GOLDER

TECHNICAL MEMORANDUM

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TO Karyn Lewis, Project Manager
Lupin Mines

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COUPLED THERMAL-SEEPAGE MODELLING FOR PERFORMANCE EVALUATION OF THE ESKER COVER FOR THE WASTE ROCK "DOME" AT LUPIN MINE

1.0 INTRODUCTION

The Lupin Mine (the Site) is a past producing mine located in western Nunavut, approximately 400 kilometres (km) northeast of Yellowknife, Northwest Territories and is owned by Lupin Mines Incorporated (LMI). Development of the Site to extract gold began in 1980 and operations occurred from 1983 until 2005. From 2005 to present, the Site has been in "care and maintenance" with mine operations suspended and progressive rehabilitation works conducted.

LMI is requesting the renewal and amendment of the existing Type "A" Water Licence No: 2AM-LUP1520, to allow for Final Closure and Reclamation of the Lupin Mine Project (Lupin). The Nunavut Water Board (NWB or Board) Water Licence Application No. 2AM-LUP1520 Technical Meeting was held between June 6 and 7, 2019 in Kugluktuk. Appendix D of the June 18, 2018 Pre-Hearing Conference Decision Report outlines the agreed upon List of Commitments (Commitments). Golder completed a geochemical source term and seepage water quality model in response to Commitment No.1 (below).

No.	Party responsible for commitment	Party who raised	Issue – TM Commitment
1.	LMI	CIRNAC	Completion of Human Health Ecological Risk Assessment (HHERA) (to include geochemical, thermal and seep modelling studies)

Historical mining at Lupin Mine produced approximately 1 million cubic metres ($m^{3)}$ of waste rock (Golder, 2018). The waste rock was used to construct various elements of mine infrastructure, including roads, the airstrip and a large pad in the area of the mine, mill and camp.

As part of the implementation of final closure, it is proposed (Golder, 2018) to consolidate much of the waste rock in the mine mill camp area into a central "dome" and to cap it with an infiltration reduction cover comprising a 1.0 m thick layer of esker sand and gravel. The objective of the cover is to reduce the surface exposure of waste rock and also to reduce the amount of infiltration into the waste rock in order to control the volume of rock-contact seepage out of the toe of the dome. The reduction in surface infiltration relies in part on the cover being frozen during winter and early spring to promote surface runoff rather than infiltration during the freshet period.

After closure, the waste rock "dome" at Lupin Mine is expected to be roughly circular and to cover an area of about 30 hectares. It will contain about 820,000 m^3 of waste rock and it will have a surface slope of about 1.6%.

This technical memorandum presents the results of coupled thermal-seepage numerical modelling prepared to evaluate the performance of the esker cover under current (2019) climatic conditions and with consideration to climate change in the long term.

2.0 SITE CLIMATIC CONDITIONS

2.1 Historical Averages

Table 1 summarizes historical average monthly air temperature, rainfall and snowfall rates obtained from the Environment Canada Lupin A weather station between 1982 and 2006. The average estimated monthly potential evaporation is also included in Table 1 as presented in Golder (2004).

Table 1: Average climatic conditions for the Lupin Mine based on data from the Environment Canada Lupin A weather station between 1982 and 2006.

Month	Mean Air Temperature (°C)	Mean Rainfall (mm)	Mean Snowfall (cm)	Mean Total Precipitation (mm)	Mean Lake Evaporation (mm)
January	-29.5	0.0	9.4	9.4	0.0
February	-28.5	0.0	7.8	7.8	0.0
March	-24.6	0.0	12.8	12.8	0.0
April	-15.6	0.3	14.4	14.7	0.0
May	-5.9	5.5	12.8	18.3	0.0
June	6.3	24.0	3.7	27.7	53.0
July	11.5	38.3	3.9	42.2	97.1
August	8.8	56.2	3.7	59.9	73.7
September	2.2	25.3	17.1	42.4	18.4
October	-8.5	0.5	27.8	28.3	0.0
November	-20.0	0.0	16.8	16.8	0.0
December	-26.2	0.0	13.1	13.1	0.0
Annual	*-10.8*	*150.1*	*143.3*	*293.4*	*242*

2.2 Climate Change Projections

Based on information provided by Environment and Climate Change Canada (ECCC), annual mean temperature for Canada's North is projected to increase by approximately 1.8ºC (1.2 - 2.5) for a low emission scenario (RCP2.6) to 2.7ºC (2.0 - 3.5) for a high emission scenario (RCP8.5) through 2031–2050, and by 2.1ºC (1.3 - 2.5) for RCP2.6 to 7.8ºC (6.2 - 8.4) for RCP8.5 through 2081–2100; all values relative to the 1986–2005 mean value.

Averaging the projected temperature increases to 2100 between the 2.1ºC (RCP2.6) and 7.8ºC (RCP8.5) yields a median value of 4.95ºC, which was used in this modelling exercise for consideration of long-term climate change.

3.0 NUMERICAL MODELLING

Two-dimensional (2D) coupled thermal-seepage modelling was prepared using the software package GeoStudio 2019 (v. 10.0.2), developed by Geoslope International Ltd. The finite element codes TEMP/W and SEEP/W were used for the thermal and seepage components of the model, respectively.

In a coupled analysis, thermal and hydraulic boundary conditions are combined to compute variations in ground temperatures and water fluxes with time within the model domain. Water fluxes, variation in hydraulic heads and variation in water contents and unsaturated hydraulic conductivity of the materials are computed in the seepage component of the analysis, which passes the results for each model time step to the thermal component of the model. TEMP/W then adjusts the materials' thermal properties based on changes in water contents and recalculates temperatures within the model geometry based on the thermal boundary conditions applied to the model. The results are passed back to SEEP/W that in turn adjusts the materials' hydraulic conductivity based on ground temperatures, whether frozen or thawed conditions, and recalculates flow paths and water volumes for the different water balance components. This interactive process between SEEP/W and TEMP/W continues to the end of the model duration.

The following sections describes the model preparation process, model geometry, input parameters and boundary conditions.

3.1 Model Setup

A simplified axisymmetric model geometry was defined that incorporates a 1-m thick granular esker cover placed on top of a 309 m radius waste rock pile that is 6 m thick in the center and 1.4 m thick at the edge, with an average surface grading of 1.6%, with 10H:1V side slopes at the perimeter. The waste rock is underlain by 15 m of natural ground in the model geometry.

An axisymmetric geometry has rotational symmetry about a vertical axis, which is in the center of the waste rock dome. Water flow volumes are computed for the entire dome area assuming a circular shape and total surface area of about 30 ha (In this respect, the axisymmetric model is different from unit flows that are computed in a conventional 2D model geometry).

The model geometry is shown in Figure 1.

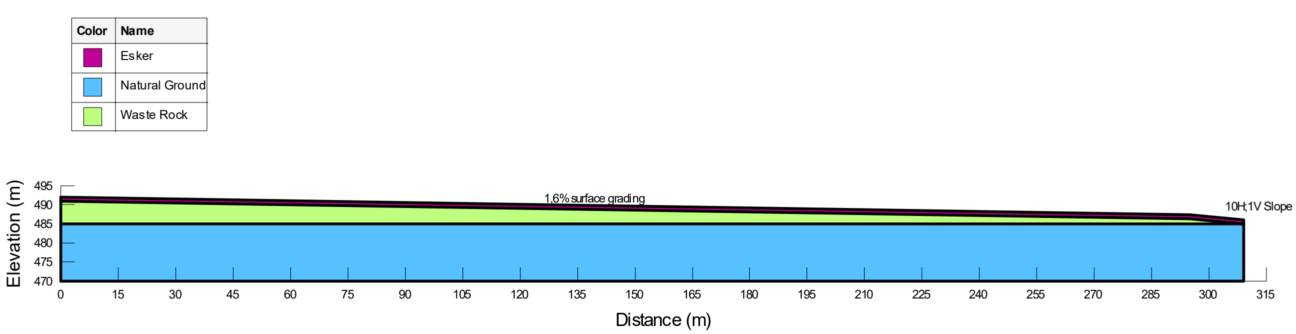

Figure 1: 2D axisymmetric model geometry.

The models spanned a period of 2 years, beginning on January 1st of the initial year. Models were prepared for both current conditions and for a long-term scenario (Year 2100) with consideration to climate change. For current conditions, the average air temperatures summarized in Table 1 were adjusted by 0.7°C to reflect increase in the average air temperatures between 2005 and 2019, using an annual increase rate of 0.0495°C/year (i.e., mean 100-year increase of 4.95°C as discussed in Section 2.2).

3.2 Boundary Conditions

3.2.1 Current Conditions Model

A Land-Climate-Interaction (LCI) boundary condition was applied to the top of the model geometry in the seepage component of the analysis. This type of boundary condition requires the input of functions for climatic parameters (i.e., potential evaporation, precipitation, air temperature, solar radiation and snow depth). The average monthly values of air temperatures summarized in Table 1 were adjusted by 0.7ºC to account for increasing air temperatures from 2005 to 2019, using an annual increase rate of 0.0495ºC/year. The model used data for potential evaporation as presented in Table 1, while a solar radiation function was created based on the site's geographic latitude using the built-in method available in the GeoStudio software package. The precipitation function was based on hourly and daily data available from the Environment Canada weather stations Lupin A and Lupin CS.

The Lupin A weather station is located on the mine site itself and was associated with the airstrip. The Lupin CS weather station is located on an island in Contwoyto Lake and probably captures climatic conditions that are influenced more by the proximity to the water compared to the Lupin A weather station that is at the mine. Although data from the Lupin A station is more representative of site conditions, hourly precipitation data were only available from Lupin CS, and rainfall intensity is a critical input parameter in the model because the software considers evaporation to be zero during rainfall events.

The year of 2005 was chosen to obtain precipitation data for the total amounts of rainfall and snowfall measured at the Lupin A station were close to the historical averages (i.e., 160 mm precipitation in 2005 vs. 150 mm historical average, and 147.2 mm snowfall in 2005 vs. 143.3 mm historical average). Hourly data were available from the Lupin CS weather station from May 5 to September 29, and daily data from the Lupin A weather station was used for other times of the year, assuming a 3-hour rain intensity that was an average of the hourly data, with rainfall events assumed to occur between 9 am and noon. The total amount of precipitation with combined data from the Lupin A and CS stations for 2005 was 299.5 mm, which is closer to the total precipitation historical average of 293.4 mm.

A Surface Energy Balance (SEB) boundary type was used on top of the model geometry in the thermal component of the coupled model. This type of boundary also uses functions for air temperature, solar radiation and snow depth, which were the same functions defined for the LCI boundary. In addition, both LCI and SEB boundaries were arbitrarily assigned a constant relative humidity of 50% and wind speed of 0.05 m/s.

A constant ground temperature of -6ºC was used as boundary condition along the base of the model geometry based on limited data available from site thermistors presented in Golder (2004).

The phreatic surface was defined to be 1 m below the natural ground during all times, based on field observations described in SNC (2006).

3.2.2 Long-Term Model

For the long-term model scenario with consideration to climate change, the air temperature function included in the LCI and SEB boundary conditions was adjusted by an increase of 4.95ºC in the monthly average air temperatures. This value is an average of temperature increase projected for the low (RCP2.6) and high (RCP8.50) emission scenarios through the end of the century as reported by ECCC.

In addition, the temperature used as boundary condition at the base of the model geometry was arbitrarily increased from the current -6ºC to -4ºC to reflect long-term warming of ground conditions.

No changes were made for the other climatic functions used in the LCI and SBE boundaries.

3.3 Material Properties

Thermal and hydraulic properties of the different materials in the models were not available and were therefore assumed or estimated as summarized in Table 2.

The thermal properties (i.e., thermal conductivity and heat capacity) of esker and waste rock were defined for thawed condition from dry to fully saturated to match the coupled nature of the analysis where the materials' water content varies over time. These functions were defined using the Johansen (1975) method for thermal conductivity and Johnston (1981) method for heat capacity, which are built-in estimation methods available in the GeoStudio software package. The thermal conductivity and heat capacity of partially frozen or frozen materials are computed internally by the solver as a function of ice, water, air and soil mineral content.

For the natural ground, a simplified approach was used as the ground remains saturated and frozen for most of the model duration, so values were assumed for hydraulic conductivity and thermal properties for frozen and unfrozen conditions.

Table 2: Materials' hydraulic and thermal properties defined for the coupled model.

Material	Unfrozen Hydraulic Conductivity (m/s)	Thermal Conductivity (W/m °C) value (condition)		Volumetric Heat Capacity (MJ/m^3 °C) value (condition)	
Esker Cover	$1.5x10^{-4}$	1.0 (dry)	2.3 (saturated)	1.45 (dry)	2.7 (saturated)
Waste Rock	$5x10^{-2}$	0.55 (dry)	2.3 (saturated)	1.27 (dry)	2.7 (saturated)
Natural Ground	$1x10^{-7}$	1.6 (unfrozen)	1.8 (frozen)	2.5 (unfrozen)	2.0 (frozen)

The unfrozen hydraulic conductivity and soil-water characteristic curve (SWCC) of the esker were estimated based on an average of available grain-size distributions presented in the Lupin TCA Closure Plan (Kinross 2005) using Hazen (1911) method for hydraulic conductivity, and Fredlund and Wilson (1997) method for SWCC. The hydraulic conductivity of the waste rock was assumed, and the SWCC of the waste rock was estimated using the built-in estimation method available in the GeoStudio software package. The hydraulic conductivity of frozen materials will be lower than the unfrozen values, and the software adjusts the hydraulic conductivity for frozen conditions based on the defined unsaturated hydraulic conductivity functions.

Figure 2 shows the SWCC and unsaturated hydraulic conductivity functions defined for esker and waste rock.

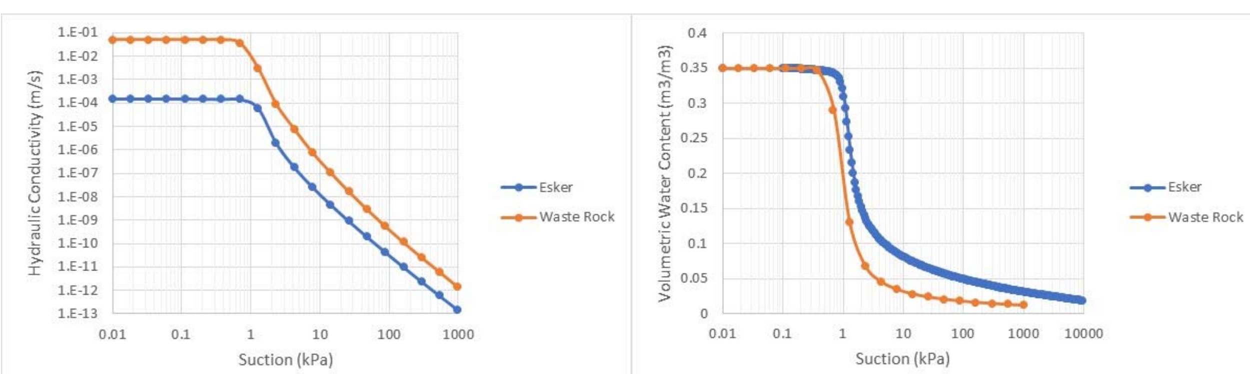

Figure 2: Unsaturated hydraulic conductivity function and soil-water characteristic curves defined for esker and waste rock.

4.0 MODEL RESULTS

4.1 Current Conditions Model Scenario

Figures 3 and 4 show temperature contours in the beginning of August and year-round temperature profiles computed near the center of the dome and at the waste rock toe area, respectively. The model results suggest that the active layer subject to seasonal freeze and thaw will be between 2.7 m and 3 m deep, meaning that the esker cover and the upper surface part of the waste rock will be thawed in summer time, allowing most of summer precipitation to infiltrate.

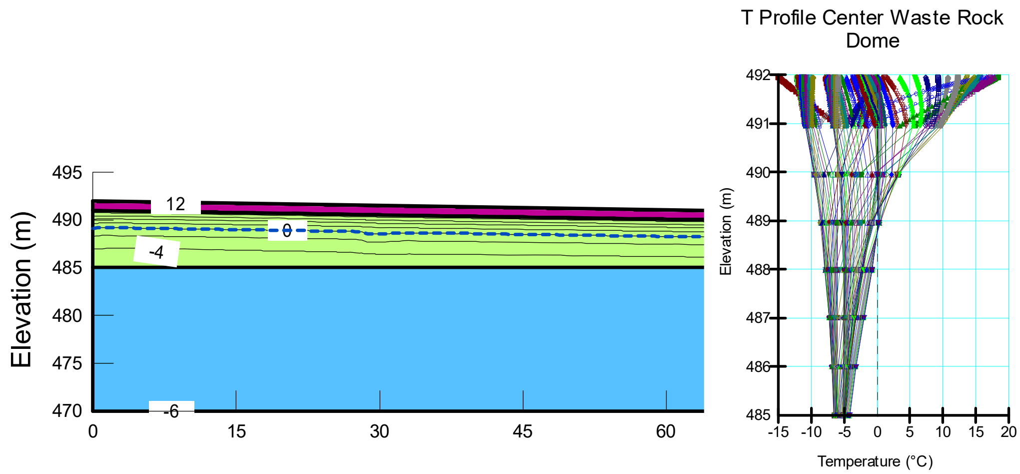

Figure 3: Temperature contours (in the beginning of August) and variation in annual ground temperature profiles at the center of the waste rock dome.

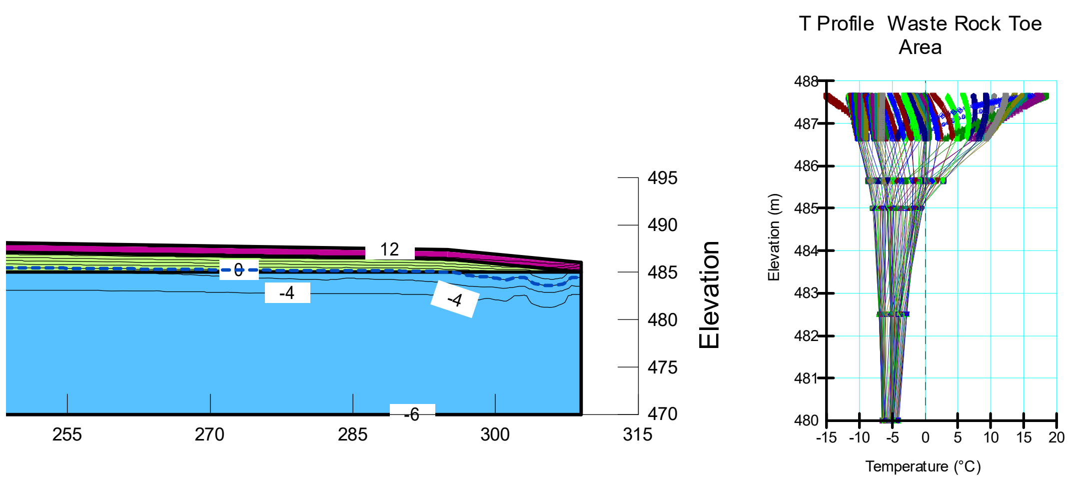

Figure 4: Temperature contours (beginning of August) and variation in annual temperature profiles at the toe of the waste rock dome.

Figure 5 shows cumulative flux volumes for the different water balance components, as well as cumulative percolation volume at the base of the esker cover into the waste rock. The values represent total volumes computed for the entire dome area of about 30 ha.

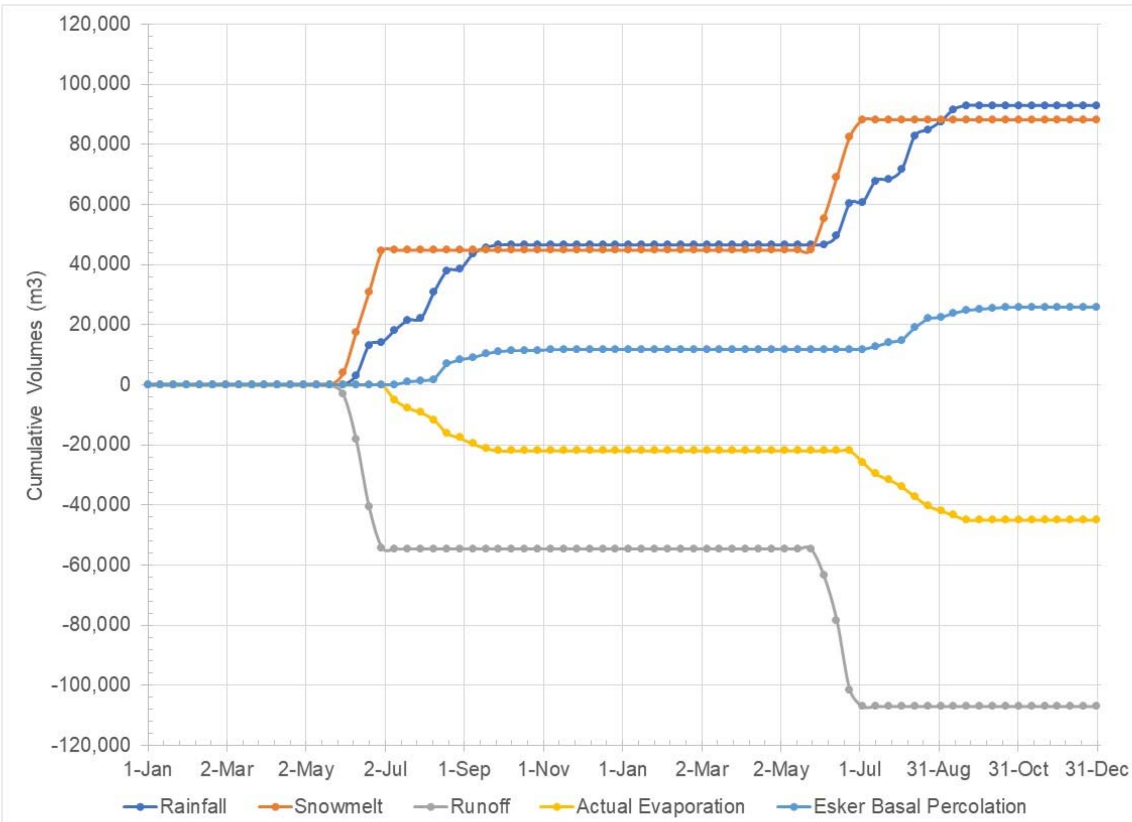

Figure 5: Cumulative water flux volumes computed for the 2-year model duration for the total 30-ha dome area.

As seen in Figure 5, runoff volumes are large during the spring freshet period as the esker and top of waste rock are still frozen, leading to almost no percolation of water at the base of the esker during the freshet. In summer, when the ground is thawed, surface infiltration and esker basal percolation occur, but part of rain water is removed by evaporation.

Figure 6 shows temporal variations in cumulative water percolation volume and temperature at the base of the esker cover (i.e., depth of 1 m) computed in the model. As anticipated, the cover performance relies heavily on the esker being frozen during the spring freshet. Water percolation is limited while the base of esker is frozen, but fluxes increase sharply after the temperature at the base of the esker layer rises above the freezing point.

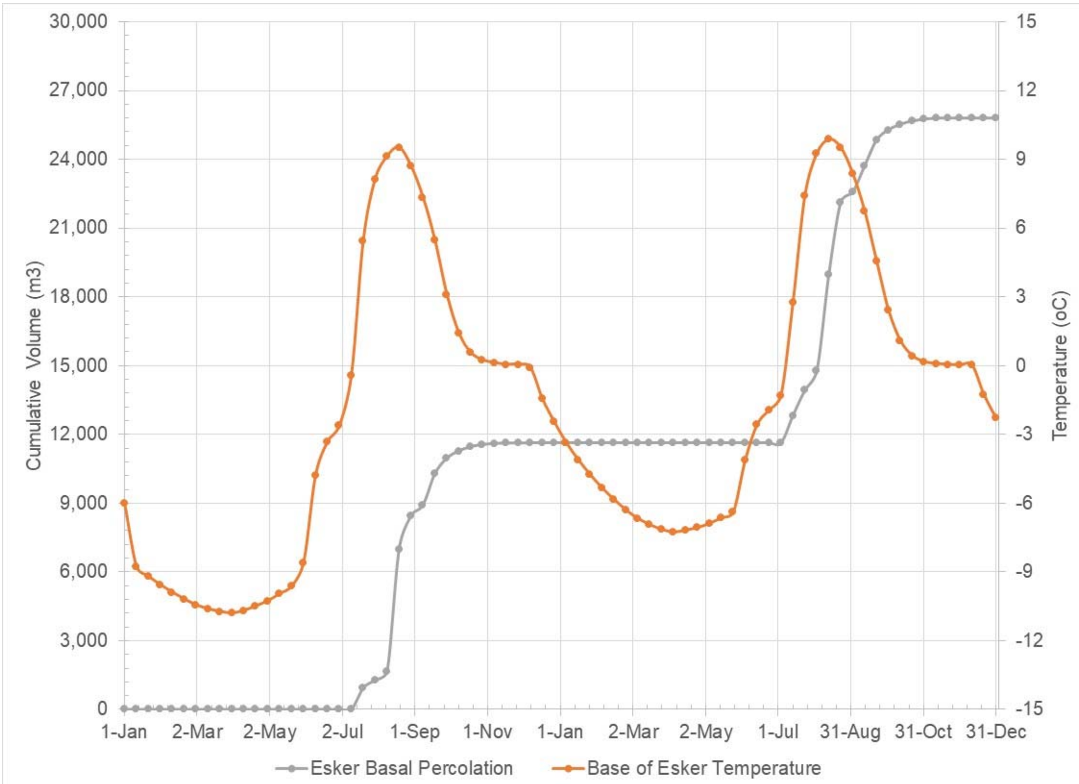

Figure 6: Comparison of computed water flow volumes and temperatures at the base of the esker cover.

Table 3 summarizes the computed flux volumes for the different water balance components in terms of total volume for the entire 30-ha dome area and in terms of unit fluxes per square metre.

Table 3: Summary of computed flux volumes.

Model Year	Rainfall	Snowmelt	Runoff	Actual Evaporation	Esker basal percolation	Percolation (% Rain + Snow)
Year 1 30-ha Flow Volumes (m^3)	46,434	44,784	-54,559	-21,849	-11,627	12.7%
Year 1 Yearly Unit Flow Volumes (m^3/m^2)	0.155	0.149	-0.182	-0.073	-0.039	
Year 2 30-ha Flow Volumes (m^3)	46,434	43,405	-52,483	-23,028	-14,166	15.8%
Year 2 Yearly Unit Flow Volumes (m^3/m^2)	0.155	0.145	-0.175	-0.077	-0.047	

Runoff volumes were greater than snowmelt volumes in both model years, indicating that all snowmelt and part of rainfall during the freshet period are removed before water can percolate at the base of the cover.
Total percolation volumes were between 13% and 16% of the total precipitation.

The total percolation volume computed for the first year was influenced by the initial conditions assumed for the models, while results computed for the second year were less impacted by the model initial conditions and the calculated total basal percolation value was consistent with the sum of the other water balance components, in spite of a small difference that was associated with numerical issues during solving of the model.

4.2 Long Term Model Scenario

Figures 7 and 8 show predicted temperature contours in the beginning of August and year-round temperature profiles computed near the center of the dome and at the waste rock dome toe area, respectively. The model results suggest that the active layer subject to seasonal freeze and thaw would deepen from 2.7 m under current conditions to about 4 m at the end of the century, and that the esker cover will be completely thawed earlier in the summer compared to current conditions, allowing more water to infiltrate the cover.

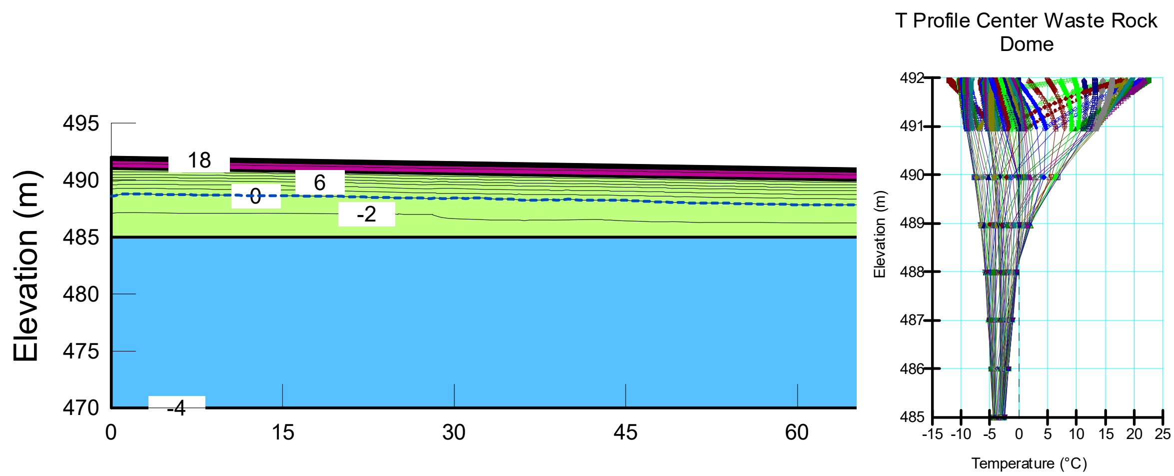

Figure 7: Temperature contours (in the beginning of August) and variation in annual temperature ground profiles at the center of the waste rock dome predicted for the end of the century.

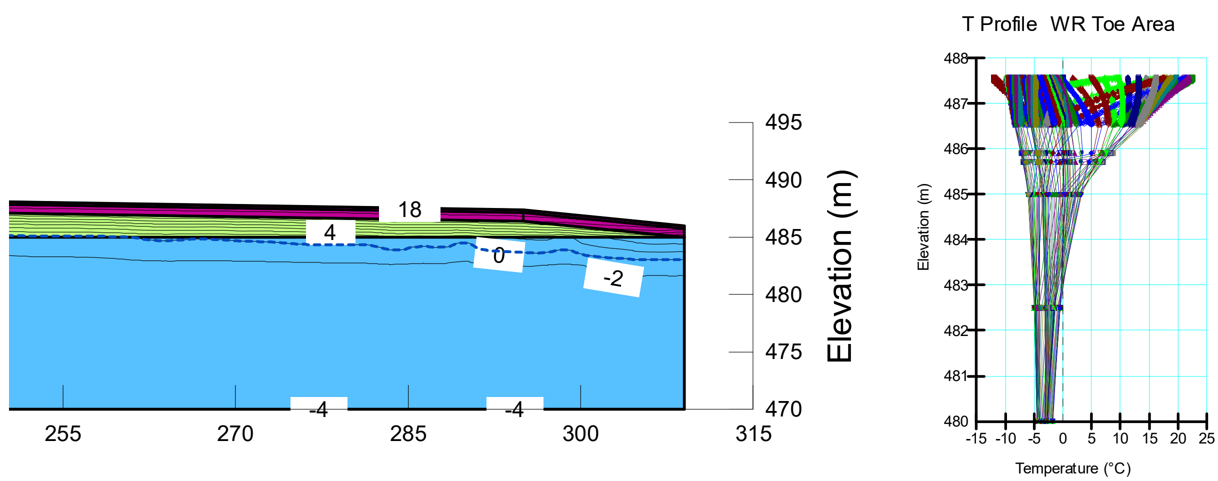

Figure 8: Temperature contours (in the beginning of August) and variation in annual ground temperature profiles at the toe area of the waste rock dome predicted for the end of the century.

Figure 9 shows cumulative flux volumes computed for the different water balance components, as well as cumulative percolation volume at the base of the esker cover into the waste rock. The values represent total flow volumes computed for the entire dome area of about 30 hectares.

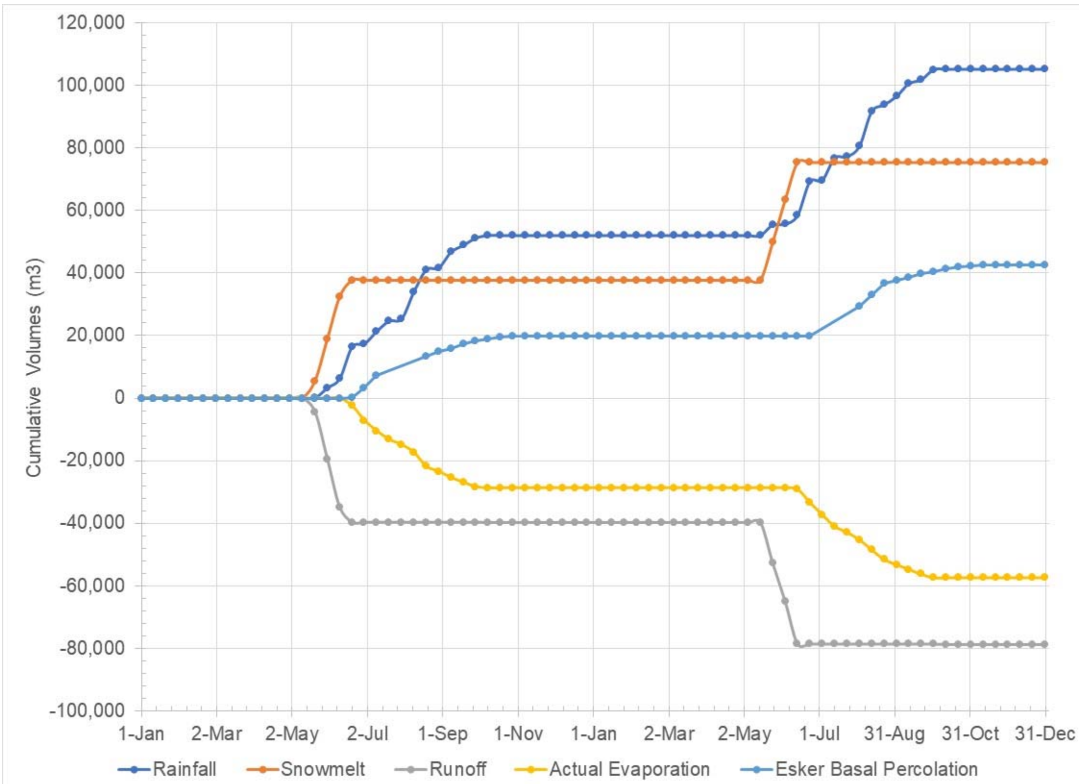

Figure 9: Predicted water volumes for the 30-ha dome area at the end of the century with climate change.

Figure 10 shows temporal variation in cumulative water percolation volume and temperature at the base of esker predicted for the end of the century. For comparison purposes, Figure 10 also shows computed temperatures at the base of esker under current conditions.

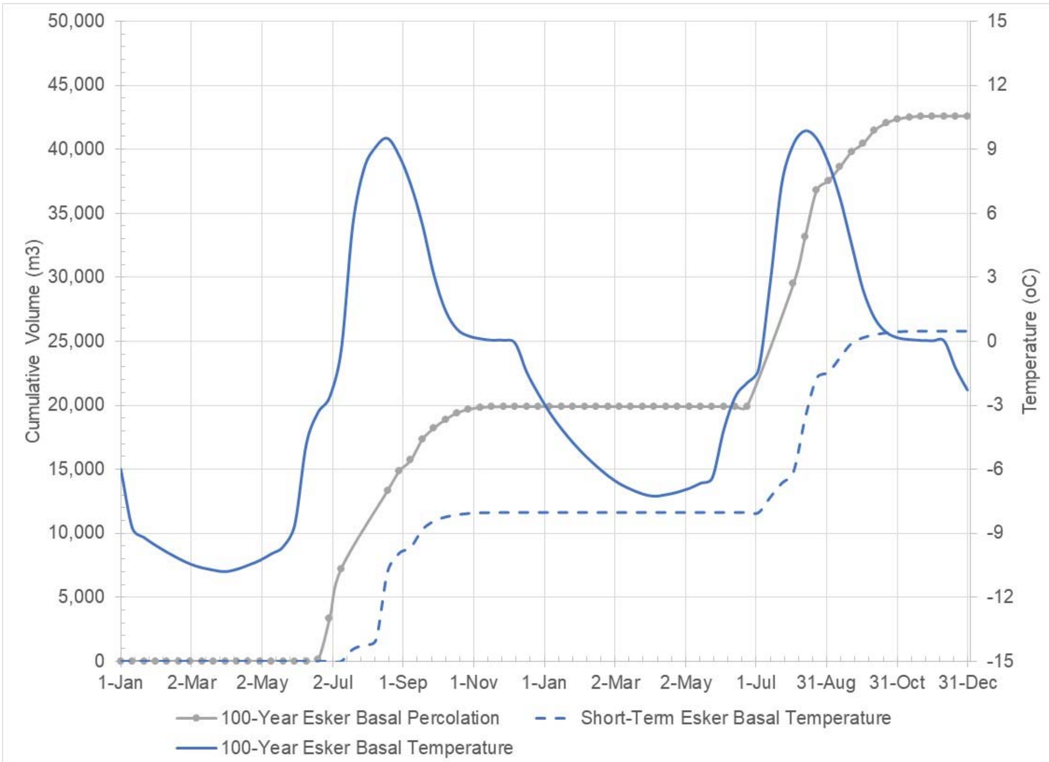

Figure 10: Water flow volumes and temperatures at the base of the esker cover predicted for the end of the century with climate change.

Table 4 summarizes computed flux volumes for the different water balance components in terms of total volumes for the entire 30-ha dome area and in terms of unit fluxes per square metre.

Table 4: Summary of computed flux volumes predicted for the end of the century.

Model Year	Rainfall	Snowmelt	Runoff	Actual Evaporation	Esker basal percolation	Percolation (% Rain + Snow)
Year 1 30-ha Flow Volumes (m^3)	52,073	37,675	-39,763	-28,625	-19,904	22.2%
Year 1 Yearly Unit Flow Volumes (m^3/m^2)	0.174	0.126	-0.133	-0.095	-0.066	
Year 2 30-ha Flow Volumes (m^3)	53,153	37,765	-38,941	-28,724	-22,687	25.0%
Year 2 Yearly Unit Flow Volumes (m^3/m^2)	0.177	0.126	-0.130	-0.096	-0.076	

As seen in Figure 10, climate change will cause the ground to warm and the esker cover to thaw earlier in the year, resulting in much higher percolation rates. In addition, warmer air temperatures will cause more of the precipitation to fall as rainfall when the ground is not yet frozen enough to prevent surface infiltration. The basal percolation rate would increase from about 16% under current conditions to up to 25% with the average increase in air temperature of 4.95°C.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Coupled seepage-thermal analyses were conducted to evaluate the potential performance of a granular esker cover in terms of limiting surface infiltration and water percolation into the waste rock pile at the Lupin Mine. The model results show that, under current (2019) conditions, percolation at the base of esker would be up to 16% of the total precipitation, with the base of esker remaining frozen until the beginning of July. Most of snowmelt and rainfall during the freshet would be shed off the cover, and part of rainfall during summer would be removed by evaporation.

The model results also suggest that the infiltration through the esker layer would increase over time when considerations of climate change are incorporated with an average increase of 4.95^{o}C in air temperatures through the end of the century. In this scenario, the esker would thaw earlier in the year and more of the precipitation would fall as rain, leading to an increase in percolation rates at the base of the esker from 16% to between 22% and 25%.

It is recommended that supplemental thermistors strings and, if possible, construction and monitoring of field trials be implemented before the final cover is constructed. The use of field trials typically brings several technical and financial advantages and provides valuable information to refine the cover design and optimize performance.

6.0 CLOSURE

We trust the information presented in this document meets your expectation and needs. Should you have any question or concerns, or requires further assistance with the design, construction and monitoring of the esker cover, please do not hesitate to contact Golder.

Yours Truly,

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https://golderassociates.sharepoint.com/sites/107254/project files/5 technical work/7000 thermal & seepage model/7030 reporting/final/19120487_rev0_tm-coupled seepage-thermal modelling-lupin mines_15 oct.docx

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