ALPINFRA ENGINEERING

Town of CANMORE

PIGEON CREEK
DEBRIS FLOOD MITIGATION

OPTION ANALYSIS REPORT
FINAL

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00 CONTENTS

00.01 Figures

01 GENERAL

01.01 Project Background

During the June 2013 storm event, extensive flooding and gravel debris aggradation occurred at the alluvial fan of Pigeon Creek. At Thunderstone Quarry, flooding led to inundation of the lower areas and to damages. Quarried and stockpiled material was also mobilized and carried downstream. Culverts at Highway 1 were partly blocked and avulsions downstream of Highway 1 occurred.

The channel of Pigeon Creek underpasses the exiting exit ramp of the southern lane of Highway 1 which leads to Calgary, the Highway lanes, 2nd Avenue, as well as the new access road to the Rivers Bend Development by means of arch pipe corrugated steel culverts. A set of two culverts is installed at each underpass. Each culvert pairs have a design discharge capacity of 55m^3/s for clear water. However, since the clear water flood discharge of a 100 year 2hour rainfall event is estimated to be approximately 110m^3/s, and 144m^3/s for the 300 year 2hour event, the culverts appear to be undersized for adequate flood discharge. Furthermore, substantial bed load content must be considered, lowering the effective discharge capacity of culverts.

Because flood peak estimates from previous studies are differing substantially from each other, a complementary hydrological analysis was conducted within the current option analysis. Values discussed above are resulting from this investigation.

The quarry, the highway, existing houses and areas currently under development are severely endangered in case of future flood events. Therefore, the Town of Canmore retained ALPINFRA to perform an option analysis of long term mitigation measures.

ALPINFRAS work is based on the BGC Project Memorandum on the Pigeon Creek Forensic Analysis and Short Term Debris Flood Mitigation as well as on the final version of the Pigeon Creek Hazard Assessment, issued by TETRA TECH in November 2016.

01.02 Limitations

ALPINFRA prepared this report for the Town of Canmore. It focuses on the concept for long term hazard mitigation measures. Any use a third party makes of this report or any reliance on decisions based on it, is done within the responsibility of such a third party. The current report on options for mitigation measures does not show a final or detail design. Because of that, ALPINFRA takes no responsibility for damages, if any, suffered by any third party because of decisions made or actions based on this report. ALPINFRA accepts no responsibility for changes in real estate values that may occur as a consequence of this report. In terms of protection to our client, the public, and ALPINFRA, we submit this report as basis for further analysis and detail design work. Authorization outside of this use needs our approval. The report and the design worked out within this concept are to be understood as preliminary. Design drawings are not suitable as basis for permitting or construction but for making decisions. Divergences at assumed geotechnical frame conditions are possible, resulting in the requirement of re-designing current mitigation measures or designing new options.

Town of Canmore Statement of Limitations:

This document represents an assessment of options for mitigation for the anticipated long-term development of the area. The intent of this work is to allow decision makers to understand potential land requirements, mitigation costs, and other impacts of full build-out of development to inform high-level planning activities. Further hazard and risk assessment, conceptual and detailed design of mitigation, and option analysis will be required at the time of development in order to inform any decisions around mitigation and development.

Mitigation requirements for existing development are not addressed in this document and are to be informed by the Tetra Tech EBA Pigeon Creek Hazard Assessment of November 2016 and by the BGC Engineering Pigeon Creek Debris-Flood Risk Assessment of September 2016.

02 PROJECT AREA

02.01 Overview

Pigeon Creek is a mountain creek that drains into the Bow River approximately 8 km southeast of Canmore at Dead Man's Flats. The watershed, 55 km² in total, is nearly entirely located within the Bow Valley Wildlife Provincial Park and reaches from the Rimwall (2,685 MASL) in the west, Wind Mountain (3,153 MASL) in the south and Pigeon Mountain (2,394 MASL) in the east. The watershed consists of three sub-catchments that merge 1 km upstream of the Upper Spray Falls. These are the West Wind Creek, Wind Creek and Pigeon Creek.

Downstream of the Spray Falls, Pigeon Creek flows through Thunderstone Quarries, crosses the Trans-Canada Highway and its exit ramp and flows alongside condominium complexes and developmental area at Dead Man's Flats, where it discharges into Bow River at an elevation of 1,291 MASL.

From the highest altitudes, down to approximately 2,000 MASL, the slopes are almost entirely bare of any vegetation, exhibiting considerable sediment sources. Below 2,000 MASL, the terrain is mainly covered with dense coniferous forest. The Pigeon Creek watershed (red) and its alluvial fan (blue) are outlined in Figure 1. Figure 2 is showing the waterfall and the Thunderstone Quarry. Figure 3 shows the creek directly upstream of the highway ramp.

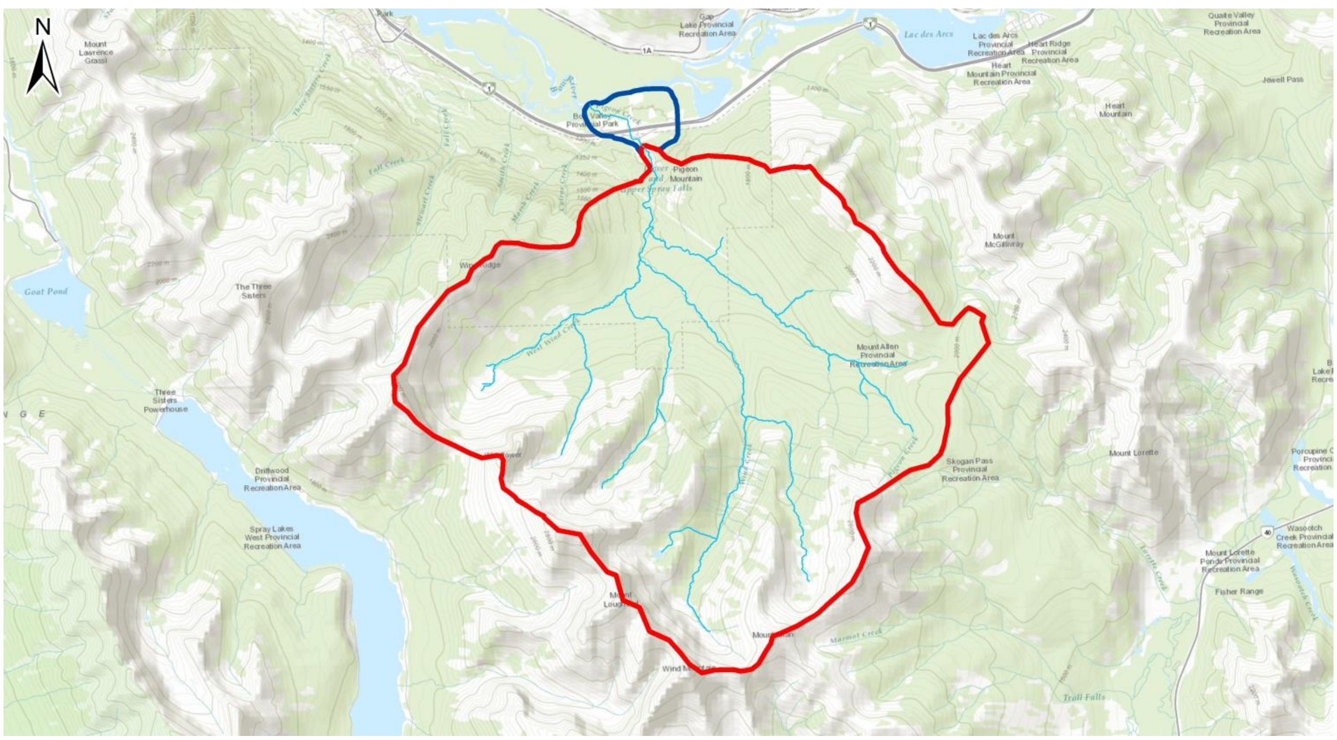

FIGURE 1: LOCATION OF PIGEON CREEK WATERSHED (RED) AND FAN (BLUE) (BASEMAP: ESRI, UNSPECIFIED SCALE)

FIGURE 2: VIEWING NORTH, PIGEON CREEK DOWNSTREAM OF LOWER SPRAY FALL, FLOWING THROUGH THUNDERSTONE QUARRIES

FIGURE 3: VIEW DOWNSTREAM OF THUNDERSTONE QUARRIES TO THE CROSSING OF THE HIGHWAY RAMP

02.02 Current Situation

02.02.01 Channel at Thunderstone Quarry

Within flood recovery works at the Thunderstone Quarry, the channel banks have been stabilized with plain stone pitching as shown in Figure 4.

FIGURE 4: UPDATE OF THE CHANNEL AT THUNDERSTONE QUARRY

02.02.02 Downstream Channel

The channel sections between existing culverts of the highway ramp, Highway 1 and 2nd Avenue, the access road to the Rivers Bend Development, as well as the downstream section have been redesigned by Canadian Hydrotech Corporation for short term mitigation. The final design details can be found in the issued for permitting and issued for construction packages (CHT 2016). This channel update was under construction at the time of the preparation of the current report. The design discharge of the channel update is $55m^3/s$ for clear water discharge according to the design discharge capacity of existing culverts. The state of construction in September 2016 is shown in Figure 6 and Figure 5.

FIGURE 5: STATE OF CHANNEL CONSTRUCTION WORKS IN SEPTEMBER 2016 DOWNSTREAM OF RIVERSBEND ACCESS

FIGURE 6: STATE OF CHANNEL CONSTRUCTION WORKS IN SEPTEMBER 2016 BETWEEN 2ND AVENUE AND RIVERS BEND ACCESS

03 BASIC DATA

03.01 Basic Data Sources

Following basic data sources were provided to ALPINFRA as basis for the option analysis and analyses presented herein.

a) BGC Project Memorandum on the Pigeon Creek Forensic Analysis and Short Term Debris Flood Mitigation.

b) Final Pigeon Creek Hazard Assessment (TETRA TECH November 2016).

c) IDF-Curve for the Kananaskis Climate Station.

d) Bare Earth LiDAR Data with a ground resolution of 1m, recorded at June 28th, 2013 by LSI LiDAR Services International Inc. The data covers 93% of the entire Pigeon Creek watershed.

03.02 Project memo of BGC

The project memo of BGC on the Pigeon Creek Forensic Analysis and Short-Term Debris Flood Mitigation highlights the torrential hazards caused by Pigeon Creek, potentially leading to impacts to the developed area on the Pigeon Creek alluvial fan. BGC is outlining that flood discharge and flood related erosion in the catchment area is leading to inundation and deposition of gravel-debris at the Pigeon Creek fan and the developed area. As outlined in the memo, Pigeon Creek floods and debris floods are mainly induced by heavy rainfall and landslide dam outbreak floods are of minor relevance.

03.03 Hydro-Climatic Analysis of the June 2013 Storm Event from BGC

In BGC’s Hydro-Climatic Analysis (BGC 2014b), available rainfall and precipitation data was collected and summarized. The collected data builds an essential basis for all hydrological calculations presented within the current report.

03.04 Complementary Hydrological Study of ALPINFRA (2015)

ALPINFRA prepared a complementary hydrological study including a bedload transport analysis. It serves as a basis for the discussion regarding flood discharges with other engineering companies and for this option analysis. This hydrological study is now part of the actual option analysis report (see chapter 04).

03.05 Pigeon Creek Hazard Assessment of Tetra Tech (2016)

The study by Tetra Tech contains a geological and hydrogeological characterization of the Pigeon Creek watershed and describes the progress of settlement and development of the alluvial fan. Furthermore, Tetra Tech investigated the June 2013 event and calculated return period-related flood discharges and bedload volumes. Table 1 and Figure 7 are summarizing return period related sediment volumes as stated in TETRA TECH´s report issued in November 2016.

TABLE 1: SEDIMENT VOLUMES ACCORDING TO THE HAZARD ASSESSMENT OF TETTRA TECH (2016)

	Unit Sediment Yield (m^3/km^2)		Sediment Yield (m^3/km^2)	Total Sediment Yield (m^3)
	Three Sisters Creek	Cougar Creek	Pigeon Creek	Pigeon Creek
Drainage Area (km^2)	10	42.9	55	55
Return Period (Years)				
10-30	1,000	700	700	36,000
30-100	1,400	930	1,000	54,000
100-300	1,800	1,400	1,500	74,000
300-1000	2,200	3,730	2,000	100,000
1000-3000	2,600	6,000	2,500	131,000

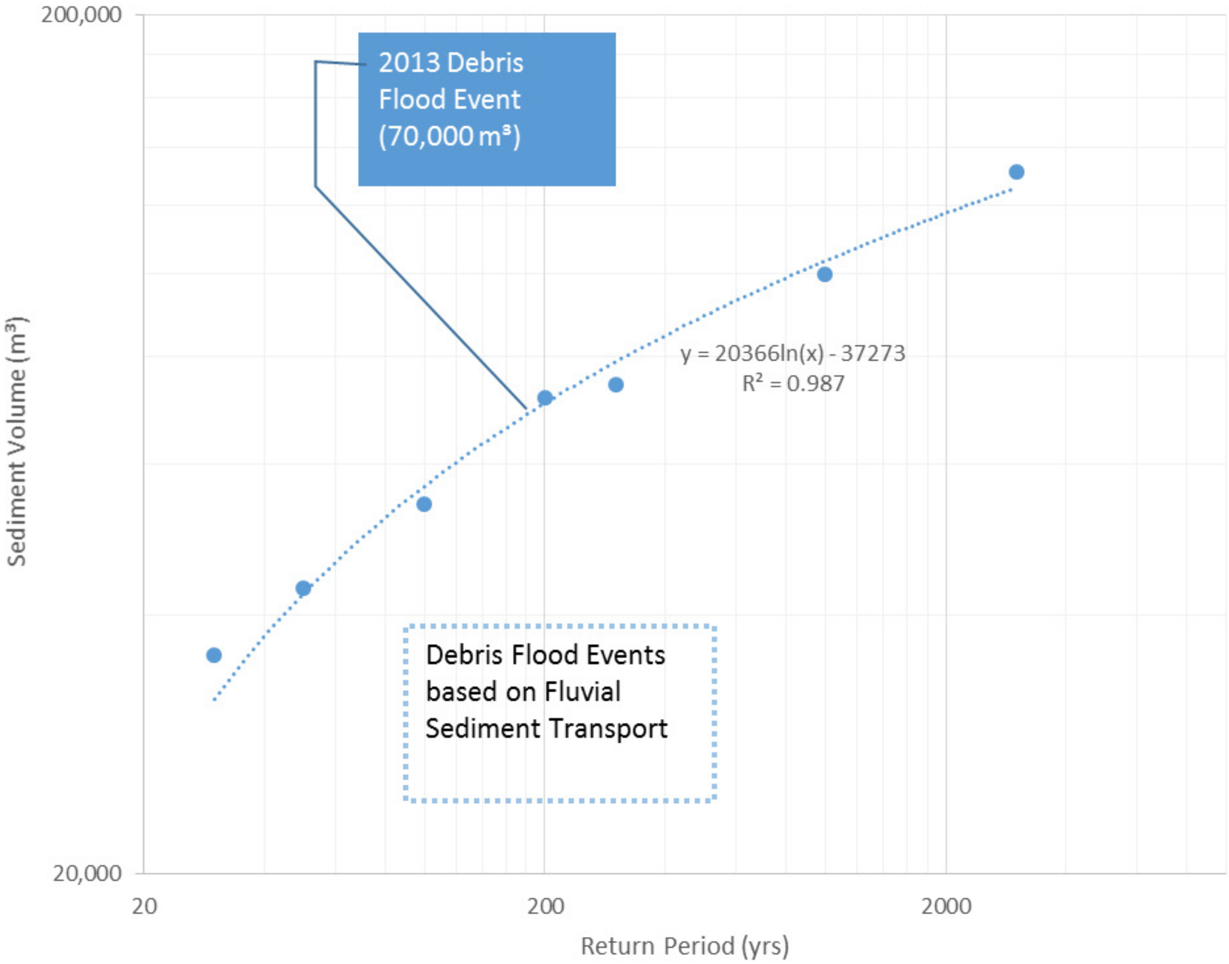

FIGURE 7: SEDIMENT VOLUMES VERSUS RETURN PERIODS FORT HE PIGEON CREEK CATCHMENT

04 COMPLEMENTARY HYDROLOGICAL ANALYSIS

04.01 Methodology

04.01.01 General Approach and Calculation Software

Precipitation discharge models are used for investigating the runoff regime of a watershed under consideration of particular precipitation scenarios and local runoff characteristics and provide hydrographs for the specific precipitation scenarios.

Precipitation discharge analyses presented herein were conducted by means of the software tool Hydrologic Modeling System of the Hydrologic Engineering Center of the US Army Corps of Engineers (HEC-HMS). A detailed description of the model and applied input parameters are available at http://www.hec.usace.army.mil/.

Prior to an initial discharge calculation, specific run-off characteristics were assigned to sub-catchments and the stream sections, based on basic data as listed in chapter 02, geomorphic mapping as well as experience gained from assessments of similar, well-calibrated case studies available to and/or conducted by ALPINFRA. Within further calculation runs calibration and adjustment was done both to reach robust calculation results for different scenarios and to reach accordance with observed maximum discharges at the lower section of the Pigeon Creek.

04.01.02 Model Setup

The calculation parameters were assigned by means of the software module HEC-GeoHMS, a geospatial hydrology toolkit. Thereby, the watershed was divided into sub-catchments and each sub catchment was connected with the neighboring catchment according to flow direction. For each sub-catchment area, parameters for runoff formation, run-off concentration and retention in the channel bed were calculated. Resulting hydrographs are governed by topographic conditions, type of land use, assumed soil texture and forest coverage. The flow resistance in the channel bed is resulting from the stream geometry, the stream inclination and roughness.

The pre-processing procedure was conducted by applying the HEC-GeoHMS toolkit prior to the runoff calculation. Within this procedure, HEC-GeoHMS extracts topographic, topologic and hydrologic information from digital spatial data. Within the next step, the run-off calculation is performed by using the HEC-HMS software. During modelling, constant and recurring checks, as well as adaptions, were made to reach robustness and plausibility. Figure 8 shows the model pattern used which contains the delineated sub-catchments, the channel network and nodes.

04.02 Model Description

04.02.01 Definition of Sub-Catchments

The Pigeon Creek catchment was divided into 29 sub-catchments, with an area of approximately 2 km² each (see Figure 8).

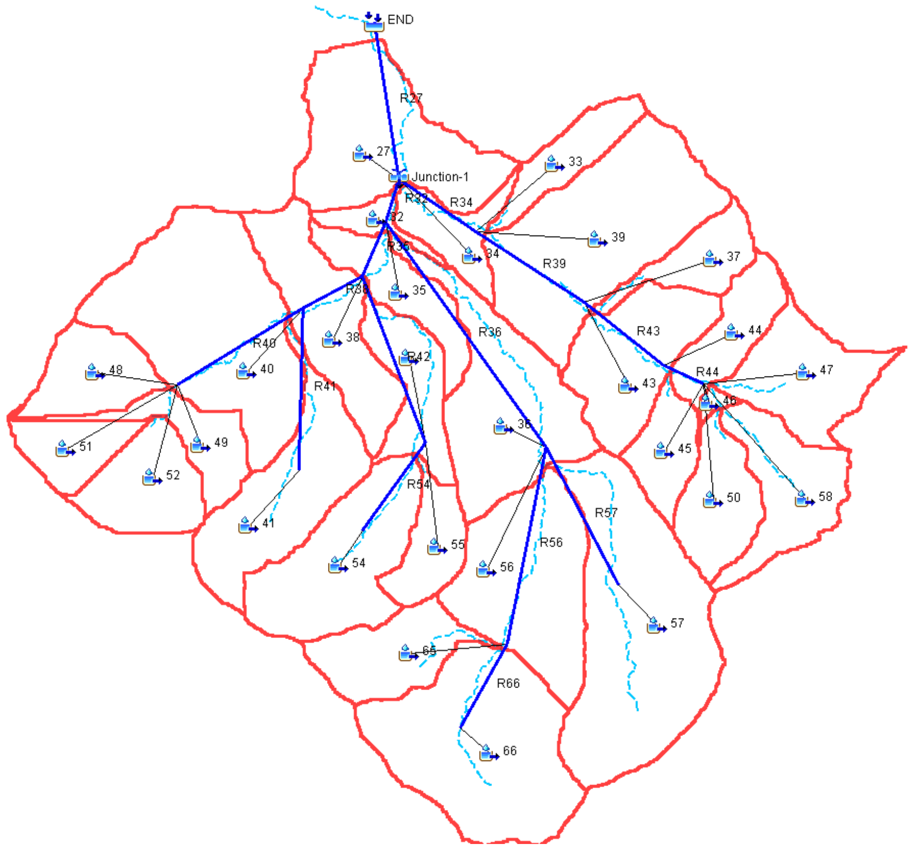

FIGURE 8: GENERAL MODEL SET-UP FOR THE PIGEON CREEK CATCHMENT AREA.

04.02.02 Parameters

04.02.02.01 Curve Number and Initial Abstraction

The Runoff Curve Number (CN-value) is an empirical parameter developed by the Soil Conservation Service (SCS) at the US Department of Agriculture (USDA) and determines the amount of rainfall contributing to direct runoff. The Curve Number depends on the soil type, land use and hydrologic conditions and is the basis for further calculations within the modeling. The higher the Curve Number, the higher is the amount of direct runoff and the lower the amount of water infiltrating into the ground.

The initial CN-values for each sub catchment of Pigeon Creek were determined based on the geologic situation and the vegetation cover.

The initial abstraction describes the amount of water before runoff, theoretically being absorbed by the watershed (infiltrated or stored by interception and evaporation), without increasing the discharge. Initial loss is calculated using the formula:

$$initial\ abstraction\ [mm] = 0.1 \cdot \left(\left(\frac{25{,}400}{CN} \right) - 254 \right)$$

TABLE 2: INITIAL LOSS VALUES DEPENDING ON THE CN-VALUE

SCS Curve Number	Initial abstraction [mm]
40	38.1
50	25.4
60	16.9
70	10.9
80	6.4

04.02.02.02 Base-flow

The base flow describes the amount of discharge added to the stream by groundwater inflow. During short term floods or rapidly rising floods, the base flow which is reaching the stream is temporarily delayed, and thereby this effect reduces the peak discharge. The "recession base flow method" was applied within the current analyses.

04.02.02.03 Time of concentration

The time of concentration was individually determined for each sub-catchment area according to the approach developed by Kirpich (Maniak, 1993).

The appropriate determination of the time of concentration is essential to compute realistic overall results both for the whole watershed and for the sub-catchment areas. Significant differing precipitation conditions can occur at different areas of a catchment area.

04.02.02.04 Dynamic factor of loss

By calibrating and back calculating a number of precipitation runoff analyses, considerable experience was gained for determining loss-factors based on an algorithm by Koehler (Koehler, 1999). According to Koehler, the effective precipitation changes with the event duration and intensity. The ratio of precipitation that effectively is being discharged increases linearly at the early stage of a runoff event. However, after a certain time this ratio remains constant. Koehler's approach respects the increase of the discharge coefficients with increasing rainfall duration, as well as their dependence on rainfall intensity (Nachtnebel, 2007).

Thereby, the runoff coefficient develops dynamically. The initial runoff coefficient, which depends on pre-wetting and specific region characteristics, increases with progressive rainfall until the maximum value is reached. From this stage on, the value remains constant.

Applying this method, CN-values were assigned to each sub-catchment area, based upon preceded rainfall and on the characteristics of the sub-catchment areas as listed in Table 3. The SCS method adapts the originally assigned CN-value by including antecedent moisture conditions.

Furthermore, an increase rate for the precipitation related runoff coefficients was estimated based on similar case studies where back analysis was done. The increase rate takes into account that direct runoff increases with precipitation. The longer the precipitation lasts, the more soil-saturation and the less infiltration takes place. The increase rate depends primarily on the rainfall duration and, to a lesser extent, on the rainfall intensity. The initial run-off parameters assumed within the current assessment are listed in Table 3.

TABLE 3: CALCULATION PARAMETERS RELATED TO A RETURN PERIOD OF 100 YEARS AND A PRECIPITATION DURATION OF 5HOURS

subbasin	area km²	% forest cover	CN	start run-off coefficient	max run-off coefficient	Initial loss mm	subbasin	area km²	% forest cover	CN	start run-off coefficient	max run-off coefficient	Initial loss mm	subbasin	area km²	% forest cover	CN	start run-off coefficient	max run-off coefficient	Initial loss mm	subbasin	area km²	% forest cover	CN	start run-off coefficient	max run-off coefficient	Initial loss mm
27	3.09	95%	61	0.07	0.36	32.3	39	4.06	90%	62	0.08	0.38	30.9	47	1.76	90%	62	0.08	0.38	30.9	56	2.97	10%	80	0.33	0.60	12.9
32	0.38	100%	60	0.06	0.35	33.9	40	4.38	70%	67	0.12	0.44	25.5	48	1.23	10%	80	0.33	0.60	12.9	57	4.85	10%	80	0.33	0.60	12.9
33	0.91	95%	61	0.07	0.36	32.3	41	2.53	15%	79	0.31	0.59	13.7	49	1.00	20%	78	0.29	0.57	14.7	58	1.68	95%	61	0.07	0.36	32.3
34	0.88	100%	60	0.06	0.35	33.9	42	1.26	100%	60	0.06	0.35	33.9	50	1.30	50%	71	0.18	0.50	20.7	65	1.44	0%	82	0.38	0.62	11.2
35	1.18	100%	60	0.06	0.35	33.9	43	2.06	95%	61	0.07	0.36	32.3	51	0.87	0%	82	0.38	0.62	11.2	66	4.05	0%	82	0.38	0.62	11.2
36	2.97	100%	60	0.06	0.35	33.9	44	1.07	40%	73	0.21	0.52	18.6	52	1.42	0%	82	0.38	0.62	11.2							
37	0.91	40%	73	0.21	0.52	18.6	45	0.87	90%	62	0.08	0.38	30.9	54	2.60	0%	82	0.38	0.62	11.2							
38	2.16	95%	61	0.07	0.36	32.3	46	0.10	100%	60	0.06	0.35	33.9	55	0.92	0%	82	0.38	0.62	11.2							

04.02.02.05 Flood Routing

For calculating stream and overland flow, the Muskingum-Cunge method was applied. This method is based on topographic data and stream profiles.

04.02.03 Precipitation Data

The precipitation data was extracted from the hydro-climatic analysis of the June 2013 storm event (BGC 2014a). The intensity-duration-frequency curve (IDF-curve) for the nearby Kananaskis station is shown in Figure 9. This figure shows the rainfall intensities for different durations and return periods. In general, the intensities decrease with increasing rainfall duration.

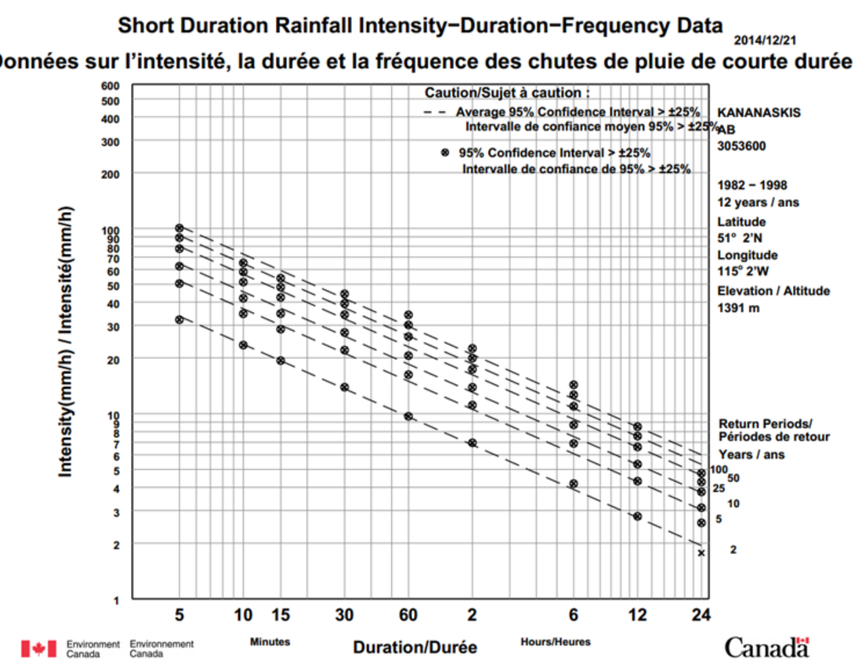

FIGURE 9: IDF CURVE, KANANASKIS CLIMATE STATION

The values shown in the IDF-curve are the maximum values for a certain scenario and are technically only valid for a single point. Because the rainfall intensity is not equal at each point of the catchment area, a reduction factor has to be applied for bigger watersheds. In this case, the reduction of the rainfall intensities was neglected because the Pigeon Creek watershed can be seen as a relatively small and considerably high rainfall intensities have to be reckoned with.

04.02.03.01 Deriving effective Rainfall

The effective rainfall is the amount of the total rainfall that is converting into discharge. The effective rainfall is computed by the total rainfall minus all losses described in the chapters above (initial abstraction and watershed storage expressed in the runoff coefficient). The result represents the volume of water discharged over a certain period. This period is determined by the rainfall duration.

The resulting average discharge coefficient for the overall catchment area at the beginning of the applied rainfall is between 0.06 and 0.38. The discharge parameters, assigned within the current assessment, are based upon the assumption of high pre-precipitation and resulting pre-saturation.

04.03 Back Calculation of the June 2013 Storm Event

Since no precipitation records are available at the Kananaskis climate station for the June 2013, the records from the closest nearby stations at the Marmot Basin (see Figure 11) were taken into account.

BGC derived a maximum peak discharge of 105 cubic meters per second (cms) at the lower section of Pigeon Creek, close to and upstream of the waterfall. This value is credible since the analyzed creek section shows clear indications of the maximum flow height (see Figure 10) and the channel section is formed of bedrock (BGC, 2015). Figure 10 shows a profile with indicated maximum flow height of Pigeon Creek above the fan apex (see page 6 in the Forensic Analysis report of BGC, 2015). The average channel gradient on the fan is 2.3%.

FIGURE 10: SECTION AT PIGEON CREEK INDICATING THE MAXIMUM FLOW HEIGHT ON JUNE 2013 (FIG. 6-3 BGC 2015)

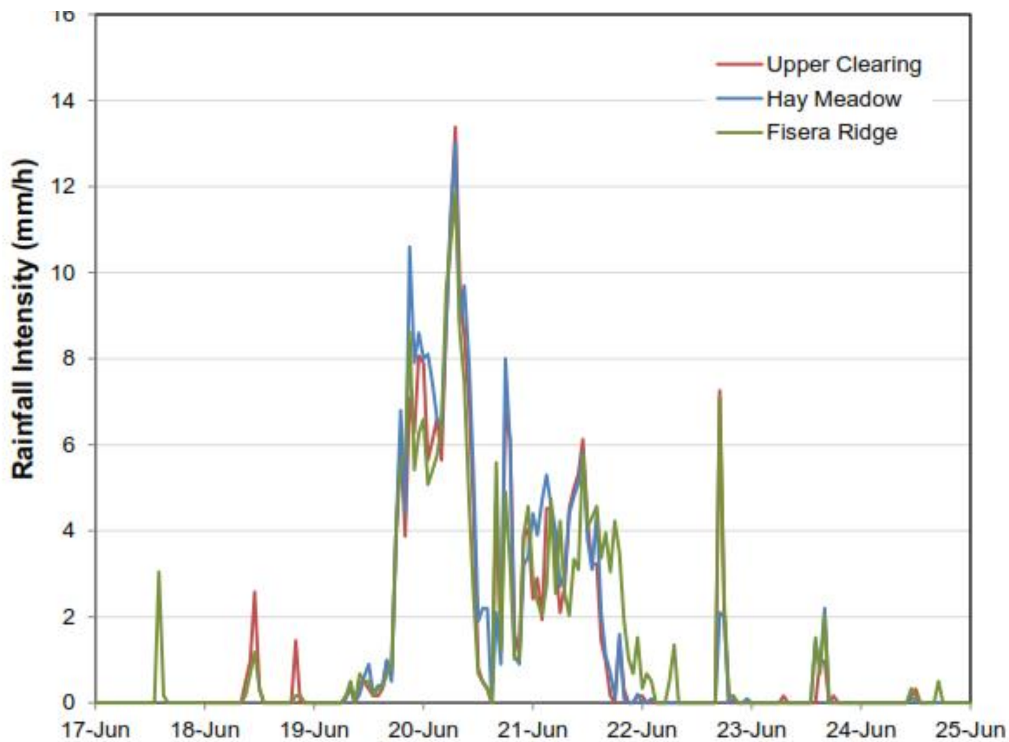

FIGURE 11: HOURLY RAINFALL INTENSITY FOR THE JUNE 2013 EVENT, RECORDED AT CLIMATE STATIONS IN THE MARMOT BASIN

Processing the recorded precipitation data from climate station in the Marmot Basin for the June 2013 event, by means of the model described in chapter 04.01, results in a peak discharge of 103.9cms (see Figure 12).

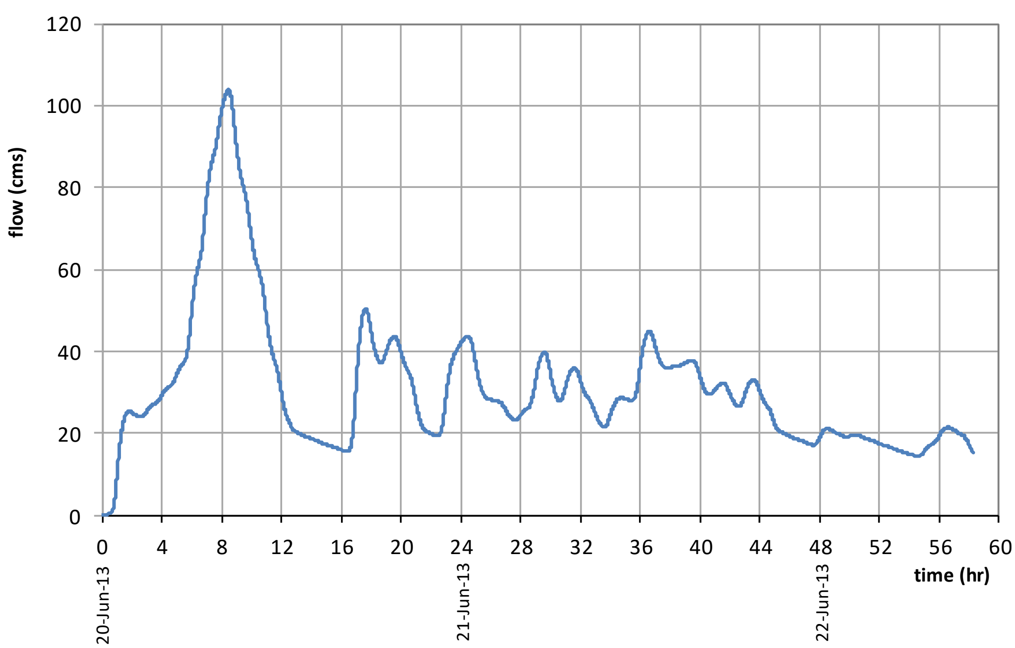

FIGURE 12: CALCULATED DISCHARGE HYDROGRAPH FOR THE JUNE 2013 EVENT FIGURE 11.

04.04 Derivation of Design Floods

For deriving inflow scenarios representing design floods with a statistical recurrence time of 100 years and 300 years, synthetic block rainfall events with durations between 1 hour and 48 hours have been modeled. Rainfall intensities were extrapolated from the IDF curve shown in Figure 9, which is based on data from Kananaskis climate station.

The model was built up based on the principles as outlined in chapter 04.02. Figure 13 shows the design discharge hydrographs resulting from modeling a 2 hour, 5 hour and 9-hour rainfall, all related to a return period of 100 years. The synthetic hydrograph is located at the fan apex of Pigeon Creek, approximately at the water fall. Figure 14 shows results for a return period of 300 years. Table 4 summarizes calculated peak discharges for return periods of 100 years, 300 years, as well as 1,000 years.

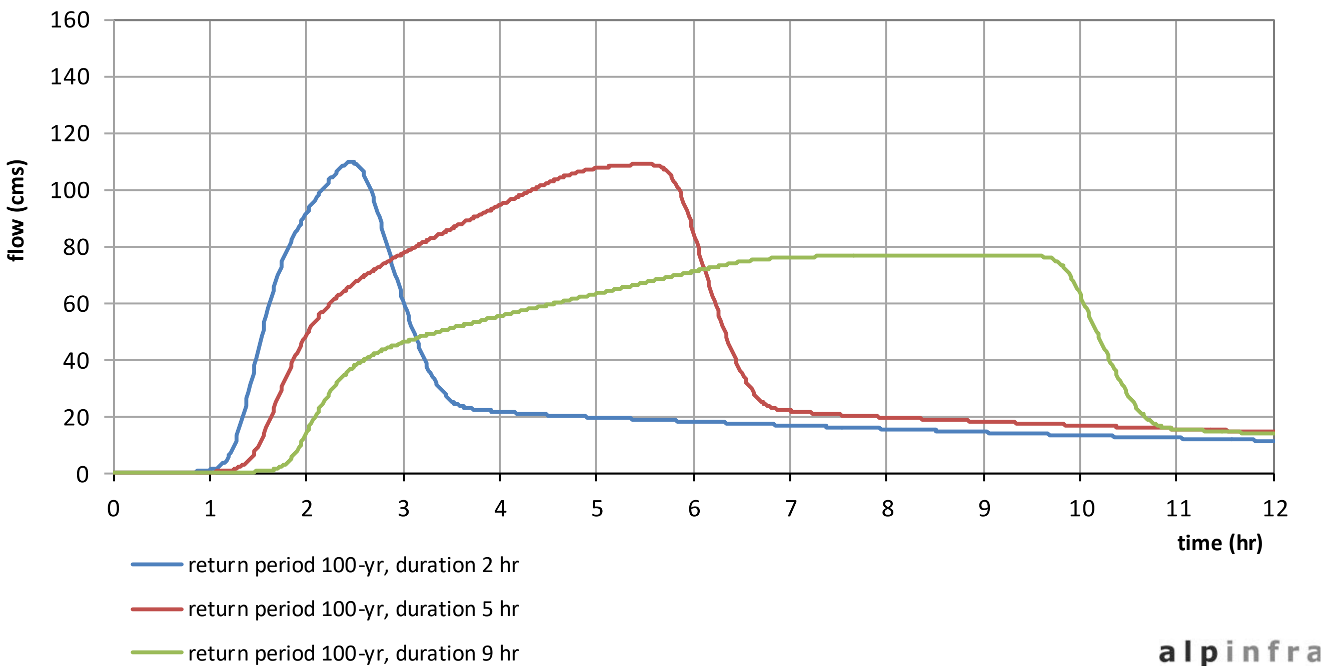

FIGURE 13: DESIGN DISCHARGE HYDROGRAPHS AT THE FAN APEX LOCATION FOR A RETURN PERIOD OF 100 YEARS

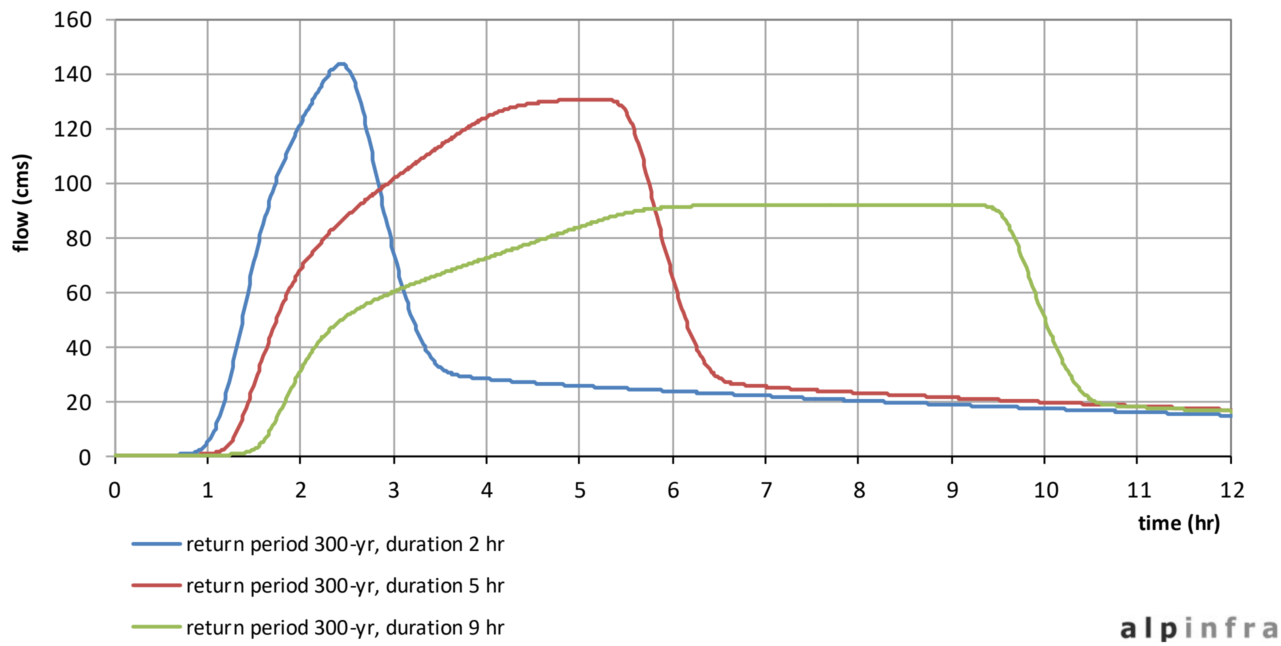

FIGURE 14: DESIGN DISCHARGE HYDROGRAPHS AT THE FAN APEX LOCATION FOR A RETURN PERIOD OF 300 YEARS

TABLE 4: RESULTS OF THE CALCULATED RETURN PERIOD RELATED PEAK DISCHARGES

Scenario	**100 years**	**300 years**	**1000 years**
Rainfall Duration	Peak Discharge [cms]	Peak Discharge [cms]	Peak Discharge [cms]
2 hours	109.6	143.6	189.7
5 hours	108.8	130.7	158.5
9 hours	76.6	92.0	109.4
12 hours	62.7	75.0	88.5
24 hours	45.2	57.6	68.1
48 hours	28.6	41.0	48.4

04.05 Investigation of the Highway 1 Culverts

The arch pipe corrugated steel culvert sets (2 culverts at each crossing) at the highway ramp and the crossings downstream are specified with a discharge capacity of 55m³/s.

FIGURE 15: HIGHWAY 1 CULVERTS IN MARCH 2015 (LEFT), CULVERT AT THE RAMP IN AUGUST 2015 (RIGHT)

Based on the results of the hydrological assessment discussed above, the culverts are capable of discharging flood events with estimated return periods in a range of 10 to 25 years (see Figure 16). Because bedload content has to be a considered during flood events, it is very likely that gravel debris would aggrade in front of the culverts, reducing their discharge capacity substantially.

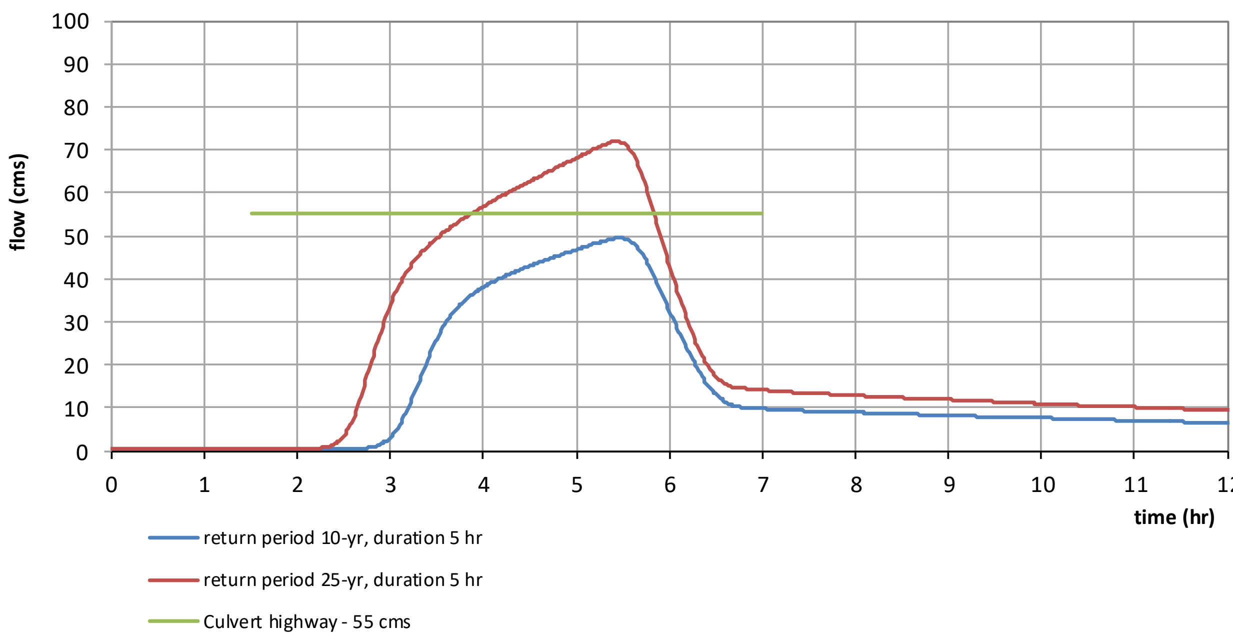

FIGURE 16: CULVERT HIGHWAY 1 - 55 CMS CORRESPONDS TO A RETURN PERIOD OF 10-25 YEARS

04.06 Bed Load Modeling

04.06.01 General Aspects

The assessment of bed-load transport in debris floods is one of the most challenging tasks in hydrological studies. The reliability of results strongly depends on the availability of sediment volume records for past floods and the possibility of calibrating models. For bedload transport estimation, several approaches are available; most of them are based on the early work of Smart und Jäggi (1983). This analysis uses the approach of

Rickenmann (1990), who adopted the formula of Smart and Jäggi (1983) based on extensive empirical flood studies conducted on steep creek alluvial fans in Switzerland.

Ahead of bedload transport analyses in this study, a geomorphologic analysis was conducted for identifying potential active sediment sources contributing to bedload during floods. In addition, the sediment which was aggraded at the alluvial fan during the June 2013 event was characterized granulometrically by means of a detailed photo analysis. The topographical basis is a high-resolution LIDAR data set.

For sedimentological homogeneous creek sections, upstream of the waterfall, the bed-load discharge was calculated by applying discharge scenarios as discussed in chapter 04.04. Erodible sediment has been taken into account according to the geomorphic map (see Drawing No. 16515-GEO001-00 and 16515-GEO002-00), indicating potential and active erosional scars, and erosion gullies.

04.06.01.01 The Process of Sediment Mobilization

In general, gravel under-saturated (sediment-poor) flood discharge, and in particular clear water discharge, will pick-up sediments until saturation is reached (high sediment take). The sediment take depends on the sediment pre-saturation of the flood discharge, the actual flow regime, and the grain sizes of the sediment. Selective mobilization of grain sizes can take place. Smaller grains are getting eroded and mobilized at lower flow velocities and are kept dispersed longer than bigger components. If the amount of gravel is limited, the discharge cannot be saturated to the potential saturation limit. This is relevant just in very few cases and normally there is an excess of potential available sediment. If saturation is reached, no more sediment take is possible. However, undercutting of slopes is then possible, which sometimes results in slope failure and channel blockages. This consequently can change the flow regime of the creek.

04.06.01.02 The Process of Aggradation

At lower flow velocities, as a consequence of a decrease in gradient or widening of the creek bed (enlargement of the hydraulic radius), saturation limit becomes lower and aggradation takes place. Aggradation tendencies are sometimes leading to an increase of gradient at the downstream section of the aggradation area and to remobilization of aggraded material. The dynamics of erosion and aggradation are complex and strongly influenced by the geotechnical frame conditions, but in most cases driven by the actual discharge. A detailed discussion of the bedload transport formulas is available in Rickenmann (1990).

04.06.02 Back Calculated Sediment Volumes of the June 2013 Event

The back calculated June 2013 event, as shown in Figure 12, was combined with a bedload calculation according to the approach of Rickenmann (1990). The calculation gives an overall debris volume of approximately 80,000m³, potentially passing the waterfall directly upstream of the Thunderstorm Quarry. Because of the existing topography, it must be assumed that a substantial portion was aggraded at the alluvial fan and a portion of the sediment was transported into and flushed downstream by the Bow River. Figure 17 is showing the discharge and related overall bedload volume estimated for the June 2013 event at the waterfall.

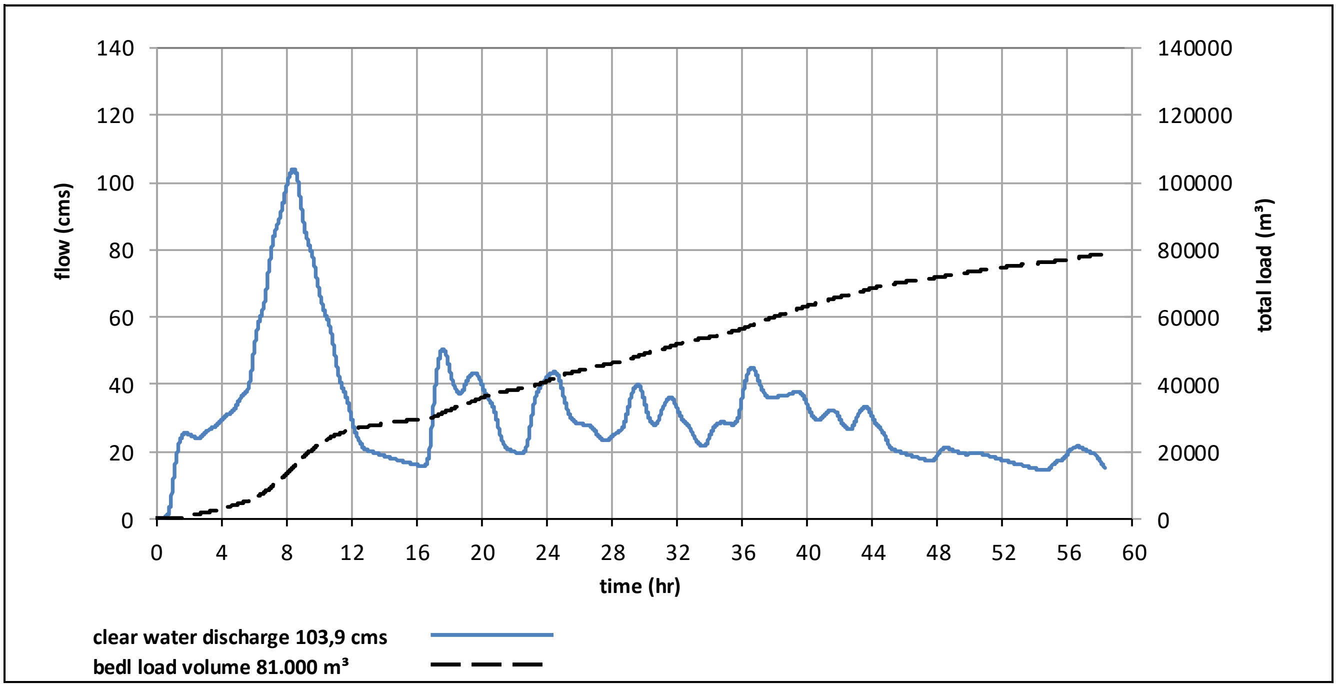

FIGURE 17: CALCULATED DISCHARGE HYDROGRAPH AND DERIVED BED LOAD VOLUMES FOR THE JUNE 2013 EVENT AT PIGEON CREEK ALLUVIAL FAN.

04.06.03 Calculation of Design Bedload Volumes

Applying the approaches as outlined above, a 100 year, 5-hour rainfall event results in an overall debris volume estimate of close to 25,000 m³ (see Figure 18). A 100 year 24-hour rainfall event results in a debris volume estimate of 59,000 m³ (see Figure 19). Table 4 is summarizing calculated peak discharges for all analyzed scenarios.

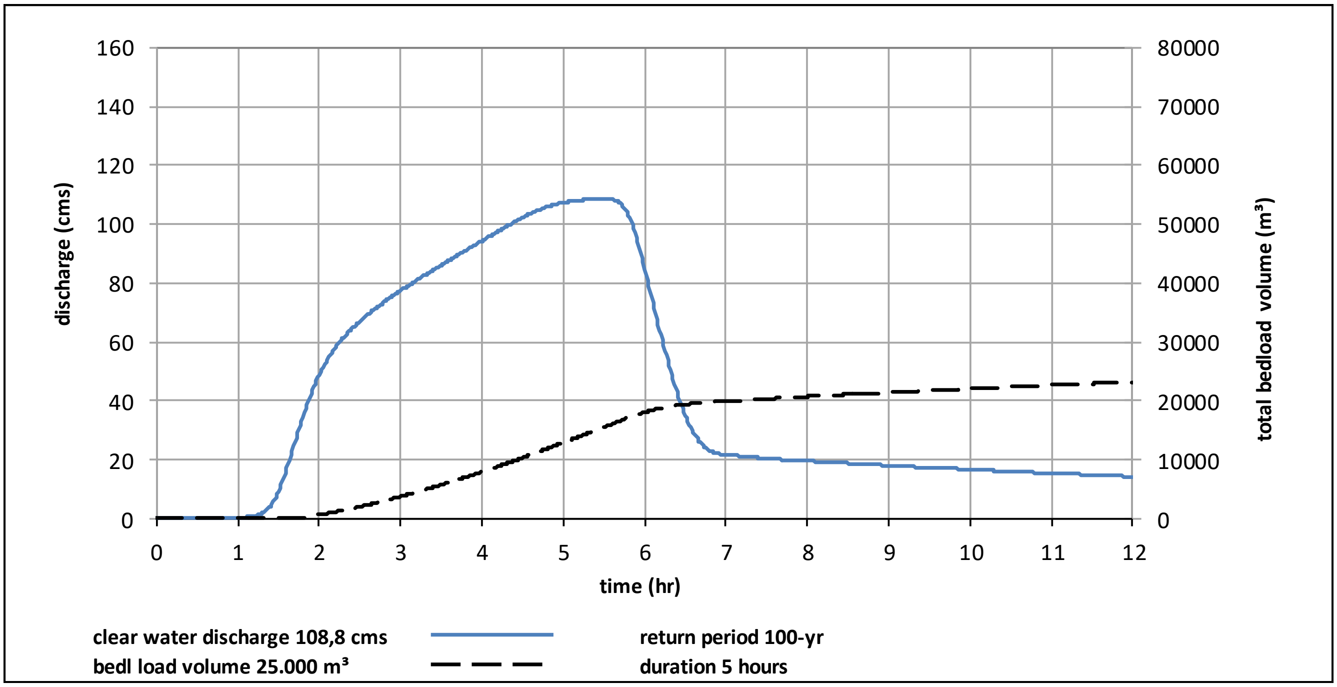

FIGURE 18: CALCULATED DISCHARGE HYDROGRAPH AND BED LOAD FOR A 5-HR, 100-YEAR RETURN PERIOD RAINFALL SCENARIO

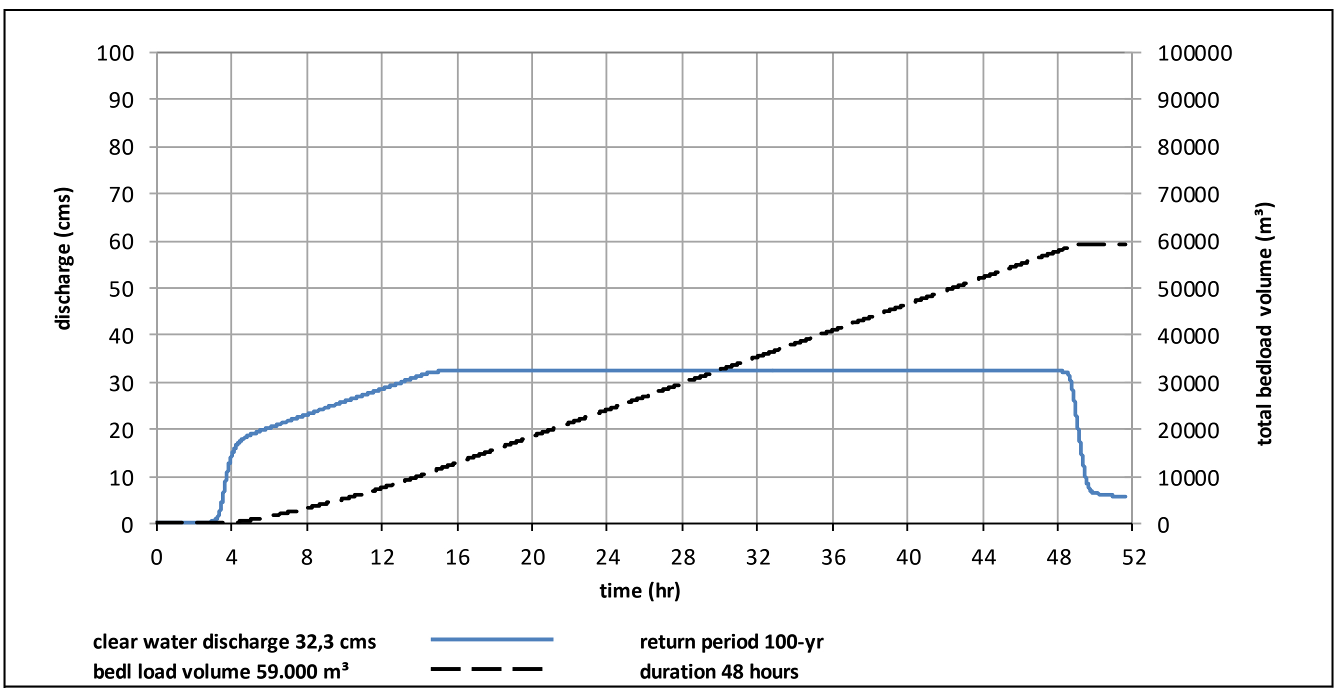

FIGURE 19: CALCULATED DISCHARGE HYDROGRAPH AND BED LOAD FOR A 24-HR, 100-YEAR RETURN PERIOD RAINFALL SCENARIO

04.06.04 Effect of Climate Change Considerations

The bedload volumes as shown in Figure 20 were calculated based on a 12-hour rainfall event considering the moderate climate change scenario RCP 4.5 (Representative Concentration Pathway where radiative forcing peaks at 4.5 W/m2 by the year 2100) (IPCC 2014). RCP 4.5 provides a future concentration scenario that would lead to moderate climate change severity. Applying the RCP 4.5 scenario results in an increase of precipitation for a 12-hour rainfall scenario from 102 mm to 119 mm. This is an increase of approximately 17%.

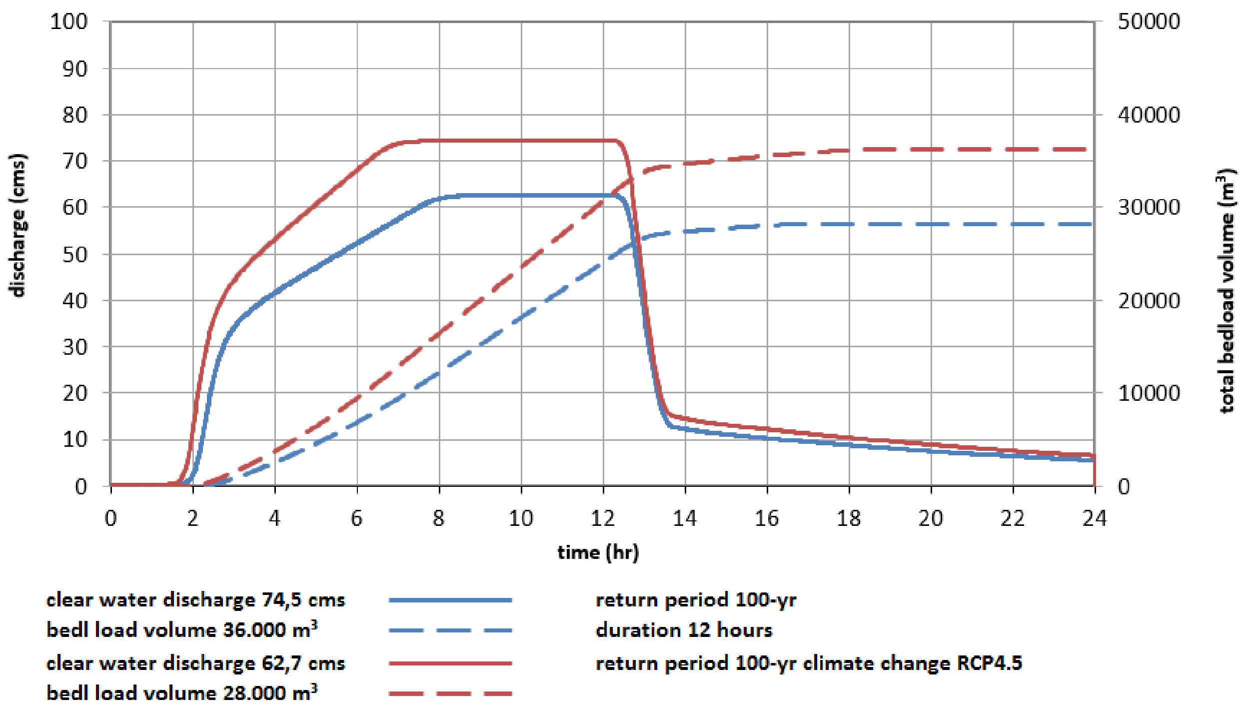

FIGURE 20: RUN-OFF AND BEDLOAD VOLUMES FOR A 12-HR, 100-YR RETURN PERIOD RAINFALL SCENARIO, CONSIDERING CLIMATE CHANGE

Taking the RCP 4.5 climate change scenario into account, the peak discharge of a 12-hour precipitation event with a return period of 100 years would increase by 19%, from 62.7 cms to 74.5 cms. The bedload transport would increase by 27% from 28.000 m³ to 36.000 m³. This shows that the increased discharge, possibly caused by climate change effects, leads to a proportionally higher increase of bedload transport that has to be considered.

05 GEOMORPHIC MAPPING

As a rough and first basis for the estimation of mobilizable sediment volumes, and the general geomorphic process activity of the catchment, a geomorphic map was produced. It displays main scarps, rill erosion, slope erosion, areas affected by deep seated sagging and related tension cracks, as well assoil creeping. The related maps are the drawings 16515-GEO001-00 and 16515-GEO002-00.

06 BRIEF DESCRIPTION OF INVESTIGATED MITIGATION OPTIONS

Within the development of mitigation options, two general strategies have been investigated as listed below.

Options A and B

These options would only retain sediment, not the flood discharge. Therefore, a sediment retention structure downstream of the waterfall, next to Thunderstone Quarry, would be necessary. The unretained remaining flood discharge is split by a side weir to allow for a maximum discharge of $55m^3/s$ through the existing culverts. An overflow channel would accommodate the flood waters exceeding the $55m^3/s$ threshold.

For Option A, the side weir is proposed to be directly upstream of the culvert of the highway ramp. The overflow channel is aligned along the existing highway ramp leading to an existing depression. In case of a flood event, the highway might be inundated as there is no underpass or another set of culverts at this section of the highway.

For Option B, the side weir is proposed to be directly downstream of the sediment retention structure. The floodwater exceeding $55m^3/s$ would be discharged through a new underpass across George Biggy Senior Road and be directed to an existing wildlife underpass located at the east end of the highway access ramp to Calgary.

Option C

Option C would retain water and sediment during a flood event. A debris flood retention structure, directly upstream of the section where a power line crosses Pigeon Creek, is required. The retention structure is capable of retaining approximately $550,000m^3$ of flood water for reducing the remaining peak discharge to a maximum of $55m^3/s$, which corresponds to the maximum discharge capacity of the existing culverts. Because the remaining flood discharge will mobilize sediment from the creek section downstream of the structure, a smaller debris net located directly upstream of the existing culverts of the highway ramp is a part of Option C.

Option D

Option D was ruled out at an early stage of the development of mitigation strategies. It comprises of the update of the existing culverts to a design discharge capacity for a 100-300yr return period flood, including bedload transport. The channel between, and downstream of the culverts, would be updated accordingly as well. Per ministerial order from Alberta Environment and Parks, the replacement of culverts and updating of the downstream channel to a size adequate for discharging a 100-300yr flood is ruled out.

07 OPTION A

Option A consists of a combination of the following mitigation measures:

- A sediment retention structure directly downstream of the waterfall, next to Thunderstone Quarries, capable of retaining sediment from a 100 to 300-year return-period storm event, with an estimated sediment volume of 75,000m³.
- Adaption of the George Biggy Sr. Road, next to Thunderstone Quarry, for integration into the sediment retention structure as an overpass to a future development of the Three Sisters Parkway. The alignment of the road will remain as it is, but a junction to a new access road will be provided in advance for future development purposes. The overpass will lead over the spillway by means of a simple bridge construction, providing the required freeboard for the spillway. Nevertheless, in case of a major flood event, the bridge would be closed off for safety reasons for the duration of the event.
- Channel update downstream of the retention structure for a safe clear water discharge of the 100 to 300-year flood.
- A side weir, directly upstream of the existing culverts which are feeding through the highway exit ramp. The side weir splits the discharge to a maximum of 50m³/s being transported in the updated downstream channel section and discharged through the existing culverts. The exceeding flood discharge would be directed to the existing depression at the west via an overflow channel. Because of limited capacities of existing culverts currently installed near the existing depression, impoundment cannot be properly controlled and potential inundation of the highway must be accepted with this option. The overflow channel shall be updated for a safe discharge of approximately 55m³/s which represents the 100 to 300-year flood discharge, exceeding 50m³/s.
- Update of the main channel downstream of the highway to a maximum discharge capacity of 55m³/s plus safety freeboard. The updates are currently under construction. The design provides grade control structures, in form of reinforced concrete ground sills, and bank protection by means of plain and grouted stone pitching.

This conceptual design provided with the current option analysis report is preliminary and detailed dimensioning needs to be performed within the subsequent design stage for the selected option. This includes the detailed determination of structure heights and freeboards, rake spacing for remaining gravel passage, grades of embankment slopes and crest widths, static dimensioning of construction elements, and determination of final dimensions. A 2D hydraulic check of flow control structures considering bedload transport is also required within the next design steps.

Remaining bedload discharge passing the sediment retention structure will potentially aggrade downstream of the structure. Periodic cleaning of the culverts and the channel downstream of the highway will be required. The cleaning frequency depends on the detailed hydraulic layout of the sediment retention structure. The main structures as shown by conceptual design drawings are listed in Table 5.

TABLE 5: CONCEPTUAL DESIGN DRAWINGS FOR OPTION A

Map No.	Map Type	Content	Scale
LTMM PC-OPTION A-302 R02	Plan View	OPTION A - Overview	1:4,000
LTMM PC-OPTION A-303 R02	Sections	OPTION A - Retention Structure	1:500 / 1:1,000
LTMM PC-OPTION A-304 R02	Cross Sections	OPTION A - Side Weir and Bypass Channel	1:200
LTMM PC-OPTION A-305 R02	Cross Sections	OPTION A - Downstream Channel	1:200

08 OPTION B

Option B consists of a combination of the following mitigation measures:

- A sediment retention structure directly downstream of the waterfall, next to Thunderstone Quarry, capable of retaining sediment from a 100 to 300-year return-period event, with an estimated sediment volume of approximately 75,000m³.
- Adaption of the George Biggy Sr. Road, next to Thunderstone Quarry for integration into the sediment retention structure as an overpass to a future development of the Three Sisters Parkway. The alignment of the road will remain as it is, but a junction to a new access road will be provided in advance for future development purposes. The overpass will lead over the spillway by means of a simple bridge construction, providing the required freeboard for the spillway. Nevertheless, in case of a major flood event, the bridge would be closed off for safety reasons for the duration of the event.
- Channel update downstream of the retention structure for a safe clear water discharge of the 100 to 300-year flood.
- A side weir and a new culvert directly downstream of the retention structure. The side weir limits the discharge through the downstream channel and existing highway culverts to 50m³/s, which is slightly below their clear water design capacity of 55m³/s. The exceeding flood discharge will be directed to an overflow channel which will cross George Biggy Sr. Road through a new culvert.
- An approximately 1km long overflow channel, downstream of the new side weir and new culvert at George Biggy Sr. Road will discharge the floodwater exceeding 50m³/s eastwards toward the existing wildlife highway underpass. This underpass is located approximately 650m east of the highway junction. The overflow channel is designed as a flood trough. The outside bend of the channel, where it meets the highway embankment, as well as the section parallel to the highway ramp, shall be updated with bank and bed protection to avoid erosion. The flood water will be discharged into a ditch directly north of the wildlife highway underpass.
- A diverting structure, directly downstream of the wildlife highway underpass, shall protect the gas line facility, located north of the highway close to the wildlife underpass.
- Update of the main channel downstream of the highway to a discharge capacity of 54m³/s plus safety freeboard. The updates are currently under construction. The design provides grade control structures, in form of reinforced concrete ground sills, and bank protection by means of plain and grouted stone pitching.

This conceptual design provided with the current option analysis report is preliminary and detailed dimensioning needs to be performed within the subsequent design stage for the selected option. This includes the detailed determination of structure heights and freeboards, rake spacing for remaining gravel passage, inclinations of embankment slopes and crest widths, static dimensioning of construction elements and final determination of dimensions. A 2D hydraulic check of flow control structures considering bedload transport is also required within the next design steps.

Remaining bedload discharge passing the sediment retention structure will potentially aggrade downstream of the structure. Periodic cleaning of culverts and the channel downstream of the highway will be required. The cleaning frequency depends on the detailed hydraulic layout of the sediment retention structure.

The main structures, as shown by conceptual design drawings, are listed in Table 6.

TABLE 6: CONCEPTUAL DESIGN DRAWINGS FOR OPTION B

Map No.	Map Type	Content	Scale
LTMM PC-OPTION B-402 R02	Plan View	OPTION B - Overview	1:5,000
LTMM PC-OPTION B-403 R02	Sections	OPTION B - Side Weir and Dam Structure	1:500 / 1:1,000
LTMM PC-OPTION B-404 R02	Sections	OPTION B - Channel Bypass and Raising of Causeway	1:500 / 1:2,000
LTMM PC-OPTION B-405 R02	Cross Sections	OPTION B - Channel north of Highway 1	1:200

09 OPTION C

Option C consists of a combination of following mitigation measures:

- A flood retention structure approximately 650m upstream of the waterfall, directly upstream of the power line corridor. The retention structure is capable of retaining flood water from a 100 to 300-year return period event with a retention volume of approximately 550,000m³. The remaining peak discharge is 50m³/s, according to the design discharge capacity of the existing culverts at Highway 1. The retention structure, as well as a possible access road, would be located outside of the Bow Valley Wildland Provincial Park.
- A complementary sediment retention structure, in form of a debris net, directly upstream of the existing Highway 1 culverts, would retain sediment potentially mobilized downstream of the flood retention structure, as well as bedload supplied by the tributary creek joining Pigeon Creek directly upstream of the waterfall. This debris net size is designed for an estimated sediment volume of 3,500m³. This would protect the existing culverts from blocking and would avoid aggradation in the downstream channel section.
- Update of the channel downstream and between the existing highway culverts to a discharge capacity plus safety freeboard. This section is currently under construction. The design provides grade control structures in form of reinforced concrete ground sills and bank protection by means of plain and grouted stone pitching.

This conceptual design provided with the current option analysis report is preliminary and detailed dimensioning needs to be performed within the subsequent design stage for the selected option. This includes the detailed determination of structure heights and freeboards, rake spacing for remaining gravel passage, inclinations of embankment slopes and crest widths, static dimensioning of construction elements and final determination of dimensions. A 2D hydraulic check of flow control structures considering bedload transport is also required within the next design steps.

The remaining bedload discharge passing through the proposed mitigation structure will potentially aggrade downstream. Periodic cleaning of culverts and the channel downstream of the highway would be required. The cleaning frequency depends on the detailed hydraulic layout of new structures. The main structures, as shown by conceptual design drawings, are listed in Table 7.

TABLE 7: CONCEPTUAL DESIGN DRAWINGS FOR OPTION C

Map No.	Map Type	Content	Scale
LTMM PC-OPTION C-502 R02	Plan View	OPTION C - Overview	1:7,500
LTMM PC-OPTION C-503 R02	Cross Sections	OPTION C - Debris Net and Cross Section	1:200
LTMM PC-OPTION C-504 R02	Cross Section	OPTION C - Flood Retention	1:400
LTMM PC-OPTION C-505 R02	Longitudinal Section	OPTION C - Flood Retention	1:1,000

10 COMPARISON OF OPTIONS

Option A

The selected location of the sediment retention structure, part of the design of Option A and Option B, has an ideal topography for sediment retention. Its access is relatively easy and does not require the construction of a new access road. However, parts of Thunderstone Quarry would be occupied. Furthermore, raising of George Biggy Sr. Road is required to avoid avulsions to the east. The gas line needs to be rearranged.

For Option A, the impoundment of the existing ditch, 400m west of the existing highway culverts, could result in inundation of Highway 1. This risk has to be acceptable. This also potentially includes the inundation of existing infrastructure and buildings.

Option B

For Option B, the proposed side weir in combination with the overflow channel and culvert under George Biggy Sr. Road would assure a safe flood water discharge through the existing highway culverts, the updated channel downstream of the highway, and the flood overflow channel. The construction of a new flood overflow channel, with a length of approximately 1km, as well as a new culvert, is more cost intensive compared to Option A.

Option C

In contrast to Option A and Option B, Option C requires the construction of a new access road to the flood retention structure, as well as a comparatively costly debris flood retention structure, including underground sealing measures. Because of the given distance from the structure to the existing highway culverts, as well as the tributary creek directly upstream of the waterfall, remaining sediment uptake during floods require complementary sediment retention upstream of the existing highway culverts. However, Option C does not require construction of additional flow control structures, such as side weirs or overflow channels.

All options require an update of the channel section between the waterfall and the highway culverts. Recurring cleaning of existing culverts and the downstream channel is required for Options A and B, whereas Option C requires a periodic cleaning of the proposed debris net, directly upstream of Highway 1.

11 REFERENCES

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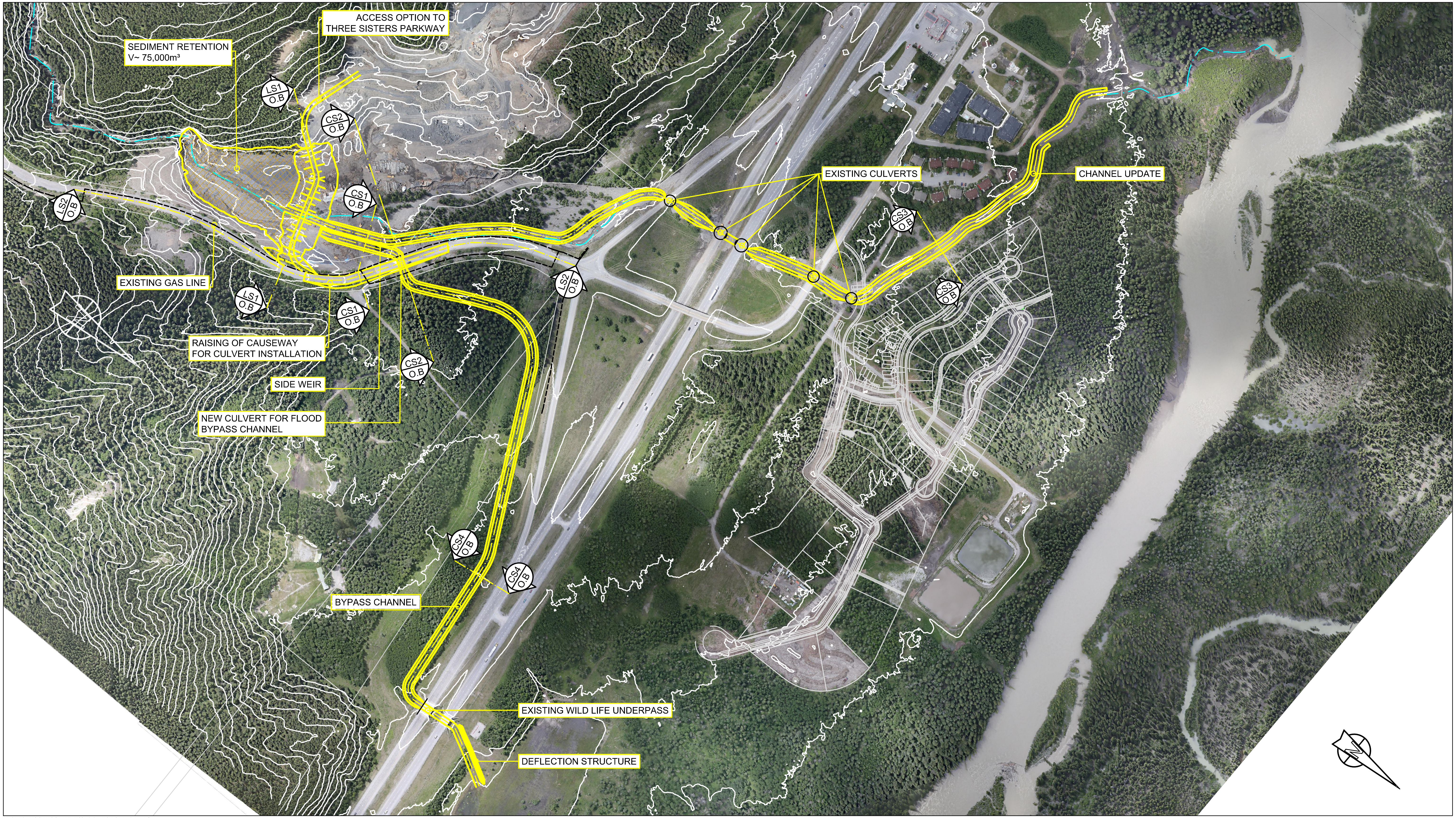

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02	2016/11/25	UPDATE OF DRAWINGS	ALe	MSc	
01	2015/11/26	REARRANGEMENT OF DOWNSTREAM CHANNEL	ALe	MSc	

SCALE: 1:5,000

DATE: November 25, 2016

DRAWING: ALe

DESIGN: ALe

REVIEW: MSc

APPROVED:

PROFESSIONAL SEAL:

CLIENT: Town of CANMORE

ENGINEERING: alpinfra SALZBURG - INNSBRUCK - WIEN

PROJECT: FLOOD MITIGATION - PIGEON CREEK

OPTION ANALYSIS

CONTENT: PLAN VIEW

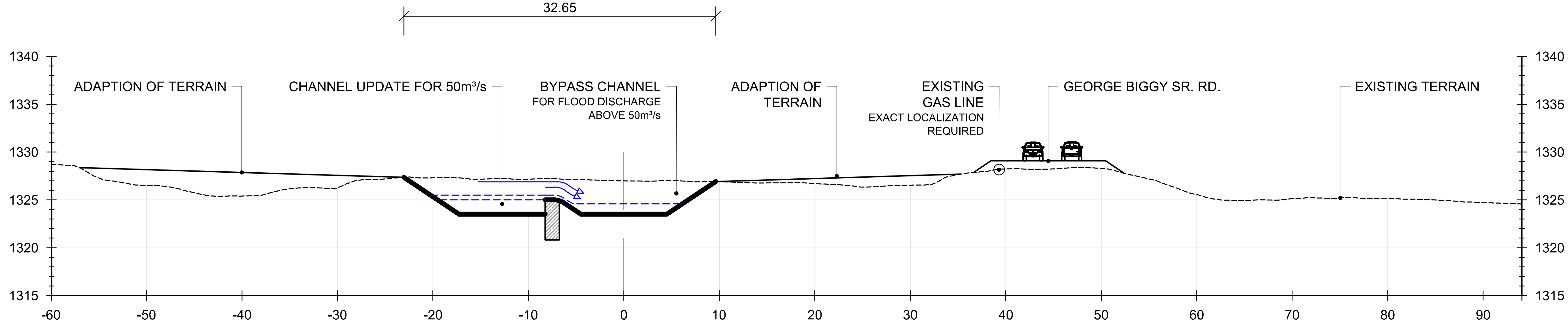
OPTION ANALYSIS - OPTION B

OVERVIEW

PROJECT No.: 16515

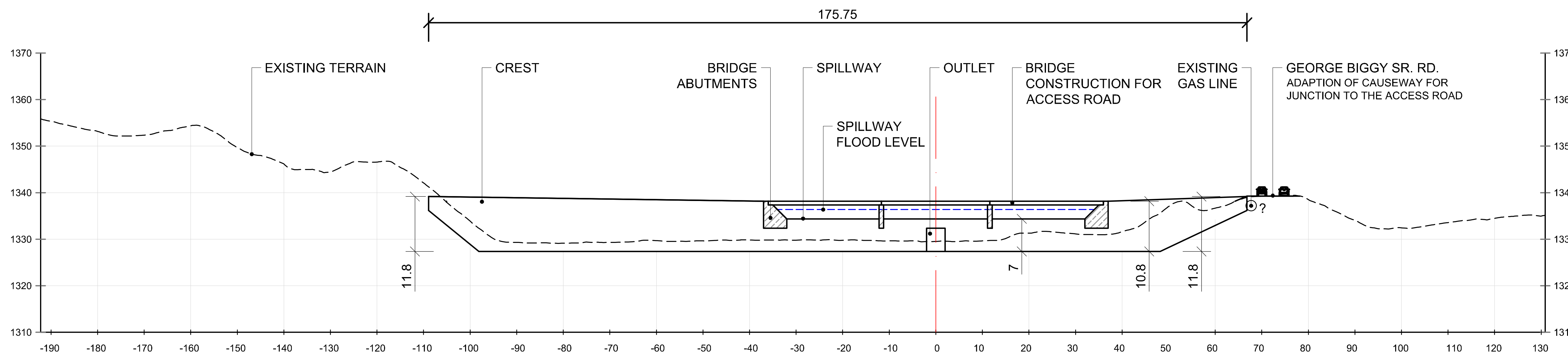
DRAWING No.: LTMM PC-OPTION B-402 R02

REV: 02



CS1 O.B CROSS SECTION SIDE WEIR 1:500

SEDIMENT RETENTION STRUCTURE KM 1+644



LS1 O.B LONGITUDINAL SECTION DAM km 1+644 1:1,000

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01	2015/11/26	REARRANGEMENT OF DOWNSTREAM CHANNEL	ALe	MSc	

SCALE: 1:500 / 1:1,000
DATE: November 25, 2016
DRAWING: ALe
DESIGN: ALe
REVIEW: MSc
APPROVED:

PROFESSIONAL SEAL:

CLIENT: Town of CANMORE

ENGINEERING: alpinfra SALZBURG - INNSBRUCK - WIEN

PROJECT: FLOOD MITIGATION - PIGEON CREEK
OPTION ANALYSIS

CONTENT: CROSS SECTION AND LONGITUDINAL SECTION
OPTION ANALYSIS - OPTION B
SIDE WEIR AND DAM STRUCTURE

PROJECT No.: 16515
DRAWING No.: LTMM PC-OPTION B-403 R02
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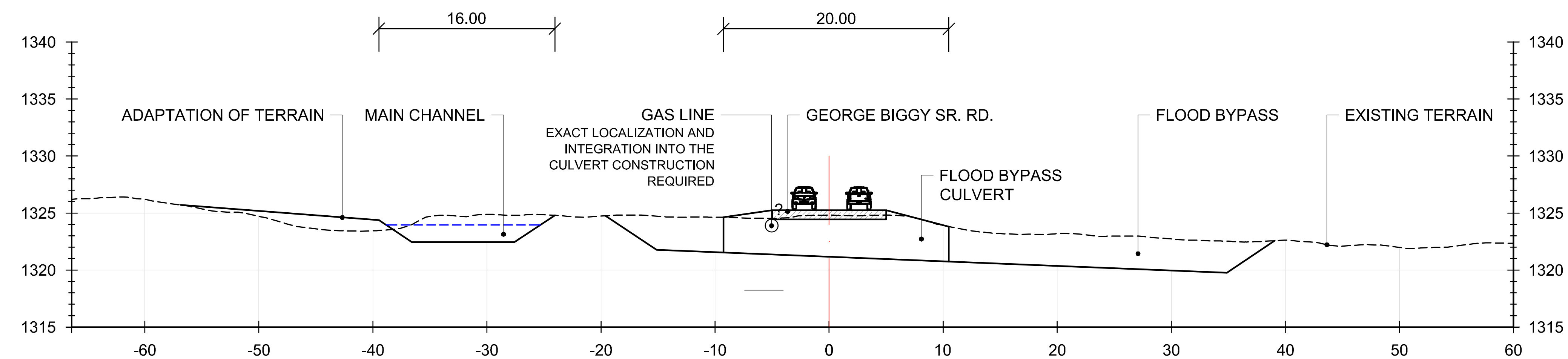
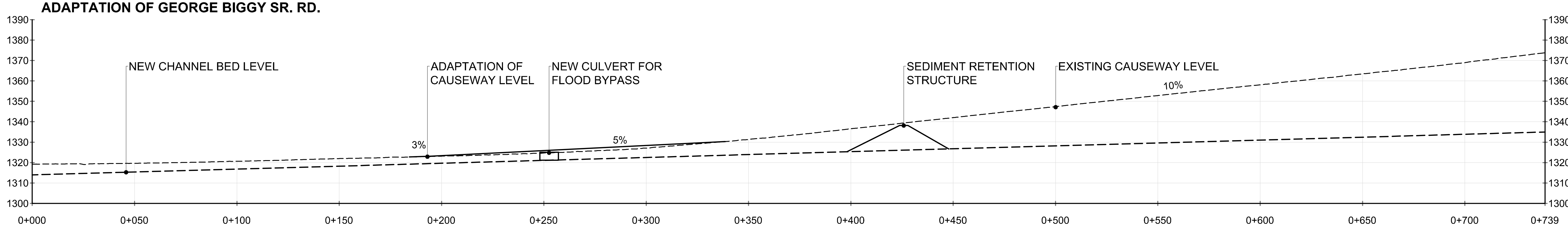


CS2 / O.B CROSS SECTION CULVERT
1:500

ADAPTATION OF GEORGE BIGGY SR. RD.



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1:2,000

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01	2015/11/26	REARRANGEMENT OF DOWNSTREAM CHANNEL	ALe	MSc	

SCALE: 1:500 / 1:2,000
DATE: November 25, 2016
DRAWING: ALe
DESIGN: ALe
REVIEW: MSc
APPROVED:

PROFESSIONAL SEAL:

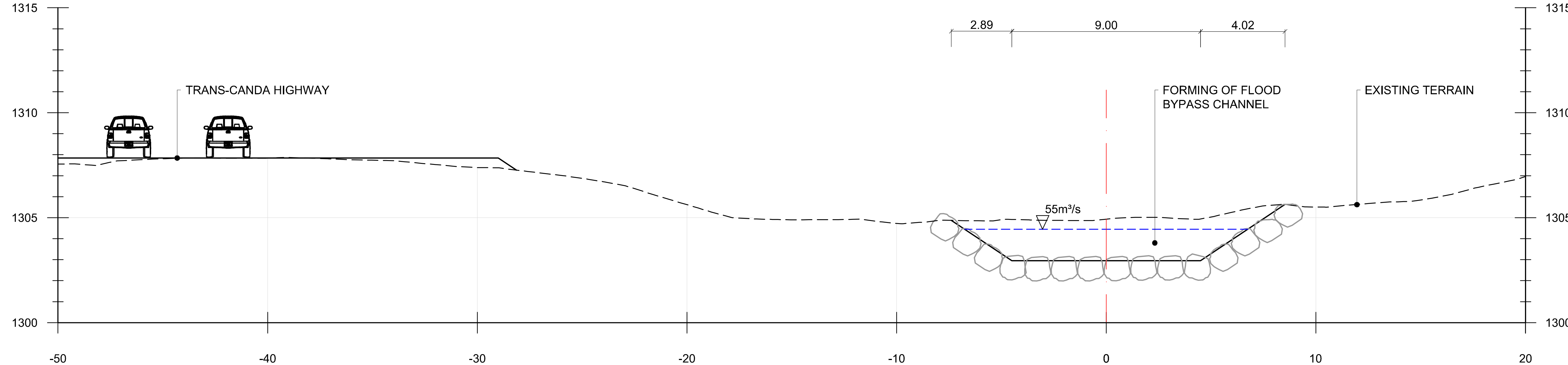
CLIENT: Town of CANMORE

ENGINEERING: alpinfra
SALZBURG - INNSBRUCK - WIEN

PROJECT: FLOOD MITIGATION - PIGEON CREEK
OPTION ANALYSIS

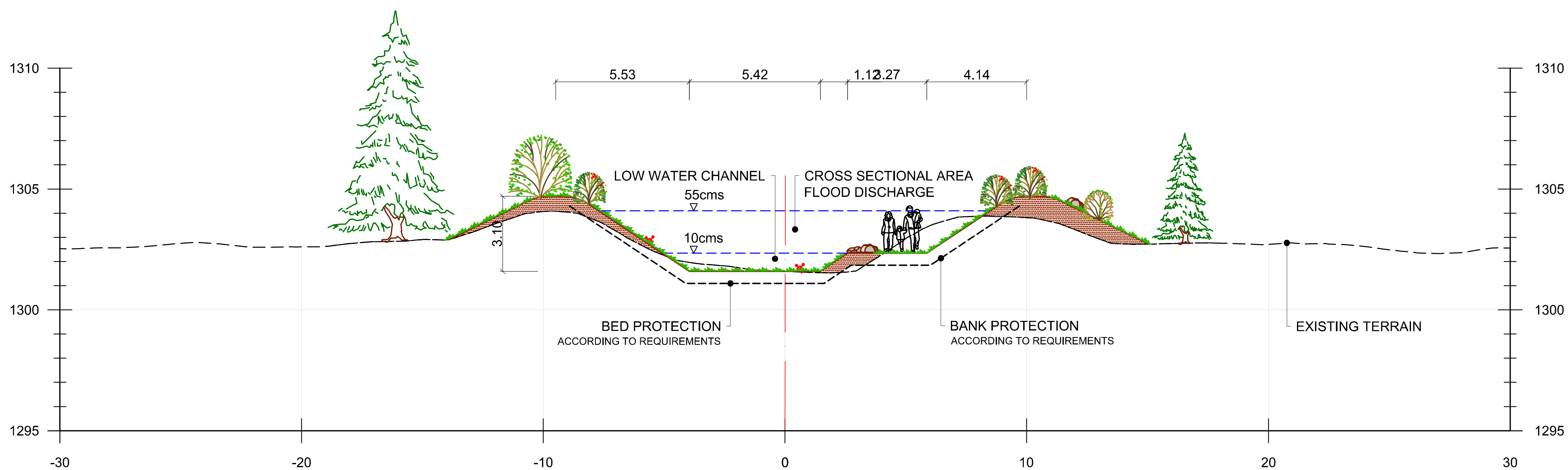
CONTENT: CROSS SECTION AND LONGITUDINAL SECTION
OPTION ANALYSIS - OPTION B
FLOOD BYPASS AND ADAPTATION OF CAUSEWAY

PROJECT No.: 16515
DRAWING No.: LTMM PC-OPTION B-404 R02
REV.: 02



CS4 O.B CROSS SECTION BYPASS CHANNEL

1:200



CS3 O.B CROSS SECTION CHANNEL

KM 0+675 1:200

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01	2015/11/26	REARRANGEMENT OF DOWNSTREAM CHANNEL	ALe	MSc	

SCALE:	1:200
DATE:	November 25, 2016
DRAWING:	ALe
DESIGN:	ALe
REVIEW:	MSc
APPROVED:	

PROFESSIONAL SEAL:

CLIENT: Town of CANMORE

ENGINEERING: alpinfra SALZBURG - INNSBRUCK - WIEN

PROJECT: FLOOD MITIGATION - PIGEON CREEK

OPTION ANALYSIS

CONTENT: CROSS SECTIONS

OPTION ANALYSIS - OPTION B
DOWNSTREAM CHANNEL

PROJECT No.:	DRAWING No.:	REV:
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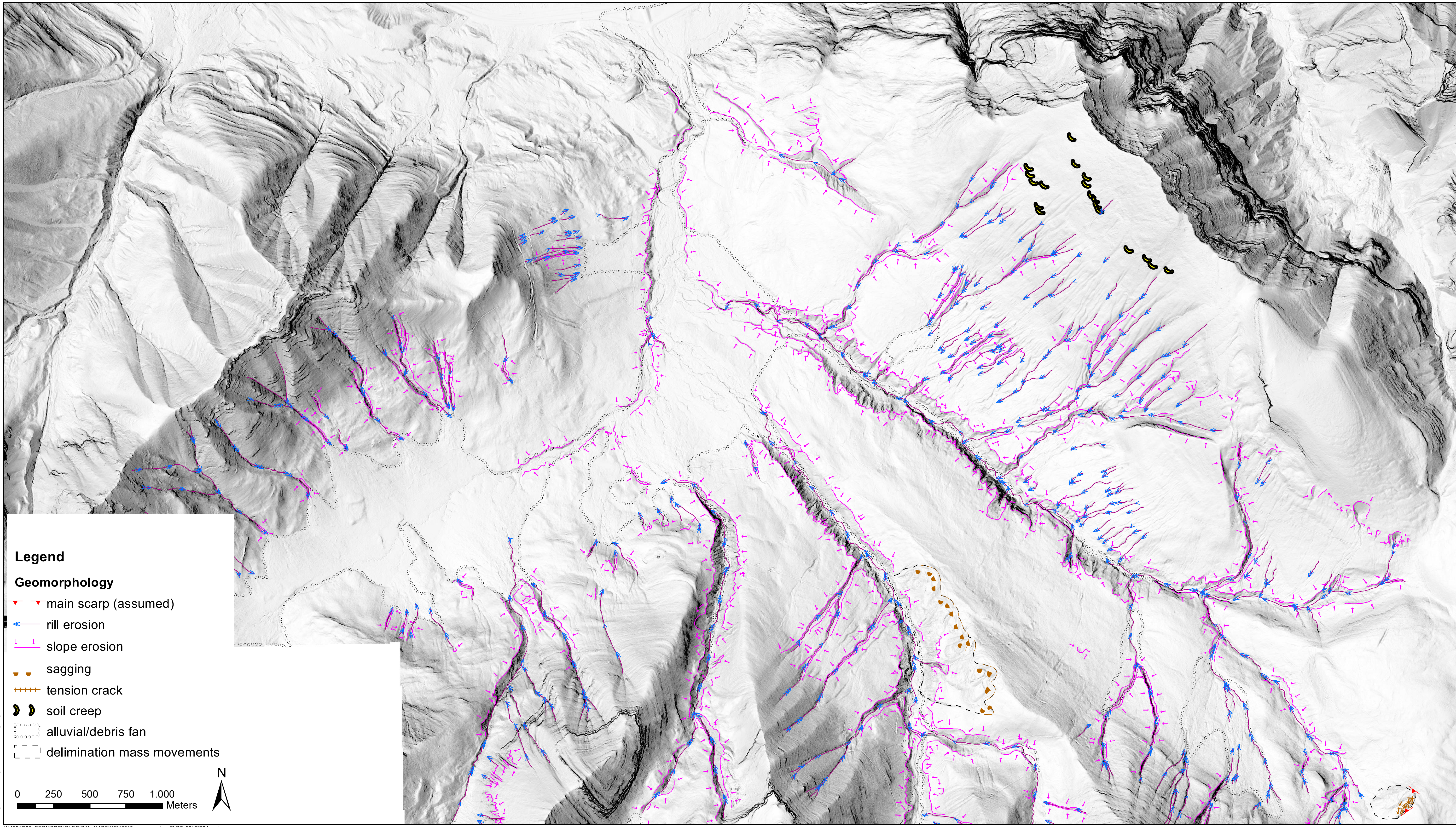

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DATE: 2015/05/04
DRAWING: DMo
DESIGN: DPo
REVIEW: MSc
APPROVED: MSc

PROFESSIONAL SEAL:

CLIENT: Town of CANMORE

ENGINEERING: alpinfra
SALZBURG - INNSBRUCK - WIEN

PROJECT: FLOOD MITIGATION - PIGEON CREEK
OPTION ANALYSIS

CONTENT: OVERVIEW MAP
PRELIMINARY GEOMORPHOLOGIC MAP
LOWER CATCHMENT

PROJECT No.: 16515
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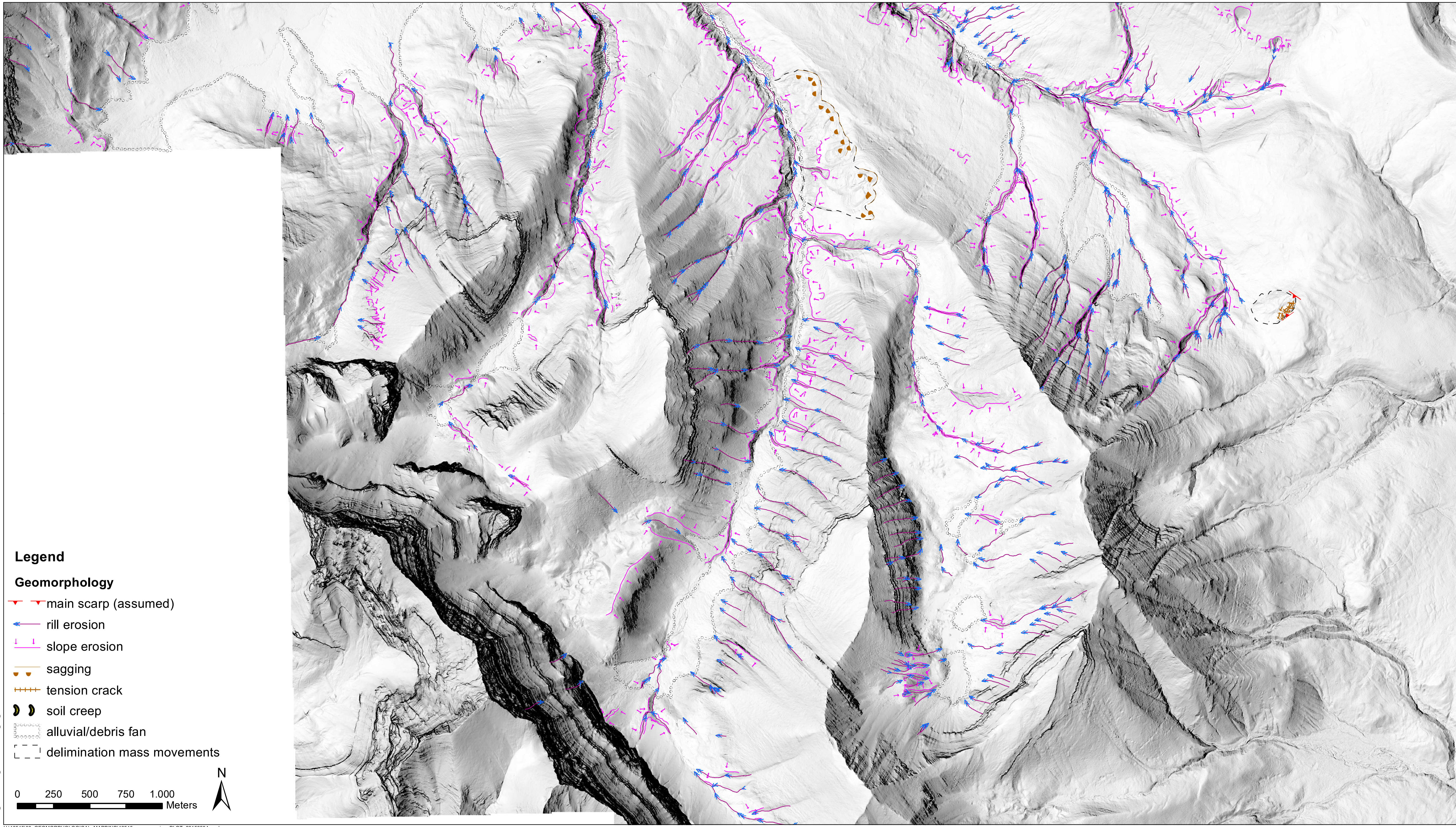
REV.: 00



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REVIEW:	MSc
APPROVED:	MSc

PROFESSIONAL SEAL:

CLIENT: Town of CANMORE

ENGINEERING: alpinfra
SALZBURG - INNSBRUCK - WIEN

PROJECT:
FLOOD MITIGATION - PIGEON CREEK
OPTION ANALYSIS

CONTENT: OVERVIEW MAP
PRELIMINARY GEOMORPHOLOGIC MAP
UPPER CATCHMENT

PROJECT No.:	DRAWING No.:	REV:
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