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Naviq Consulting Inc.
Specialist Geotechnical and Permafrost Engineering

GEOTHERMAL ANALYSIS OF PROPOSED SEWAGE LAGOON

CLYDE RIVER, NU

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GEOTHERMAL ANALYSIS OF PROPOSED SEWAGE LAGOON: CLYDE RIVER, NU

REV	DESCRIPTION	ORIGINATOR	REVIEWER	NCI APPROVAL	DATE (DD-MON-YYYY)	CLIENT APPROVAL	DATE (DD-MON-YYYY)
0	Issued for Design	Jim Oswell	Ron Coutts	Jim Oswell	29 Feb. 2008	N/A	N/A

EXECUTIVE SUMMARY

This report provides details of geothermal analyses conducted in support of the design of a sewage lagoon structure near Clyde River, NU. The analyses considered a variety of conditions including climate warming, pore water salinity effects, initial soil temperatures in the containment structures and others.

Soil conditions were taken from a geotechnical report prepared for the project by Trow Associates Inc. Climatic data were obtained from Environment Canada climate normals.

The geothermal modeling show that seasonal thawing of the lagoon structure (dyke) thaws to a depth about 2 m below the crest on a season basis. This depth of seasonal thawing is relatively insensitive to the applied climate warming rate.

For the site specific conditions assumed, it is considered that a controlling design isotherm of -2 °C be used. This value includes an amount to account for freezing point depression of high saline soils, and for uncertainties in some input parameters for the geothermal modeling.

The application of a frozen core dam concept as a primary containment method is not considered to be prudent based on the analyses conducted. Therefore, an impermeable liner or other seepage barrier should be incorporated into the design. Details on the installation of the liner at the upstream toe of the dyke are discussed.

No secondary cooling of the dyke structure is presently recommended. However, monitoring of ground temperatures and seepage through the dyke structure should be implemented. Secondary cooling, by way of thermosyphons, may be required if operational monitoring indicate warmer than anticipated temperatures or seepage within the dyke structure.

It is recommended that drainage piping or access man holes in or through the dyke structure be avoided because of a number of geothermal and geotechnical issues related to performance of the dyke structure.

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1.0 INTRODUCTION

Naviq Consulting Inc. (NCI) was retained by Trow Associates Inc. (Trow) of Ottawa, ON to provide permafrost engineering and geothermal analysis with respect to the design of a municipal waste-water (sewage) lagoon in Clyde River, NU. The scope of work is described in a proposal from NCI to Trow, dated June 21, 2007 (Naviq Proposal: JP-07-03).

The scope of work included input to the geotechnical investigations for the lagoon structure to be conducted by Trow, assessment of design concepts for the lagoon structures and geothermal modeling to assess the functionality of the lagoon structures over the design life, recognizing issues such as potential permafrost degradation and climate warming.

This report addresses the geothermal modeling of the proposed containment structures.

2.0 GEOTECHNICAL INVESTIGATIONS AND RELATED INFORMATION

Trow undertook a geotechnical investigation at the site of the proposed lagoon on August 19 to 24, 2007. Nine boreholes were drilled along the containment berms for the existing lagoon and in the vicinity of the proposed lagoon. This section provides a summary of the geotechnical character of the subsurface conditions. For a full description of the site conditions, and other important details of the investigation and testing, the reader is referred to the full report (Trow, 2007).

2.1 Subsurface Conditions

The boreholes at the existing lagoon site were advanced to depths of 1.2 m to 5.7 m. At the time of the geotechnical investigation, the active layer was estimated to range in thickness from about 0.5 m to 1.6 m.

The general stratigraphy at the borehole locations within the existing lagoon area generally consisted of sand and gravel overlying sand Till. The surface layer of sand and gravel may represent fill soils placed as part of the lagoon berm construction. It was observed at the borehole locations to be up to 1.5 m thick, but may be thicker in other locations. The sand Till underlying the sand and gravel layer was up to 4 m thick. The water content was measured to be in the order of 10 percent by dry weight. In two boreholes, the sand Till was underlain by sand and gravel.

The three boreholes drilled in the vicinity of the new lagoon site were drilled to depths ranging from 0.9 m to 7.5 m. The stratigraphy was variable at the borehole locations. In one borehole (BH 6) silty sand was encountered at the ground surface, which was underlain by alternating layers of ice and silty sand. These layers of ice and mineral soil ranged in approximate thickness from 0.5 m to 1.0 m. In Borehole 8 topsoil and sand were encountered at the ground surface, underlain by silty Till and then bedrock at a depth of about 3 m.

2.2 Ground Temperatures

Thermistor cables were installed in two boreholes at the site. Table 2-1 presents the results of the ground temperature monitoring, as reported by Trow (2007).

TABLE 2-1: Ground temperatures measured at the existing and proposed lagoon site on September 18, 2007 (Trow, 2007)

Borehole 2 (Existing Lagoon Site)			Borehole 6 (Proposed Lagoon Site)	
Depth (m)	Temperature (°C)		Temperature (°C)	
	August 24, 2007	November 29, 2007	August 24, 2007	November 29, 2007
0	7	-18.5	11.5	-17.9
0.76	4	-15.6	3	-9.3
1.2	1.4	-	1	-6.3
1.7	0.3	-6.5	0	-4.5
2.1	0	-4.8	-1.5	-3.5
2.6	-0.2	-9.2	-3.0	-3.2
3.0	-0.1	-4.0	-4.0	-3.5
3.5	0	-4.0	-5.0	-4.0
4.0	0	-4.0	-5.8	-4.5

Published literature also reports ground temperatures in Clyde River. Table 2-2 presents lat fall ground temperatures with depth from Nixon (1988).

TABLE 2-2: Late fall ground temperatures measured in Clyde River (Nixon, 1988)

Depth (m)	Temperature (°C)
1.0	-3.0
2.0	-5.5
3.0	-6.5
4.0	-7.5
5.0	-8.2
7.0	-9.5
8.5	-10.0

Comparison of Table 2-1 and Table 2-2 suggests that the lagoon site may be slightly warmer from a geothermal perspective.

2.3 Lagoon Structure Dimensions and Construction

The lagoon containment dykes are understood to have the following dimensions:

Crest width	4 m
Typical dyke height	4 m to 6 m
Downstream face slope	2.75H:1V
Upstream face slope	3.5H:1V

The containment structure is assumed to be constructed from locally available sand and gravel soils, which are placed in controlled lifts on top of the undisturbed terrain and compacted 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 topsoil layer outside of the footprint of the dykes.

The containment structure is to be designed, constructed and operated as an impermeable dyke, using an internal liner, either HDPE or bentonite panels (geosynthetic clay liner) to provide the primary containment. Permafrost that may develop within the containment berm will provide secondary containment. It is understood that removal of treated effluent will be by pumping over the dykes. No discharge conduits will be constructed through the structure.

Within the lagoon containment area, a layer of water saturated sludge, 0.5 m thick was assumed to be present overlying the native soils.

3.0 GEOTHERMAL ANALYSIS OF CONTAINMENT STRUCTURE

The geothermal performance of the lagoon dykes is a function of the thermal energy balance between the atmosphere and the ground surface on and around the dykes. As such, ground surface temperatures vary continuously throughout the year. When climate warming is considered, the seasonal ground surface temperatures increases upward at a specified constant rate.

This subsection outlines the various boundary conditions that have been applied to the physical problem, lists the various analyses considered, and presents the results of the analyses. Numerical modeling results are presented in Section 4 of this report.

3.1 Numerical Model Input Parameters and Boundary Conditions

3.1.1 Climatic Data

Clyde River is located at 70° 29.4’ N and 68° 31’ W, along the northeast coast of Baffin Island, NU. It is located in the zone of continuous permafrost. Clyde River historical climatic data records are available from the early 1970s.

The long-term mean annual air temperature for the area is -12.5 °C. The freezing index is approximately 4950 °C-days and the thawing index is approximately 325 °C-days.

Typical snow cover throughout the winter and spring months is about 500 mm. The last date of snow cover is in early July. Summer mean monthly air temperatures during June, July and August are + 0.7 °C, + 4.4 °C, and +3.9 °C, respectively. Winter mean monthly air temperatures during December, January and February are -24.8 °C, -28.1 °C, and -29.6 °C, respectively.

3.1.2 Ground Temperatures and Permafrost Depth

Ground temperatures were measured at the proposed lagoon site by Trow during their geotechnical investigations. Table 2-1 present these data. Table 2-2 presents ground temperatures from another site in Clyde River reported by Nixon (1988).

Mean annual ground temperatures, based on a semi-empirical correlation to mean annual air temperature, are expected to be in the order of -9 °C, which is consistent with the Nixon (1988) data.

Permafrost is likely to extend over 500 m below ground surface.

3.1.3 Climate Warming

The design life of the containment structure is expected to be in the order of 20 years. For this period, climate warming is assumed to be active and should be accounted for in the design of the structure. One method of addressing the potential for regional warming in a particular location is to extrapolate the historical warming rate forward for the design life of the project. Figure 3-1 presents the mean annual air temperature for the Clyde River airport for the period of 1977 through 2007. A linear regression best-fit line was fitted to the data, and the slope of the regression line represents the annual historical warming trend. For the available data, the historical warming rate is 0.02 °C/year. This warming rate, derived from Environment Canada data is much lower than other Baffin Island communities. An assessment of climate warming rates in eleven communities in the Baffin region (including Igloolik and Hall Beach) found the average climate warming rate was in the order of 0.08 °C/year. Therefore, this higher, more conservative, value has been adopted for the geothermal analyses undertaken from this study.

If projected forward for a design life of 20 years, the mean annual air temperature may rise by approximately 1.6 °C.

Climate warming is incorporated into the geothermal modeling by increasing the mean annual air temperature for each year of the simulation. In the case of the lagoon contents (sewage), a temperature warming rate of one-half the air temperature rate was applied (0.04 °C/year).

3.1.4 Soil Pore Water Salinity

The soils in the Baffin Island region are known to contain salts within the soil. 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.

Hivon and Sego (1993) reported on the pore water salinity of soils across northern Canada. For Clyde River, they report that soil pore water salinity ranges from 0.6 to 44.5 PPT (parts per thousand). For reference, normal seawater has a salinity of about 35 PPT. Nixon (1988) also reported salinity values in Clyde River that showed salinity values to generally increase with depth, being near zero at the ground surface and in the order of 9 PPT at a depth of 15 m.

Freezing point depression is a linear function. For soil pore water with salinity of 35 PPT, the freezing point will be depressed to about –2°C.

For this analysis, a typical soil salinity of 20 PPT was assumed, with a corresponding freezing/thawing temperature of about -1 °C. This is considered to a relative conservative value based on the salinity – depth profile presented by Nixon (1988) and recognizing the potential depth of thermal impact imposed by the lagoon structure.

3.1.5 Initial Dyke Soil Temperatures

The long-term thermal performance of the dyke structure and subgrade is not impacted by the initial placement temperature of the dyke soils. However, in the initial period, during and immediately following construction, the dyke soils will be unfrozen and likely above normal soil temperatures. Therefore, in the initial time period following construction, cooling of the dyke structure and/or warming of the subgrade by the warm dyke soils could have some short-term thermal impact on performance.

For these analyses, it was assumed that the dyke soils will have an initial temperature of +8 °C, representative of the fact that the soil lifts placed during construction will be warmed by sunshine (solar radiation). The +8 °C value is based on the mean monthly summer air temperature of +5 °C in July, and multiplied by an N-factor of 1.6, a value generally typical of gravelly soils. For the numerical modeling, it assumed that the lagoon dyke is “instantaneously” constructed on about July 15.

3.1.6 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 dyke height and lagoon volume is based on projected community population growth over the next 20 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 of each year. Refilling of the lagoon would take place from September through July of the following year.

For the geothermal analyses a constant lagoon elevation at one-half the height of the dyke was assumed. The assumption of the fixed lagoon elevation is considered to very conservative in the initial life of the structure as the mean annual height of the sewage in the early period of the facility will be much less than that assumed. In later years of the structure, the fixed elevation of the lagoon will be essentially neutral from a modeling perspective because the sewage height will fluctuate throughout the year.

For the lagoon contents, two temperature regimes were considered. In the first case, the lagoon temperature was assumed to be +1 °C all year around. This temperature is considered to be conservative. In the second case, a more realistic modeling scenario would be to vary the temperature of the surface of the lagoon 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. The second scenario is based on the assumption that deposition of sewage by truck discharge into the lagoon over the winter months will result in the in-coming sewage freezing before the next deposition is made, and that a frozen mass of sewage builds up over the winter months. Hence, it would be unlikely that a layer of unfrozen sewage would develop under a layer of ice or frozen sewage.

NCI considered the impact of seasonal temperature boundary conditions for the geothermal analyses of a lagoon structure. Figure 3-2 presents the modeling results. The temperature of the "disturbed" lagoon surface in late August is calculated to be about +1 °C from a surface energy balance model. This condition is considered to represent the surface of the lagoon after draw down. Immediately thereafter the surface temperature begins to decrease. Therefore, the application of the +1 °C lagoon surface temperature throughout the year was considered conservative, and represents the first scenario described above. The seasonal variation of the lagoon temperature is also shown on Figure 3-2. This boundary condition was obtained by taking the disturbed ground surface boundary condition (as was applied to the dyke) and setting it to -1 °C whenever it dropped below -1 °C, that is, in the cold winter months. The -1 °C temperature ends at about the third week of June and begins again in about the second week of September.

The second lagoon temperature boundary condition has an average temperature of +0.58 °C over the entire climate warming period, which is just slightly less than the more conservative assumption of +1 °C for the liquid sewage temperature boundary condition.

When long-term climate warming was considered in the analyses, a warming rate of 0.04 °C/year was applied to the lagoon temperature of +1 °C. Thus after 20 years, the lagoon content temperature was assumed to be +1.8 °C, for the first case. For the second case, the climate warming rate was applied over all 20 years of lagoon operation, so each year the window of lagoon temperatures above -1 °C lengthens slightly each year.)

3.2 Analysis Scenarios

The first modeling step was to perform a one-dimensional model calibration whereby climate data representative of Clyde River was input to the model, and calibration was performed such that the model calculated long-term ground temperatures at depth that were also generally representative of Clyde River. In this case, the long-term ground temperature was about -9 °C. The purpose of this analysis was to establish the surface boundary conditions (surface energy balance) that would result in ground temperatures typical of the local environment. The metrological inputs included: monthly air temperature, snow cover, surface albedo, and evapotranspiration rates. Snow thermal conductivity and factors for summer albedo and evapotranspiration were adjusted to achieve model-computed ground temperatures that were consistent with representative ground temperatures for Clyde River. Figure 3-3 presents the annual maximum, minimum and average temperature with depth and illustrates that the model computes a mean annual ground temperature of -9 °C using representative climate data for Clyde River. Comparison of the temperature – depth profile in Figure 3-3 with the temperature data presented in Table 2-2 indicates that the calculated ground temperatures are warmer than what Nixon (1988) measured in the community. Therefore, for the purposes of this geothermal assessment the assumed conditions are conservative.

Two-dimensional geothermal analyses were conducted using the commercial program

TEMP/W, developed by Geo-Slope International.

The analyses conducted for this study included the following:

- Time to freeze-in the dyke structure, following initial construction. This analysis was intended to assess the time required for the dyke structure to reach a thermal "dynamic steady-state" following construction and to determine if dyke core temperatures would be below freezing after the first winter.
- Assessment of the maximum thaw depth across the dyke structure and in the dyke foundation in the long-term, ignoring climate warming effects.
- Assessment of the maximum thaw depth across the dyke structure and in the dyke foundation in the long-term, including climate warming effects as discussed above.

4.0 GEOTHERMAL MODELING RESULTS

This section addresses the results of the geothermal modeling described in Section 3. In interpreting geothermal modeling 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.

As noted in Section 3, the pore water salinity that may be present in the soils in and around Clyde River can be high. For this study, a pore water salinity of 20 PPT has been assumed. This will result in a freezing and thawing temperature depression of about 1 °C.

For design purposes, it is prudent to incorporate conservatism to account for uncertainty in the input design parameters. Conservatism can be incorporated by using a colder design temperature lower than would be normally needed. In this case the controlling parameter is the thawing temperature of the soils, which is -1 °C when pore water salinity is accounted for. For design purposes therefore, it is proposed that the "adjusted" controlling temperature be assigned as -2 °C, one degree below the control temperature.

4.1 Freeze Back of Lagoon Dyke Following Construction

The geothermal analysis assumed the entire dyke structure was instantaneously constructed and in-place on the native subgrade soil on about July 15 of the first year. The initial temperature of the dyke was assumed to be a uniform temperature of +8 °C, underlain by soils with temperatures ranging from near freezing or slightly warmer at the ground surface to about -11 °C at depth.

The analysis showed that the dyke would cool to ambient conditions by mid-winter the following year. That is, for construction in July, the dyke structure would be at ambient temperatures around mid-February the following year, just over six months after construction.

This means that the structure will not retain a zone of unfrozen soil when the next thaw season begins. Hence, no artificial cooling of the structure by mechanical or other methods is required.

4.2 Long-Term Thermal Performance – No Climate Warming

Figure 4-1 presents a cross-section of the lagoon structure showing the temperature contours in late summer. Because no climate warming is applied to this particular analysis, the results presented are representative of the temperatures in Years 1 through Year 20.

This figure shows that the -2 °C isotherm progresses to about 4 m below the crest of the dyke during thawing each year. This means that, under the conditions analyzed, more than 90% of the dyke cross section warms to -2 °C or warmer annually.

An unfrozen zone (talik) develops under the lagoon, based on a melting temperature of -1 °C. If ice-rich soils are present these soils may melt, resulting in settlement of lagoon base and potentially the upstream toe of the dyke structure.

The downstream terrain is thermally unaffected by the presence of the lagoon structure. A small amount of warming of the soil at the downstream toe of the dyke may result in some localized thaw settlement.

4.3 Long-Term Thermal Performance – Climate Warming

4.3.1 Lagoon Temperature at +1 °C

Figure 4-2 presents a cross-section of the lagoon structure showing the temperature contours in late summer after 20 years of operation for the case where the lagoon surface is held at a constant temperature of +1 °C. This scenario was shown in Section 3 to be a conservative approach.

The progression of the -2 °C isotherm within the dyke structure is slightly deeper than for the non-climate warming case. Essentially the entire dyke cross-section reaches a temperature of -2 °C or warmer by late summer in Year 20. On the upstream side of the dyke structure, the -2 °C isotherm has shifted towards the center of the dyke, compared to the non-climate warming case. This transition arises because of the climate warming effect. The volume of the unfrozen zone under the lagoon area is significantly greater than for the case of no climate warming. This could result in much more thaw settlement of the subgrade compared to the non-climate warming case.

On the downstream side, the -2 °C isotherm is has deepened by about 0.3 m compared to the non climate warming scenario. This could lead to additional thaw settlement relative to the non-climate warming case.

4.3.2 Lagoon Temperature with Seasonal Variation

Figure 4-3 presents a cross-section of the lagoon structure showing the temperature contours in late summer after 20 years of operation for the case where the lagoon surface temperature varies with ambient air temperatures in the summer and held at -1 °C during the winter months. This scenario assumes that the deposition of sewage into the lagoon is such that the contents freeze before the next deposition, and no unfrozen sewage layer persists beneath any ice layer. This scenario is likely closer to the actual thermal conditions that will occur within the lagoon during operations.

Comparisons of this scenario are made to Figure 4-2, representing the fixed lagoon temperature scenario. The 0 °C isotherm is positioned further into the lagoon area than for the fixed lagoon temperature case. This is the result of the slightly colder mean annual temperature of the lagoon surface applied in this modeling scenario: +0.58 °C versus +1 °C. The progression of the -2 °C isotherm within the dyke structure is essentially the same as for the fixed lagoon temperature modeling scenario. Therefore, in terms of design decisions made on the basis of the -2 °C isotherm, the fixed lagoon temperature discussions are applicable.

5.0 RECOMMENDATONS

This section provides recommendations for the design, construction and operation of the sewage lagoon structure, based on the geothermal modeling presented in this report.

1. The use of highly saline soils for the dyke construction has been assumed in this analysis. If low saline soils can be located and used for the dyke construction, then a controlling design isotherm of -1 °C instead of -2 °C may be used. This would be advantageous in terms of geothermal performance.
2. The seasonal thawing of the dyke 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 modeling conducted for this study. For this reason, it is recommended that primary containment be provided by a liner or other impermeable barrier or system. (This analysis ignores the fact that the maximum thaw in the lagoon dyke occurs after the annual draw-down of the lagoon, so that seepage through the unfrozen zone of the dyke may not occur.)
3. A liner or barrier in the dyke structure to provide primary containment should be located along the upstream face of the dyke. At the upstream toe of the dyke, the liner should be keyed into the native soil. On the cross-sections shown in Figure 4-1 and Figure 4-2 the key-trench should be located in the order of Station 45. The liner should be placed to a depth of 2 m below the native ground surface. This would place the base of the liner key beneath the 0 °C isotherm. It is not likely feasible from a construction perspective to install a key trench to intersect the -1 °C isotherm in the climate warming case, and virtually impractical to intersect the -2 °C isotherm.
4. These analyses have assumed that the lagoon dykes will be constructed without any perforations or apertures. Drainage culverts and access man holes are two examples of openings that may be installed in or through the dyke structure. These apertures represent sources of geothermal discontinuities that could negatively impact the temperature regime in the vicinity of the apertures. In addition, it is possible that a drainage pipe through the dyke could experience freeze-up and ice blockage for much of the year. Therefore, from a geothermal perspective, it is recommended that no drainage pipes or vertical access man holes be installed through or in the dyke structure.
5. Where drainage pipes are installed through the lagoon dyke, it will be necessary to pass the drainage pipe through the impermeable liner. Such a perforation represents a potentially serious source for leakage as it is often difficult to ensure an impermeable seal around the liner-drain pipe connection. Therefore, from a geotechnical perspective, it is recommended that no drainage pipes be installed through the dyke structure.
6. Given the limitations in installing a vertical cut-off barrier to impede seepage towards the center of the dyke structure, as discussed in Recommendation 3, it is further recommended that the thermal and seepage performance of the dyke structure be incorporated into its design and operation. Sealed PVC casings should be installed through the dyke structure and into the subgrade soils into which thermistor cables may be installed to monitor ground temperatures. These casings should be installed at

approximately 15 m to 20 m centers along the crest of the dyke. Selected casings should be “battered” to the upstream side so to provide the opportunity to monitor dyke and subgrade temperatures on the upstream side.

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.

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.

7. It is considered that the need for a secondary cooling system, such as thermosyphons is not supported by the current analysis, subject to the implementation of the above recommendations. If, during operations, monitoring of the dyke and subgrade temperatures indicates a warming of the structure higher than predicted by this study, then thermosyphons may be considered. Based on a preliminary assessment, vertical thermosyphons, installed along the crest at approximately 2 m centers to a depth of about 2 m below the base of the dyke would provide additional cooling of the core of the dyke to maintain a frozen core. Shallow rigid insulation could also be installed in conjunction with the thermosyphons to reduce the seasonal active layer thickness.

6.0 CLOSURE

This report has been prepared for the exclusive use of Trow Associates Inc. for the specific application and project described herein.

If at any time, the soil or climatic conditions be found to be different from what has been assumed in this report, NCI should be notified and given the opportunity to examine the different conditions and the impact they may have on the analyses and recommendations provided herein.

Prepared by:
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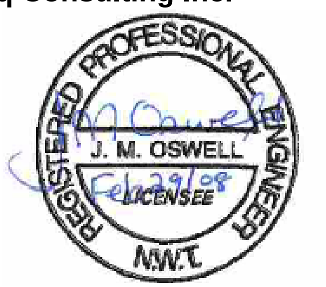

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NAPEGG Permit to Practice: Pending

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FIGURES

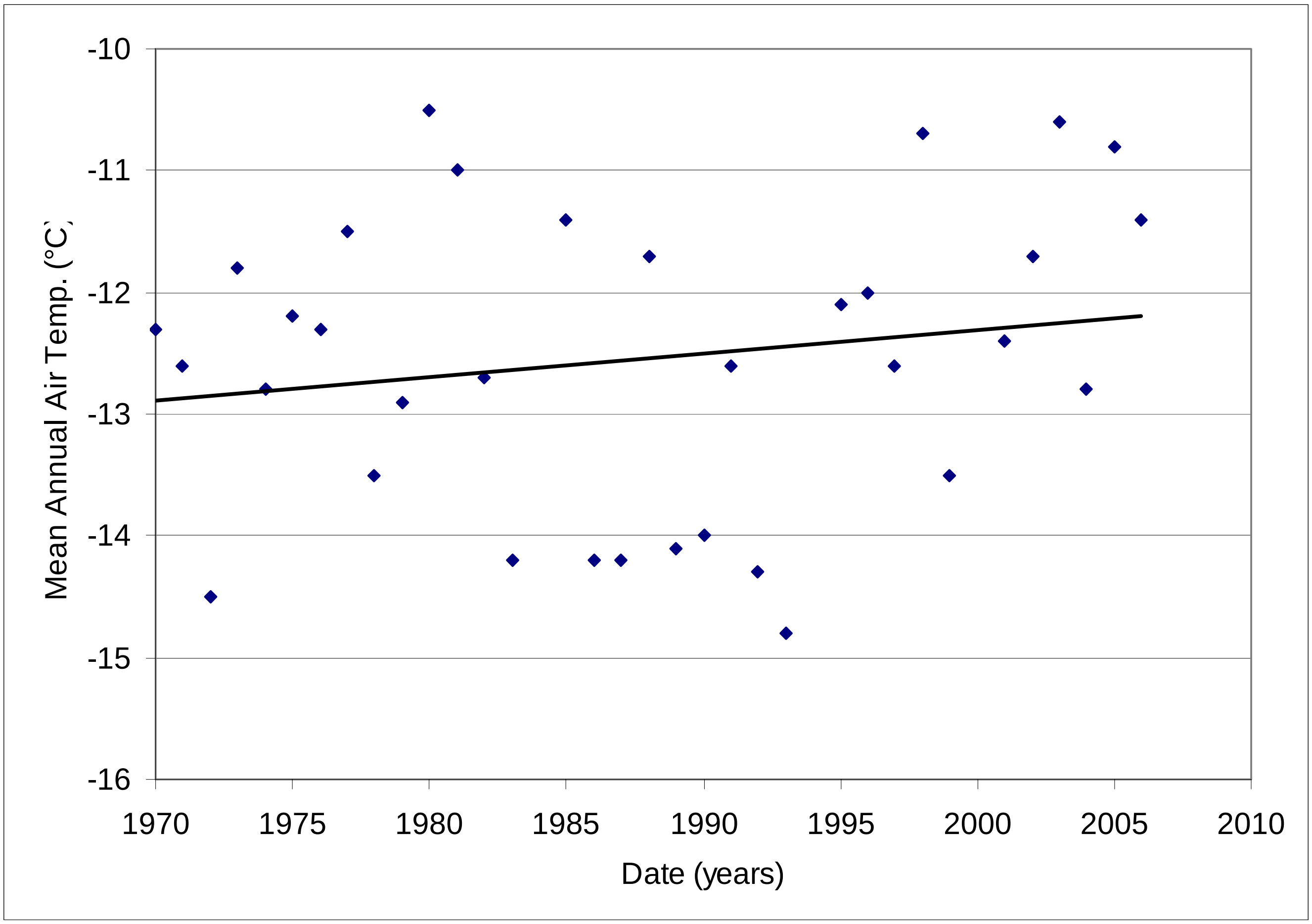

Figure 3-1. Historical variation in mean annual air temperature (1970 through 2007).
Data source: Environment Canada website.

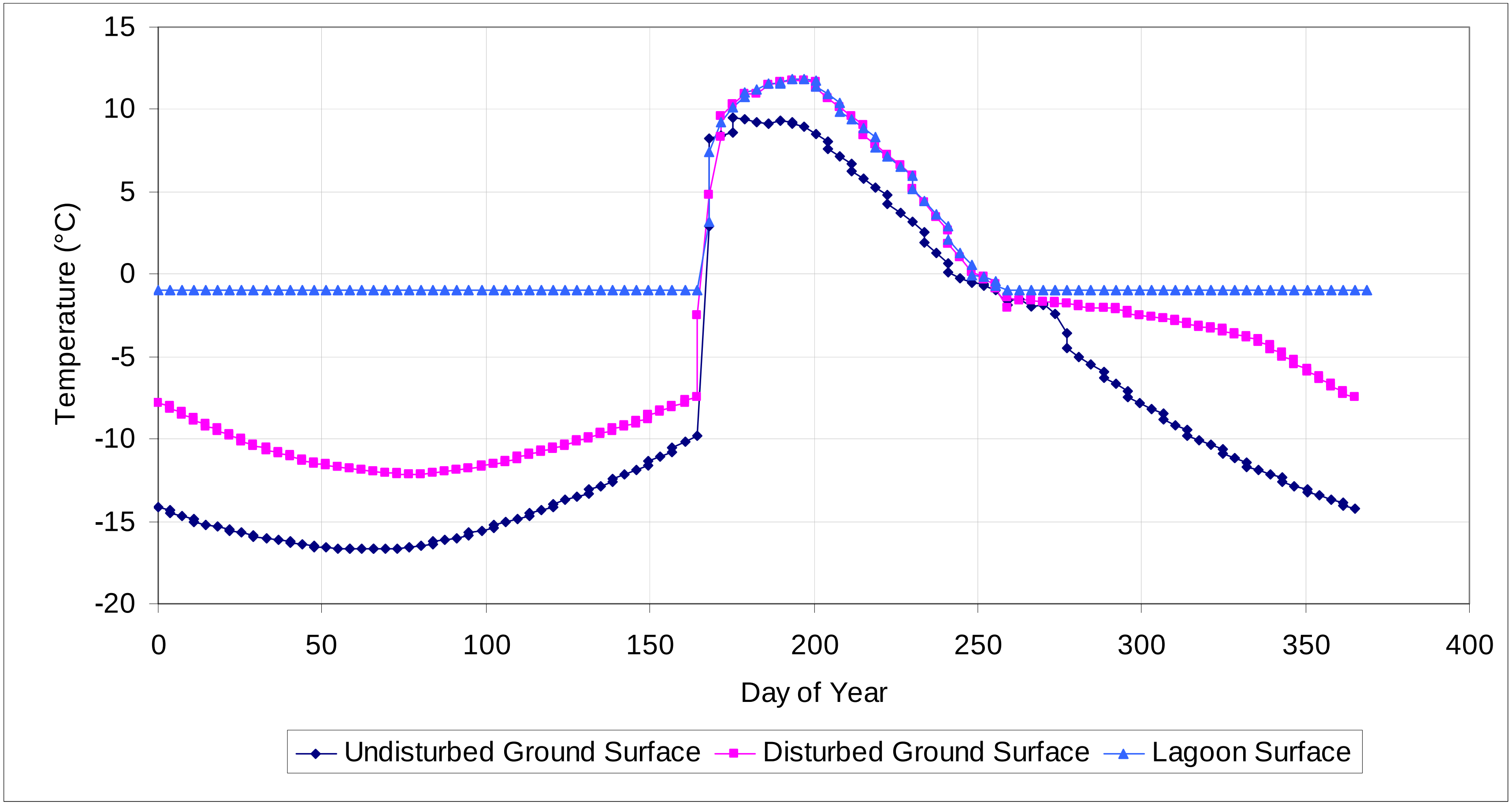

Figure 3-2. Temperature profile with time for undisturbed surface, disturbed surface and lagoon surface.

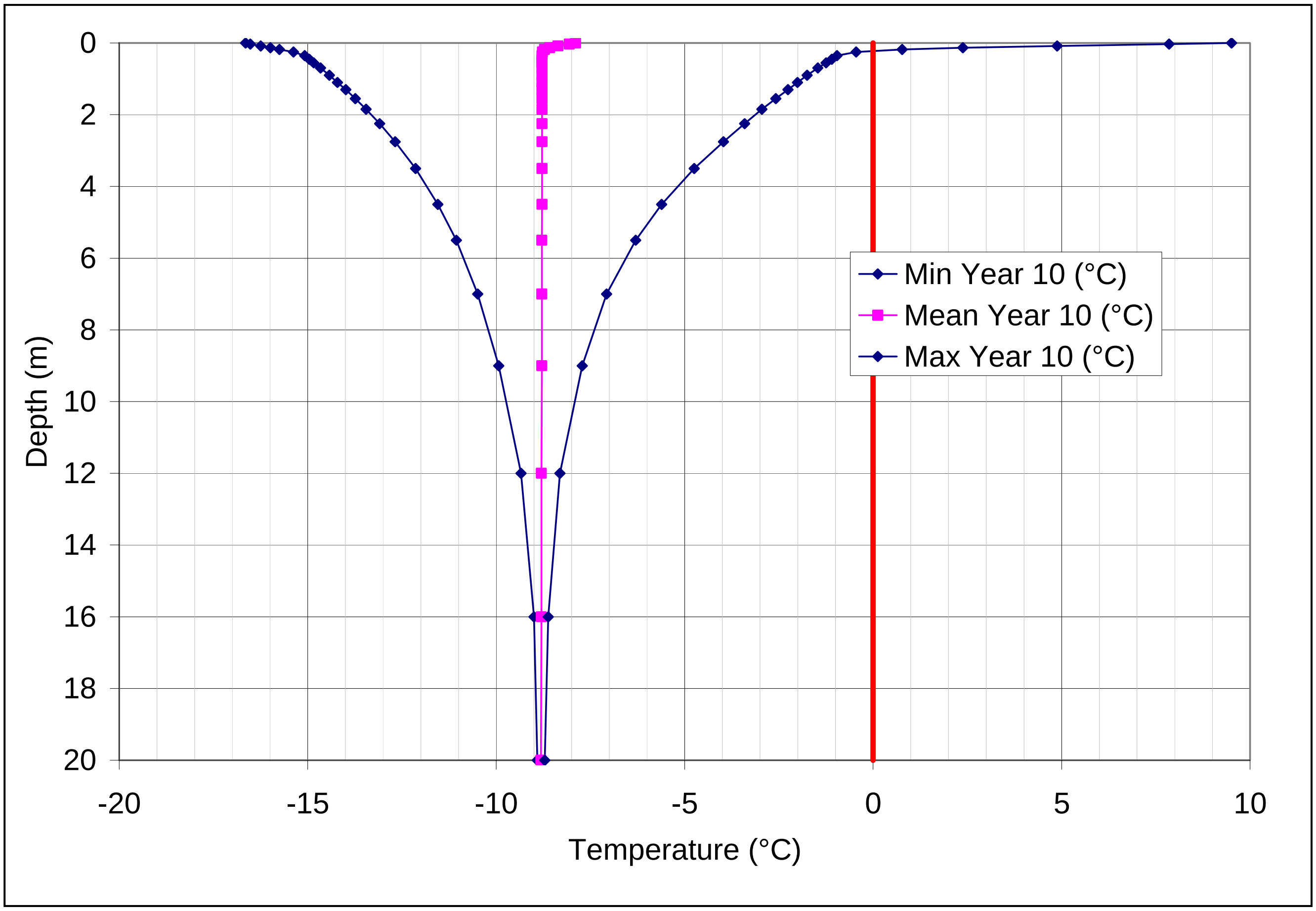

Figure 3-3. Undisturbed ground temperature profile, based on one-dimensional geothermal modeling.

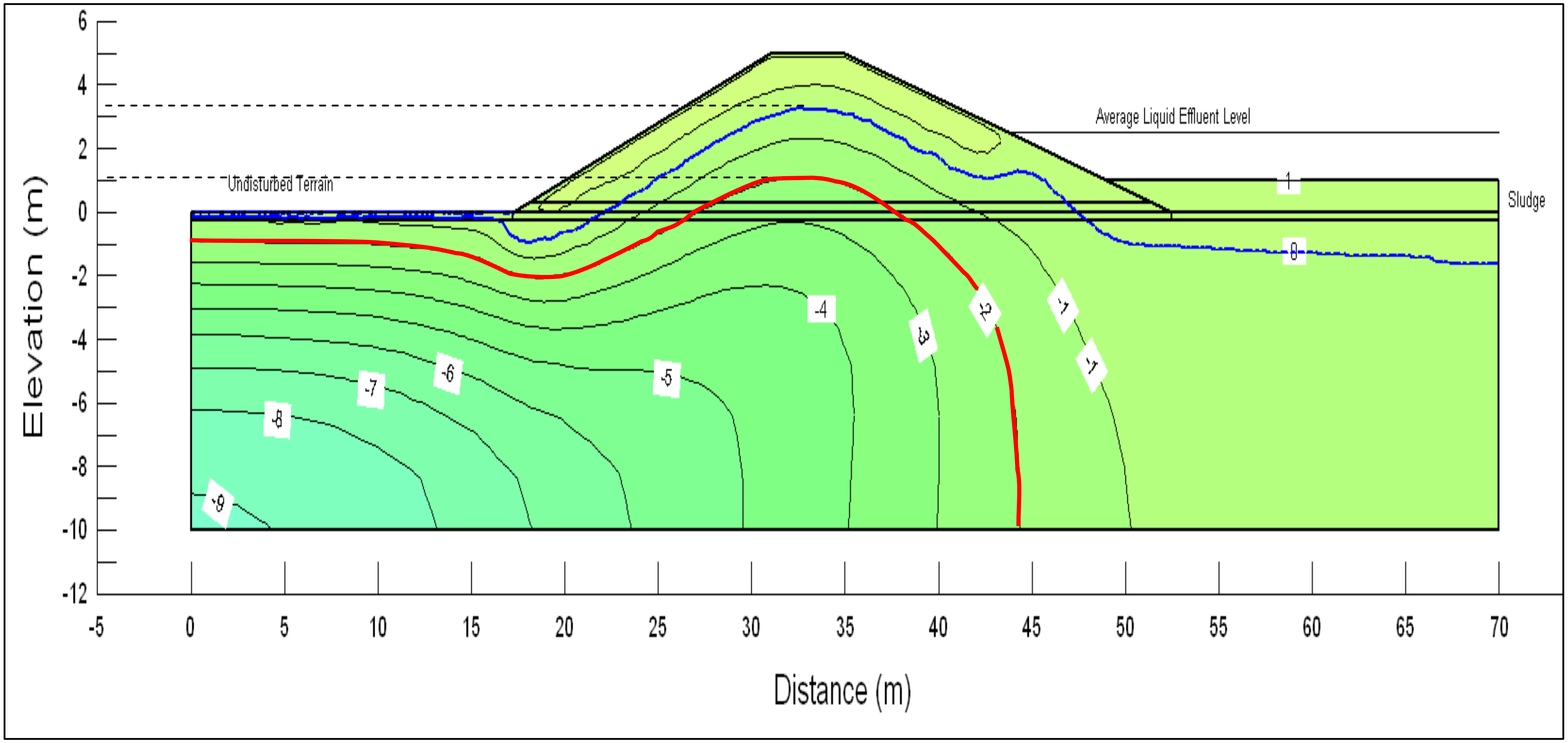

Figure 4-1. Cross-section of dyke structure showing ground temperature contours at maximum thaw during years 1 through 20 with lagoon held at constant +1 °C all year around. No climate warming effects are included.

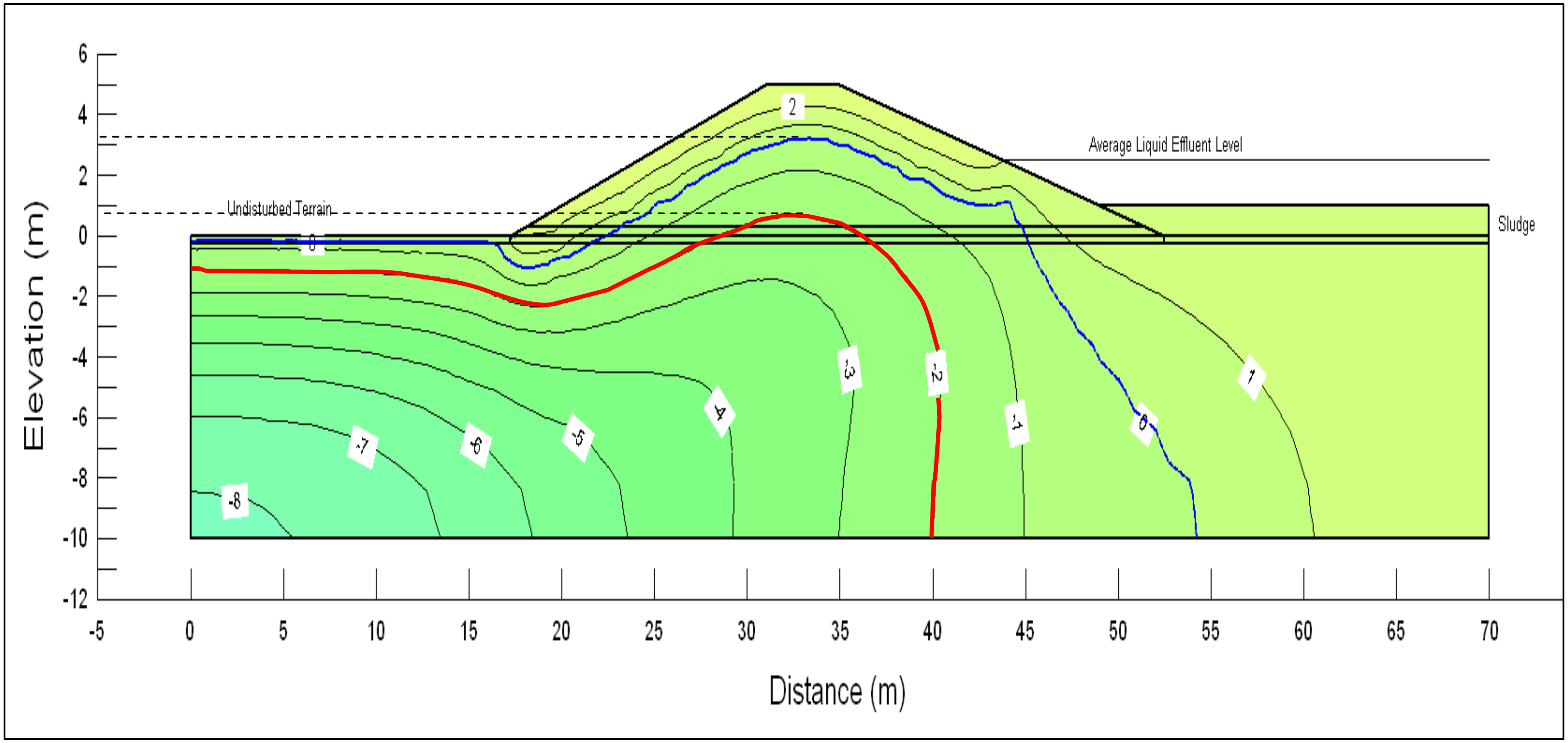

Figure 4-2. Cross-section of dyke structure showing ground temperature contours at maximum thaw after 20 years with lagoon held at constant +1 °C all year around. Climate warming effects are included.

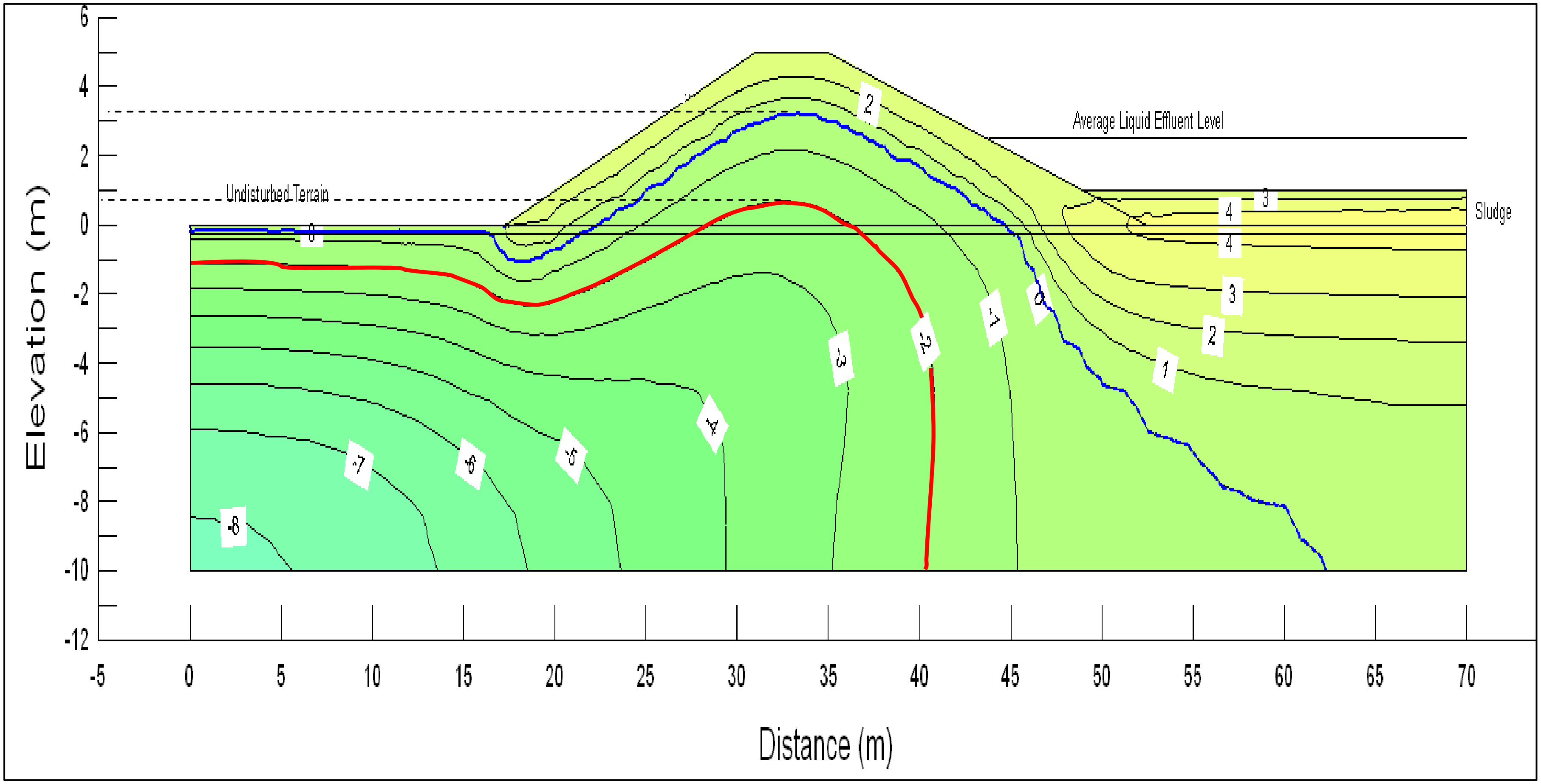

Figure 4-3. Cross-section of dyke structure showing ground temperature contours at maximum thaw after 20 years with seasonal variation in lagoon temperatures. Climate warming effects are included.