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BGC PROJECT MEMORANDUM

To:	**Nunavut Water Board**	**Date:**	**17.01.2008**
Attention:	**Dionne Filiatrault, P. Eng., Acting Executive Director**	**Cc:**	**D. Hohnstein**
From:	**Lukas Arenson (Ext. 116)**	**Project No.:**	**0308-003-03-01**
Project Name:	**Review of Final Submissions for Hamlet of Cape Dorset Sewage Lagoon Type B Water License Application**		
Title:	**Independent Geothermal Evaluation of Proposed Design**		

1.0 INTRODUCTION

This memorandum was prepared by BGC Engineering Inc. (BGC) at the request of the Nunavut Water Board (NWB or Board) to review the geothermal analysis of the final submissions and carry out an independent geothermal analysis for the Hamlet of Cape Dorset Sewage Lagoon Type B Water Licence Application.

A general review of the Hamlet of Cape Dorset Sewage Lagoon Type B Water Licence Application was submitted to the Board on January 8, 2007. This memorandum therefore concentrates on the independent geothermal analysis.

The water retention capability of the sewage lagoon is a key water licensing issue for this facility. The Engineer on Record, Dillon Consulting Ltd. (Dillon), with geotechnical input from AMEC Earth and Environmental (AMEC), has designed the berm with a geosynthetic clay liner (GCL) embedded in a cutoff trench excavated into the top of the permafrost. The lagoon basin is unlined. The integrity of the sewage lagoon strongly depends on the aggradation and maintenance of permafrost within the berm and foundation throughout its design life (understood to be thirty years). Retention of the waste water in the lagoon is critical so that minimum treatment objectives can be met.

Although an updated geothermal analysis (dated August 21, 2007) was prepared by AMEC and discussed at the October 1, 2007 pre-hearing, BGC did not feel it was relevant to undertake an in-depth critique of the analysis results until the as-built construction details from the November 15, 2007 submissions were provided. The as-built configuration was noted to be different from the original design drawings and the design cross section evaluated in the geothermal model. Specifically, the geothermal model was based on a berm section that excluded the presence of the liner. In AMEC's opinion, demonstrating that the berm and foundation would freeze back and remain frozen without a liner is a conservative design assumption supporting the conclusion that the lagoon did not need to be lined. BGC believes that this design rationale has not been fully substantiated by the design calculations.

AMEC's updated geothermal design (August 21, 2007) predicted ground temperatures in the undisturbed terrain downstream of the berm cooling from approximately -5°C to colder than -6°C over a thirty year period. This contradicts AMEC's November 1, 2006 report where they stated that from the measured ground temperature data, that the mean annual permafrost temperature at a depth of 15 m was extrapolated to be in a range of -4.0°C to -5.0°C. The thermal instability suggests that the selected input parameters are inconsistent with the assumed initial temperature conditions. Furthermore, AMEC also predicted that the berm foundation will also progressively cool over the thirty-year design life, which is inconsistent with typical geothermal response of embankments on permafrost. Considering that the design concept for the sewage lagoon relies on the presence of permafrost to provide containment, BGC believes that an independent geothermal analysis of the sewage lagoon design is necessary to improve the level of confidence that the sewage lagoon will perform as designed.

It is BGC's view that the AMEC's geothermal design appears incomplete in several key areas:

- The geothermal model was not calibrated against observed permafrost conditions.
- The applied air temperature boundary was based on mean monthly values for the time period of 1970 to 2000; the sensitivity of the geothermal design to the potential occurrence of long-term climate warming and extreme warm-years was not explicitly evaluated.
- The as-built configuration of the GCL was not modeled.
- The potential thermal effects of seepage through the berm were not evaluated.
- The warming effect of density-driven convection in the lagoon waste water was not addressed.

2.0 SCOPE OF WORK

The purpose of the independent geothermal analysis is to satisfy the following objectives:

- To support BGC's intervention statement, specifically to back up any comments or critique of AMEC's geothermal analysis.
- To provide the Board with an independent assessment and improve the level of confidence that the as-built configuration will sufficiently contain the sewage contents, such that waste water treatment objectives are met.
- To identify sensitive or critical parameters/issues that must be addressed either by additional investigations, monitoring, engineering or construction (remediation) on the part of the proponent.
- To provide technical guidance for drafting the terms and conditions of the water licence to address the above identified issues.

Specifically, BGC has carried out the following tasks:

- Review available information, such as climatic data, soil properties, berm sections and commentary on AMEC's models and assumptions.
- Conduct a 1-D thermal model calibration.
- Carry out a 2-D simulation of the sewage lagoon in operation over the thirty-year design life.
- Assess sensitivity cases, such as convective heat transfer, long-term climate warming, and extreme warm years.

3.0 AVAILABLE INFORMATION

3.1 List of Proponents' reports

The following reports were made available to BGC:

Table 1: Reports Made Available to BGC

Title	Report Type	Date
Geotechnical Investigation for P-Lake Seage Lagoon, Cape Dorset, NU	AMEC Report	October 13, 2005
P Lake Area Sewage Lagoon System, Final Design Report	Dillon Consulting Limited	January 2006
Cutoff Trench Excavation Sewage Lagoon Berms Construction Monitoring Cape Dorset, NU	AMEC Report	August 20, 2007
Additional Geotechnical Analyses for P-Lake Sewage Lagoon, Cape Dorset, NU	AMEC Report	August 21, 2007
Geotechnical Investigation - Sewage Lagoon, Cape Dorset, NU	AMEC Memo	November 1, 2006
Response to October 10, 2007 letter from NWB	Letter from GNCGS	November 13, 2007
Additional Stability and Seepage Analyses for P-Lake Sewage Lagoon,Cape Dorset, NU,	AMEC Report	November 15, 2007
As-built drawings: 000 Cover 100 Site Plan 101 Lagoon Containment Berms and Truck Turnaround Pad 102 Road Plan and Profile Station 0+000 to 0+360 103 Road Plan and Profile Station 0+360 to 0+700 104 Road Plan and Profile Station 0+700 to 0+932.55 105 Design Cross Sections Station 0+000 to 0+600 106 Design Cross Sections Station 0+625 to 0+933.75 107 Lagoon Road Plan and Profile Station 2+000 to	Dillon Consulting Limited	November 2007

Title	Report Type	Date
2+306.05 108 Lagoon Road Cross Sections Station 2+000 to 2+300 109 Berm Plans and Elevations 110 Earthworks & Sewage Discharge Details and Sections 111 Guardrail - Delineator - Gate Details and Sections 112 Lagoon Berm Sections and Details 113 Access Manhole Details		

The information presented, combined with BGC's experience with similar materials and site conditions, were used to estimate appropriate soil and thermal properties and boundary conditions.

3.2 Climate

3.2.1 Air Temperatures

In their geothermal analyses, AMEC used mean monthly air temperatures from the period of 1970 to 2000. Mean month-end snow cover data were also provided, but were not explicitly used in the geothermal analysis.

Below (Table 2) compares the mean annual air temperature at Environment Canada's meteorological station at Cape Dorset for the period of 1970 to 2000 with the annual record since 2000.

Table 2: Mean Annual Air Temperatures, Cape Dorset, NU

Average 1970 – 2000	2000	2001	2002[1]	2003	2004	2005	2006	2007[2]
-9.1°C	-7.7°C	-7.3°C	-7.9°C	-7.2°C	-8.8°C	-7.4°C	-6.1°C	-8.6

[1] No data for July
[2] Data for October – December has undergone only preliminary quality checking

Source: Environment Canada (http://climate.weatheroffice.ec.gc.ca)

The data show that air temperatures since 2000 have been consistently warmer than the mean over the 1970-2000 period.

3.2.2 Global Warming

AMEC did not explicitly incorporate global warming in their geothermal analysis. They reported that applying a climate warming trend of 0.5C/decade would not adversely impact the containment provided by the permafrost foundation and frozen berm over the thirty-year design life.

For design purposes, BGC proposes applying a climate warming trend of 0.7°C/decade.

3.2.3 Modelled Scenarios

Daily air temperatures were utilised in the numerical model. A sinusoidal temperature versus time curve that approximated the average temperature conditions and freezing and thawing days was generated and used to represent the air temperature boundary.

Figure 2 shows the air temperature versus time curves used in the geothermal analysis.

The long-term climate-warming trend was modeled by increasing the daily air temperatures by 0.07C/year over the thirty-year design life.

3.2.4 Snow Cover

Similar to the approach used by AMEC, snow cover was not modelled explicitly. Adequate factors were used to estimate ground surface temperatures from air temperature data. The n-factors were chosen according to known values from literature and model calibration analysis described below. Changing snow cover due to climate change was not considered.

3.3 Subsurface Conditions

AMEC's geotechnical investigation (dated October 13, 2005) documents surficial materials including glacial till, talus and marine beach deposits. Isolated deposits of glacial silty sand and gravel (till) overlay bedrock in the uplands. The granular talus material varies from silt to gravel size. During excavation of the cutoff trench in early-July 2007, a thin peat cover was reported over some sections of the cutoff trench. Excavation met refusal in either hard frozen soil or bedrock. Hard frozen soil with no visible ice was reported at depths below ground surface ranging from 1.0 m to 1.5 m. Bedrock depth was variable, ranging from the ground surface to below the depth of excavation (greater than 2.5 m). There was no description of the bedrock condition (e.g., rock quality, joint orientations, presence of ground ice) during excavation of the cutoff trench. In a response letter (dated November 13, 2007) the bedrock is described as competent with occasional closed fractures. Groundwater levels appeared to be perched immediately above the permafrost table. Apart from these visual descriptions, there were no laboratory index tests carried out on any soil sample from the site.

3.4 Design Intent of Berm and Sewage Lagoon Operation

It is our understanding that the design life for the sewage lagoon is 30 years. Containment of the sewage depends on two main elements: permafrost and GCL. GCL minimizes seepage through the berm (constructed of pervious sands and gravels). The GCL is keyed into permafrost soil or bedrock to minimize seepage beneath the berm. The existing permafrost underneath the whole lagoon is also intended to remain perennially frozen, thereby providing a nearly-impervious barrier to seepage beneath the lagoon.

4.0 THERMAL ANALYSES METHODOLOGY

4.1 GeoStudio 2007

The commercially available two-dimensional finite element software package GeoStudio 2007 (GeoSlope International, Ltd., Calgary, AB) was used for the geothermal analysis. GeoStudio 2007 is a modular software package that includes Temp/W (thermal analysis), Seep/W (seepage analysis), and Slope/W (slope stability). The software package allows one to carry out transient, coupled thermal-seepage analysis. In contrast to AMEC's thermal model SimTemp, GeoStudio 2007 accounts for the influence of convective heat transfer due to seepage.

4.2 Model Calibration

The only ground temperature measurements recorded at this site was from a 3 m deep thermistor string in which one measurement was recorded on September 14, 2006. The depth and limited number of ground temperature measurements are inadequate for interpreting actual permafrost conditions. In addition, the September 14, 2006 temperature measurements are not considered by BGC to be representative of true ground temperatures as they were taken shortly after drilling with an airtrack and do not represent stabilized readings. Furthermore, there have been no measurements of soil index properties. The soil characteristics were therefore estimated based on engineering judgment and the reported observations during the cutoff trench excavation.

The overburden was described as typically hard frozen from a depth below original ground surface of 1.0 m to 1.5 m. No visible ice was reported. Photos attached to the AMEC report showed that the top layer (~1 m) of the soil appeared dry and unsaturated.

Based on observations from the cutoff trench excavation (dated August 20, 2007), the native soil profile was modelled as 1.5 m thick unsaturated silt – clay overlying 1.5 m thick saturated silt – clay over gneiss bedrock. The initial groundwater table was assumed to be at a depth of 1.5 m. An additional case, representing bedrock from the ground surface, was also evaluated to test the sensitivity of the design to foundation condition.

A one-dimensional model was used for thermal model calibration. Mean ground temperatures were estimated by applying the mean air temperature conditions for a period of 75 years, followed by the mean monthly temperatures from 2006 - 2007. N-factors were used to account for the insulating effects of the vegetation and snow cover. Based on the calibration analysis, n-factors for ground with a thin vegetation cover were estimated to be 0.63 and 0.93 for freezing and thawing, respectively. A geothermal gradient of 0.02°C/m was applied at the lower boundary of the model.

Using the calibrated soil parameters two additional conditions were modelled: (i) average (1970 – 2000) conditions, and (ii) average (1970 – 2000) conditions without a soil layer, i.e. bedrock at the surface and with different n-factors.

The thaw depth was the major parameter against which the model was calibrated. Not all soils freeze at 0°C. In fine-grained soils, there can be a significant amount of unfrozen water locked into the soil even at negative temperatures. Because no ground temperatures were measured during excavation of the cutoff trench, it was assumed that the descriptor "*hard frozen*" corresponded to a ground temperature of -1.5°C, the temperature at which a silty-clayey soil is practically frozen (Anderson and Morgenstern, 1973). In consequence, the depth of the -1.5°C isotherm was considered as thaw depth in the silt-clay overburden. Figure 4 shows the predicted -1.5°C isotherm history during 2006 and 2007. The predicted depth of the -1.5°C isotherm is approximately 1.5 m in early-July, which matches the upper range of observed depths to hard frozen soil during excavation of the cutoff trench. The maximum thaw penetration is predicted to occur in late-September and is approximately 2.2 m.

Under mean (1970 – 2000) climatic conditions, the predicted maximum thaw depth (-1.5°C isotherm) is 1.85 m, and for bedrock conditions it is 3.1 m (using 0°C isotherm). For each foundation profile, the predicted mean ground temperature at 15 m depth is -5.3°C, which is considered reasonable for a mean annual air temperature of -9.1°C.

Based on the calibration results, the estimated soil parameters and boundary conditions are considered reasonable.

4.3 Soil parameters

The geothermal soil parameters for the bedrock and the silt-clay layers were estimated from the calibration analyses (above). Soil parameters for the berm fill and the hydraulic conductivities for these materials were estimated from well-established soil properties (Andersland and Ladanyi, 2004; Farouki, 1986). The latent heat of the material is calculated automatically depending on the actual water content using 334 MJ/(m^3·°C) as the latent heat of water. Table 3 summarizes the material properties used in the thermal analyses.

Figure 5 shows the unfrozen water content distribution used for the Silt – Clay layer. The distribution shows that at a temperature of -1.5°C, the soil is practically completely frozen.

The thermal-seepage properties of the berm fill are shown in Figure 6.

Table 3: Material Properties Used In Thermal Analyses.

Note: most parameters are not fixed, i.e. depend on the temperature and water content close to the freezing point.

Material	Material model	In-situ sat. water content (Vol %)	Thermal Conductivity (kJ/(day·m^3·°C))		Volumetric heat capacity (kJ/(m^3·°C))		Hydraulic conductivity (m/s)
			Frozen	**Unfrozen**	**Frozen**	**Unfrozen**	
Bedrock	Simplified thermal model	1.9	251	251	2260	2150	$1 \cdot 10^{-8}$
Silt – Clay saturated	Full thermal	12.8	173	164	1700	2160	$1 \cdot 10^{-6}$
Silt – Clay unsaturated	Full thermal	7.5	123	121	1510	1780	$1 \cdot 10^{-6}$
Berm	Coupled convective thermal	11.1	255	182	1710	1490	$1 \cdot 10^{-5}$
Water	Full thermal	100	192	48.5	1880	4220	-
GCL	Only for seepage					Normal: $1 \cdot 10^{-10}$ Parallel: $1 \cdot 10^{-5}$	

5.0 2D THERMAL MODEL

The 2D thermal model was set up using a geometry consisting of 5283 elements. The construction of the berm and the incremental filling of the lagoon was simulated as realistic as possible using various stages:

- Stage 1: Initial temperature conditions of the ground without a berm, based on the results of the calibration analysis using the 2007 air temperatures. For the subsequent air temperatures, the average conditions (1970 – 2000) were utilised with a warming trend of 7°C/100 years.
- Stage 2: On August 1st, the berm is constructed, including backfilling of the cutoff trench. The berm fill was assumed to have an initial temperature of 6.8°C, which corresponds to the air temperature on August 1st. for the average (1970 – 2000) conditions.
- Stage 3: Lagoon remains empty until January 31st, 2008.

- Stage 4: Incremental filling of the lagoon by 0.45 m increments at the start of each month until September 1st. On October 1st, the lagoon is emptied to 0.45 m. At each incremental step, the initial temperature of the added sewage was 4°C. The unsaturated silt – clay layer of the foundation on the upstream side of the berm was changed into a saturated silt – clay layer at that time.
- Stage 5: On the first day of the following 11 months (Nov. – Sept.), 0.45 m of water was added into the lagoon and emptied again (to 0.45 m depth) on October 1st. This cycle was repeated annually until the end of the simulation.

The modelled geometry matched the typical as-built geometry (Figs. 7 & 8).

5.1 Boundary Conditions

In order to account for expected snow drift, three different n-freezing factors were used along the downstream slope of the berm. Furthermore, because the density of water is highest at a temperature of 4°C, temperature variations along a column of water can cause warm water to sink to the bottom of the lagoon, thereby inducing convective heat transfer. The Geo-Studio 2007 model does not explicitly simulate convective heat transfer within the lagoon due to density-driven mixing. The thermal effects of natural convection in the lagoon were simulated by assigning a high n-factor over the lagoon surface during the summer. Table 4 summarizes the n-factors used in the thermal models.

Table 4: N-Factors Used As Thermal Boundaries.

Boundary	n-freezing (winter)	n-thawing (summer)
Natural soil	0.65	0.93
Berm (lower third)	0.5	1.8
Berm (middle third)	0.6	1.8
Berm (upper third)	0.7	1.8
Berm (crest)	0.8	1.8
Lagoon Contents	0.4	2.0
Bedrock	0.65	1.3

Hydraulic boundary conditions were set so that the groundwater table on the downstream side of the berm is at a depth of 1.5 m. On the upstream-side, a zero pore water pressure boundary was set at the lagoon surface.

5.2 Results of 2D analyses

Figure 9 shows the temperature trend of point A at the bottom of the GCL in the cutoff trench, which is the most critical element of the design. This point is located at a depth of 2 m from the original ground. Day 450 marks August 1st, i.e. the day that construction of the berm has been completed, and the dashed line shows when water is added to the lagoon the first time (February 1st). Figure 9 indicates that over the first 6 months following berm construction, the fill in the cutoff trench warms slightly in response to the warm berm fill placed during summer construction. Subsequently, the general trend is one of cooling over the next five years, followed by a warming trend until the end of the simulation.

Figures 10 – 14 show the 0°C isotherm for the 1st, 5th, 10th, 20th and 30th year after berm construction. Figure 15 - 19 shows the locations of the -2°C isotherm for the same years. These figures show the maximum penetration of the temperature. The berm fill begins to freeze over the first year following berm construction as permafrost aggrades up to the base of the berm. Under mean climatic conditions, the active layer penetration (depth of 0°C isotherm) below the berm crest is predicted to be approximately 3.5 m. After the first year following berm construction, the cutoff trench fill is predicted to be generally colder than -2°C.

5.3 System Sensitivity

An additional three models were simulated to test the sensitivity of the geothermal analyses to the following scenarios:

- Extreme warm year during the first year following berm construction;
- Bedrock outcrop foundation; and
- Higher hydraulic conductivity of the berm fill and foundation.

Figure 20 shows the isotherms on October 31st, 1 year after completion for the average (1970 – 2000) temperature case. This case is compared with the extreme warm 2006 – 2007 condition (Fig. 21) and a pure bedrock foundation situation (Fig. 22). The bedrock conditions show the deepest thaw penetration under the toe of the berm. For an extreme warm summer event (2006-2007 conditions) the centre of the berm (3.4m depth) is warmer than 0°C at the end of October. However, all three scenarios show that the trench fill temperatures vary between -1.0°C and -2.6°C at the end of October. They all confirm that the most critical aspects in the thermal design of the berm configuration are: i) the time required for the cutoff trench fill and berm fill to sufficiently freeze before sewage contents can be added, and ii) the GCL must be keyed into permafrost soils or bedrock. For design purposes, -2°C was selected as the temperature at which the foundation material is considered practically completely frozen and impermeable to seepage.

The temperature trend during the first three years was also compared for point A in Figure 23. The cases for the 2006 – 2007 warm year and the bedrock foundation just reach a maximum of -2°C at point A after the first winter.

5.4 Effect of Hydraulic Conductivity

In order to investigate the sensitivity of the system to higher hydraulic conductivities, the model was run using a value of $1 \cdot 10^{-3}$ m/s for the berm and $1 \cdot 10^{-5}$ m/s for the silt – clay layer. The results show that the temperature at the bottom of the cutoff trench increases by about 0.1ºC after the first year. With time, the difference decreases. Even though the total water flow through the berm increases, its effects on the berm temperatures appear to be minor.

5.5 Discussion of Results

5.5.1 Berm Foundation

The coupled seepage and thermal models show that permafrost aggradation is observed for all scenarios modelled. The berm foundation is predicted to be generally colder than -2°C. However, if the temperatures are significantly warmer than the 1970 – 2000 average or if the berm is founded on a bedrock outcrop, it is possible that parts of the berm foundation may be warmer than -2°C. Under a climate warming trend of 7°C/100 years, the results indicate that the permafrost foundation begins to warm at a rate of approximately 3.8°C/100 years. Permafrost containment is predicted to be provided over the 30 year design life. Beyond thirty years, permafrost warming due to climate change may be sufficiently great that parts of the permafrost foundation may become pervious to seepage.

5.5.2 Lagoon Foundation

Similar to the temperature trend observed beneath the berm, the temperatures under the lagoon are predicted to cool rapidly during the first 3 to 4 years of operation, followed by a warming trend. The mean ground temperature beneath the lagoon is predicted to warm from -5°C to -4°C over the thirty-year design life. Based on the proposed operation of the sewage lagoon, the lagoon foundation is predicted to remain frozen over its design life (Fig. 24).

5.5.3 Lagoon operation

The operational control of the lagoon level is a critical element for the thermal design of the sewage lagoon. The incremental filling of the lagoon over the course of the year and its near-emptying at the end of summer has a significant effect on foundation temperatures. The incremental filling results in complete freezing of the sewage during the cold winter months. Because ice has a high thermal conductivity, the net effect is that the lagoon foundation is cooled during the winter. In addition gravity driven natural convection within the lake is minimized. If the lagoon were maintained near full capacity year-round, or if the sewage were first added during the spring or summer, the lagoon may not freeze to the bottom, which would cause the lagoon foundation to warm and potentially develop a talik.

The low lagoon level during the winter further allows cooling of the berm from both sides, whereas during the summer the upstream-side of the berm is insulated by the thick mass of frozen sewage.

The results of the thermal analyses showed that the base of the lagoon contents may not thaw during the summer, which could affect the emptying of the lagoon planned for September. The observed thermal state of the sewage contents during a minimum of the first two years of operation should be reviewed by a geotechnical engineer to confirm the thermal design of the sewage lagoon.

5.5.4 Seepage

Seepage through the berm was not directly part of these investigations. However, seepage influences the temperatures in the berm and a short discussion is presented to demonstrate that the modelling results are reasonable. Figure 25 shows the change in ground water table during the second year of operation. The water from the lagoon slowly starts to saturate the berm on the upstream-side of the GCL. Once it reaches the liner, it also moves parallel to it because there is a sand layer with a higher permeability. Because the GCL is not impermeable, water will seep though and start to saturate the downstream side of the berm as well. However, only very little water seeps through the GCL and the water level in the downstream half of the berm is kept low. This has also a positive effect on the stability of the down-stream slope.

Seepage during the summer months is primarily through the GCL and unfrozen berm fill, which demonstrates that the system depends on a proper construction and integrity of the GCL. An increase in the hydraulic conductivity by two orders of magnitude for the berm and one order of magnitude for the silt-clay foundation, respectively, almost doubles the flow rate. There was, however, nearly no measurable effect on berm and foundation temperatures. The thermal influence of the increased seepage was only noted in the first years following construction of the berm, before permafrost fully developed within the berm fill and around the cutoff trench fill.

5.5.5 Comparison with AMEC Results

The results of the geothermal analysis carried out by BGC are briefly compared with the geothermal modeling results available from AMEC (dated, October 13, 2005 and August 21, 2007). The original design used a waterproof liner at a depth of 1 m below the upstream slope (1V:2H), whereas the updated design (2007) assumed that an impermeable liner will be installed within the berm near the centre of the crest. Because seepage was not included in the thermal analysis, the liner was not modelled. The slopes further changed to 1V:2.5H. BGC used the as-built configuration with the GCL located as shown in Figure 7.

AMEC predicted the temperature at the bottom of the berm under the centre of the crest after 30 years of operation to be -2.5°C (2005 report) and -5°C (2007 report). In addition, the 2007 results showed cooling trends for that location in the long-term: -4.5°C (5 years), -4.9°C (10 years), whereas the 2005 model showed steady temperatures for these times. BGC's result on the other hand showed a cooling trend at base of the berm only for the first five years before constant warming is observed in response to the applied climate-warming trend. After 30 years of operation (end of summer) the temperature at the base of the berm is -2.0°C. It is important to note that due to the phase lag the warmest temperatures at that depth are not obtained at the end of the summer but during winter. BGC predicts that after 30 years of long-term climate warming temperatures may reach up to -1.3°C. No data are available for comparison in the AMEC reports.

Generally it can be noted that the predicted ground temperatures presented here are warmer and the isolines more complex than the geothermal model results presented by AMEC. The results of the long-term simulations further show significant differences in temperature. The results presented herein confirmed the initial impression that berm temperatures have to be monitored closely. The reasons for the differences are

- the estimated soil parameters and n-factors have been calibrated against reported active layer observations,
- improved thermal model utilising unfrozen water content functions,
- incorporating convection due to seepage that influences energy transfer, in particular on the upstream side of the GCL,
- explicit modeling of climate warming trend, and
- consideration of density-driven convective heat transfer within lagoon contents.

Despite these differences, the results of the geothermal analysis indicate that the as-built berm configuration is appropriate for the given climatic conditions and proposed operating conditions.

6.0 CONCLUSIONS AND RECOMMENDATIONS

An independent geothermal analysis was carried out by BGC to confirm the integrity of the sewage lagoon enclosure at Cape Dorset, NU. The geothermal analysis not only accounted for the geothermal properties of the soil, but also considered convective heat transfer due to water seepage through the berm and foundation.

The key objective of this thermal analysis was to determine if the proposed design will contain the sewage lagoon contents over the design life of this structure. It is understood that containment design is based on ice-saturated frozen soil or rock within the foundation of the berm and where the GCL is keyed into the permafrost. Within the berm, the GCL is the primary barrier to seepage, in particular near the upper portion of the berm that regularly thaws during the summer. Because soils, unlike water, do not generally freeze at 0°C, channels of unfrozen water may exist in the soil at temperatures below 0°C, thereby allowing flow through the partially frozen soil. A temperature of -2°C was selected as the design temperature below which permafrost soil or rock was considered impervious to seepage.

The conclusions based on the geothermal modelling carried out by BGC, include:

- The as-built berm configuration is suitable for the proposed operating conditions.
- Assuming that lagoon filling does not start until the first February after construction the GCL is expected to freeze into the bedrock foundation and seepage through the berm (mainly through the silt layer in the foundation) will not occur. Convection due to seepage will only partially thaw the upstream side of the berm.
- With an estimated active layer thickness of 3 to 4 m into the berm the GCL is the primary form of containment during the summer.
- It is predicted that the berm foundation will remain sufficiently frozen (colder than -2°C) over the thirty-year design life although permafrost containment may be impacted if the sewage lagoon operates for more than thirty years under the design long-term climate warming scenario modelled.
- Even under an extreme warm year scenario following the berm construction, the foundation of the berm meets the -2°C criterion after the first winter.
- The foundation beneath the lagoon is predicted to remain in a permafrost condition.
- The integrity of the system strongly depends on the operation and management of the lagoon contents. Changes in the way and schedule that the lagoon is filled and emptied may affect temperatures in the lagoon and berm foundations and adversely impact the design concept.
- The base of the lagoon may be frozen year-round. When modelling the monthly 0.45 m increments of lagoon filling, and assuming that the lagoon level is lowest at the end of summer (September), the lagoon contents are predicted to be completely frozen each year between October and April. The summer may be too short and cold to fully thaw the lagoon. This may cause problems related to sewage management. On the other hand, if sewage is first added to the lagoon during the spring or summer, the sewage contents may not completely freeze to the bottom of the lagoon and could cause the permafrost foundation to thaw. The observed thermal state of the lagoon contents should be reviewed by a geotechnical engineer during a minimum of the first two years of operation to confirm the thermal design of the sewage lagoon.
- Where the liner is embedded in a bedrock foundation, the active layer is deeper (~ 3 m) than the constructed cutoff trench depth (2.0 to 2.5 m). Berms founded on a bedrock foundation are predicted to be colder than -2°C after the first winter following berm construction. Over the thirty-year design life, part of the bedrock foundation may warm to above -2°C but still remain colder than 0°C. As bedrock, even jointed, is expected to freeze at temperatures just below 0°C, permafrost containment is still expected, provided that the joints are ice-saturated.

It is critical that thermistors be installed in the berm to confirm that freeze-back has occurred within the foundation and the berm. Temperature data must be routinely collected and reported in the annual inspection reports. BGC recommends that a minimum of three deep (20-25 m) thermistors be installed from the berm crest as a licence requirement.

7.0 CLOSURE

BGC Engineering Inc. (BGC) prepared this report for the account of Nunavut Water Board. The material in it reflects the judgment of BGC staff in light of the information available to BGC at the time of report preparation. Any use which a third party makes of this report, or any reliance on decisions to be based on it are the responsibility of such third parties. BGC accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this report.

Dillon and AMEC are the Engineers of Record for this project and are wholly responsible for the design and performance of the noted project and its components. None of the review comments provided herein by BGC absolves Dillon and AMEC of that responsibility and again, BGC accepts no responsibility for any damages suffered by third parties based on the review comments provided herein.

As a mutual protection to our client, the public, and ourselves, all reports and drawings are submitted for the confidential information of our client for a specific project. Authorization for any use and/or publication of this report or any data, statements, conclusions or abstracts from or regarding our reports and drawings, through any form of print or electronic media, including without limitation, posting or reproduction of same on any website, is reserved pending BGC's written approval. If this report is issued in an electronic format, an original paper copy is on file at BGC Engineering Inc. and that copy is the primary reference with precedence over any electronic copy of the document, or any extracts from our documents published by others.

It is hoped that the foregoing satisfies the requirements of the assessment you requested. Please do not hesitate to contact the undersigned if you have any questions or require additional information.

We trust this information meets with your requirements. Please feel free to contact the undersigned at your convenience should you have any questions or require additional investigations.

Thank you for the opportunity to undertake this assessment.

Yours sincerely
BGC ENGINEERING INC.
per:

Original signed:

Lukas Arenson, Dr.Sc.Techn.ETH, Dipl.Ing.ETH
Geotechnical Engineer

Original signed and Stamped

Jack Seto, M.Sc., P.Eng.
Senior Geotechnical Engineer

FIGURES

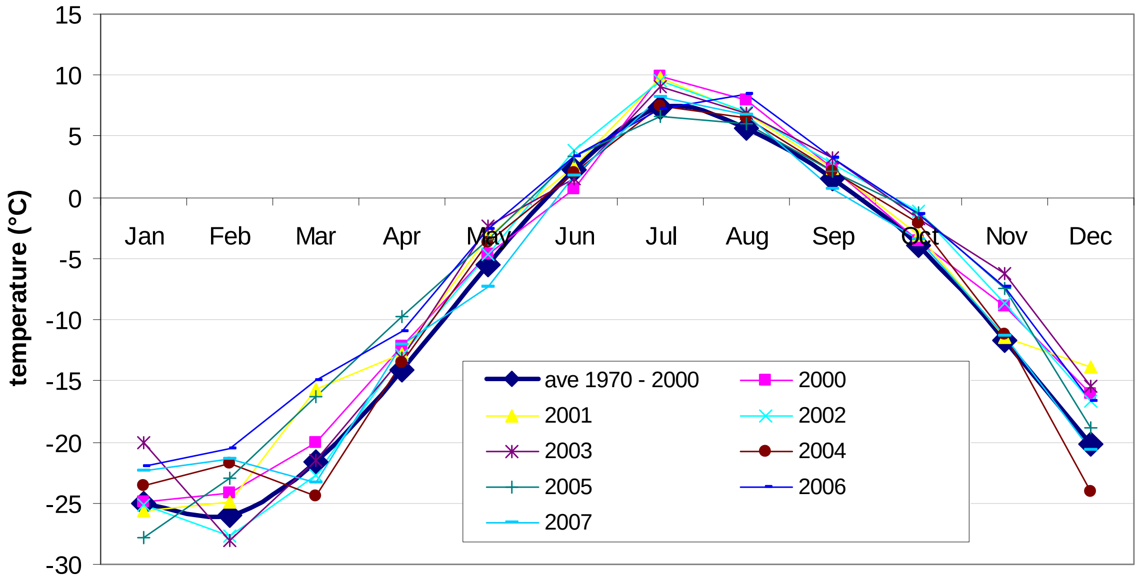


Figure 1. Mean Monthly Air Temperatures, Cape Dorset, NU (source: Environment Canada).

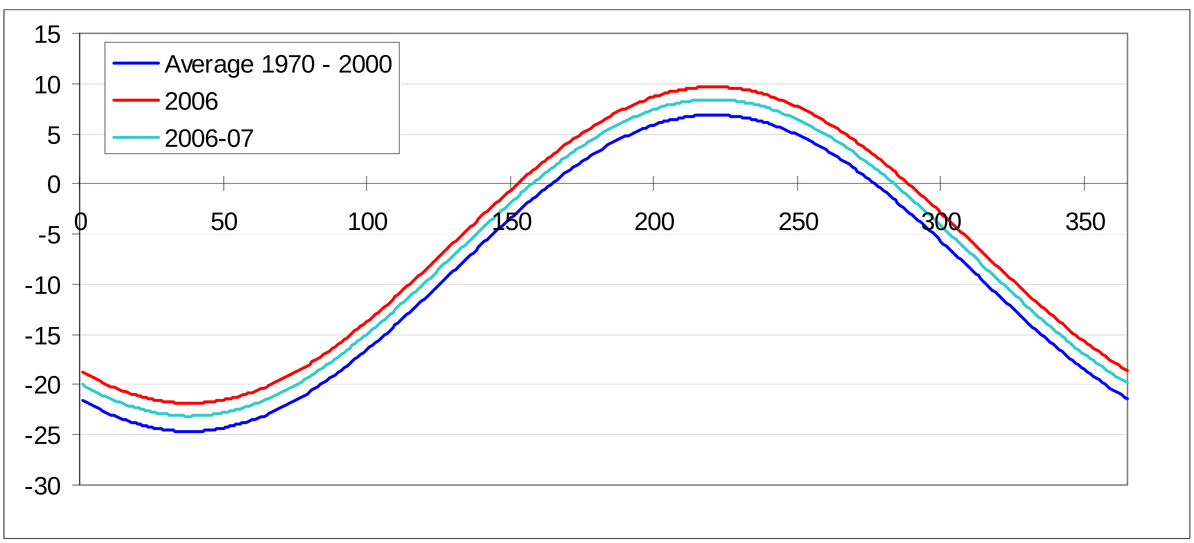


Figure 2. Sinusoidal air temperature variations used in geothermal analysis. Day 0 refers to January 1.

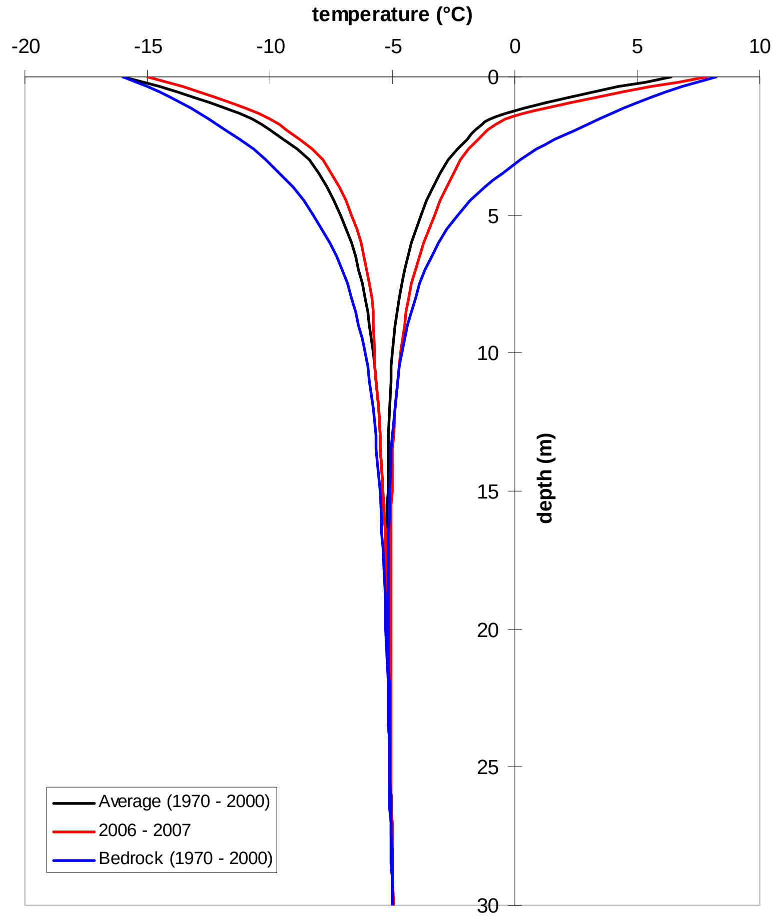


Figure 3. Temperature trumpets for different temperature boundary conditions (1D calibration model).

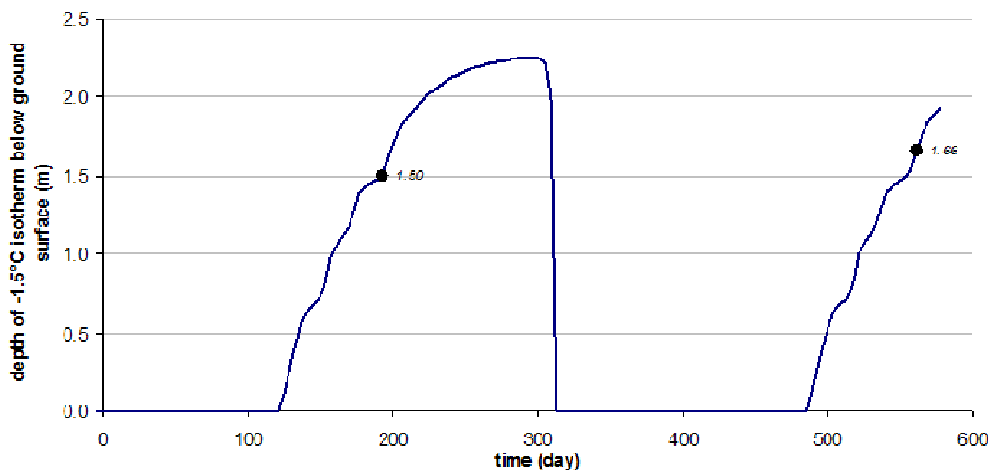


Figure 4. Predicted -1.5°C isotherm history for 2006 – 2007. Day 0 refers to January 1, 2006.

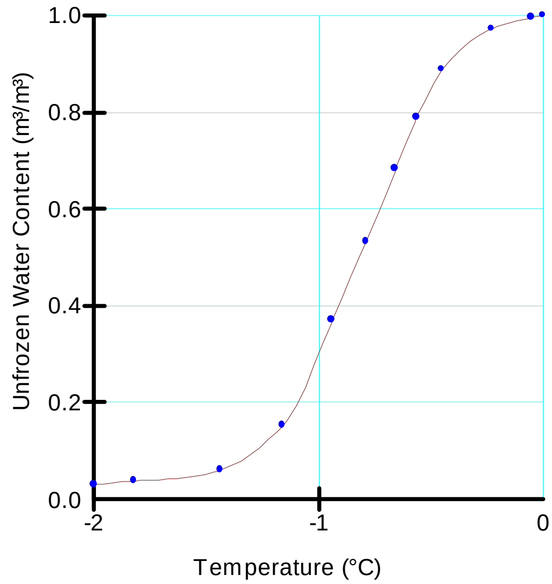


Figure 5. Temperature dependent unfrozen water content for Silt – Clay layer.

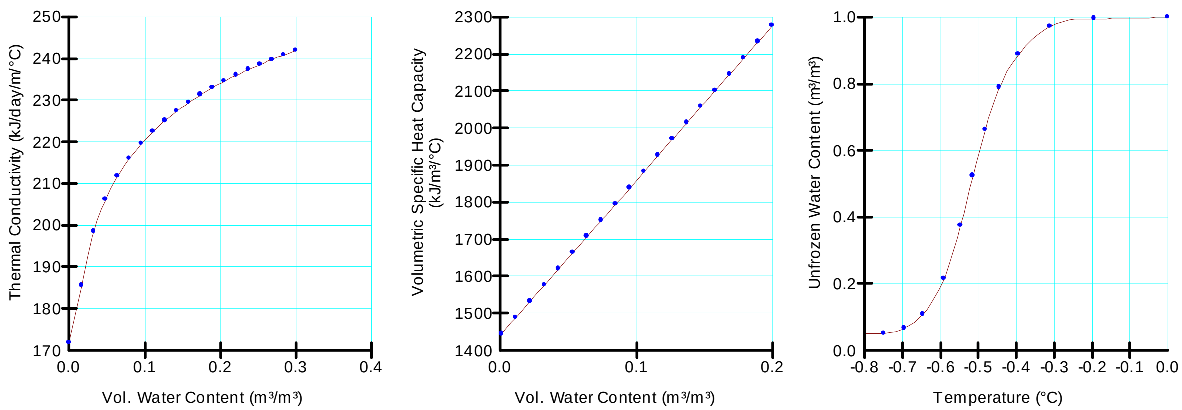


Figure 6. Thermal properties for berm material.

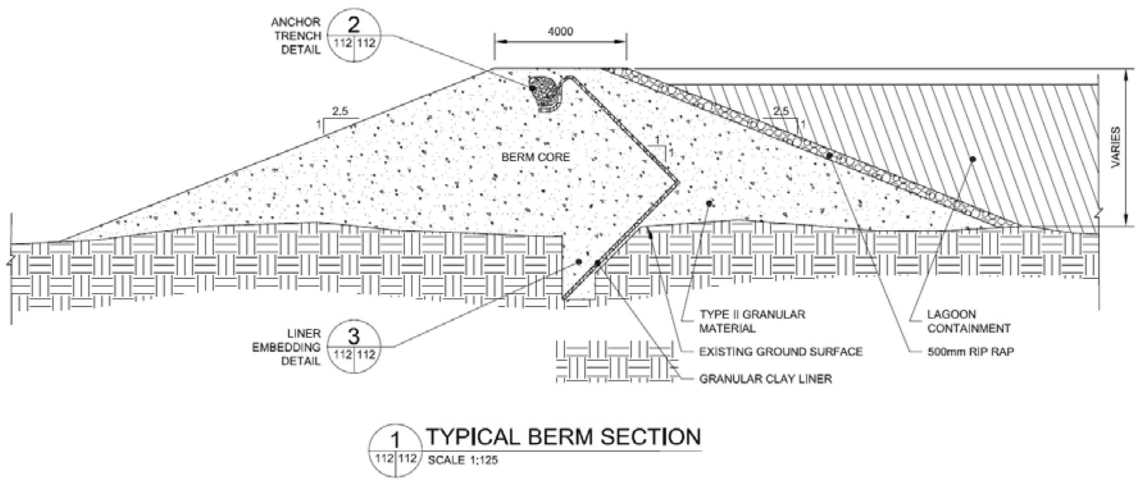


Figure 7. As-built lagoon berm section (from Dillion Drawing #112, Nov 2007).

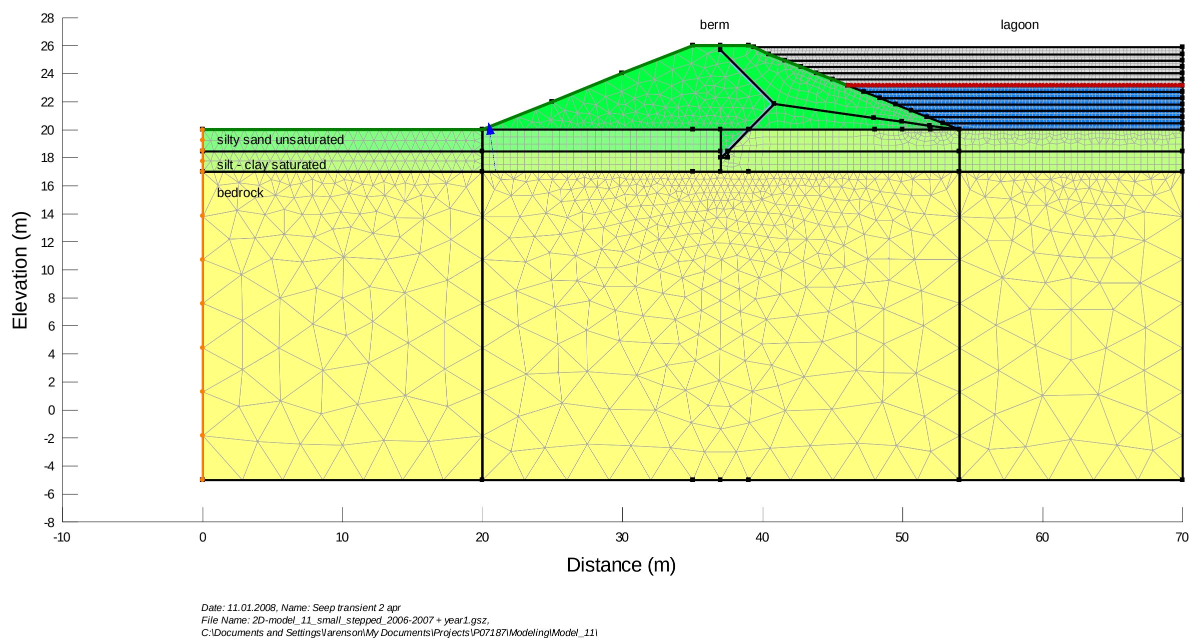
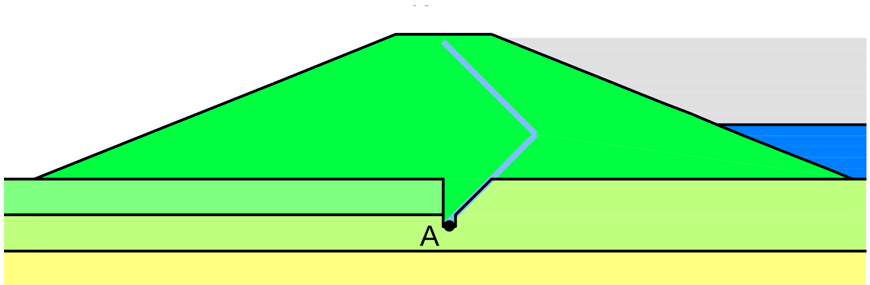


Figure 8. FEM geometry (situation shows month of April of the second year in operation).



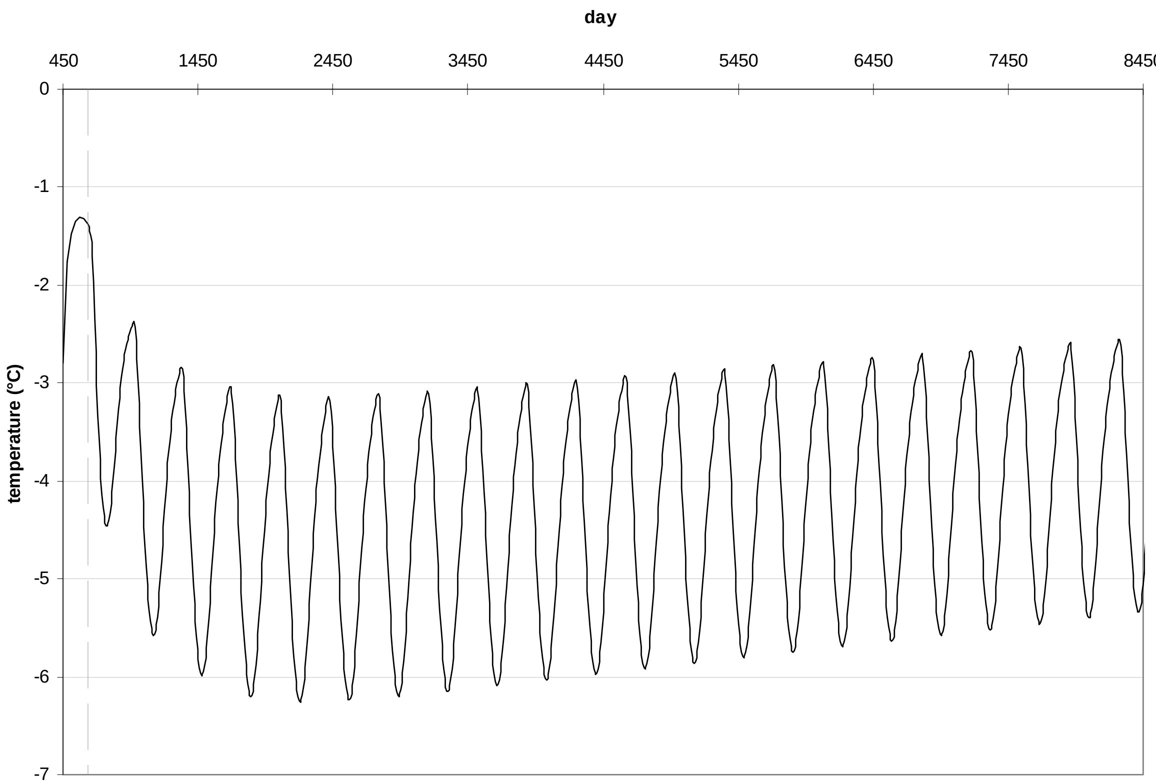


Figure 9. Temperature history at the bottom end of GCL in cutoff trench. Day 450 is August 1.

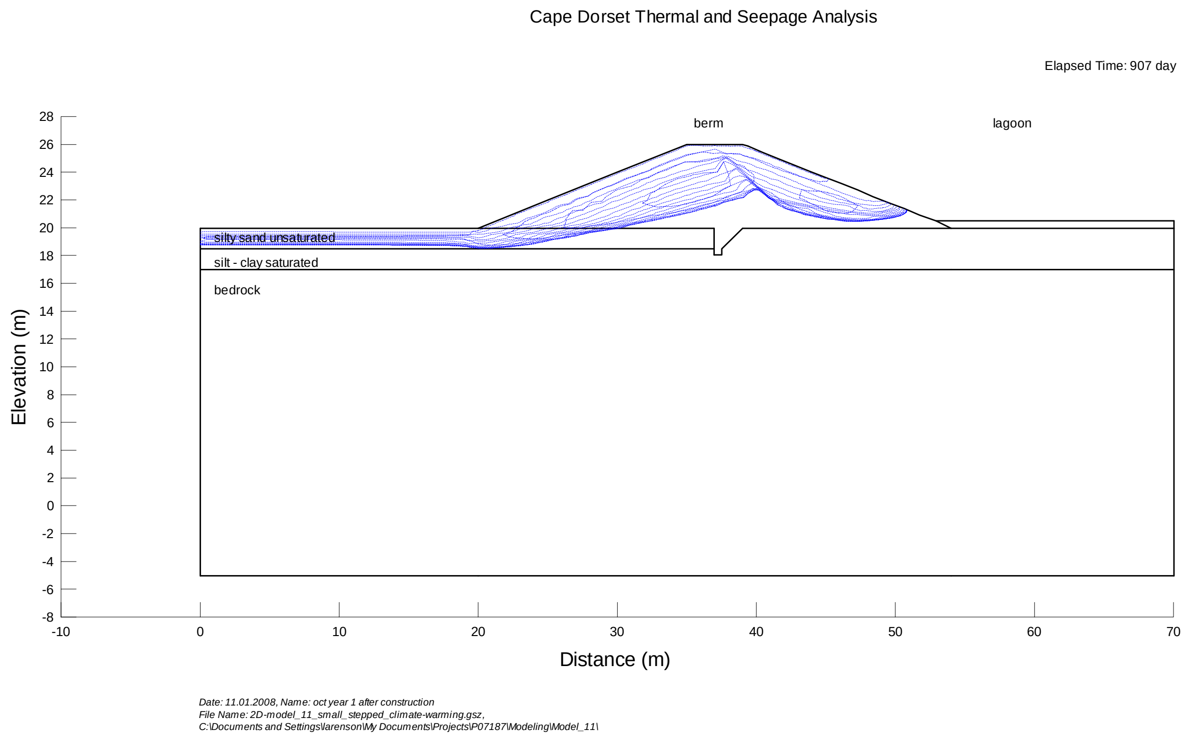


Figure 10. 0°C Isolines, February – October, 1st year after construction.

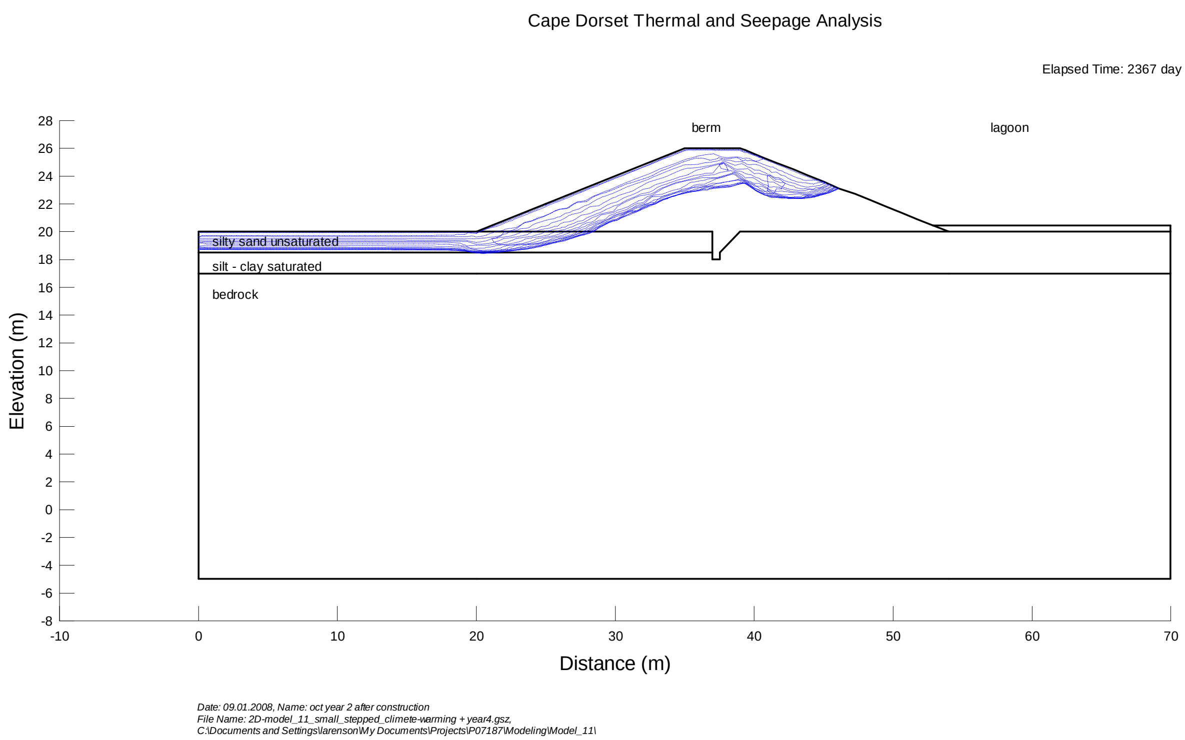


Figure 11. 0°C Isolines, 5th year after construction.

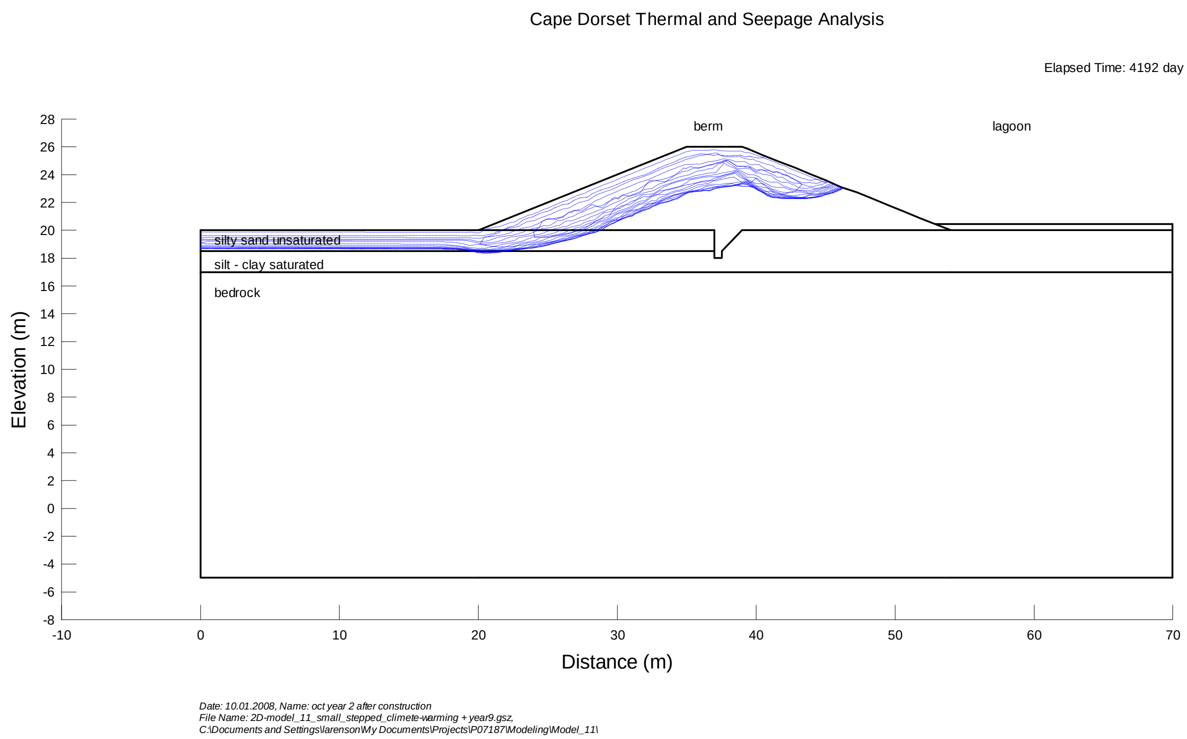


Figure 12. 0°C Isolines, 10th year after construction.

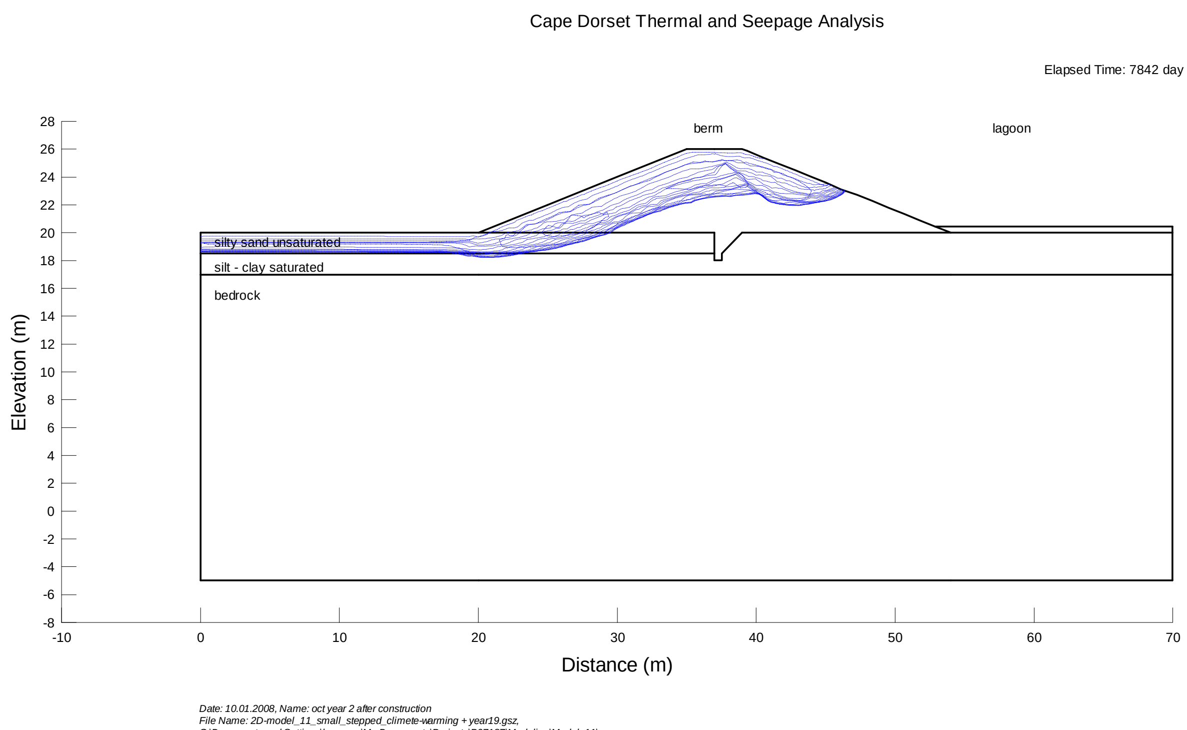


Figure 13. 0°C Isolines, 20th year after construction.

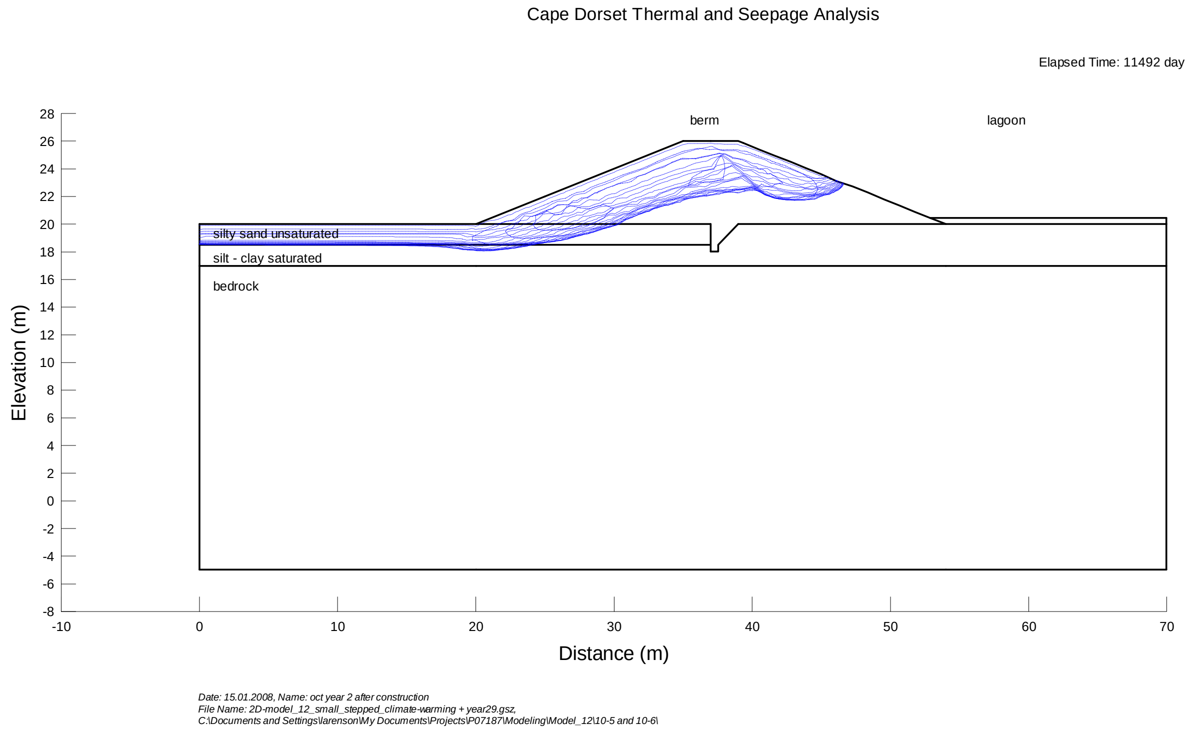


Figure 14. 0°C Isolines, 30th year after construction.

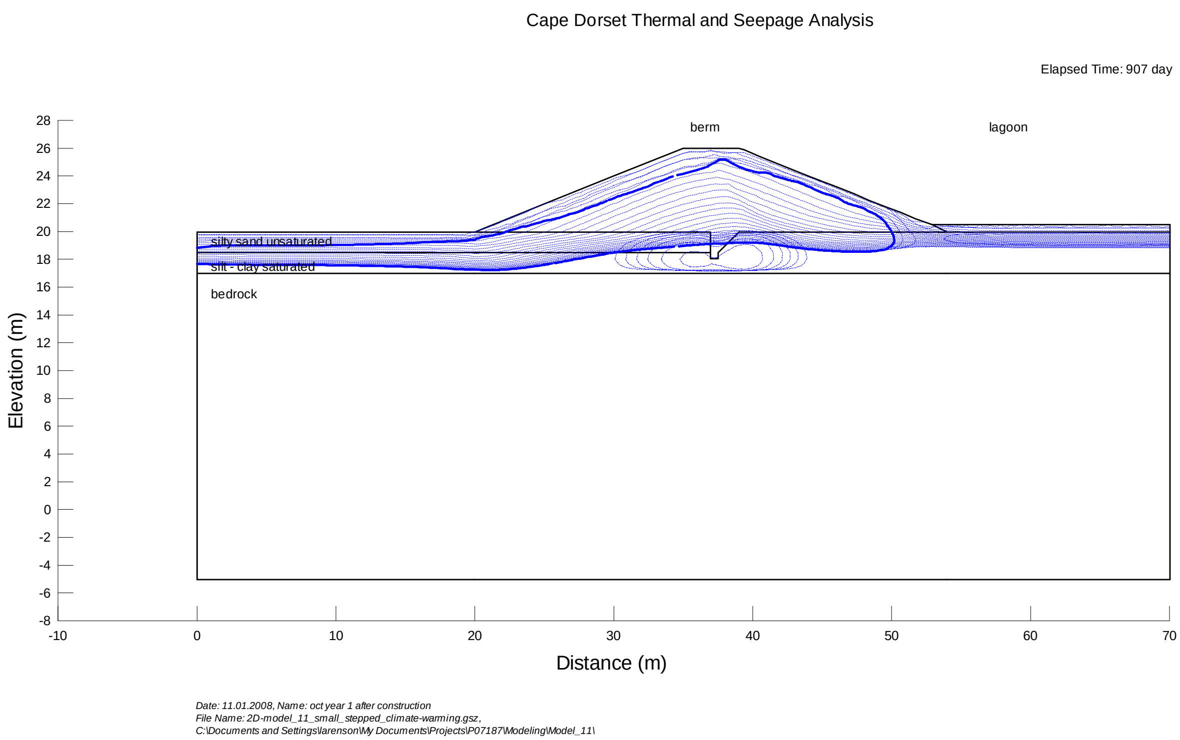


Figure 15. -2°C Isolines, February – October, 1st year after construction.

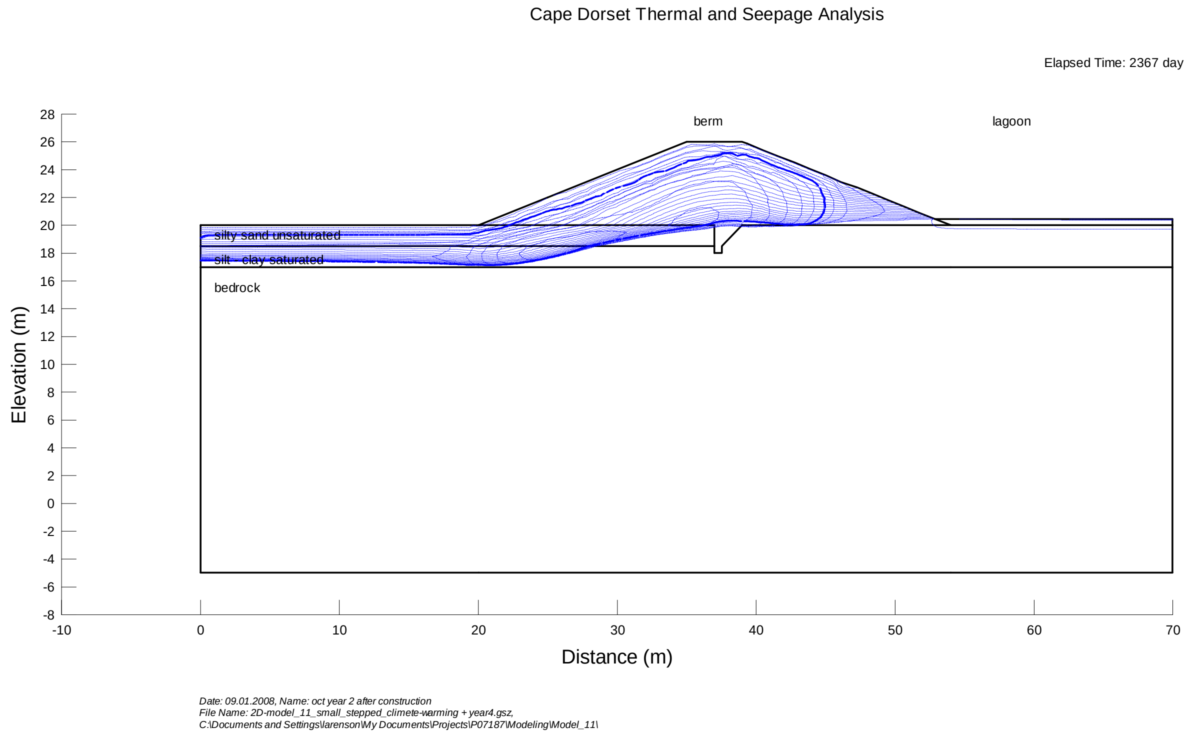


Figure 16. -2°C Isolines, 5th year after construction.

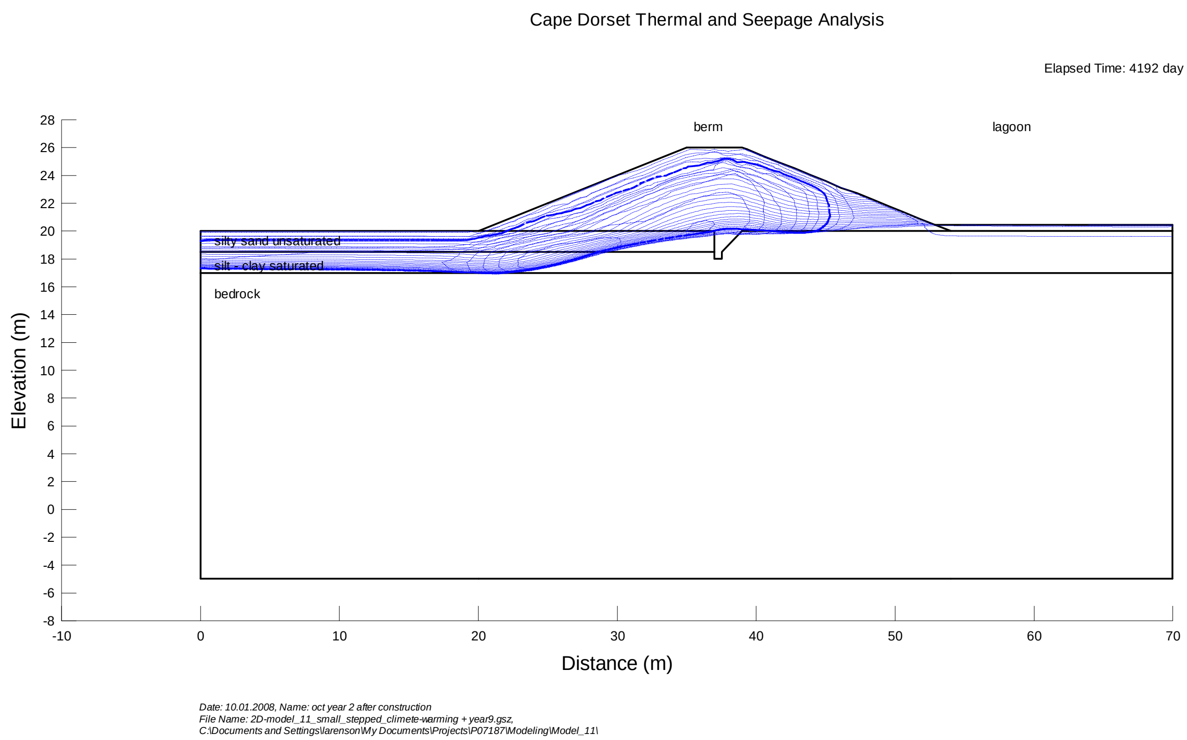


Figure 17. -2°C Isolines, 10th year after construction.

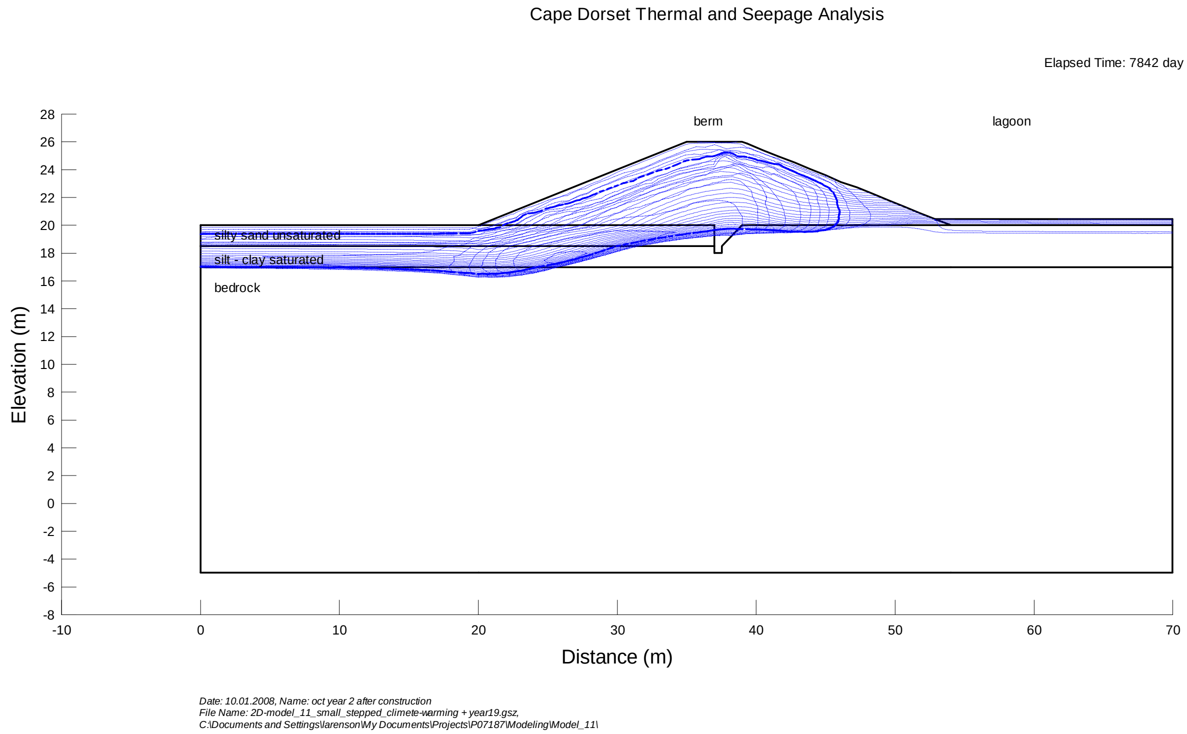


Figure 18. -2°C Isolines, 20th year after construction.

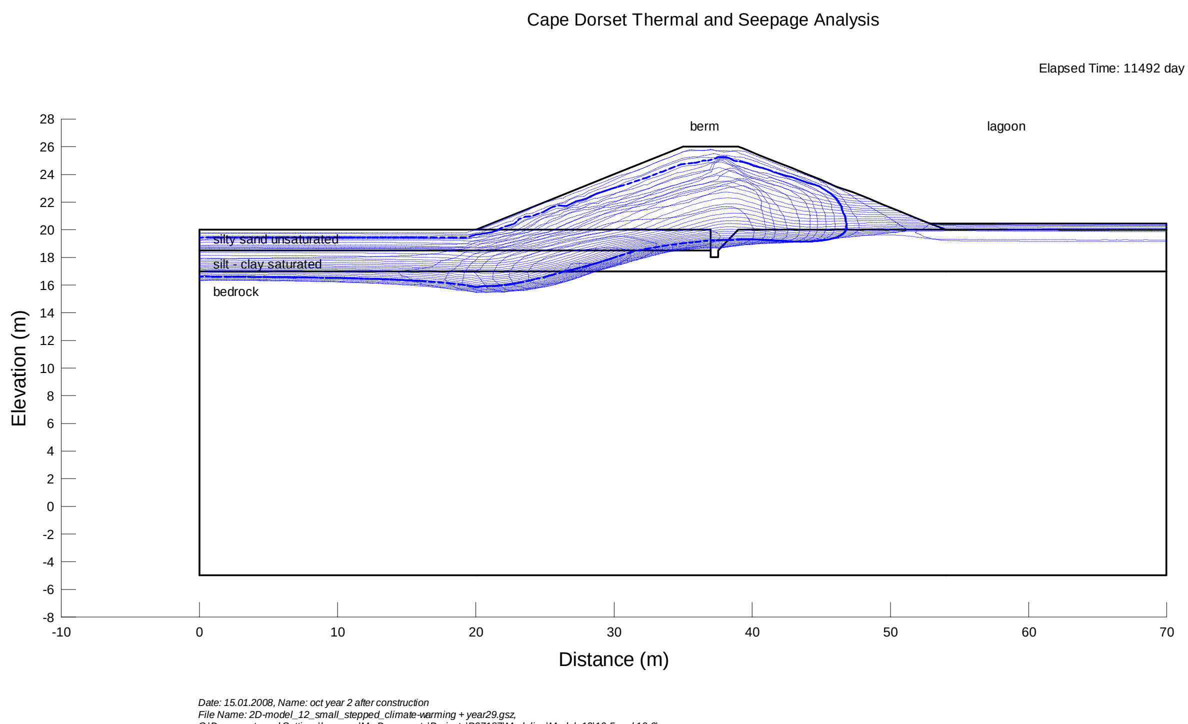


Figure 19. -2°C Isolines, 30th year after construction.

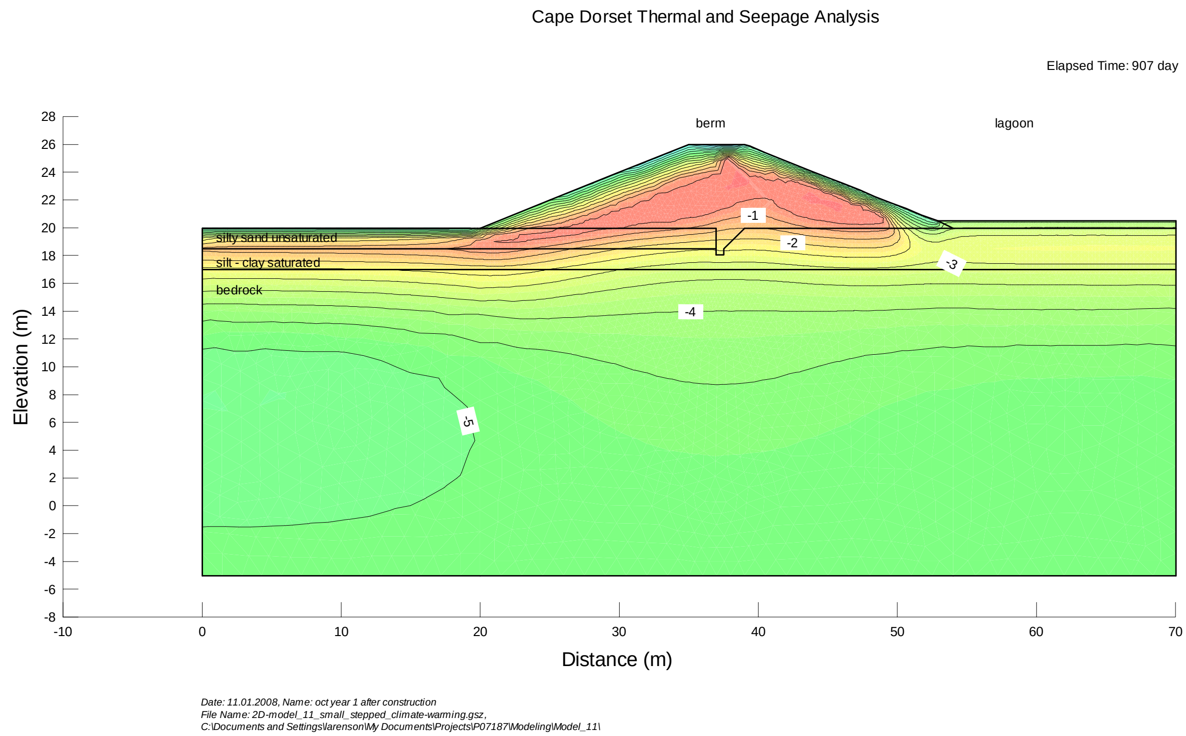


Figure 20. Isotherms, October 31, 1 year after berm construction, average (1970 – 2000) air temperatures.

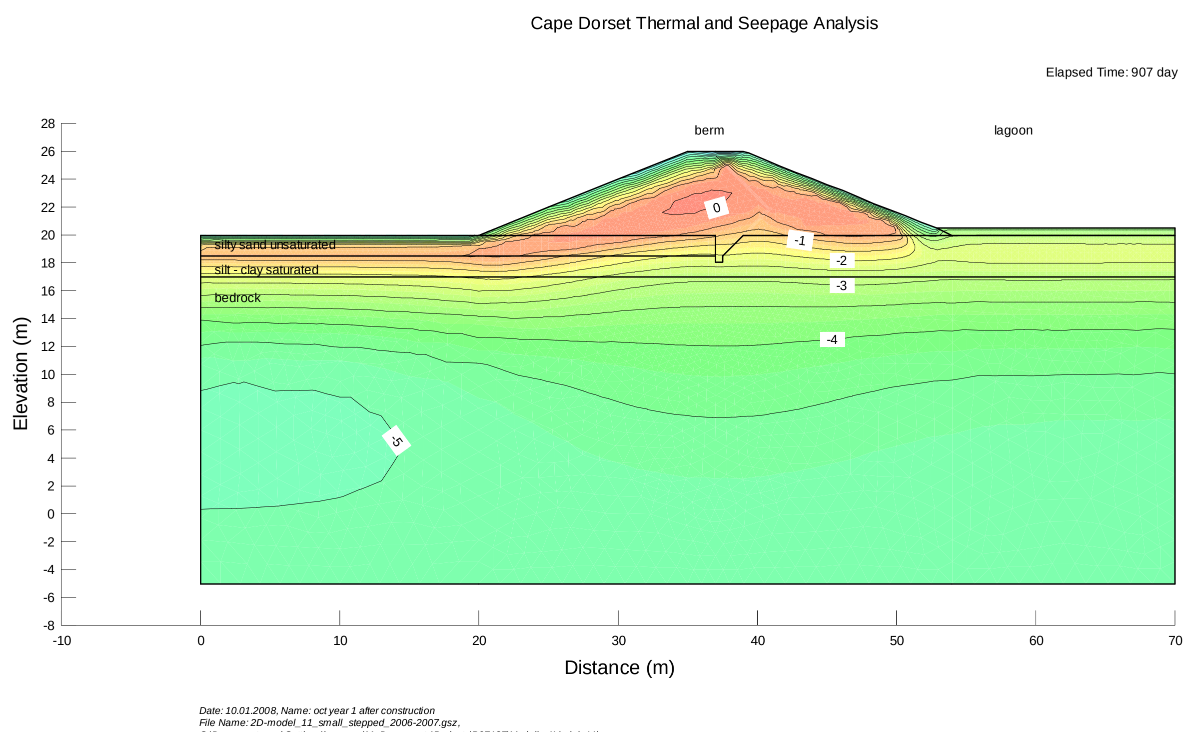


Figure 21. Isotherms, October 31, 1 year after berm construction, 2006 - 2007 air temperatures.

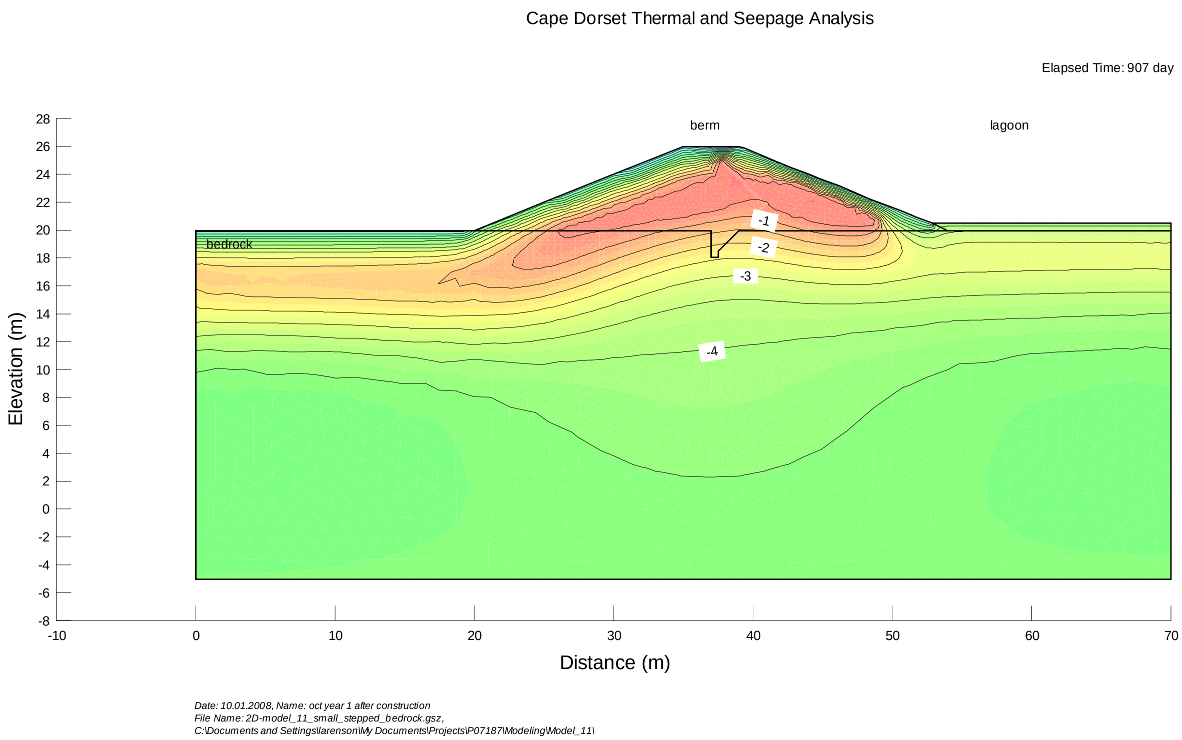


Figure 22. Isotherms, October 31, 1 year after berm construction, average (1970 – 2000) air temperatures, bedrock foundation.

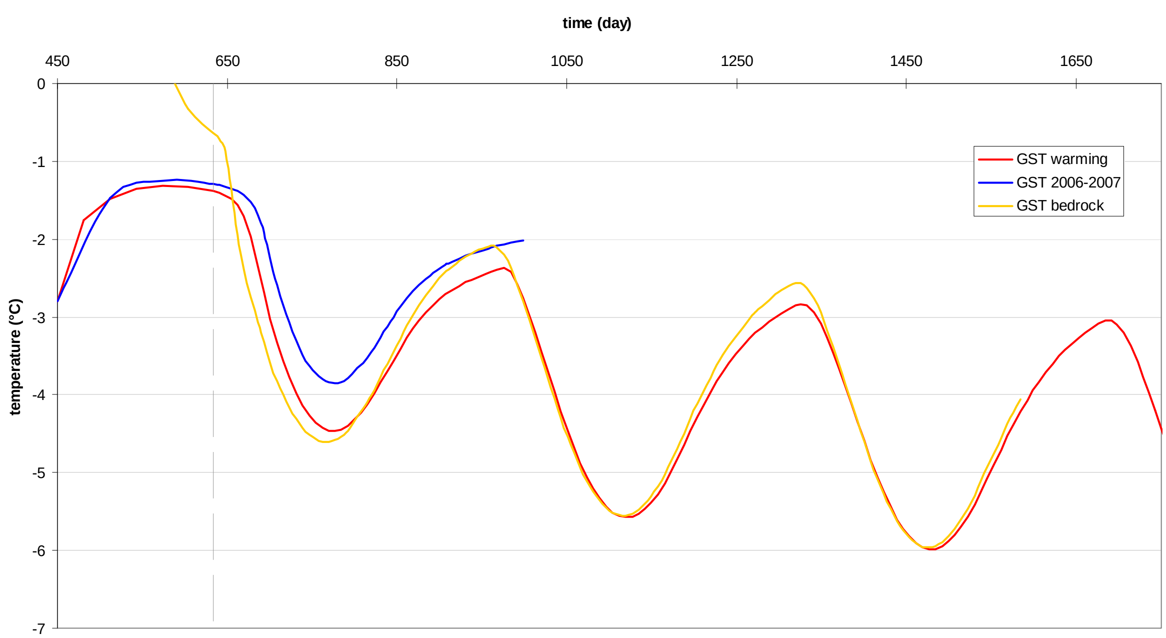


Figure 23. Temperature at point A for three different scenarios.

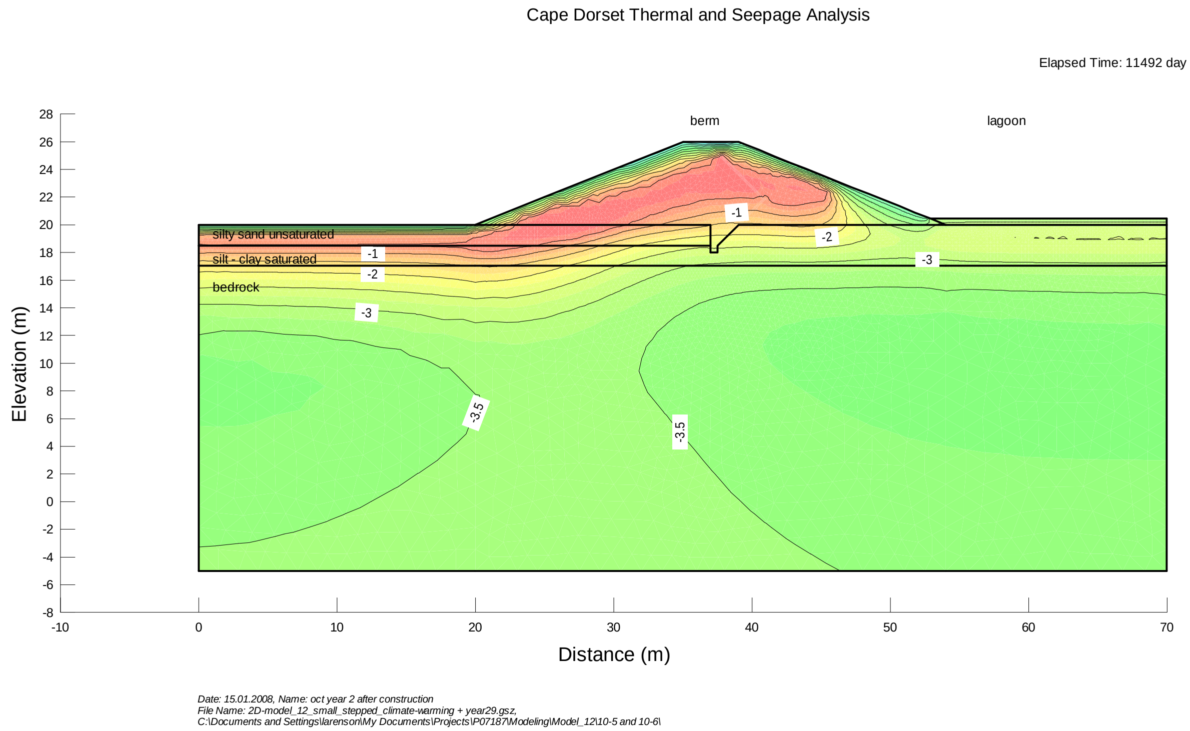


Figure 24. Predicted isotherms, October 31, after 30 years of operation using the average (1970 – 2000) air temperatures conditions and a warming trend of 0.7°C/decade.

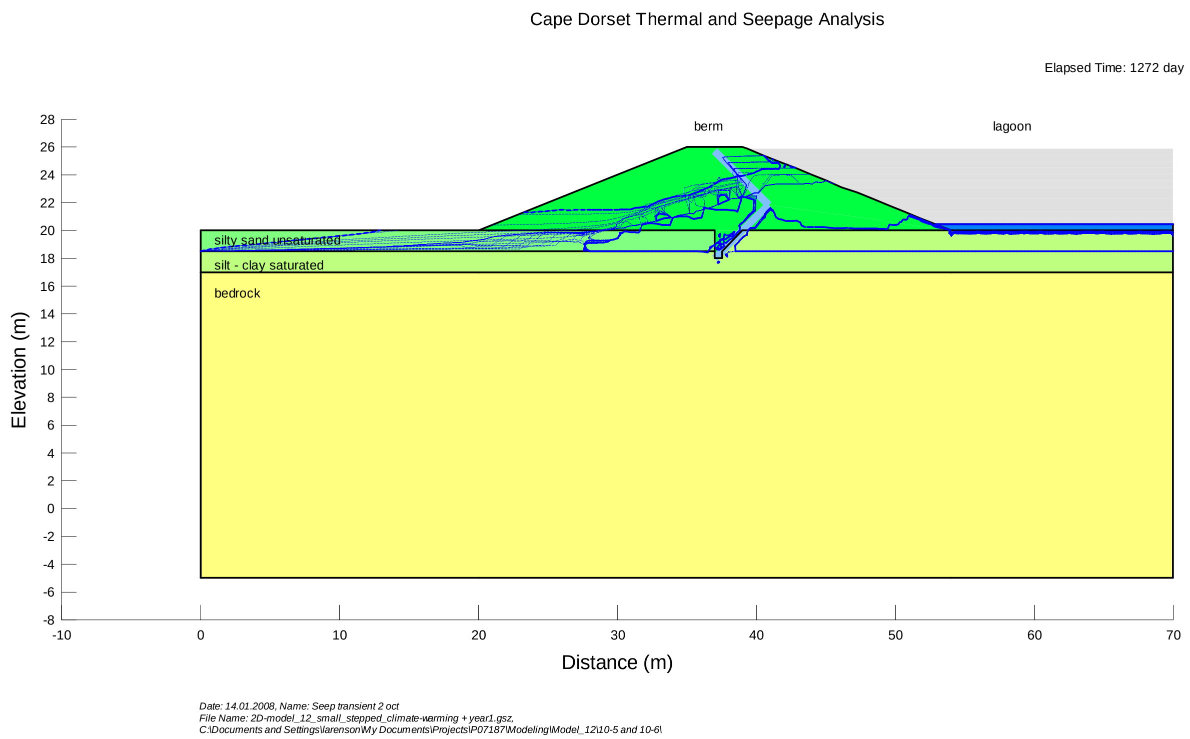


Figure 25. Predicted piezometric surfaces during year 2 of operation.