

KERR WOOD LEIDAL ASSOCIATES

CHEEKEYE RIVER DEBRIS FLOW SIMULATIONS

FINAL

PROJECT NO: 0464-001
December 14, 2007

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BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

#500-1045 Howe Street
Vancouver, B.C.
Canada V6Z 2A9
Tel: 604.684.5900
Fax: 604.684.5909

December 14, 2007

Project No. 0464-001

Mr. M. Currie, P. Eng.
Kerr Wood Leidal Associates
Still Creek Road
Burnaby, BC
V5C 6G9

Dear Mr. Currie,

Re: CHEEKEYE RIVER DEBRIS FLOW SIMULATIONS

Please find attached seven copies of our above referenced draft report dated December 14, 2007.

Should you have any questions or comments, please do not hesitate to contact me at the number listed above.

Yours sincerely,

BGC ENGINEERING INC.
per:

A handwritten signature in blue ink, appearing to read 'Matthias Jakob', is written over a light blue circular stamp. The signature is fluid and cursive.

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

Enc.

MJ/LB

EXECUTIVE SUMMARY

This report summarizes an evaluation of processes and parameters influencing debris flow path and runout on the Cheekeye Fan. Results of computerized debris flow simulations are also summarized. Frequency–magnitude relationships for debris flows on the fan have been developed in a previous BGC report (2007a) and are tabulated below.

Return Period (yrs)	Annual Probability (1/yrs)	Volume (Mm³)	Peak Discharge (m³/s)
20	0.04	0.2	700
50	0.02	0.4	1500
100	0.01	0.6	2500
200	0.005	0.8	3400
500	0.002	1.4	6700
2500	0.0004	2.4	12,600
10,000	0.00001	2.8	15,000

This report describes flow scenarios and details debris flow simulations conducted with a two-dimensional debris flow runout model (FLO-2D). The report describes the underlying assumptions of the model, critiques its rheological model, and discusses how certain shortfalls of the model can be addressed.

The model is calibrated with the best studied event, the Garbage Dump debris flow that occurred some 800 years ago, and which is discussed in detail by BGC (2007a). A perfect simulation of the Garbage Dump debris flow with modelling is not possible because the exact topography at the time of the event is somewhat speculative. However, runout distance and deposit thickness are well known and serve as a good basis for calibration.

The analyses conclude that under existing conditions debris flows exceeding a 50-year return period are likely to avulse onto the southern fan sector. Debris flows of several thousand years return period would inundate large portions of the fan, sever Highway 99, CN Rail, and the Squamish Valley road, and would impact development on the fan.

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LIMITATIONS OF REPORT

BGC prepared this report for the account of Kerr Wood Leidal Associates Ltd. (KWL) and McDonald Development Corporation (MDC). It presents the results of debris flow simulations on Cheekeye River. Other hydrologic and geomorphic processes, such as flooding, debris floods and bank erosion are not explicitly included in this study.

The material in this report reflects the judgment of BGC staff in light of the information available to BGC at the time of report preparation. Any use which a Third Party makes of this report 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 report. In particular, BGC accepts no responsibility for changes in real estate values that may occur as a consequence of this report.

As a mutual protection to our clients, the public, and ourselves, this report is submitted for the confidential information of KWL and MDC. KWL and MDC are authorized to use this report for the purpose of the Cheekeye Fan project, and may distribute this report as reasonably required for evaluation, implementation and approval of the project.

Anyone outside KWL and MDC receiving a copy of this report ought to recognize that these documents represent an interim step in the risk management process as defined by Canadian Standards Association Guidelines.

1.0 INTRODUCTION

BGC Engineering Inc. (BGC) was retained by Kerr Wood Leidal Associates (KWL) to simulate debris flows on Cheekeye fan and describe potential processes and parameters that may influence flow paths and deposition. The objectives of this report are to:

- discuss the processes and scenarios that could lead to debris flows of various return periods on the Cheekeye fan;
- discuss the assumptions and variables of the two-dimensional debris flow model chosen for the analysis;
- critique the software's rheological model in light of current understanding of debris flow mechanics;
- simulate the well-understood Garbage Dump debris flow by calibrating input parameters to obtain a model in which runout distance and deposit thickness are similar to those observed;
- provide a calibrated model for debris flows on Cheekeye River based on the Garbage Dump debris flow and more recent (last 60 years) debris flows along the channel of Cheekeye River; and
- discuss how the calibrated model will be used in a subsequent report (BGC, 2007c) to select and optimize mitigation measures along Cheekeye River and on the Cheekeye fan.

According to these objectives, the report is structured into a discussion of failure scenarios and flow characteristics (Section 2), debris flow modelling including model setup, limitations and critique (Section 3), model calibration (Section 4), and predictive model run results (Section 5).

2.0 FAILURE SCENARIOS AND FLOW CHARACTERISTICS

This chapter addresses the various processes and parameters that may influence debris flows along their transport zone and on the fan surface of Cheekeye River. The exact flow sequence of the design debris flow on Cheekeye River cannot be described in detail because it will hinge upon factors including:

- a) location and size of the original slope failure or within the channel;
- b) discharge in the feeder channels and main channel at the time of the failure;
- c) amount of snow on the slope aprons in the initiation and runout zones;
- d) the porosity and water content of the source area rock; and
- e) the volume of the original failure versus the amount of debris entrained.

These factors are judgement-based and lean on findings of similar studies elsewhere.

Frequency–magnitude relationships for debris flows reaching the fan apex of Cheekeye River have been developed in a previous BGC report (2007a) and are summarized below in Table 1. Debris flows of varying return period can be distinguished from one another by the source of initiation, as described below.

Table 1: Cheekeye River debris flow frequency-magnitude (after BGC, 2007a)

Return Period (yrs)	Annual Probability (1/yrs)	Volume (Mm³)	Peak Discharge (m³/s)
20	0.04	0.2	700
50	0.02	0.4	1500
100	0.01	0.6	2500
200	0.005	0.8	3400
500	0.002	1.4	6700
2500	0.0004	2.4	12,600
10,000	0.00001	2.8	15,000

2.1 Flow Initiation and Transport

2.1.1 <200-year Return Period Debris Flow

Debris flows with return periods from 20 to approximately 200 years are likely to be triggered by heavy rainfall during the summer or fall. One or several shallow debris avalanches or slumps could originate anywhere along the southwest-facing lower slopes of the upper Cheekeye watershed. The individual failure sites could be relatively small (10^3 - 10^4 m³) and unrecognizable as little as a few days after the event.

The ensuing debris flows would largely remain channelized until they reach Cheakamus River, though events in excess of 50 years could partially avulse downstream of the fan apex. Bank erosion through undercutting can be expected with the eroded material being entrained in the debris flow. Tree toppling from undercut banks is also expected. The 1991, 1980 and 1954 events, which were eye-witnessed, are examples of this magnitude event.

Events exceeding the 100-year return period (more than approximately 600,000 m³ in volume) would likely cause temporary damming of Cheakamus River as evidenced by dated tree scars on the west side of the river (Jakob and Friele, unpublished data). Those landslide dams would be short-lived and would likely breach within minutes or hours, depending on the discharge of Cheakamus River at the time of the debris flow as well as the geometry of the landslide dam. Significant aggradation can be expected to occur in the downstream channel sections after the landslide dam is overtopped and fails.

2.1.2 500-year Return Period Debris Flow

The typical 500-year return period debris flow may be triggered by one or several larger (>10⁵ m³) debris avalanches or slumps in the talus aprons of the upper Cheekeye watershed. These failures would be clearly discernable after the event for at least several years. Alternatively, a rock slope failure tens of thousands of cubic meters in size could detach from the west-facing faces of Dalton Dome, Atwell Peak, Cheekeye Ridge or Brohm Ridge. Such a failure could impact the talus slopes below, and under unfavourable conditions could lead to the development of a flow slide of portions of the talus.

Flows discharging from the upper feeder channels will remain channelized until the fan apex, but will likely avulse upstream of Highway 99 (Figure 1). Lateral flow spreading beyond the current channel confinement can be expected. The abutments and approach embankments of the Highway 99 bridge across Cheekeye River have constricted the cross-section of the channel at this location. This alteration would likely increase the likelihood and/or volume of debris flows travelling down the highway. Similar to the higher return period events discussed above, this event would very likely cause damming of Cheakamus River and subsequent outbreak floods.

2.1.3 >2500-year Return Period Debris Flow

Debris flows with return periods of 2500 to 10,000 years are anticipated to originate as rock avalanches (10⁶-10⁷ m³ range) in the more competent dacitic lavas around Dalton Dome and the vent area near Atwell Peak, or as a deep-seated failure from Cheekeye Ridge or Brohm ridge (BGC, 2007a). Alternatively, it could be initiated by a deep-seated large (>10⁶ m³) debris avalanche in the weakly cemented pyroclastic rocks on the southern flanks of the Garibaldi massif. These debris flows are likely to be very large, high velocity (10-20 m/s) events that are potentially erosive, at least in the feeder channels.

Flows can be clay rich (>5%) if originating from hydrothermally altered, weakened rock and clay-poor if originating from competent rock and entraining gravels, sands and fines in the transport zone. Irrespective of host-rock water content, a rock avalanche or deep-seated debris avalanche may quickly liquefy at impact with partially saturated colluvium mantling the edifice. It is well known that volcanic debris flows change flow characteristics along their transport zone (i.e. Vallance, 2005). In medial and distal reaches, such flows can change from sediment-rich debris flow phase to water-rich hyperconcentrated flow phase as evidenced by test pits in the distal parts of the Garbage Dump debris flow.

It is important to note that the rock avalanche-generated events appear to follow a less steep frequency-magnitude curve than indicated by the rainfall-generated events (see Figures 8 and 9 in BGC 2007a). This contrasts frequency-magnitude relationships from other volcanoes in the Pacific Northwest (i.e. Mount Rainier, Mount Hood, Mount Baker), which are substantially more ice clad than the west flank of the Mount Garibaldi massif. This flatter curve is attributed to limited available water, which would constrain the amount of debris that could be transported to the fan in the form of a debris flow (BGC 2007a).

In the transport reaches the flow would be fully fluidized, may travel at velocities of up to 40 m/s^1 in the upper feeder channels and begin rapid entrainment of materials with estimated yield rates of several tens cubic metres per metre channel length with a decreasing yield rate in the medial and distal parts of the transport zone where sediment supply declines. Factors expected to influence yield rates include:

- Erosion along the flow margins of water-rich debris flows allows effective sediment entrainment by bank undercutting.
- Fully bulked flows are expected to have sediment concentrations of 65-75%. Additional material can be entrained if the water content of entrainable sediment is favourable.

An average yield rate of $100\text{-}150 \text{ m}^3/\text{m}$ for channel segments upstream of the fan apex is conceivable based on channel characteristics (channel side slopes are colluvial mantled) and geometries, though yield rates will change significantly between different channel segments and are likely to fluctuate during the event. With a total flow length between 7 km and 10 km from the point of origin, bulking could result in an additional volume of approximately 0.7 Mm^3 to 1.5 Mm^3 as discussed in BGC 2007a.

By the time the debris flow reaches slope segments covered by trees, the peak discharge will exceed bankfull flow and it is expected that thousands of trees, some of which will be over 50 m high, will be entrained into the debris flow. Due to their lower density (less than 1000 kg/m^3) trees will largely float on top of the flow and be clustered at the surge front where they may be responsible for substantial flow resistance, particularly in confined channel sections.

¹ Debris flow velocities are estimated from a review of the literature, specifically work summarized by Pierson (1998).

The tree entrainment process is important in that the large amount of organic debris will likely transform any proposed slotted debris flow barrier into a quasi-impermeable dam at impact because trees are known to swivel at impact with channel obstacles, align themselves perpendicular to the flow direction and thus block any open structure.

It is likely that the design event will contain numerous surges with the first surge likely to be the largest, unless subsequent large failures occur in the watersheds. Surges may develop through sloughing of undercut slopes into the main flow, and additional debris avalanches or rock slides in the source area that have suddenly been over steepened by the original event and by remobilization of channel deposits as well as the formation of secondary landslide dams. The temporal spacing of surge waves may range from less than one minute to tens of minutes. A period of quiescence of several hours, days or perhaps longer may be followed by a renewed sequence of events, as additional materials in the edifice headwaters collapse or loose channel material is reworked by high intensity rainfall. The typical longitudinal flow profile of each surge may display a coarser front with numerous trees followed by increasingly liquid hyperconcentrated flow. At 7 to 11 km distance from the source area, the debris flow velocity may be reduced to 15-30 m/s at the location of the proposed barrier (BGC, 2007c).

2.2 Deposition

Debris flow deposition is perhaps the least predictable part of the process spectrum. The investigation of the Garbage Dump debris flow has suggested that a high friction plug preceded the more liquid afterflow. The coarse high friction plug appeared to have been deposited immediately downstream of the dogleg and diverted the afterflow to the south down a presumed older channel network and over the adjacent fan surface.

This process, which is described in greater detail in Section 3, shows that there is a substantial degree of uncertainty involved in trying to predict where and when a debris flow will commence deposition, or where and when during the event channel avulsion will occur due to temporary partial blockages. Modelling is unable to predict such largely random behaviour and a significant amount of geoscience judgement is required to assess the what-if scenarios.

For example, if a more rigid plug were to deposit downstream of the fan apex, the majority of the afterflow could avulse to the south toward Brackendale with little debris continuing down the existing main channel. A further surge wave could break through once again with more afterflow descending the existing channel. The same scenario could be repeated downstream of the fan apex with debris spilling out south of the Garbage Dump debris flow deposit. The following section describes the calibration of potential debris flows using commercially available debris flow runout software.

3.0 DEBRIS FLOW MODELLING

The two-dimensional hydraulic model FLO-2D was chosen to simulate debris flow intensities (maximum flow depth and velocity) on Cheekeye Fan. FLO-2D is well suited for this type of application as it can model unconfined flows across fan surfaces, simulates flows of varying sediment concentrations, and has been tested in numerous applications worldwide. FLO-2D was previously used to model Cheekeye River debris flows for the District of Squamish (KWL, 2003) in order to evaluate mitigative works that were proposed at that time.

3.1 Model Background

FLO-2D is a volume conservation model that conveys a flood or debris flow within defined channel segments and as overland flow. Flow progression is controlled by topography and flow resistance. The governing equations include the continuity equation and the two-dimensional equation of motion (dynamic wave momentum equation). The two dimensional representation of the motion equation is defined using a finite difference grid system, and is solved by computing average flow velocity across a grid element boundary one direction at a time with eight potential flow directions. Pressure, friction, convective and local accelerations components in the momentum equation are retained. The differential form of the continuity and momentum equations are solved with a central finite difference scheme.

3.1.1 Shear Stress

FLO-2D routes debris flows as a fluid continuum using a quadratic rheologic model for predicting viscous and yield stresses as a function of sediment concentration. Because sediment concentration changes for a given grid element and time step, dilution effects, debris flow cessation and remobilization of deposits are simulated. Yield strength must be exceeded by an applied stress to initiate flow.

FLO-2D models the shear stress in hyperconcentrated flows and debris flows as a summation of five shear stress components: the cohesive yield stress (τ_c), the Mohr-Coulomb shear (τ_{mc}), the viscous shear stress (τ_v), the turbulent shear stress (τ_t), and the dispersive shear stress (τ_d):

$$\tau = \tau_c + \tau_{mc} + \tau_v + \tau_t + \tau_d \quad (\text{Eq. 1})$$

When written in terms of shear rates (dv/dy), the following rheological model can be defined (O'Brien and Julien, 1985):

$$\tau = \tau_y + \eta \left(\frac{dv}{dy} \right) + C \left(\frac{dv}{dy} \right)^2 \quad (\text{Eq. 2})$$

$$\tau_y = \tau_c + \tau_{mc} \quad (\text{Eq. 3})$$

where η is the dynamic viscosity, τ_c is the cohesive yield strength, and C is the inertial shear stress coefficient. The first two terms in Eq. 2 are referred to as the Bingham shear stresses². The sum of the yield stress and viscous stress defines the total shear stress of a cohesive debris flow in a viscous flow regime. The last term is the sum of the dispersive and turbulent shear stresses for debris flows in the inertial regime. A debris flow model that incorporates only the Bingham stresses and ignores the inertial stresses assumes that the simulated debris flow is viscous. However, not all debris flows are fully viscous, particularly the more fluid and turbulent afterflow.

All of these components can be written in terms of shear rates giving a quadratic rheological model as a function of sediment concentration that adds a turbulent and dispersive term to the Bingham equation. The following empirical relationships are used to compute yield stress and viscosity in FLO-2D:

$$\eta = \alpha_1 e^{\beta_1 C_v} \quad (\text{Eq. 4})$$

$$\tau_y = \alpha_2 e^{\beta_2 C_v} \quad (\text{Eq. 5})$$

where α_i and β_i are empirical coefficients defined by laboratory experiment and C_v is volumetric sediment concentration (O'Brien and Julien, 1988).

Both viscosity and yield stress are functions of the volumetric sediment concentration of silts, clays and fine sands but do not include large clastic materials rafted with the flow. Coefficients for yield stress and viscosity have been determined from laboratory experiments based mostly on fine-grained mudflows in Colorado and have been supplemented from data in China (Table 9, p. 54 in FLO-2D manual).

3.2 Model Critique and Limitations

Debris flow modelling has been subject to increased research and scrutiny over the past ten years. While this report does not discuss the various debris flow models that have been developed in detail, some discussion of the validity of debris flow models is appropriate to better understand their strengths and limitations.

Identification of an appropriate debris flow rheology has been regarded as a key to the modelling and prediction of debris flow characteristics and behaviour, leading to a long debate on the most appropriate rheological formula to be used. Contrasting this focus on a single rheological model are field observations that have proven that a single rheology cannot satisfactorily describe the range of mechanical behaviour exhibited by debris flows.

² The Bingham model assumes a linear relation between shear stress and shear rate.

Field observations and flume experiments suggest that rheologies vary temporally, spatially and exhibit feedbacks that depend on evolving debris flow dynamics (Iverson, 2003).

3.2.1 Basic Debris Flow Attributes

Field observations from across the world suggest the following basic attributes of debris flows (Iverson, 2003):

- Debris flows originate from individual or distributed source areas in which static regolith mobilize suddenly through introduction of surface or groundwater, or due to a rapid increase in pore water pressures through undrained loading. Debris liquefies through loading or frictional failure and begins to mix with water and entrain additional debris.
- Steep surge fronts often form at the heads of debris flows and secondary surges develop behind the leading front. Coarse debris accumulates at the surge front due to particle size segregation and migration, or frontal entrainment. The surge fronts advance mostly by sliding and tumbling rather than fluid-like flow. The typically more fluid afterflow (hyperconcentrated flow) pushes the bouldery front.
- Lateral flow levees form along channel margins and on the fan because the coarse-grained debris at the surge front pushes sediment to the side where higher friction causes deposition.
- Depositional lobes form where frictional resistance imposed by coarse-grained flow fronts and margins is sufficient to halt the more fluid afterflow, or where interstitial water can readily drain out of unconfined flow areas.
- Fresh debris flow deposits remain in an unstable saturated state for some time after which they consolidate. Rigidity sets in once drainage has removed most pore water.

Furthermore, flume experiments suggest that:

- Basal pore-fluid pressure nearly equal to the basal total normal stress persists during motion and deposition suggesting full liquefaction. Liquefaction commences due to sudden contraction of water-filled pores during debris flow initiation.
- The high permeability of debris flow surge fronts leads to dissipation of pore pressures below those necessary for liquefaction.
- Flow separation into liquefied and unliquefied portions precludes specification of a single rheological model.
- High fines content enhances runout distance, as it inhibits pore pressure dissipation and allows liquefaction to persist.
- Pore fluid pressure and grain agitation (“granular temperature”) influence the apparent rheology of debris (Iverson and Vallance, 2001).

All of the above observations indicate that a single rheologic model is unattainable because non-hydrostatic forces cannot exist in steady states. More advanced models such as the Coulomb mixture theory strive to account for unsteady flow behaviour. While it is realized that the mathematical representation of rheology is perhaps inadequate, finding a reasonably realistic simplification lies at the heart of modelling complex processes, at least until such time as better formulated alternatives are available.

3.2.2 Yield Strength

Yield strength is an important input parameter in debris flow models including FLO-2D. Reported yield strength values have focused on the fine-grained “matrix” component of debris flows, which can readily be sampled (e.g. Kang and Zhang, 1980; O'Brien and Julien, 1988; Phillips and Davies, 1991; Major and Pierson, 1992; Coussot and Piau, 1995; Locat, 1997; Parsons et al., 2001). Yield strength varied between 10 and 400 Pa in these studies. However, these published values are not consistent with the governing equations of debris flow models. For example, using a one dimensional static limit-equilibrium equation ($\tau = \rho gh \sin\Theta$) on slopes $>5^\circ$ indicates that debris thickness should be less than 0.2 m for the published yield strength values. In contrast, debris flow deposits in excess of 5 m are observed on the Cheekeye Fan. Back-calculating yield strength for typical values on the Cheekeye fan ($\rho = 2000 \text{ kg/m}^3$, $h = 1\text{-}5 \text{ m}$, $\Theta = 1\text{-}5^\circ$), results in a range of 340 to 8500 Pa.

Criticisms of debris flow models have also focused on the use of fixed yield strength values, which place limitations on debris flow rheology. The issue lies with the temporal and spatial transience of influencing factors such as pore water pressures. Poorly or unsorted debris flow materials gain most of their strength from intergranular friction proportional to intergranular normal stress and not from yield strength as a rheological property. Therefore, yield strength varies as debris flow thickness and particle size varies in time and space during flow. A fixed yield strength value would only be valid if a debris flow consisted of a homogeneous liquefied sediment mixture. The central question to rheologically-based modelling is therefore whether the temporal and spatial-dependency of yield strength can be ignored or if its transiency will render modelling results useless.

3.2.3 Viscous Stress and Rate Dependency

Debris flow models, such as FLO-2D, often include a static functional relationship between shear resistance and shear rate. The Bingham model assumes a linear relation between shear stress and shear rate. Bingham models fitted to muddy slurries typically yield viscosities between 0.1 and 50 Pas. If such viscosities are multiplied with typical debris flow shear rates ($<10 \text{ s}^{-1}$), resulting resisting stresses are in the order of 500 Pa. The implication is that shear stresses at the largely drained, highly frictional front of a debris flow may be an order of magnitude higher than the liquefied debris mass following the coarse debris flow front. The question then becomes how well developed can a coarse bouldery surge front be and what influence does it exert on the rest of the debris flow? To answer this question, it is

worth examining an observed case. This comparison may allow a conclusion whether differences in shear stress can be ignored or if their neglect could lead to significantly different model outcomes.

3.2.4 Observed flow behaviour

With regard to modelling, hazard and risk analysis, the large (lower return period) flows become increasingly important as they yield a higher damage potential. Therefore, the Garbage Dump debris flow may serve as a good example whether spatial and temporal fluxes in flow rheology affect flow behaviour and thus may affect modelling results.

The distribution of sediments on the Cheekeye fan is discussed in BGC (2007a), including the areal extent of the Garbage Dump (GD) debris flow. We assume that the principal channel at the time of the GD debris flow followed the main depositional lobe. Evidence for this assumption includes older channel deposits observed along this alignment. The GD debris flow appears to have occurred in at least two stages. The first stage appears to have been a coarse primary surge with a significant number of trees and large boulders. These elements were observed in abundance during a test pitting program conducted in 2006. This surge is likely responsible for the large well-defined lobe that is up to 6 m thick below the Dogleg (Figure 1). The lobe thins abruptly on its margins except for the principal tongue that can be traced to Squamish River. It is presumed that this first surge front was highly frictional due to a higher concentration of boulders and trees in an area where flow confinement was suddenly lost (the Dogleg). At this moment, the front may be best described by a Coulomb friction model with high resisting stresses. This surge front likely blocked portions of the modern channel, which may have been a minor branch of the main channel. Deposition of the surge front also diverted the liquefied afterflow toward the central fan portion along the tongue shown in Figure 1. This liquefied afterflow would likely have significantly lower resisting stresses. Typical grain sizes found in this tongue are less than 200 mm in diameter. As the deposit further thinned, yield strength values may have dropped below 100 Pa. At this stage, grains were typically less than 100 mm in diameter and were suspended in a muddy matrix. This deposit can be traced to Squamish River.

This example illustrates the temporal and spatial variability of debris flow behaviour, which may affect model outcomes. In particular, it is virtually impossible to predict where a coarser lobe may deposit and divert the hyperconcentrated afterflow. Irrespective of the model used, these developments cannot be reliably simulated and geoscientific judgement must be applied in anticipating these changes in flow behaviour. With respect to mitigation, sudden deposition of a coarse bouldery front must be anticipated, unless mitigation aims towards stopping the initial surge or surges, which lowers the probability of sudden changes in flow direction. As discussed later in BGC (2007c), this has important implications on the choice and design of debris flow mitigation.

3.3 Summary

The preceding discussion provides context when interpreting the model results presented in the following sections. The principal issue is whether a rheological model, such as the Bingham model used in FLO-2D, is an adequate representation of expected debris flows on the Cheekeye Fan. Following from this, it is questionable if the debris flow can be treated as a continuously liquefied slurry if gravitational normal stresses affecting friction in unliquefied parts dominate or affect flow behaviour. It is acknowledged that spatial and temporal fluxes in shear stress and yield strength are likely, and that a single rheological model is inadequate to represent the true mechanics of debris flows. Alternative approaches have been presented by Hutter et al. (1996) and Iverson (1997). Their approach uses Coulomb mixture theory that describes the behaviour of debris flow mixtures from the onset of motion through deposition and post-depositional consolidation. However, there are no commercially available models yet that could be used to apply these approaches to Cheekeye River.

Given the high flow depths of higher return period flows and the typically high fines content of volcanic debris flows (which limits shear stresses due to frictional effects), we assume that the quadratic model is an adequate bulk rheological representation of flows on Cheekeye fan. Recent work has confirmed that the quadratic shear stress model used in FLO-2D appears to be a reasonable approximation for observed debris flows elsewhere (Bertolo and Wiczorek, 2005; Cetina, et al. 2006). BGC believes that calibration of known deposits to obtain approximations of runout distance and distributed deposit thickness in combination with repeated model runs and sensitivity analyses will provide an adequate representation of realistic flow behaviour. Ultimately, the exact mathematical representation of flow behaviour is less important than a realistic representation of observed or back-calculated flow runout and deposition characteristics.

Deviations from modelled flow can occur due to temporary dam formations, blockage by log jams, or sudden scour of unconsolidated debris flow deposits during further debris flow surges. Irrespective of the rheological model used or other advanced approaches, these events are largely random and can not be modelled. Geoscientific judgement is required to incorporate these scenarios into an overall hazard assessment.

4.0 DEBRIS FLOW MODEL CALIBRATION

This section discusses calibration of the FLO-2D model to Cheekeye Fan based on analysis of the Garbage Dump debris flow. Input parameters to the model are summarized first.

4.1 Input Parameters

The following section provides a summary of input parameters used to model debris flows of varying return periods that may impact the Cheekeye Fan.

4.1.1 Input Topography

The topography that was used for the model is based on LIDAR imagery flown in September 2006. LIDAR points were achieved with a point spacing of 1 point/m² and a relative vertical accuracy of +/- 15 cm on hard (well reflecting) surfaces. 20 cm digital orthomosaics were generated. From these data, one metre contours were extracted and input to the FLO-2D model from which a 20 m square grid was generated for modelling purposes.

4.1.2 Input Hydrograph

Input hydrographs are based on the volume and peak discharge summarized in Table 1. Hydrographs were created to match the desired volume and peak discharge based on previous frequency-magnitude analysis (BGC, 2007a). Hydrographs were created with single surges (one peak) and multiple surges (several peaks) to test for potential differences in runout distance and lateral spread. Initial trial runs indicate that there are no significant differences between model runs with one peak or multiple surges. The hydrograph and sediment concentration for the modelled Garbage Dump debris flow are shown in Figure 2.

4.1.3 Sediment Concentration

Sediment concentration and sediment grain size distribution will determine the viscosity and yield strength of the flow materials, which in turn determines how sediment flows over and is distributed across the fan surface. The FLO-2D manual provides examples of volumetric sediment concentrations for landslides and mudflows (Table 7 in the manual) with peak sediment concentrations of 55%. These data were obtained from mudflow deposits in Colorado. Volcanic debris flows may achieve higher sediment concentrations. For example, Jordan (1994) reports volumetric sediment concentrations of up to 80% for volcanic debris flows in the Mount Meager area.

Sediment concentration as described in this report is volumetric:

$$S_c = \left(\frac{V_s}{V_t} \right) * 100\%$$

where S_c = sediment concentration, V_s = volume of solids, and V_t = total volume (solids + water). Sediment concentration can also be referenced by weight. Because the specific gravity of sediment (~2.65) is greater than water (~1.0), sediment concentrations by weight are greater than volumetric sediment concentrations.

Model trials with sediment concentrations exceeding 55%, however, result in erroneous results. The software developer Jim O'Brien (pers. comm., 2007) explained that sediment concentration relates to the fines (matrix) not the bulk sample. Therefore, a bulk sample measured from the flow itself would likely have a higher sediment concentration than 55% due to the larger grain sizes. Mudflows used for calibration in the FLO-2D manual behave as Bingham fluids with low shear rates ($<10\text{s}^{-1}$), and are therefore unlikely to be representative of coarse non-liquefied bouldery fronts. This could imply that simulated flow velocities may be too high for some channel sections in which a coarser drained front could affect flow velocity.

Debris flows typically undergo different phases of flow during their descent as entrainment of channel and bank materials may increase sediment concentration on the climbing limb of the hydrograph. Decreasing sediment concentrations and hyperconcentrated afterflow are observed in the falling limb of the hydrograph once the initial surge front passes. Therefore, the debris flow will display phases with high sediment concentrations but low concentrations of fine particles (typically the initial surge) where dispersive stresses prevail, and fluid phases with dominantly turbulent stresses. FLO -2D accounts for changes in sediment concentration by allowing its specification for each unit time of the input hydrograph.

Sediment concentration was modelled to increase toward the peak of the hydrograph and decline on the falling limb. Maximum and minimum values of 55% to 10% were input to the modelled hydrographs (Figure 2).

4.1.4 Yield Strength and Viscosity

Without repeat testing of fresh debris flow materials, ideally during various flow phases, rheological parameters must be estimated from empirical data or back-calculated. For this project, we used empirical coefficients reported in the FLO-2D manual and Bertolo and Wiczorek (2005). Table 2 summarizes the input parameters used in this study that represent debris flows with high, intermediate and low viscosities.

Table 2: Empirical coefficients used for FLO-2D debris flow modelling

Scenario	Viscosity Coefficient (α_1)	Viscosity Exponent (β_1)	Yield Stress Coefficient (α_2)	Yield Stress Exponent (β_2)
High viscosity	2.7	11.0	0.05	14.5
Intermediate viscosity	1.0	11.0	0.1	15.0
Low viscosity	0.13	12.0	2.7	10.4

The high viscosity scenario is based on the research of Bertolo and Wieczorek (2005) who modelled debris flows in Yosemite Valley with FLO-2D. These values were back-calculated to obtain the best match between observed debris flow deposition and modelled results. Yosemite Valley is known for its very coarse granitic debris flows, which are likely to be characterized by a well developed non-liquefied bouldery front. A high viscosity model is therefore considered a fair approximation. The low viscosity values are based on calibration of the runout distance of the Garbage Dump debris (see next section). The intermediate values fall between the upper and lower limits.

4.1.5 Turbulent and Dispersive Stresses

Flow resistance of the turbulent and dispersive shear stress components are combined in FLO-2D into an equivalent Manning's n-value for the flow. Manning's was estimated as 0.10 for the vegetated fan surface and varied between 0.035 and 0.06 for the channel. Paved roads had an assumed Manning's n value of 0.025.

4.2 Model Calibration

To calibrate the model for additional runs, we simulated the Garbage Dump debris flow. To accomplish this task, the Garbage Dump debris flow topographic surface was artificially removed from the LIDAR topography based on deposit depths determine in BGC 2007a, and the three viscosity scenarios listed in Table 2 were run. The goal was to recreate the approximate distribution, deposition depth and runout distance as observed in the field today. Total volume of the Garbage Dump was modelled to 2.1 Mm^3 with a discharge of $12,000 \text{ m}^3/\text{s}$ and peak matrix sediment concentrations of up to 55% (volumetric).

Figures 3a, b, and c show the output file for the low, intermediate and high viscosity runs. The low viscosity run approximates the Garbage Dump debris flow in terms of runout distance, but overestimates area inundated. It also distributes debris more evenly than observed for the original Garbage Dump debris flow. We attribute the lack of topographic match to the impossibility of being able to accurately replicate the fan topography 900 years ago and that FLO-2D is not able to simulate rigid plugs that lead to flow diversion. Because the Garbage Dump event was not observed on the southern fan sections, this model supports the assumptions made by BGC (2007a) that the channel in the vicinity of the Highway 99 bridge was significantly more incised. An alternative explanation could be that the Garbage Dump debris flow could have had a much lower peak discharge and thus longer flow duration than the one modelled.

The intermediate and high viscosity runs show little difference in term of runout and area inundated but do display disparate maximum flow depths in the channel upstream of the fan apex.

These initial calibration runs are not entirely satisfactory with regard to replication of the Garbage Dump debris flow. As explained above, the single-phase bulk rheologic model that

was implemented cannot simulate flow avulsions that may be caused by a rigid plug. For this reason, a two-phase flow was also simulated. Rather than redefining the mechanistic underpinnings of the model (i.e. change from a quadratic flow model to a Coulomb frictional model to simulate the rigid plug), we use the principal of equivalent fluids. In this instance we use the high viscosity parameter combination (Table 2) for the rigid plug and the low viscosity parameter combination for the more liquid afterflow. The flow volumes were split according to the distributed volumes as mapped in the field and calculated by interpolation. Table 3 summarizes the modelling assumptions:

Table 3: Input parameters for the simulated two-phase Garbage Dump debris flow

Flow Phase	(α_1)	(β_1)	(α_2)	(β_2)	Total volume (m ³)	Peak Discharge (m ³ /s)
Rigid Plug	2.7	11.0	0.05	14.5	900,000	11,000
Afterflow	0.13	12.0	2.7	10.4	1,000,000	3,200

Peak discharge for the rigid plug and afterflow phases of the debris flow was calculated using Equations 6 and 7 respectively. The former equation is applicable for bouldery debris flows found in Southern BC, while the latter is representative of volcanic debris flows (Bovis and Jakob, 1999).

$$Q_p = \left[\frac{V}{28} \right]^{0.9} \quad [\text{Eq. 6}]$$

$$Q_p = \left[\frac{V}{343} \right]^{1.01} \quad [\text{Eq. 7}]$$

where Q_p is peak discharge (m³/s) and V is total sediment volume (m³).

Note that the volumes of the rigid plug and the more liquid afterflow do not sum to the total volume of 2.1 Mm³ as reported in BGC (2007a). The difference is explained by portions of the afterflow having likely descended down the existing channel of Cheekeye River. This portion (estimated as 0.2 Mm³) was not modelled separately because it remained largely confined to the former channel of Cheekeye River, which then spilled into Cheakamus River. The model of the rigid plug was started immediately upstream of the dogleg; the model for the afterflow was started southwest of the dogleg to ensure that the flow followed approximately the pre-existing topography.

Debris flow matrix volume concentrations range between 20% and 50% on the rising and falling limbs of the hydrograph with peak concentrations of 55%. The shape of the hydrograph was purposely chosen to be very steep for the rising and falling limbs of the Rigid

Plug flow phase. Based on the input parameters of Table 3, modelling results for the two-phase debris flow are shown in Figure 4. The two-phase modelling results provide an overall better-fit to the observed depositional pattern of the Garbage Dump debris flow. The extent of inundation is greater for the simulated flows, but it is expected that some areas would get inundated without much deposition occurring. Furthermore, it is not possible to create an exact replica of the 900 year BP fan topography and some deviation in flow direction and deposition pattern are expected.

It should be recognized that the modelled Garbage Dump debris flow under the two-phase scenario may not be representative of all future flows. Depending on source area rocks, peak discharge-volume relationships, and sediment concentration, flow rheology may differ substantially from the calibrated case. This subject is further discussed in Section 5.

5.0 PREDICTIVE MODEL RUNS

5.1 Results

The number of model runs is dictated by the objectives of the debris flow hazard and risk assessment. First, it is desirable to know existing risk over a large spectrum of return periods and second it is desirable to know the return period range that is successfully mitigated by structural means.

Using a low viscosity scenario (Table 2), debris flows were simulated for the 20, 50, 100, 200, 500, 2500 and 10,000-year events (Figures 5 to 11). The topography that was used in the analysis is based on LIDAR with a 50 m grid spacing. The main features observed from these model results can be summarized as follows:

- All events are likely to reach Cheakamus River.
- The 20-year event will likely remain fully channelized in Cheekeye River until it reaches Cheakamus River. Avulsion downstream of the fan apex is possible if a rigid plug were to form of organic materials or coarse bouldery debris, which cannot be modelled adequately (Figure 5).
- Events including and exceeding the 50-year return period will likely spill out of the channel upstream of Highway 99 and flow toward the south (Figures 6 to 11).
- Events exceeding the 50-year return period are increasingly likely to destroy the Highway 99 bridge as well as the CN Rail bridge.
- Events exceeding the 50-year return period are likely to dam Cheakamus River for periods ranging from hours to days. The landslide dam will be long and likely not more than 3 to 6 m deep and is therefore unlikely to fail catastrophically, but rather through rapid incision, which will create an elongated sediment wedge from the Cheekeye confluence to the Squamish River.
- Flows exceeding and including the 500-year return period will likely affect the majority of the Cheekeye subdivision with flow depths and velocities capable of destroying existing structures.
- Flows exceeding and including the 500-year return period will likely affect buildings of I.R. 11 to the northwest of Cheakamus River.
- Events exceeding the 50-year return period are likely to avulse from the lower channel sections downstream of the Dogleg and impact portions of the existing Cheekeye subdivision.
- For flows avulsing at the fan apex, lower flow resistance on roads will allow debris to travel down Highway 99 toward the south and Squamish Valley road toward the southwest.

- The 2500-year and 10,000-year events are likely to impact northern portions of Brackendale, though flow depth and flow velocities may be low enough to prevent structural damage. Flow could also avulse into Alice Lake Park by the flow overwhelming the sill separating Stump Lake from the Cheekeye River drainage. Water from Stump Lake could be displaced towards the south.

Four additional scenarios were modelled (the 2500-year and the 10,000-year return period event (see Section 4.2)). In the first two scenarios, the 2500-year (2.4 Mm³) and 10,000-year return period events (2.8 Mm³) are forced to avulse at the Highway 99 bridge. A rigid plug is assumed to arrest largely at the bridge flow constriction, thus forcing the afterflow to discharge onto the central and southern fan portions. Substantial flow to the north is not possible since it is uphill. The second model run allows the debris flow to follow the channel to the Dogleg, where a rigid plug deposits under existing topography (similar to the GD debris flow). The less viscous afterflow then bypasses the rigid plug to the south. Input parameters for these two scenarios are summarized in Tables 4 and 5.

Table 4: Input parameters for the simulated two-phase 2500-year return period debris flow (2.4 Mm³)

Scenario	Flow Phase	(α_1)	(β_1)	(α_2)	(β_2)	Volume (Mm ³)	Peak Discharge (m ³ /s)
Fan Apex Avulsion	Rigid Plug	2.0	17.0	0.0345	24.0	1.1	14,000
	Afterflow	0.13	12.0	2.7	10.4	1.3	4,100
Dogleg Avulsion	Rigid Plug	2.7	11.0	0.05	14.5	1.1	14,000
	Afterflow	0.13	12.0	2.7	10.4	1.3	4,100

Table 5: Input parameters for the simulated two-phase 10,000-year return period debris flow (2.8 Mm³)

Scenario	Flow Phase	(α_1)	(β_1)	(α_2)	(β_2)	Volume (Mm ³)	Peak Discharge (m ³ /s)
Fan Apex Avulsion	Rigid Plug	2.0	17.0	0.0345	24.0	1.2	15,000
	Afterflow	0.13	12.0	2.7	10.4	1.6	5,100
Dogleg Avulsion	Rigid Plug	2.7	11.0	0.05	14.5	1.2	15,000
	Afterflow	0.13	12.0	2.7	10.4	1.6	5,100

BGC used different viscosity and yield stress parameters for simulation of a rigid plug forming at the fan apex than those applied to the rigid plug of the Garbage Dump debris flow and the second model run for a rigid plug at the dogleg under existing topography. A much more viscous flow was required at this location to simulate deposition and the damming of the Highway 99 bridge. Input parameters were adjusted by trial and error to force flow towards the southern and central fan portions could not have been achieved.

Model results for the four scenarios (avulsion at fan apex and avulsion at dogleg for the 2500 and 10,000-year events, respectively) are shown in Figures 12, 13, 14 and 15. These scenarios are considered the most likely outcomes under existing conditions, though a large number of variations are possible.

Figures 12 and 13 illustrate that in the event a rigid plug forms near the fan apex and deflects a large portion of the liquid portion of the debris toward the south and southwest, debris would likely impact large portions of Brackendale as well as inundate Highway 99 from the Cheekeye bridge to the southern fan margin and the CN Rail tracks through Brackendale. Using some judgement and comparing the modelled flow depth to the observed deposit thickness at the Garbage Dump debris flow inundation may range between several centimetres at the most distal portions of the runout to approximately 1 m in the inhabited portions of Brackendale, with higher flow depths in local depressions. Flow velocities in the distal fan areas would likely range between 1 and 3 m/s.

Figures 14 and 15 shows that the rigid plug at the Dogleg would divert much debris towards the southwestern fan sector, but large amounts of debris are likely to still reach Cheakamus River and impact the Cheekeye Subdivision. The liquid afterflow would reach the northern portions of Brackendale with some of the flow discharging into Squamish River west of the airport. The B.C. Hydro corridor, Squamish Valley Road and Government road would be inundated as shown, as well as CN Rail between Brackendale and the airport. Inundation depth and flow velocities in the inhabited area of Brackendale would likely be similar as for the fan apex avulsion scenario.

These scenarios demonstrate that fans generated by debris flows are dynamic landforms in which hazard posed by fluid landslides is likely to shift over time as some portions of the fan abruptly aggrade, while others are scoured through fluvial erosion over time. In the case of Cheekeye Fan, very high return period flows (several thousand years), have the potential of sudden shifts of fan activity from the northern fan sector back to the southern fan portions.

Previous sections discussed some of the uncertainties that stem from rheological considerations inherent in FLO-2D. The following section addresses additional uncertainties that are based on experience, and geomorphic considerations. A discussion of these uncertainties is warranted to avert the illusion of exactness that computer models may suggest.

5.2 Additional Uncertainties

Several sources of uncertainties exist that cannot readily be modelled. They are discussed in this section qualitatively to understand the repercussions and effects on flow behaviour.

5.2.1 Brohm River Damming

Brohm River, which joins the Cheekeye River on the right bank near the fan apex, would be temporarily backed up or completely dammed by most modelled debris flows. Debris flows

with return periods of 20 years to 500 years would likely occur during very wet weather as it is presumed that those events are triggered by very heavy rain, and thus would occur at a time of high discharge on Brohm River. Blockage would likely be limited to higher return period flows (> 200 years) and to less than one hour since the Brohm River drainage upstream of the confluence is steep and only about 30,000 m³ water could be stored. As the temporary debris dam is overtopped or fails, debris flow material deposited in the Cheekeye River channel would likely be re-entrained perhaps leading to a series of secondary surge waves of hyperconcentrated flow. This process is difficult to model, but could lead to additional hazard in the form of secondary surges overrunning deposited debris along the channel and extending the runout distances in some fan sectors.

5.2.2 Brohm River Discharge

For scenarios where debris flows do not dam Brohm River (likely for return periods <200 years), Brohm River could add significant water volumes to Cheekeye River debris flows. This process of flow dilution towards a lower sediment concentration could change flow behaviour from mostly laminar to mostly turbulent. This effect could slow the flow or, if the sediment concentration of the debris flow was very high, could accelerate the flow by adding mobility. The high water discharge would also aid in mobilizing or incising into channel debris during the falling limb of the debris flow hydrograph. A complete blockage of the area near the confluence is conceivable if the narrow bedrock canyon at the Highway 99 bridge is blocked by woody debris. In this case it is conceivable that water from Brohm River could be diverted across the deposit and towards the south.

6.0 CONCLUSIONS

This report has addressed debris flow failure scenarios and flow characteristic focussing on likely triggers and processes in the transportation zone. This information is complementary to BGC's 2007a report on debris flow frequency and magnitude.

The second section of the report explains, critiques and justifies the debris flow model used and concludes that FLO-2D provides an adequate representation for debris flow modelling on Cheekeye Fan.

The well-studied Garbage Dump debris flow was simulated to obtain a well-calibrated base model that yields variables that can be used for modelling over a wide range of magnitudes. The Garbage Dump debris flow appears to have occurred as a two phase flow with a rigid plug consisting of a higher boulder concentration and a higher density of trees being followed by a more fluid afterflow. This flow behaviour may be characteristic for future flows and the two flow phases were thus modelled separately. Uniting the two model runs graphically demonstrates good agreement of the observed Garbage Dump debris flow extent with the modelling results.

Debris flows were modelled for return periods of 20 to 10,000 years using low viscosity variables, which would appear most likely in a mitigated scenario and are thus most relevant to risk calculations. The results of these model runs were described qualitatively. Flows exceeding 50 years will likely avulse and lead to damage in existing subdivisions, avulse onto Highway 99 and will affect CN Rail. Larger flows could affect the community of Brackendale.

To account for the rigid plug behaviour identified in the Garbage Dump debris flow, BGC also modelled two additional two phase scenarios for the 1:10,000 year return period debris flow with rigid plugs forming at the fan apex and at the Dogleg under existing topographic conditions. More fluid afterflow was then allowed to flow south past the flow constriction. These results are instructive to assess current hazard on Cheekeye fan but are unlikely to be representative for flows under the mitigated scenario, when the rigid plug flow phase would be captured by the debris barrier.

Uncertainties in flow behaviour have been addressed for Brohm River impoundment and blockages at Highway 99.

7.0 CLOSURE

This report presents the results of the debris flow simulation conducted on Cheekeye River.

We trust the information provided will allow KWL and MDC to proceed with the next steps. Please do not hesitate to contact us if you have any questions or comments, or if we may be of further assistance.

BGC ENGINEERING INC.

per:

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

Reviewed:

Hamish Weatherly, M.Sc., P.Geo.
Senior Hydrologist/Fluvial Geomorphologist

Scott McDougall, Ph.D., E.I.T
Geotechnical Engineer

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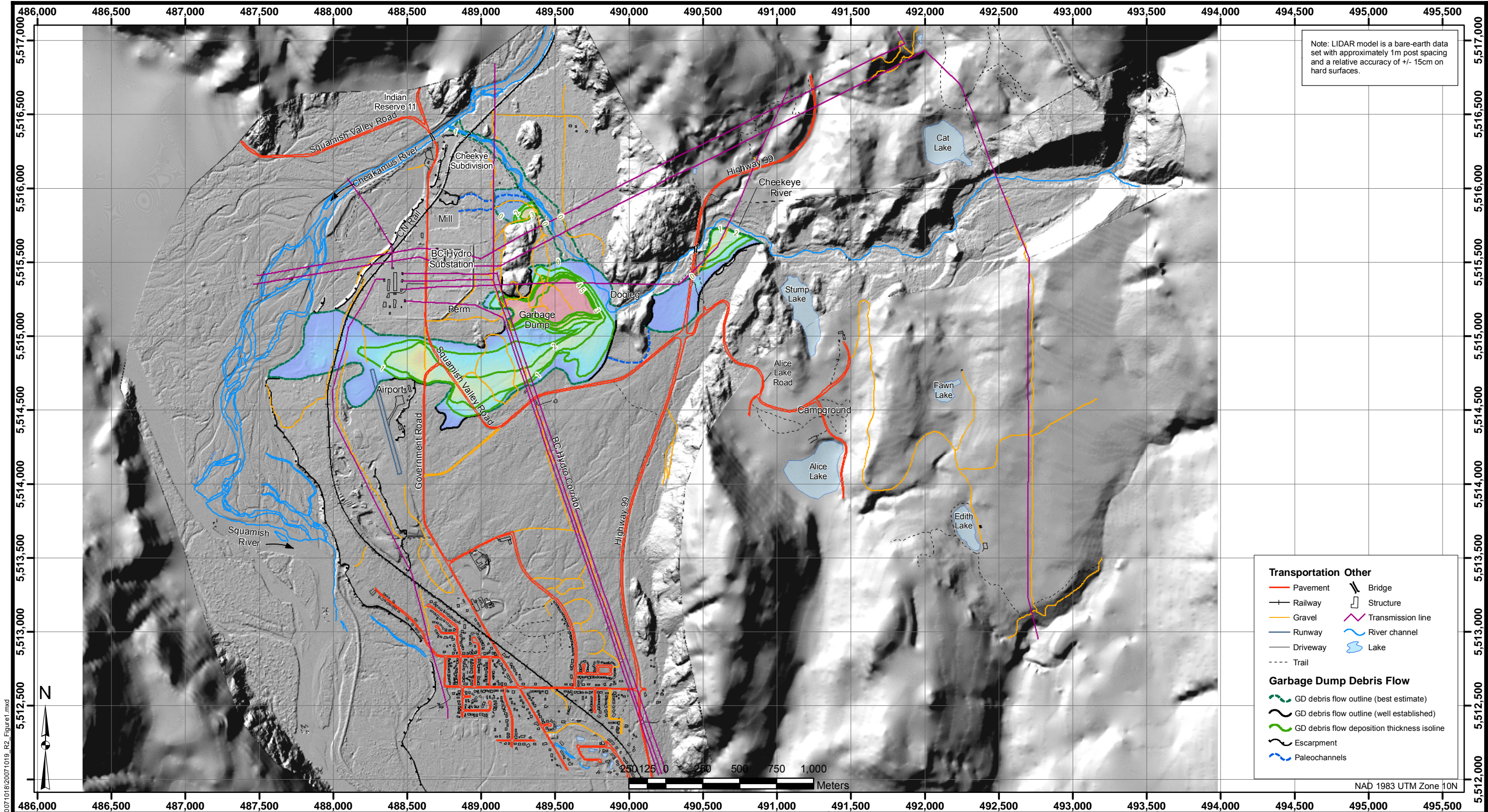
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FIGURES

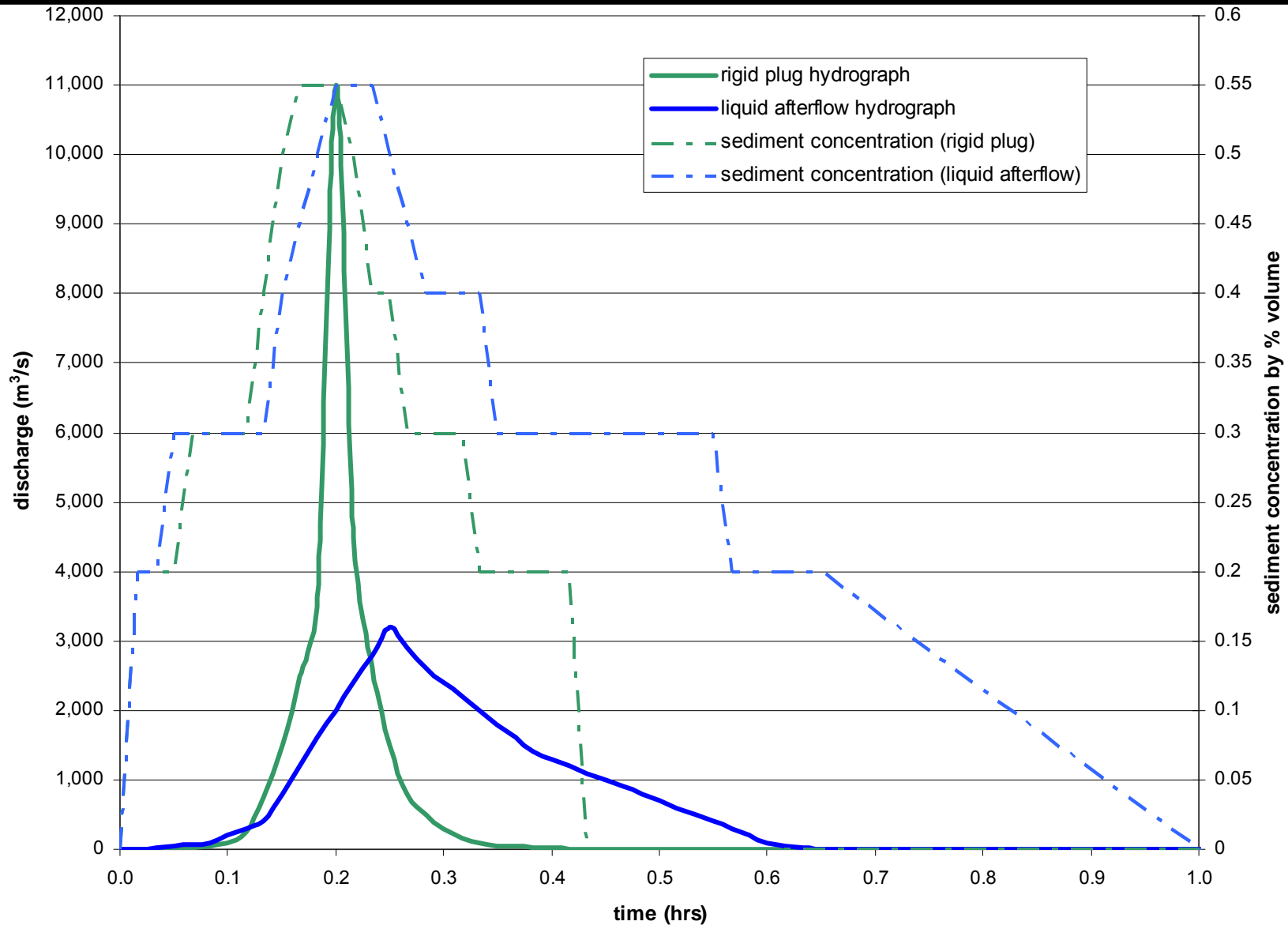


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FIG TO BE READ WITH BGC REPORT TITLED "CHEEKEYE FAN DEBRIS FLOW SIMULATION" DATED DEC 2007

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SCALE:	NA	DESIGNED:	MJ
DATE:	DEC 2007	CHECKED:	MJ
DRAWN:	TNR	APPROVED:	MJ

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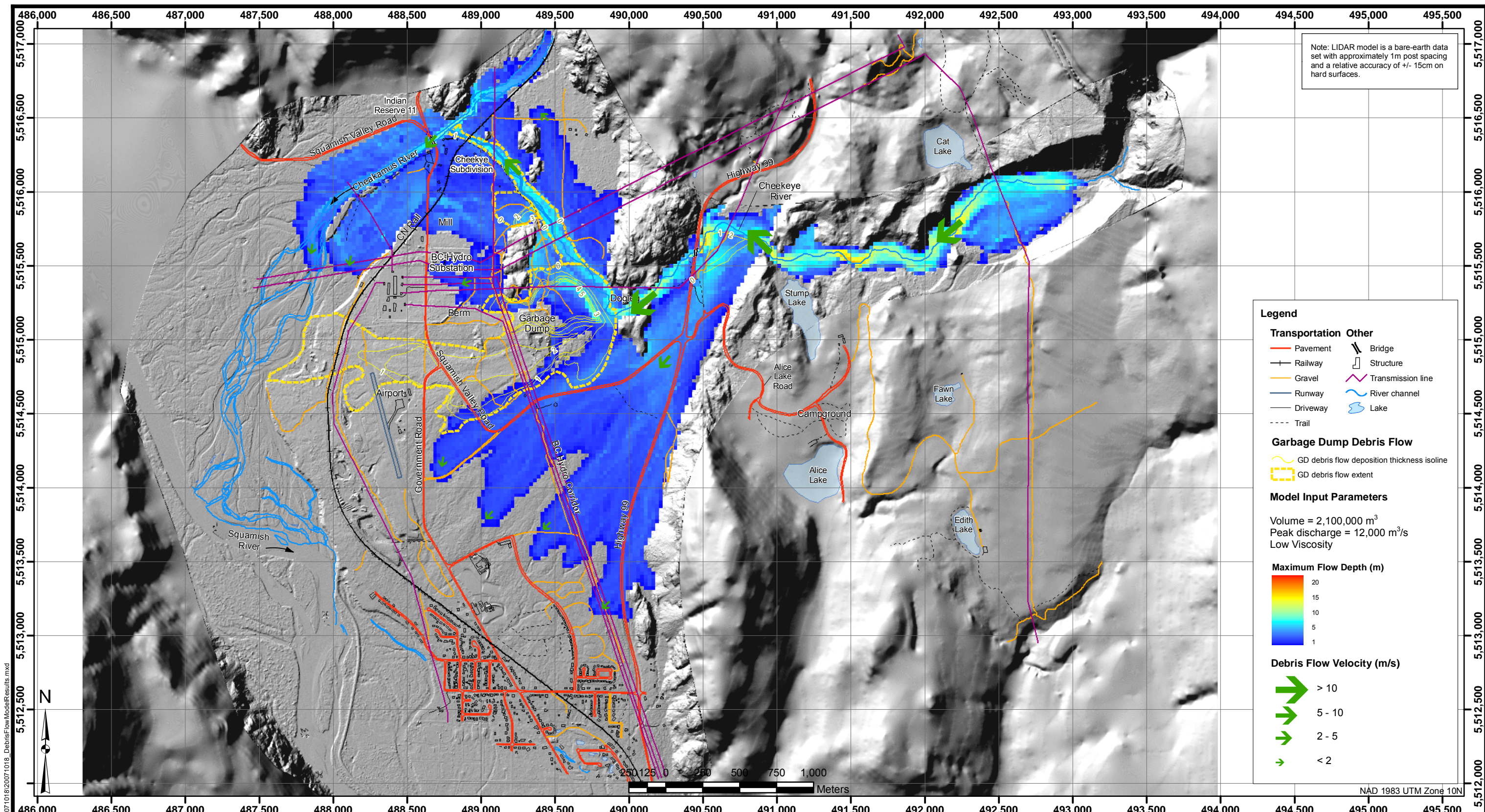
BGC ENGINEERING INC.

AN APPLIED EARTH SCIENCES COMPANY

CLIENT: MDC

PROJECT: CHEEKEYE RIVER DEBRIS FLOW MODELING		
TITLE: HYDROGRAPH AND SEDIMENT CONCENTRATION FOR THE SIMULATED GARBAGE DUMP DEBRIS FLOW		
PROJECT No.: 0464-001	FIG No.: 2	REV.:

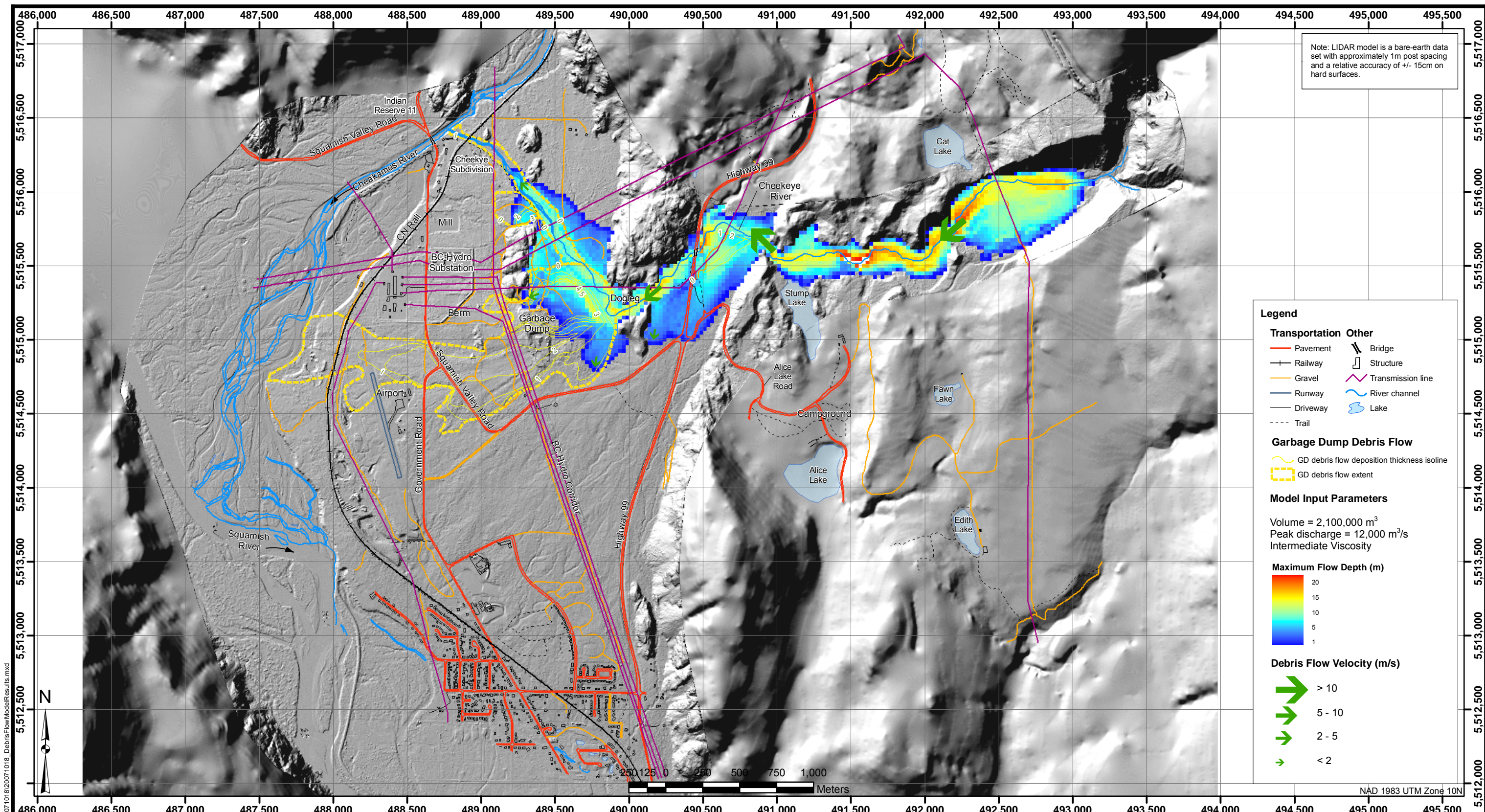
FIG TO BE READ WITH BGC REPORT TITLED "CHEEKEYE FAN DEBRIS FLOW SIMULATION" DATED DEC 2007



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							DATE: DEC 2007			TITLE: DEBRIS FLOW INTENSITY							
							DRAWN: TNR			GARBAGE DUMP DEBRIS FLOW - LOW VISCOSITY							
							DESIGNED: TNR										
							CHECKED: MJ										
							APPROVED: MJ		CLIENT: MDC		PROJECT No.: 0464-001		FIG No.: 3a		REV.:		
REV.	DATE	REVISION NOTES				DRAWN	CHECK	APPR.									

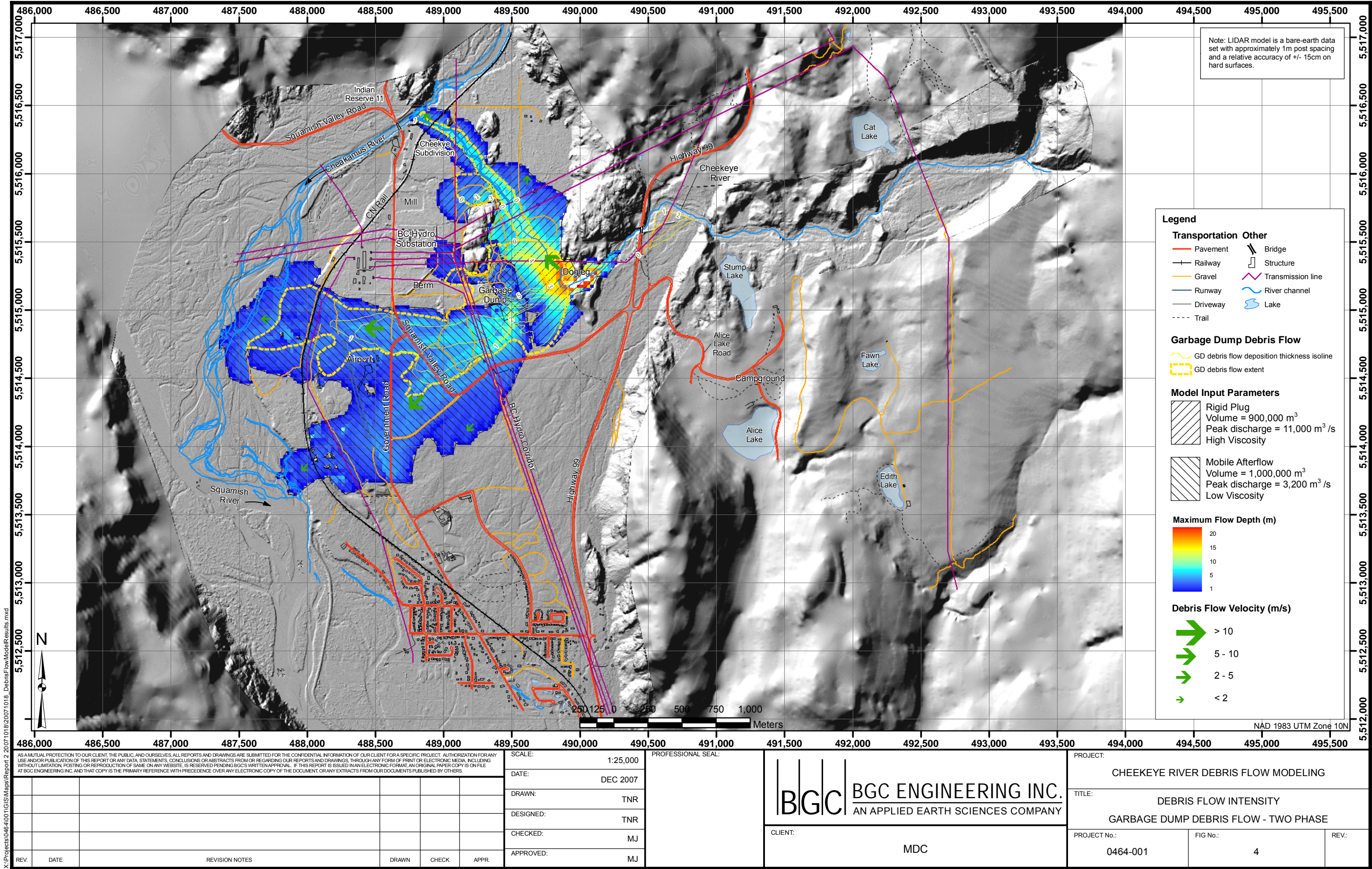
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							DATE: DEC 2007					TITLE: DEBRIS FLOW INTENSITY GARBAGE DUMP DEBRIS FLOW - INTERMEDIATE VISCOSITY		
							DRAWN: TNR							
							DESIGNED: TNR							
							CHECKED: MJ							
							APPROVED: MJ		PROJECT No.: 0464-001			FIG No.: 3b		REV.:
REV.	DATE	REVISION NOTES				DRAWN	CHECK	APPR.						

FIG TO BE READ WITH BGC REPORT TITLED "CHEEKEYE FAN DEBRIS FLOW SIMULATION" DATED DEC 2007



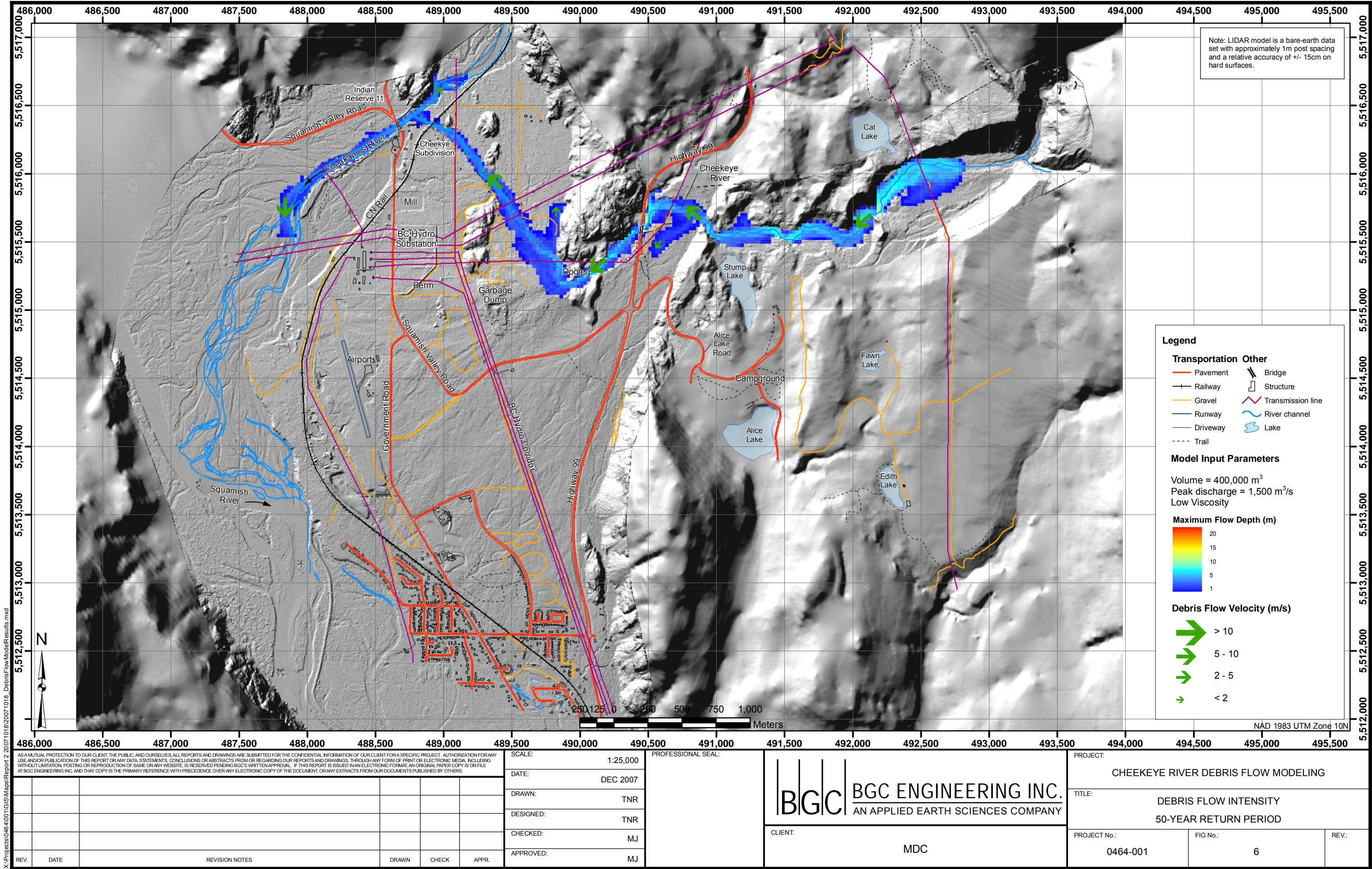
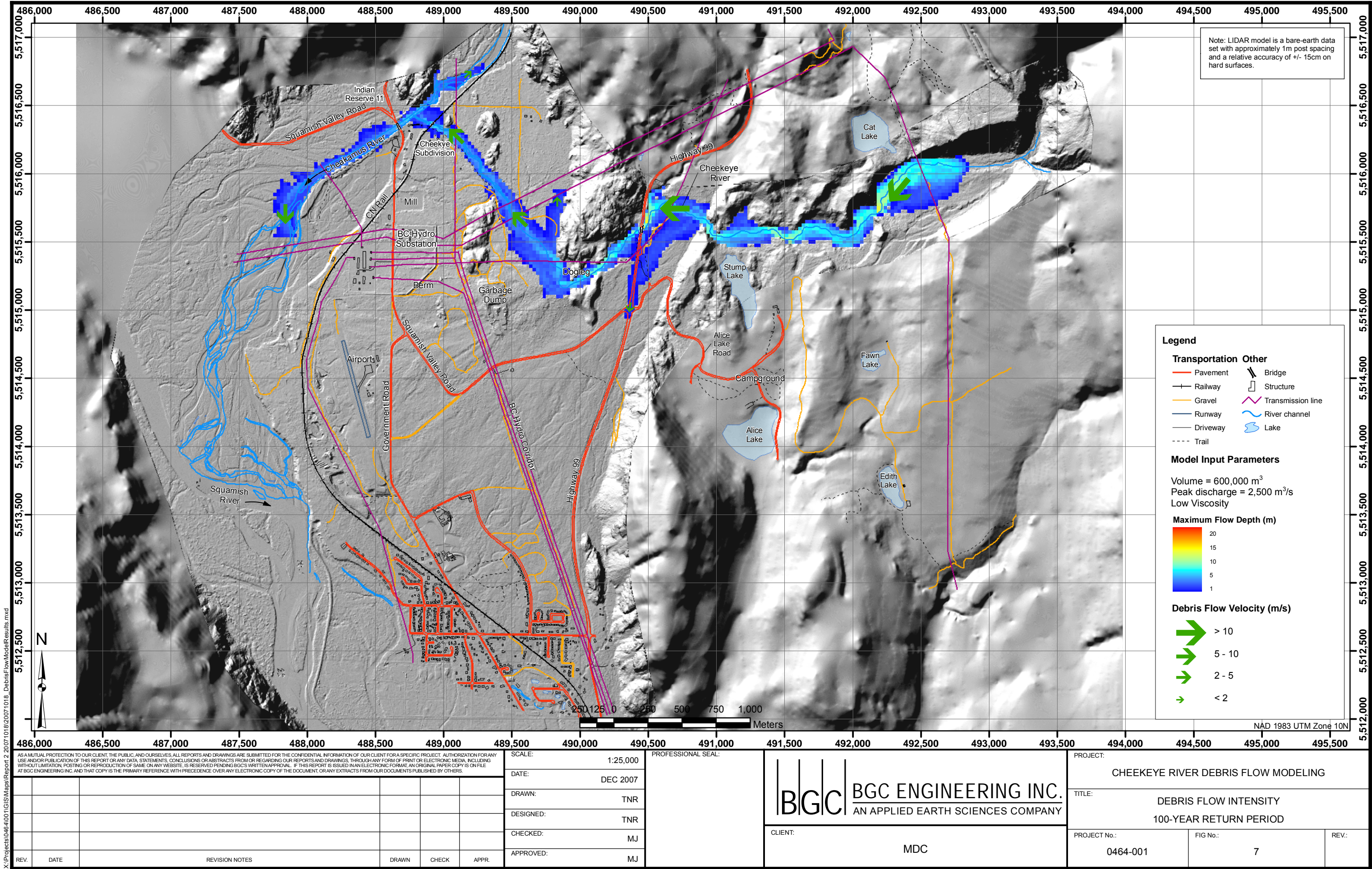
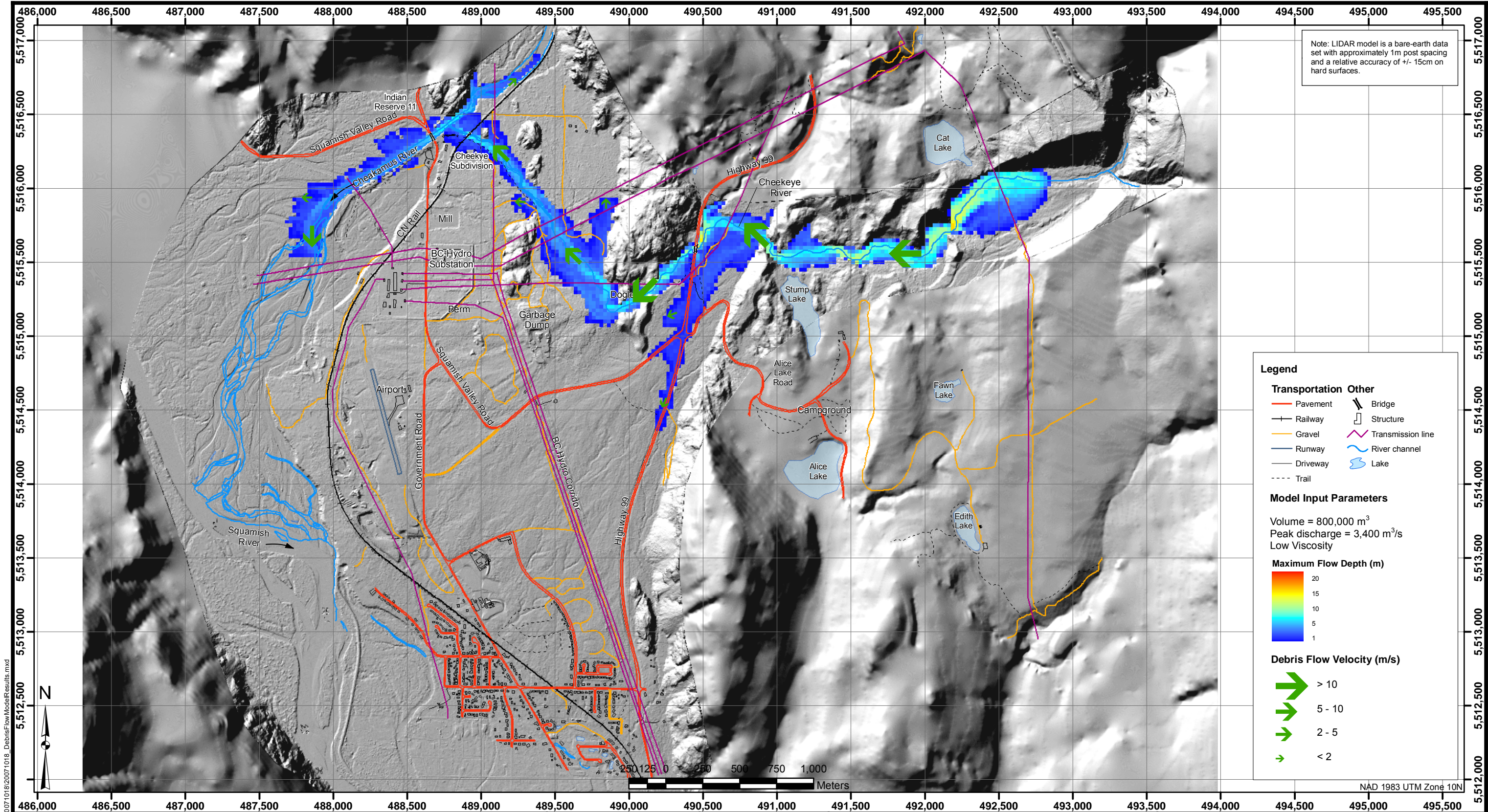


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REV.	DATE	REVISION NOTES	DRAWN	CHECK	APPR.

SCALE:	1:25,000
DATE:	DEC 2007
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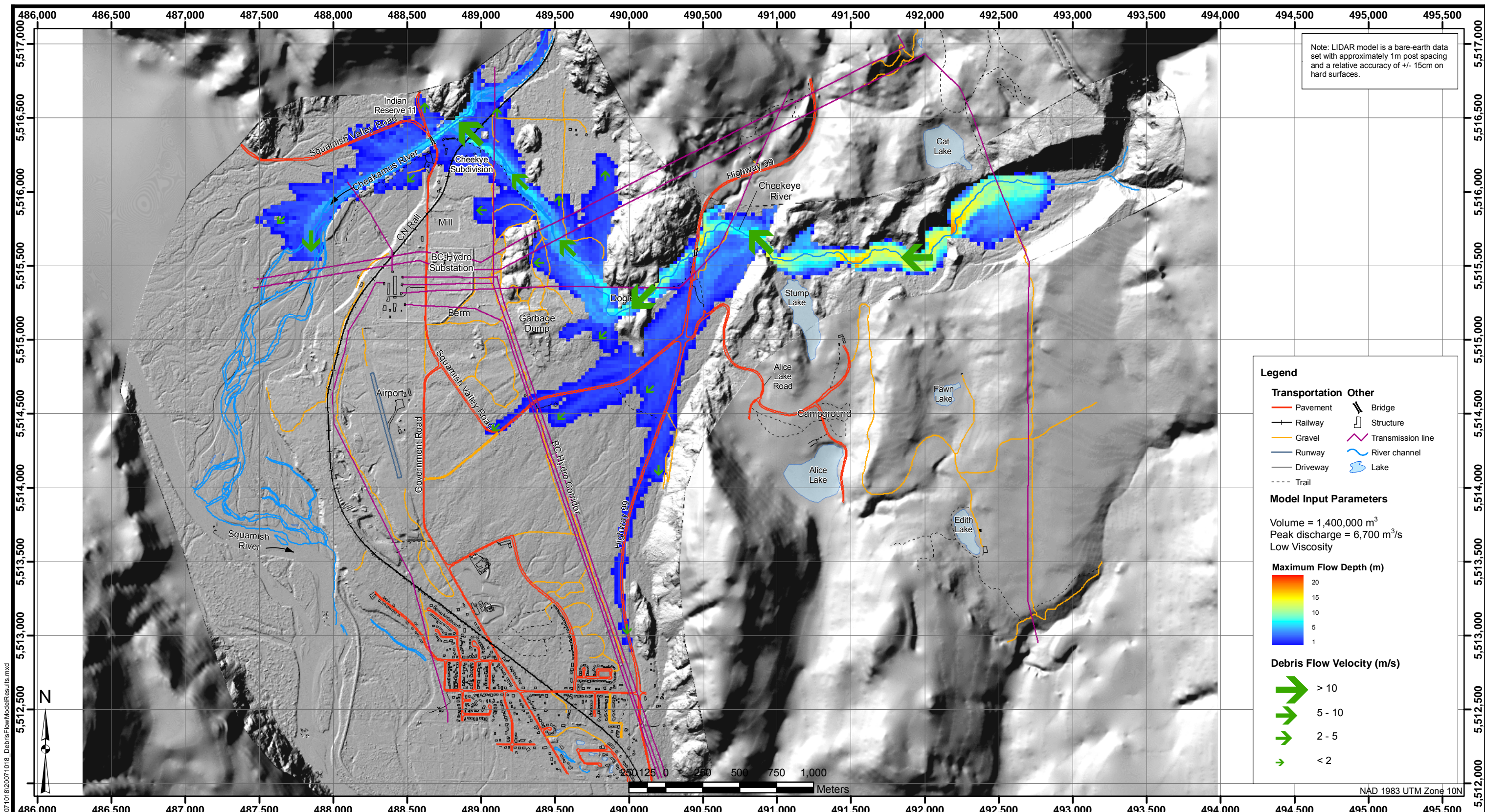
PROFESSIONAL SEAL:

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AN APPLIED EARTH SCIENCES COMPANY

CLIENT:
MDC

PROJECT: CHEEKEYE RIVER DEBRIS FLOW MODELING		
TITLE: DEBRIS FLOW INTENSITY 200-YEAR RETURN PERIOD		
PROJECT No.: 0464-001	FIG No.: 8	REV.:

FIG TO BE READ WITH BGC REPORT TITLED "CHEEKEYE FAN DEBRIS FLOW SIMULATION" DATED DEC 2007




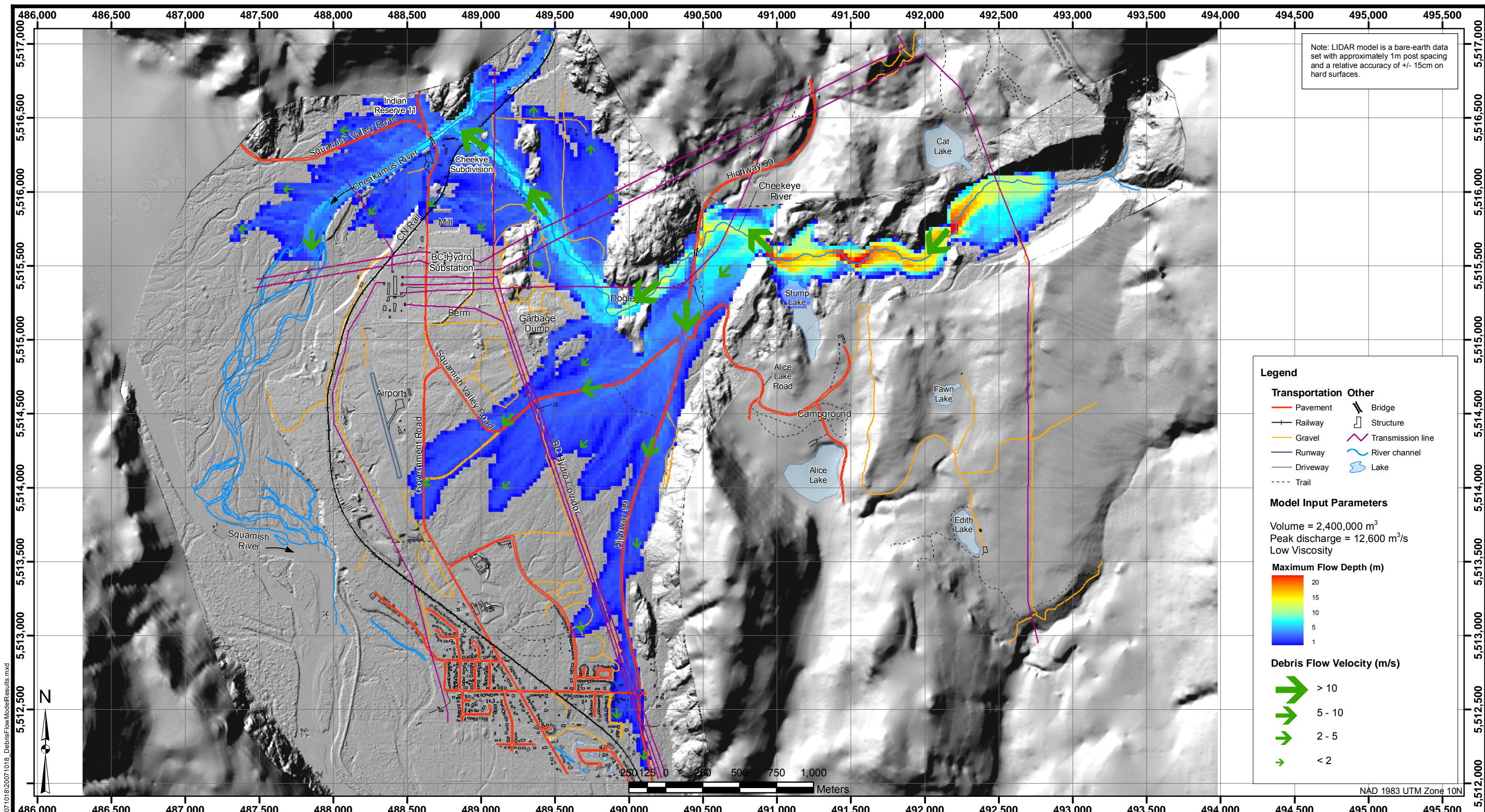
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							DRAWN: TNR									
							DESIGNED: TNR									
							CHECKED: MJ									
							APPROVED: MJ		CLIENT: MDC		PROJECT No.: 0464-001		FIG No.: 9		REV.:	
REV.	DATE	REVISION NOTES				DRAWN	CHECK	APPR.								

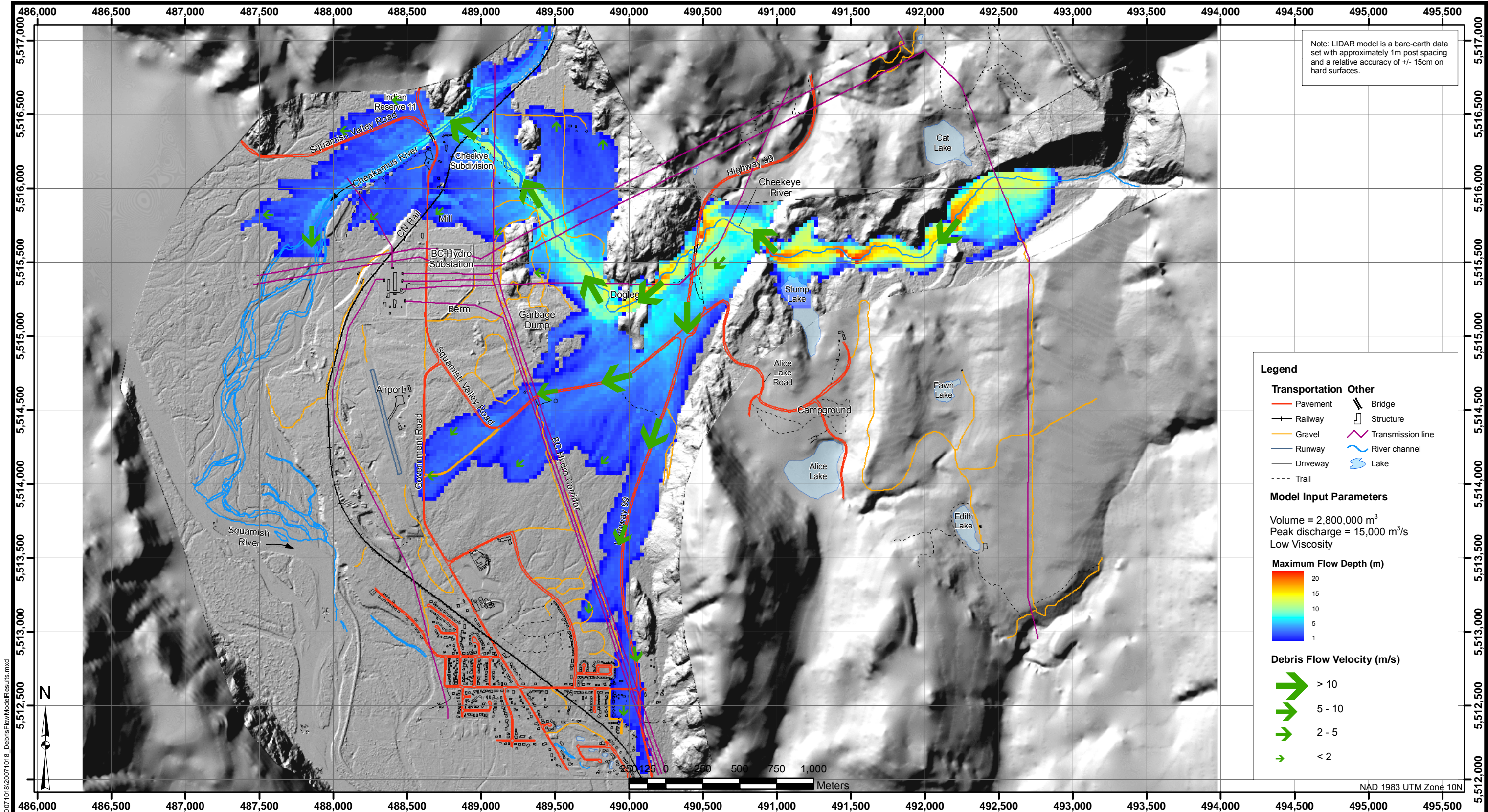
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							DATE: DEC 2007			TITLE: DEBRIS FLOW INTENSITY 2500-YEAR RETURN PERIOD			
							DRAWN: TNR						
							DESIGNED: TNR						
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REV.	DATE	REVISION NOTES			DRAWN	CHECK	APPR.	PROJECT No.: 0464-001					
							FIG No.: 10						
							REV.:						

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REV.	DATE	REVISION NOTES	DRAWN	CHECK	APPR.

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DATE:	DEC 2007
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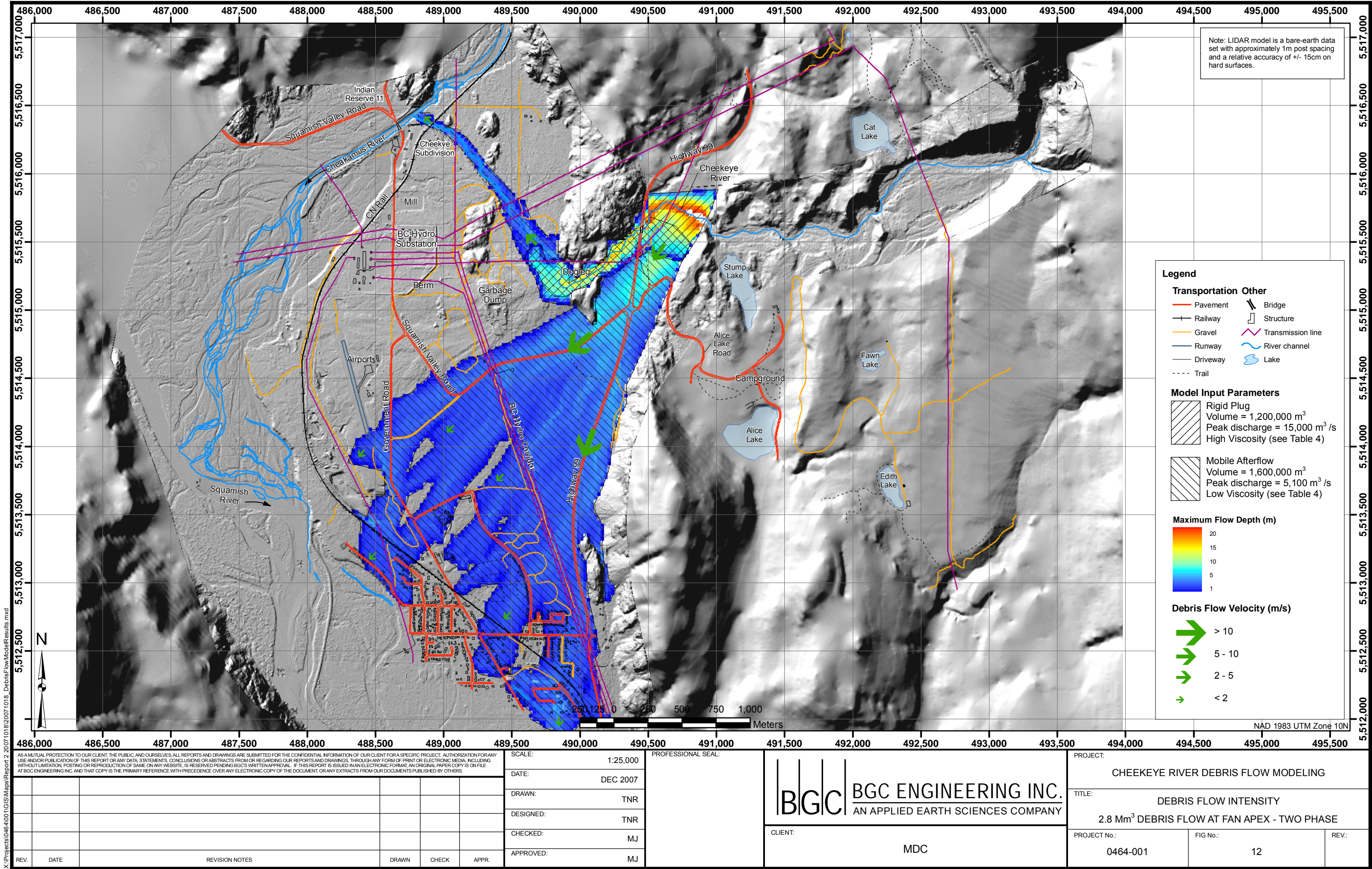
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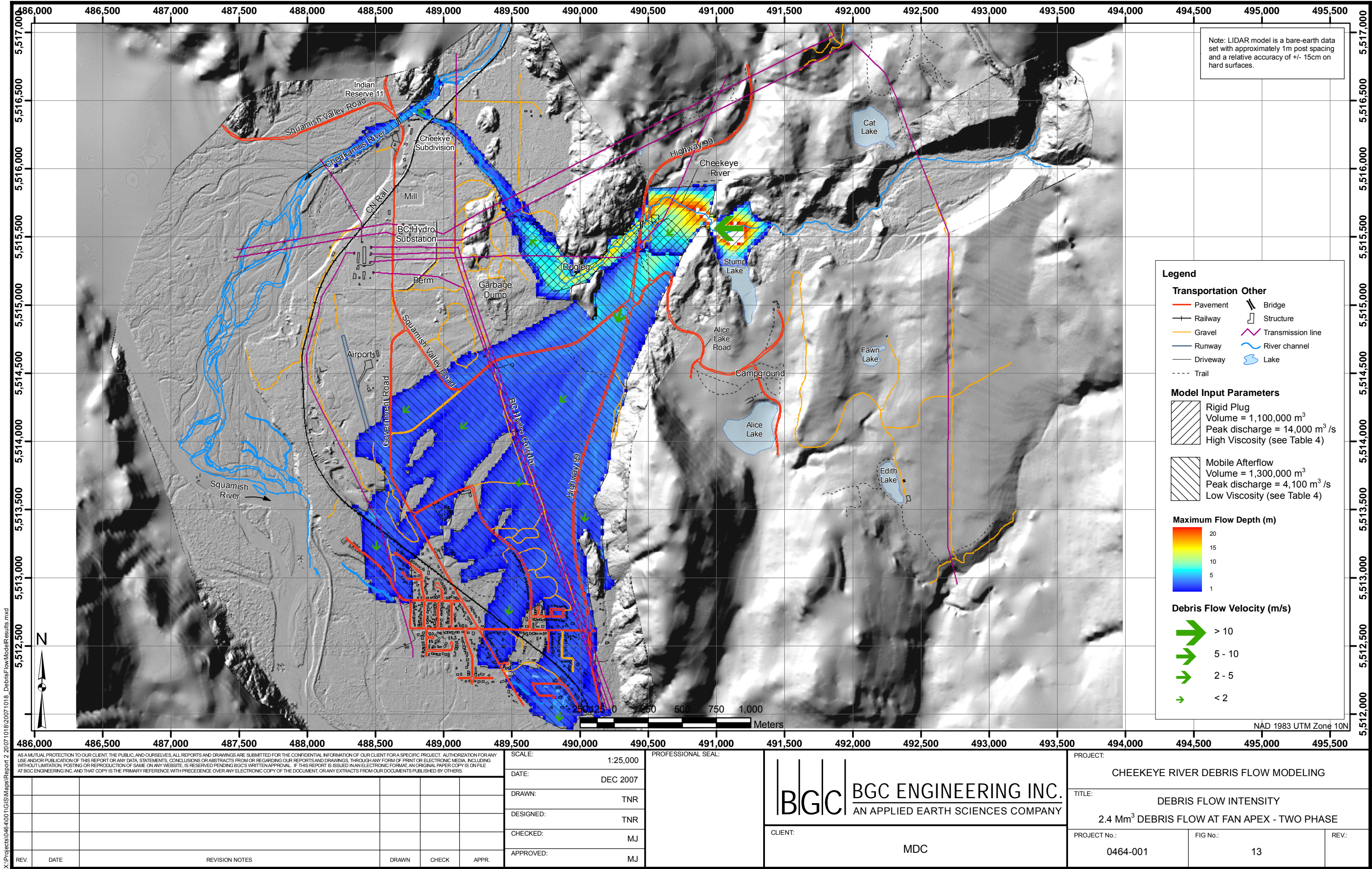
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AN APPLIED EARTH SCIENCES COMPANY

CLIENT:
MDC

PROJECT: CHEEKEYE RIVER DEBRIS FLOW MODELING		
TITLE: DEBRIS FLOW INTENSITY 10,000-YEAR RETURN PERIOD		
PROJECT No.: 0464-001	FIG No.: 11	REV.:

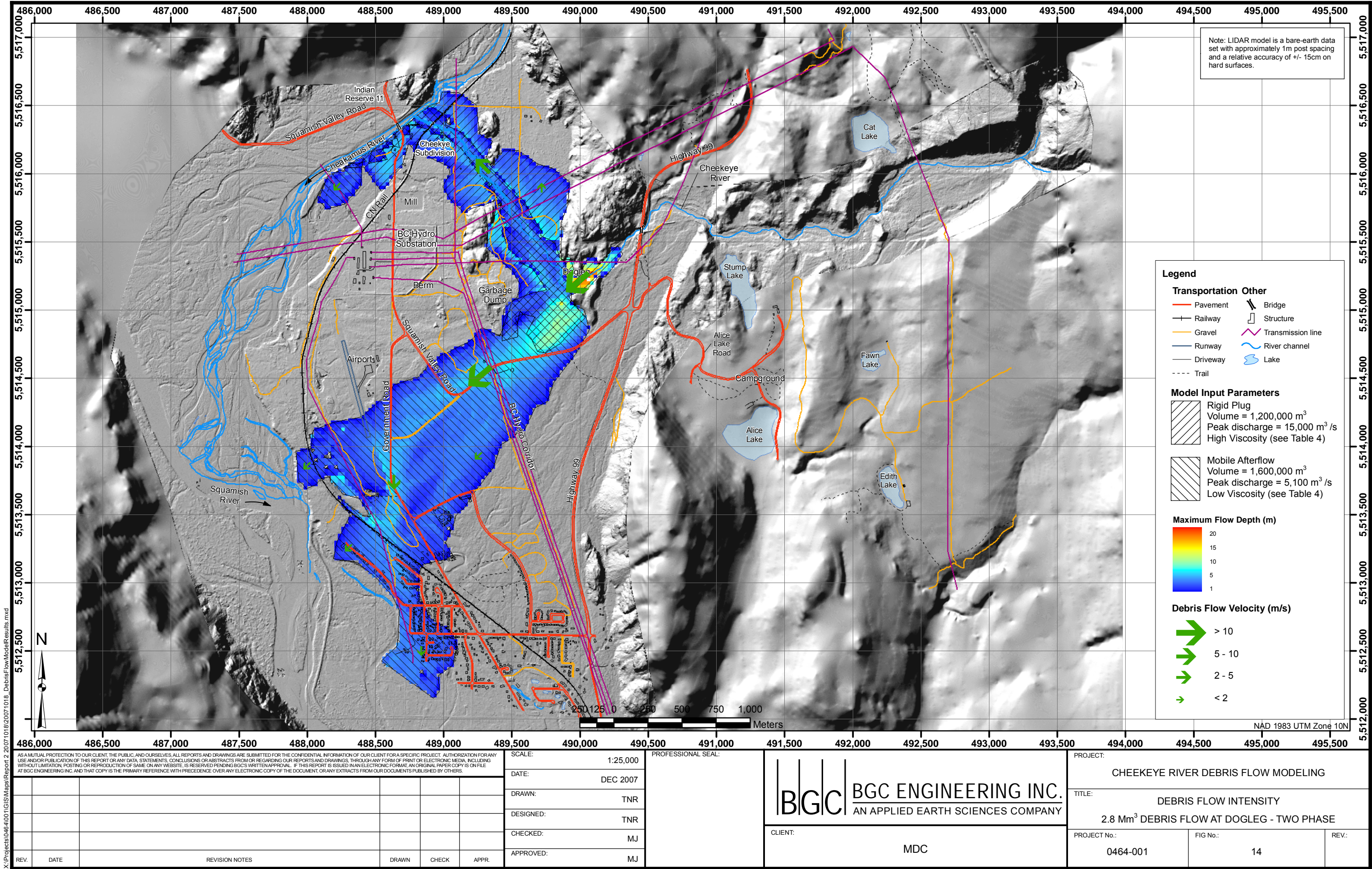
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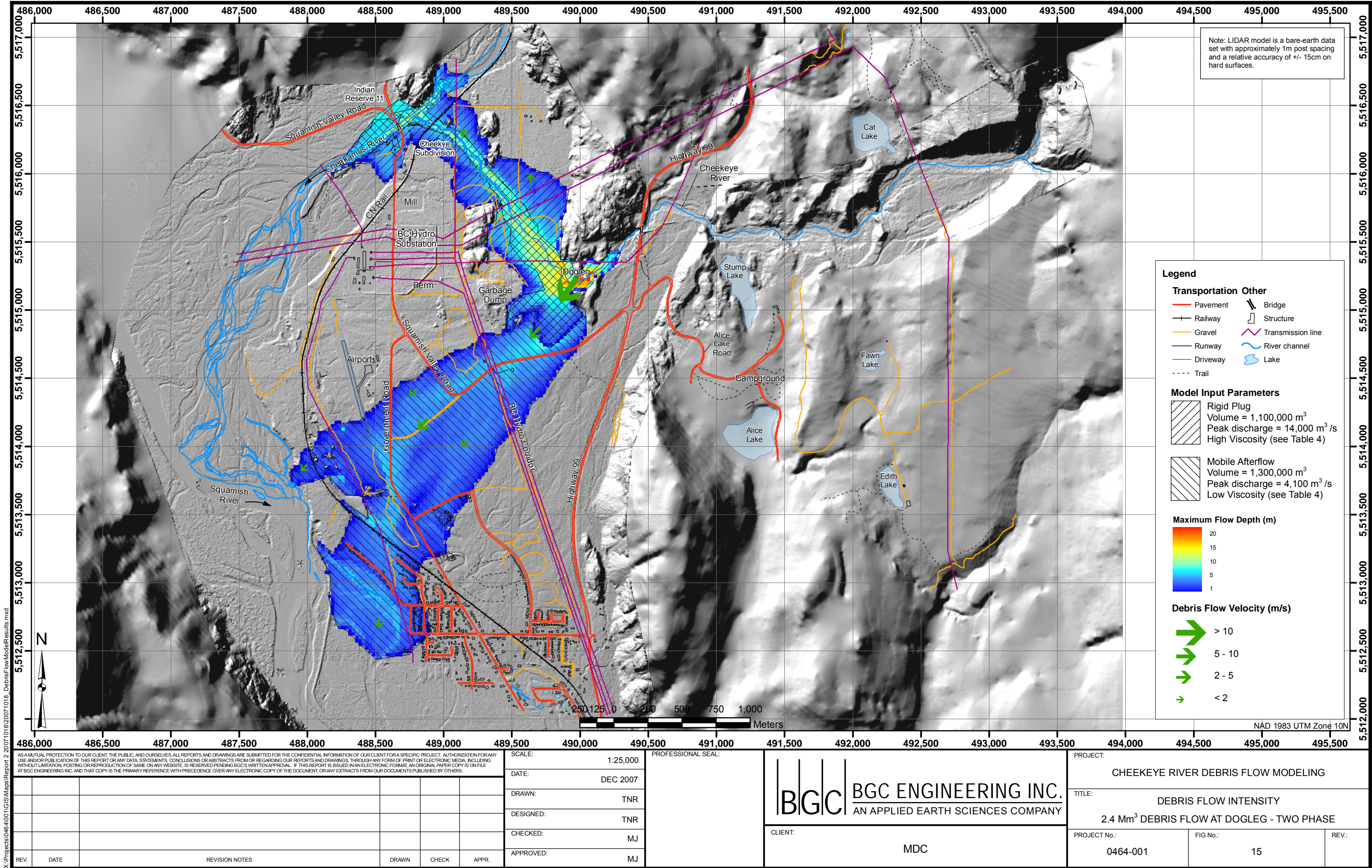




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