# GEOTHERMAL ANALYSIS OF PROPOSED WASTEWATER LAGOON NAUJAAT (REPULSE BAY), NU

**Prepared for:**

**Exp Services Inc.**
**Moncton, NB**

**Prepared by:**

**Naviq Consulting Inc.**
**Calgary AB**

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**GEOTHERMAL ANALYSIS OF PROPOSED WASTEWATER LAGOON: NAUJAAT, NU**

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## EXECUTIVE SUMMARY

This report provides details of geothermal analyses conducted in support of the design of a wastewater treatment lagoon berm structure near Naujaat (Repulse Bay), NU. The analyses considered a variety of conditions including climate warming, pore water salinity effects, snow drifting, and others.

A geothermal modelling study by Naviq Consulting Inc. addressing permafrost temperatures of a waste water lagoon was undertaken and reported to Exp Services Inc. (Exp) in 2013 (Naviq, 2013). In that analyses of that study there were several important aspects of the 2013 work that differ from the current study. Two factors were:

1. The 2013 analysis considered the presence of an existing water body at the time of lagoon construction. Details of the water body were uncertain; geothermal modelling considered several potential scenarios. As a result a pre-existing talik (unfrozen zone) was assumed to be present. The existence of a talik would negatively impact the seepage containment through the berms.
2. The climate warming rate applied in the 2013 was 0.16°C/year. This value was considered at the time to be very high. For the current analysis a more modest climate warming rate of 0.08°C/year was used based on a re-examination of the annual air temperature data through 2020.

Soil conditions were taken from a geotechnical report prepared for the project by Exp in 2013. Climatic and solar radiation data were taken from Environment Canada climate normals and National Research Council datasets, respectively.

The current seasonal active layer was assumed to be approximately 1.5 m.

The geothermal modelling indicates seasonal thawing of the lagoon berm to a depth of 1.8 m (based on the 0°C isotherm) below the crest on a seasonal basis after 30 years, with climate warming applied at 0.08°C/year.

For the site-specific conditions assumed, it is recommended that a controlling design isotherm of -2°C be used. This value includes an amount to account for freezing point depression from moderately saline soils and from potential dissolved solutes in the effluent, and for inherent uncertainties in some geothermal modelling input parameters.

Both the 2013 and the current geothermal modelling confirmed that the reliance on a frozen core dam concept as the primary containment method is not a long-term viable design strategy. Therefore, a liner or other barrier should be incorporated into the design. However, for the current design case where an impermeable liner extends from near the crest of the containment berm to 2 m below the natural ground elevation, the geothermal modelling showed the potential for long-term thawing to near the base of the cut-off liner and partially unfrozen soil behind the

liner at an elevation below the maximum annual fluid level in the lagoon. The maximum annual thaw within the berm was shown to be caused by a combination of unfrozen effluent in the lagoon and by the assumed climate warming. With partially unfrozen soil within the berm at locations below the liner and below the maximum annual fluid level in the lagoon, seepage could initiate through the containment berm in a progressively deteriorating process.

To address the risk of long-term thawing near the base of the impermeable liner the placement of a horizontal thermosyphon was considered to mitigate long-term thawing. The placement of a single horizontal thermosyphon along the length of the containment berm was shown by the geothermal modelling to provide long-term ground temperatures below the base of the cut-off liner colder than -2°C. However, placement of a horizontal thermosyphon at the base of the liner would not address seasonal thawing near the crest of the berm. The study also considered the installation of a thermosyphon placed immediately below the crest of the berm overlain by rigid polystyrene insulation. This latter arrangement was found provide improved thermal performance of the containment structure.

Comments are provided that discuss the issues of thermosyphons installation and additional design considerations.

It is recommended that drainage piping or access manholes in or through the containment structure be avoided because of a number of geothermal and geotechnical issues related to performance of the earthen berm structure.

**REVISION LOG**

The following table lists the changes made in this version of the report compared to previous revisions.

| Section/Figure | Description of Revision |
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## 1.0 INTRODUCTION

Naviq Consulting Inc. (Naviq) was retained by Exp Services Inc. (Exp) of Moncton, NB, to provide geothermal analyses with respect to the design of a municipal wastewater (sewage) treatment lagoon in Naujaat (formerly Repulse Bay), NU.

The primary scope of work was to conduct a geothermal assessment of the proposed lagoon containment berms to assess the geothermal behavior of the structure over its projected 30 year lifespan.

A Naviq report addressing geothermal modelling of a waste water lagoon at this site was undertaken and reported to Exp Services Inc. in 2013. The 2013 geothermal modelling confirmed that the reliance on a frozen core dam concept as the primary containment method is not a prudent design strategy. Furthermore, in the 2013 analysis there were several important aspects that differ from the current analysis. Two factors were:

1. The 2013 analysis considered the presence of an existing water body at the time of lagoon construction. Details of the water body were uncertain; geothermal modelling considered several potential scenarios. As a result, a pre-existing talik (unfrozen zone) was assumed to be present. The existence of a talik would negatively impact the seepage containment through the berms.
2. The climate warming rate applied in the 2013 was 0.16°C/year. This value was considered at the time to be very high. For the current analysis a more modest climate warming rate of 0.08°C/year; this rate was based on a re-examination of the annual air temperature data through 2020.

The objective of the thermal analysis was to determine if permafrost conditions would persist over the 30-year design life of the berm, under current normal climate conditions, and with a climate warming rate of 0.08°C/yr. Furthermore, an analysis was completed to assess the technical benefit for installation of a horizontal thermosyphon to maintain or enhance permafrost conditions within the central core of the containment berm. This report addresses the geothermal modelling of the proposed containment structure.

## 2.0 GEOTECHNICAL INVESTIGATIONS AND RELATED INFORMATION

Exp undertook a geotechnical investigation at the site of the proposed lagoon from October 3 to October 11, 2012. Seven boreholes were drilled within the proposed footprint of the proposed lagoon containment berms. This section provides a summary of the subsurface geotechnical conditions. For a full description of the site conditions, and other important details of the investigation and testing, the reader is referred to the geotechnical investigation report (Exp, 2013). It is noted that Naviq was advised that the current (2020) lagoon location may not be the same as the 2013 location and as such the geotechnical investigation conducted in 2013 may not be wholly applicable to the current analysis. Comments on additional/supplemental subsurface investigations are provided in Section 6.0.

### 2.1 Subsurface Conditions

The boreholes at the proposed lagoon site were advanced to depths of 1.2 m and 6.1 m. At the time of the geotechnical investigation, the active layer was assessed to be in the order of 0.5 m to 1.0 m.

The ground surface at the borehole locations consisted of a thin surface layer of organics or topsoil-like material. This layer was underlain by silt and sand with a minor fraction of gravel and clay sized material. The natural gravimetric moisture content of these soils was typically measured to be over 20 percent. Underlying the silt and sand stratum, sandy gravel or granitic bedrock was encountered. In Borehole 1 the sandy gravel encountered was less than 1 m thick and underlain by bedrock. In Borehole 4 and 6, no bedrock was encountered to a depth of 4.7 m and 1.2 m, respectively. In Borehole 5, bedrock was present from the ground surface.

Bedrock was assessed to consist of granite, being of good quality and generally unweathered.

Table 2.1 presents the subsurface stratigraphy that was used for the purposes of the geothermal analyses. The assumed 5 m thickness of unconsolidated materials overlying bedrock is considered a conservative approach for the assessment of containment transport via frozen soils.

Table 2.1 Subsurface stratigraphy used for the geothermal assessment

| Soil unit | Top of stratum (m) | Bottom of stratum (m) | Water content (%) | Dry density (kN/m$^3$) |
|---|---|---|---|---|
| Sand and gravel | 0 | 3 | 20 | 19 |
| Granitic bedrock (unweathered) | 5 | 20+ | 5 | 22 |

### 2.2 Ground Temperatures

Exp installed thermistor cables in two boreholes at the lagoon site in 2013. The ground temperatures were measured for several days in early October 2013. These short-term recorded temperatures are not sufficient to provide a full ground temperature profile. However, data from the Geological Survey of Canada (Ednie and Smith, 2015) provide additional local ground temperature data. Figure 2 presents these ground temperature data.

Based on this data, the mean annual ground temperature in Naujaat is approximately -8.0˚C, and the active layer is estimated to be 1.2 m deep.

### 2.3 Lagoon Structure Dimensions and Construction

The 2020 design drawings of the lagoon containment system were provided by Exp to Naviq. The majority of the planned containment berms appear to be placed within cut sections, likely into bedrock. Only the southwest side of the lagoon appears to have a conventional, above

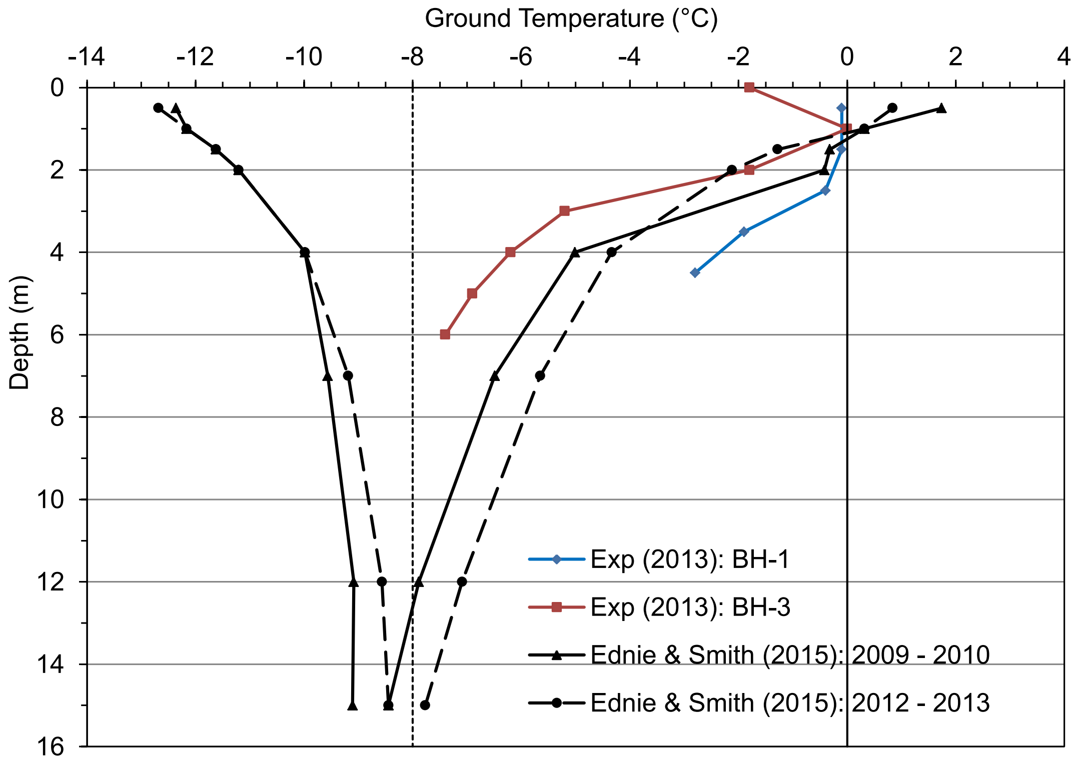


Figure 2.1 Ground temperature data for Naujaat, NU.

grade containment berm profile. For the geothermal modelling, the lagoon containment berm was assumed to have the following dimensions:

| | |
|---|---|
| Crest width | 4.2 m |
| Typical berm height | 5.5 m |
| Downstream face slope | 4.0H:1V |
| Upstream face slope | 3.0H:1V |

It was assumed that the containment structure will be constructed from locally available soils, placed in controlled lifts, and compacted in non-freezing conditions to achieve an engineered level of compaction. This construction method will necessitate construction in the summer months. Furthermore, this construction method is intended to avoid damage to the organic layer outside of the footprint of the lagoon structure.

The planned impermeable liner within the containment berm will extend 2 m below the existing grade, to be installed as berm construction proceeds. The presence of the liner was ignored in the geothermal analysis.

### 2.4 Hydraulic Conductivity of Native Soils

The ability of a containment berm and the native soils to retain lagoon effluent will depend in part on the hydraulic conductivity of these materials. Exp provided estimates of the hydraulic conductivity of the soils. Table 2.1 lists these values.

For this study an average hydraulic conductivity of the berm and subgrade soils was assumed to be 4.1 x $10^{-7}$ m/s. As part of this study, a preliminary analysis was conducted to assess seepage through an unfrozen containment berm and subgrade, with, and without an impermeable liner.

Table 2.1 Estimated hydraulic conductivity of overburden soils (Exp, 2013)

| Borehole number | Depth (m) | Soil Description | Estimated hydraulic conductivity (m/s) |
|---|---|---|---|
| 1 | 0.6 – 1.2 | Silt and sand, some gravel | 3 x $10^{-7}$ |
| 1 | 1.5 – 1.8 | Sandy gravel, some silt | 1.6 x $10^{-5}$ |
| 2 | 0.6 – 1.3 | Gravelly sandy silt | 4 x $10^{-8}$ |
| 3 | 3.1 – 3.3 | Silt and sand, trace gravel | 9 x $10^{-8}$ |
| 6 | 0.0 – 0.6 | Silty gravelly sand | 4.9 x $10^{-7}$ |
| 6 | 0.6 – 1.2 | Silty sand, some gravel | 6.4 x $10^{-7}$ |
| 7 | 1.5 – 1.7 | Gravelly silt and sand | 3.6 x $10^{-7}$ |

## 3.0 GEOTHERMAL ANALYSIS OF BERM CONTAINMENT STUCTURE

The geothermal performance of the lagoon berms is a function of the thermal energy balance between the atmosphere and the ground surface on and around the berms. As such, ground surface temperatures vary continuously throughout the year. When climate warming is considered in a geothermal model, the seasonal air temperature variations are increased at a specified constant rate over time. The mean annual ground temperatures will respond to long-term changes in the mean annual air temperature.

The controlling design temperature for the analysis should account for freezing point depression from pore water salinity and from dissolved solutes in the effluent, and for the inherent uncertainty of model input parameters.

This section outlines the various boundary conditions that have been applied to the physical problem and lists the various analyses considered. Numerical modelling results are presented in Section 5 of this report.

### 3.1 Numerical Model Input Parameters and Boundary Conditions

#### 3.1.1 Climatic Data and Climate Warming

The Hamlet of Naujaat is located at 66°31'17" N latitude, 86°13' 29" W longitude, near the southern end of Melville Peninsula. It is located in the continuous permafrost zone. Environment Canada climate normal data (1981 – 2010) indicate that the mean annual air temperature for Naujaat is -12.1°C. Reliable metrological data for the community is unavailable after about 2011. To account for long-term climate warming, the long-term mean annual air temperature

(MAAT) data for four other Nunavut communities was analyzed; Rankin Inlet (south), Cape Dorset (east), Hall Beach (north) and Kugaaruk (northwest). Figure 3.1 shows a map with these communities relative to Naujaat.

Figure 3.2 presents the 25 to 30-year MAAT data for each of these communities along with the linear warming trends. Table 3.1 lists the estimated air temperature warming rate from each of the communities. The average air temperature warming rate for the four communities over the 25 to 30-year time period was 0.06°C/year. To ensure conservatism, and recognizing other Baffin Island communities are experiencing air warming rates in the order of 0.08°C/year, is it was decided to use a warming rate of 0.08°C/year. Using this value, the 1981 to 2010 climate normal mean monthly air temperatures were extrapolated from 2010, rendering a 2019 mean monthly air temperature of -11.4°C.


Figure 3.1 Map showing location of Naujaat relative to communities used to assess long-term climate warming and wind speed.

Table 3.1 Estimated climate warming rates for four communities.

| Community | MAAT warming rate (°C/year) |
|---|---|
| Rankin Inlet | 0.068 |
| Cape Dorset | 0.068 |
| Hall Beach | 0.059 |
| Kugaaruk | 0.05 |
| Average | 0.061 |
| Climate warming rate for Naujaat geothermal modelling | 0.08 (see text) |

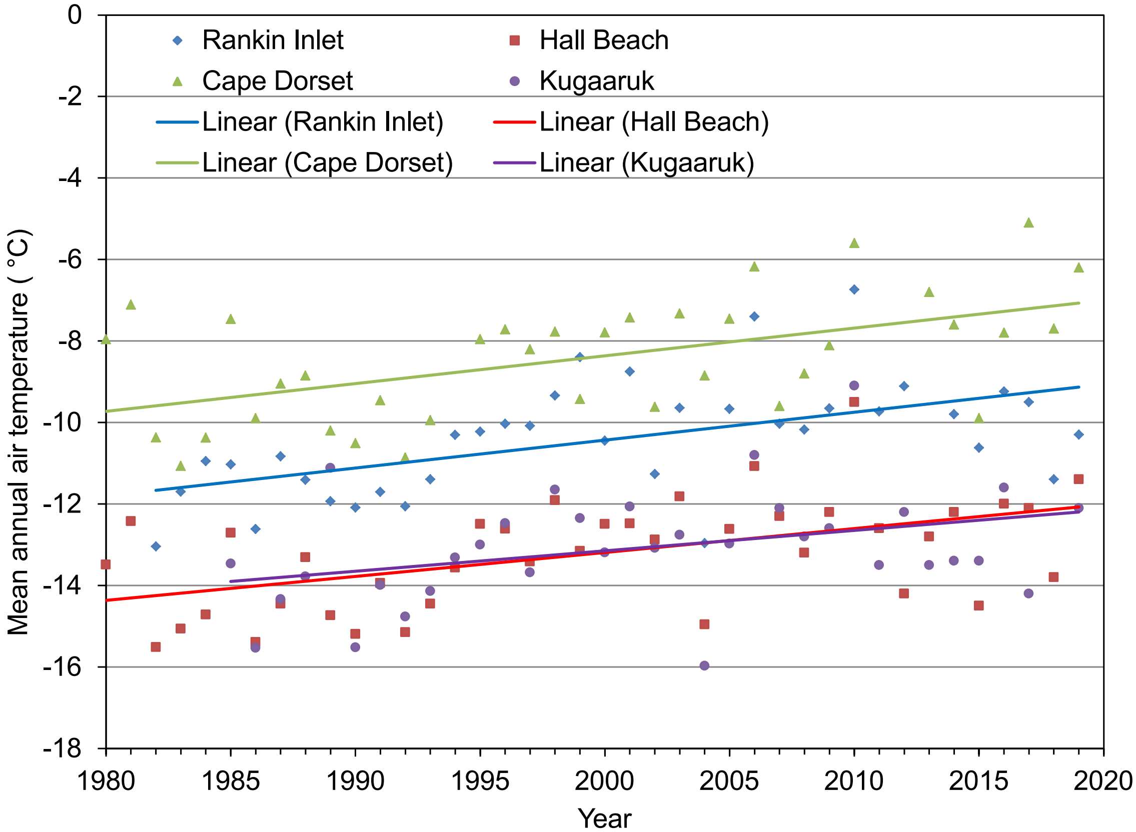


Figure 3.2 Long-term MAAT data for four communities used to assess climate warming for Naujaat.

Canadian Standards Association (CSA, 2010) published predicted climate warming scenarios for northern Canada based on the use of several global circulation models. For the mid-Arctic latitude zone of eastern Canada, an average air temperature rise of 1.3°C between 2011 and 2040 is predicted. This represents an annual air temperature increase of approximately 0.04°C, which is considerably lower than the warming rate based on historical air temperature data for this region, discussed above.

Climate warming was modelled by increasing normal monthly air temperatures by 2.4°C (equivalent to 0.08°C/year over 30 years) and then running the model to reach dynamic steady-state, which is a state where ground temperatures vary seasonally throughout the year but are stabilized year-to-year. This approach is a computationally efficient way to model climate warming and is considered conservative for this project because it results in a mean annual ground temperature increase faster than would be experienced in reality. The current approach is conservative when considering ground temperatures at depth, but the approach will result in near surface ground temperatures that would be similar to a ramped climate warming approach.

Total annual snowfall is about 1.8 m. Snow and sub-freezing temperatures are possible all year-round.

Table 3.2 lists the meteorological data inputs for the geothermal modelling acquired from Environment Canada and Natural Resources Canada.

### 3.1.2 Geothermal Material Properties

Table 3.3 present the thermal properties of the two soil units used in the modelling.

Table 3.2 Metrological Input for geothermal model.

| Month | Mean monthly air temperature[1] (°C) | Mean daily snow thickness[2] (mm) | Mean monthly wind[3] (kph) | Solar radiation[4] ($W/m^2$) |
|---|---|---|---|---|
| January | -30.6 | 209 | 19.9 | 5.0 |
| February | -30.7 | 181 | 19.9 | 30.0 |
| March | -25.1 | 203 | 20.0 | 99.2 |
| April | -16.4 | 208 | 20.2 | 192.5 |
| May | -6.2 | 152 | 20.0 | 258.3 |
| June | 3.8 | 22 | 18.4 | 263.8 |
| July | 9.5 | 0 | 17.5 | 224.2 |
| August | 7.5 | 0 | 19.1 | 152.5 |
| September | 1.6 | 5 | 21.3 | 82.1 |
| October | -6.6 | 80 | 24.2 | 34.2 |
| November | -18.1 | 125 | 23.1 | 8.8 |
| December | 25.1 | 213 | 20.7 | 1.7 |
| Average | -11.4 | 117 | 20.4 | 112.9 |

Notes: 1. Extrapolated from Environment Canada 1981-2020 climate normal values for an annual air warming rate of 0.08°C/year from 2010 to 2019.
2. From Environment Canada 1981-2010 climate normals.
3. No station data for wind speed is available. Monthly wind speed was estimated as taken as the average monthly wind speed for Rankin Inlet, Cape Dorset and Hall Beach, from Environmental Canada 1981-2000 climate normal values.
4. From Natural Resources Canada, accessed online: http://www.nrcan.gc.ca/18366.

Table 3.3 Thermal data of soils for input to geothermal model.

| Material | Thermal Conductivity Thawed (W/m-°C) | Thermal Conductivity Frozen (W/m-°C) | Water Content (g/g) | Unfrozen Water Content Parameter A | Unfrozen Water Content Parameter B | Dry Density (kg/m$^3$) | Heat Capacity Thawed (kJ/d-m-°C) | Heat Capacity Frozen (kJ/d-m-°C) |
|---|---|---|---|---|---|---|---|---|
| Sand and gravel | 2.2 | 3.1 | 0.02 | 0.02 | -0.41 | 1700 | 2630 | 1920 |
| Granitic Bedrock (unweath weath-ered) | 4.0 | 4.0 | 0.05 | 0.005 | -0.90 | 2200 | 1988 | 1777 |

#### 3.1.3 Ground Temperatures and Permafrost Depth

Ground temperatures were measured at the proposed lagoon site by Exp during their geotechnical investigations. Figure 2.1 present these data.

Mean annual ground temperatures, based on the available data are expected to be in the order of -8.0°C.

Permafrost is likely to extend over 300 m below ground surface.

#### 3.1.4 Soil Pore Water Salinity

The soils in the Baffin Island region are known to contain dissolved salts within the soil pore water. The effect of salinity is to depress the freezing and thawing temperature below 0°C. This means that saline soils will freeze and thaw at temperatures colder than 0°C and this depressed temperature must be used to assess the freeze-thaw behaviour of the soils.

Exp (2013) did not report soil salinity for the project site. Hivon and Sego (1993) reported on the pore water salinity of soils across northern Canada. They reported salinities in Naujaat (Repulse Bay) in the range of 0.5 to 10.4 PPT.

From the above information it is considered prudent to assume a conservative soil pore water salinity of about 8 PPT. Freezing point depression is a linear function of pore water salinity. For soil pore water with a salinity of 35 PPT, the freezing point will be depressed to about –2°C. For this analysis a soil salinity of 8 PPT was assumed, with a corresponding freezing/thawing temperature of about -0.5°C.

#### 3.1.5 Lagoon Content Elevation and Temperatures

The elevation and temperature of the lagoon contents will be seasonally variable and transient over the life of the structure. It is understood that the lagoon berm height and lagoon volume is based on projected community population growth over the next 30 years. Hence, full lagoon sewage elevations are not expected to be reached for many years.

The operation of the lagoon assumes that the effluent will be removed seasonally, typically between early August and mid-September each year. Refilling of the lagoon would occur from September through July of the following year.

As one potentially conservative assumption for the geothermal analyses, a continuously full lagoon was assumed. The assumption of the fixed lagoon elevation is considered to be conservative, in that it may consider the case where the lagoon is not drawn down for several years on a seasonal basis, as is normal practice.

For the lagoon contents, a single temperature regime was considered. The lagoon temperature was assumed to be +0.5°C all year around. In a previous study (Naviq, 2008) for a sewage lagoon at Clyde River, NU, Naviq compared two scenarios for lagoon temperatures where in the first case the lagoon temperature was held constant at +1°C all year around, and in the second case the temperature of the surface of the lagoon varied according to seasonal conditions, with higher surface temperatures when the lagoon was empty in late summer, and cooler, but still "warmer than ambient" temperatures during the winter months. Comparison of the results of this modelling showed that the constant positive temperature approach was more conservative and was therefore adopted for this study.

## 3.2 Model Domain

The two-dimensional (2D) model domain extended 40 m vertically and 120 m horizontally, as shown in Figure 3.3. The boundaries were set far enough from the berm location that they would not affect the computed temperatures near the berm. The general location of the existing ground surface was set to an elevation of 0 m in the model domain. The berm geometry as follows: crest elevation 5.5 m above original ground surface, crest width 4.2 m, lagoon-side slope 3:1, downstream slope 4:1, coarse-grained mineral soils to a depth of 5.0 m overlying bedrock.

For reference, the assumed horizontal high and low lagoon fluid level lines on the lagoon-side of the berm are shown on Figure 3.3. Also shown is the location of the liner within the berm provided by Exp.

The finite element mesh was developed to provide higher density of nodes in locations with high thermal gradients and consisted of 5593 nodes and 5520 elements.

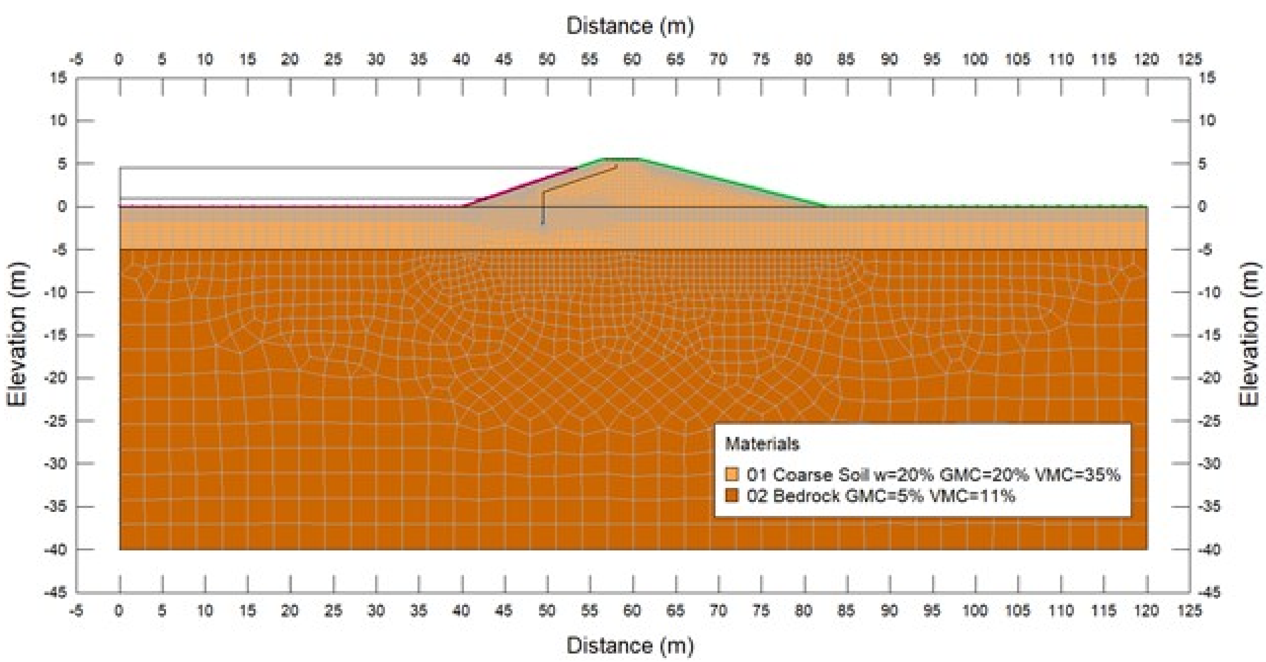


Figure 3.3 Thermal model domain

### 3.3 Geothermal Analysis Scenarios and Model Calibrations

Geothermal analyses were conducted using the commercial program TEMP/W, developed by Geo-Slope International. This program is capable of analyzing a variety of complex temperature problems, both steady-state and transient in nature. Both one-dimensional and two-dimensional problems can be modelled.

The first modelling step was to perform a one-dimensional model calibration whereby climate data representative of Naujaat were input to the model, and calibration was performed such that the model-calculated mean annual ground temperatures were representative of Naujaat. The purpose of the calibration was to establish the surface boundary conditions (surface energy balance) that result in ground temperatures typical of the local environment. The meteorological inputs included mean monthly data for air temperature, wind speed, solar radiation, and snow cover, together with ground properties such as winter and summer surface albedos (reflectivity), and evapotranspiration factors.

The geothermal analyses were performed to provide the expected long-term berm temperatures for the following cases:

- Case1 - Current normal climate conditions without a horizontal thermosyphon.
- Case 2 – Same as Case 1 except with climate warming at 0.08°C/year for 30 years (2.4°C total air temperature increase).
- Case 3 - Current climate conditions (same as Case 1) but with a horizontal thermosyphon located below the liner beneath the upstream slope of the berm (50 m evaporator length, 13 $m^2$ radiator area).
- Case 4 - Climate warming conditions (as in Case 2) but with horizontal thermosyphon (as in Case 3).
- Case 5 - Identical to Case 4 except with a horizontal thermosyphon located beneath the downstream slope of the berm.
- Case 6 - Identical to Case 5 except with the horizontal thermosyphon moved horizontally to a location beneath the crest of the berm.
- Case 7 - Identical to Case 5 except with the horizontal thermosyphon located 1.5 m below the centerline of the crest of the berm and overlain by a 50 mm thick layer of rigid insulation, buried 0.3 m below the crest of the berm.

The ground surface away from the effluent containment areas (that is, remote from the lagoon on the downstream face of the containment berm) was modelled using a surface energy balance (SEB) boundary condition based on the normal climate data for the site presented in the previous section. Using a separate one-dimensional thermal analysis, the pre-construction (undisturbed) thermal model was calibrated by varying the average long-term thermal conductivity of the snow cover such that the SEB boundary condition for the undisturbed ground surface reproduced the target mean annual ground temperature of -8°C at 10 m depth.

For the post-construction thermal analysis cases (with berm), it was assumed that snow drifting would increase the snow depth on both slopes of the berm; accordingly, to simulate snow drifting, the time-dependent snow thickness for the SEB boundary condition was increased by a factor of two along lagoon-side of the berm from the berm crest to the elevation of the fluid level, and along the entirety of the downstream berm face from the crest to the original ground surface elevation and then along the horizontal ground surface for an additional 4.0 m.

The ground surface and berm slope beneath the fluid in the lagoon was modelled using a constant temperature boundary condition of +0.5°C.

The horizontal thermosyphon was modelled by assuming that the horizontal evaporator section was 50 m in length with a radiator area of 13 $m^2$. Increasing the length of the evaporator section or decreasing the radiator area would each decrease the heat extraction per unit length of the thermosyphon evaporator section. Similarly, greater heat extraction per unit length of the thermosyphon evaporator section can be obtained by decreasing the evaporator length or increasing the radiator area. Parametric assessment of these thermosyphon variables were outside the scope of work reported here.

## 4.0 PRELIMINARY SEEPAGE ANALYSIS RESULTS

Before the thermal analyses proceeded, a check of the upper-bound fluid seepage rate through the berm was completed for the case with no permafrost (i.e., no containment provided by frozen soil), both with, and without, the liner system.

Figure 4.1 shows steady-state seepage through the berm and native subgrade in an unfrozen state including head contours, the phreatic surface (water table), and flow lines. The primary objective of this analysis was to determine the location of the phreatic surface downgradient of the liner and to determine the upper-bound fluid flow rate through the berm in the absence of permafrost.

The hydraulic conductivity for the berm soil of $4.1 \times 10^{-7}$ m/s was calculated as the geometric average of seven estimated hydraulic conductivity values of overburden soils provided by Exp (email communication, April 16, 2020). See Table 2.1.

The seepage analysis showed that the flow through the unfrozen berm and subgrade with the liner installed to a depth of 2.0 m below the original ground surface (with 3.0 m of coarse-grained soil remaining below that depth to the bedrock at 5.0 m depth) was 0.025 $m^3$/day per meter length of berm (equivalent to 2.5 $m^3$/day for each 100 m of berm length). Another steady-state seepage analysis completed without the liner showed that the seepage through the unlined and unfrozen berm was 0.35 $m^3$/day per metre length of berm. Hence, in the event that permafrost was not a fluid containment mechanism, the liner would reduce the fluid flow through the berm by only about 30%.

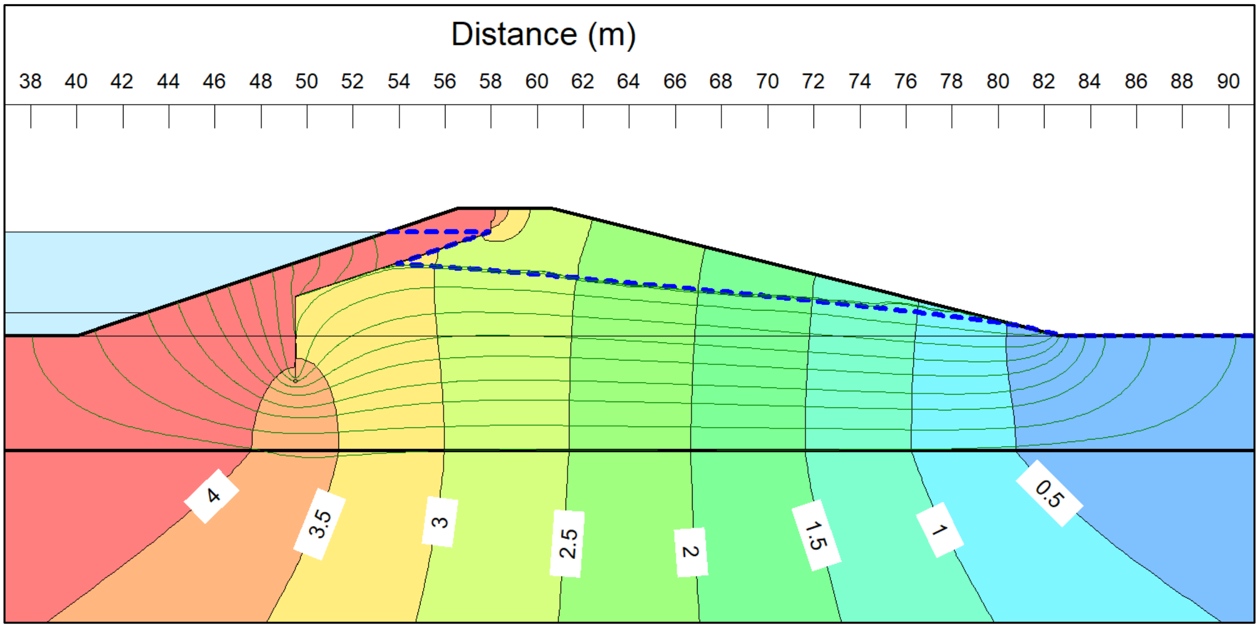


Figure 4.1 Steady-state seepage head contours and flow lines through unfrozen berm with liner.

For seepage control using an impermeable liner, it is essential that the elevation of the top of the liner be higher than the maximum effluent level in the lagoon.

## 5.0 GEOTHERMAL MODELLING RESULTS

This section addresses the results of the geothermal modelling described in Section 3. In interpreting geothermal modelling the results are a reflection of the assumptions made as input parameters and boundary conditions. If these values are representative of the actual conditions, then the results should be comparably representative of the future conditions.

For design purposes, it is prudent to incorporate conservatism to account for uncertainty in the model input parameters. For example, conservatism can be incorporated by using a colder design temperature than would be normally needed. In this case the controlling parameter is the thawing temperature of the soils, which is estimated to be -0.5°C when pore water salinity is accounted for. For design purposes therefore, it is proposed that the design temperature be assigned as -2°C, one and one-half degrees below the salinity based freezing/thawing temperature of the soil. In the discussion of the thermal results, we assume seepage may occur at temperatures warmer than -2°C.

### 5.1 Long-Term Berm Temperatures without a Horizontal Thermosyphon

Thermal analyses were completed to assess the long-term berm temperatures with high and low lagoon fluid levels under normal climate conditions and under climate warming conditions.

Although the berm fluid level will vary during the year because of fluid decanting in August each year and gradual refilling of the lagoon over the subsequent 12 months, the two fluid level extremes were considered to assess the permafrost conditions in the berm under these two bounding cases. For each of these cases, the thermal analysis considered a constant effluent level throughout the year (i.e., continuous high or continuous low fluid level). In addition, these two cases were considered under normal climate conditions (circa 2020 mean monthly air temperatures) and under conditions of 30 years of climate warming at 0.08°C/year. The climate warming was applied as step-change air temperature increase of +2.4°C above the 2020 monthly air temperatures and the simulation was run long enough to achieve dynamic steady-state. These combinations of variables established the first four thermal analysis cases.

In all of the thermal analysis cases, it was assumed that there was no convective heat transfer via groundwater flow; hence, all heat transfer within the berm and subgrade was by heat conduction.

Figure 5.1 shows the berm temperatures in late August for Case 1 (normal climate, high fluid level, no thermosyphon) and Figure 5.2 shows results for Case 2 which is identical to Case 1 except that a low fluid level was considered. Late August was chosen for comparison of results as this is when thaw depth is deepest and the ground temperatures within the berm are generally the warmest. Comparison of Figure 5.1 and Figure 5.2 shows that the temperatures at the base of the liner for the high and low fluid level cases are -1.2°C and -2.9°C, respectively. Hence, warmer berm soil temperatures occur when the lagoon fluid level is higher.

As shown in Figure 5.1, the -2°C design isotherm in late August is at an elevation of approximately -3.5 m below the base of the liner. This implies that effluent seepage could occur by

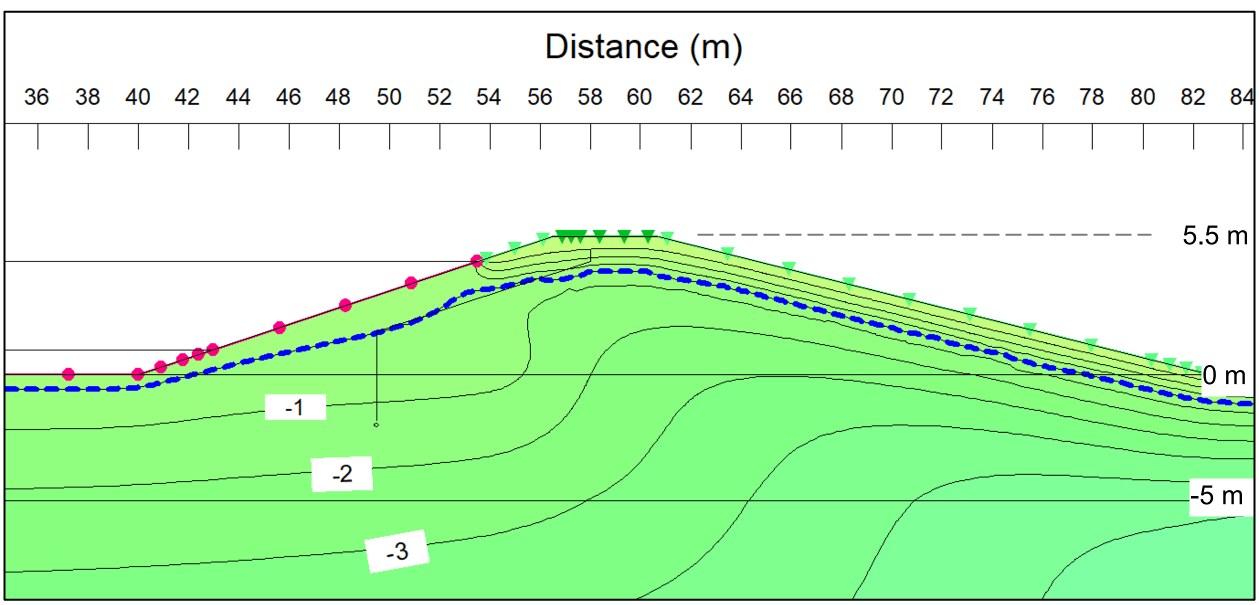


Figure 5.1 Case 1: Berm temperatures (late August), normal climate, high fluid level, no thermosyphon, no groundwater flow.

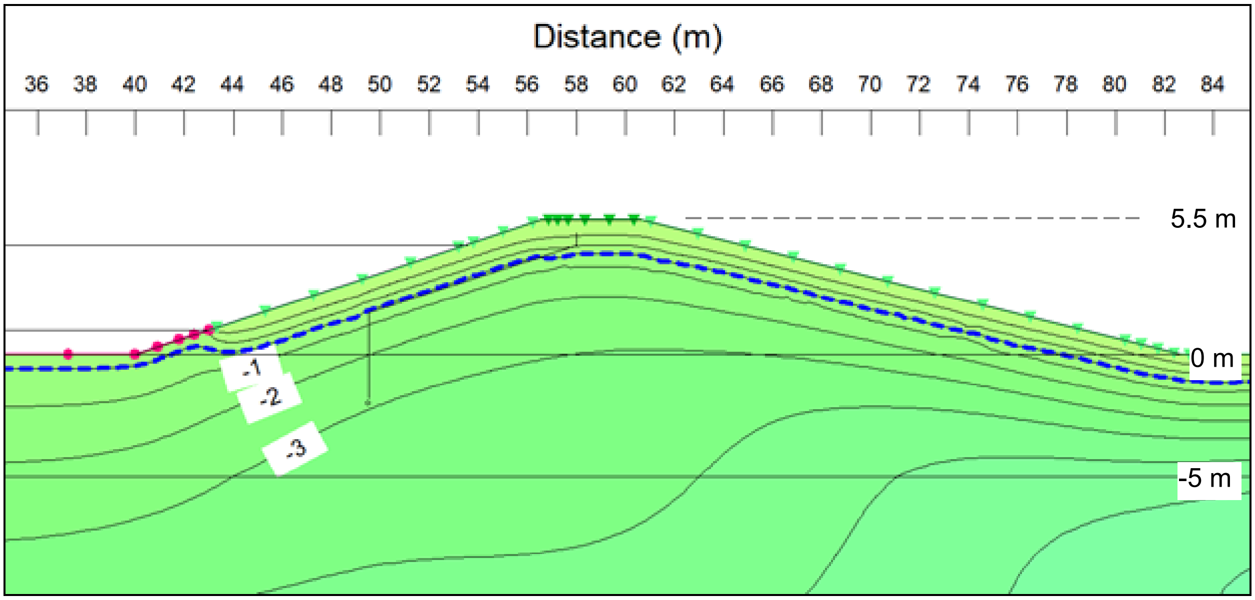


Figure 5.2 Case 2: Berm temperatures (late August), normal climate, low fluid level, no thermosyphon, no groundwater flow.

passing around the base of the liner. In the event that there was a leak in the liner, then lagoon fluid would overtop the maximum permafrost elevation (that is, through the seasonal active layer and freezing point depressed zone) and flow down the other side; this would introduce heat into the interior of the berm, thaw the frozen soil within the berm, decrease the maximum elevation of the frozen soil, and hence produce a positive feedback loop whereby increased thawing causes increased flow, which in turn causes even more thawing and fluid flow though the berm.

Considering the design isotherm of -2°C, it is seen that approximately one-half of the berm structure thaws during late summer (Figure 5.2) for the case where the lagoon is maintained in a continuously full condition.

Figure 5.3 and Figure 5.4 (Cases 3 and 4, respectively) were the same as Cases 1 and 2 except with the addition of climate warming (0.08°C/year over 30 years resulting in a +2.4°C increase in air temperature). For the high fluid level case (Figure 5.3) the temperature at the base of the liner in late August is about -1.2°C, which is the same temperature as for Case 1 without climate warming. The two cases have essentially identical temperatures regimes because in both cases the lagoon fluid temperature dominates the ground temperatures beneath the lagoon. Again in Case 3, a fluid leak through the liner near maximum lagoon fluid level would overtop the elevation of the -2°C isotherm within the berm, and fluid flow through the berm subsequently increase via thaw of frozen soil in the berm. The -2°C isotherm below the liner base is at an elevation of about -4.5 m, nearly 2.5 m below the base of the liner. This suggests that effluent seepage around the base of the liner is possible.

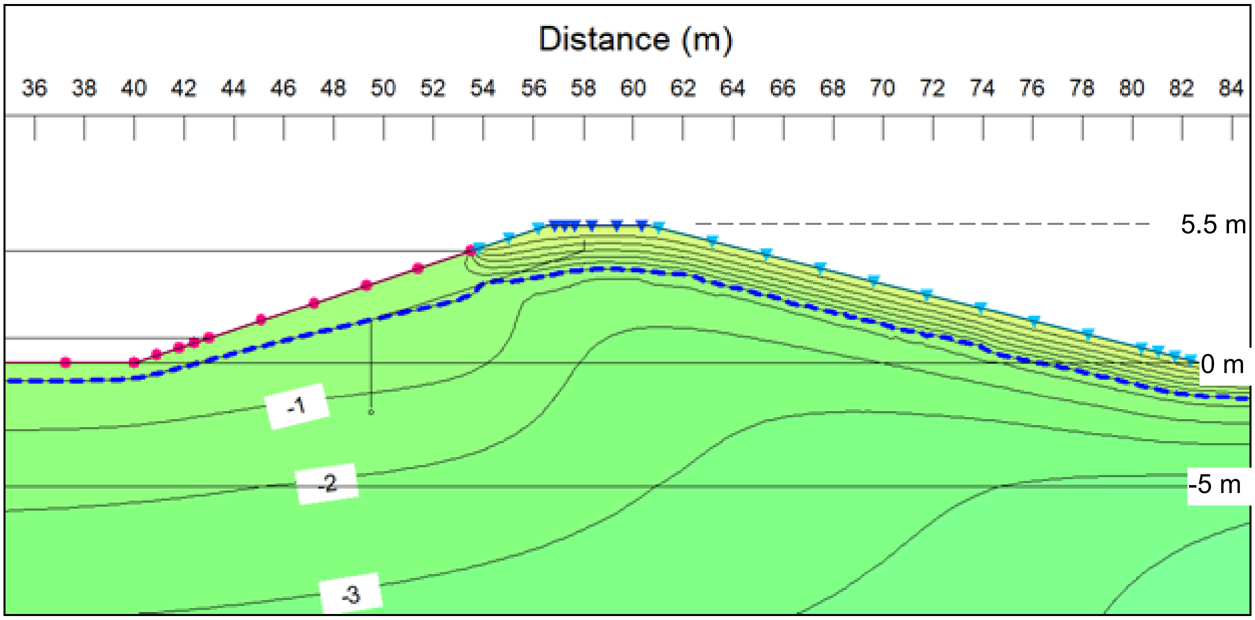


Figure 5.3 Case 3: Berm temperatures (late August) with climate warming (0.08°C/year for 30 years), high fluid level, no thermosyphon, no groundwater flow.

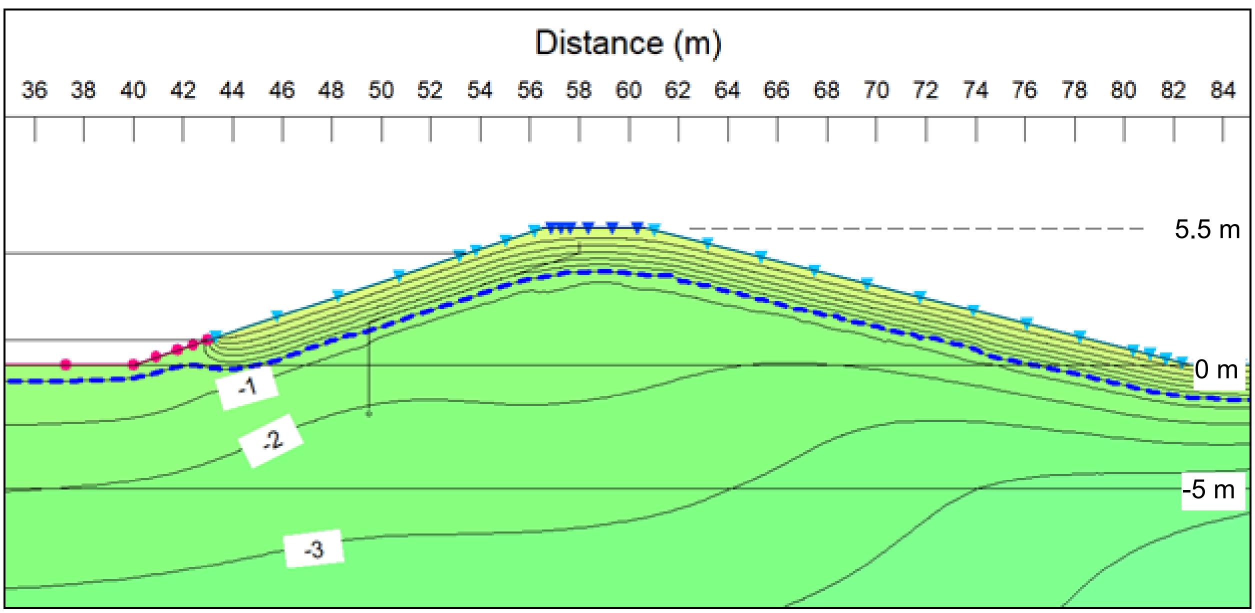


Figure 5.4 Case 4: Berm Temperatures (late August) with climate warming (0.08°C/year for 30 years), low fluid level, no thermosyphon, no groundwater flow.

For the low fluid level case (Figure 5.4), the temperature at the base of the liner is about -2.0°C (compared to -2.9°C for the case without climate warming, Figure 5.2). Even in this case (Case 4), if the fluid level was maintained low for an extended period of one or more years and then filled to the highest fluid level, any leak in the mid to upper section of the liner system would overtop the maximum elevation of the frozen soil in the berm.

### 5.2 Long-Term Berm Temperatures with a Horizontal Thermosyphon

Based on comparison of the high and low fluid level cases presented above, Case 3 (Figure 5.3) is considered to be the design case in the event additional thermal mitigation is not provided to assist with effluent containment. It is seen that the temperature at the bottom of the impermeable liner is warmer than the design isotherm of -2°C. Thus, considering a design isotherm of -2°C, this scenario does not represent a viable long-term design case.

Figure 5.5 and Figure 5.6 show the 30-year berm and subgrade temperatures in late February and in late August, respectively, when a horizontal thermosyphon (50 m evaporator length, 13 $m^2$ radiator area) is located directly below the base of the liner. Comparison of Figure 5.6 (Case 5) and Figure 5.3 (Case 3) show that in late August the soil temperatures at the base of the liner are -2.0°C and -1.2°C, respectively, indicating that the thermosyphon provides colder frozen soil temperatures. However, the -2°C thaw isotherm is at an approximate depth of 3.5 m below the crest of the berm, or about 2.5 m below the maximum fluid level in the lagoon. Hence, although the thermosyphon enhances frozen ground temperatures at the base of the impermeable liner, there remains a pathway for fluid flow through the berm over the top of the frozen zone should there be any fluid leaks in the upper liner system.

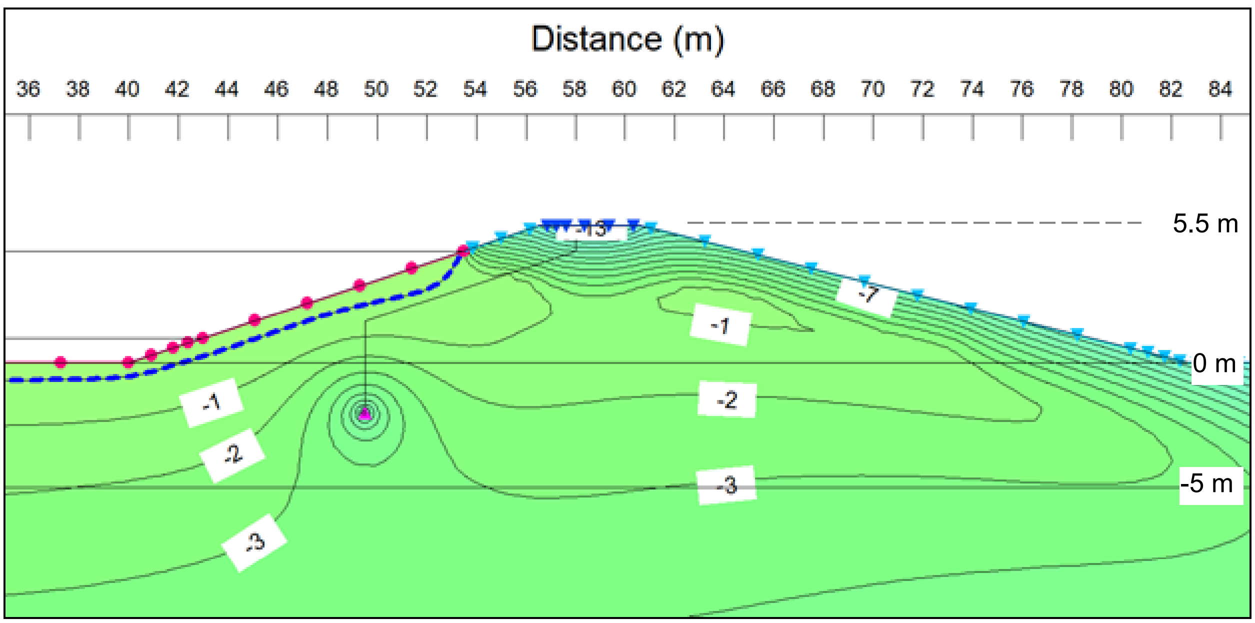


Figure 5.5 Case 5: Berm Temperatures (late February) with climate warming (0.08°C/year for 30 years), high fluid level, thermosyphon below berm slope, no groundwater flow.

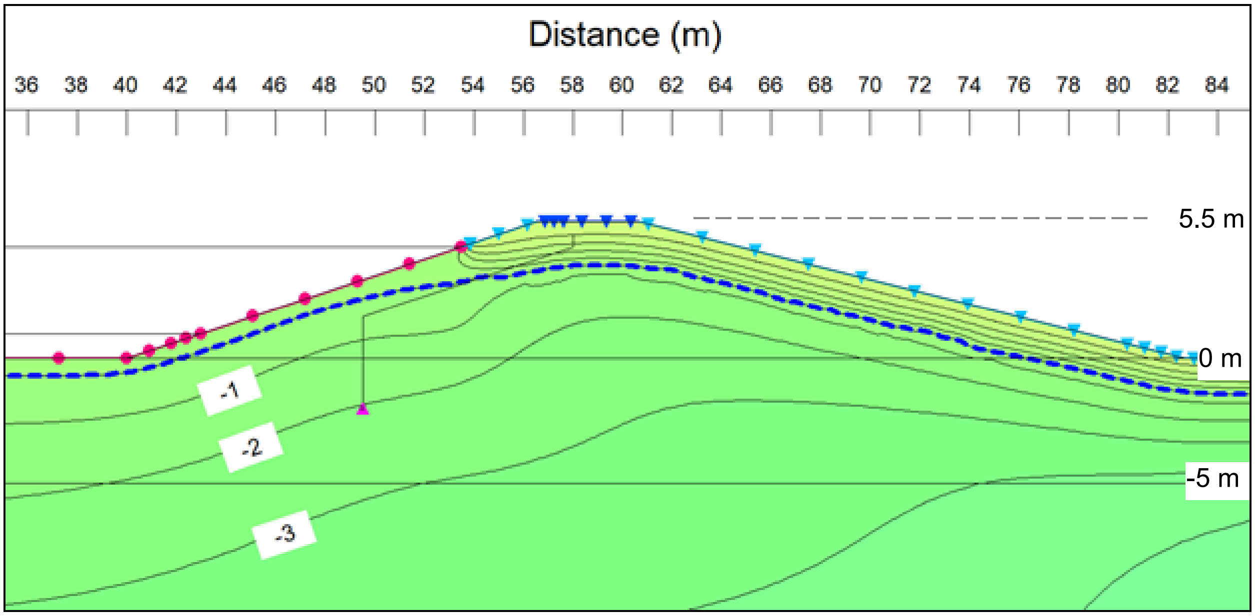


Figure 5.6 Case 5: Berm Temperatures (late August) with climate warming (0.08°C/year for 30 years), high fluid level, thermosyphon below berm slope, no groundwater flow.

A thermal analysis was then completed to determine if moving the horizontal thermosyphon evaporator section towards the central part of the berm would provide improved colder berm temperatures, Figure 5.7 and Figure 5.8 show the thermosyphon location and the berm temperatures in late February and late August, respectively. February berm temperatures are well frozen with the interior upstream face at -2°C. Within the central berm area in late August (Figure 5.8), the revised placement of the horizontal thermosyphon does not lessen the annual maximum depth of the -2°C isotherm, and hence in the event of a leak in the upper part of the liner, effluent could still overtop the frozen zone in this case.

Finally, the scenario was considered where a horizontal thermosyphon was placed 1.5 m below the crest of the containment berm, overlain with 50 mm of rigid extruded polystyrene insulation buried 0.3 m below the surface of the crest. Figure 5.9 presents the 30-year climate warming results for late August. For this scenario, the entire central core of the containment berm remains frozen through the summer, providing secondary containment. The -1.5°C isotherm would be above the maximum lagoon fluid level and the -2.0°C isotherm would be just below the maximum lagoon fluid level in late August, corresponding to the start of the annual decant of the lagoon.

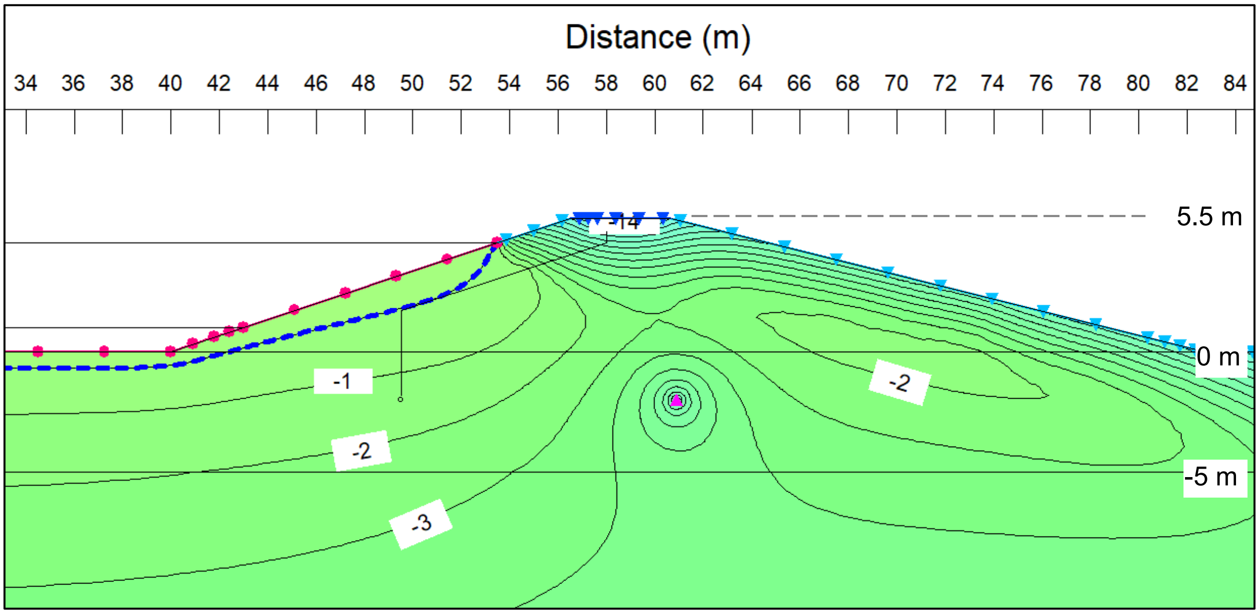


Figure 5.7 Case 6: Berm Temperatures (late February) with climate warming (0.08°C/year for 30 years), high fluid level, thermosyphon below berm crest, no groundwater flow.

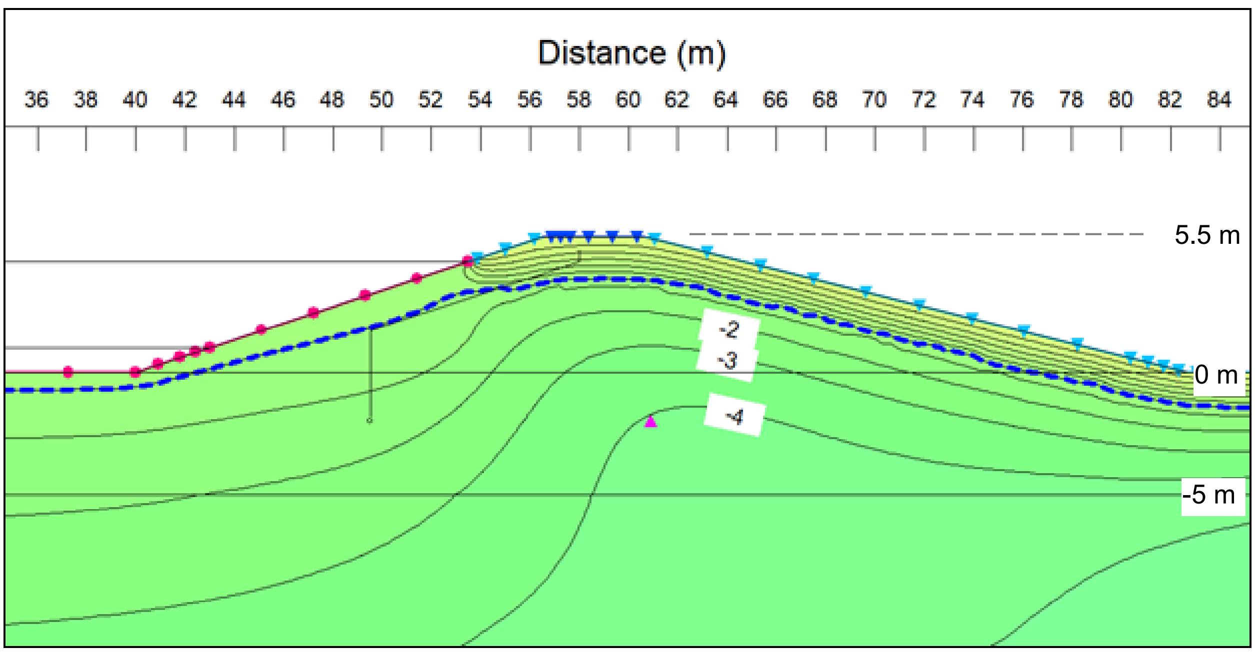


Figure 5.8 Case 6: Berm Temperatures (late August) with climate warming (0.08°C/year for 30 years), high fluid level, thermosyphon below berm crest, no groundwater flow.

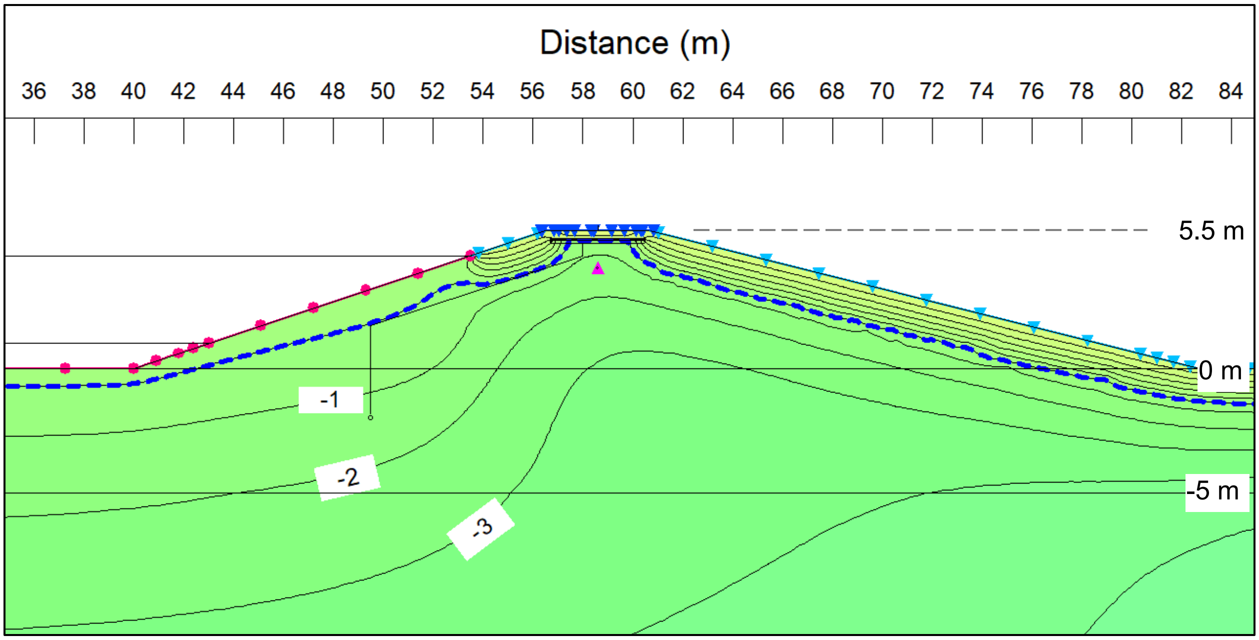


Figure 5.9 Case 7: Berm Temperatures (late August) with climate warming (0.08°C/year for 30 years), high fluid level, thermosyphon at berm crest with 50 mm thick rigid insulation, no groundwater flow.

The thermosyphon and insulation placement shown in Figure 5.9 has not been optimized. There may be benefit in increasing the thickness of the insulation, placing insulation part way down the berm slopes or providing two horizontal thermosyphons adjacent to each other at a spacing of about 2 m. These variations can be considered should this be desired.

## 6.0 DISCUSSION OF MODELLING RESULTS AND IMPLICATION TO LAGOON DESIGN

Section 3 described the various geothermal model inputs and the analyses that were to be undertaken for this study. Section 5 presented the results of the geothermal modelling. This section provides a discussion of the implications of the modelling results to the lagoon design. This discussion assumes that the top of the liner is above the maximum effluent level in the lagoon. Hence, any seepage is through leaks within the liner or via flow below the base of the liner.

The geothermal modelling showed that long-term thawing into the containment berm will develop in the absence of thermal mitigation. If the impermeable liner installed through the berm on the upstream side of the structure were to have leaks within the higher section, it is likely that effluent seepage would occur through the upper part of the unfrozen containment berm in the summer months. This seepage would induce thermal degradation of the frozen core of the berm leading to additional seepage pathways and increasing seepage volume.

The use of a horizontal thermosyphon placed at the base of the impermeable liner to enhance frozen conditions within the containment berm was shown to be of limited effectiveness. The cooler ground temperatures exist for a radius of several meters around the thermosyphon position but, if placed at depth within the berm, do not provide frozen conditions near the crest of the berm where seepage may develop in the event of leakage in the liner. When the horizontal thermosyphon is placed immediately below the berm crest and combined with an overlying layer of rigid insulation, the overall thermal conditions in the berm are improved.

In light of the modelling results there are several potential options for containment berm design. In the first instance, and which is considered to be the technically preferred approach, the containment berm should be constructed with the impermeable liner installed to at least 2 m into native soils (or 1 m into bedrock, whichever comes first) on the upstream side, with a horizontal thermosyphon installed at a depth of about 1.5 m below the crest overlain with a layer of rigid polystyrene insulation placed at a depth of about 0.3 m below the top of the berm. This combination of liner and thermosyphons with insulation will collectively act to provide the highest potential for effluent containment.

A second design approach is to not install the thermosyphons and insulation at the time of initial construction and rely solely on the integrity of the liner to maintain containment. If effluent seepage is detected during operational monitoring, then the thermosyphon and insulation could be installed as a retrofit in an attempt to re-freeze the berm and re-establish containment. This latter approach may be economically attractive as it defers the capital cost of the thermosyphons and insulation, but it raises technical challenges and the associated risk of not re-freezing of the containment structure. Depending how the seepage develops and progresses, it may be neither technically nor economically feasible to re-freeze the berm section and arrest seepage. For example, this mitigation would require the lagoon to be drawn-down to a minimum level to allow the seepage to stop and the berm to refreeze over the winter and permafrost to be reestablished within the berm structure.

The placement of thermosyphons and rigid insulation immediately below the berm crest has not been optimized. The objective of considering this scenario was to examine its technical viability. Additional studies are needed to consider the optimal thickness and placement of the rigid insulation and the number of horizontal thermosyphons. Ideally it would be desirable to raise the elevation of the -2°C isotherm closer to the crest.

The geothermal modelling reported herein assumed a berm crest width of 4.2 m. It is understood that this represents the narrowest crest width for the project and that wider berm crest widths up to 7 m may be constructed. It is likely that the results of this modelling will be generally applicable to containment berms of a greater width, up to 7 m.

## 7.0 RECOMMENDATIONS

This section provides recommendations for the design, construction, and operation of the waste water lagoon structure, based on the geothermal modelling and discussions presented in this report.

1. The use of low to moderately saline soils for the berm construction and native soils has been assumed in this analysis. Testing of the berm materials should be performed to confirm the pore water salinity does not exceed 8 PPT.
2. The seasonal thawing of the berm structure, even in the absence of climate warming effects, means that a frozen-core impermeable design approach may not be feasible, based on the geothermal modelling conducted for this study. For this reason, it is recommended that primary containment be provided by a liner or other impermeable barrier or system
3. An impermeable liner installed in the containment berm to provide primary containment should ideally be located along the upstream face of the earth structure. At the upstream toe of the berm, the liner should be keyed into the native soil or bedrock.
4. Additional investigations to assess the actual depth to bedrock at the containment berm locations should be undertaken. Some geophysical techniques may be effective in mapping the depth to bedrock along the length of the containment berms.
5. Selection of the liner material requires careful consideration. Current industry practice is understood to favour the use of high density polyurethane (HDPE) liners and geosynthetic clay liners (GCL). Both these systems have reportedly experienced performance issues in cold temperature applications. An alternative liner material that is gaining favor in locations such as the North Slope of Alaska (Prudhoe Bay area) is polymeric geomembranes, which may include thermoplastic polyurethane. Polyether polyurethane materials are reported to provide good low temperature properties. These materials are reportedly satisfactory for liner materials, landfill covers, potable water and fuel containment liners and similar applications.
6. The geothermal analyses assumed the lagoon berms will be constructed without any perforations or apertures. Discharge culverts and access manholes are two examples of openings that may be installed in or through the berm structure. These apertures represent sources of geothermal and hydraulic discontinuities that could negatively impact the temperature or seepage regime in the vicinity of the apertures. In addition, it is possible that a drainage pipe through the berm could experience freeze-up and ice blockage for much of the year. Therefore, from a geothermal and seepage perspective, it is recommended that no drainage pipes or vertical access man holes be installed horizontally through or in the berm structure.
7. From a geothermal perspective, it is recommended that the horizontal thermosyphons be placed immediately below the crest of the containment berm, overlain by an appropriate thickness of rigid extruded polystyrene insulation. The combination of an impermeable liner and thermosyphon and insulation provides the best containment performance of the berms. The thermosyphons and insulation should be installed at the time of initial construction.
8. Additional consideration of the placement of the horizontal thermosyphon and rigid insulation should be taken prior to finalizing the design. There may be technical advantages of using a thicker and wider layer of insulation than what was considered in the modelling (Case 7).

9. Thermal and seepage performance monitoring of the containment structure be incorporated into its design and operation. Sealed PVC casings should be installed through the structure and into the subgrade soils into which thermistor cables may be installed to monitor ground temperatures. These installations should, ideally, be 10 m to 15 m deep. These casings should be installed at approximately 15 m to 20 m centers along the crest of the containment berm. Installation of the vertical monitoring casings should be located to avoid penetrating the seepage control liner.

   To monitor seepage, vertical slotted standpipes should be installed at approximately 15 m to 20 m centers along the crest of the dyke. These standpipes should be of a diameter to permit the recovery of liquid within the standpipe for environmental/biological testing. Under design operation conditions, these monitoring wells would be either continuously dry or fill with ice. The presence of any liquid water would likely indicate the presence of seepage.

   As noted, care should be taken to ensure that the monitoring casings do not penetrate the impermeable liner. Additional specifications on monitoring installations and instrumentation may be provided on request.

## 8.0 CLOSURE

This report has been prepared for the exclusive use of Exp Services Inc. for the specific application and project described herein. The use of this report by third parties or for an application not described in this report is at the sole risk and responsibility of those parties.

If at any time, site conditions, such as the soil or climatic conditions, or containment berm geometry or other factors be found to be different from what has been assumed in this report, Naviq should be notified and given the opportunity to examine the different conditions and the impact they may have on the analyses and recommendations reported herein.

This report is subject to the Terms and Conditions provided in Appendix A.

Prepared by:
**Naviq Consulting Inc.**


J.M. Oswell, Ph.D., P.Eng.
Senior Permafrost Engineer

R. Coutts, M.Sc., P.Eng.
Senior Geothermal Engineer
Ardent Innovation Inc.

NAPEG Permit to Practice: P611

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**APPENDIX A**

**TERMS AND CONDITIONS**

TERMS AND CONDITIONS

These Terms and Conditions form part of this report. Acceptance of the report by the Client shall be interpreted as acknowledgement and agreement by the Client with the Terms and Conditions provided herein. Acceptance of the Report means that the Client has not objected to the report in writing within seven days of receipt.

1. STANDARD OF CARE: Naviq Consulting Inc. (Naviq) will strive to perform Services in a manner consistent with that level of care and skill ordinarily exercised by other members of Naviq's profession currently practicing in the same locality under similar conditions.

   No other representation, guarantee, or warranty, express or implied, is included or intended in these terms and conditions, or in any communication (oral or written), report, opinion, document, or instrument of service.

2. CHANGES: Client may order changes within the general scope of the Services by altering, adding to, or deleting from the Services to be performed. Further, if Naviq believes any subsurface or physical condition at or contiguous to the site is of an unusual nature and differs materially from conditions generally encountered or generally recognized as inherent in the character of Services provided in these Terms and Conditions, a change exists. If any such change causes an increase or decrease in Naviq's cost of, or the time required for, the performance of any part of the Services, a mutually acceptable equitable adjustment shall be made to the price and performance schedule.

3. FORCE MAJEURE: Should performance of Services by Naviq be affected by causes beyond its reasonable control, Force Majeure results. Force Majeure includes, but is not restricted to: acts of God; acts of a legislative, administrative or judicial entity; acts of contractors other than contractors engaged directly by Naviq; fires; floods; labor disturbances; and unusually severe weather. Naviq will be granted a time extension and the parties will negotiate an equitable adjustment to the price for the Services, where appropriate, based upon the effect of the Force Majeure on performance by Naviq.

4. INSTRUMENTS OF SERVICE: All reports, drawings, plans, or other documents (or copies) furnished to Naviq by the Client, shall at Client's written request, be returned on completion of the Services hereunder; provided, however, that Naviq may retain one copy of all such documents. All reports, drawings, plans, documents, software, source code, object code, field notes and work product (or copies thereof) in any form prepared or furnished by Naviq under these Terms and Conditions are instruments of service. Exclusive ownership, copyright and title to all instruments of service remain with Naviq. Client's right of use of instruments of service, if any, is limited to that use reasonably considered necessary for performance of the Client's duties and obligations. The instruments of service are not intended or represented to be suitable for reuse by Client or others on extensions of the work or on any other project.

5. CLIENT'S RESPONSIBILITIES: Client agrees to: (i) provide Naviq all available material, data, and information pertaining to the Services, including, without limitation as appropriate, the composition, quantity, toxicity, or potentially hazardous properties of any material known or believed to be present at any site, any hazards that may be present, the nature and location of underground or otherwise not readily apparent utilities, summaries and assessments of the site's past and present compliance status, and the status of any filed or pending judicial or administrative action concerning the site; (ii) convey and discuss such materials, data, and information with Naviq; and (iii) ensure cooperation of Client's employees.

   Client shall indemnify, defend, and save Naviq harmless from and against any liability, claim, judgment, demand, or cause of action arising out of or relating to: (i) Client's breach of these Terms and Conditions; (ii) the negligent acts or omissions of Client or its employees, contractors, or agents; (iii) any allegation that Naviq is the owner or operator of a site, or arranged for the treatment, transportation or disposal of hazardous materials, including all adverse health effects thereof and (iv) site access or damages to any subterranean structures or any damage required for site access.

In addition, where the Services include preparation of plans and specifications and/or construction oversight activities for Client, Client agrees to have its construction contractors agree in writing to indemnify and save harmless Naviq from and against loss, damage, injury, or liability attributable to personal injury or property damage arising out of or resulting from such contractors' performance or nonperformance of their work.

6. LIMITATION OF LIABILITY: As part of the consideration Naviq requires for provision of the Services, Client agrees that any claim for damages filed against Naviq by Client or any contractor or subcontractor hired directly or indirectly by Client will be filed solely against Naviq or its successors or assigns and that no individual person shall be made personally liable for damages, in whole or in part.

   Client's sole and exclusive remedy for any alleged breach of Naviq's standard of care hereunder shall be to require Naviq to re-perform any defective Services. Notwithstanding any other provision of these Terms and Conditions, the total liability of Naviq, its officers, directors and employees for liabilities, claims, judgments, demands and causes of action arising under or related to the Services or these Terms and Conditions, whether based in contract or tort, shall be limited to the total fee compensation actually paid to Naviq for the Services or $10,000, whichever is less. All claims by Client shall be deemed relinquished unless filed within one (1) year after substantial completion of the Services.

   Naviq and Client shall not be responsible to each other for any special, incidental, indirect, or consequential damages (including lost profits) incurred by either Naviq or Client or for which either party may be liable to any third party, which damages have been or are occasioned by Services performed or reports prepared or other work performed hereunder.

7. DISPUTE RESOLUTION: If a claim, dispute, or controversy arises out of or relates to the interpretation, application, enforcement, or performance of Services under these Terms and Conditions, Naviq and Client agree first to try in good faith to settle the dispute by negotiations between senior management. If such negotiations are unsuccessful, the parties agree to attempt to settle the dispute by good faith mediation. If the dispute can not be resolved through mediation and unless otherwise mutually agreed, the dispute shall be settled by litigation in an appropriate court in the Province of Alberta. Client hereby waives the right to trial by jury for any disputes arising out of these Terms and Conditions.

   The non-prevailing party in any litigation shall reimburse the prevailing party for the prevailing party's documented legal costs (including reasonable attorneys' fees), in addition to whatever other judgments or settlement sums may be due.

8. WAIVER OF TERMS AND CONDITIONS: The failure of either Naviq or Client in any one or more instances to enforce one or more of these Terms and Conditions or to exercise any right or privilege in these Terms and Conditions or the waiver by Naviq or Client of any breach of the these Terms and Conditions shall not be construed as thereafter waiving any such terms, conditions, rights, or privileges, and the same shall continue and remain in force and effect as if no such failure to enforce had occurred.

9. SEVERABILITY: Notwithstanding any possible future finding by a duly constituted authority that a particular term or provision is invalid, void, or unenforceable, these Terms and Conditions have been made with the clear intention that the validity and enforceability of the remaining parts, terms, and provisions shall not be affected thereby.

10. GOVERNING LAWS: This Agreement shall be governed and construed in accordance with the laws of the Province of Alberta.