Appendix 10-C

Potential Interactions between the Glacier Section of Brucejack Access Road and Knipple Glacier Ablation

ERM

BRUCEJACK GOLD MINE PROJECT
POTENTIAL INTERACTIONS BETWEEN THE GLACIER SECTION OF BRUCEJACK ACCESS ROAD AND KNIPPLE GLACIER ABLATION

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BRUCEJACK GOLD MINE PROJECT

POTENTIAL INTERACTIONS BETWEEN THE GLACIER SECTION OF BRUCEJACK ACCESS ROAD AND KNIPPLE GLACIER ABLATION

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Terminology used in this document is defined where it is first used. The following list will assist readers who may choose to review only portions of the document.

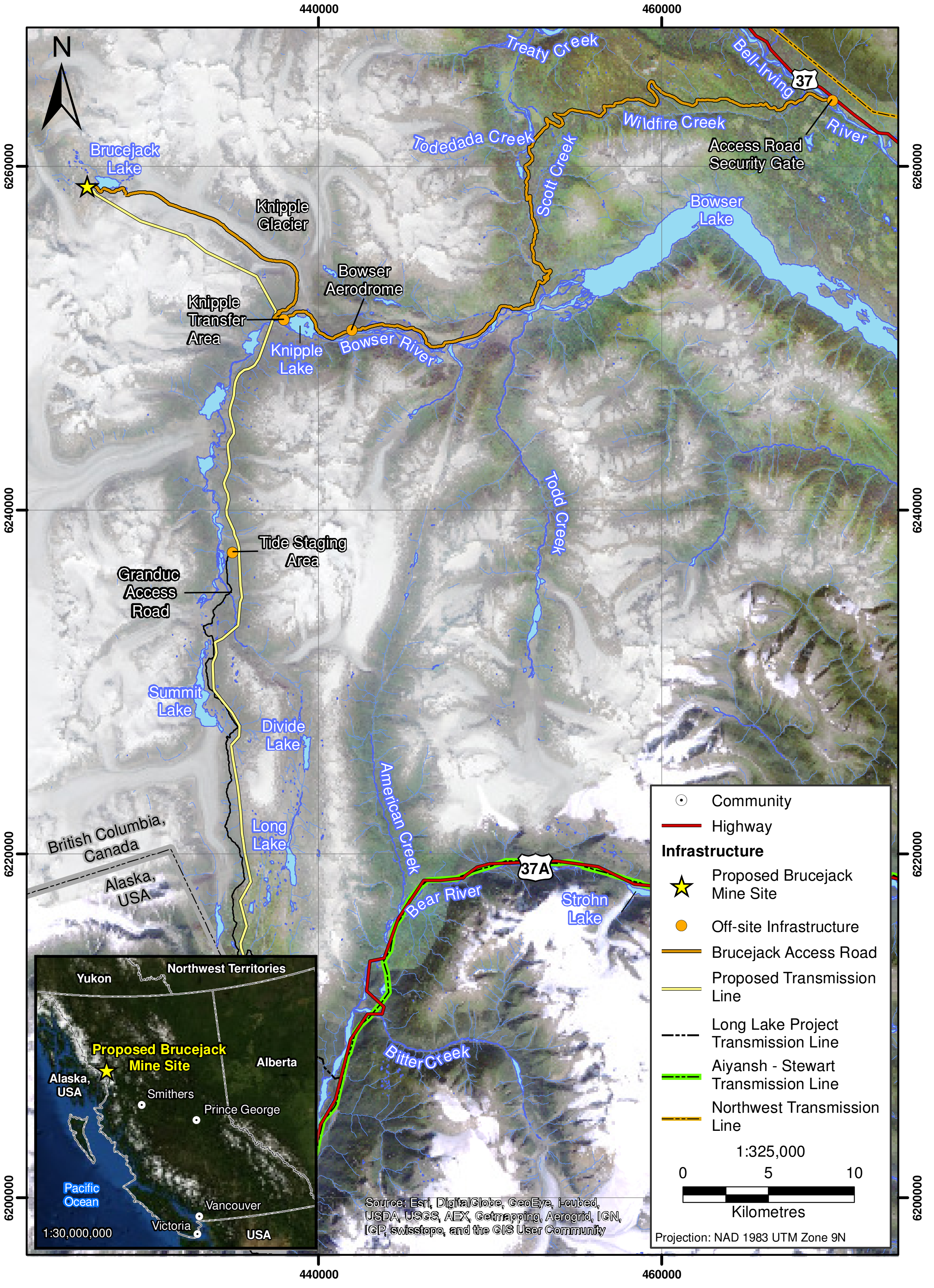
DEM	Digital Elevation Model
masl	Metres above sea level
The Project	The Brucejack Gold Mine Project
TRIM	Terrain Resource Information Management

1. Introduction

1. Introduction

The Brucejack Gold Mine Project (the Project) is located in the highly glacierized ranges of the northern Coast Mountains of British Columbia. The proposed ground access to the mine will be partially over the Knipple Glacier (KG), with the roll-on point above the glacier terminus and the roll-off point in the mid-accumulation zone of the main flow of the glacier (Figure 1-1). The glacier portion of the road comprises approximately 11 km of the total access road (Figure 1-2; Plates 1-1 to 1-12). This document addresses the potential impacts that the access road may have on the glaciohydrology of the Knipple Glacier. Additionally, the potential impacts of the glacier dynamics on the proposed glacier access road are assessed. Finally, the document concludes with a proposed monitoring program.

Figure 1-1
Brucejack Access Road



Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Projection: NAD 1983 UTM Zone 9N

Figure 1-2
Knipple Glacier Portion of the Access Road

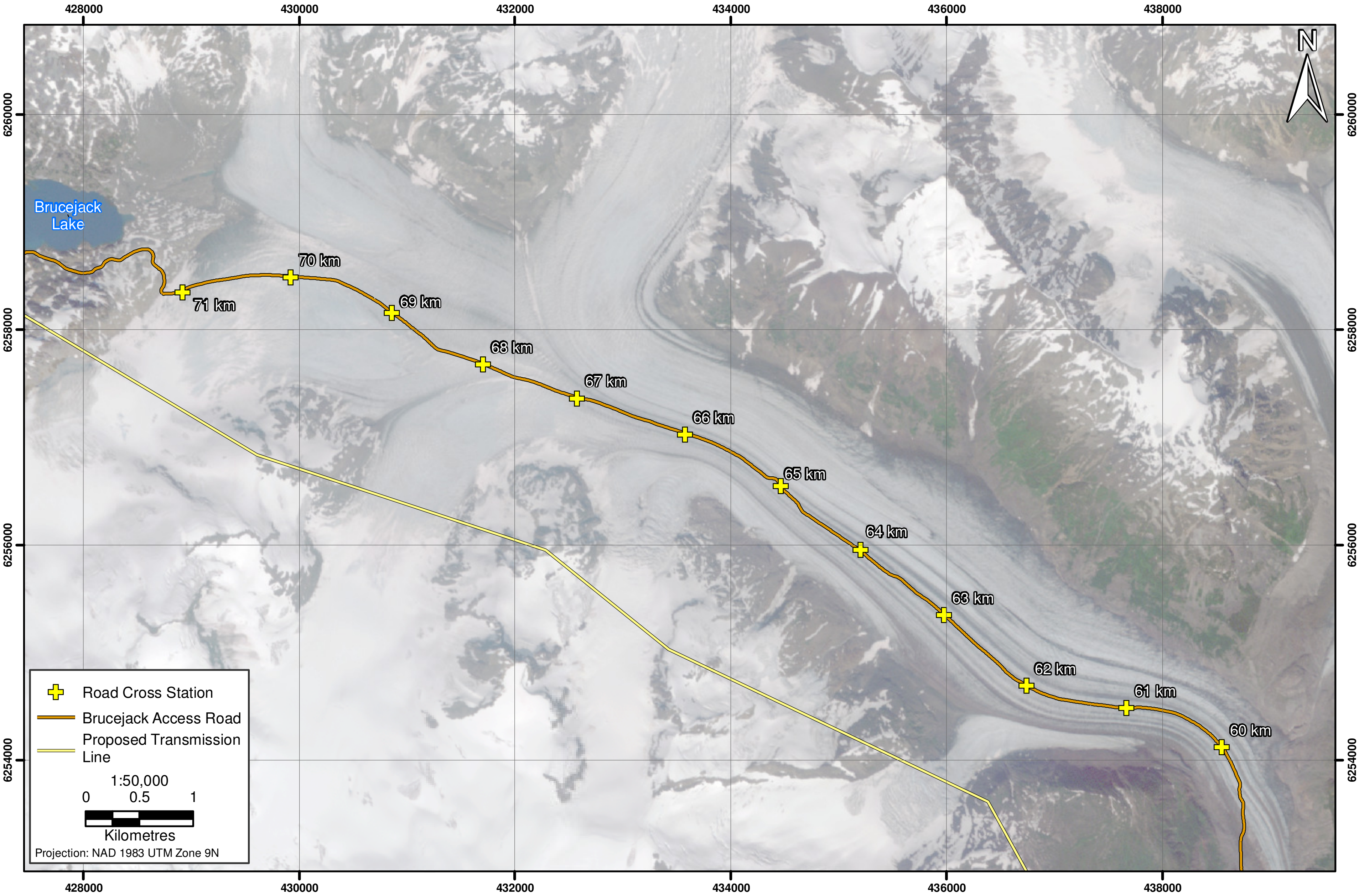


Plate 1-1. Access Road on Knipple Glacier at 60 km Section. View is towards the top of the glacier. Photo taken July 2013.

Plate 1-2. Access Road on Knipple Glacier at 61 km Section. View is towards the top of the glacier. Photo taken July 2013.

Plate 1-3. Access Road on Knipple Glacier at 62 km Section. View is towards the top of the glacier. Photo taken July 2013.

Plate 1-4. Access Road on Knipple Glacier at 63 km Section. View is towards the top of the glacier. Photo taken July 2013.

Plate 1-5. Access Road on Knipple Glacier at 64 km Section. View is towards the top of the glacier. Photo taken July 2013.

Plate 1-6. Access Road on Knipple Glacier at 65 km Section. View is towards the top of the glacier. Photo taken July 2013.

Plate 1-7. Access Road on Knipple Glacier at 66 km Section. View is towards the top of the glacier. Photo taken July 2013.

Plate 1-8. Access Road on Knipple Glacier at 67 km Section. View is towards the top of the glacier. Photo taken July 2013.

Plate 1-9. Access Road on Knipple Glacier at 68 km Section. View is towards the top of the glacier. Photo taken July 2013.

Plate 1-10. Access Road on Knipple Glacier at 69 km Section. View is towards the top of the glacier. Photo taken July 2013.

Plate 1-11. Access Road on Knipple Glacier at 70 km Section. View is towards the top of the glacier. Photo taken July 2013.

Plate 1-12. Access Road on Knipple Glacier at 71 km Section. View is towards the top of the glacier. Photo taken July 2013.

2. Background

2. Background

The majority of glaciers in coastal Alaska and adjacent regions in Canada have been thinning over the last several centuries. This is generally attributed to changes in temperature and precipitation, although in some cases the mass loss is also attributed to glacier ice calving into marine environments and lakes at their termini. In general, Coastal glaciers are sensitive to climate perturbations because of their overall low elevations (Larsen et al. 2007; Arendt et al. 2002; Arendt et al. 2006). There has been variability in the mass balance in coastal glaciers over the last century, with periods of positive mass balance occurring as recently as the early 1970s, likely related to inter-decadal oscillations in climate (Larocque and Smith 2005; Wood and Smith 2013; Wood et al. 2011). However, the overall regional trend is one of declining glacier volume (i.e., overall negative mass balance) throughout the region over the last century with negative mass balance years dominating (Wood et al. 2011). The recent loss of glacier volume in the Coast Range is double the previous two decades (Schiefer et al. 2007). This regional mass loss appears to be accelerating and may be attributed to increasing summer temperatures in some areas (Dyurgerov and McCabe 2006), with summer temperature increases of 0.5-1.0°C over the period of 1948-2000 (Larsen et al. 2007). Other areas suggest that winter precipitation is the most important control on mass balance (Moore and Demuth 2002). Glacier change may be influenced by short-term temperature variability (daily to annual timescales) as well as by longer term changes in mean temperature (Farinotti 2013).

Mass balance refers to the annual mass change of an entire glacier, and can be an indication of the relative “health” of a glacier. A glacier is said to be in “dynamic equilibrium” when it is neither gaining nor losing mass. In such a state, mass is added to the glacier in the upper reaches through the accumulation of annual snowpack at the same rate that it is lost through ablation processes at lower elevations. Despite the neutral change in mass, the glacier still maintains an active “flow” component in which mass is dynamically transported from the accumulation zone to the ablation zone through a combination of internal deformation and basal sliding (the “ice flux” is in balance). When a glacier has an extended period of non-neutral mass balance, then the glacier is said to be in “disequilibrium”. In the case of negative mass balance, this usually means that there is more mass lost at lower elevations than gained at higher elevations. This can be a result of increased summer ablation or lower winter snow accumulations, or often a combination of both.

Glaciers adjust slowly to changes in climate, with response typically occurring over decades. Within this disequilibrium, there are a range of responses in glacier dynamics including glacier thinning, terminus retreat and changes in flow (Berthier and Vincent 2012). The specific response of a given glacier is dependent on several factors, including the local climate, the glacier geometry and the geology and topography of the glacial bed (which influences flow velocities). For example, research in the European Alps has indicated that two thirds of the thinning of ice at the glacier termini is due to decreased ice velocity (slowing of ice transport down glacier) and only one third is due to ablation (Berthier and Vincent 2012). These factors, along with specific climatic factors, will influence whether glaciers in disequilibrium will eventually retreat to a position (in altitude) in which they can maintain equilibrium in the future (Stahl et al. 2008). As another example, a glacier with a large accumulation area ratio (ratio of accumulation area to total glacier area) will respond quite differently than a glacier that primarily resides at lower elevations and no longer retains much seasonal snow. Although glacier mass balance and glacier retreat are not synonymous, they are dynamically related in that a glacier that is retreating will likely have long-term negative mass balance. Possible exceptions to this are in cases where ice is “stored” up glacier, such as in the quiescent stage of a surging glacier (Melvold and Hagen 1998). Regionally, Arendt et al. (2002) studied glacier volume changes in Alaska and the northern Canadian Coast mountains using laser altimetry and found that the average glacier thinning over the period of 1993-1999 was 1.8 m/year, with the greatest change occurring at elevations below 750 masl. This was a large increase over the previous period (1950s to mid-1990s) in which average surface lowering was 0.7 m/year (Arendt et al. 2002).

Historical reconstructions of glacier mass balance using dendroclimatology proxies have noted a correlation between mass balance and inter-decadal climate observations (Larocque and Smith 2005; Moore and Demuth, 2002; Wood and Smith, 2013; Wood et al., 2011). However, despite the correlations, there has been widespread regional glacier volume loss that is indicative of a more pervasive climate forcing (Arendt et al. 2002; Arendt et al. 2006; Hodge et al. 1998; Larsen et al. 2007; Schiefer et al. 2007). The glacier retreat observed in the glaciers surrounding the Project area should be taken as a potential average, with greater (most likely) and lesser (less likely) retreat rates possible, dependent on short term climate oscillations (e.g., phase of the Pacific Decadal Oscillation) and background climate perturbations. In recent years there has been an increase in the rate of ice loss globally, along with a general decline in winter snow cover in the Northern Hemisphere (IPCC 2013). Model projections indicate that glacier ice decline will continue under all scenarios and there is a predicted decline in winter snowpack in the northern hemisphere of 7-25% by the end of the 21st century, depending on the projection scenario (IPCC 2013). Modeled glacier retreat rates in the BC Coast mountains suggest that retreat will continue for another century even if the climate is stabilized (Stahl et al. 2008).

Any projects undertaken in glaciated regions, such as the proposed access road on Knipple Glacier, need to be cognizant of the dynamic and complex response of glaciers to climate. Given the current state of glacier disequilibrium in the region of the Project, operating and maintaining the mine access road on the glacier surface will require a thorough understanding of the glacier dynamics, and careful consideration of the possibility of adverse impacts of glacier dynamics related to the project.

3. Glaciohydrological Effects of the Access Road on the Knipple Glacier

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This document provides a preliminary assessment on the effects of the glacier portion of the Brucejack Access Road on glacier ablation. Although, access road activities (e.g., surface grading) could potentially alter snowmelt, such an effect is not the focus of this document. The influence of the road on glacier ablation will occur primarily through alteration of the surface energy balance, and the specific enhancement or reduction of melt will depend on the type of road construction. Glacier melt is controlled by the energy balance at the snow or ice surface, with a net positive energy flux resulting in melt. Net positive conditions (resulting in a net loss in water equivalence) in this region dominantly occur during the ablation season, approximately April to September (*Rescan* 2013a), so the impacts during the ablation season will be the primary focus of this discussion. It is noted that mid-winter melt events may occur at low elevations; however, this will be insubstantial relative to summer melt.

Different access road activities and processes could potentially affect glacier ablation. These include debris and dust deposition, surface grading, and heat transfer from vehicle use. Based on the literature (Nicholson and Benn 2006; Østrem 1959; Oerlemans et al. 2009; Adhikary et al. 2000) debris and dust deposition were considered as primary factors with potential effects on glacier ablation. While effects of dust deposition are assessed in Chapters 7 and 10, this document investigates the effects of debris on glacier ablation.

Debris on the glacier surface, such as from vehicle traffic or road construction, may either increase or decrease the amount of melt depending on the debris thickness. The addition of a thin layer of debris will increase the melt, by decreasing the albedo (or shortwave reflectivity) of the ice surface. This occurs up to a certain thickness, termed the "effective" thickness. Beyond this effective thickness, there is a decline in melt as the debris layer insulates the ice surface. At greater than 2 to 4 mm thickness, glacier melt becomes less than clean ice, and melt decreases as the debris effectively insulates the ice surface (Nicholson and Benn 2006; Østrem 1959). Østrem (1959) provided an empirical relationship that quantifies the relationship between the thickness of debris on the ice surface and the daily ablation rate. This empirical relationship has been derived for various glaciers, and is somewhat site specific (Mattson 2000; Mattson and Gardner 1991; Mattson et al. 1993).

Accurately quantifying the change in melt as a result of debris cover for Knipple Glacier would require collecting empirical data from the site (ice and debris temperatures, and meteorological data) or through a numerical modeling approach using site specific data (Nicholson and Benn 2006). However, herein a semi-quantitative assessment is made using empirical values from the literature and data on summer ablation (b_s) from a nearby glacier as a proxy. The expected change in ablation is assessed for two scenarios:

- The road is maintained directly on the ice surface (i.e., on-ice option). It is assumed that the road width is 6 m and a debris layer of 2 mm is deposited on the ice. This is a conservative assumption, because once the vehicles leave gravel road, they will deposit debris up to a short distance along the glacier.
- A subgrade road is built wherein a debris cover is placed on the ice surface (i.e., on-subgrade option). It is assumed that the road width is 18 m to ensure stability at the road edges (Cypress 2011) and the subgrade is 300 mm thick.

Although the on-ice option has been adopted and implemented in the Project (Plates 1-1 to 1-12), this document presents assessment and results for both originally proposed options.

A first approximation of the impact of the access road on the glaciohydrology is quantified here. First, the total expected summer ablation on Knipple Glacier is estimated. Summer glacier ablation data from the nearby Mitchell Glacier, located approximately 8 km to the northwest of Knipple Glacier, (Rescan 2013a, 2013b) are used as a proxy for the ablation that can be expected on Knipple Glacier. The upper accumulation area of Mitchell Glacier is directly adjacent to the upper accumulation areas of Knipple Glacier and both glaciers are valley outflow glaciers with similar altitudinal ranges (Table 3-1). Due to the close proximity and the similar characteristics of these glaciers it is expected that the summer mass balance data from Mitchell Glacier provides a good initial estimate of the expected ablation on Knipple Glacier. Although the lowest elevations on Knipple Glacier are 300 metres lower than on Mitchell Glacier, the lowest elevation of the proposed access road is approximately 950 masl; therefore, the expected changes to the ablation at those elevations are well captured by the measurement elevations on Mitchell Glacier.

Table 3-1. Characteristics of Mitchell and Knipple Glaciers

Glacier	Area (km^2)	Min Elev (masl)	Max Elev (masl)	Ave Elev (masl)
Mitchell	16	998	2463	1788
Knipple	58.8	703	2549	1608

The expected summer ablation (b_s) on Knipple Glacier is estimated by applying a quadratic equation relating the melt to elevation, derived for Mitchell Glacier (Rescan 2013a, 2013b), to all cells of a digital elevation model (DEM) for Knipple Glacier:

$$b_s = p_1Z^2 + p_2Z + p_3 \tag{Eq. 1}$$

Where Z is the elevation of a given location on the glacier, and p_1, p_2, and p_3 are quadratic fitting coefficients. The fitted parameters p_1, p_2, and p_3 for Mitchell Glacier in 2010 and 2012 are given in Table 3-2. The DEM resolution for Knipple Glacier was 20 m and was derived from TRIM data acquired in 1982. The DEM surface elevations are likely inaccurate due to glacier changes in the past 21 years. However, the glacier extent was digitized based on recent (2010) georeferenced imagery. Mitchell Glacier summer ablation data from years 2010 and 2012 were chosen (Table 3-2), as these years represent a range of mass balance conditions. During 2010 the average b_s on Mitchell Glacier was -2.33 metres of water equivalent (m w.e.) and in 2012 average b_s was -1.49 m w.e. These years represent overall negative (-1.33 m w.e., 2010) and positive (1.00 m w.e., 2012) net mass balance. The use of two years of data provides a bracket of the range of summer ablation that is recently typical in this region.

Table 3-2. Coefficients for the Quadratic Equation of Summer Ablation (b_s) with Elevation for Mitchell Glacier for 2010 and 2012

Year	p1	p2	p3
2010	-3.28E-06	1.63E-02	-20.654
2012	-4.80E-06	1.89E-02	-19.434

Source: Rescan (2013a, 2013b)

The road occupies 0.10% of the total glacier area (Table 3-3) for the on-ice option, assuming a road width of 6 m. If the on-subgrade was used, assuming a road width of 18 m, the road would cover 0.31%

of the total glacier area (Table 3-3). Calculating the b_s with Eq. 1, the expected average ablation loss is -2.0 to -3.3 m w.e. on Knipple Glacier, with greater amounts over the road area (-3.6 to -5.6 m w.e.) (Table 3-3) due to the lower overall elevation of the road (~ 950 to 1,450 masl) relative to the entire glacier surface. Similarly, the maximum calculated b_s is -8.5 to -10.8 m w.e. for Knipple Glacier and -5.7 to -8.0 m w.e. for the road area, with the higher values for Knipple Glacier occurring at the lowest elevations (below the elevation of proposed road construction). The minimum calculated b_s is -0.3 to -0.8 m w.e. for Knipple Glacier (representing ablation in the upper accumulation zone of the glacier) and -2.1 to -3.9 m w.e. for the road area (Table 3-3). These estimated values are for the road area in the absence of the road and do not consider past or present use of the glacier as road. The b_s for the road area represents 0.2% to 0.5% of the ablation that occurs on the entire Knipple Glacier (Table 3-3).

Table 3-3. Glacier and Access Road Area, and Estimated Summer Ablation (Minimum, Maximum, and Average)

	Area (m^2)	Area (%)	Min b_s* (m w.e.)	Max b_s* (m w.e.)	Ave b_s* (m w.e.)	Ave b_s* (% of total)
Knipple Glacier	58,850,500	100	-0.3 to -0.8	-8.5 to -10.8	-2.0 to -3.3	100.0
On-ice Road	60,600	0.10	-2.1 to -3.9	-5.7 to -8.0	-3.6 to -5.6	0.2
On-subgrade Road	181,800	0.31	-2.1 to -3.9	-5.7 to -8.1	-3.6 to -5.6	0.5

**Calculations in this table are for unaltered glacier surface (i.e., no road).*

Pretium conducted a glacier ablation monitoring program along the access road between June 3 and November 7, 2013. Results of this program are summarized in Table 3-4. It is seen that the measured melt data in Table 3-4 (between 3.9 to 11.1 m) are sufficiently close to the estimated range in Table 3-3 (2.1 to 8.0 m w.e.).

Table 3-4. Knipple Glacier Ablation along the Access Road during June 3 to November 7, 2013

Road Station (km)	Easting	Northing	Total Melt (metres of ice)	Total Melt (m w.e.)[1]
60	438,573	6,254,094	12.3	11.1
61	437,700	6,254,487	9.6	8.6
62	436,732	6,254,696	8.7	7.8
63	435,979	6,255,349	8.6	7.7
64	435,190	6,255,954	7.7	6.9
65[2]	434,440	6,256,592	4.4	3.9
66	433,561	6,257,042	6.4	5.7
67	432,615	6,257,354	6.4	5.8
68[2]	431,676	6,257,693	6.9	6.2
69	430,826	6,258,184	n/a[3]	n/a[3]
70	429,901	6,258,496	4.9	4.4
71[2]	428,922	6,258,360	4.7	4.2

[1] Density of ice was assumed to be 900 kg/m^3 (Paterson 1994).
[2] Monitored during June 3 to September 27, 20133: Road was diverted at this station, ablation data were not used.

The ratio of melt at effective and threshold debris thicknesses, relative to melt on natural glacier ice are used to estimate the order of magnitude of the change in melt resulting from road construction.

Values of 2 mm of debris on the ice surface for an “on-ice” road and 30 cm of debris for a sub-grade road construction were used in the calculations. The value of 2mm was chosen as this is the value at which “maximum” enhancement of melt may occur (i.e., increased albedo, but no insulating effect, *Nicholson and Benn*, 2006) therefore allowing a calculation of the maximum expected enhancement of melt from on-ice road construction.

The data on daily ice melt from four different studies were used to establish the average ratios (*Mattson et al.* 1993; *Nicholson and Benn*, 2006):

$$M_{\max} = \frac{\sum \frac{m_{d2}}{m_c}}{n} \qquad \text{(Eq. 2)}$$

Where M_{max} is the maximum melt expected with a thin debris cover (expressed as a dimensionless ratio), m_{d2} is the daily melt for 2 mm of debris (cm/d), m_c is the daily melt for clean ice (cm/d) and n is the number of study sites. Similarly, the minimum melt expected with a 300 mm debris cover was calculated as:

$$M_{\min} = \frac{\sum \frac{m_{300}}{m_c}}{n} \qquad \text{(Eq.3)}$$

Where M_{min} is the minimum melt (again expressed as a dimensionless ratio), and m_{300} is the daily melt for 300 mm of debris (cm/d).

The available data on debris cover melt was used to generate ratios, rather than explicitly using the melt data. This decision was made because summer ablation-elevation regression equations from a nearby study site were considered to be more representative of conditions at this site.

These calculations resulted in M_{max} of 1.25 (for on-ice operations) and M_{min} of 0.15 (for sub-grade operations), representing an enhancement and reduction of melt, respectively. These ratios were applied to the average b_s in Table 3-3 to obtain an estimate of the impact of the road on b_s (Table 3-5).

Table 3-5. Expected Changes in b_s Resulting from Road Use on Knipple Glacier

	Area (m^2)	b_s - Ice (m^3)	b_s - Road (m^3)	Δb_s (m^3)	Δb_s* (mm w.e./m^2)	Δb_s (% of KG b_s)
On-ice Road	60,600	-278,800	-348,500	69,700	1	-0.04
On-subgrade Road	181,800	-836,300	-125,400	-710,900	-12	0.46

**Expressed as specific discharge for the glacier area (Δb_s* (mm w.e.) =Δb_s (m^3)/KG area (m^2)*1000).*

The expected changes to b_s of Knipple Glacier due to road use are negligible. On-ice road operations will result in an increase in specific discharge (mm w.e/glacier area) of approximately 1 mm w.e. and subgrade road operations would decrease specific discharge by 12 mm w.e. Overall these changes represent much less than 1% of the expected b_s of Knipple Glacier without the access road. These estimates are “order of magnitude” estimates based on assumptions on the expected change in melt. Regardless, from these order of magnitude calculations it is ascertained that road use is anticipated to have a negligible to minor effect on the glacier hydrology, with the least impact incurred by situating the road directly on the ice surface.

The change in b_s for a sub-grade road is negligible overall, but will be locally very important. This type of road will require extensive maintenance due to the substantial lowering of the surrounding clean-ice surface. For example, at the lower road elevations an annual surface ice lowering of greater than 8 m can be expected (Table 3-3). This would lead to the road surface becoming increasingly elevated above the surrounding ice which could lead to safety and road stability issues. Therefore, an on-ice road is preferred from this perspective as the running surface of the road would have less elevational difference with the surrounding ice.

4. Impacts of the Knipple Glacier on the Project

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The Knipple Glacier dynamics, including glacier ablation, terminus retreat and glacier movement may result in negative impacts on the proposed glacier-portion of the access road. Specifically, glacier dynamics have the potential to change the viability of the road and/or require extensive on-going maintenance of road structures. Predicting how Knipple Glacier responds within the current regional glacier disequilibrium will be aided by the collection of field data. Some specific aspects of the dynamics of Knipple Glacier and their relevance to the access road are discussed in further detail below.

4.1 TERMINUS RETREAT

Anecdotally, terminus retreat of Knipple Glacier has been 300 m over the last 11 years (Cypress 2011). Nearby regional glaciers, i.e., Mitchell and McTagg Glaciers in the KSM project area (to the NW of the Project), are undergoing terminus retreat ranging from 15 to 50 m/year (Rescan 2013a, 2013b). At present, the terminus position of Knipple Glacier is approximately 715 masl, with the current “roll-on” point at approximately 990 masl. Given that this is approximately two kilometers up glacier from the current terminus location, if retreat rates continue as they are at present it may be several decades before the glacier recedes to the roll-on location of the glacier road. The operational length of the project is expected to be 22 years; therefore, at current retreat rates terminus recession is not anticipated to intersect with the access road. However, should retreat rates accelerate, or if glacier flow velocities decline (see further discussion below), a change in the terminus location may be required.

4.2 GLACIER SURFACE VELOCITIES

Glacier surface velocities are of direct concern to the access road in terms of maintaining road structures and the potential for on-going maintenance and/or relocation of infrastructure (especially crevasse crossing structures). Typical surface velocities in nearby glaciers, i.e., Mitchell and McTagg Glaciers, ranges from 10 to 105 m/year (Rescan 2013a, 2013b), with the largest velocities observed at glacier mid-elevations. In addition to surface flow velocities, data on the glacier basal topography can help to understand future patterns of crevasse development. Such understanding, in conjunction with field observations, will be helpful in informing on-going operations and maintenance of the road on the glacier surface.

An additional consideration will be determining the potential for the Knipple Glacier to surge. Surge type glaciers can be identified by glacier dynamics such as high surface velocities and rapid terminus advance, and from geomorphic features such as looped medial moraines, surface folding and heavy surface crevassing (Copland et al. 2003). There has been no observation of rapid terminus advance of Knipple Glacier in recent years, and it does not exhibit looped moraines and surface folding. Additionally, glacier surges are typically preceded by an accumulation of mass in the reservoir or accumulation zone, for which sustained positive mass balance conditions are required, or some other resistance to glacier motion such as a change in the hydrological or thermal regime (Jiskoot et al. 2000). However, there is some evidence that a depression in bedrock topography may allow a sufficient build up in mass such that a glacier can surge even in negative mass balance conditions (Flowers et al. 2011). Long glaciers with relatively steep slopes and underlain by sedimentary geology are also more likely to surge (Jiskoot et al. 2000). A high ratio of accumulation area relative to ablation area is another common characteristic of surging glaciers (Cuffey and Paterson 2010). Surges in Alaskan and Yukon glaciers are commonly related to increased basal water pressures resulting from poor drainage, rather than the sediment features in Svalbard glaciers (Tavi et al. 2003). Increases in surface elevation of the ice and a slow surface velocity may provide indication that a surge glacier is in a quiescent stage and that is has surge potential (Melvold and Hagen 1998).

Surge-type behavior on Knipple Glacier would impact the viability of the glacier access road. Therefore, despite the lack of geomorphic evidence for prior surge behavior, it would be prudent to maintain measurements of surface ice elevation, in addition to collecting data on glacial bed topography at the roll-on area in particular.

4.3 PROPOSED GLACIER MONITORING PLAN

The glaciohydrological impacts of the access road on the Knipple Glacier are expected to be negligible. Therefore, the primary glacier monitoring recommendations are directed towards the potential impacts of glacier dynamics on the access road. The monitoring recommendations are below.

4.3.1 Radar Ice Thickness Measurements

An ice radar survey has been conducted over the roll-on region of the access road on Knipple Glacier. Should new crevasse fields open glacial bed topography surveys may be undertaken elsewhere along the glacier. Ice radar survey data can provide data on the:

- ice thickness — this is important for understanding how glacier change (especially ice volume loss) may impact the viability of the road over the life of the Project . Data on ice thickness at the glacier terminus will aid in understanding potential terminus retreat dynamics;
- subsurface topography of the glacier — this data is important for understanding glacier flow dynamics (e.g., how likely the glacier is to surge or whether impediments to subsurface water drainage exist). Substantial depressions in the sub-glacial topography have been implicated in surging mechanisms because they form a barrier to ice flow (Flowers et al. 2011);
- ice thickness relative to the relationship to subsurface topography — this is important for understanding the dynamics of crevasse development; and
- cross-sectional glacier flow velocities — in conjunction with mass balance data, lateral cross-sectional glacier thickness profiling can be used to calculate whether the glacier flow is “in balance” (i.e., the accumulation at the upper elevations of the glacier is balanced with flow down the length of the glacier). Out-of-balance conditions wherein mass accumulates and is not transported down glacier can be indicative of the potential for a glacier surge (at worst) or may predicate future crevasse development.

4.3.2 Installation and Monitoring of Ablation Stakes along the Glacier Length

Installation of stakes along a primary altitudinal transect and several transects perpendicular to flow is recommended. The purpose of this network would be to monitor positional changes in the stakes for assessing glacier surface flow velocities, in addition to quantifying surface elevation changes. This network would also be used for monitoring summer ablation.

Monitoring of glacier surface velocities will improve understanding of the flow dynamics of Knipple Glacier and subsequently, understanding of where changes in crevasse structure may occur. Changes in crevasse position will strongly affect the maintenance of the access road.

4.3.3 Geographical Position Surveys of the Glacier Terminus

Annuals surveys of the terminus position of Knipple Glacier will aid to quantify the retreat (or less likely, advance) rate of the glacier.

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