Whale Tail Project - Thermal Modelling of the Whale Tail and IVR WRSFs

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AGNICO EAGLE

O'Kane Consultants




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EXECUTIVE SUMMARY

O'Kane Consultants Inc. (OKC) was retained by Agnico Eagle Mines Limited – Meadowbank Division (Agnico Eagle), to complete an updated thermal assessment of the Whale Tail and IVR waste rock storage facilities (WRSFs) at the Amaruq property. The objective of the thermal modelling assessment is to address mitigation measures developed for high-risk failure modes of the WRSFs developed by Agnico Eagle (OKC, 2019a) under the Intergovernmental Panel on Climate Change's (IPCC) Representative Concentration Pathway 6 (RCP6) scenario:

- Add cover system hydraulic performance to modelling to inform on timing of risk for contribution of arsenic loading from WRSF cover material.
- Confirm the assumption that timing for arsenic release from the thermal cover material is overly conservative.
- Calibrate material properties to available lithology and perform sensitivity analysis on the modelled material properties.

The thermal modelling also provides recommendations for the final configuration of the WRSF and WRSF cover systems such that Agnico Eagle can select a landform and cover system design for the WRSFs that is physically and chemically stable and optimizes risk and cost for Agnico Eagle.

Chemical stability of the WRSFs will be demonstrated by achieving seepage and/or runoff from the WRSFs that meets site water quality objectives. Acceptable water quality from the WRSF is proposed to be achieved by maintaining frozen conditions within the waste rock to the extent required to control generation and mobilization of potentially acid generating or metal leaching (PAG/ML) products. Frozen conditions within the waste rock will be maintained using a thermal cover system which limits the annual depth of thaw within the PAG/ML waste rock.

In accordance with permitted conditions (Agnico Eagle, 2018a), a base case cover system of 4.7 m of NPAG/ML material was modelled to ensure that the cover system objectives will be met. Model material properties were calibrated to field data obtained at the nearby Portage site. Two-dimensional (2D) thermal and seepage numerical modelling, using modelling software, GeoStudio Version 10, was completed to assess the base case design. Sensitivity analyses of slope aspect, cover system material texture, and WRSF geometry were evaluated to provide recommendations for an updated cover system design. In addition, expected performance, in terms of freeze-back, was assessed under RCP6 climate change conditions.

The thermal assessment determined that permafrost will form in the WRSF, while thaw will be limited to near surface and occurs primarily in response to two mechanisms. The first, which has been studied previously, is a function of annual climate cycling resulting in freeze/thaw of the cover system in response to annual seasonal temperature changes. Thaw at surface generally begins in late April, and gradually increases in depth until approximately late July, at which time the depth of thaw recedes until

September when the surface returns to a frozen condition. This climatic cycling is generally constrained to the depth of the proposed cover system.

Secondarily, convective heating (heat being transported with airflow) results in deeper thaw which begins to occur at the height of thaw caused by climatic cycling (typically observed in July) and extends into the fall and winter, or in some cases year-round. This deeper thaw mechanism is caused by warmer air being drawn into the WRSF, and subsequently not being able to dissipate due to the presence of ice lenses where air permeability is very low. The extent and depth of these ice lenses, which cause pore-air entrapment, is highly dependent on assumed material properties used in modelling. As thaw occurs, the active layer infiltration into the active layer as snow melt and rainfall occurs; however, the underlying layer of permafrost prevents water from draining as the hydraulic conductivity of the permafrost layer is greatly reduced (Scott, 1968). Infiltrating water becomes trapped above the layer of permafrost creating zones of high saturation which freeze in the winter, resulting in the formation of ice rich zones near the extent of the active layer (Pipkin, 1994).

While the secondary thaw mechanism, convective heating, is likely to result in thawing of waste rock below the cover system, the likelihood of a 4.7 m cover system thickness being insufficient, leading to unacceptable water quality in the receiver is expected to remain very low. This is due to the several factors, including:

- Very low volumetric water content in the thawed waste rock, resulting in very low likelihood of mobilization of seepage from waste rock;
- Lower pyrite oxidation rates within the thawed waste rock compared to the cover system material (as a result of consistent near-freezing temperatures within the waste rock) resulting in low to moderate likelihood of production of metal leaching and acid rock drainage (ML/ARD) products;
- Limited volume of total waste rock within the estimated thawed waste rock zone, resulting in low to moderate likelihood of production of ML/ARD products; and
- Limited volume of PAG/ML waste rock in the estimated thawed waste rock zone, resulting in low likelihood of production of ML/ARD products.

Increasing the cover system depth to constrain convective heating to within the cover system offers diminishing returns in terms of risk reduction. Rather, the design of the cover system should ensure that warming due to the primary thaw mechanism, annual climatic cycling, which has greater potential for both ML/ARD production and mobilization, is constrained to the cover system depth for the range of expected cover system material textures. This is accomplished given the proposed 4.7 m thermal cover system.

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1 INTRODUCTION

O'Kane Consultants Inc. (OKC) was retained by Agnico Eagle Mines Limited – Meadowbank Division (Agnico Eagle), to complete an updated thermal assessment of the waste rock storage facilities (WRSFs) and proposed WRSF cover systems at the Amaruq property as well as a qualitative assessment of temporary ore stockpiles. OKC developed a conceptual model of the WRSFs as well as a Failure Modes and Effects Analysis to support closure planning at Amaruq. The thermal analysis presented in this report improves on the conceptual model by completing two-dimensional (2D) thermal and seepage numerical modelling using GeoStudio Version 10. The model was calibrated to field data obtained at the Portage WRSF an analogue facility operated at Agnico Eagle's nearby Meadowbank operation.

1.1 Project Objectives and Scope

The objective of the modelling program is to update and enhance the thermal modelling completed to date. In addition, the thermal modelling program directly addresses the following high risks and associated mitigation measures identified in the 2019 FMEA (OKC, 2019a):

- *Source of water from NPAG / NML cover material placed on WRSF leads to increased arsenic and unacceptable water quality.* The addition of cover system hydraulic performance to modelling will inform on timing of risk for contribution to arsenic loading from WRSF cover material. Current site wide load modelling indicates that under very conservative cover system flow assumptions, As is at or below water quality criteria in Mammoth Lake.

- *Modelling is overly conservative in terms of mass and timing of arsenic release from cover material leading to lower than predicted impacts to water quality*. The assumption is that timing for arsenic release from the thermal cover material is overly conservative as assumed for the modelling completed as of the FMEA workshop, but mass is not. Receiving capacity in Mammoth indicates that a more gradual timing of release from the cover material would likely allow for some relief from the existing base case assumption of 'plug flow' occurring throughout the extent of the thermal cover material.

- *Incorrect numerical modelling inputs for physical and hydraulic characteristics and numerical modelling not capturing mechanisms and control on mechanisms, leading to cover system thickness not meeting freeze-back objectives.* To reduce risk, a reassessment of calibration with lithology properties will need to be done, as well as a sensitivity analysis on the model and confirming the cover thickness of NPAG / NML material during Year 1 through field performance monitoring.

The 2019 FMEA considered that modelling and design includes consideration of climate change as a 'base case', thereby mitigating risk related to climate change uncertainty. The thermal modelling program specifically addresses the risk of *incorrect numerical modelling inputs for future climate,* *leading to cover system thickness not meeting freeze-back objectives.* This risk was mitigated by considering base case climate inputs for numerical consistent with Environment and Climate Change Canada (ECCC) Representative Concentration Pathway 6 (RCP6) climate change scenario.

Thermal modelling of the WRSFs will assist in developing the expected seasonal active layer thickness under climate change conditions, as well as determine if permafrost conditions within the WRSFs are sustainable under climate change conditions. The ultimate objective of the project is to demonstrate the physical and chemical stability of the Whale Tail and IVR WRSFs while optimizing risk and cost for Agnico Eagle. Demonstrating chemical stability of the Whale Tail and IVR WRSFs will be assessed based on meeting acceptable receiver water quality, which will be evaluated separately through a site wide load balance. Achieving acceptable water quality from the WRSF will be accomplished by maintaining frozen conditions in the waste rock to the extent necessary to control the generation and mobilization of metal leaching and acid rock drainage (ML/ARD) products.

Based on these objectives, the specific deliverables for the modelling program provided herein are:

1) estimated freeze-back 'curves' which define the range of expected performance for freeze-back over time for the WRSF for different depths and aspects of the WRSF (if applicable);
2) summary of maximum depth of the thermally active layer for different slopes and aspects of the WRSF (if applicable); and
3) runoff, interflow, and basal seepage rates for different slopes and aspects of the WRSF (if applicable)

The three specific deliverables outlined will achieve the following respectively, define monitoring 'triggers' for the existing WRSF adaptive management plan, confirm and/or optimize the existing 4.7 m thermal cover system design, and provide inputs to a site-wide water balance model to inform on long term water quality at Amaruq.

1.2 Report Organization

For convenient reference, this report has been subdivided into the following sections:

- Section 2 – Provides background and presents and the conceptual model for the WRSFs;
- Section 3 – Presents the model inputs used for the simulations completed for this project;
- Section 4 – Presents the results of the one-dimensional (1D) and two-dimensional (2D) simulations and concludes with a summary of the seepage analysis; and
- Section 5 – Provides an updated conceptual model for the WRSFs based on the modelling presented hereinafter.

2 BACKGROUND

2.1 Conceptual Model

A review of available data from Meadowbank Portage WRSF was used to inform, constrain and calibrate the Whale Tail thermal modelling. Initial review of the information regarding the thermal conditions and previous modelling efforts at Meadowbank and Whale Tail indicate:

- The Portage WRSF has not frozen completely.
- The top 3 to 4 m of the WRSF thaw during the summer, but it is anticipated that this active layer (i.e. the depth at the surface of the WRSF that does not form permafrost (stay below 0°C)) will decrease in thickness once permafrost has fully formed within the WRSF.
- The active zone extends below the cover on both north and south slopes, contrary to expected behaviour.
- The previous modelling effort completed for Whale Tail recommended a thermal cover 4.7 m thick, which estimated freeze back of the WRSFs approximately 25 years after closure.

The following summarizes the conceptual model of the hydrologic and thermal regime at the Whale Tail and IVR WRSFs:

- The existing proposed thermal cover system (4.7 m of NAG/NML material) is not expected to promote runoff / interflow from the cover system due to sufficient infiltration capacity of the waste rock and cover system materials as a result of the expected coarser texture of materials.
- High infiltration rates will result in gradually (over several years) increasing interflow and/or basal flow reporting to WRSF collection ponds as the WRSF is constructed and reaches its final extent.
- Slopes are expected to be more susceptible to infiltration entering waste rock prior to freeze back compared to the plateau.
- Cover system material (NAG/NML) is expected to experience less weathering (increase in fines) compared to Portage due to lithology (greywacke vs. ultramafic) resulting in higher long-term infiltration rates and higher propensity for convective cooling compared to Portage.
- Decreased reactivity due to frozen conditions in waste rock is expected to result in decreased arsenic load generation (but not zero load generation). Any interflow / runoff from the thermal cover system is not expected to report to collection ponds as ‘plug flow’ due to the variance in transit times across the landform. Put simply, incident precipitation at the toe of the WRSF will report to water collection systems much sooner than precipitation which lands on the plateau of the landform.

Any contaminants of potential concern present within the thermal cover system material (e.g. arsenic), will therefore also be released gradually.

- The thermal and hydrologic regimes are expected to be different based on North and South aspect.
- Mineral oxidation is occurring within the WRSF resulting in some heat generation, but the main driver of heating is air flow.

2.2 Description of Numerical Modelling Program

The GeoStudio Version 10 suite of modelling programs was used in combination for this project: SEEP/W; TEMP/W; AIR/W, and CTRAN/W. This version of GeoStudio was substantially upgraded from previous versions to allow for more accurate representation of various processes. SEEP/W, a 1D/2D finite element model, was used to predict the movement of moisture and pore-water pressure distribution within the porous materials such as soil and rock. The latest version of SEEP/W incorporates a module allowing for soil-plant-atmosphere (SPA) modelling. The SPA model of SEEP/W is capable of calculating pressure head (suction) and temperature profiles in the material profile in response to climatic forcing (such as evaporation) and lower boundary conditions (such as a water table) as well as evaluating the impact of frozen conditions on moisture storage and transport for a given soil or rock material.

TEMP/W, a 1D/2D finite element model, was used to model thermal changes in porous systems due to various changes in the environment, internal changes in temperature, or any other influencing condition that may result in a change of temperature in the subsurface such as heat transfer due to the movement of water. By coupling the TEMP/W simulation with a SEEP/W simulation, a more accurate temperature condition in the subsurface can be estimated. AIR/W, a 2D finite element model, is executed within the SEEP/W model and used to model air pressure and flow within a system in response to changes in pressure conditions at the boundary, or changes in water pressure. CTRAN/W with the addition of the gas consumption and exothermic reactions add-in couples the gas, heat, water and air transfer processes to simulate the exothermic oxidation process. A more detailed description of the modelling software used for the Whale Tail thermal modelling is presented in the memorandum outlining the Whale Tail conceptual model (OKC, 2019), attached in Appendix A.

3 MODEL INPUTS

Model inputs for the Amaruq WRSFs can be divided into five types:

1) Climate / Upper Boundary Conditions;
2) Materials;
3) Geometry;
4) Lower and Edge Boundary Conditions; and
5) Initial Conditions.

The following sections describe the inputs used.

3.1 Climate

Daily inputs of maximum and minimum air temperature; maximum and minimum relative humidity (RH); average wind speed; daily net radiation; and precipitation (amount and duration) are required for modelling. Historical values for all these parameters were compiled from the following data sources to develop a 'representative average year' (Table 3.1):

- Baker Lake, 1964 to present (Environment and Climate Change Canada, 2018 and Environment and Climate Change Canada, 2014); and
- Meadowbank – 2012 to 2018.

Table 3.1: Summary of average climate parameters for 54-year Amaruq historical climate database.

Month	**Temperature (°C)**		**Relative Humidity (%)**		**Wind (m/s)**	**Net Radiation[1] (MJ/m2/day)**	**Precipitation (mm)**
	Maximum	Minimum	Maximum	Minimum			
January	-28.0	-35.0	72	61	6.4	-2.0	8
February	-27.8	-35.0	72	60	6.3	-1.6	7
March	-22.6	-31.2	73	61	5.9	-0.6	11
April	-12.6	-22.0	81	68	5.9	4.1	16
May	-2.6	-9.8	90	76	5.5	7.1	15
June	9.0	0.5	90	62	4.8	8.9	22
July	16.8	6.2	89	52	4.6	8.9	37
August	14.3	5.4	92	59	5.0	5.6	42
September	6.2	-0.4	93	68	5.5	2.2	44
October	-3.7	-10.0	91	77	6.0	-0.4	30
November	-15.8	-23.2	81	68	6.1	-2.0	19
December	-23.5	-30.7	75	63	6.2	-2.2	11
Annual	-7.4	-15.3	83	67	5.7	2.4	262

1 Net radiation for a level location (e.g. the plateau of the WRSF)

The representative average year was adapted to account for creation of micro-climates on WRSF embankments due to changes in wind speed and net radiation, as well as climate change predictions over the next 150 years. To maintain consistency with other design work ongoing at Amaruq, climate change was represented by the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5), Representative Concentration Pathway 6 (RCP6). Refer to Appendix A for a detailed description of the climate database basis and development.

3.2 Materials

The material properties or functions developed for each material based on available geochemical and geotechnical testing (eg. particle size distributions) are as follows:

- water retention curves (WRC – suction versus volumetric water content);
- hydraulic conductivity function (k-function – suction versus hydraulic conductivity);
- air conductivity function;
- thermal conductivity function (volumetric water content versus thermal conductivity);
- volumetric specific heat function (volumetric water content versus volumetric specific heat capacity);

- unfrozen water content function (unfrozen water content versus temperature); and
- geochemical reactivity.

As there exists some uncertainty in material properties, a range in material properties was investigated during sensitivity modelling in order to quantify the effect of any changes from the initial material inputs. Refer to Appendix A for a detailed description of material properties used in modelling.

3.3 Geometry

Five cross sections (three through Whale Tail WRSF and two through IVR WRSF) were selected for long term modelling (Figure 3.1). These cross sections were 'built-up' over time to simulate conditions at placement and prior to construction of a thermal cover system of overlying waste rock layers (Appendix B). Sensitivity analyses were completed for the NW-SE Whale Tail cross section labelled 'A' in Figure 3.1 and shown in Figure 3.2 as it is expected to have the most diverse range in behaviour due to the potential for advective cooling in the predominant wind direction. Figure 3.3 shows the NW-SE IVR cross section labelled 'D' in Figure 3.1.

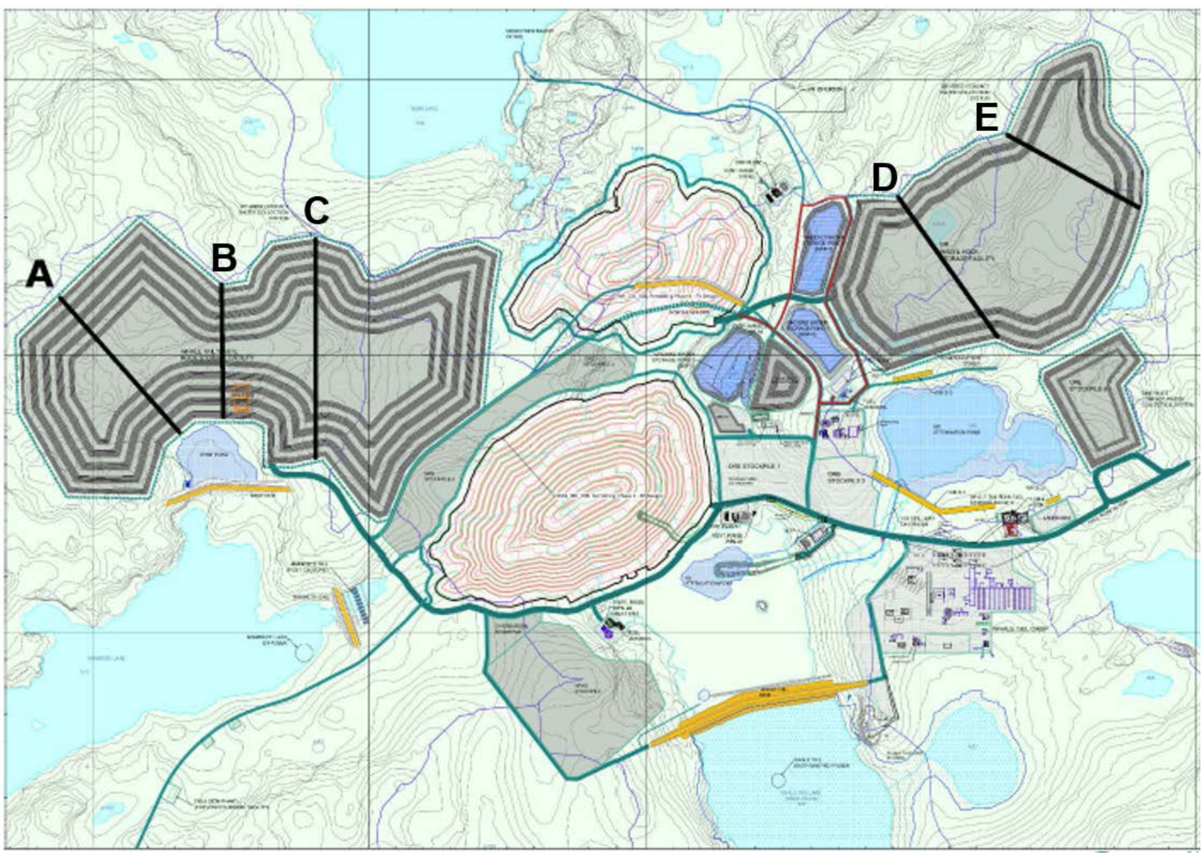

Figure 3.1: Locations of five cross-sections of Whale Tail and IVR WRSFs.

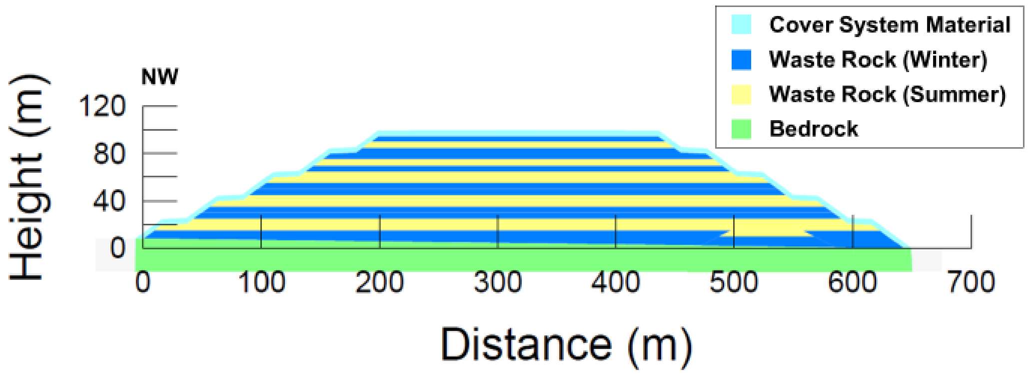

Figure 3.2: Northwest-Southeast cross-section through Whale Tail WRSF at closure (A).

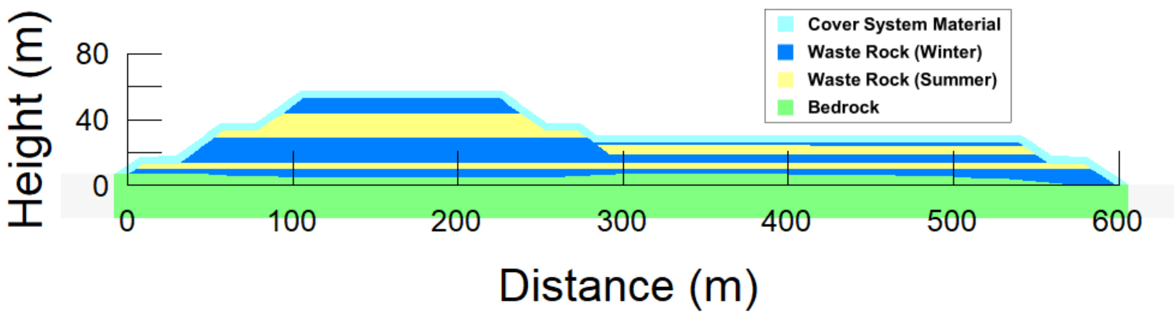

Figure 3.3: Northwest-Southeast cross-section through IVR WRSF at closure (D).

3.4 Internal Boundary Conditions

3.4.1 Hydraulic Boundary Conditions

The lower boundary of the 1D models were simulated as a unit hydraulic gradient. This boundary condition assumes that at the lower boundary the suction (and as a result, water content and hydraulic conductivity) are constant with depth. For this situation, the total head equals the gravitational head, which results in a unit hydraulic gradient. In other words, a unit hydraulic gradient represents a location in the material profile where water movement is controlled mainly by gravity.

A zero-flow boundary was used for the lower boundary of the 2D model (at the base of the bedrock), which assumes that the bedrock at depth is impermeable. On the surface of the WRSF, a net infiltration boundary condition was applied based on the results of 1D simulations

3.4.2 Gas Boundary Conditions

A barometric air pressure condition referenced to 160 masl elevation and adjusted for daily air temperature was applied to the exterior of the 2D cross sections. A constant oxygen concentration representing atmospheric conditions (280 g/m^3) was also applied to the exterior of the 2D cross sections

3.4.3 Temperature Boundary Conditions

A depth of zero amplitude condition of -5°C at the base of the bedrock (approximately 20 m depth below surface) was used for the lower boundary of the 2D models (Agnico Eagle 2018b). To simulate exothermic reactions from the oxidation of waste rock, the Gas Consumption and Exothermic Reaction boundary condition was applied to the waste rock material. This boundary condition couples the oxygen consumption due to mineral oxidation to heat generated by the associated exothermic reactions. Optimal oxidation rates were calculated from humidity cell tests (Golder, 2018a) as 0.052 kg O_2/t/year for the cover material and 0.062 kg O_2/t/year for the waste rock material. These rates represent the oxidation rate under optimal conditions. The add-in adjusts the reaction rate at each timestep, and node based on the current temperature and oxygen concentration. Daily minimum and maximum temperature boundaries were applied to the exterior of the 2D cross sections as described in Section 3.1.

3.5 Initial Conditions

3.5.1 Hydraulic Conditions

Both waste rock and cover system material were assumed to be placed at an initial volumetric water content of approximately 0.05 cm^3/cm^3.

3.5.2 Gas Conditions

The initial concentration of oxygen in the pore space of both the waste rock and cover system material at placement was assumed to be consistent with atmospheric conditions (280 g/m^3). Initial air pressure in the WRSF was set to represent atmospheric levels (0 kPa).

3.5.3 Temperature Conditions

The initial thermal conditions were dependent on the time of year the material was placed. Where waste rock was assumed to be placed between April and September, the temperature at placement was assumed to be 3°C. Average air temperature during this same period is approximately 2.6°C. Where waste rock was placed between October and March, the waste rock temperature was assumed to be -15°C, the average between air and permafrost temperature. Average air temperature during this same period is approximately -24°C, while permafrost temperatures at depths of zero amplitude are in the range of -3.0°C to -8.4°C (Agnico Eagle, 2018b). These conservatisms were applied to achieve an average annual 'placed' temperature (-6°C) slightly higher than the annual average air temperature (-11°C) as the ground temperature is expected to be higher than the air temperature due to increased heat capacity. Cover system material was assumed to be placed consistently at 0°C. This simplification was made as the cover is to be placed throughout the various seasons of mine operations. In addition, the cover system temperature is expected to equilibrate rapidly to external temperature conditions, resulting in minimal impact in long-term thermal results due to simplification in the initial placement temperature assumptions.

Table 3.2 summarizes the initial conditions used in modelling.

Table 3.2: Initial conditions used in numerical modelling simulations

Parameter	Material	Value	Note
Temperature	Waste Rock	3°C	Placed in summer
Temperature	Waste Rock	-15°C	Placed in winter
Oxygen	Waste Rock	280 g/m^3	Representative of atmospheric levels
Air Pressure	Waste Rock	0 kPa	Representative of atmospheric levels
Hydraulic Head	Waste Rock	-30 kPa	Simulate dry placement

4 MODEL RESULTS

4.1 1D Results

One dimensional SPA modelling was initially completed to calibrate material properties to temperatures measured by thermistor RSF-3 at the Portage WRSF at the nearby Meadowbank mine.

4.1.1 Preliminary Calibration to Portage Field Conditions

Observed temperature data from the Portage WRSF at Meadowbank was used to calibrate the model for the Whale Tail and IVR facilities. Initial conditions were based on the average temperature at the base of the thermistor string, approximately -1.8°C. Figure 4.1, shows the results of the modelled temperature results plotted against the observed temperatures from the RSF-3 thermistor at the Portage WRSF.

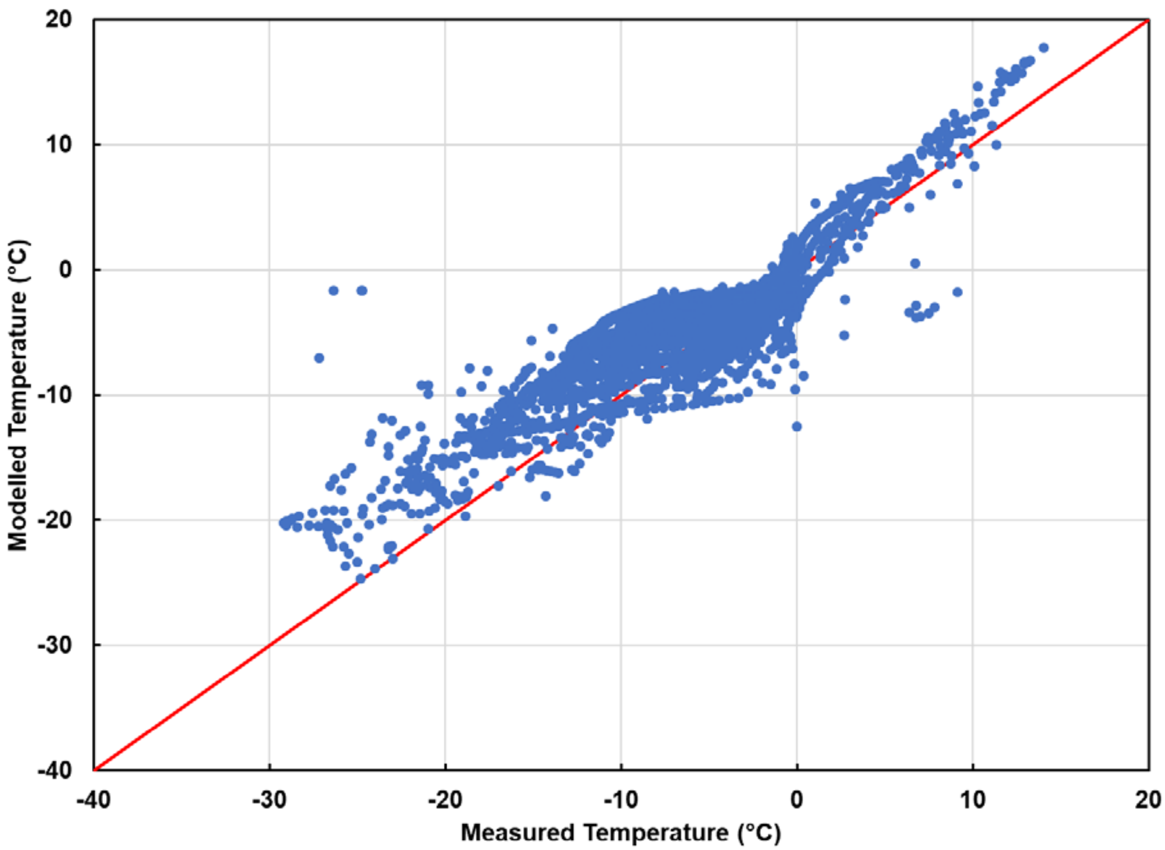

Figure 4.1 Calibration results of 1D modelling to measured temperatures at RSF-3 at Portage WRSF.

The results of the modelling show a strong correlation with the Portage observed data, with the exception of a few outliers, as most of the data points follow along the 1:1 (red) line.

4.2 2D Results

Following calibration of material properties, modelling of long-term 2D cross sections (Figure 3.1) was completed to develop freeze-back curves, thermal active layer depths and a landform water balance. A 150-year period (2018-2168) was modelled, including construction of the WRSF, using six-hour timesteps saved daily. The following sections summarize the results of the long-term 2D modelling.

4.2.1 Updated Conceptual Model

Examination of the modelling results yielded the confirmation of some aspects of the conceptual model and the requirement to update the conceptual model in others. The following summarizes the updated conceptual model of the hydrologic and thermal regime at the Whale Tail and IVR WRSFs:

- The existing proposed thermal cover system (4.7 m of NAG/NML material) does not promote runoff and interflow from the cover system due to sufficient infiltration capacity of the waste rock and cover system materials as a result of the coarser texture of materials.
- High infiltration rates during placement will result in the gradual formation of ice lenses deep within the pile along bench surfaces placed in summer.
- High infiltration into the active zone in the long-term will result in the formation of ice lenses below the active layer. Precipitation from multiple years will infiltrate and freeze-back, gradually forming ice lenses. Interflow along the slopes of the WRSF (within the WRSF cover system or waste rock), generally re-infiltrates deeper into the WRSF in discontinuous zones of the ice lenses discussed above.
- Any interflow from the thermal cover system is not expected to report to collection ponds as ‘plug flow’ as was implied in the previous model due to the variance in transit times across the landform and the propensity of interflow to re-infiltrate. Put simply, incident precipitation on the lower bench of the WRSF may report to water collection systems while precipitation which lands on the remainder of the landform will infiltrate. Any contaminants of potential concern present within the thermal cover system material (e.g. arsenic), will therefore also be released gradually.
- The WRSF can be expected to freeze back within the center of the pile in the first lift of waste rock in 15 to 20 years. Until this time, the non-frozen waste rock at depth is expected to be hydraulically encapsulated by frozen areas surrounding the non-frozen areas. These variations are due to differing pile geometry.
- The existence of ice lenses along the slopes of the WRSF results in three separate gas and heat flow patterns:

a) Discontinuous zones within the ice lenses formed along the slope and along the benches of the WRSF result in preferential gas pathways that promote convective cooling at depth and venting of warmer air through the plateau of the WRSF.

b) Similarly, smaller convective cooling cells form along each bench slope, resulting in venting of warmer air through the flat area of each bench.

c) Lastly, the formation of discontinuous ice lenses parallel to the slope of the WRSF forms shallow preferential gas transport pathways along the slope of each bench along the WRSF.

The three distinct gas and heat flow patterns are shown conceptually in Figure 4.2 where the ice lenses are shown as zones of high saturation.

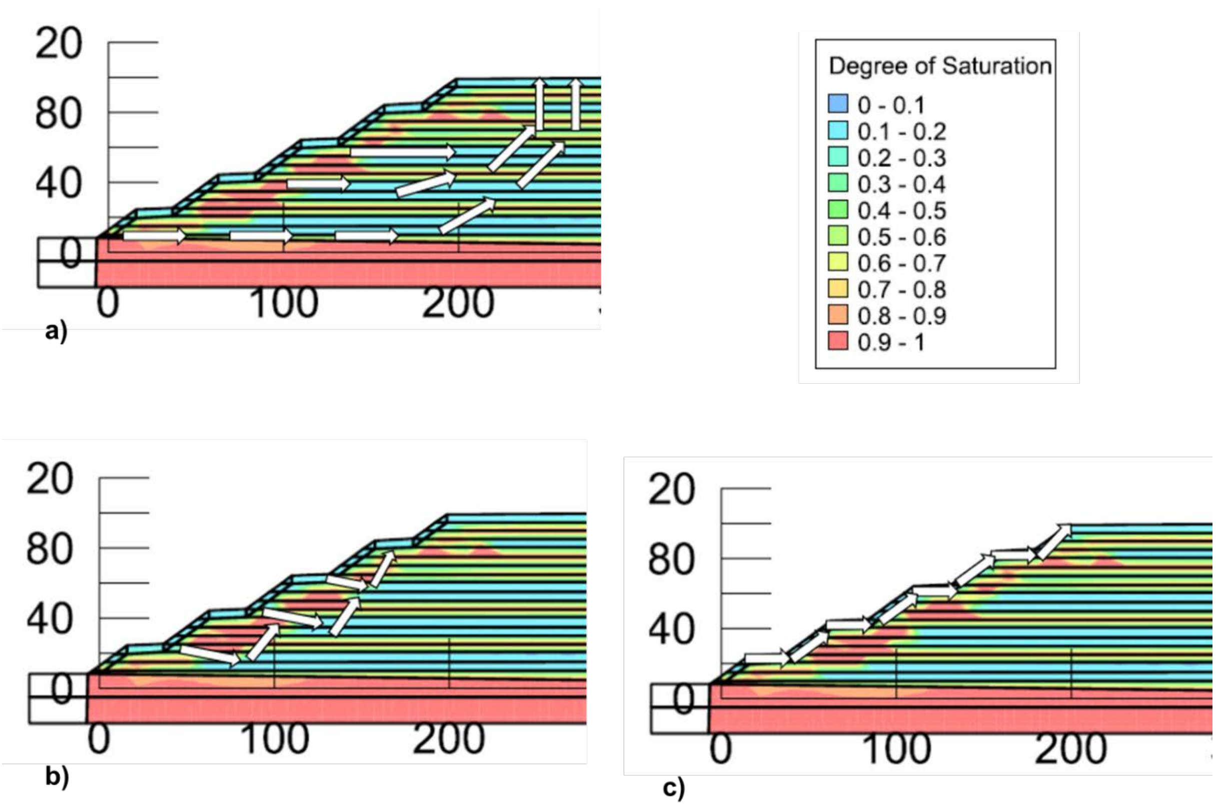

Figure 4.2: Sketch of typical gas flow patterns in the Whale Tail WRSF a) deep convective cooling, b) shallow convective cooling, and c) shallow surface airflow, indicating the degree of water saturation.

4.2.2 Freeze-back Curves

Typical freeze-back curves were developed for depths beyond the influence of annual climatic variability. Along northern slope aspects, freeze-back of waste rock placed in the summer can be expected to occur within approximately three years, while along southern aspects, freeze-back can be expected to take up to five years (Figure 4.3). At depth within the pile, freeze-back is highly dependent upon pile width. For Section B, freeze-back at depth may occur in less than 10 years, while for wider sections (for example Section C), freeze-back at depth may take up to 25 years.

Along the plateau of the WRSF, freeze-back times are more variable than along the slopes. This is partly due to the difference in proximity to the edge the outside of the WRSF. For example, the mid-point of the plateau of Section B is more susceptible to convective heating and cooling than Section C. The formation of ice lenses deep within the WRSF along waste rock placed in summer have a substantial effect on the convective air flow paths. These ice lenses form from one season of precipitation that infiltrates before the layer freezes-back. If modelling results are selected along a preferential convective 'vent' along the plateau (Figure 4.2 a)), then freeze-back can be delayed as warmer air is forced upwards (Figure 4.4). In practice, the large convective cells are likely to form where zones of coarser-textured waste rock are inter-connected forming natural vents for preferential air movement.

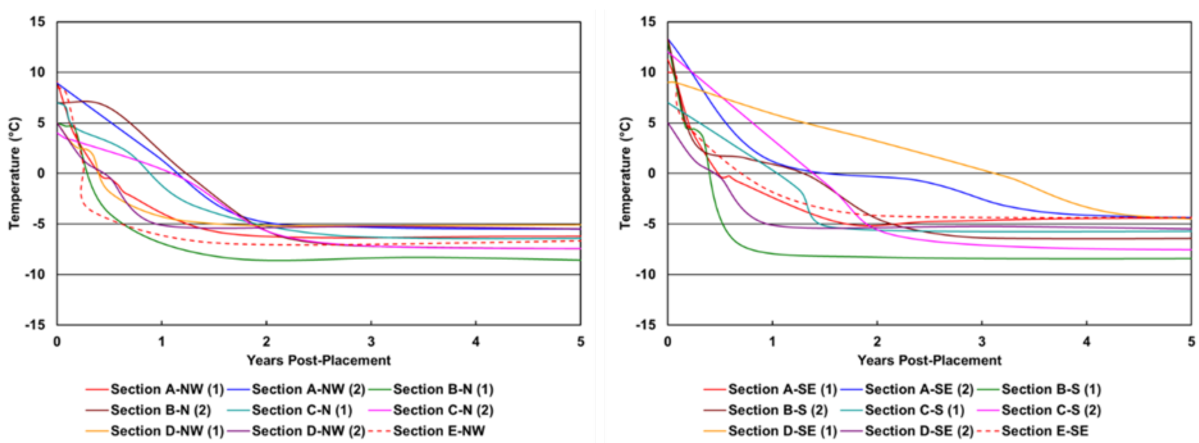

Figure 4.3: Typical freeze back curves in waste rock for north (left) and south (right) slopes at a depth of 7 m below the cover system surface.

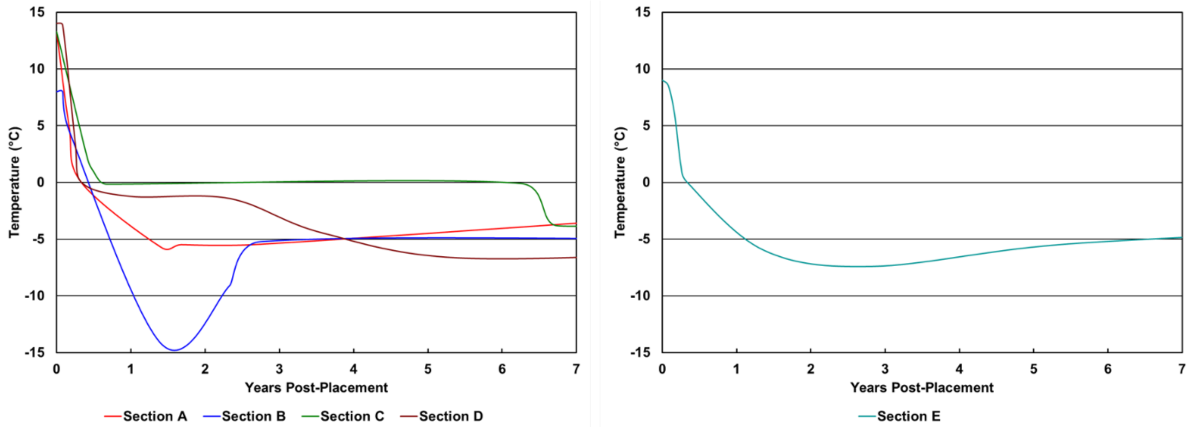

Figure 4.4: Typical freeze back curves in waste rock along the plateau at a depth of 39 m (left) and 18 m (right) below the cover system surface.

4.2.3 Active Thermal Layer Depth

The thermal modelling of Section A indicated an active layer greater than the proposed base case 4.7 m cover. The increase in thermally active depth compared to previous modelling is a result of the inclusion of gas transport mechanisms to the modelling. The formation of ice lenses (Section 4.2.1) results in two separate warming mechanisms occurring near surface. Warming from above, as a result of climatic forcing, is the primary driver of near-surface thaw. Secondarily, shallow convective cooling drives warmer air deeper into the pile in the fall when surface temperatures are decreasing in zones where the ice layer is discontinuous. This results in pore-air entrapment disconnected from the annual thaw zone along the margins of ice lenses which have saturated or near-saturated conditions and therefore reduced air permeability. The very low air permeability barrier (ice lenses) result in pockets of thaw beyond the depth of the thermal cover system throughout the WRSF long-term. The following figures (Figure 4.6 to Figure 4.8) illustrate average long-term near surface thermal conditions for Section A at several locations along the slope and the plateau area (Figure 4.5) between 2093 and 2118. Average long-term near surface thermal conditions for IVR Section D are shown in Figure 4.9 to Figure 4.11. Sections B to E in Whale Tail an IVR exhibited similar trends in temperature regardless of slope aspect.

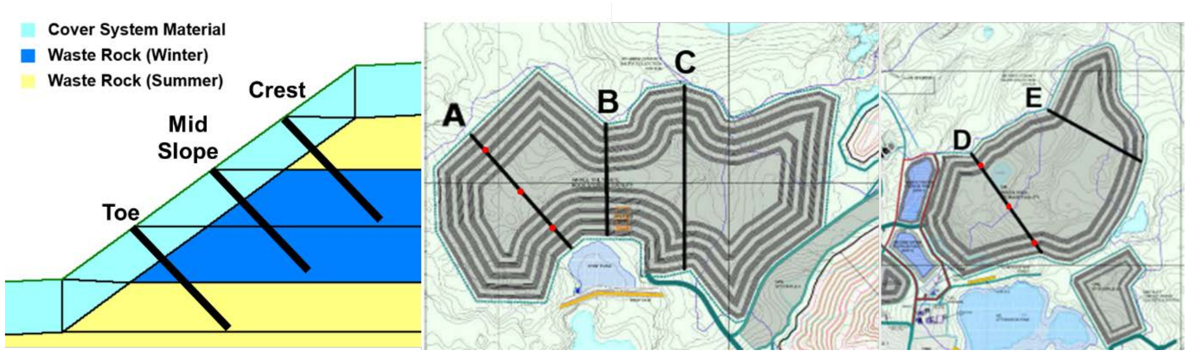

Figure 4.5: Plan and section view of the typical thermal locations rendered below. The colours on the section view indicate the material and placement timing.

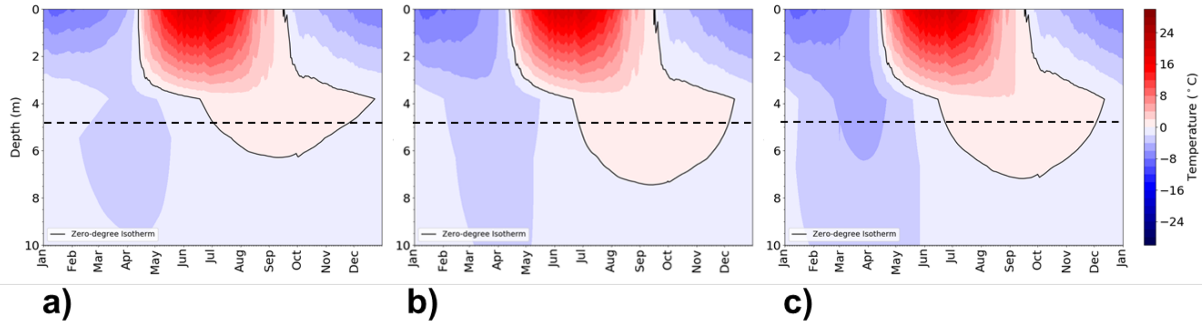

Figure 4.6: Annual long term near surface temperature along the NW slope of Section A and the a) crest, b) mid slope, and c) toe location with the proposed cover system interface shown by the black dashed line.

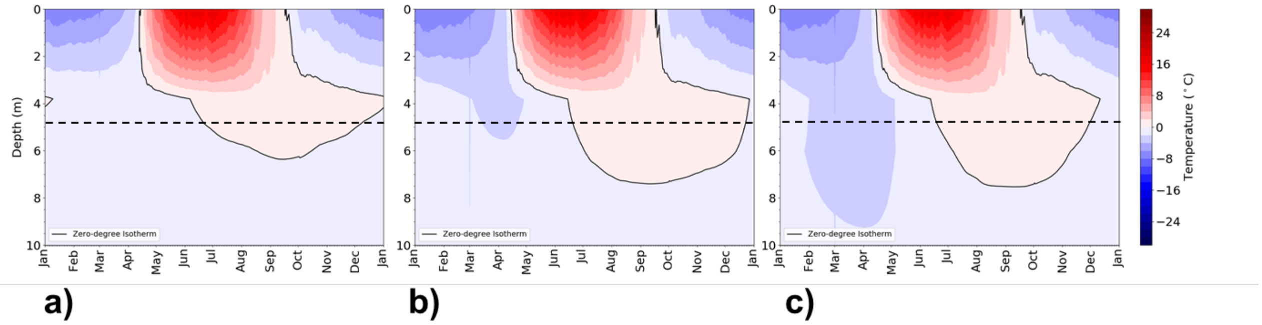

Figure 4.7: Annual long term near surface temperature along the SE slope of Section A and the a) crest, b) mid slope, and c) toe location with the proposed cover system interface shown by the black dashed line.

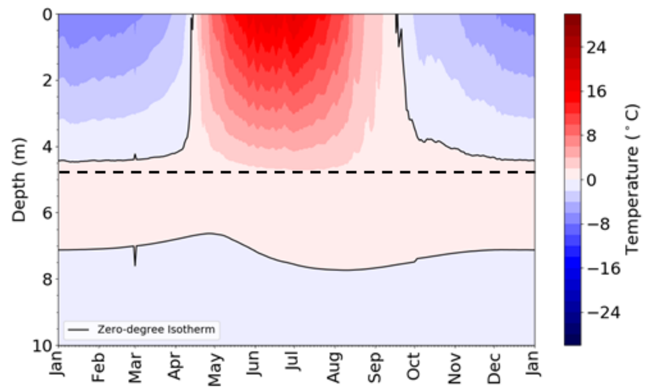

Figure 4.8: Annual long term near surface temperature along the plateau of Section A with the proposed cover system interface shown by the black dashed line.

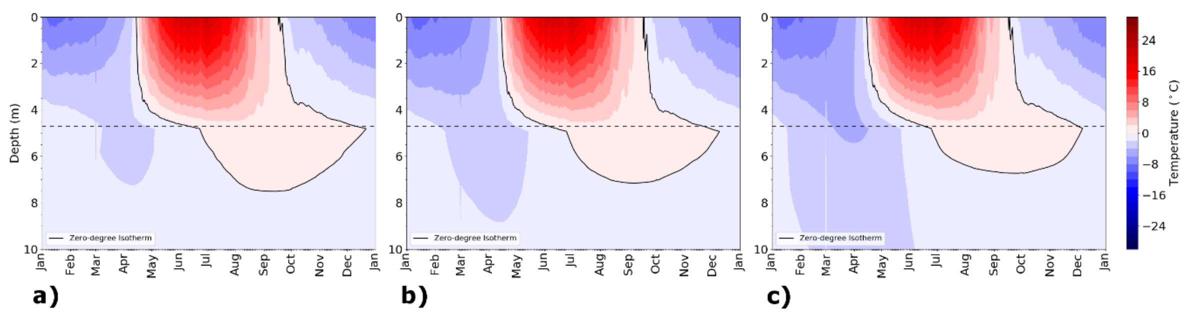

Figure 4.9: Annual long term near surface temperature along the NW slope of Section D and the a) crest, b) mid slope, and c) toe location with the proposed cover system interface shown by the black dashed line.

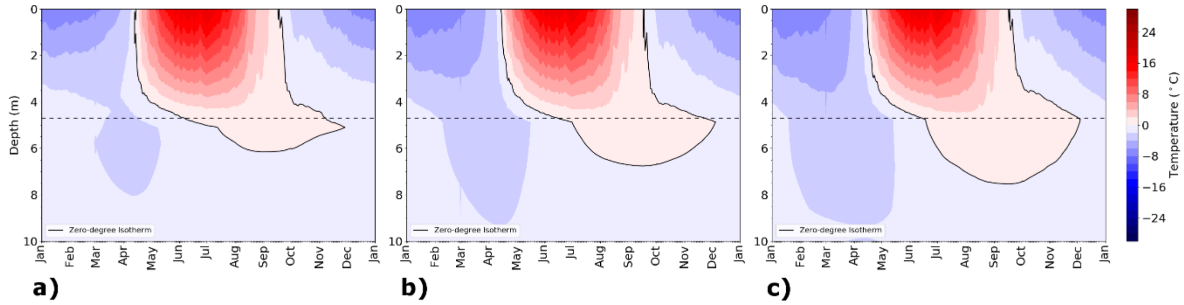

Figure 4.10: Annual long term near surface temperature along the SE slope of Section D and the a) crest, b) mid slope, and c) toe location with the proposed cover system interface shown by the black dashed line.

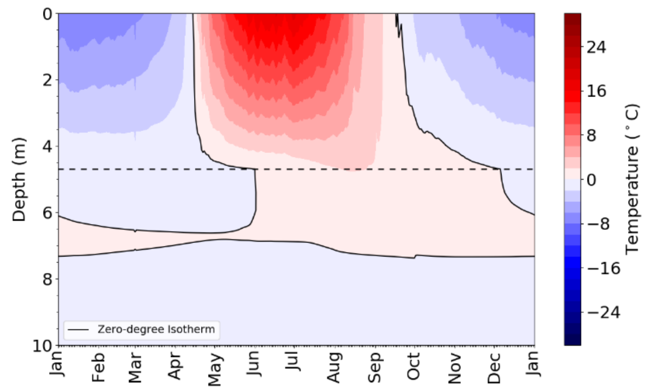

Figure 4.11: Annual long term near surface temperature along the plateau of Section D with the proposed cover system interface shown by the black dashed line.

The primary mechanism responsible for thaw, annual climate cycling, is constrained to the cover system. This is relatively consistent with previous thermal modelling work (Golder, 2018b) completed to date. The effect of annual climate cycling is loosely represented by the contours greater than 2°C (contoured 'bulb' occurring between late April and September). The secondary thaw mechanism, heat re-distribution due to gas movement, is a by-product of heat trapped within the WRSF due to the presence of ice lenses.

While the thermal regime is governed by two separate mechanisms, annual climate cycling and pore-air entrapment along ice lenses, the hydrologic regime must be accounted for to fully understand the effect of the depth of thaw on cover system performance. Figure 4.9 compares the unfrozen volumetric water content, or the portion of pore water available to be mobilized, compared to thaw depth at the same location. Figure 4.9 illustrates that the warming caused by pore-air entrapment does not equate the mobilization of water through the WRSF. For very low volumetric water content (less than 0.05 cm^3/cm^3), the hydraulic conductivity of the waste rock material is less that 1×10^{-7} cm/s. This very low hydraulic conductivity limits the movement of moisture in the thawed zone below to cover system to the range of 5 cm/year.

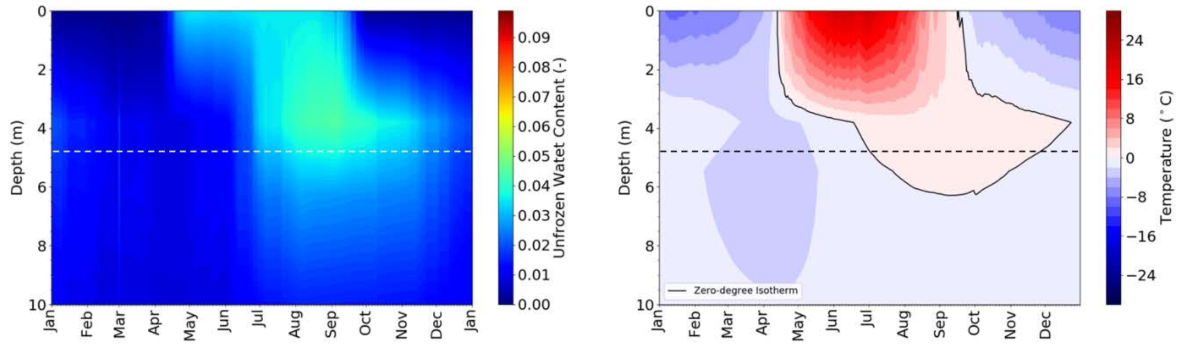

Figure 4.12: Annual long term near surface unfrozen volumetric water content (left) and temperature (right) along the NW slope of Section A at the crest location with the proposed cover system interface shown by the white and black dashed lines respectively.

4.2.4 Landform Water Balance

A landform water balance was completed to aid in the thermal modelling of the Whale Tail and IVR WRSFs. This work included estimates of runoff, interflow, and basal seepage rates for different slopes and aspects of the WRSF.

Table 4.1 summarizes the hydrologic regime at the Whale Tail and IVR WRSFs.

Table 4.1: Runoff distribution by month for the Whale Tail and IVR WRSF.

Month	Percent of Total Annual Runoff by Month (%)
January	0%
February	0%
March	0%
April	0%
May	0%
June	85-90%
July	5-10%
August	5-10%
September	<5%
October	0%
November	0%
December	0%

The SE aspect is expected to receive higher net radiation than the NE or Plateau, resulting in greater evaporation, soil heating, and sublimation. The increased evaporation will also reduce the amount of water available to runoff and/or infiltrate. The surface water balance for the different aspects of the WRSF is provided in Table 4.2.

Table 4.2: Summary of average surface water balance for different aspects of the WRSF

Water Balance Parameters	Plateau	SE Aspect	NW Aspect
Total Precipitation (mm)	296 mm	296 mm	296 mm
Rainfall (% of Total Precipitation)	55-60%	55-60%	55-60%
Snow (% of Total Precipitation)	40-45%	40-45%	40-45%
Actual Evaporation (% of Total Precipitation)	25-30%	30-35%	25-30%
Runoff (% of Total Precipitation)	<5%	<5%	10-15%
Net Percolation (% of Total Precipitation)	30-35%	25-30%	20-25%
Sublimation (% of Total Precipitation)	35-40%	40-45%	40-45%

Basal seepage from the landform is negligible as the base layer of the WRSF is consistently frozen from the time of placement and net percolation, flowing vertically through the WRSF, freezes back at depth.

There is some interflow within the cover system on the slopes of the WRSF, between May and June, due to the vertical infiltration along the toe of each bench of the WRSF. However, the only precipitation expected to exit the landform as interflow occurs along the lowest bench of the WRSF.

4.2.5 Sensitivity Scenarios

In an effort to capture the inherent variability of the WRSF, several sensitivity scenarios were modelled. These included:

- the effect of aspect on thermal and hydrological regime;
- the effect of cover system material texture on thermal and hydrological regime; and
- the effect of bench height on thermal and hydrological regime.

4.2.5.1 Effect of Aspect

No observable effect to the thermal regime in terms of depth of thaw was realized through modelling Section A to E. However, freeze-back was predicted to take longer along southern aspects than northern aspects. In terms of the hydrological regime, changing slope aspect resulted in changes to the surface water balance. Long term average runoff tended to be greater along northerly aspects (10% to 15% of total annual precipitation), compared to southerly aspects (<5% of total annual precipitation), due to decreased evaporation and net radiation. Aspect was not found to have a consistent effect of the volume of interflow observed exiting the WRSF as interflow was <1% of total annual precipitation for all aspects.

4.2.5.2 Effect of Material Texture

The effect of material texture on the depth of the active layer in shown below (Figure 4.10). Finer-textured cover system material increases the depth of thaw occurring due to annual climatic cycling but reduces the overall depth of thaw that occurs from shallow surface airflow and shallow convective cooling. The finer-textured cover material results in more precipitation being retained in the pore space of the cover system material (versus infiltrating deeper into the WRSF) compared to the base case. The higher proportion of pore space occupied by water versus air increases the thermal conductivity of the cover system materials, increasing the rate at which the cover system thaws and cools in response to climatic forcing.

Conversely, air permeability of finer-textured material is lower compared to the base case, resulting in a reduced capacity for convective cooling and shallow surface airflow. The net effect is that the ice lenses which cause pore-air entrapment move further into the pile, which allows heat to dissipate in the fall, unlike the base case.

It is unlikely that the cover system material will be coarser than the original material texture estimates. However, a coarser-textured cover system results in more propagation of heat through convective flow in August to November, increasing the overall depth of thaw. There is the potential that weathering of the cover system material will result in an overall finer texture occurring over time, however based on lithology, the cover system rock is less likely to break down compared to Portage (Greywacke vs. ultramafic).

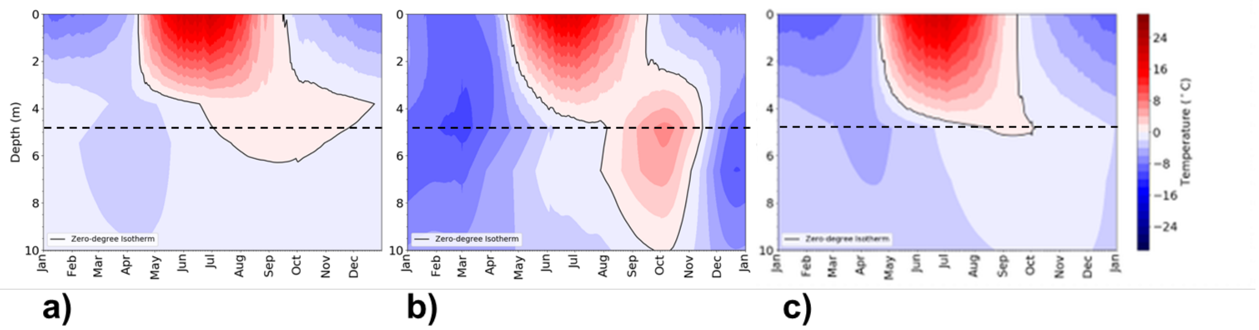

Figure 4.13: Annual long term near surface temperature along the NW slope of Section A at the crest location for a) base case conditions, b) coarser-textured cover system material, and c) finer-textured cover system material with the proposed cover system interface shown by the black dashed line.

While cover system texture has a notable effect on the active layer of the WRSF, there was no notable effect on the timing of freeze-back or the volume of interflow expected to exit the WRSF as the finer-texture material maintains a high propensity for infiltration.

4.2.5.3 Effect of Increased Bench Height

The effect of bench height on the depth of the active layer in shown below (Figure 4.11). Increasing the bench height from 20 m to 30 m or 40 m did not have an effect of the overall depth of thaw mid slope. It appears annual climatic driven thaw reaches a greater depth as bench height increases. The deeper, pore-air entrapment thaw that occurs in the fall appears to behave similarly for all bench heights. This is consistent with the shallow air flow conceptual model, as the existence of ice lenses result in pore-air entrapment and the ice lenses are located at a similar depth for all bench heights modelled. The formation of ice lenses below the active zone is a result of infiltration creating zones of high saturation which freeze in the winter and is commonly observed in permafrost environments (Pipkin, 1994).

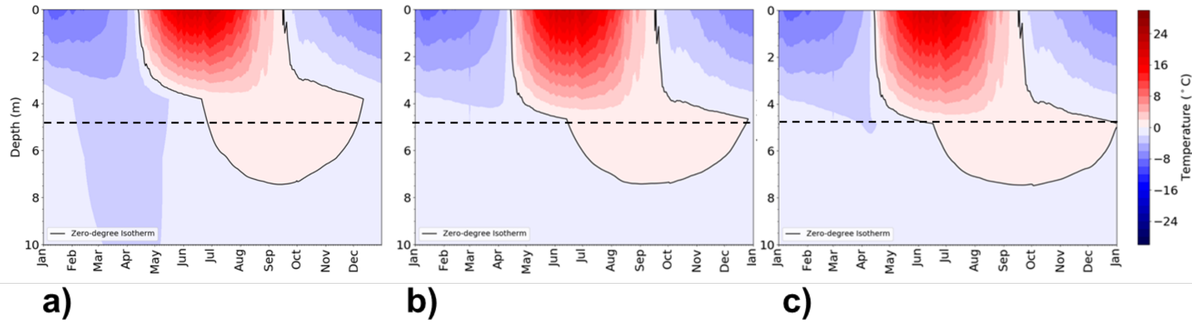

Figure 4.14: Annual long term near surface temperature along the NW slope of Section A at the mid slope location for a) base case conditions, b) 30 m bench height, and c) 40 m bench height with the proposed cover system interface shown by the black dashed line.

There was no notable effect on the timing of freeze-back curves or the volume of interflow expected to exit the WRSF based on increasing the height of the WRSF benches.

4.3 Temporary Ore Stockpile Assessment

The model results can be used to qualitatively estimate the thermal and hydraulic regime within the temporary ore stockpiles. The applicability of these results is dependent upon the assumed geometry and material properties of the ore stockpiles. For this qualitative assessment, it was assumed that the geometry of the ore stockpiles would be similar to the Whale Tail and IVR WRSFs and the geometry specified in Agnico Eagle (2018c). If the ore is assumed to have similar material properties as the waste rock, the model results can be qualitatively applied to the ore stockpiles.

The temporary ore stockpiles will be smaller than the WRSF, with a maximum height of approximately 15 to 20 m, based on the calculated footprints and predicted ore tonnage. These smaller stockpiles are therefore more likely to exhibit the behaviour of the thinner sections of the IVR WRSF where only two lifts are placed. The influence of convection, both for freezing and thawing, is likely to be greater in the ore stockpiles due to their smaller footprint and height. However, the proposed 5 m lifts would limit the side slope surface area available for convective inflow.

During the first three years (2019 to 2021), prior to any ore being removed from the stockpiles, approximately 60% of the ore is placed during Q2 and Q3, where the model assumes a positive placement temperature. This will likely lengthen the freeze-back timing of the stockpile, as the majority of the material will have to freeze-back, as opposed to being placed in a frozen state. Starting in Q4 2021, ore will be continuously removed from the stockpiles until Q2 2023, when ore will start to be added back. This period of removal will expose inner areas of the stockpile to annual climatic cycling, potentially altering their frozen condition and deepening the active layer. From Q2 2023 to Q4 2024, ore is added to the stockpiles. During this time, approximately 80% of the ore is placed during Q1 and Q4, where the placement temperature is below zero. The majority of the ore stockpile is likely to be frozen during this period. From Q1 2025 onward, ore is removed until the stockpiles are completely depleted.

5 DISCUSSION AND RECOMMENDATIONS

The ultimate objective of the seepage and thermal modelling is to demonstrate the chemical stability of the Whale Tail and IVR WRSFs while optimizing risk and cost for Agnico Eagle. The risk being optimized in this study is based on meeting or not meeting acceptable receiver water quality. The term 'risk' encompasses both the concepts of likelihood of failure and the severity of the expected consequences if failure were to occur (Figure 5.1). In the context of this thermal modelling assessment, failure of the WRSF cover system is defined as unacceptable receiver water quality as a result of load from seepage, runoff, or interflow from the WRSF. The thermal assessment of the WRSF is limited to commenting on the likelihood of this risk occurring based on the likelihood of both *production and mobilization* of ML/ARD products. The severity of consequence of failure of the thermal cover system will be assessed separately through a site wide load balance.

		Consequence Severity				
		Insignificant (I)	Minor (Mi)	Moderate (Mo)	Major (M)	Catastrophic (C)
Probability	Very High (VH)	Medium	Medium	High	Very High	Very High
	High (H)	Low	Moderate	High	High	Very High
	Moderate (M)	Low	Moderate	Medium	High	High
	Low (L)	Low	Low	Moderate	Medium	Medium
	Very Low (VL)	Low	Low	Low	Low	Medium

Figure 5.1: Agnico Eagle's risk matrix for derivation of risk ranking.

Given a total depth of thaw beyond the cover depth, OKC would rank the likelihood of production of ML/ARD products as moderate in the surficial waste rock material. Previous definitions of likelihood produced by Agnico Eagle define 'moderate' likelihood as "a similar outcome has arisen at some time previously in local operations" (OKC, 2019a). The 'moderate' ranking is based on the expected volume of waste rock subject to thawing, the decreased pyrite oxidation rates at near freezing temperatures, as well as the proportion of waste rock estimated to be PAG/ML.

The likelihood of mobilization of any ML/ARD products must also be considered. Given the hydrologic regime of the WRSF confirmed by modelling, OKC classifies the risk of seepage from waste rock exiting the WRSF and reaching the receiver as moderate for the lowest bench of the WRSF only, and very low for the remainder of the WRSF landforms. A very low likelihood indicates "No experience of this happening in the broader worldwide industry but is theoretically possible" (OKC, 2019a).

Given these classifications of likelihood, should the consequence of unacceptable receiver water quality as a result of load from the WRSF be catastrophic, the risk could be classified at 'High' for the lower slopes of the WRSF and 'Moderate' for the remainder of the WRSF. These risks should be verified by Agnico Eagle to ensure that the likelihoods provided herein are consistent with Agnico Eagle's risk profile.

		Consequence Severity				
		Insignificant (I)	*Minor (Mi)*	*Moderate (Mo)*	*Major (M)*	*Catastrophic (C)*
Probability	*Very High (VH)*	Medium	Medium	High	Very High	Very High
	High (H)	Low	Moderate	High	High	Very High
	Moderate (M)	Low	Moderate	Medium	High	High
	Low (L)	Low	Low	Moderate	Medium	Medium
	Very Low (VL)	Low	Low	Low	Low	Medium

Figure 5.2: Agnico Eagle's risk matrix for derivation of risk ranking with OKC's risk ranking for unacceptable receiver water quality as a result of load from the WRSF at the lower bench of the WRSFs shown in red, and the remainder of the WRSFs shown in blue.

Based on the thermal and hydrologic regime described by the thermal modelling program, as well as the assumed likelihood of risk associated with the proposed thermal cover system, OKC recommends the following mitigation measures for the proposed thermal cover system.

- Based on OKC's definition and interpretation of the likelihood of risk, the overall risk of the proposed cover system is expected to be acceptable (moderate or less). As a result, OKC does not recommend a design change to increase the thickness of the cover system beyond 4.7 m. The interpretation of likelihood should be confirmed internally by Agnico Eagle and results of the thermal assessment should be incorporated into the existing site-wide load balance to confirm the consequence severity.

- Should Agnico Eagle consider the likelihood of risk to be higher, or the consequence severity found to be major or catastrophic as a result of the site-wide load balance, OKC recommends that targeted improvements to the cover system design be made.

- Agnico Eagle should consider monitoring freeze-back along the lowest bench of the WRSF in waste rock that is placed unfrozen. Monitoring freeze-back will allow the performance of the cover system to be confirmed during the construction period as freeze-back curves near surface should occur within approximately three to five years (Figure 4.3 and Figure 4.4). This should provide sufficient time to implement adaptive management strategies during the life of mine.

- Agnico Eagle should consider *in situ* monitoring to refine material properties, particularly thermal conductivity, air permeability, and hydraulic conductivity of both waste rock and cover system material. As changes in material properties have a considerable effect on the thermal, hydrologic, and gas flow regime, developing site-calibrated material properties will improve confidence in the performance of the cover system, particularly in terms of confirming heat re-distribution resulting in deeper thaw depths than previously predicted. Should this phenomenon be confirmed *in situ* during the initial stages of construction, targeted adaptive management strategies can be implemented to mitigate this risk.

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Appendix A

Conceptual Model for Thermal Modelling of Whale Tail and IVR WRSFs

O'Kane Consultants

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Memorandum

To: Michel Groleau – Nunavut Permitting Lead, Agnico Eagle Mines Ltd.

From: Robert Shurniak, Numerical Modelling Group Leader

Cc: Jenyfer Mosquera – Agnico Eagle Mines Ltd.

Our ref: 948-011-M-004 Rev 1

Date: February 19, 2019

Re: **Agnico Eagle Mines Ltd. Whale Tail Mine Site - Conceptual Model for Thermal Modelling of Whale Tail and IVR WRSFs**

Agnico Eagle Mines Limited – Meadowbank Division (AEM) is proposing to develop the Whale Tail Pit Project to continue mine operations and milling at Meadowbank Mine located in the Kivalliq Region of Nunavut. The Amaruq property is a 408 km^2 site located on Inuit Owned Land approximately 150 km north of the hamlet of Baker Lake, and approximately 50 km northwest of Meadowbank Mine, in the Kivalliq Region of Nunavut. The Amaruq site is located in a region of continuous permafrost where the average daily temperature is approximately -11.3°C. The mean annual total precipitation is approximately 330 mm, with about 170 mm falling as rain and 160 mm falling as snow[1].

Project Understanding

The deposit is planned to be mined as an open pit (i.e., Whale Tail Pit), and ore will be hauled to Meadowbank Mine for milling. The planned project involves: one year of construction, three years of mine operation, eight years of closure-related activities, and the post-closure period. The Whale Tail Phase 1 and 2, and IVR WRSFs are located north-west and north-east, respectively, of the open pit. Waste rock and overburden will be trucked to the WRSFs throughout mine operations. The current plan for WRSF construction incorporates 20-m high benches composed of four 5-m thick lifts. Each bench toe will start at a setback distance of 20 m from the crest of the previous bench to form an overall side slope of 2.5H:1V[1]. However, recent geotechnical analyses have indicated that the maximum bench height is 40 m with a set-back of 20m[2]. It is understood that this design change is under consideration by AEM. WRSF construction on permafrost is expected to increase temperatures gradually in the upper permafrost zone, but the WRSF itself is expected to freeze back over time and have an active layer formed on the upper portion. A near surface active layer (zone) will exist, and it is anticipated climate change will extend the depth of the active layer in the pile; however, the thick WRSF will constitute a protection to the underlying permafrost. If heat generation occurs associated with the oxidation of sulphide-bearing minerals within the WRSFs, the process of freeze-back could be delayed and, depending on the location of the heat generation source, the upper portion of the permafrost foundation could be impacted.

[1] AEM, 2018. Whale Tail Pit Project – Thermal Monitoring Plan. Version 1. May 2018
[2] SNC Lavalin, 2018. Stability Analyses of the Waste Rock Storage Facility Rev.PB. December 18, 2019.

There are six major bedrock types found at Whale Tail deposit. Variable thicknesses of overburden and lake sediments are also present, which will be removed upon mining[3]. Based on available test data, the diorite and south greywacke bedrock materials, which are both non-acid generating (NAG) and non-metal leaching (NML), represent approximately 17% of the waste rock to be mined from the open pit and can be used as cover material for WRSFs[4]. A closure cover system (thermal cover) will be added (when practical as part of a progressive reclamation program) on the slopes and top surface of the WRSFs to encapsulate the potentially acid generating / metal leaching (PAG/ML) waste rock. The intent of the cover system is three-fold:

- contain the yearly active layer inside the thickness of the cover;
- control acid generating reactions by maintaining a temperature below 0°C for the underlying PAG/ML waste rock; and
- control mobilization of PAG/ML products by maintaining frozen conditions within the WRSF.

thereby ensuring that the overarching closure objectives are achieved. Specifically, the closure objective that water quality in the receiving environment be protected within permitted conditions.

The Portage WRSF at the Meadowbank mine site is a fully constructed WRSF with a 4.0 m NPAG cover encapsulating PAG waste rock. Portage WRSF is instrumented with several thermistor strings that have been functioning for the past three to six years. The available data and the experience from designing, modelling and constructing the WRSF allows Portage WRSF to act as a proxy for the Whale Tail and IVR WRSFs.

Previous modelling and monitoring efforts of the Portage WRSF and the Whale Tail WRSFs have resulted in the development of a current cover system design for the Whale Tail WRSF consisting of a 4.7 m thermal cover of NAG/NML material. A failure modes and effects analysis (FMEA) of the Whale Tail WRSF indicated that several higher risk failure modes have not been addressed by previous modelling and monitoring efforts. The failure modes having the highest risks were generally related to numerical modelling and model inputs, slope aspect effects, higher unrecoverable seepage rates, longer freeze-back time of the WRSF, timing of arsenic release, and performance monitoring data. The conceptual model of performance of the Whale Tail WRSF, and subsequent numerical modelling, specifically addresses some of the higher risk failure modes identified in the FMEA, in an effort to demonstrate physical and chemical stability of the WRSF.

This memorandum begins with a summary of the current conceptual model based on OKC's current understanding of the objectives of the thermal modelling project, descriptions of the modelling software packages, thermal modelling concepts and filters, and summarizes the proposed approach to the thermal modelling.

[3] AEM, 2018. Operational ARD-ML Sampling and Testing Plan – Whale Tail Pit Addendum. Version 2. June.
[4] AEM, 2018. Whale Tail Pit – Waste Rock Management Plan. Version 3. September.

Conceptual Model

A review of available data from Meadowbank Portage WRSF can be used to inform, constrain and calibrate the Whale Tail thermal modelling. Initial review of the information regarding the thermal conditions and previous modelling efforts at Meadowbank and Whale Tail indicate:

- The Portage WRSF has not frozen completely.
- The top 3 to 4 m of the WRSF thaw during the summer, but it is anticipated that this active layer (i.e. the depth at the surface of the WRSF that does not form permafrost (stay below 0°C)) will decrease in thickness once permafrost has fully formed within the WRSF.
- The active zone extends below the cover on both north and south slopes, contrary to expected behaviour.
- The previous modelling effort completed for Whale Tail[5] recommended a thermal cover 4.7 m thick, which estimated freeze back of the WRSFs approximately 25 years after closure.

The following statements form the conceptual model for thermal behaviour of the Whale Tail and IVR WRSFs under current and future climate conditions. The conceptual model is based on available documentation and monitoring data gathered since construction of the Meadowbank Portage WRSF and available data from the Amaruq mine site.

1) The base case assumes that average annual temperature at Whale Tail will increase 3.06 °C by 2070 based on Representative Concentration Pathways (RCP) 6.0.
    - The anticipated rise in average annual temperature are likely to increase the potential for a thicker active layer.
2) The base case assumes that average annual precipitation at Whale Tail will increase 31 mm by 2070 based on RCP 6.0.
    - The anticipated rise in average annual precipitation is likely to increase the potential for a thicker active layer.
3) Slopes are expected to be more susceptible to infiltration entering waste rock prior to freeze back.
    - Based on initial wind and solar radiation analyses, it is anticipated that the northwest corner and north slopes of the WRSFs will have the coolest conditions and thinnest active zone. The next-coolest regions of the WRSFs will be the western slopes, followed by the eastern slopes. The south slopes are anticipated to be the areas with the highest potential for a thicker active layer.
4) Cover system material (NAG/NML) is expected to experience less weathering compared to Portage (increase in fines) due to lithology (greywacke vs. ultramafic).

[5] Golder Associates, 2017. Technical Memorandum – Commitment 39: Whale Tail Pit Project Waste Rock Storage Facility Cover Thermal Assessment. July 10.

- Interflow and/or basal flow reporting to WRSF collection ponds will increase gradually (over several years) as the WRSF is constructed and reaches steady-state. The existing proposed thermal cover system (4.7 m of NAG/NML material) is not expected to promote runoff / interflow from the cover system due to sufficient infiltration capacity of the waste rock and cover system materials as a result of the expected very coarse texture of materials.

5) The thermal and hydrologic regimes are expected to be different based on North and South aspect.

   - Refer to 3).

6) Reactivity of the IVR waste rock is expected to be greater than at WT.

   - Internal heating due to exothermic sulphide oxidation reactions could influence the thermal regime and delay the onset of freeze back of the WRSFs.

7) Decreased reactivity in NAG waste rock is expected to result in decreased arsenic load generation (but not zero load generation).

   - Any interflow / runoff from the thermal cover system is not expected to report to collection ponds as ‘plug flow’ due to the variance in transit times across the landform. Put simply, incident precipitation at the toe of the WRSF will report to collection ponds much sooner than precipitation which lands on the plateau of the landform. Any contaminants of potential concern present within the thermal cover system material (eg. Arsenic), will therefore also be released gradually.

8) Gradual decrease in arsenic loading over time is expected due to hydrology of WRSFs.

   - Refer to 7).

Objectives of Thermal Modelling Project

Thermal modelling of the WRSFs will assist in developing the expected seasonal active layer thickness under climate change conditions, as well as determine if permafrost conditions within the WRSFs are sustainable under climate change conditions. The ultimate objective of the project is to demonstrate the physical and chemical stability of the Whale Tail and IVR WRSFs while optimizing risk and cost for AEM. This overarching objective can be broken down and objectives defined for each component of the closure plan:

- contain the yearly active layer (i.e. the depth of material undergoing freeze-thaw cycling) within the thickness of the cover system profile;

- maintain frozen conditions within the waste rock, which will control generation and mobilization of PAG/ML products; and

- determine the time to freeze-back of the WRSFs and whether the PAG material remains frozen under predicted climate change scenarios. Freeze-back time is crucial to manage release of

PAG/ML within water draining from the base of the WRSFs into the underlying receiving environment.

Based on these objectives, the specific deliverables for the modelling program are expected to be:

1) estimated freeze-back 'curve' which will define the range of expected performance for freeze-back over time for the WRSF for different depths and aspects of the WRSF (if applicable);
2) maximum depth of the thermally active layer for different slopes and aspects of the WRSF (if applicable); and
3) runoff, interflow, and basal seepage rates for different slopes and aspects of the WRSF (if applicable)

The three specific deliverables outlined will achieve the following respectively, define monitoring 'triggers' for the existing WRSF adaptive management plan, confirm and/or optimize the existing 4.7 m thermal cover system design, and provide inputs to a site-wide water balance model to inform on long term water quality at Amaruq.

The modelling needs to account for climate change, slope aspects, dominant wind direction, range of material properties, oxidation reactions and all parameters that influence thermal conditions within the WRSF. These parameters are discussed in the following sections.

Description of Numerical Modelling Programs

GeoStudio Version 10[6] will be used to conduct the modelling for this project. This version of GeoStudio is a substantial upgrade to previous versions software as it is able to account for advective air flow as well as mineral oxidation within the WRSF and associated heat generations via an add-in module developed for the software. Four components of the GeoStudio suite of programs will be used in combination for this project: SEEP/W; TEMP/W; AIR/W, and CTRAN/W (with the oxidation and heat generation add-in incorporated into the CTRAN analysis).

SEEP/W is a 1D/2D finite element model that can be used to model the saturated and unsaturated movement of moisture and pore-water pressure distribution within porous materials such as soil and rock. The latest version of SEEP/W incorporates a module that allows for soil-plant-atmosphere (SPA) modelling that was previously included in a separate software package (VADOSE/W). This module calculates pressure head (suction) and temperature profiles in the material profile in response to climatic forcing (such as evaporation) and lower boundary conditions (such as a water table). A key feature of the module is the ability of the model to determine actual evaporation and transpiration based on potential evaporation and predicted suction, as opposed to the user being required to input these surface flux boundary conditions. The actual evapotranspiration rate is generally well below the potential rate during prolonged dry periods because the suction in the material profile increases as the surface desiccates. In addition, the module is a fully coupled (through the vapour pressure term) heat and mass transfer model, which is capable of predicting water vapour movement.

[6] GEOSLOPE, 2018. GeoStudio 2019. Online. https://www.geoslope.com

The SPA model of SEEP/W is also capable of evaluating the impact of frozen conditions on moisture storage and transport for a given soil or rock material. The change of phase from liquid to solid (i.e. water to ice) is accounted for using the apparent specific heat capacity approach, standard in thermal modelling. A heat source or sink is added at each time step based on the amount of heat released when a set volume of water changes to ice. When the ground becomes frozen, the permeability must be reduced. In the physics of freezing, there is a phenomenon whereby even in a saturated material, a "suction" develops at the ice-water interface much like that at the air-water interface in an unsaturated soil. If the temperature below freezing is known, then the suction can be computed using the Clausius Clapeyron phase equilibrium equation (Black and Tice, 1989). The SPA module does not account for this suction at the microscopic level in the mass transfer equation, but does use the actual temperature to compute what the suction should be so that the program can look up a reduced permeability from the material's hydraulic conductivity function (suction versus hydraulic conductivity). SEEP/W simulations can be completed with or without this functionality.

TEMP/W is a 1D/2D finite element model that can be used to model thermal changes in porous systems due to various changes in the environment, internal changes in temperature, or any other influencing condition that may result in a change of temperature in the subsurface. Typically, in a TEMP/W simulation, it is assumed that moisture content remains the same. However, when water movement occurs in a system, substantial heat transfer can occur as a result of this movement of water. As such, by coupling the TEMP/W simulation with a SEEP/W simulation, a more accurate temperature condition in the subsurface can be estimated.

AIR/W is a 2D finite element model that is executed within the SEEP/W model, which can be used to model air pressure and flow within a system in response to changes in pressure conditions at the boundary, or changes in water pressure. When coupled with TEMP/W, it can also calculate changes in air flow and pressure as a result of changes in air temperature.

CTRAN/W with the addition of the gas consumption and exothermic reactions add-in couples the gas, heat, water and air transfer processes to simulate the exothermic oxidation process. The add-in models the oxidation process as an irreversible first order reaction. The rate of reaction is dependent on and controlled by the availability of oxygen, as well as temperature. The add-in allows oxygen to be consumed and heat to be produced within the WRSF due to sulphide oxidation.

Thermal Modelling Concepts and Filters

Thermal modelling requires analyses of all site attributes that influence thermal conditions. This section will go through each of these filters for the Whale Tail and IVR WRSFs.

Climate

TEMP/W requires daily surface temperature data whereas SEEP/W and AIR/W require daily values of: maximum and minimum air temperature; maximum and minimum relative humidity (RH); average wind speed; daily net radiation; and precipitation (amount and duration). Historical values for all these parameters, except net radiation, are available from Environment and Climate Change Canada (2018)[7] for Baker Lake, approximately 150 km south of the Amaruq site. Solar radiation for Baker Lake is estimated

[7] Environment and Climate Change Canada, 2018. Data for Baker Lake. Online. http://climate.weather.gc.ca/index_e.html

by Environment and Climate Change Canada (2014)[8] in the Canadian Weather Energy and Engineering Datasets (CWEEDS) using the MAC3 model. This data will be used to estimate net radiation on a daily basis. Environment Canada has hourly records for Baker Lake from 1964 to present, of which the period August 1964 to November 2018 (excluding 1993) was used to create a historical 54-year database for the Whale Tail and IVR WRSFs project. Measurements from Baker Lake during 1993 were not included due to poor data quality that year. After comparing the climate data measured at Meadowbank from January 2012 to November 2018 to measurements taken at Baker Lake for the same period it was concluded that the Baker Lake data did not need to be adjusted to represent the Meadowbank site. Any missing data in the Baker Lake climate record were filled with average measurements for a given day.

Table 1 provides a summary of the average monthly conditions in the 54-year historical database developed for the Whale Tail project.

Table 1: Summary of average climate parameters for 54-year Amaruq historical climate database

Month	**Temperature (°C)**		**Relative Humidity (%)**		**Wind (m/s)**	**Net Radiation[1] (MJ/m2/day)**	**Precipitation**	
	Maximum	Minimum	Maximum	Minimum			(mm)	(days)
January	-28.0	-35.0	71.9	60.7	6.4	-2.0	8	27
February	-27.8	-35.0	70.8	60.2	6.3	-1.6	7	25
March	-22.6	-31.2	73.2	61.1	5.9	-0.6	11	22
April	-12.6	-22.0	81.2	67.9	5.9	4.1	16	20
May	-2.6	-9.8	89.7	75.5	5.5	7.1	15	21
June	9.0	0.5	89.8	61.8	4.8	8.9	22	14
July	16.8	6.2	88.6	52.3	4.6	8.9	37	13
August	14.3	5.4	91.8	58.6	5.0	5.6	42	18
September	6.2	-0.4	92.9	67.8	5.5	2.2	44	22
October	-3.7	-10.0	91.1	77.3	6.0	-0.4	30	24
November	-15.8	-23.2	81.0	68.2	6.1	-2.0	19	24
December	-23.5	-30.7	74.5	62.7	6.2	-2.2	11	25
Annual	-7.4	-15.3	83.1	64.6	5.7	2.4	262	255

1 Net radiation for a level location (e.g. the plateau of the WRSF)

A "synthetic average" climate year was defined by averaging daily climate conditions from the 54-year climate database (e.g. averaging the maximum temperature on January 1st for all 54 years). However, rainfall was not applied considering solely the daily average amount, but also the average number of rainfall events per month. Hence, rainfall was applied for the average number of rainfall days per month and on days with the highest chance of rainfall. The daily rainfall amounts for days with lower chances of rainfall were added to the next high-chance event in the month so that the synthetic average climate year had the average amount of rainfall.

The Amaruq site falls nearly at the intersection of ET (polar tundra) and Dfc (subarctic climate) classification of the Köppen-Geiger climate classification system where:

[8] Environment and Climate Change Canada, 2014. Data for Baker Lake. Online. http://climate.weather.gc.ca/prods_servs/engineering_e.html

- E – 'polar' where average temperature of the warmest month is < 10°C;
- T – 'tundra' where the average temperature of the warmest month is <10°C, but > 0°C
- D – 'continental' where average temperature of coolest month is < -3°C, and average temperature of warmest month > 10°C;
- f – 'without a dry season' where precipitation is relatively evenly distributed throughout the year; and
- c – 'cold summer' where one to three months average temperature reach < 22°C but> 10°C.

The 54-year historical database was adapted to account for climate change predictions over the next 150 years. This process is explained in the remainder of this section.

As part of the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5), the IPCC adopted new RCPs to replace the previous emission scenarios of the Special Report on Emission Scenarios (SRES)[9]. The four adopted RCPs differ from the SRES in that they represent greenhouse gas concentration trajectories, not emissions trajectories. The four scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) are named after the radiative target forcing level for 2100, which are based on the forcing of greenhouse gases and other agents and are relative to pre-industrial levels[10]. Climate at the Amaruq site is expected to remain within the subarctic (Dfc) climate category, described above, under the A1FI (former SRES emission scenarios) climate change scenario, which is similar to RCP 8.5 [11]. A 150-year climate change database for this project was developed using daily data under RCP8.5 and RCP4.5. Annual averages under RCP6.0 were developed for comparison. Brown and Caldeira (2017)[12] have shown that warming is likely to be greater than previously estimated; for example, RCP4.5 emissions are more likely to produce warming in line with RCP6.0. The global average temperature as of 2017 has already increased approximately 1.0°C over pre-industrial levels[13]. At the current trend, temperature is anticipated to rise 1.5°C over pre-industrial levels[13] between 2030 and 2052, keeping more in line with RCP8.5 than other scenarios. Figure 1 provides the concentration of all forcing agents (in parts per million (ppm) of CO2-equivalence) for the four RCP scenarios.

[9] IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.). Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA.

[10] Van Vuuren, D.P., Edmonds, J., Kainuma, M., Raihi, K., Thomson, A., Hibbard, K. Hurtt, G.C., Kram, T. Krey, V., Lamarque, J.F., et al. 2011. The representative concentration pathways: an overview. Climatic Change. Vol. 109.

[11] Rubel, F., and M. Kottek, 2010: Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification. *Meteorol. Z.*, **19**, 135-141.

[12] Brown, P.T. and Caldeira, K. 2017. Greater future global warming inferred from Earth's recent energy budget. Nature. DOI: 10.1038/nature24672

[13] IPCC. 2018. Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.). World Meteorological Organization, Geneva, Switzerland,

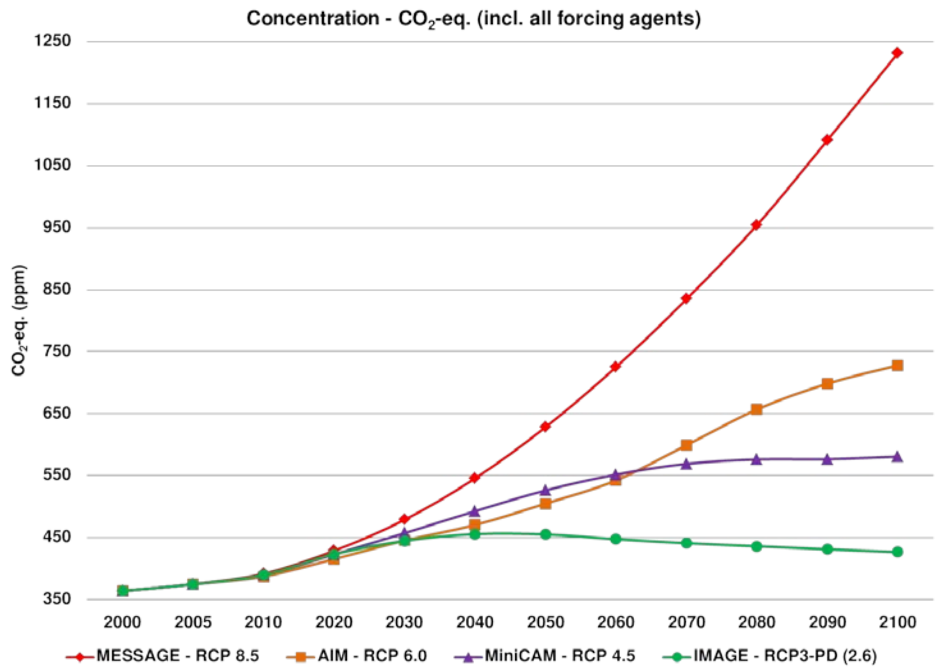

Figure 1: All forcing agents' atmospheric CO2-equivalent concentrations according to four RCP scenarios.

The climate change database for Amaruq was developed following the recommendations outlined on the Canadian Climate Data and Scenarios (CCDS) website, which is wholly supported by ECCC[14]. The website recommends the use of statistical downscaling to "downscale" a global circulation model's (GCM's) predictions to a specific location based on historical observations. Statistical downscaling is a two-step process consisting of i) development of statistical relationships between local climate variables (e.g., surface air temperature and precipitation) and large-scale predictors (e.g., pressure fields), and ii) application of such relationships to the output of GCM experiments to simulate local climate characteristics in the future. The Pacific Climate Impact Consortium (PCIC) at the University of Victoria provides statistically downscaled daily temperature and precipitation under the RCP2.6, RCP4.5 and RCP8.5 scenarios for all of Canada at a resolution of approximately 10 km[15]. For this project, the second-generation Canadian Earth System Model (CanESM2), developed by the Canadian Centre for Climate Modelling and Analysis (CCCma), was used as the predictor GCM to downscale and make climate change databases representative of Amaruq. Temperature and precipitation were derived from the PCIC output, while the other climate variables required for SEEP/W and TEMP/W (i.e. relative humidity and net radiation) were downscaled using the Statistical Downscaling Model (SDSM)[16,17,18], with the exception of wind speed due to the lack of climate change predictors.

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[14] Canadian Climate Data and Scenarios (CCDS). 2018. Online. http://climate-scenarios.canada.ca/

[15] Pacific Climate Impacts Consortium (PCIC). 2018. Online. https://pacificclimate.org/

[16] Wilby, R.L., Dawson, C.W. Murphy, C. O'Conner, P., and Hawkins, E. 2014. The Statistical DownScaling Model – Decision Centric (SDSM-DC): Conceptual basis and applications. Climate Research, 61, 251-268.

[17] Wilby, R.L. and Dawson, C.W. 2013. The Statistical DownScaling Model (SDSM): Insights from one decade of application. International Journal of Climatology, 33, 1707-1719.

[18] Wiby, R.L., Dawson, C.W. and Barrow, E.M. 2002. SDSM – a decision support tool for the assessment of regional climate change impacts. Environmental and Modelling Software, 17, 145-157.

Statistical downscaling is limited by the availability of large-scale predictors. Current CCCma CanESM2 model runs are limited temporally to 2100. In order to predict beyond 2100, the radiative forcing trend was applied to the temperature. RCP4.5 and RCP6.0 are expected to stabilize shortly after 2100, while RCP8.5 is expected to continue along the same trend until after 2200[19].

The CCCma does not provide GCM output for RCP6.0. In order to develop annual averages for RCP6.0, a weighted average function of RCP4.5 and RCP8.5 was developed based on the predicted climate change trends in Northern Canada using the Community Climate System Model, version 4 (CCSM4)[20]. Figure 2 and Figure 3 show the annual temperature and precipitation, respectively, estimated for the RCP4.5, RCP6.0 and RCP8.5 150-year climate databases developed for Amaruq. Temperatures are anticipated to rise at about the same rate (approximately 0.06°C/year) for RCP4.5 and RCP6.0 until approximately 2070, after which RCP4.5 estimates a reduction in the temperature increase rate. Under RCP8.5, temperatures are expected to increase at a higher rate (approximately 0.12°C/year) for the duration of the modelled period. All three scenarios predict an increase in precipitation with time of approximately 0.5 mm/year (75 mm total increase over 150 years) for RCP4.5, 0.6 mm/year (90 mm total increase over 150 years) for RCP6.0 and 0.7 mm/year (100 mm total increase over 150 years) for RCP8.5. RCP6.0 was selected as the scenario for the base-case simulations.

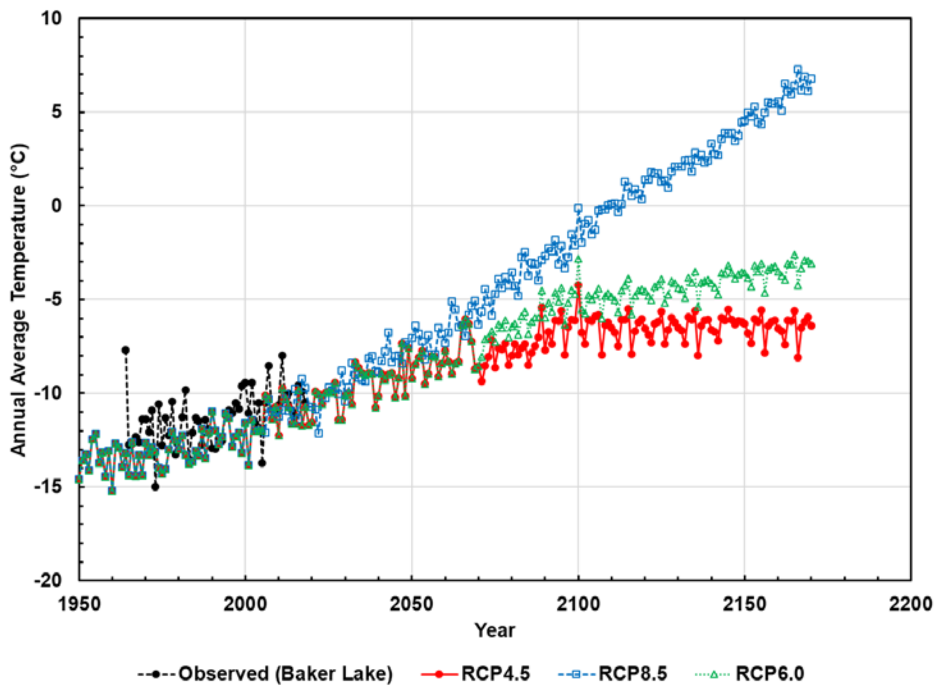


Figure 2: Annual average temperature estimated for the RCP4.5, RCP6.0 and RCP8.5 climate change scenarios. Observed temperature at Baker Lake is also shown.

[19] Meinshausen, M., S. J. Smith, K. V. Calvin, J. S. Daniel, M. L. T. Kainuma, J.-F. Lamarque, K. Matsumoto, S. A. Montzka, S. C. B. Raper, K. Riahi, A. M. Thomson, G. J. M. Velders and D. van Vuuren. 2011. The RCP Greenhouse Gas Concentrations and their Extension from 1765 to 2300. Climatic Change (Special Issue), DOI: 10.1007/s10584-011-0156-z.

[20] Peacock, S. 2012. Projected Twenty-First-Century Changes in Temperature, Precipitation, and Snow Cover over North America in CCSM4. Journal of Climate. 25. pp. 4406-4429

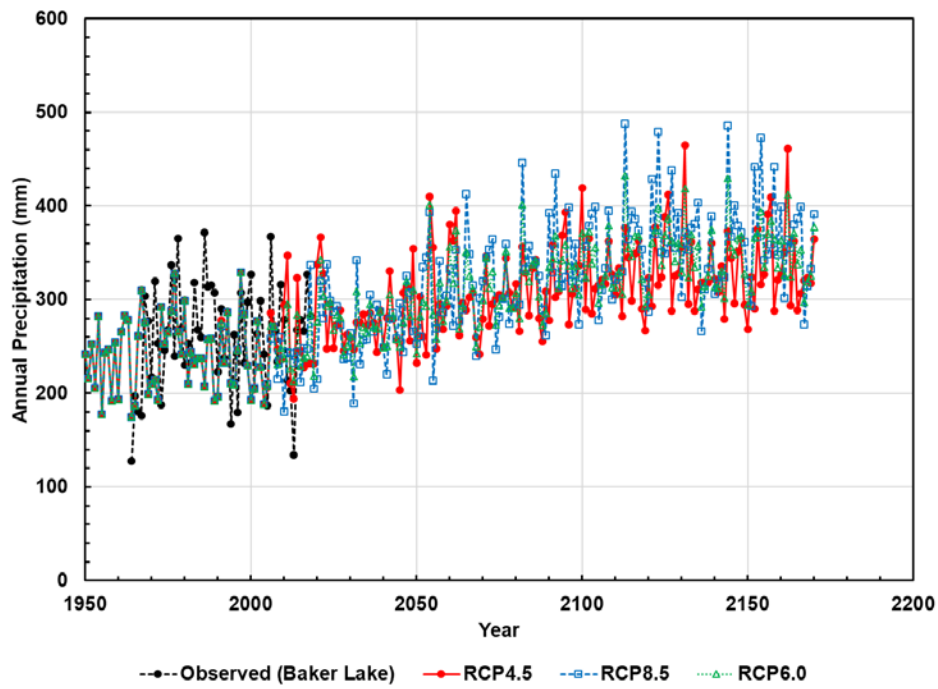


Figure 3: Annual precipitation estimated for the RCP4.5, RCP6.0 and RCP8.5 climate change scenarios. Observed precipitation at Baker Lake is also shown.

To account for creation of micro-climates on WRSF embankments, calibrations to the base 150-year climate database will be done to the net radiation and wind speed parameters. Net radiation will be adjusted for north facing and south facing according to the method proposed by Swift (1976)[21]. Wind direction and speed will also be adjusted for the modelled cross sections by creating a specific wind speed data set for NW and SW directions according to the wind roses shown in Figure 4 prepared from hourly wind speed and direction data from the Meadowbank site between December 2012 and December 2018. The effects of surrounding landforms (such as the Whale Tail WRSF) were assumed not to affect wind speed and direction. As the Whale Tail WRSF is expected to be the dominant landform in the adjacent landscape, this is a reasonable assumption.

[21] Swift, L.W.Jr.. 1976. Algorithm for Solar Radiation on Mountain Slopes. Water Resources Research Vol. 12, No. 1.

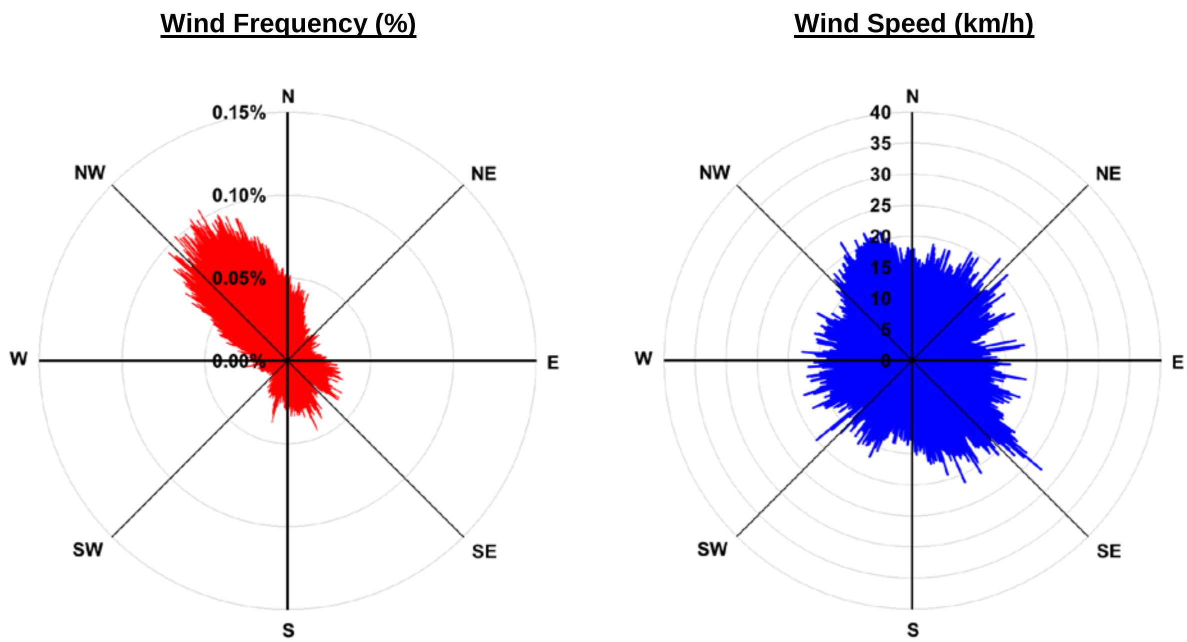


Figure 4: Wind rose for Meadowbank climate station.

Thermal Setting

The thermal setting for the Whale Tail and IVR WRSFs includes all components influencing thermal conditions within the WRSFs. Figure 7 shows the location of the Whale Tail and IVR WRSFs in the context of the Amaruq site. The WRSFs at Whale Tail are to be constructed in two phases, with the western portion of the Whale Tail WRSF being constructed during the first phase and the eastern portion and the IVR WRSF being constructed during the second phase. The Whale Tail WRSF also contains a Marginal Ore Stockpile (MAR) that may be excavated for milling at a future date, should it become economical to do so.

The Portage WRSF at the Meadowbank mine site has 19 thermistor strings installed in and around the landform (Figure 5). The thermistor strings provide temperature measurements from surface to (for some strings) within the underlying ground. These temperature records can be used to inform and calibrate the Whale Tail models. A cursory review of the thermistor data is provided in Table 2.

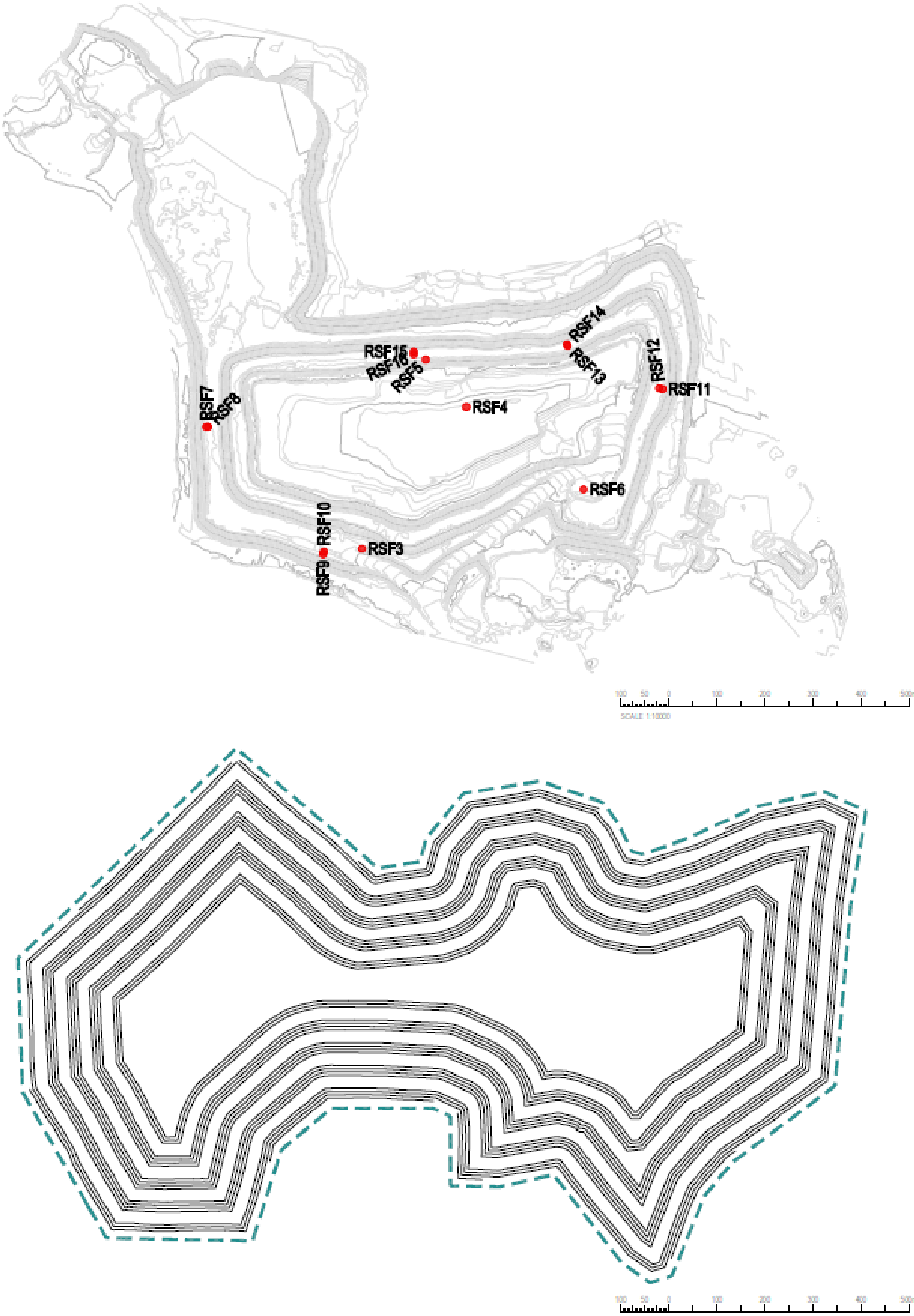


Figure 5: Portage WRSF (above) plan view, compared to Whale Tail WRSF (below) plan view.

Table 2: Summary of Thermistor Data

Location Name	Depth Range (m)	Date Range	Active Zone Depth (m)*
RF1-1	13.5 to 59.5 m	February 14, 2012 to December 6, 2018	-
RF1-2	0.0 to 14.5 m	February 20, 2012 to December 6, 2018	~2.5 m
RF1-3	0.0 to 29.7 m	April 2, 2013 to December 6, 2018	~1.2 m
RF-2	12.4 to 59.4 m	February 12, 2012 to December 6, 2018	-
RSF-1	0.0 to 49.7 m	February 7, 2013 to December 6, 2018	>3.7 m
RSF-3	0.5 to 23.5 m	November 8, 2013 to December 6, 2018	-
RSF-4	2.2 to 50.2 m	November 9, 2013 to March 5, 2015	-
RSF-5	0.0 to 40.5 m	November 11, 2013 to October 3, 2018	~3.7 m
RSF-6	0.5 to 19.5 m	November 9, 2013 to December 6, 2018	~2.7 m
RSF-7	0.9 to 5.4 m	October 2, 2015, to December 6, 2018	~3.8 m
RSF-8	0.9 to 9.9 m	October 2, 2015 to December 6, 2018	~3.8 m
RSF-9	0.7 to 5.2 m	October 1, 2015 to December 6, 2018	~4.0 m
RSF-10	0.7 to 9.7 m	October 1, 2015 to December 6, 2018	~4.5 m
RSF-11	0.8 to 5.3 m	October 4, 2015 to October 4, 2018	~3.0 m
RSF-12	0.6 to 9.6 m	October 5, 2015 to October 4, 2018	~3.0 m
RSF-13	0.9 to 5.4 m	October 4, 2015 to October 3, 2018	~1.9 m
RSF-14	0.9 to 9.9 m	October 4, 2015 to October 3, 2018	~3.2 m
RSF-15	0.7 to 5.2 m	October 4, 2015 to October 3, 2018	>5.2 m
RSF-16	0.8 to 9.8 m	October 5, 2015 to October 3, 2018	~7.7 m

*Depth at which temperature has stayed below 0°C since July 2017.

RSF-3, RSF-5, RSF-6 and RSF-15 will be the main focus of the calibration process, due to their placement in close proximity to the anticipated predominant direction of NW-SE and their longer operational period. Figure 6 shows the maximum and minimum temperature profiles for RSF-3, RSF-5, RSF-6 and RSF-15 from July 2017 to July 2018 (i.e. the last complete thermal year with data). A review of all the thermistor data and Figure 6 indicates:

- The WRSF still has not completely frozen;
- The active zone depth is within the cover at most thermistor locations, but deepens into the WRSF at several locations, including on the north slope, where conditions were expected to be coolest;
- RSF-3, located on the south slope of the WRSF, indicates heating from the slopes, as readings approach 0°C from 25 m to 30 m depth.

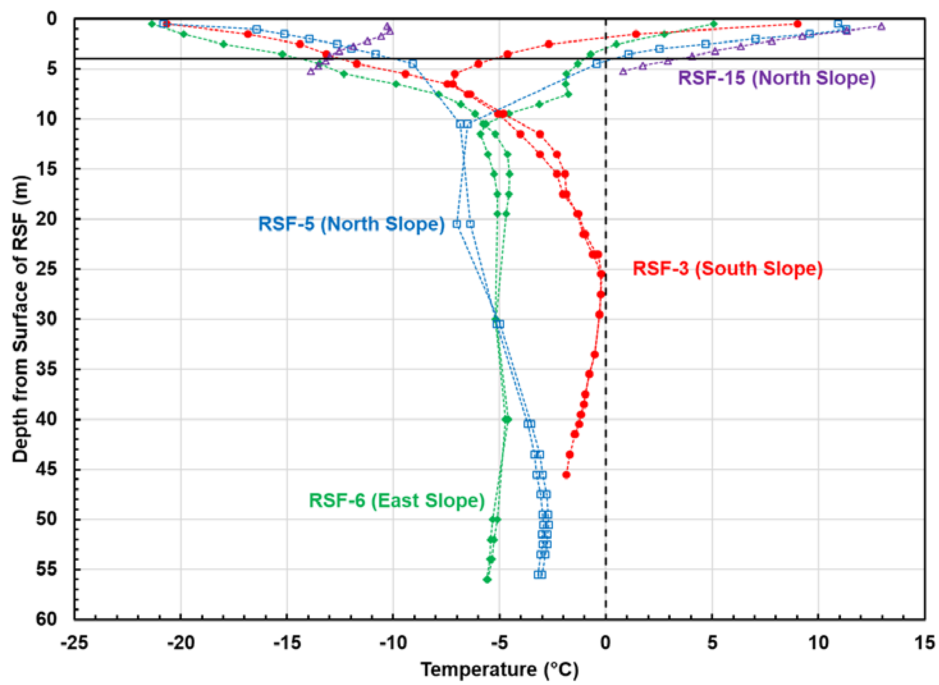


Figure 6: Maximum and minimum temperature profiles for RSF-3, RSF5, RSF-6 and RSF-15 from July 2017 to July 2018.

Five cross sections (three through Whale Tail WRSF and two through IVR WRSF) have been selected for long term modelling, the locations of which are shown in Figure 7. These will be 'built-up' over time to simulate conditions at placement and prior to construction of a thermal cover system of overlying waste rock layers. A sensitivity analysis will be performed on one of these cross sections, specifically the NW-SE Whale Tail cross section labelled 'A' in Figure 7 and shown in Figure 8 as it is expected to have the most diverse range in behaviour due to the potential for advective cooling in the predominant wind direction.

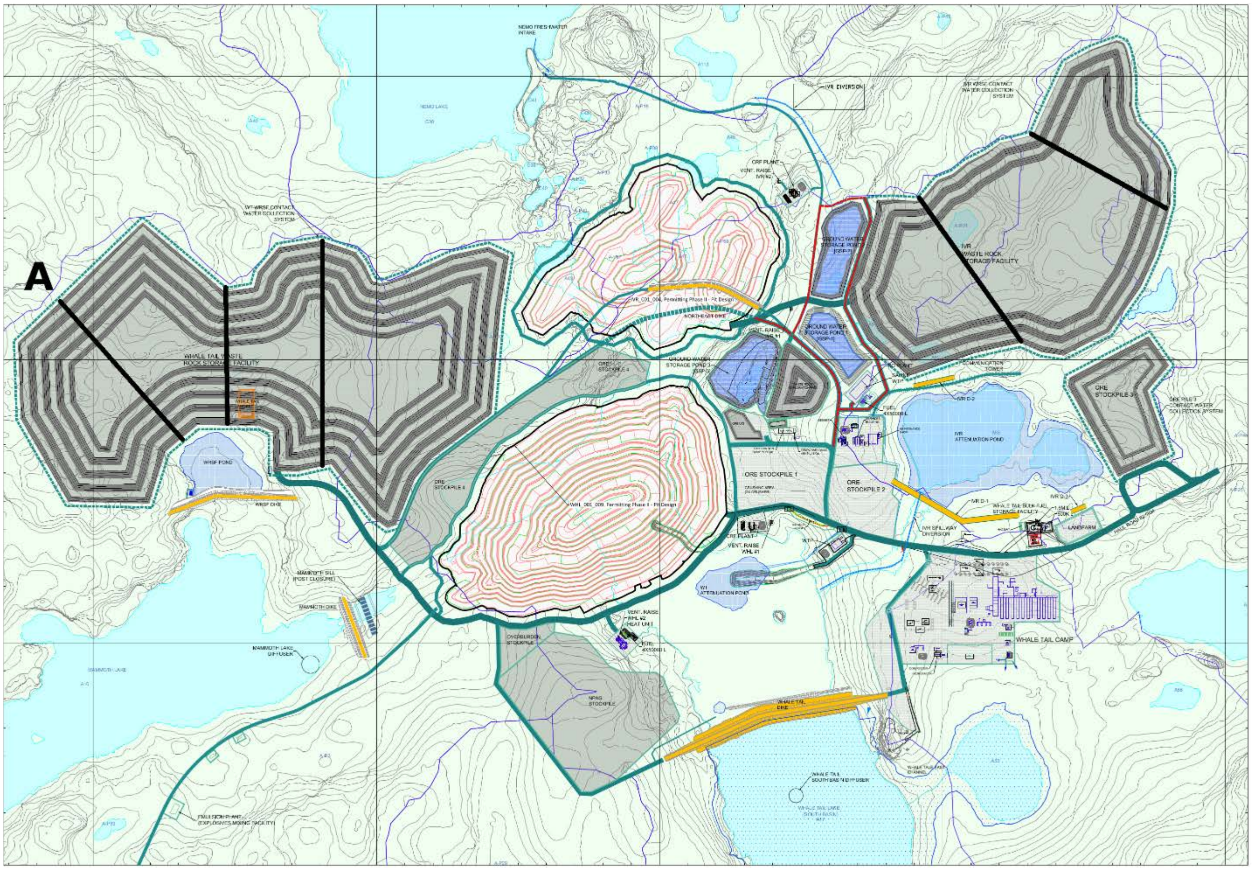


Figure 7: Locations of five cross-sections of Whale Tail and IVR WRSFs.

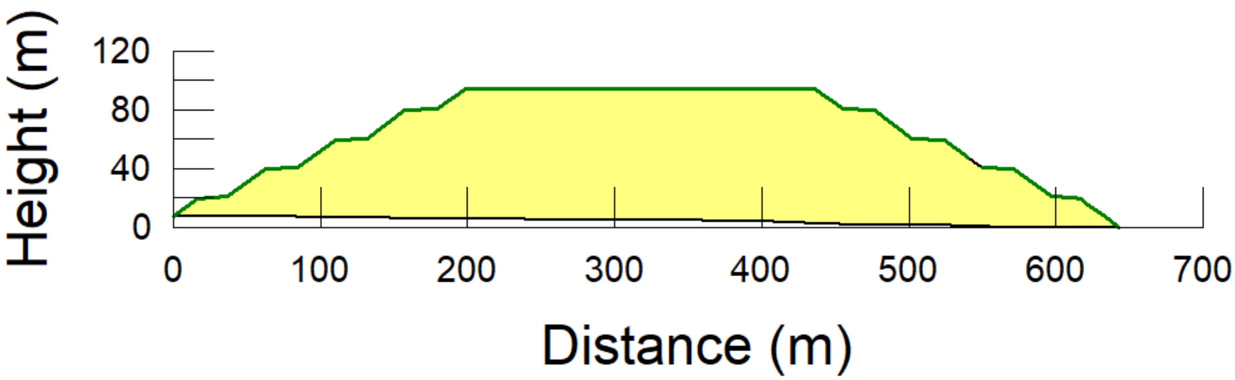


Figure 8: Northwest-Southeast cross-section through Whale Tail WRSF at closure (A).

Materials

This Section presents the material properties developed for the Whale Tail and IVR WRSFs project to be used as initial material properties for this project.

The material properties or functions developed for each material based on available geochemical and geotechnical testing (eg. particle size distributions) are as follows:

- water retention curves (WRC – suction versus volumetric water content);
- hydraulic conductivity function (k-function – suction versus hydraulic conductivity);
- air conductivity function;
- thermal conductivity function (volumetric water content versus thermal conductivity);
- volumetric specific heat function (volumetric water content versus volumetric specific heat capacity);
- unfrozen water content function (unfrozen water content versus temperature); and
- geochemical reactivity.

Figure 9 shows the range of all particle size distributions (PSDs) measured based on fragmentation analyses for the NAG and PAG waste rock for the Portage WRSF. No data is available yet for the Whale Tail waste rock, but it is currently anticipated that there will not be a major change in particle size in comparison to Portage. However, the cover material at Whale Tail is expected to consist mainly of greywacke rock and diorite which are harder than the ultramafic volcanic material used for construction of the Portage WRSF cover system[22]. The PSDs show:

- the run-of-mine (ROM) NAG waste rock (of which only three Split PSD results were available) falls almost on the average of the range of the 314 PAG waste rock fragmentation PSD samples; therefore, the ROM NAG and PAG waste rock will be simulated initially with the same material inputs (with the exception of geochemical reactivity).
- The ROM waste rock can all be classified as very coarse-textured (Figure 10). Any additional crushing and weathering will result in the formation of a finer-textured layer, mostly on highly trafficked surfaces.

The finer textured layers which form due to trafficking at the Portage WRSF are not expected to be encountered at Whale Tail WRSF. Finer-textured surface (shown in red in Figure 10) will therefore be considered in sensitivity modelling, rather than as part of the base case, in contrast to what has been previously modelled at the Portage WRSF.

[22] Golder. 2018. Technical Memorandum Whale Tail Pit Project Waste Rock Storage Facility Cover Thermal Assessment. Project No. 1789310_177_TM_Rev0. June 14, 2018.

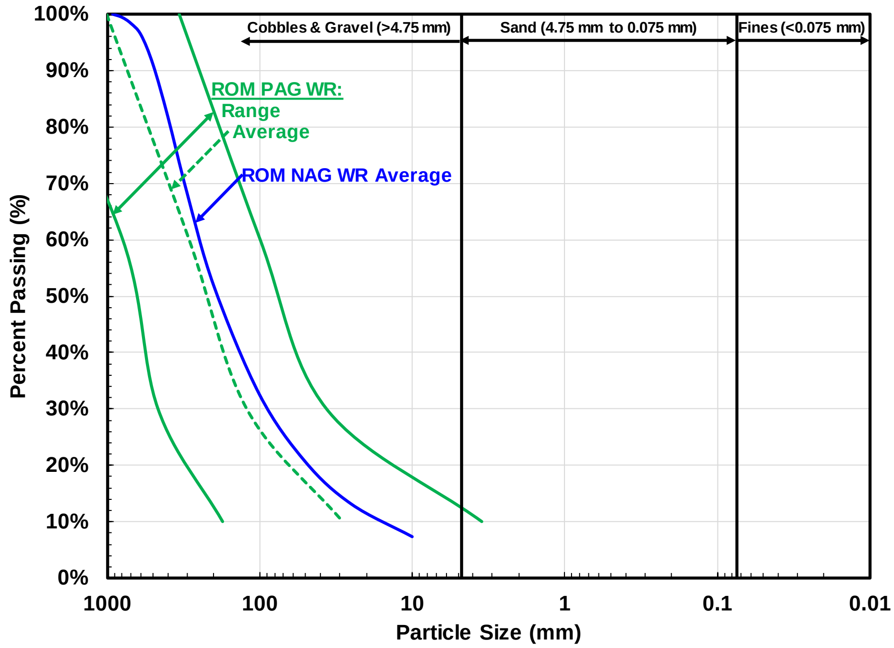


Figure 9: Particle size distributions for range of Portage waste rock samples.

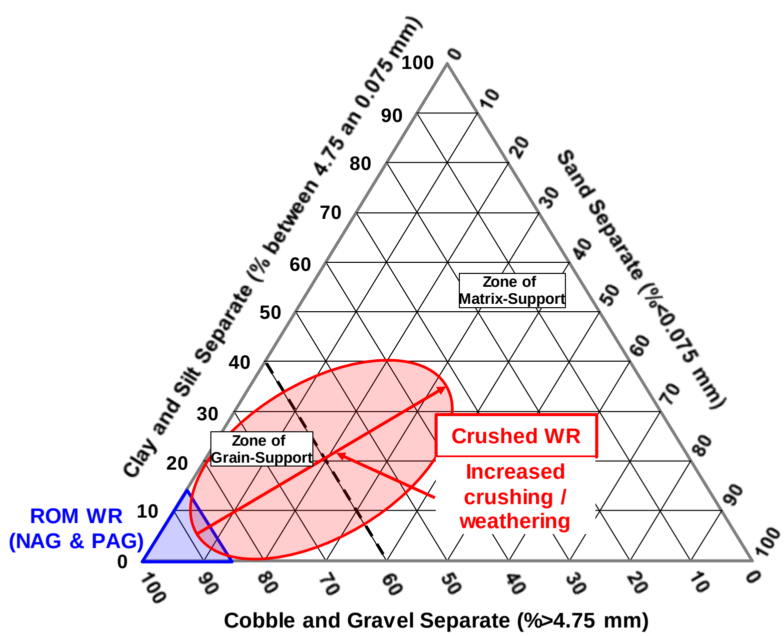


Figure 10: Texture Triangle for Portage waste rock samples.

Based on this analysis, it is the opinion of OKC that the material inputs OKC developed for the Portage WRSF thermal modelling project completed during 2016[23] should be used as the initial material inputs for the Whale Tail thermal modelling (Attachment A). As there exists some uncertainty in material properties,

[23] OKC, 2016. **Summary of Thermal Modelling of Portage RSF at Meadowbank Mine. Ref. 948-4 September 28, 2016.**

a range in material properties will be investigated during sensitivity modelling in order to quantify the effect of any changes from the initial material inputs.

Approach to Thermal Modelling

The following approach is planned to complete climate change thermal modelling of the Whale Tail and IVR WRSFs during the next 150 years:

1) *Update climate database for field response and predictive climate change modelling:* the historical climate data for the site will be updated with the latest measurements. As discussed in the previous "Climate" section, additional focus will be made to account for solar radiation and wind speed and direction on all slope aspects.

2) *Update model calibration to include latest thermistor data*: models representative of selected locations of thermistor strings will be simulated for the same period of time as the thermistor strings have been operational. The model results will then be compared to the field data to determine if the model reasonably estimates field thermal conditions. If not, the material inputs for the model will be updated and the model re-simulated and another comparison of model results to field data completed. This iterative process will be repeated until the model results provide a reasonable comparison to the field data. The completion of this task will ensure the best material properties are estimated for the 150-year simulations. Based on initial review, thermistor strings RSF-3, RSF-5, RSF-6 and RSF-15 will be the main focus of field response models, due to their placement and length of time they have been operational. Once models are accurately simulating these locations, the field response models will be extended to calibrate the models to additional thermistor strings.

3) *Development of 2D sensitivity models of a NW-SE WRSF cross-section:* to determine the main factors promoting and inhibiting freeze-back of and seepage (amount and timing) from the WRSFs. To do so accurately, the models must consider coupled gas, heat, water, and air transfer processes. Additionally, the models must be able to account for the exothermic oxidation of sulphide materials. Therefore, OKC proposes to use the TEMP/W, SEEP/W, and AIR/W components of the GeoStudio software suite in combination with the Oxidation and Heat Generation add-in module GEOSLOPE developed with OKC to simulate sulphide oxidation. OKC will develop models of the cross-section previously presented in Figure 8. Table 3 outlines the current list of proposed sensitivity scenarios.

Table 3: Expected sensitivity scenarios for Whale Tail WRSF thermal modelling

Sensitivity Scenario	Parameter Examined
1	Base Case
2	Finer-textured cover material
3	Coarser-textured cover material
4	Cover thickness evaluation (extend base case to long term)
5	Variable cover thickness 1
6	Variable cover thickness 2
7	Waste rock placement 1 – Tip Height (> 5m)
8	Waste rock placement 2 – Tip Height (>> 5m)
9*	Waste rock placement 3 – Lift Height
10*	Waste rock placement 4 – Lift Height

*Pending acceptance of PCN3.

4) *Development of long-term models of WRSFs representative cross-section*s: which will be based on findings of the sensitivity analyses, to estimate performance of the WRSFs during mine operations, closure and post-closure periods. These simulations will allow OKC to provide AEM with an estimated range of seepage and freeze-back performance for both WRSFs. OKC will develop five (5) cross sections, three of Whale Tail WRSF and two of IVR WRSF.

5) *Produce and present thermal modelling results:* a memorandum be submitted that outlines the results of the 2D base preliminary thermal models which can be circulated to all members of the project group. A meeting (via web-conference) will be held with OKC and AEM project team members in attendance, to review the results and draft report and, advise on requested edits or comments.

6) *Produce final report:* final report will be completed based on the review of the draft report (Point 4) and submitted to AEM.

Project Schedule

Table 4 provides an updated project schedule for the remaining tasks.

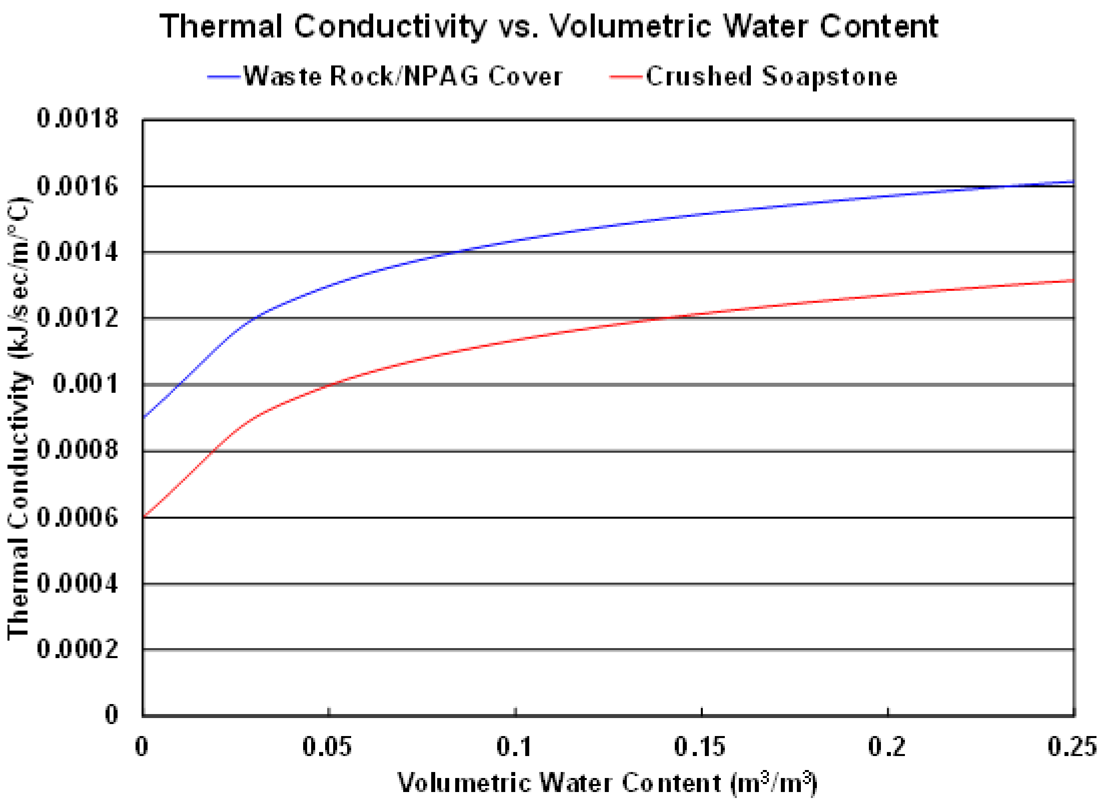
Table 4: Project Schedule as of February 18, 2019

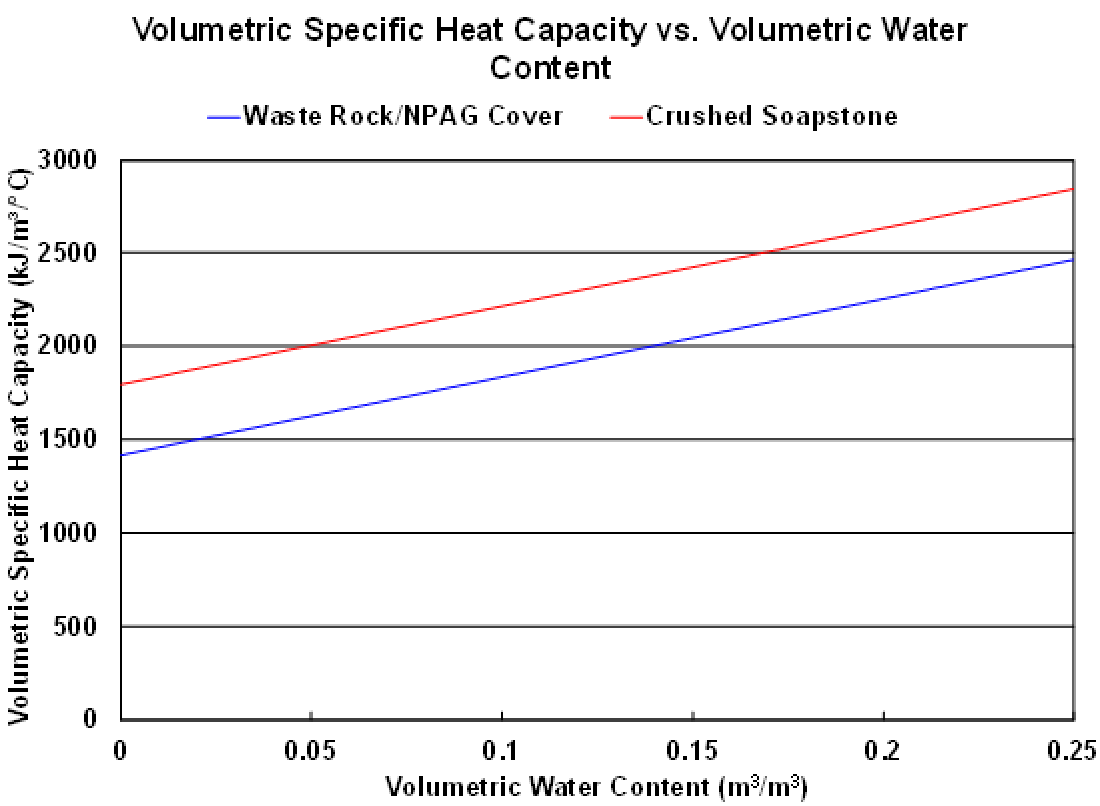
Task #	Task	Completion	Deliverable
3.2	Sensitivity Analysis	February 8, 2019	
3.2a	Development of Base Case Sensitivity Model	January 18, 2019	
3.2b	Development of Finer-Textured Cover Sensitivity Model	January 18, 2019	
3.2c	Development of Coarser-Textured Cover Sensitivity Model	January 18, 2019	
3.2d	Development of Cover Thickness Evaluation Model (Long Term)	January 25, 2019	
3.2e	Development of 1st Variable Cover Thickness Model	February 1, 2019	
3.2f	Development of 2nd Variable Cover Thickness Model	February 1, 2019	
3.2g	Development of 1st Waste Rock Placement Model	February 8, 2019	
3.2h	Development of 2nd Waste Rock Placement Model	February 8, 2019	
3.2i	Development of 3rd Waste Rock Placement Model	February 15.2018	
3.2j	Development of 4th Waste Rock Placement Model	February 15.2018	
3.3	Long Term Models	March 22, 2019	Final Report
3.3a	Development of Whale Tail WRSF Long Term Models	February 22, 2019	
3.3b	Development of IVR WRSF Long Term Models	February 22, 2019	
3.3c	Development of Whale Tail WRSF Long Term Climate Change Model	March 1, 2019	
3.3d	Write Report	March 22, 2019	

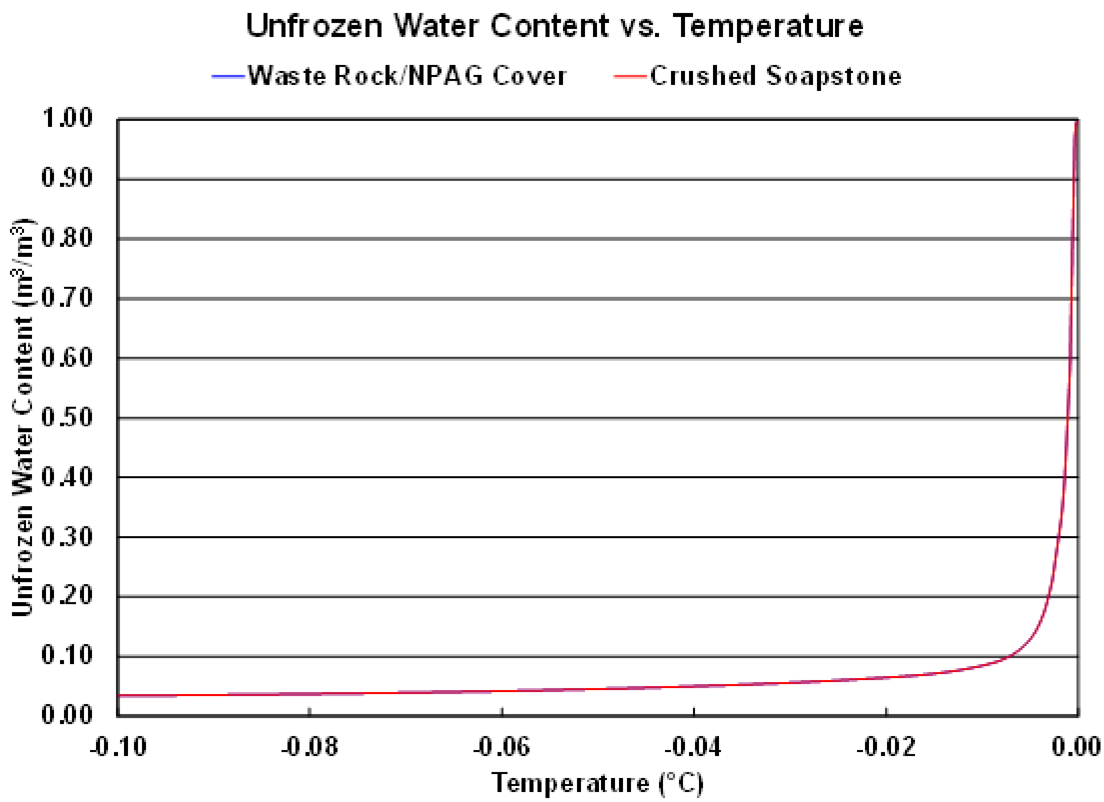
Closure

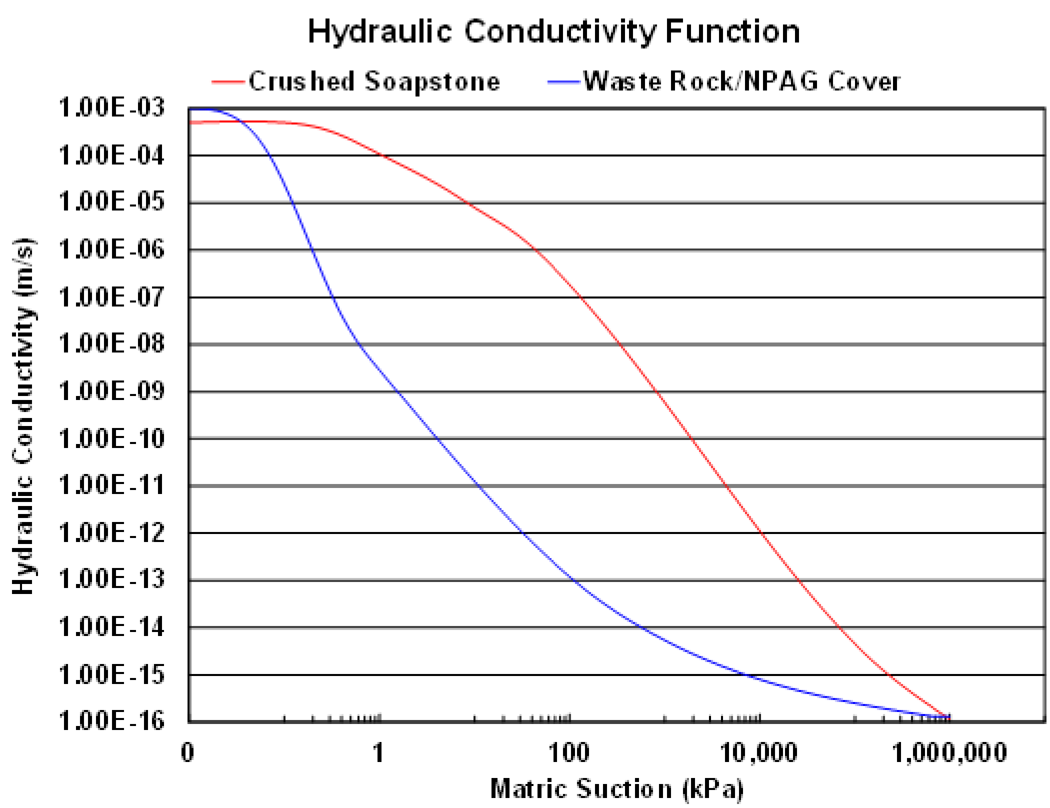
We trust information provided in this memorandum is satisfactory for your requirements. Please do not hesitate to contact me at (250) 802-3999 or rshurniak@okc-sk.com should you have any questions or comments.

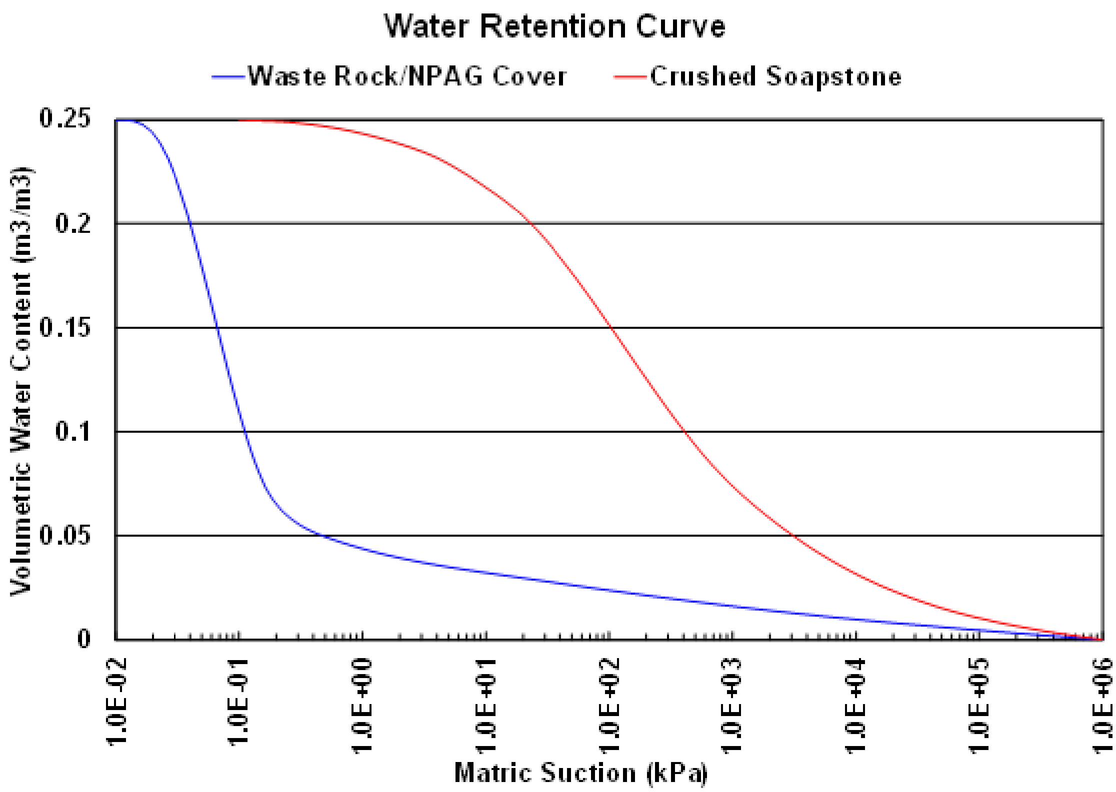
Attachment – Portage WRSF thermal model inputs

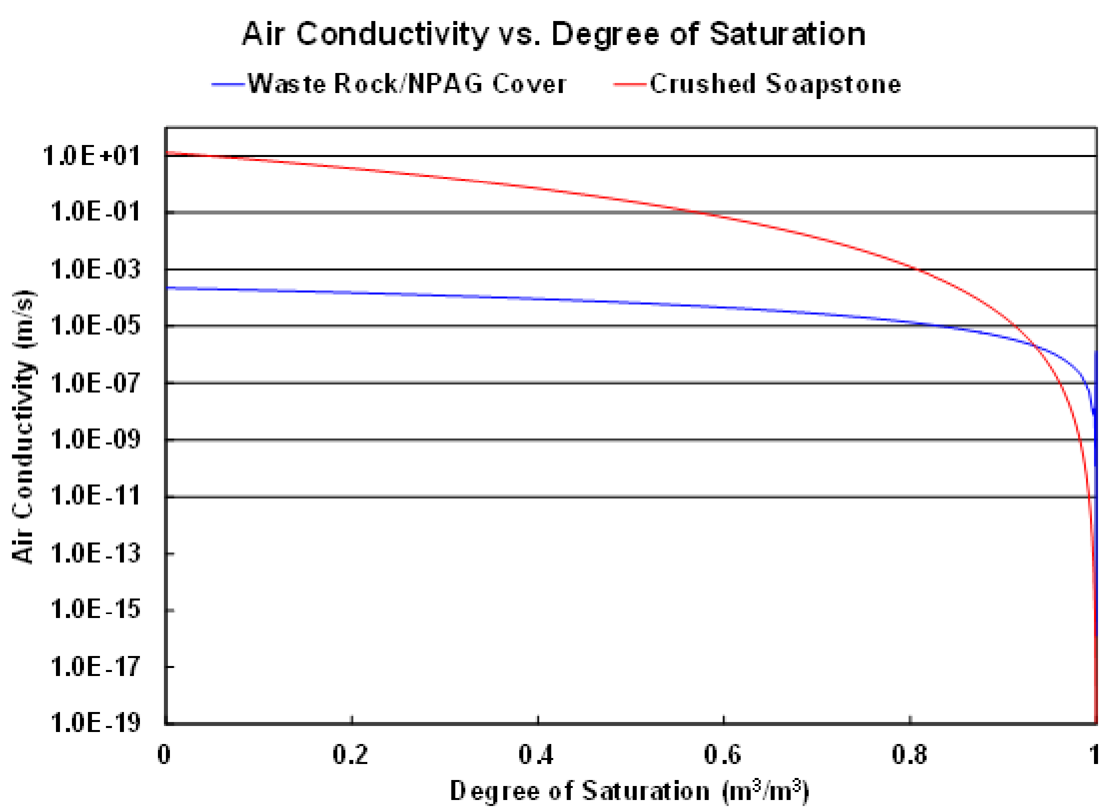

Thermal Conductivity vs. Volumetric Water Content
Waste Rock/NPAG Cover
Crushed Soapstone
Thermal Conductivity (kJ/sec/m/°C)
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
0
0.05
0.1
0.15
0.2
0.25
Volumetric Water Content (m³/m³)


Volumetric Specific Heat Capacity vs. Volumetric Water Content
Waste Rock/NPAG Cover
Crushed Soapstone
Volumetric Specific Heat Capacity (kJ/m³/°C)
3000
2500
2000
1500
1000
500
0
0
0.05
0.1
0.15
0.2
0.25
Volumetric Water Content (m³/m³)


Unfrozen Water Content vs. Temperature
Waste Rock/NPAG Cover
Crushed Soapstone
Unfrozen Water Content (m³/m³)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.08
-0.06
-0.04
-0.02
0.00
Temperature (°C)

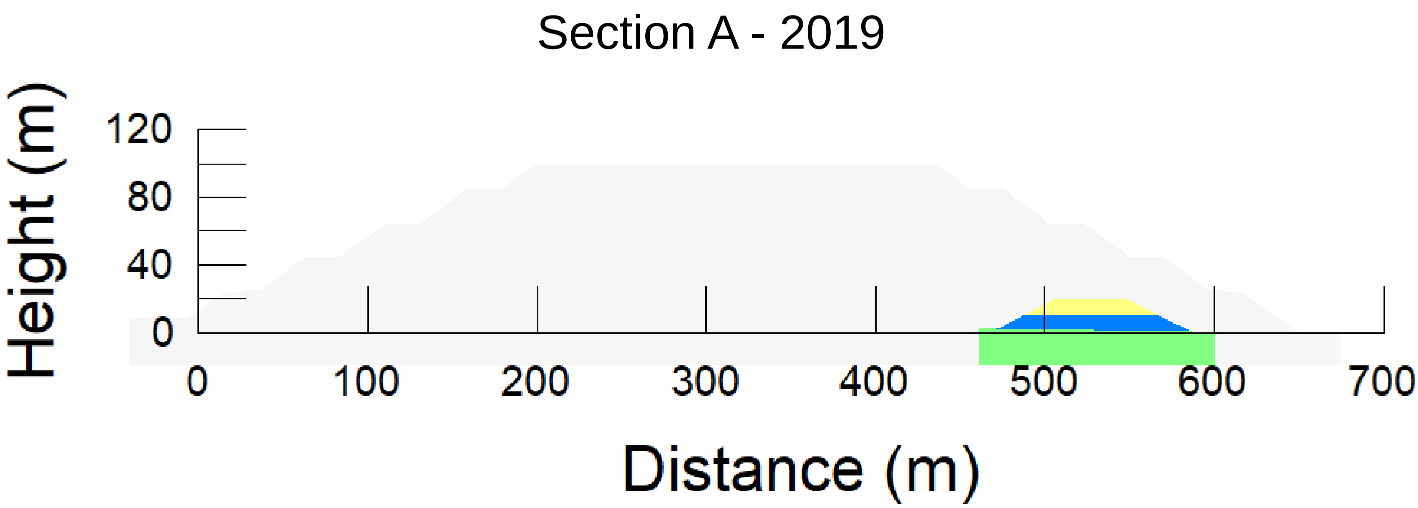

Hydraulic Conductivity Function
Crushed Soapstone
Waste Rock/NPAG Cover
Hydraulic Conductivity (m/s)
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
1.00E-13
1.00E-14
1.00E-15
1.00E-16
0
1
100
10,000
1,000,000
Matric Suction (kPa)


Water Retention Curve
Waste Rock/NPAG Cover
Crushed Soapstone
Volumetric Water Content (m3/m3)
0.25
0.2
0.15
0.1
0.05
0
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
1.0E+03
1.0E+04
1.0E+05
1.0E+06
Matric Suction (kPa)


Air Conductivity vs. Degree of Saturation
Waste Rock/NPAG Cover
Crushed Soapstone
Air Conductivity (m/s)
1.0E+01
1.0E-01
1.0E-03
1.0E-05
1.0E-07
1.0E-09
1.0E-11
1.0E-13
1.0E-15
1.0E-17
1.0E-19
0
0.2
0.4
0.6
0.8
1
Degree of Saturation (m³/m³)

Appendix B

2D Modelling Geometry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Height (m)
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40
0
0
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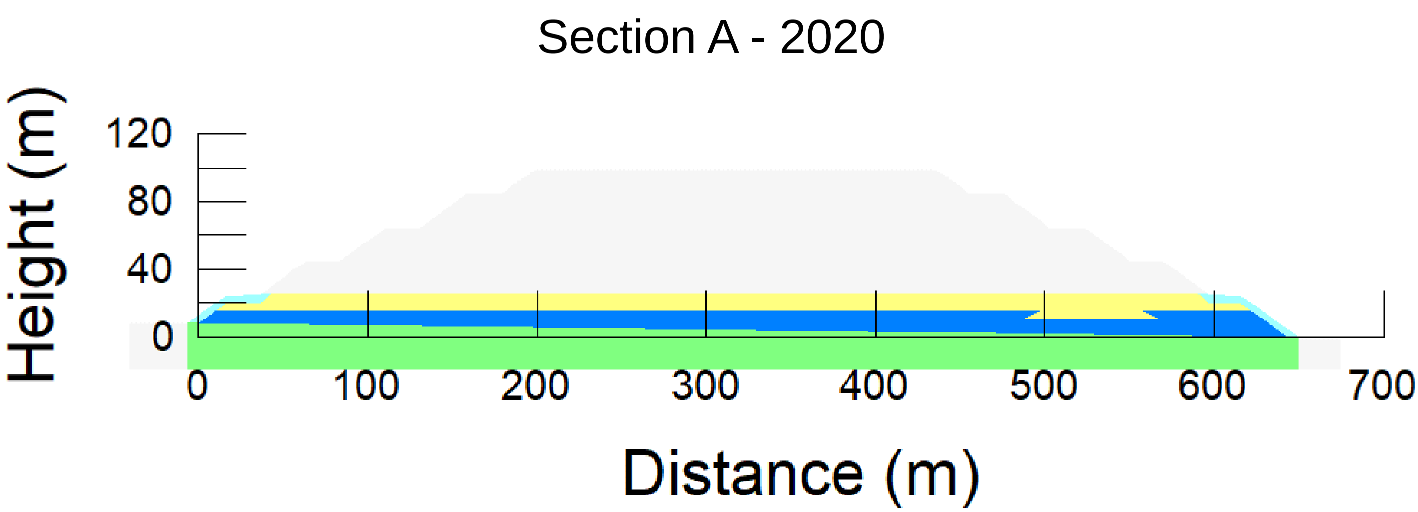
200
300
400
500
600
700
Distance (m)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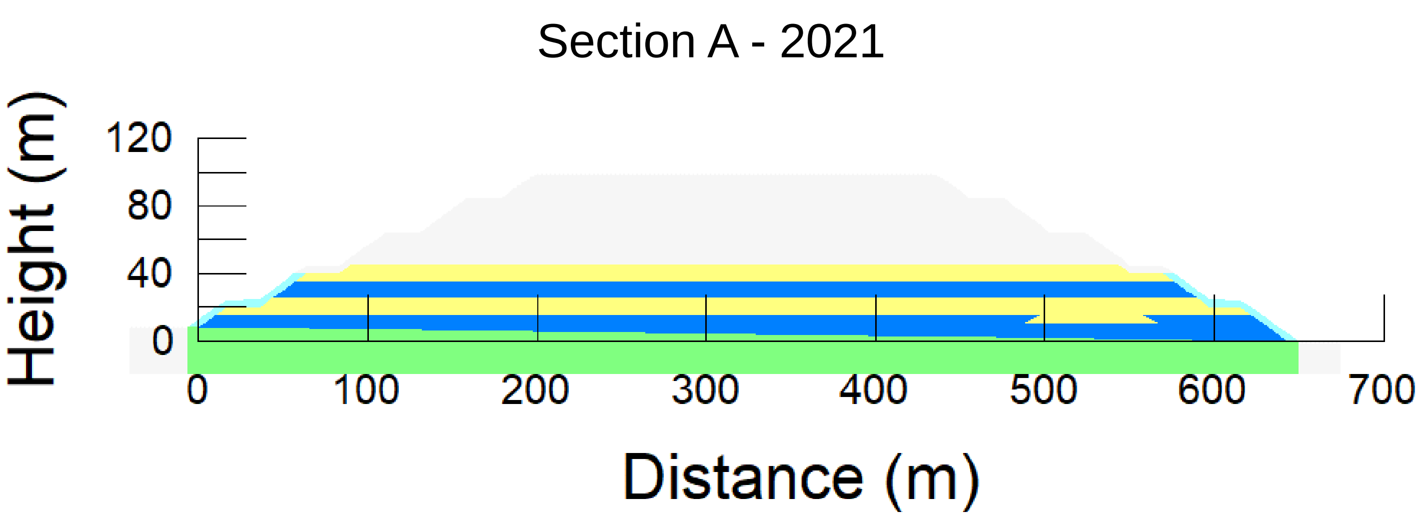
200
300
400
500
600
700
Distance (m)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200
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400
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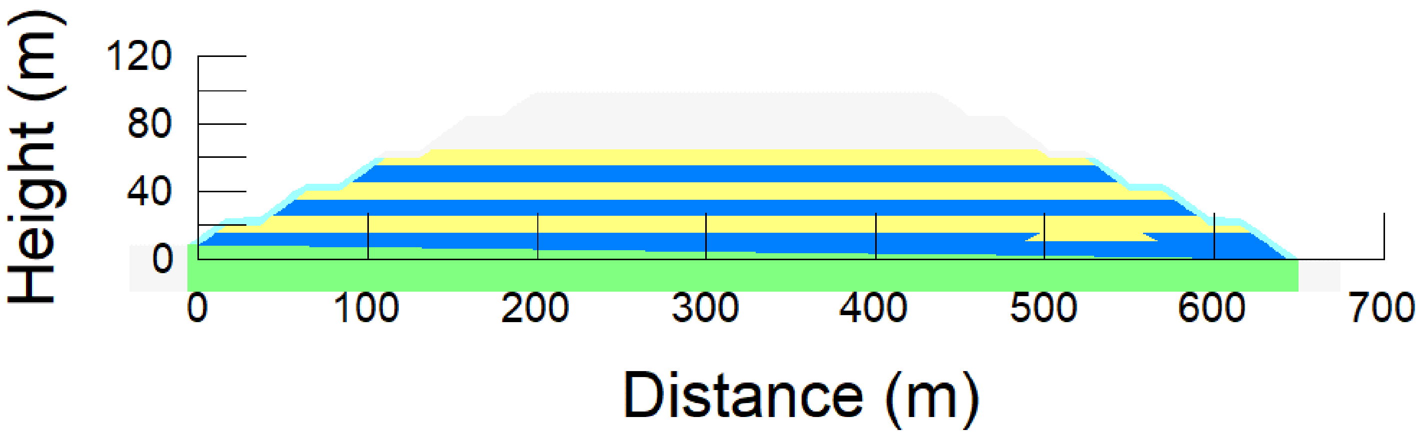
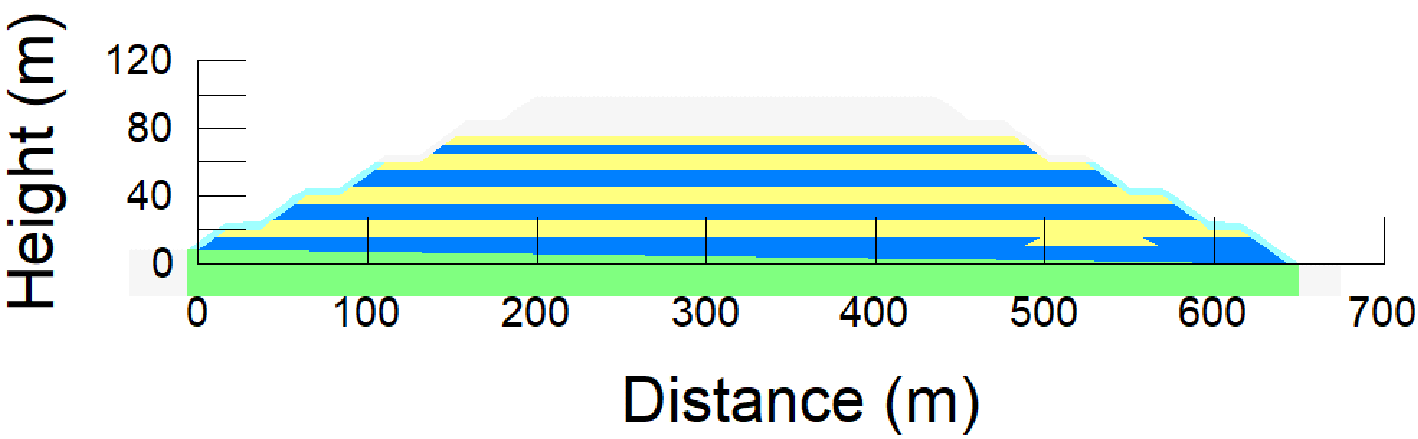
600
700
Distance (m)

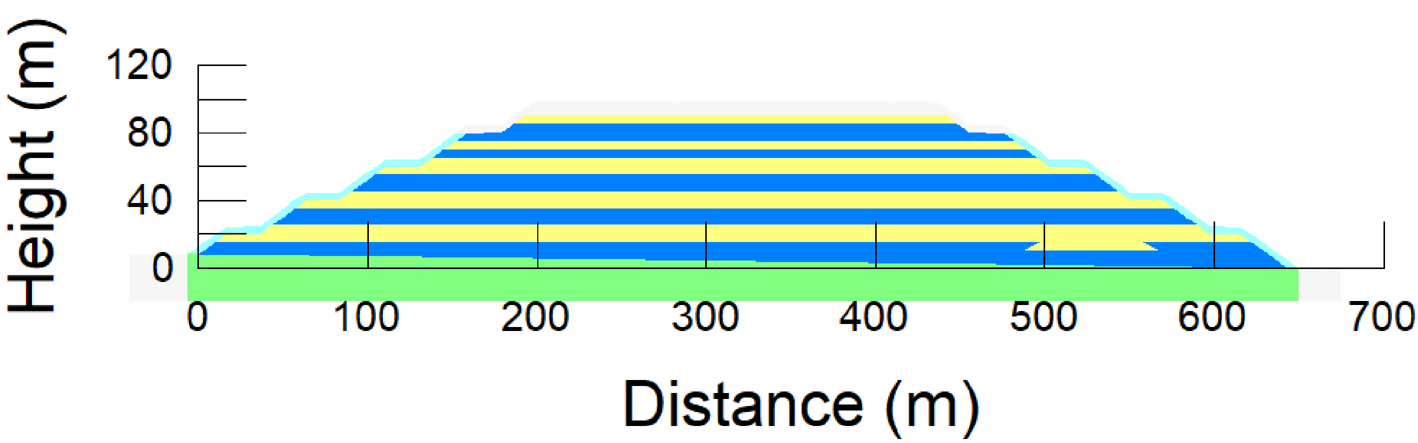
Section A - 2022

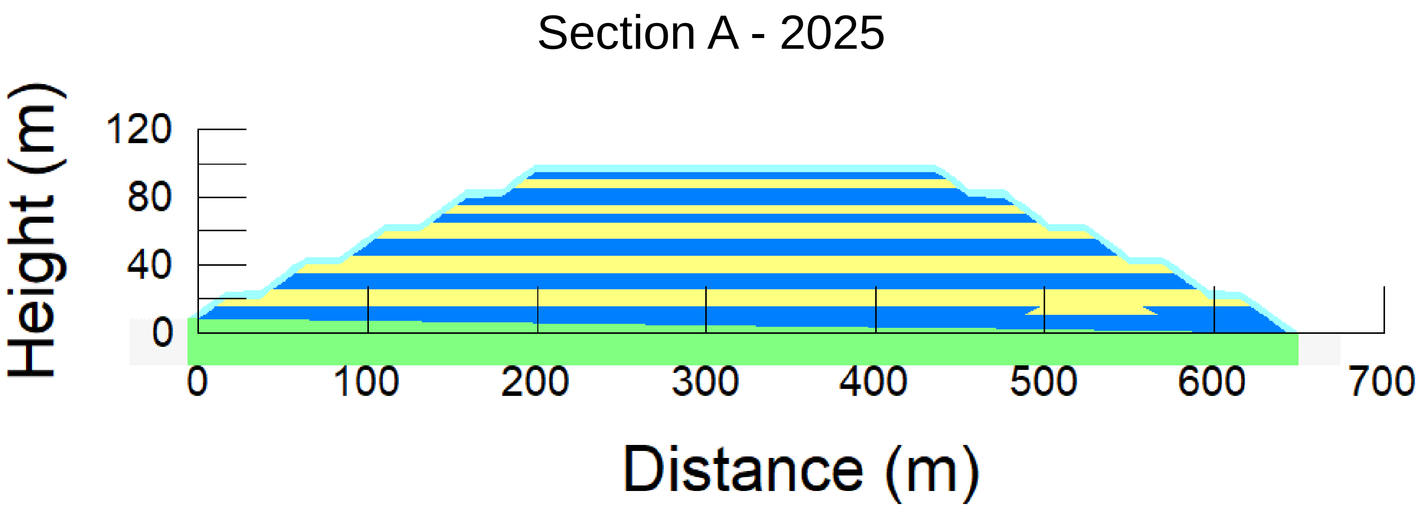


Section A - 2023



Section A - 2024




Section A - 2025
Height (m)
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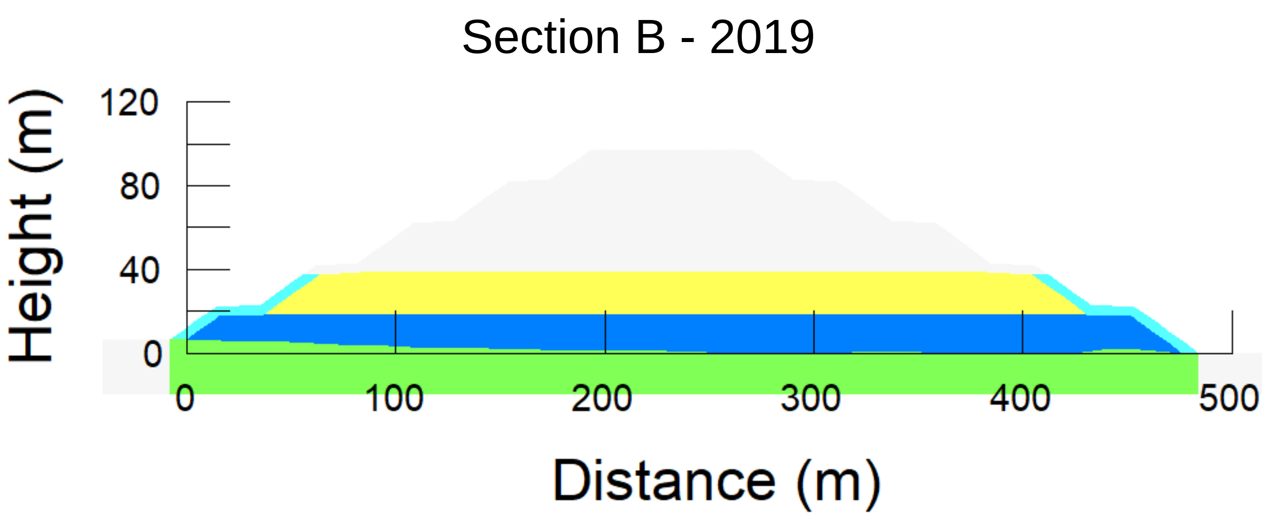
0
100
200
300
400
500
600
700
Distance (m)


Section B - 2019
Height (m)
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80
40
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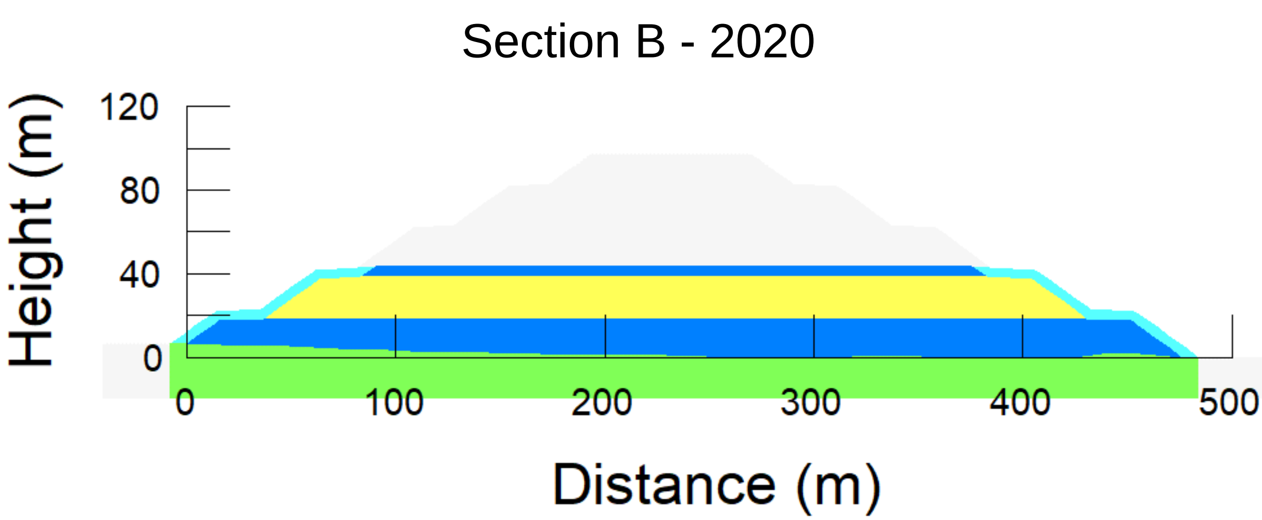
0
100
200
300
400
500
Distance (m)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Height (m)
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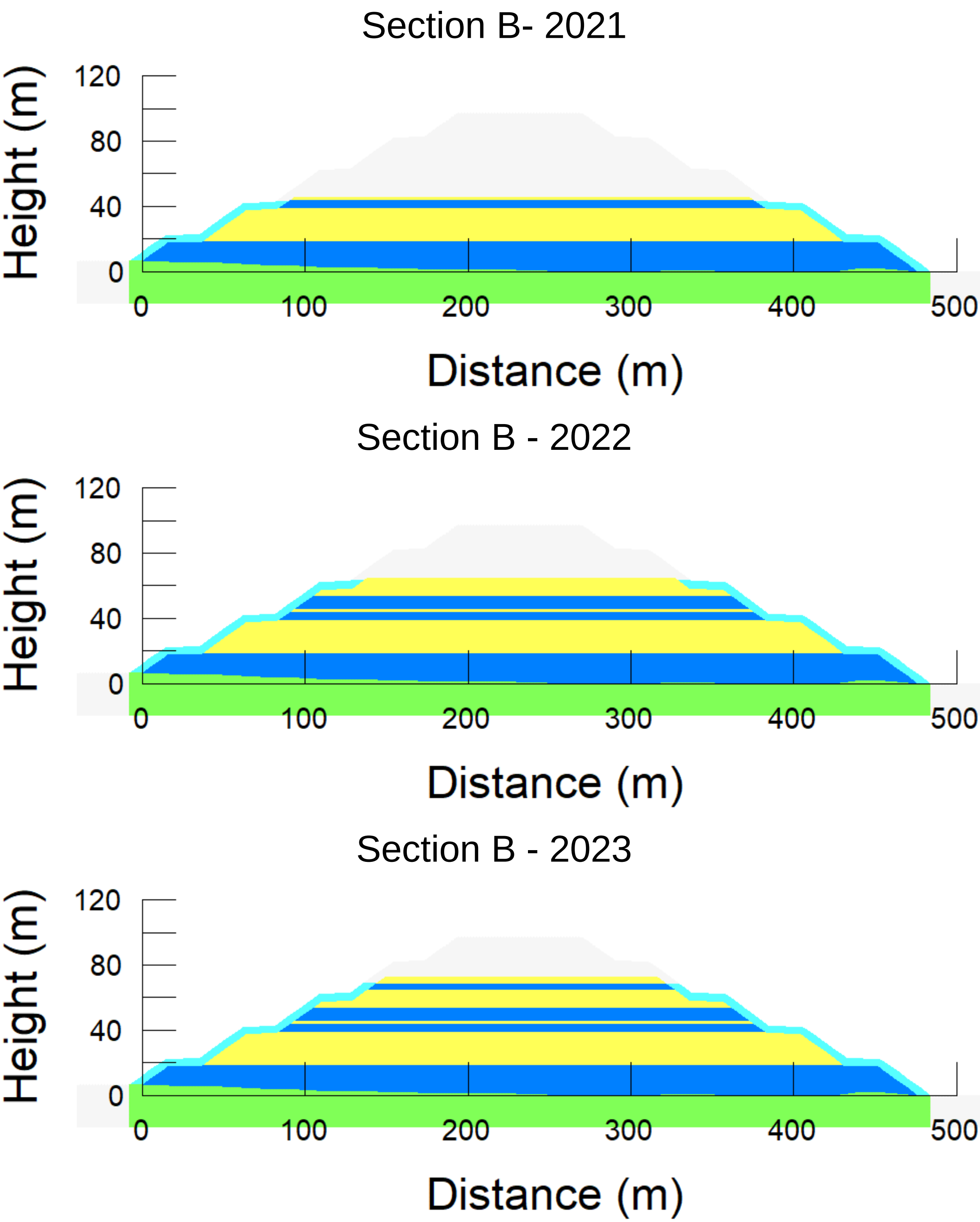
0
100
200
300
400
500
Distance (m)


Section B- 2021
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200
300
400
500
Distance (m)
Section B - 2022
Height (m)
120
80
40
0
0
100
200
300
400
500
Distance (m)
Section B - 2023
Height (m)
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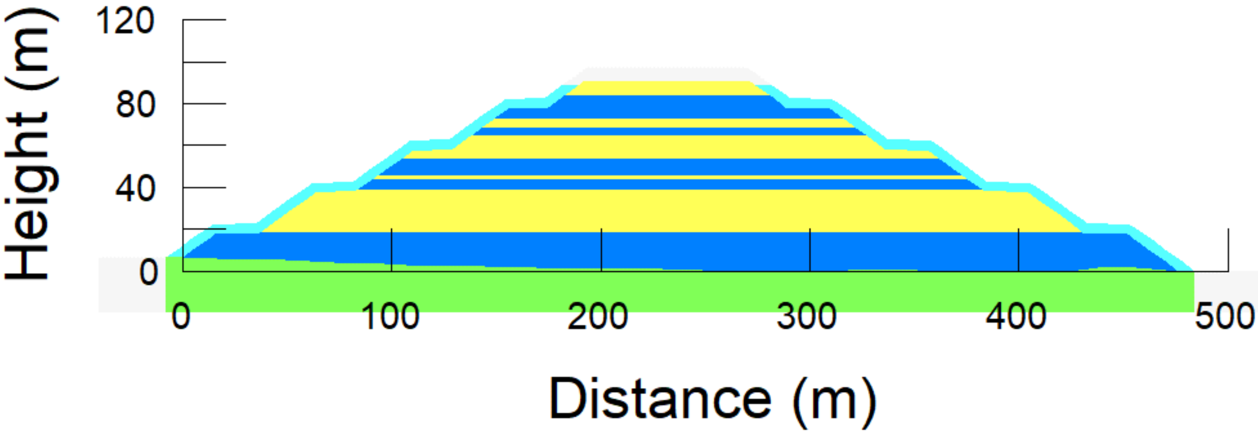
40
0
0
100
200
300
400
500
Distance (m)

Section B- 2024



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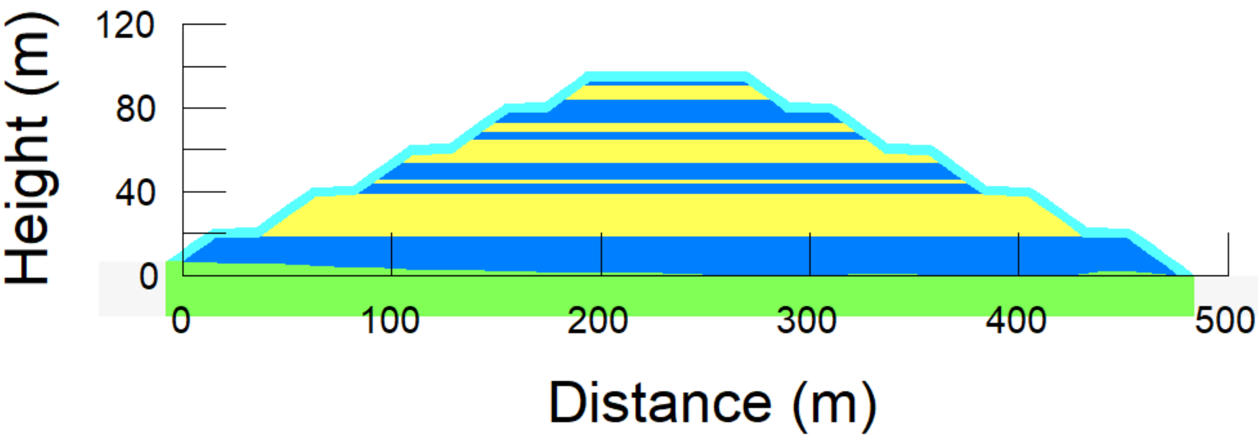
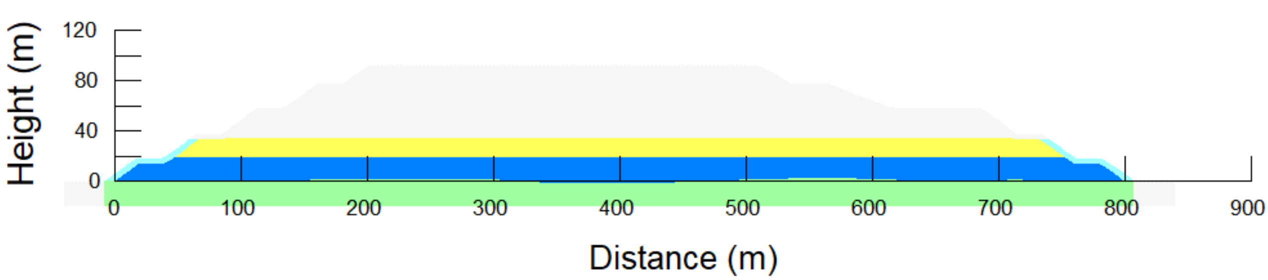


Section C - 2019



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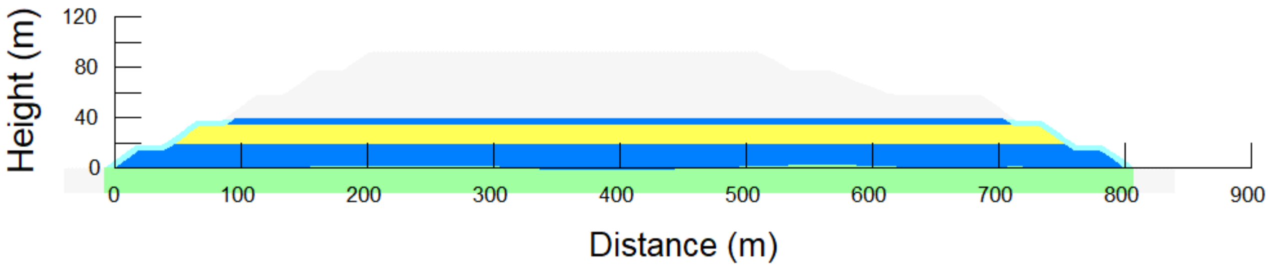

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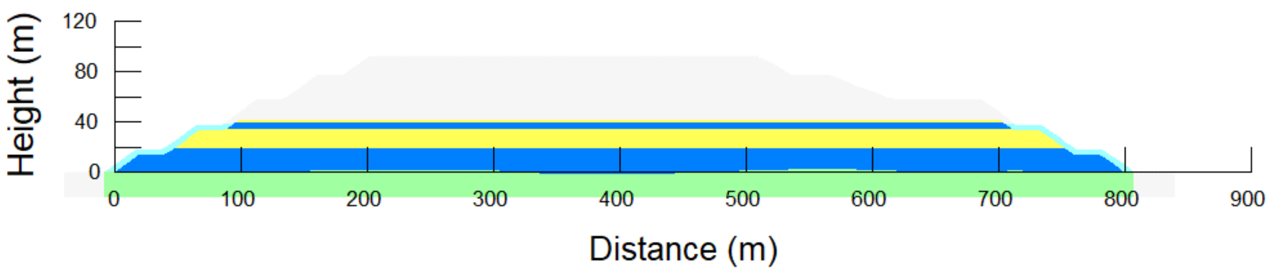

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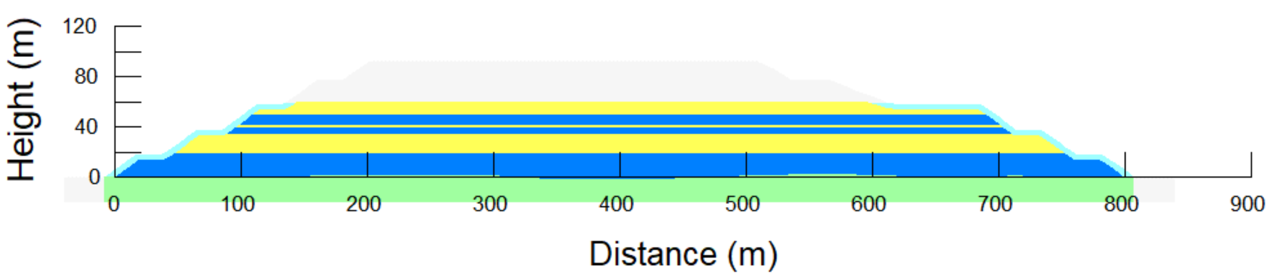

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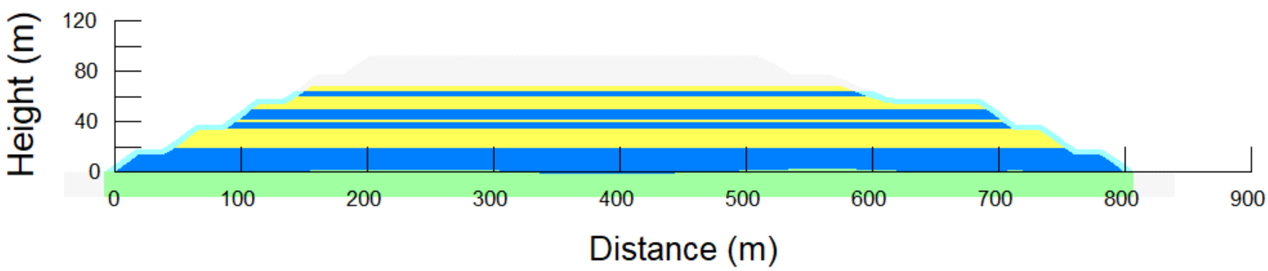

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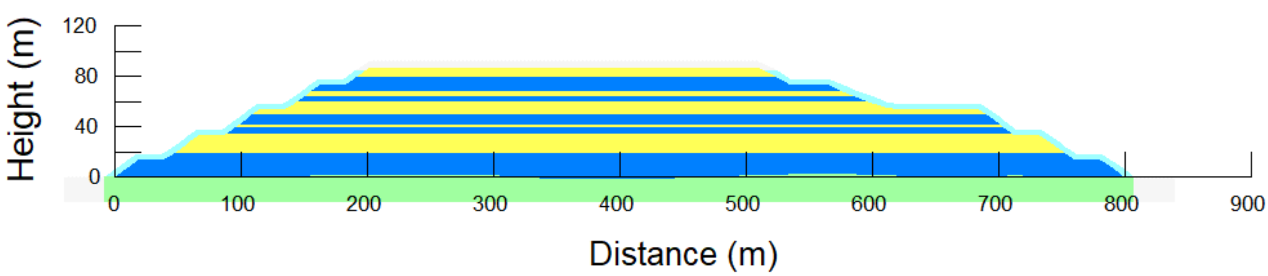

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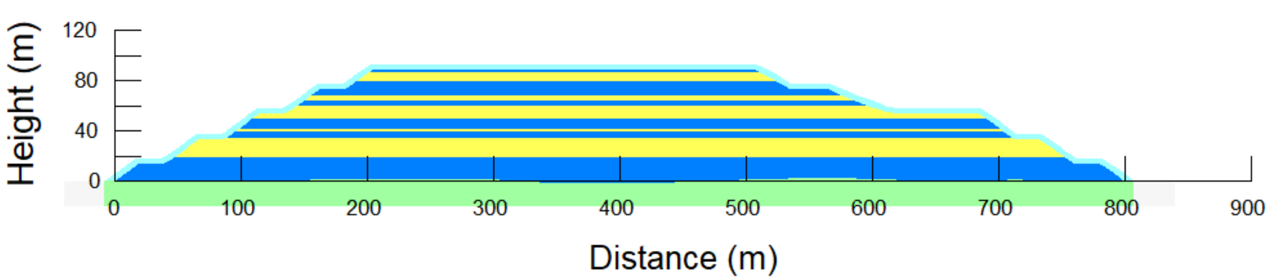

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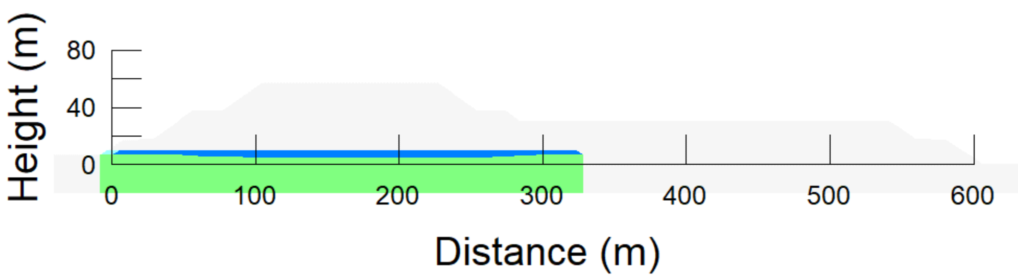

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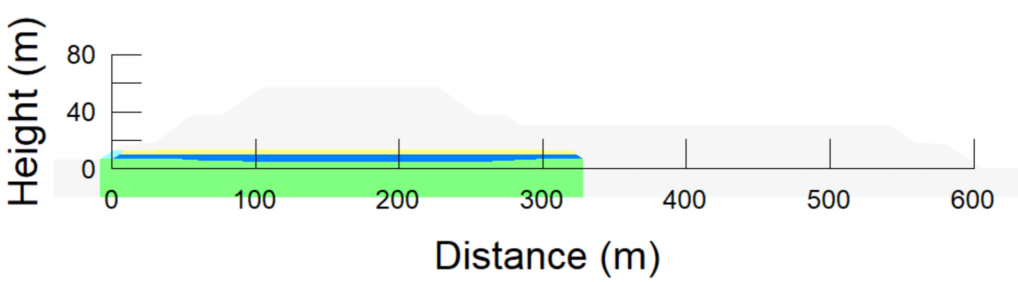

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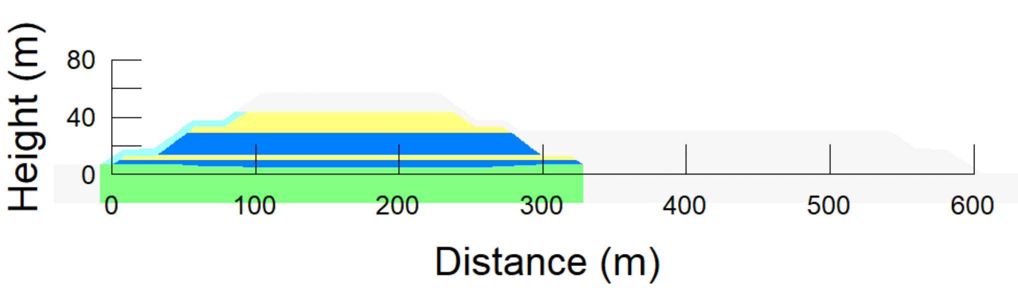

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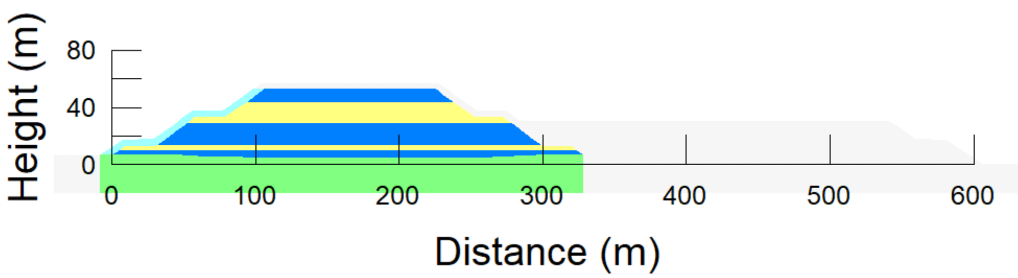

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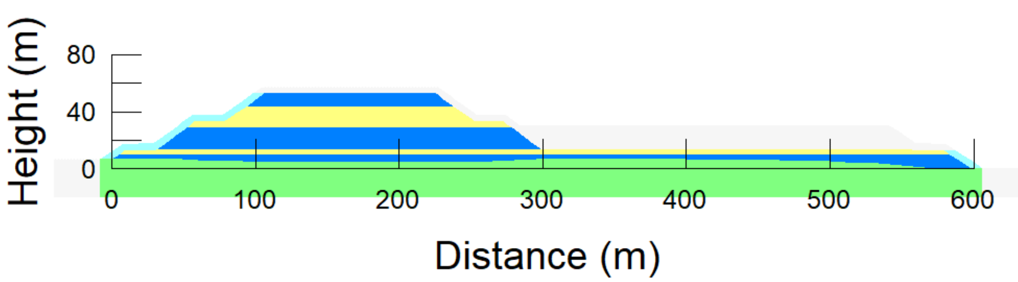

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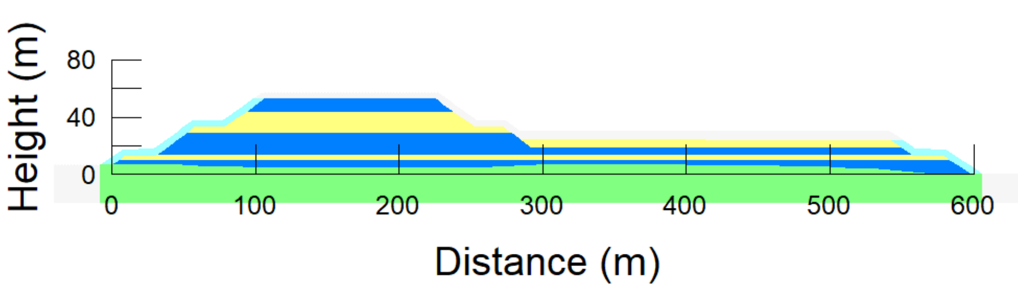

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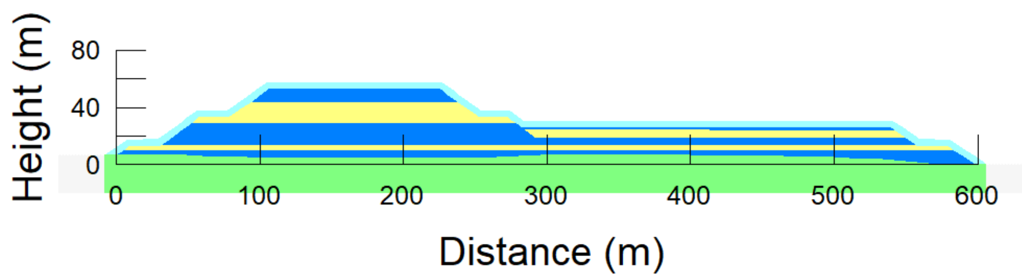
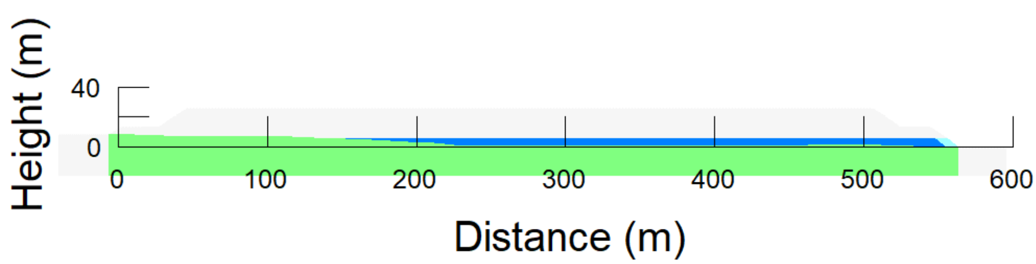


Section E - 2022



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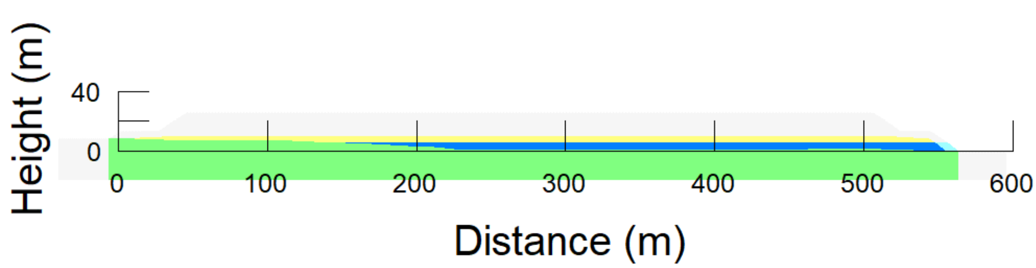

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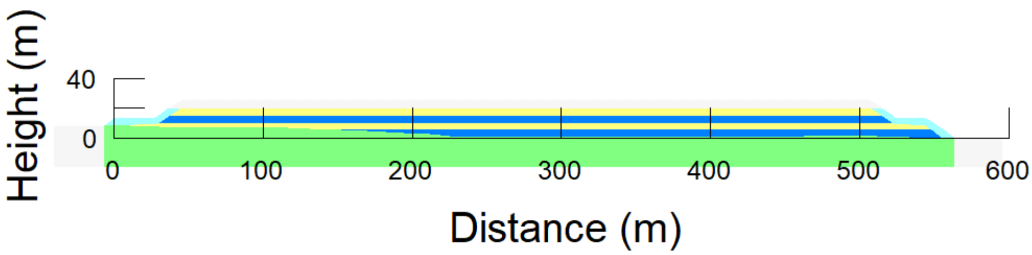

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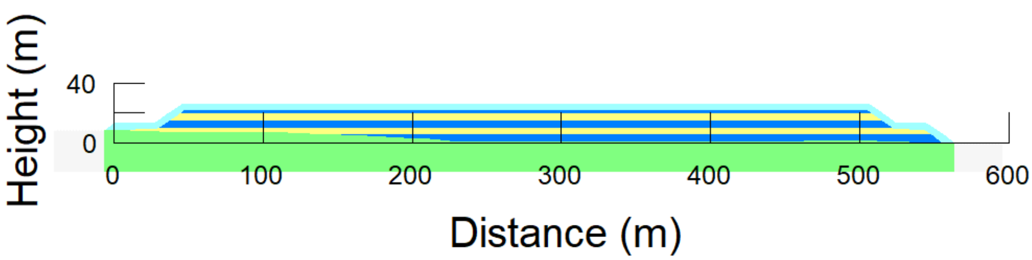
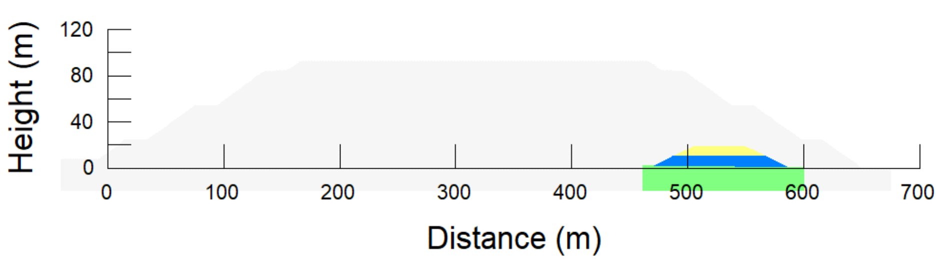
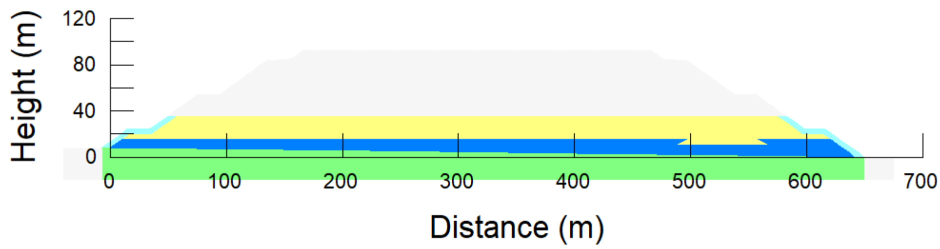


Section A – 30 m Bench - 2019

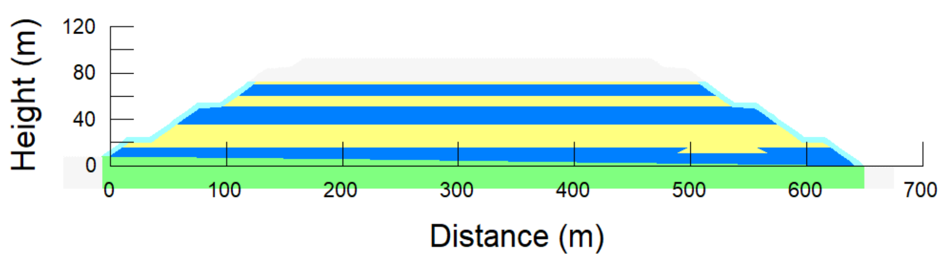


Section A – 30 m Bench - 2020

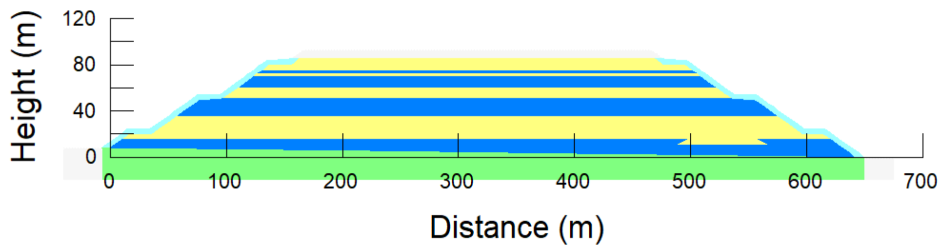


Section A – 30 m Bench - 2021

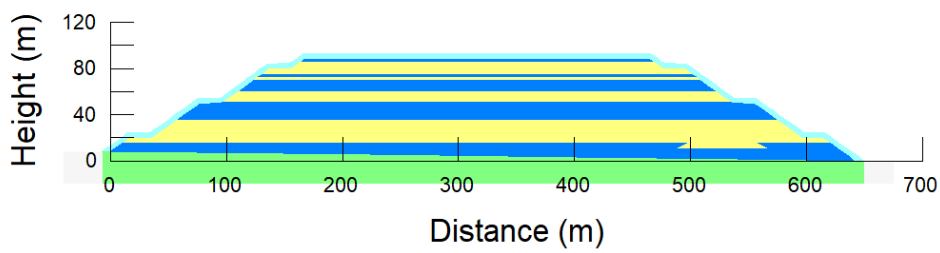
Section A – 30 m Bench - 2022



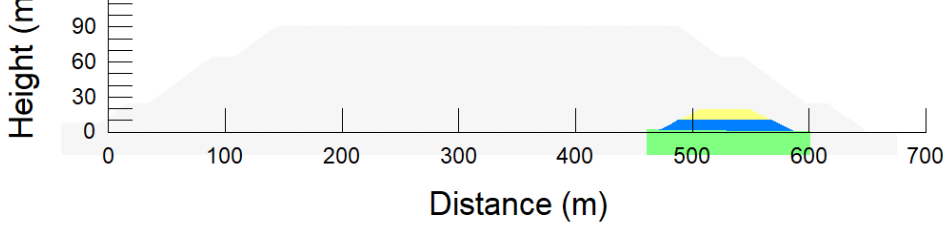
Section A – 30 m Bench - 2023



Section A – 30 m Bench - 2024



Section A – 40 m Bench - 2019



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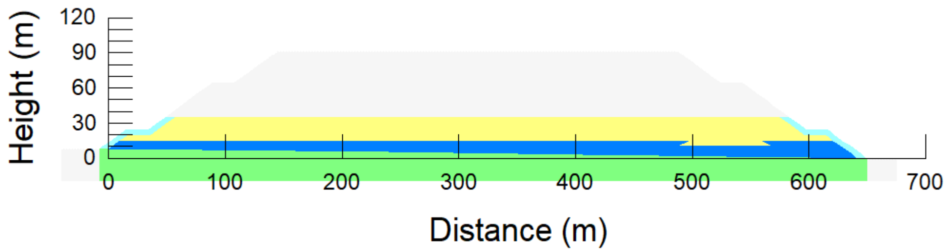

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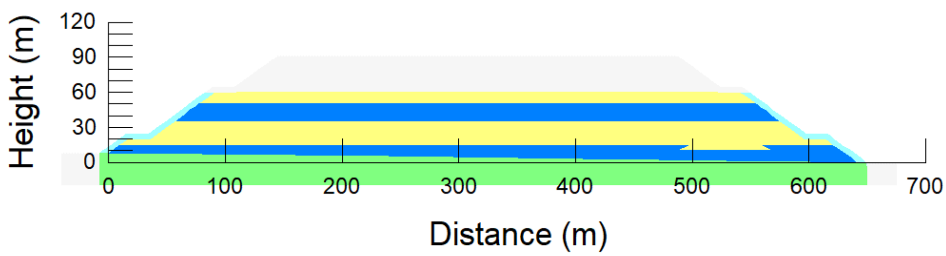

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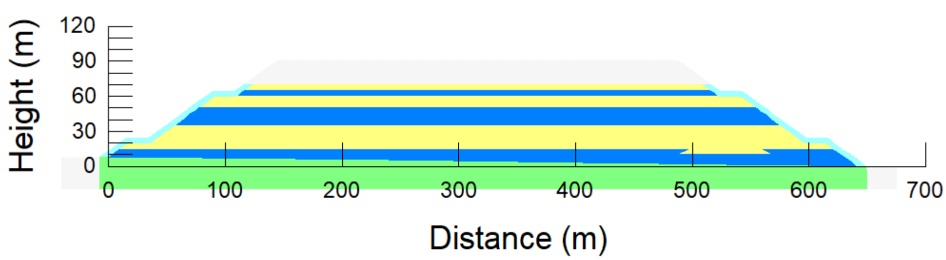

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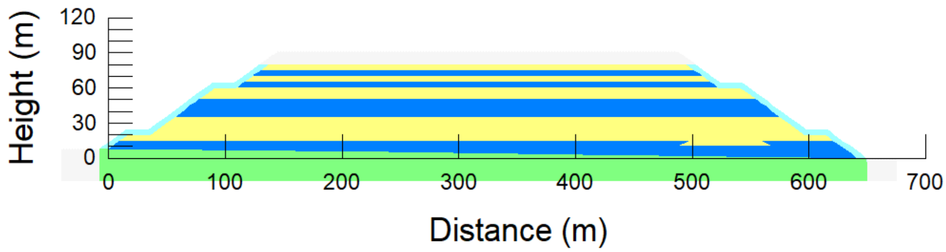

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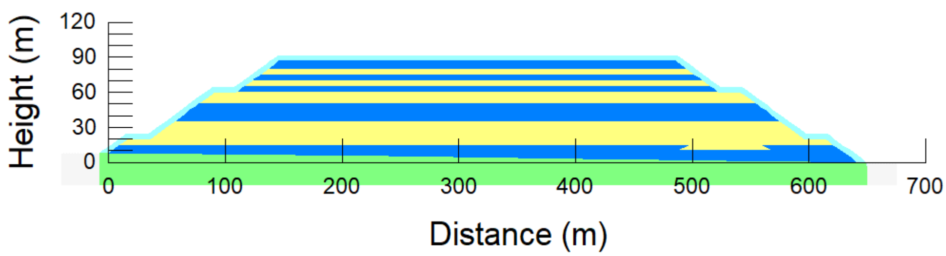

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