CGS.ca
GeoVirtual 2020 September 14-16
Resilience and Innovation

Assessment of a Closed-Loop Geothermal System for Seasonal Freeze-Back Stabilization of Permafrost

Maryam Saaly, Rob Sinclair, and David Kurz
KGS Group, Winnipeg, Manitoba, Canada
Pooneh Maghoul, Hartmut Holländer, Amir Fatollahzadeh Gheisari
Department of Civil Engineering – University of Manitoba, Winnipeg
Manitoba, Canada

ABSTRACT

Wastewater treatment lagoons are practical and cost-effective system for smaller towns across Canada to prevent wastewater seepage into the environment. Essentially all structures over permafrost that disrupt the natural winter temperatures contacting the ground surface initiates permafrost thawing over the long-term and this includes lagoons. KGS Group has been developing the concept of using conventional closed-loop geothermal systems within the sediments below the base of lagoon to allow a refrigerated solution to be circulated to freeze the soil below the lagoon. This paper assesses the effectiveness of the geothermal freeze-back concept using a heat transfer model developed in COMSOL Multiphysics. The model evaluates variable flow velocities of 0.5 m/s and 0.25 m/s with the circulation of the antifreeze solution to temperatures as low as -20°C. The results of this assessment will provide valuable understanding of the design and costs of a conventional geothermal freeze-back system for large developments over permafrost.

RÉSUMÉ

Les étangs d'épuration représentent un système pratique et rentable de prévention des fuites des eaux usées dans l'environnement pour les petites villes canadiennes. Toutes les structures (incluant les étangs d'épuration) présentes sur le pergélisol et qui perturbent les températures hivernales naturelles sur la surface du sol stimulent le dégel du pergélisol à long terme. Le groupe KGS développe le concept conventionnel qui consiste à réutiliser les installations géothermiques à circuit fermé, et qui circulent dans les sédiments sous la base des étangs d'épuration, pour permettre à la solution réfrigérante de refroidir la sol sous les installations. Cet article évalue l'efficacité du concept de recongélation en utilisant un modèle de transfert de chaleur développé à l'aide de COMSOL Multiphysics. Le modèle évalue ainsi des vitesses d'écoulement variant entre 0.5 m/s à 0.25 m/s en considérant la circulation d'une solution antigel à des températures aussi basses que -20°C. Les résultats de cette évaluation fourniront une compréhension inestimable du design ainsi que des coûts d'un système conventionnel de recongélation géothermique pour les aménagements larges sur le pergélisol.

1 INTRODUCTION

One of the many challenges developing from the ongoing progression of global warming is climate change. Climate change has considerable impacts on Northern communities including the Yukon (Huntington and Weller 2005). Consequently, people living in small, isolated communities in northern Canada are concerned about climate change risks and the impact on their lives. One of the significant climate change-related hazards in northern communities is thawing of permafrost (Barriault 2012, Gravel 2012). Therefore, it is urgent to assess and apply adaptation strategies to mitigate the climate changes risks that are rapidly impacting northern communities. Typical design approaches are to design for the loss of permafrost or design to preserve permafrost.

In this paper, a wastewater treatment lagoon system in northern Yukon is evaluated using the geothermal freeze-back techniques. The main concern for long-term performance of this lagoon system is the presence of subsurface ice lenses with the potential to result in long-term settlement predicted to be over 2 m during the first assessment of the of the site for lagoon construction (Tetra Tech 2014).

The management of thaw settlement issues has received significant research and development with a variety of potential mitigation options by KGS Group.

Such options include but are not limited to adding insulation below the lagoon to reduce downward heat and raising the lagoon elevation to increase soil cover over underlying permafrost. These options would mitigate but not eliminate thawing. KGS Group is proposing polyethylene piped systems with closed loop flow through a fluid cooler in winter. These options range in complexity, cost, and effectiveness for a relatively large lagoon; therefore, practicality and cost benefit will be important considerations for a system that must be installed below the lagoon.

In response to the potential risk of permafrost thawing, freeze-back of thawing permafrost can be a practical solution for a variety of developments. To this end, a case study has been carried out for the freeze-back system on a wastewater treatment lagoon in Ross River, Yukon, Canada. The proposed system circulates refrigerated solution from a fluid cooler developing inlet temperatures in the range of -10 to -30°C through the closed-loop system in the winter to mitigate potential thawing soil below the base of the lagoon. The freeze-back system must add sufficient cold to balance the heat moving downward through the base of the lagoon over the whole year. This paper is intended to evaluate this system as a potential solution for permafrost thawing risks of the Ross River wastewater lagoon treatment system.

2 ROSS RIVER WASTEWATER TREATMENT LAGOON

Ross River is a community of approximately 350 people located approximately 60 km east of the Town of Faro and 300 km north of Whitehorse, Yukon. The present wastewater treatment lagoon for the community is located to the west of community approximately 700 m south of the Pelly River. This two-cell lagoon system was proposed and constructed in the Fall 2017. Figure 1 illustrates the approximate location of the lagoon system. The Ross River lagoon system consists of two cells; a primary cell (100 m × 30 m) and a secondary cell (100 m × 70 m), as well as tankage for solids removal prior to the lagoon and a sludge drying bid for sludge treatment (Figure 2). For this paper, only the performance of the primary cell is studied within the proposed closed-loop system. The wastewater treatment lagoon system was designed with the assumptions summarized in Table 1.

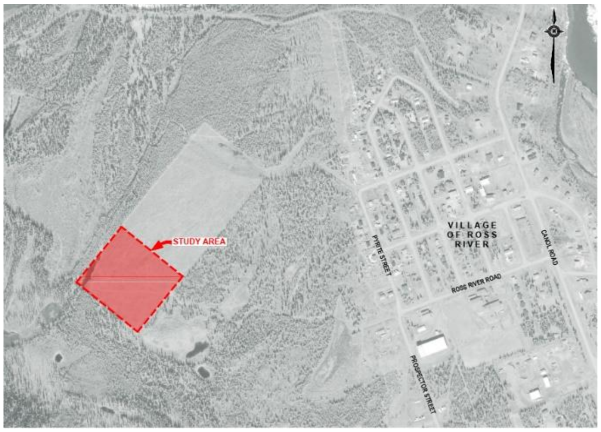

Figure 1. Site Location Plan.

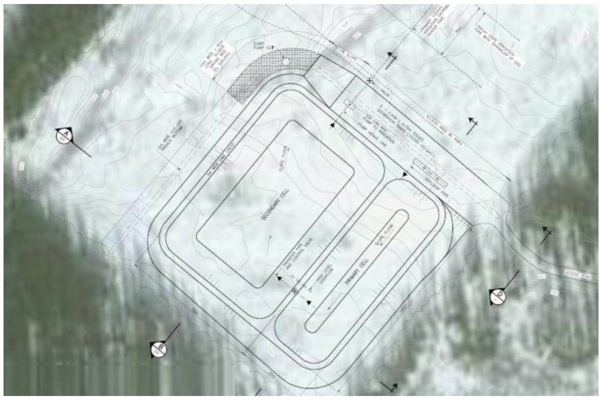

Figure 2. View of the Ross River wastewater treatment lagoon system (Sinclair and Theissen 2014).

Table 1. Wastewater volume assumption in lagoon system design (Sinclair and Theissen 2014).

Item	Quantity
Approximate Current Population	350
Per Capita Wastewater Production	110 L/day/person
Annual Wastewater Production	17,000 m^3/year
10 Month Storage Volume	14,000 m^3/year

A geotechnical investigation (Tetra Tech 2014) indicated the site stratigraphy consists of ±0.6 to 1.7 m of silt and silty fine sand overlying approximately 2 to 3+ m of sandy gravel, overlying a 3.2 to 4+ m clayey silt. Ice lensing up to 20 mm thick had been identified within the clayey silt zone during the investigation. The presence of this ice lensing was a significant design consideration, as the lagoon acts as a heat source thereby changing the thermal regime of the site permafrost. In addition, the construction of a lagoon reduces the development of seasonal frost the within the upper soils.

The lagoon wastewater temperature varies between approximately 4°C in winter to 13°C in summer months (KGS Group 2014). These temperatures will induce thawing below the lagoon base area year-round, such that a practical system to mitigate this thawing and concerns for differential settlement is required.

The following sections discuss the development of a thermal numerical model used to evaluate performance of the closed-loop geothermal freeze-back system.

3 THERMAL MODEL

One of the main challenges in long-term performance of the lagoon system is managing the thawing of permafrost below the base of the lagoon. The main heat absorption occurs downward from the lagoon bottom into the deeper subsurface. To assess the heat loss through the lagoon base and to investigate the heat exchange between the pipes and the soil below the lagoon bottom, a finite element time-dependent analysis was developed using COMSOL Multiphysics.

The soil domain of the 3D model has the dimensions of 70 m × 50 m to simulate half of the primary cell of the lagoon and 10 m depth below the lagoon base (Figure 3). Due to complexity and long computational time, half of the geometry is considered in the model and a symmetry boundary condition is assigned to one side surface of the model. Boundary conditions are discussed further in Section 3.2.

The proposed closed-loop system is modeled using pipes having diameter of 5 cm and length of 70 m which are installed with 2 m spacing 1.5 m below the lagoon base. The scope of the modeling was to determine whether the assigned pipe spacing, inlet temperatures and inlet velocities maintain freezing in the ground below the lagoon bottom.

A “normal” automatic physics-controlled sequence type with fine mesh has been applied to the model. Denser and smaller mesh has been set up around the pipes and above the pipes to increase accuracy of outputs. It should be noted that mesh refinement using "fine" automatic physic-controlled sequence has also been applied to the model that showed negligible effect on the results.

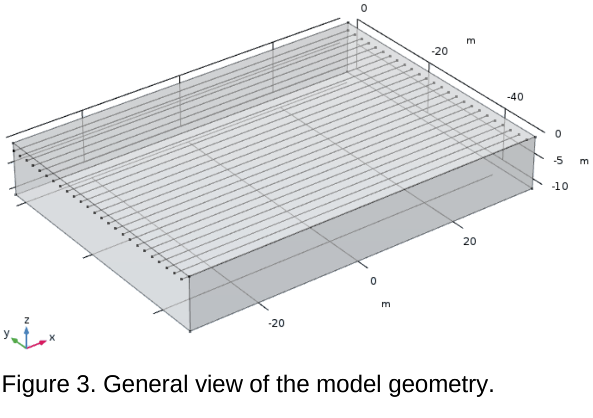

Figure 3. General view of the model geometry.

3.1 Governing Equations and Material Properties

The heat transfer in the soil domain is governed the energy conservation equation as described below:

$$\rho C \frac{\partial T}{\partial t} + \nabla . q_c = 0 \qquad [1]$$

Where ρ is the density of material [kg/m^3], C is material specific heat capacity [J/kg°C], T is temperature [°C], t is time [s], $\nabla.$ is divergence operator ($\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}$), and k is thermal conductivity of material [W/m°C]. Also, q_c is the conductive heat flux [W/m^2] which can be defined based on Fourier’s law:

$$q_c = -k\nabla T \qquad [2]$$

As the soil temperature drops below the freezing point of soil water, adjacent to and at distance from the pipes, thermal conduction will be significantly affected by presence of ice in soil pores. Therefore, transient heat conduction in the soil must include freezing and the associated latent heat of fusion during the phase change of soil pore water to ice. This freezing component is very significant to the freeze-back concept and is defined by the model using the equation below (Zhu and Michalowski 2004, Saaly, et al. 2019):

$$\rho C_p \frac{\partial T}{\partial t} - \rho_i L_f \frac{\partial \theta_i}{\partial t} - \nabla . q_c = 0 \qquad [3]$$

where ρ_i is density of ice, L_f is latent heat of fusion (latent heat of fusion for water-to-ice phase change is 333.5 kJ/kg), and θ_i is volumetric fraction of ice content. In Equation 3, ρC_p is the volumetric heat capacity of the soil which is a function of volumetric heat capacity of each component of the soil and can be estimated using the equation below:

$$\rho C_p = \rho_w C_w \theta_w + \rho_i C_i \theta_i + \rho_s C_s \theta_s \qquad [4]$$

where, θ is the volumetric fraction of each component of the soil and w, i, and s indices denote the properties of water, ice, and solid grain components.

As described in Equation 2, conductive heat flux (q_c) is a function of thermal conductivity of the material (k) whose value for the soil having three component of water, ice and soil grains can be determined using the following equation:

$$k = k_s\theta_s + k_w\theta_w + k_i\theta_i \qquad [5]$$

During the phase change of water in the pore, when soil temperature drops below freezing point (i.e., 0°C), pore water starts freezing. During the freezing process, the water fraction in the pores can be estimated using the equation proposed by (Michalowski 1993) as below:

$$\theta_w = \theta_{wr} + (\theta_{w0} - \theta_{wr})\, e^{a(T-T_0)} \qquad [6]$$

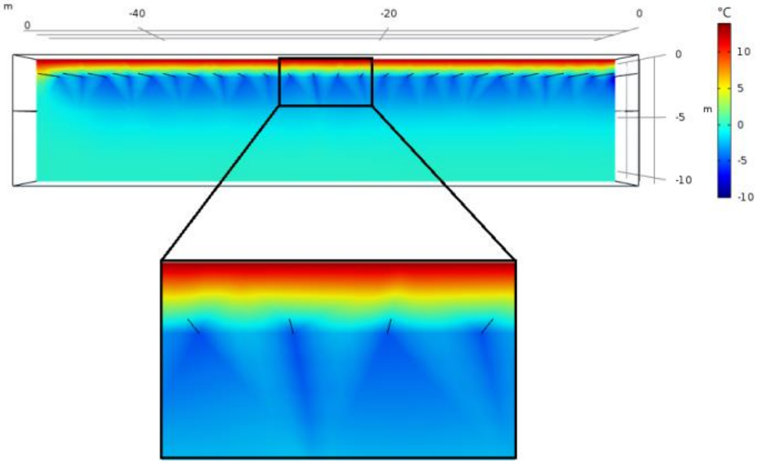

Figure 4. Temperature profile of the soil below the lagoon after the summer – Inlet fluid velocity of 0.25 m/s and temperature of -10°C.

When pore water freezes, even with sub-zero temperatures, some portion of water content remains liquid known as residual water content (θ_{wr}). Also, θ_{w0} is the initial unfrozen water content, or the porosity, α [1/°C] is the parameter that controls the curvature and is assumed here as 0.16 based on (Michalowski 1993).

As described in Equations 1 to 5, thermal properties of three constituent of the soil are listed in the table below (Côté and Konrad 2005, Saaly, et al. 2019). For simplicity of the assigned material to the model, it is considered the domain is only consisting silty clay material.

Table 2. Properties of the soil constituents

Material	Thermal Conductivity [W/m°C]	Heat Capacity [J/kg°C]	Density [kg/m^3]
Soil Particles	1.58	942	2560
Water	0.56	4188	1000
Ice	2.2	2117	950

3.2 Boundary Conditions

The boundary conditions of thermal model are as based on knowledge of the site.

3.3 Sensitivity Analysis

A chilling and pumping pipe system is proposed for the purpose of continuously maintaining the temperature below the lagoon below the freezing point (i.e. 0°C) over the long-term. To develop the freezing/cold zone below the lagoon, 5 cm (2”) High-Density Polyethylene (HDPE) pipes at a 2 m spacing are installed 1.5 m below the base of the lagoon.

To define the effect of heat leakage through the bottom of lagoon during the year, a stepped function for the temperature of the lagoon wastewater is applied on the top boundary of the model (i.e. the bottom of the lagoon). This should be noted that this heat injection from the lagoon can be decreased using a thermal insulation layer below the base of the lagoon. Since technical insulation such as polystyrene foam is costly, natural insulation such as dry sand can be applied. This heat insulation layer is not considered in the present model since no insulation layer exists in the actual design of the Ross River Lagoon system (Sinclair and Theissen 2014).

The stepped constant temperature function is equal to 13°C during April to September and 4°C during October to March. To ensure that the results are not affected by the initial temperature imposed on the model, analysis has been done over three years and the results of the third year are presented.

A symmetry boundary condition is assigned to one side boundary with dimensions of 70 m × 10 m to reduce the computational time associated with modeling the full primary cell. For the side boundaries and the bottom boundary of the soil domain, an adiabatic boundary condition has been assigned.

The initial temperature of the soil domain has been assigned to be -1°C. This temperature is an average based on observations during the geotechnical investigation, that soil on site was reported to be frozen near the surface, and the depth of permafrost was reported to be approximately 12 m below ground surface.

Cold water is continuously circulated in these pipes to transfer cold into the surrounding soil. To determine the proper inlet temperature and flow velocity of the piping system, a sensitivity analysis was carried out on the temperature of the soil below the lagoon with respect to the inlet temperature and the inlet velocity of heat carrier fluid. To this end, three different inlet temperatures of -10°C, -15°C, -20°C and two different velocities of 0.25 m/s and 0.50 m/s have been used for the heat carrier fluid.

4 RESULTS

The main challenge of this concept is to maintain the temperature of the soil below lagoon low enough to balance the continuous year-long heat flow through the lagoon base into the subsurface. In other words, the proposed freeze back system must ensure that the cold input is equal to or slightly more than the downward heat flow to mitigate all heat injection through the lagoon base. This will include the most challenging period during summer when temperature of the lagoon will rise up to 13°C for most of the summer. The highest ground temperatures under the lagoon will be experienced shortly after the summer months.

The most conservative case in the sensitivity analyses is the condition when inlet temperature of the fluid is the warmest (i.e. -10°C) and the velocity is the lowest (i.e. 0.25 m/s). Figure 4 shows that for this conservative case the piping system is able to mitigate the heat leakage from the lagoon, thus protecting the permafrost zone from thawing. This implies that the system is able to function within the other cases with lower inlet temperatures and higher inlet velocities.

4.1 Sensitivity Analysis to Inlet Temperature and Inlet Velocity of Heat Carrier Fluid

A sensitivity analysis was carried out to determine the impact of different parameters related to the fluid cooler on temperature of the ground below the lagoon base. Figure 5 illustrates results of the sensitivity analysis in terms of effective radial distance from the pipe (i.e. the radial distance where the pipes impact the soil and maintain it in a frozen state).

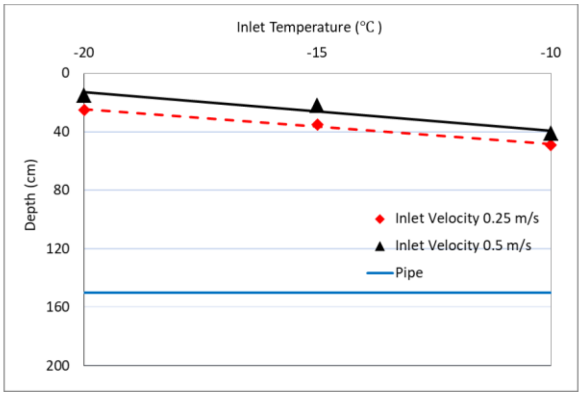

Figure 5. Frost penetration depth at the end of September of the third year of simulation for the various cases.

As the inlet velocity of fluid increases, a larger radial distance around the pipes is frozen. Results indicate that the cases with an inlet velocity of 0.5 m/s develop up to 22 cm radially more frost than the cases with an inlet velocity of 0.25 m/s. This is not unexpected as it shows that the higher velocity fluid will pass through the heat exchanger at a higher gradient than the lower velocity resulting in lower temperature.

In addition, Figure 5 shows that a minimum spacing of 2 m is required for the most conservative case because the effective freezing radial distance of the pipe is 101 cm for each pipe. This means that for each two adjacent pipes, a minimum distance of approximately 200 cm is required to have a consistent block for the leakage of heat from the lagoon into the soil below the pipe.

The average annual energy transferred to the ground from each pipe for each case (i.e. different inlet velocities and different inlet temperatures) is summarized in Table 3.

Table 3. Average annual energy transfer between each pipe and the surrounding soil

Inlet	Energy Transfer [MWh]		
Velocity [m/s]	Inlet T -10°C	Inlet T -15°C	Inlet T -20°C
0.25	15.68	25.62	26.34
0.50	20.35	28.55	38.6

For the case with inlet velocity of 0.5 m/s, each 5°C decrease in inlet temperature can increase the annual energy transfer through each pipe by between 24% to 28%. For the case with 0.25 m/s, the energy transfer through each pipe increase up to 38% while inlet temperature of the pipes decreases by 5°C. As the magnitude of energy transfer between pipes and soil increases, more cold is injected from the pipes to the soil and correspondingly, soil temperature decreases.

5 CONSTRUCTION COST ANALYSIS

5.1 Construction Component

The Ross River lagoon facility has power (220V, single phase) to a seacan that is spacious enough to accommodate some additional equipment. The main components for the freeze-back option below the lagoon are presented schematically Figure 6.

Polyethylene Geothermal Piping:
The design uses high-density polyethylene (HDPE) piping installed 1.5 m below the lagoon bottom of both cells using a track trench with a reel system for continuous feed of the 50 mm (2”) diameter geothermal pipes. The trench would be backfilled with sand and saturated with water. The silty clay lagoon liner would be built over these 2 m spaced pipe trenches.

HDPE Header Pipes:
(i) Central Header: 250 mm (10”), 500 mm burial depth, 140 m length.
(ii) Perimeter Headers (two): 200 mm (8”), 500 mm burial depth, 2 x 120 m, 240 m.

Fluid Cooler:
The fluid cooler sizing was based on the lower flow rate in the geothermal pipes. The thermal modeling demonstrated that adequate freezing of the soil would occur. The flow for a 50 mm (2") diameter HDPE pipe at 0.25 m/s is 0.5 L/s (6.4 Igpm) or for 100 pipes, 50 L/s (770 Igpm). The fluid cooler for geothermal winter chillers at the Manitoba Hydro Dorsey Converter Station is shown in Figure 7.

Recirculation Pumping System:
The recirculation piping system has been designed for low head losses. The pumping system includes the two-end suction centrifugal pumps each capable of 50 L/s at 3 m of head. These pumps well be located inside the electrified seacan currently onsite.

The effectiveness and costs of the geothermal freeze-back can be effectively developed by thermal modeling of heat flow of any structures over permafrost.

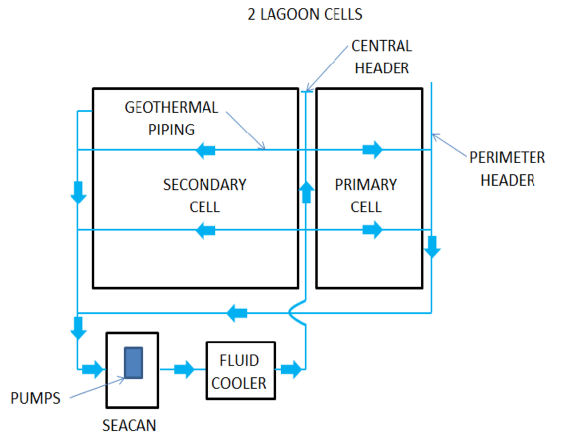

Figure 6. Schematic Proposed Geothermal Freeze-Back Concept.

Figure 7. Manitoba Hydro Dorsey AC/DC Convertor Station Geothermal System New Glycol Winter Chiller (R. Sinclair 2003).

5.2 Estimated Installation Costs

Polyethylene Geothermal Piping:
6000 m (50 runs at 120 m each) $15/m = $90,000

HDPE Header Pipes:
Central Header: 250 mm HDPE, shallow burial, 140 m @ $100/m = $14,000
Perimeter Headers: 200 mm HDPE, shallow burial 2 x 150 m @ $80/m = $24,000

Fluid Cooler:
50 L/s (3 – 745 watt 1 HP fans) installed on gravel pads; FOB Ross River $125,000.

Recirculation Pumping System:
2 – 3.725 kW centrifugal pump installed; 2 x $7,500 = $15,000.

Including 10% contingency, the grand total of the project cost will be approximately $295,000. The constructed cost of the Ross River lagoon system was approximately $1.5M such that the additional cost would amount to approximately 20 to 25% of the construction cost. This would need to be weighed against on-going settlement repairs and possibly catastrophic failure due to factors including the thawing of permafrost.

The main system now incorporated into permafrost protection projects is thermosyphons. These systems add cold energy through natural evaporative refrigeration cycle and are generally effective but also expensive. Cost figures from Arctic Foundations of Canada (Arctic Foundation of Canada 2017) indicated the costs for a single unit of approximate $3,100 CAD. Each unit has an effective freezing area of 7 m^2 for a cost of approximately $440 CAD/$m^2$. This is approximately ten times the unit cost estimated for a geothermal freeze-back concept with a wind/battery off-grid developed concept.

Individual homes and small buildings are routinely developed with closed-loop geothermal heating system with a freeze-back system being of similar complexity and cost (Barriault 2012).

6 CONCLUDING REMARKS

This study was intended for evaluating the performance of a closed-loop system buried 1.5 m below the base of the Ross River wastewater treatment lagoon. The heat-exchanger pipes are designed to reject heat to the soil and avoid thawing of permafrost. A 3D thermal model is developed in COMSOL Multiphysics. Based on the numerical analysis, the following concluding remarks are made:

- The optimum spacing between the pipes with inlet velocity of 0.25 m/s and inlet temperature of -10°C is at least 2 m. This means that with 2 m spacing, no heat leakage through the base of the lagoon passed through the pipes.

- The pipes spacing can be increased by decreasing the inlet temperature or increasing the inlet velocity of heat carrier fluid.
- The estimated cost of the proposed freeze-back system is approximately $295,000 or about 20% of the approximate $1.5M lagoon construction cost.

6.1 References

Arctic Foundation of Canada. "Keeping It Frozen." http://arcticfoundations.ca/service/thermopiles/ , Winnipeg, 2017.

Barriault, A. *Climatic Adaptations to Construction in Nunavut.* Nunavut Housing Corporation, Northern Forum, 2012.

Côté, Jean, and J.M. Konrad. "A generalized thermal conductivity model for soils and construction material." *Canadian Geotechnical Journal* (Canadian Geotechnical Journal), 2005: 443-458.

Dmsteen, B. *Keeping It Frozen.* Arctic Foundation of Canada, 2017.

Gravel, J.F. "Impact of climate change on habitat development in Nunavik." *Northern Forum.* Quebec City, 2012.

Huntington, H., and G. Weller. *An Introduction to the Arctic Climate Impact.* Arctic Climate Impact Assessment Scientific Report, Cambridge University Press, 2005.

Michalowski, R.L. "A Constitutive Model of Saturated Soils for Frost Heave Simulations." *Cold Regions Science and Technology*, 1993: 47-63.

Saaly, Maryam, Pooneh Maghoul, Miroslava Kavgic, and Dimos Polyzois. "Performance Analysis of a proposed geothermal pile system for heating and cooling energy demand for a building in cold regions." *Sustaintable Cities and Society*, 2019: 669-682.

Sinclair, R. *Final Report: Dorsey Converter Station Groundwater Cooling Feasibility Study.* Winnipeg: KGS Group, 2003.

Sinclair, Robert, and Kenton Theissen. *Ross River wastewater treatment system, Ross River, Yukon.* Final design report, Winnipeg: KGS Group, 2014.

Tetra Tech, EBA. "Geotechnical Evaluation - Proposed Waterwater Disposal Facility, Ross River, YT." 2014.

Zhu, M., and R.L. Michalowski. "Simulation of Heat Transfer in Freezing Soils Using ABAQUS." *ABAQUS 2004 Users' Conference.* 2004.