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1.0 INTRODUCTION

This technical note is part of the detailed engineering of the water management infrastructure of the Whale Tail project. Agnico Eagle Mines Limited, Meadowbank Division ("Agnico Eagle") is intending to develop Whale Tail Pit, a satellite deposit on the Whale Tail property, as a continuation of mine operations. The Whale Tail property is a 408 km² site located on Inuit Owned Land, approximately 150 km north of the Hamlet of Baker Lake and approximately 50 km northwest of the Meadowbank Mine in the Kivalliq region of Nunavut.

SNC-Lavalin was retained in September 2017 to develop the detailed engineering of the water management infrastructure. The current document is the third thermal analysis performed as part of the detailed engineering work of the Whale Tail project. The thermal analysis report of the main dewatering dike (the Whale Tail Dike) was released in June 2018 (SNC-Lavalin, 2018a). It is a comprehensive report that includes detailed information about the available field data, methodology, assumptions, results and recommendations. SNC-Lavalin (2018b) also carried out a thermal analysis at the Mammoth Dike, which is a smaller dike built at the east end of Mammoth Lake (Figure 1-1).

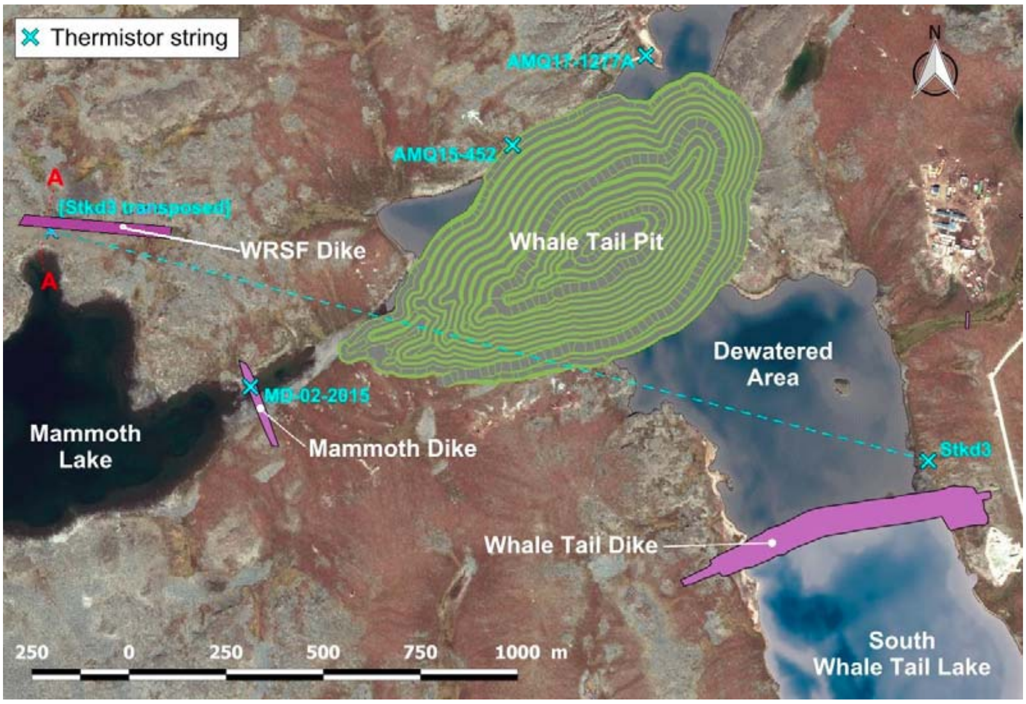


Figure 1-1: WRSF Dike general location

This current technical note presents the thermal analysis carried out at the waste rock storage facility (WRSF) Dike. The methodology used for the thermal modeling is described, the main results are discussed and some recommendations are made.

The main objective of this study is to assess the long-term thermal regime of WRSF Dike and its foundation over the lifespan of the infrastructure. For this modeling report, a lifespan of 20 years were retained.

2.0 METHODOLOGY

The thermal analyses were carried out with the finite element software product TEMP/W of the GeoStudio software suite (version 8.16.2.14053, GEO-SLOPE 2017). It can be used to model thermal changes in the ground by analyzing both simple and highly complex geothermal problems (GEO-SLOPE International Ltd., 2014).

2.1 Section Analyzed

For this study, a single section of the dike was used for the thermal modeling shown on Figure 2-1. The material properties and boundary conditions used in the thermal modeling are discussed in subsequent sections of the report. It is recognized that the cross section presented bellow doesn't have the same elevation as that shown on the design drawings. However, the impact on the modeling results is judged minor due to the following: (i) the performance of the dike will be evaluated in term of the design capacity to maintain the Fine Filter Amended with Bentonite (FFAB) in a frozen state and (ii) the thermal analyses is based on a steady state pond level of 155 m.

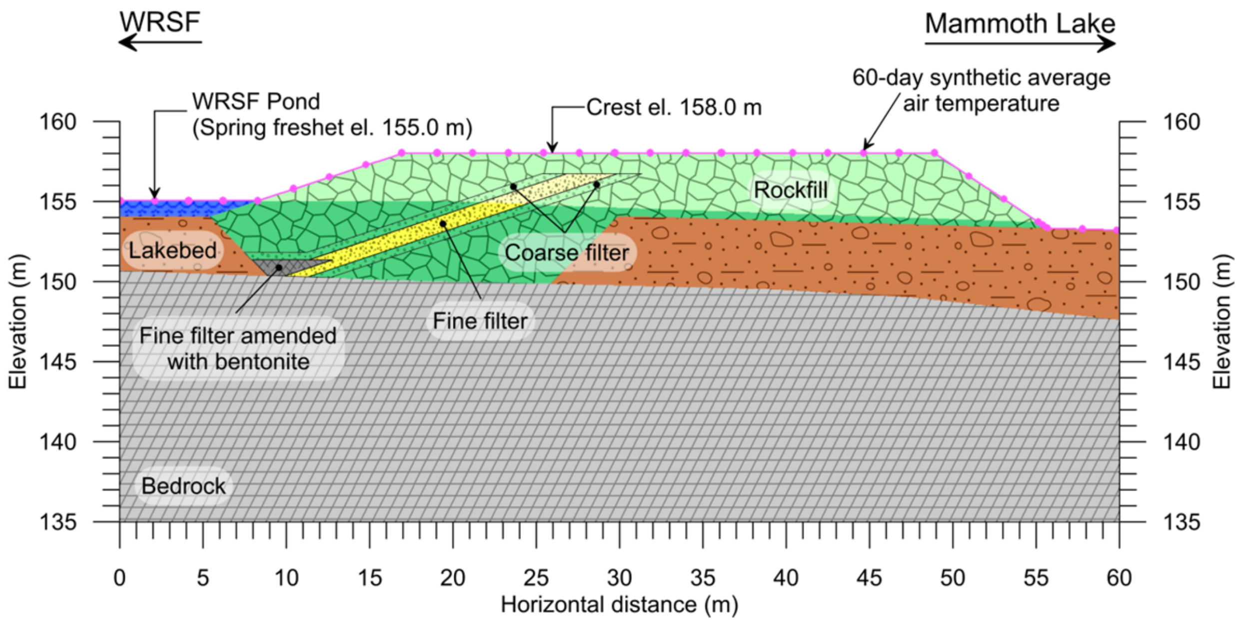


Figure 2-1: Cross section of the WRSF Dike as modeled in the finite element software

2.2 Existing Thermistor String

There is currently no thermistor string in the WRSF area. The closest thermistor string (MD-02-2015) is located in the channel between Whale Tail Lake and Mammoth Lake as shown on Figure 1-1. However, the thermistor MD-02-2015 cannot solely be used for the calibration of the whole thermal model as in the previous thermal analysis because the site conditions vary between the Mammoth and the WRSF Dikes. The former is located within the eastern end of Mammoth Lake on a lake floor composed of boulders, whereas the latter is located more inland north of Mammoth Lake.

In order to calibrate the model, it was decided to use the thermistor string Stkd3 located at the east abutment of the Whale Tail Dike (WTD), shown on Figure 1-1, for the following reasons:

- Both thermistor strings are located on the shore at a distance of approximately 100-110 m from the 151 m elevation contour line, which is about 1.5 m under water;
- The Stkd3 string has 8 beads between depths of 1 m and 15 m, which covers the zone of interest for the calibration process;
- A lot of temperature data are available for the Thermistor String Stkd3 with readings between May 2017 and May 2018 (see Figure 2-2).

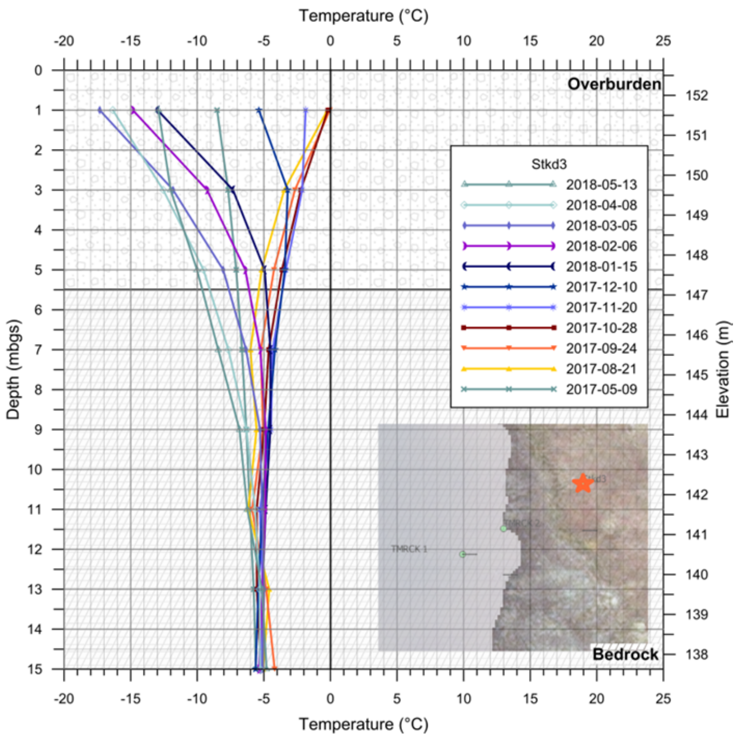


Figure 2-2: Temperature readings of thermistor string Stkd3 between May 2017 and May 2018

Other thermistor strings, for example in Boreholes AMQ15-452 and AMQ17-1277A (see Figure 1-1) could have been considered for the calibration since they are located on the shore at the north of the Whale Tail Lake. However, those boreholes have been drilled inclined and were designed to characterize the thermal regime under the Whale Tail Lake at great depths.

2.3 Modeling Assumptions and Boundary Conditions

2.3.1 Air Temperature

There is no weather station at the Whale Tail site. The two nearest Environment Canada meteorological stations are located about 100 km from the Whale Tail Pit mine site: Back River (2300MQM) and Baker Lake A (2300503). However, for this mandate, it was assumed that the measurements at the Meadowbank weather station between 2012 and 2016 (Figure 2-3A) located approximately 50 km south of Whale Tail Project are representative for the purpose of the thermal analysis.

The mean annual air temperature (MAAT) for the 2012 to 2016 period is -11°C. A 365-day synthetic air temperature curve was computed from the 2012-2016 daily average. This implies averaging the daily air temperature for all five years recorded (Figure 2-3B).

In order to simplify the modeling process, the synthetic daily air temperature was converted into a synthetic 60-day average air temperature, reducing considerably the temperature data set. This 60-day average air temperature curve is plotted by only using the 2012-2016 daily average temperature every 60 days. Although data accuracy is decreased, the general trend reflecting the annual variation in air temperature is preserved (Figure 2-3B). This simplified 60-day synthetic air temperature curve was hence repeated periodically for the duration of the modeling.

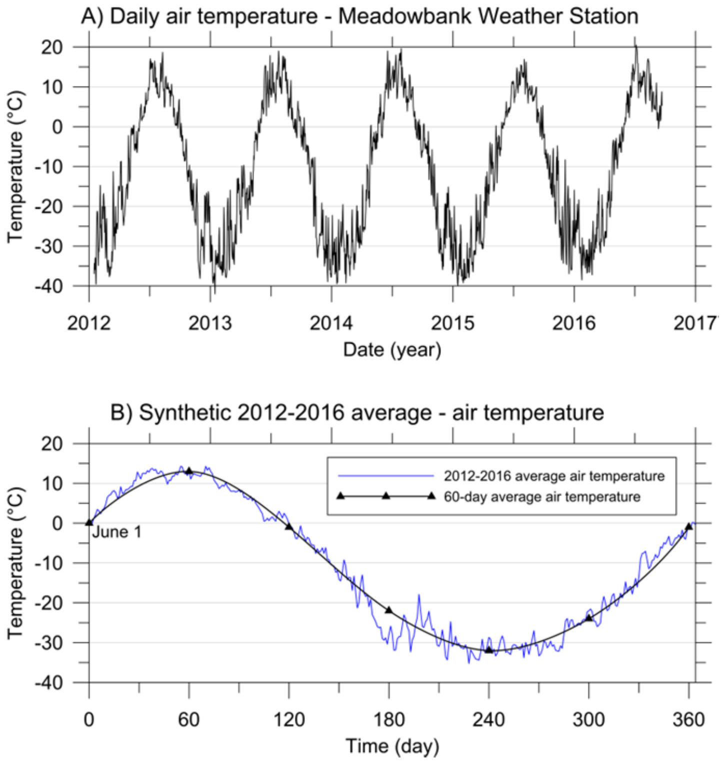


Figure 2-3: Air temperature curves

Climate warming expected to occur over the next 20 years has been purposely neglected in this study. Hence, the air temperature data was not modified by any rate of increase and is simply repeated yearly for the entire duration of the modeling.

2.3.2 Precipitations

It has been assumed that there is no significant snow accumulation that could affect the thermal regime of the simulated model. The effect of precipitation and the impact of convective heat transfer could be included in the model by coupling the heat transfer regime with seepage, but it has not been taken into account for this thermal analysis.

2.3.3 Material Properties

Seven distinct materials where used for the thermal analysis:

> Bedrock;

> Saturated and unsaturated fine filter;

> Saturated and unsaturated rockfill / coarse filter

> Saturated ice-poor till;

> Water.

All the physical and thermal properties of the materials listed above are found in the previous thermal analyses (SNC-Lavalin, 2018a; 2018b). The same input parameters are used for the present study as summarized in Table 2-1. SNC-Lavalin (2018c) indicated that ice-poor till was recovered in most boreholes; it is thus assumed that the saturated ice-poor till properties are representative of the actual soil conditions.

Table 2-1: Physical and thermal properties of the materials used in the thermal model

Layer	1 - Bedrock	2 – Saturated ice-poor till	3 – Saturated fine filter[c]	4 – Unsaturated fine filter	5 –Saturated rockfill / coarse filter	6 - Unsaturated rockfill / coarse filter	7 - Water / Ice
Description	Undifferentiated foliated granitoid rocks.	Sandy gravel with some silt (GW-GM).	Poorly graded sand (SP).	Poorly graded sand (SP).	Crushed rock material / Boulders, sandy gravel with some silt	Crushed rock material.	Water from the WRSF Pond
Geotechnical Parameter							
Dry density, ρ_d (kg/m³)	2667	1866	2208	2208	2241	2241	-
Density of soil solids, ρ_s (kg/m³)	2710	2700	2650	2650	2650	2650	-
Bulk density, ρ (kg/m³)	2683	2175	2375	2284	2284	2263	-
Gravimetric water content, w	0.6 %	16.5 %	7.5 %	3.4 %	6.9 %	1.0 %	-
Volumetric water content, θ_w	1.6 %	30.9 %	16.7 %	7.5 %	15.4 %	2.2 %	100 %
Degree of saturation, S_r	100 %	100 %	100 %	45 %	100 %	15 %	-
Porosity, n	0.02	0.31	0.17	0.17	0.15	0.15	-
Void ratio, e	0.02	0.45	0.20	0.20	0.18	0.18	-
Specific surface area, S_s (m²/g)	6[a]	15[b]	0	0	0	0	-
Geothermal Parameters							
Unfrozen thermal conductivity, k_u (kJ/day/m/°C)	211	141	171	138	173	119	52
Frozen thermal conductivity, k_f (kJ/day/m/°C)	216	199	213	116	212	108	194
Unfrozen Heat capacity, C_u (kJ/m³/°C)	2161	2675	2365	1982	2338	1785	4190
Frozen Heat capacity, C_f (kJ/m³/°C)	2124	1969	1983	1810	1985	1734	1900

(a)Reference: Basalt (Anderson & Tice, 1972)
(b)Reference: West Lebanon Gravel (Smith & Tice, 1988)
(c)The geothermal properties of the fine filter amended with bentonite are considered the same to those of the saturated fine filter

2.3.4 Phase Change of Water – Freezing Point Depression

Freezing point depression is associated with a specific temperature where free water starts to freeze. For pure water, the freezing point is equal to 0°C. It can be predominantly affected by the salinity (total dissolved solids in the solution). Due to lack of data, the assumption was made that the freezing point of water was 0 °C. This assumption was used for all thermal analyses presented in this study.

2.3.5 Surface n-factor

To simplify the calculations during thermal modeling (and due to limited field data), the differences between air temperature and ground surface temperature can be evaluated in the model with an estimation of the n-factor. Ground surface boundary conditions were correlated with the air temperature using an empirically determined n-factor coefficient. The freezing n-factor n_f corresponds to the ratio between the surface freezing index and the air freezing index, whereas the thawing n-factor n_t corresponds to the ratio between the surface thawing index and the air thawing index. The freezing index is the sum of negative degree-days over a given period (thawing index is the sum of positive degree-days). The previous thermal analyses carried out at the WTD (SNC-Lavalin, 2017; 2018a) used empirical values of n_f = 1.0 and n_t = 1.3, based on trial and error simulations. The thermal analysis carried out at the Mammoth Dike used values of n_f = 0.6 and n_t = 2.0 following the calibration of the model. In the current study, new values of n_f = 0.7 and n_t = 2.0 were used as explained further in section 2.4.

2.3.6 Geothermal Gradient

The previous thermal analyses (SNC-Lavalin, 2017; 2018a; 2018b) used a geothermal gradient of 0.0217 C/m. The same value was used in the current study.

2.3.7 WRSF Pond water level

During normal operation, the WRSF Pond is expected to have an operational level of 155.0 m. However, the water level in the pond could rise following high spring freshets or after a significant rain event as the WRSF Pond collects runoff water from the WRSF. In order to simplify the modeling process, a constant water level of 155.0 m is assumed for the analysis where the pond is modeled.

2.3.8 Boundary Conditions

2.3.8.1 Upper surface boundary

In the steady-state analysis, the upper surface boundary corresponds to the Mean Annual Ground Temperature (MAGT) at the surface. This value was calculated using the air temperature dataset, and by multiplying the values over 0 °C by n_t (2.0) and the values below 0 °C by n_f (0.7). By correlating the air temperature with the corresponding n-factor, the MAGT can be estimated at -4.18 °C.

In the transient analysis, the synthetic 60-day average air temperature presented in Figure 2-3 was used. The air temperature values were converted to ground temperature values using a thermal modifier function (n-factors). The thermal function is a periodic function with a period of 365 days, repeating itself for the duration of the analysis.

2.3.8.2 Bottom of the model

A constant temperature of 0 °C was used as a boundary condition for the bottom of the model instead of a heat flux associated with the geothermal gradient. Elevation -310 m was used for the base of permafrost, which was found empirically during the calibration process. It is the same elevation used for the thermal analyses carried out at the WTD (SNC-Lavalin, 2018a).

2.3.8.3 Side of the model

Zero heat flux is imposed on the sides of the model to avoid errors in the temperature distribution near the sides of the model.

2.3.8.4 Dike Temperature

The initial temperature of the dike, which includes the rockfill and filters, is fixed at 10 °C. The surface boundary condition is applied to the whole dike for one day in the transient analysis, after which the boundary condition is removed. This allows simulating the thermal effect of the construction of the dike starting on June 1st, the date the construction of the dike is considered completed.

2.3.8.5 WRSF Pond Temperature

In the conservative analysis (see Section 3.2), it is assumed that the water temperature is 3 °C just before the winter. The surface boundary condition is applied to the whole pond for one day in the transient analysis, after which the boundary condition is removed. This implies that the water in the pond of the model is allowed to freeze during winter.

2.4 Calibration of the Model

The model was calibrated using the thermistor string Stkd3 located at the east abutment of the WTD. The main goal of calibrating the model is to ensure that boundary conditions and thermal properties of the materials used in the model reflect what is observed in the field. It is assumed that the thermal regime at the WRSF Dike is similar to that at the Stkd3 location. The model is 220 m wide and 470 m high. The dimensions of the models in the current study are sufficient to allow the results not to be influenced by the size of the model. The lateral boundary effects are negligible because the main focus of the analysis is in the centre of the model. The mesh size increases gradually from 3 m at the surface to 20 m on the sides and at the bottom of the model. When the dike is modeled, the mesh size of its components is reduced to 1 m. The geometry of the cross section of the WRSF Dike used for calibration of the material properties and boundary conditions are shown in Figure 2-4.

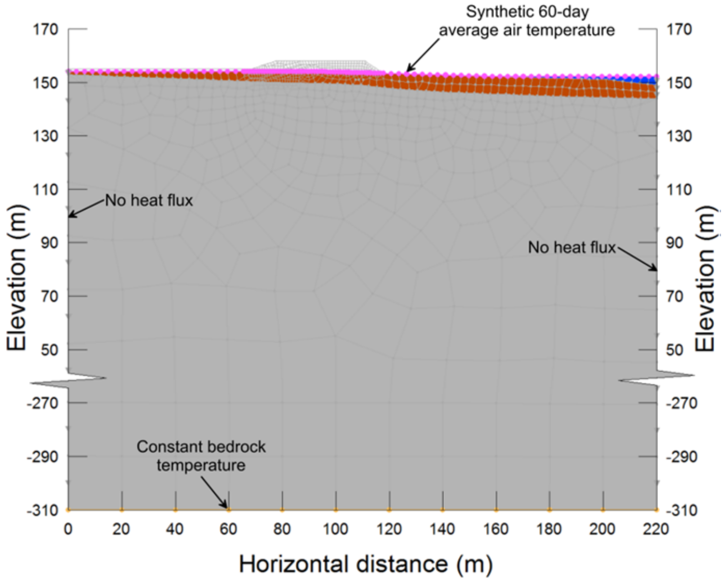


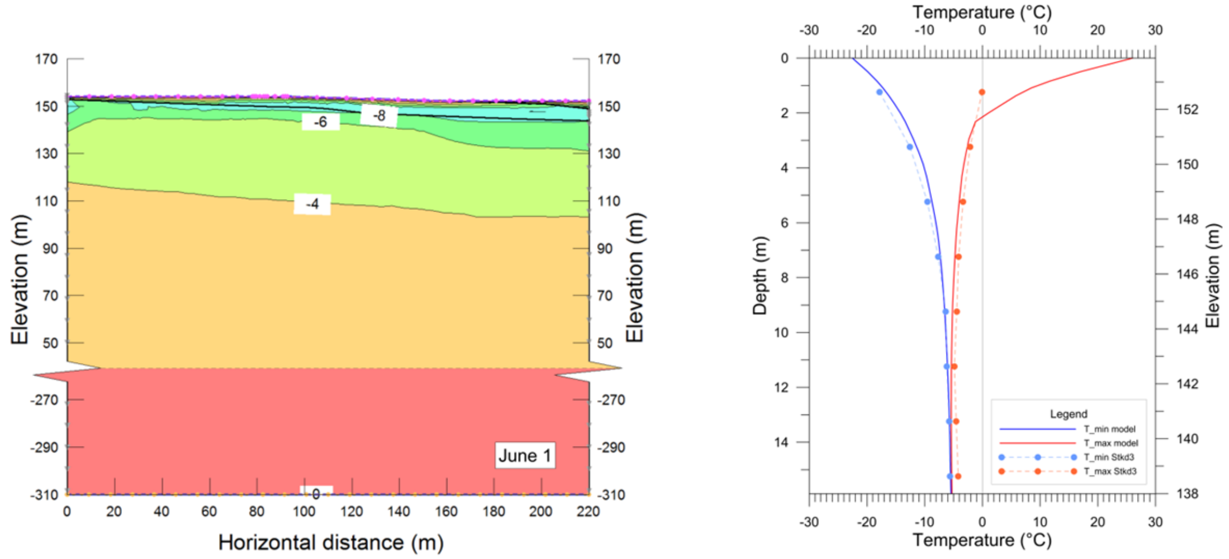
Figure 2-4: Geometry and boundary conditions of the cross section at the WRSF Dike

Using the boundary conditions described in section 2.3.8 and the thermal properties of the materials listed in Table 2-1, a steady-state analysis was carried out to establish the permanent thermal regime around the WRSF Dike. A 9-year transient analysis based on the initial conditions was then conducted to make sure that the steady-state results remained in equilibrium with the variation of air temperature with time. A 1-year transient analysis with a tight time step was finally performed to assess the annual variation of temperature at different depths in order to obtain the trumpet curves at the thermistor locations (Table 2-2).

Table 2-2: Modeling sequence for the calibration of the model

Modeling Sequence	Type of analysis	Duration	Time step	Saving increment	Parent analysis
Sequence 1 Calibration	Steady-State	-	-	-	-
Sequence 2 Initial conditions	Transient	9 years	5 days	5 days	Sequence 1 Calibration
Sequence 3 Initial conditions	Transient	1 year	1 day	1 day	Sequence 2 Initial conditions

If the observed data fit the annual variation generated by the model, it would mean good agreement between it and the field conditions. The thermal regime after 10 years and the range of annual ground temperature variations of the 10th year of transient analysis are shown in Figure 2-5.



(A) (B)

Figure 2-5: Inferred thermal regime in the WRSF Dike area after 10 years of transient analysis (A) and comparison between the range of annual ground temperature variation from the model and from the Stkd3 thermistor string (B)

Figure 2-5A shows the spatial temperature distribution along the whole model by June 1, which is the results of thermal equilibrium between the constant temperature boundary condition at the bottom and synthetic average 2012-2016 air temperature boundary condition at the top. Figure 2-5B compares the maximum and minimum temperature curves obtained from the model with the 2017-2018 annual ground temperature variation curves at the Stkd3 location. The agreement between the model and the Stkd3 readings is good on the whole depth of the thermistor string. There is a small difference above the 2 m depth of the active layer between the model and the readings from the thermistor string, but that could be due to the different soil strata thicknesses and properties between the WRSF Dike and the east abutment of the WTD. In general, the model replicates well the thermal regime at the Stkd3 location, but that does not make the model representative of the actual site conditions since they are not known. However, it is considered that the differences in thermal regime between the two locations are nevertheless small.

The model was calibrated using a modifier function for the 60-day synthetic air temperature boundary condition. This function is a 2-step data function comprising a value for the sub-zero temperatures on the one hand and another value for the positive temperatures on the other hand. Those factors correspond to the freezing n-factor of n_f and the thawing n-factor n_t, respectively. Those factors allow changing the air temperature dataset to ground surface temperature by accounting for net radiation, vegetation, snow cover, ground thermal properties, surface relief, and subsurface drainage (Andersland & Ladanyi, 2004). The n-factors were determined empirically by fitting the trumpet curves from the model with the readings from the thermistor string. Values of $n_f = 0.7$ and $n_t = 2.0$ were found suitable for this study, and are within the range of typical values for a gravel material (Lunardini, 1978; 1985).

By applying the n-factors to the 2012-2016 air temperature dataset, a mean annual ground temperature (MAGT) of -4.18 °C was calculated for the east abutment (and also used for the WRSF Dike) areas. The elevation of the base of permafrost was empirically determined at -310 m. This corresponds to the base of permafrost elevation used in the WTD thermal analysis (SNC-Lavalin, 2018a), which makes sense because the Stkd3 thermistor string is located in permafrost within the footprint of the WTD. It is assumed that the WRSF Dike is located on a perennially frozen environment because it will be constructed approximately 60 m from the shore of a small bay located north of Mammoth Lake.

3.0 THERMAL MODELING

3.1 Objective

The main objective of the thermal modeling of the cross section of the WRSF Dike is to understand its thermal regime, especially in the impervious zone. Once completed, the model is used to optimize the design of the dike if required. The performance of the dike will also be compared with the modeling results.

3.2 Geometry and Modeling Sequence

The geometry of the model is based on the cross section as shown in Figure 2-1. The details about the components of the dike and its geometry can be found in the technical report on the detailed design of the WRSF Dike (SNC-Lavalin, 2018d), to which this technical note is appended. The thermal analyses carried out at the Mammoth Dike showed that widening the crest of the dike in the upstream direction by six (6) metres has a positive impact on permafrost aggradation (SNC-Lavalin, 2018b). It was thus decided to also widen the crest of the WRSF Dike in the upstream direction in the current thermal analyses to benefit from this favourable thermal effect on the (FFAB) layer at the bottom of the key trench of the dike, even though the actual design shown on the drawings has a narrower crest. Therefore, if the thermistor strings planned to be installed show freeze thaw effect on the FFAB layer, it is possible (if required) to widen the dike crest in the upstream direction fairly quickly to correct the problem. The safety berms were not considered in the analyses to simplify the modeling process.

The model was first calibrated for the current field conditions as described in section 2.4. The 10 years of transient analysis for the calibration of the thermal model represents the last 10 years (2009-2019) assuming similar climate conditions throughout the years. The beginning of the thermal analysis for the WRSF Dike starts by June 1st, 2019.

Three (3) different scenarios have been looked at in the current study:

> Scenario #1: worst case scenario, where the WRSF Pond contains water during the wintertime only;

> Scenario #2: the water level in the WRSF Pond is constant at an elevation of 155.0 m;

> Scenario #3: the WRSF remains dry for the whole duration of the operations.

The modeling sequences of each of the aforementioned scenarios are described in the following sections.

3.2.1 Scenario #1: Worst case scenario

The worst case scenario corresponds to the case where the heat flow towards the impervious zone of the dike (the FFAB) would be maximized. This could lead to freeze and thaw (F-T) cycles in the impermeable material, which should be avoided to ensure the proper performance of the infrastructure. It was determined that a dry pond during the summer would maximize heat intake into the ground as the air temperature is higher than the ground temperature. However, the presence of a water pond during the winter would limit the heat extraction. The combination of those two elements on annual cycles as described in Table 3-1 lead to the worst case scenario in terms of heat intake into the core of the dike.

After 10 years simulation as described in section 2.4, it is assumed that the dike is constructed by June 1 with materials at a uniform temperature of 10 °C, which is conservative for this time of the year (the materials temperature should be colder than 10 °C at the beginning of June). In the worst case scenario, there is no water modeled during the summer as it would damp temperature variation in the underlying ground and reduce the heat intake on the upstream side of the foundation. The transient analysis continues during the summer by applying the

60-day average air temperature boundary condition at the top of the model with the n-factor modifying function. Once sub-zero air temperatures are modeled (which approximately correspond to September 30), a new region with water is added into the model. Then, a 1-day transient analysis with a water temperature of 3 °C for the WRSF Pond is carried out. This is to ensure that the water is initially in the unfrozen state in the model. During the winter, the water freezes and releases latent heat due to its high heat capacity. This reduces heat extraction from the ground in the pond area, keeping the foundation warmer.

Table 3-1: Modeling sequence of scenario #1: worst case scenario

#	Type of analysis	Duration	Time step	Saving increment	Initial conditions
1	Transient	1 day	1 day	1 day	10th year of calibration (June 1), construction of the dike at 10 °C†
2	Transient	119 day	1 day	1 day	Analysis #1
3	Transient	1 day	1 day	1 day	Analysis #2, water temperature at 3°C‡
4	Transient	244 days	1 day	1 day	Analysis #3
5*	Transient	120 day	1 day	1 day	Analysis #4
6*	Transient	1 day	1 day	1 day	Analysis #5, water temperature at 3°C‡
7*	Transient	244 days	1 day	1 day	Analysis #6

*Steps #5 to #7 are repeated on a 365-day cycle 9 times for a total analysis duration of 10 years
†See section 2.3.8.4
‡See section 2.3.8.5

At the end of the first winter (May 31), a new 365-day cycle begins. It includes 3 different steps:

> A 120-day transient analysis simulating the summer, where air temperature are above 0°C and no water is modeled in the pond;

> A 1-day transient analysis where the air temperature goes below 0 °C and the WRSF Pond is set at a temperature of 3 °C;

> A 244-day transient analysis simulating the winter, where the water in the WRSF Pond is allowed to freeze and release latent heat.

As mentioned in Table 3-1, those three steps are repeated 9 times from the second year of modeling, for a total duration of 10 years. A total of 34 steps including the calibrations are required in the modeling software in order to carry out a 10-year transient analysis, which increases the modeling time. A 10-year thermal analysis was considered sufficient in order to get an idea of the long-term thermal regime within the core of the dike.

3.2.2 Scenarios #2 and #3: with and without water in the WRSF Pond

Scenarios #2 and #3 have a constant WRSF Pond elevation of 155.0 m and a dry pond, respectively. Both scenarios have the same modeling sequence, the only difference being the presence of water on the upstream side of the WRSF Dike in Scenario #2. Because the presence of water in the WRSF Pond cannot be scheduled with precision, the thermal effect of the water is assessed on the model by comparing Scenarios #2 and #3. The modeling sequence of both scenarios is described in Table 3-2. The analysis starts with a one-day transient period, simulating the construction of the dike with an initial material temperature of 10 °C by June 1, which is the same initial condition compared with Scenario #1. For Scenario #2 only, the initial water temperature is 3 °C. Then, a 19-year transient analysis is carried out on both scenarios. The 20th year of modeling has a tighter time step in order to assess the amplitude of ground temperature variation of the foundation.

Table 3-2: Modeling sequence of scenarios #2 and #3

#	Type of analysis	Duration	Time step	Saving increment	Initial conditions
1	Transient	1 day	1 day	1 day	10th year of calibration (June 1), construction of the dike at 10 °C†, water temperature at 3°C‡ (scenario #2 only)
2	Transient	19 years	5 days	5 days	Analysis #1
3	Transient	365 days	1 day	1 day	Analysis #2

† See section 2.3.8.4
‡ See section 2.3.8.5

Because the modeling sequence described in Table 3-2 is much simpler compared with the worst case scenario, a 20-year transient analysis was carried out in order to evaluate the long term thermal regime within the core of the dike.

3.3 Modeling Results

In order to assess the effect of the WRSF Pond on the thermal regime within the WRSF Dike, the three (3) scenarios were compared to each other graphically as shown in Figure 3-1.

The temperature was recorded at one specific point as shown by the red star symbol on Figure 3-1. This point corresponds to the top of the Fine Filter Amended with Bentonite (FFAB) layer at the bottom of the key trench on the upstream side of the dike, considered sensitive to freeze-thaw (F-T) cycles. By comparing the temperature as a function of time at that specific location for the three scenarios, one can assess if the FFAB layer will be exposed to F-T cycles for the first 10 years of operation.

As mentioned in Section 2.3.8.4, the initial temperature of the dike, which includes the FFAB, is 10 °C. The model then allows the dike temperature to vary according to the top boundary condition, which is the synthetic 60-day average air temperature with the n-factor modifying function. After approximately six (6) to seven (7) years, the permanent thermal regime seems to have established within the core of the dike.

In Scenario #1, which is the most conservative scenario, the thaw front is very close to the top of the FFAB every year. This implies that the top of the FFAB could be exposed to annual F-T cycles in the long term, assuming that the thermal conditions in the model are representative of the current thermal regime in the field. If similar or cooler temperatures are observed in the WRSF Dike area compared with Stkd3 readings, it is expected that the core of the dike will remain in the frozen state during the operations because Scenario #1 assumes the worst field conditions in terms of heat extraction. It is highly unlikely that the worst case scenario will repeat itself year after year during the operational life of the infrastructure.

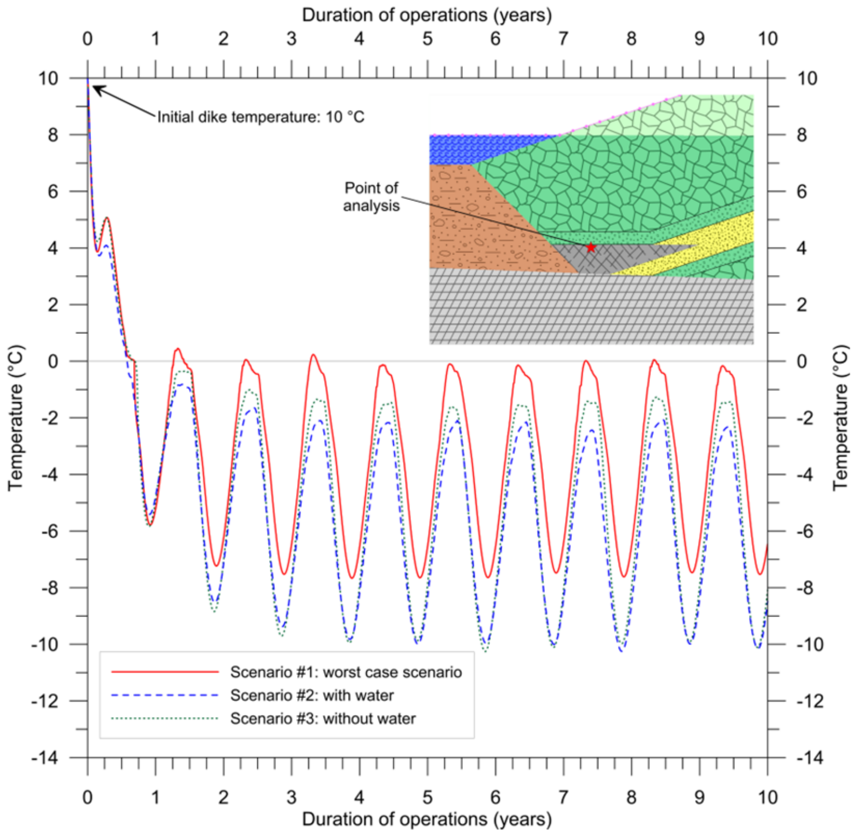


Figure 3-1: Comparison between three scenarios for the core temperature of the WRSF Dike

The FFAB remains in the frozen state from the first year of operation in both Scenarios #2 and #3. The only difference between these two scenarios is the amplitude of the annual temperature variation, which is lower in Scenario #2. This is because the WRSF Pond water level is constant at 155.0 m in Scenario #2, while it is dry in Scenario #3. The high heat capacity of the water has a damping effect on the temperature fluctuations of the dike foundation that can be observed in Figure 3-1. However, both scenarios reach a minimum temperature at the top of the impervious zone of -10 °C, while Scenario #2 stays approximately 1 °C cooler during the summer due to the presence of the pond.

It is interesting to point out that the minimum temperature of Scenario #1 occurs a few days after Scenarios #2 and #3. This is due to the initial temperature of 3 °C in the pond at the beginning of the winter, delaying the freezing process of the water. This boundary condition was applied in order to stay on the conservative side as Scenario #1 simulates the worst case. In terms of temperature variation, Scenarios #1 and #2 have similar amplitudes, except that the worst case Scenario 1 is about 2.5 °C warmer due to the conservative boundary condition.

As mentioned in Section 3.2.1, the modeling of Scenario #1 required a lot of steps and significant modeling time. Moreover, because the boundary conditions are very conservative, it is not expected that those conditions will be repeated year after year during the mine operation. For those reasons, the thermal regime within the dike after 20 years was assessed in the second most conservative scenario only, which is Scenario #3. The absence of water in the pond leads to higher foundation temperatures during the summer. This implies that the thaw front will penetrate deeper into the foundation in scenario #3. The maximum thaw depth profile within the WRSF Dike is shown in Figure 3-2.

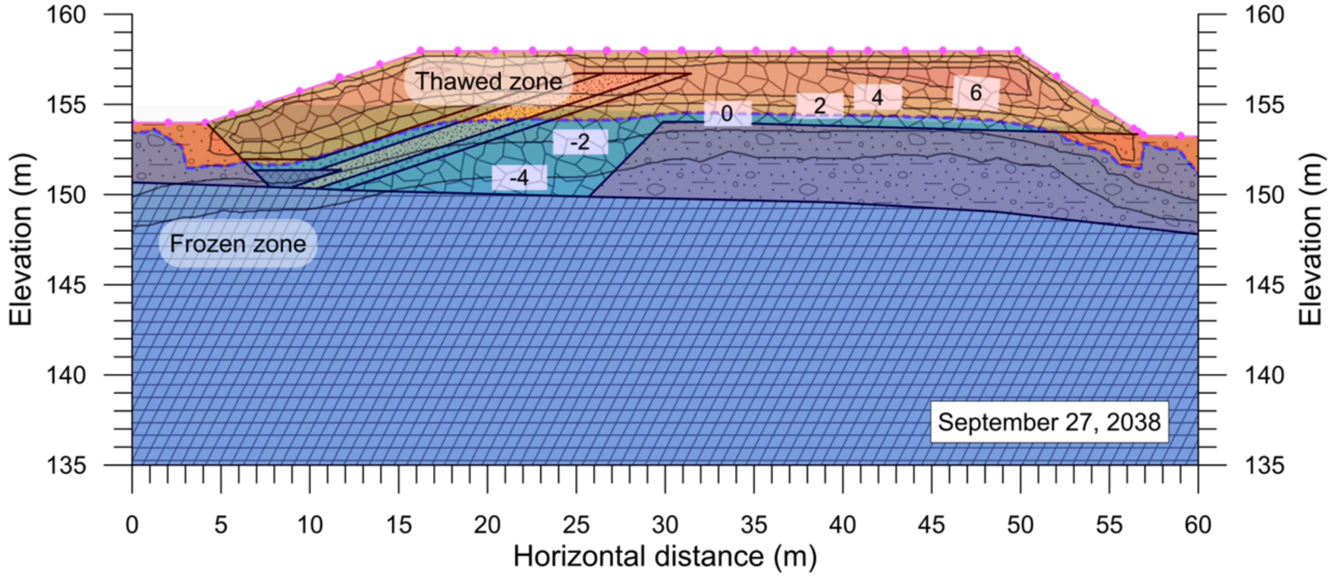


Figure 3-2: Thermal regime within the WRSF Dike at the end of September after 20 years of mining operations for scenario #3

The thaw front reaches its lowest elevation by September 27 every year. The 0°C isotherm follows more or less the dike geometry, for the underlying soil properties simulated. The FFAB layer remains in the frozen state, although the thaw front reaches the coarse filter layer located just above it. This implies that the factor of safety in terms of preventing the FFAB from being subject to F-T cycles is marginal for the boundary conditions considered in Section 2.3.8.

The thermal regime is based on the Stkd3 thermistor string located at the east abutment of the WTD. Although the analyses have assumed that the temperature regime at Stkd3 and is similar to that at the WRSF, the fact remains that the two sites are located separated by about 2,350 m. Significant differences in the thermal regime could occur due to the presence of water bodies nearby, different ground thermal properties and subsurface drainage conditions, etc. It is also important to point out that variations in water level and temperature were not taken into account in the thermal analyses even though they could have an impact on the local thermal regime. Moreover, the impact of expected trend of global warming was not taken into account.

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Thermal analyses were carried out on a cross section of the WRSF Dike in order to determine the thermal regime at that location. The dike cross section used for the thermal modeling was taken from the permitting level engineering report of the water management infrastructure at Whale Tail and confirmed by the 2018 geotechnical investigation (SNC-Lavalin, 2018c). However, the dike was simulated considering the widening of its crest by six (6) m in the upstream direction to promote freezing of FFAB continuously based on experience acquired during the thermal modeling of the Mammoth Dike (SNC-Lavalin, 2018b). This widening ould be implemented if justified by the thermistor data to be collected and analysed. The thermal model was calibrated using a thermistor string located at the east abutment of the WTD approximately 2,350 m from the WRSF Dike. Similar thermal conditions were assumed for the two locations based on their similar distance from the 151.0 m submerged elevation contour line. Empirical n-factors were used in order to calibrate the model with the factual data available. Three different scenarios were studied: the worst case scenario, where the WRSF Pond contains water during winter only, a scenario where the water level is at a constant elevation of 155.0 m in the WRSF Pond, and a scenario where the WRSF Pond stays dry during the operations.

Results of the thermal analyses show that:

> The presence of water in the WRSF Pond has a damping effect on temperature fluctuations in the underlying foundation;

> Even by applying the worst case scenario repeatedly year after year, the thaw front would barely reach the top of the FFAB layer;

> Even if the basin stays dry during the mining operations, the FFAB should remain in the frozen state and not be exposed to F-T cycles. However, the factor of safety against exposure to F-T is marginal.

4.2 Recommendations

As a follow-up to the main conclusions drawn above from the thermal analyses, the following recommendations are made:

> Since the calibration of the model is based on a thermistor string installed over 2 km from the study site, the installation of thermistor strings within the footprint of the WRSF Dike would help confirm the thermal regime, and thus the accuracy of the current thermal analyses. Specifically; additional thermistor strings should be installed within the dike during its construction in order to monitor the thermal regime of the impervious zone;

> If warmer conditions compared to that assumed in this study are encountered at the site, the enlargement of the crest of the dike in the upstream direction will raise the permafrost table and prevent FFAB layer from being subjected to F-T cycles.

It is pertinent to mention that the models assume that the construction of the dike will be completed in June 2018. However, as per the latest schedule for the project[1], the construction of the WRSF Dike will start at the end of

[1] Whale Tail Earthwork - Construction - Schedule - 2018-07-29 - Update - Submitted July 29.pdf

September. The construction of the dike during the cold season as planned will promote heat extraction, hence be beneficial to the thermal regime of the foundation and the FFAB, ensuring the performance of the WRSF Dike as designed. It is, however, recommended to monitor the temperature regime adequately with a series of thermistor strings to be installed within the dike and the FFAB during the operation and closure.

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SNC·LAVALIN
5500 des Galeries Blvd. Suite 200
Québec (Quebec) Canada G2K 2E2
Phone: 418-621-5500 - Fax: 418-621-8887
www.snclavalin.com