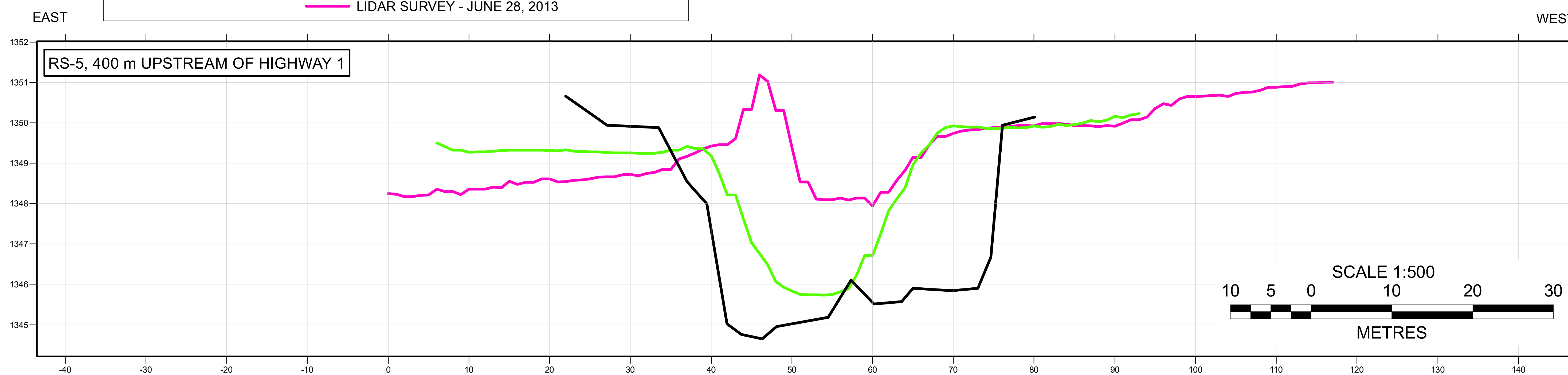


LEGEND

2012 ALPINE SURVEY

POST-RECONSTRUCTION SURVEY - AUGUST 2013

LIDAR SURVEY - JUNE 28, 2013



REV.	DATE	REVISION NOTES	DRAWN	CHECK	APPR.

SCALE:	1:500
DATE:	DEC 2013
DRAWN:	JS
DESIGNED:	HW
CHECKED:	MJ
APPROVED:	JC

PROFESSIONAL SEAL:

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: Town of CANMORE

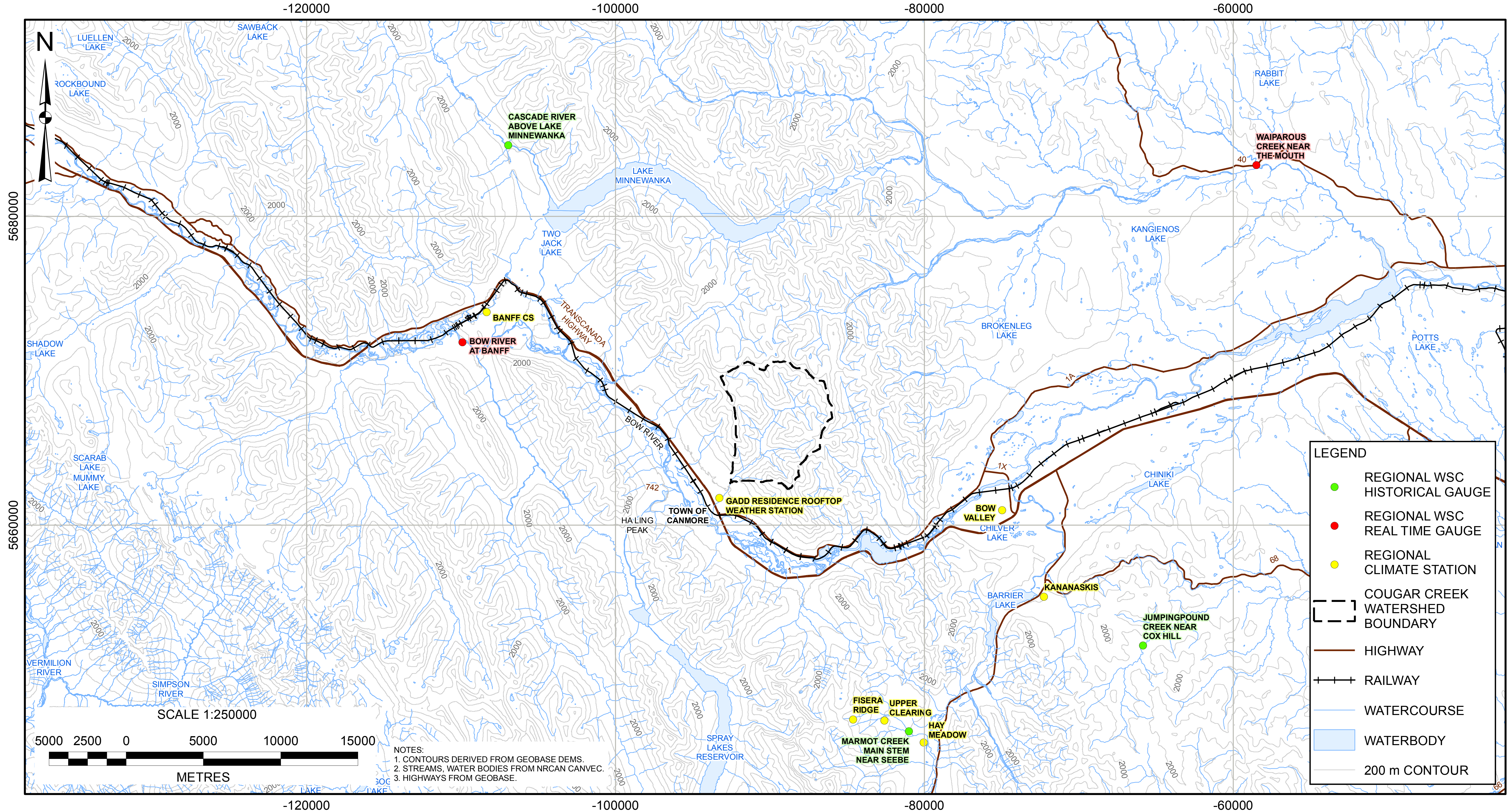
PROJECT: COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION

TITLE: COUGAR CREEK CROSS-SECTION COMPARISON

PROJECT No.:	DWG No.:	REV.:
1261001	10	

X:\Projects\1261\001\Workspace\20130828_Report_Cougar_Creek_2013_Forensic_Analysis_And_Short_term_Debris_Flow_Mitigation\10_Cougar_Creek_Cross_Section_Comparison.mxd

DWG TO BE READ WITH BGC REPORT TITLED "COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION" DATED DECEMBER 2013



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REV.	DATE	REVISION NOTES	DRAWN	CHECK	APPR.

SCALE:	1:250000
DATE:	DEC 2013
DRAWN:	LL
DESIGNED:	AP
CHECKED:	HW
APPROVED:	MJ

PROFESSIONAL SEAL:

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:

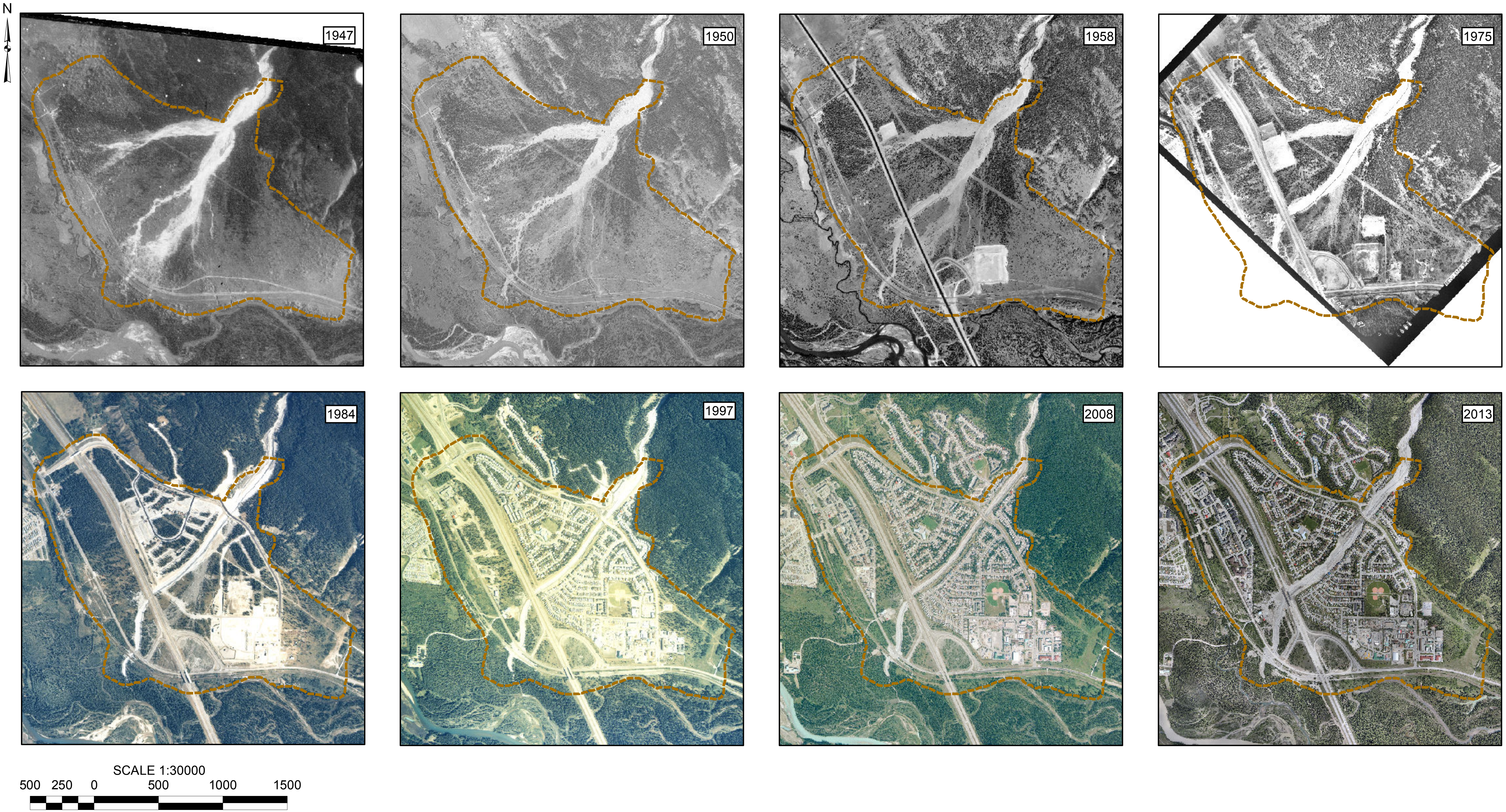
PROJECT: COUGAR CREEK, FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION

TITLE: REGIONAL CLIMATE AND HYDROMETRIC STATIONS

PROJECT No.:	DWG No.:	REV.:
1261001	11	

X:\Projects\1261001\Workspace\20130828_Report_Cougar_Creek_2013_Forensic_Analysis_And_Short_term_Debris_Flow_Mitigation\11_Regional_Climate_and_Hydrometric_Stations.mxd

DWG TO BE READ WITH BGC REPORT TITLED "COUGAR CREEK, FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION" DATED DECEMBER 2013



3TM

REV.	DATE	REVISION NOTES	DRAWN	CHECK	APPR.

SCALE:	1:30000
DATE:	DEC 2013
DRAWN:	JS
DESIGNED:	MJ
CHECKED:	HW
APPROVED:	JC

PROFESSIONAL SEAL:

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: Town of CANMORE

PROJECT: COUGAR CREEK 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION

TITLE: HISTORICAL AIR PHOTO COMPARISON

PROJECT No.:	DWG No.:	REV.:
1261001	12	

X:\Projects\1261001\Workspace\20130828_Report_Cougar_Creek_2013_Forensic_Analysis_And_Short_term_Debris_Flow_Mitigation\12_Fan_Comparison.mxd

DWG TO BE READ WITH BGC REPORT TITLED "COUGAR CREEK 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION" DATED DECEMBER 2013

3TM

X:\Projects\1261\001\Workspace\20130828_Report_Cougar_Creek_2013_Forensic_Analysis_And_Short_term_Debris_Flow_Mitigation\13_1947_Orthophoto_Of_Cougar_Creek_Fan.mxd

REV.	DATE	REVISION NOTES	DRAWN	CHECK	APPR.

SCALE:	1:10000
DATE:	DEC 2013
DRAWN:	JS
DESIGNED:	HW
CHECKED:	MJ
APPROVED:	JC

PROFESSIONAL SEAL:

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

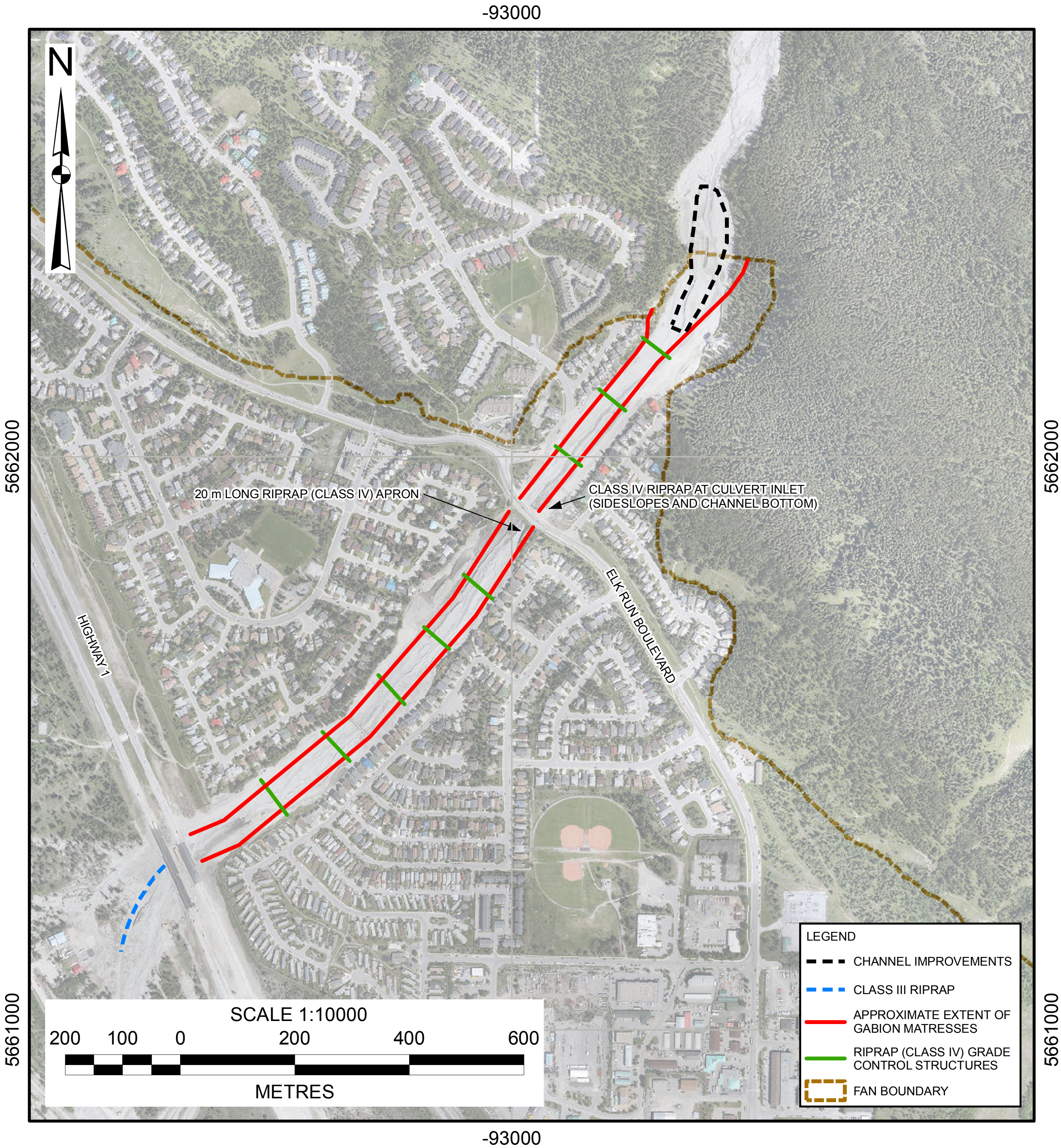
CLIENT: Town of CANMORE

PROJECT: COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION

TITLE: COUGAR CREEK FAN 1947 ORTHOPHOTO

PROJECT No.:	DWG No.:	REV.:
1261001	13	

DWG TO BE READ WITH BGC REPORT TITLED "COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION" DATED DECEMBER 2013



3TM

SCALE:	1:10000	DESIGNED:	HW
DATE:	DEC 2013	CHECKED:	MJ
DRAWN:	JS	APPROVED:	JC

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: Town of CANMORE

PROJECT:
COUGAR CREEK, 2013 FORENSIC ANALYSIS
AND SHORT-TERM DEBRIS FLOOD MITIGATION

TITLE:
CONCEPTUAL SHORT-TERM MITIGATION DESIGN

PROJECT No.:	DWG No.:	REV.:
1261001	14	

X:\Projects\1261001\Workspace\20130828_Report_Cougar_Creek_2013_Forensic_Analysis_And_Short_term_Debris_Flow_Mitigation\14_Conceptual_Short_Term_Mitigation_Design.mxd

DWG TO BE READ WITH BGC REPORT TITLED "COUGAR CREEK, 2013 FORENSIC ANALYSIS AND SHORT-TERM DEBRIS FLOOD MITIGATION" DATED DECEMBER 2013