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A sensitivity analysis on pond size and distance in thermal behavior of adjacent permafrost affected soils – Hudson Bay Railway

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ABSTRACT: Climate change has brought an increase in the global air and ground surface temperature. Due to polar amplification, northern regions are among the most vulnerable to climate change effects. Many of these regions are underlain by permafrost, which is highly sensitive to rising air temperatures. Warming conditions can accelerate permafrost thaw and increase the thickness of the active layer, leading to significant environmental and infrastructural impacts. Permafrost thaw reduces soil strength and stability, thereby posing serious risks to the serviceability and long-term functionality of infrastructure built in these regions. Hudson Bay Railway (HBR) in northern Manitoba, Canada, is an example of vulnerable infrastructure to climate change effects. The presence of ponds and lakes in the Hudson Bay Lowland, acting as heat sinks or sources, is a significant factor that can alter the thermal regime of adjacent permafrost-affected soils. In thermal modelling of the ground beneath the railway embankment, it is essential to account for the thermal influence of nearby ponds and lakes. In the present study, a sensitivity analysis was conducted using analytical solutions implemented in MATLAB to evaluate the effects of pond size and distance from the rail embankment. The results indicate that distance from the pond center to the embankment plays a more dominant role than surface area in influencing subsurface temperatures. Specifically, even a large pond, comparable in size to a small lake, has a negligible thermal effect if located 500–1000 meters from the railway. In contrast, small ponds with radius less than 10 meters are found to cause noticeable warming in the adjacent soil if located close to the embankment. This study focuses on the surface area (size) of the pond, while the effect of pond depth, whether shallow or deep, is not considered in the analysis.

KEYWORDS: Pond, permafrost, thermal modeling, analytical solutions, Hudson Bay Railway.

1 INTRODUCTION

Ground that stays at or below 0°C for at least two consecutive years is referred to as permafrost (Everdingen 2005). This definition is applicable regardless of the cementation, water substance phase, or material composition (Nelson 2003). Ground ice melting and permafrost thawing can be accelerated because of rising air and ground temperatures. For northern regions, polar amplification, a major contributing factor, is causing surface air temperatures to increase at a rate of at least twice the global average (Park et al. 2021). In ice rich permafrost regions, climate change effects present significant hazards to infrastructure due to excessive soil deformations and loss of strength. A prime instance of this is the Hudson Bay Railway (HBR) in northern Manitoba, Canada. Climate change impacting permafrost thaw, and associated ground ice, leads to large settlements and degradation of strength and stability. This alters hydrological processes with respect to the timing and magnitude of surface and subsurface water movement and wetland dynamics. These effects may result in the impairment or loss of infrastructure, transformation of the topographical and hydrological landscape, and disturbance or disruption in ecosystem (Kenny et al. 2018).

Permafrost regions make up between 40% and 50% of Canada's 10 million square kilometers of total land area (Brown 1960), and 24% of the land in the northern hemisphere (Nelson 2003). This vast expanse of permafrost land has seen the construction of railroads, highways, pipelines, and airport runways. For many communities in northern Manitoba, particularly those inhabited by Indigenous people, the HBR is the only ground transportation option available, making it essential to the social and economic development of these locations. The condition of HBR also has an immediate effect on industries that depend on this railway to deliver goods to the port of Churchill and then beyond. To efficiently manage geohazard risks in HBR, the first step is to assess the severity and location of the hazard and then develop suitable mitigation strategies to preserve the railway's serviceability.

Predicting the effects of ground thermal regime on thermal stability of permafrost has been previously investigated using analytical solutions and one-dimensional numerical models (Morgenstern and Nixon 1971, Nixon 1973, Nixon and McRoberts 1973, Goodrich 1982). While these approaches are useful for providing general insights and preliminary estimates, they often ignore the presence of surface water bodies and varying surface materials. Numerous shallow and deep ponds exist along the Hudson Bay Railway corridor, potentially influencing the ground thermal regime. Due to differences in vegetation cover, surface material type, snow accumulation rates, and even topography between the ponds and the surrounding terrain, these water bodies can act as heat sources or sinks, affecting the thermal stability of the adjacent permafrost-affected soil.

To assess permafrost stability beneath and adjacent to the rail embankment, this study investigates the thermal effects of ponds on the adjacent soil through a sensitivity analysis based on analytical solutions, focusing on pond size and distance. Findings highlight that the proximity to the pond exerts a stronger influence than the pond's size. The results will serve to inform numerical modelling procedures simulating permafrost degradation beneath and adjacent to the rail embankment, of which this study forms a foundational part.

2 STUDY AREA

The Hudson Bay Railway, 820 km rail corridor, starts at The Pas (53°48′ N, 101°12′ W), at KP 0, and ends at port of Churchill (58°45' N, 94°10′ W), at KP820.4 (Figure 1). The focus area of current research along the HBR would be from Gillam (KP524) to Churchill (KP820). The majority of the route is below 150 meters above mean sea level and is located in the Hudson Bay Lowland physical geography region. The surficial geology around Gillam is categorized as offshore glaciolacustrine (clay, silt, and minor sand) having a thickness of 1 to 20 meters and proximal glaciofluvial (sand and gravel) (Matile and Keller 2006). The majority of the northern HBR section extended to Churchill is offshore glaciomarine sediments (clay, silt, and small amounts of sand). These deposits are laminated and have a thickness ranging from 1 to 20 meters, with peat covering them (Matile and Keller 2006).

The Tyrell Sea's southwest boundaries form the northern boundary of the HBR (Dredge and Dyke 2020).

Figure 1. Map of HBR route and permafrost distribution along the railway.

The vegetation along the Hudson Bay Railway between Gillam and Churchill reflects a subarctic ecosystem characterized by fens and peatlands. Tamarack and black spruce dominate, with scattered birch also present. Tree density progressively decreases toward the north. (Figure 2). The quantity and variety of tree species have decreased due to unfavorable climate conditions, thin soils, and frequent wildfires. Dwarf trees are scattered throughout peatlands, whereas larger trees are found in sheltered places like stream valleys (Dredge and Dyke 2020).

Along the Hudson Bay Railway, permafrost is primarily found in peatlands with elevated palsas and peat plateaus formed by ice lenses beneath the peat, bordered by unfrozen fens (EBA Engineering Consultants Ltd. 1977). Vegetation reflects moisture conditions, black spruce and mosses dominate the drier plateaus, while sedges prevail in wetter fens. Their extent depends on local relief, drainage, and climate, and can be altered by natural or human disturbances (EBA Engineering Consultants Ltd. 1982). Permafrost thickness in the region ranges from about 1 m in the southern discontinuous zone to nearly 100 m farther north (EBA Engineering Consultants Ltd. 1982), with active layer thickness (ALT) varying between 0.6 m and 2 m (Figure 1). Little differences in temperature exist between the permafrost beneath a peat plateau and the nearby unfrozen fen, according to temperature profiles from EBA investigations conducted in the 1980's at the peat plateau's center, edge, and neighboring fen. Thawing of this warm permafrost can be triggered by minor surface disturbances that change the thermal regime. The permafrost boundary moves laterally into the peat plateau as slumping uncovers frozen ground, resulting in further degradation (EBA Engineering Consultants Ltd. 1982). An intersection of fen and peat plateau can be seen in Figure 3.

Figure 2. Black spruce and tamarack in a. fens, b. peat plateaus.

Field observations directly guided the model configuration. Differences in vegetation and moisture regime were reflected in variations of surface albedo, snow accumulation, thermal conductivity, heat capacity, and latent heat, all of which influence the surface energy balance and temperature boundary conditions. The contrasting surface temperatures of ponds and surrounding peatlands were examined for different pond sizes to quantify their thermal influence on adjacent permafrost-affected soils.

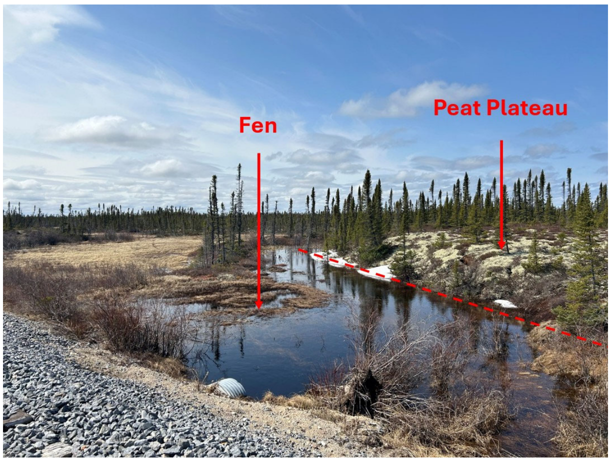


Figure 3. Peat plateau-fen intersection.

3 ANALYTICAL SOLUTION AND MODELING

There are numerous ponds in the HBR region, ranging in size from a few meters in diameter to small lakes. To better estimate the thermal regime within the soil, it is essential to evaluate the moderating effects of these ponds on the thermal conditions of the adjacent ground. Due to differences in surface material type, vegetation cover, topography, and snow accumulation rates between the ponds and the surrounding terrain, the surface temperatures of these two areas are not the same. This temperature difference drives heat transfer beneath the ground surface, potentially triggering permafrost thaw and degradation below and adjacent to the embankment. This study aims to investigate the influence of nearby ponds on the thermal response of the soil beneath the rail embankment. To this end, a sensitivity analysis is conducted using analytical solutions in MATLAB procedures to assess the effects of pond size and distance from the embankment.

In most geotechnical engineering applications, heat conduction is the dominant mode of heat transfer within the soil. However, convective processes, such as groundwater flow, may also become important in permafrost environments, particularly in the presence of numerous ponds or large nearby water bodies. By assuming conduction as the only mode of heat transfer and neglecting the effects of phase change, the governing heat transfer equation in a two-dimensional domain simplifies to (Andersland and Anderson 1978):

$$\frac{\partial \theta}{\partial t} = \kappa \left(\frac{\partial^2 \theta}{\partial z^2} + \frac{\partial^2 \theta}{\partial x^2} \right) \tag{1}$$

where θ represents temperature, t is time, z is depth, x is horizontal distance, and κ is the thermal diffusivity of the soil.

Under steady-state conditions, where surface boundary conditions remain constant over time, the temperature distribution within the soil tends toward a steady profile. In this case, the governing equation reduces to the well-known Laplace equation. Analytical solutions to this equation can determine the steady-state temperature distribution beneath surface regions subjected to heating or cooling. However, these solutions do not account for the depth of the heated or cooled area and cannot capture transient effects. Andersland and Anderson (1978) presented a solution for the temperature distribution near the interface between a heated and a cooler surface area, incorporating the influence of a geothermal gradient G :

$$T = \frac{T_s - T_g}{\pi} \tan^{-1} \frac{z}{x} + Gz + T_g \tag{2}$$

where T is field temperature, T_g is mean ground surface temperature outside heated or cooled area, T_s is temperature of heated or cooled area, and G is geothermal gradient. Based on this, if a pond with a diameter of $2r$ is present, the temperature distribution in the soil beneath the surrounding ground surface can be expressed as (Andersland and Anderson 1978):

$$T = \frac{T_s - T_g}{\pi} \tan^{-1} \frac{2rz}{x^2 + z^2 - r^2} + Gz + T_g \tag{3}$$

where r is radius of the pond, z is the depth from ground surface, and x is the horizontal distance from pond center. It is important to note that this formulation neglects the effect of pond depth. Shallow ponds may freeze completely, whereas deeper ponds can retain unfrozen water at warmer temperatures near the bottom, potentially altering the subsurface thermal regime at greater depths. Only the influence of differing surface boundary conditions between the pond and the surrounding ground is considered in the analysis. Geothermal gradient G is assumed to be 0.02 ℃$/m$ in this analysis. Dyke and Sladen (2010) reported mean annual ground temperatures (MAGT) for ponds and adjacent peat plateaus in the Hudson Bay Lowland, which are used in the present study. Based on their findings, the mean annual surface temperature is assumed to be -2.3 ℃ for the pond and -3.7 ℃ for the surrounding ground. The analytical models used in this study generate soil temperature profiles to a depth of 15 m at any specified distance from the pond. For instance, Figure 4 presents the soil temperature contours for a pond with a diameter of 10 m, extending up to 200 m from the pond center ($x = 200$). The models cover a range of pond sizes, from small ponds with a 2.5 m radius to larger ones with a radius of 250 m. To capture the lateral thermal influence of the pond, the temperature distribution within the soil is calculated at various distances from the pond center, ranging from 5 to 1000 m. It is worth noting that this analytical model neglects the effects of pond depth and phase change within the water and frozen soil, and assumes steady-state thermal conditions. These simplifications may introduce accuracy errors; however, they are commonly adopted in preliminary sensitivity analyses to isolate dominant thermal mechanisms. A more rigorous evaluation would require advanced transient numerical simulations that incorporate hydrological processes and latent heat effects.

4 RESULTS AND DISCUSSION

Two sets of analyses were conducted to investigate the effects of pond size and distance on the thermal regime of the adjacent ground. In the first set, the results of which are presented in Figure 5, the thermal influence of various pond sizes including 2.5, 5, 10, 25, 50, 100, and 250 m, was evaluated at a range of distances from the pond center to the embankment, specifically at 5, 10, 20, 50, 100, 200, 500, and 1000 m. The selected pond sizes at each distance reflect observed conditions in the study area, where smaller ponds are typically found closer to the rail embankment, while larger ponds are located farther away.

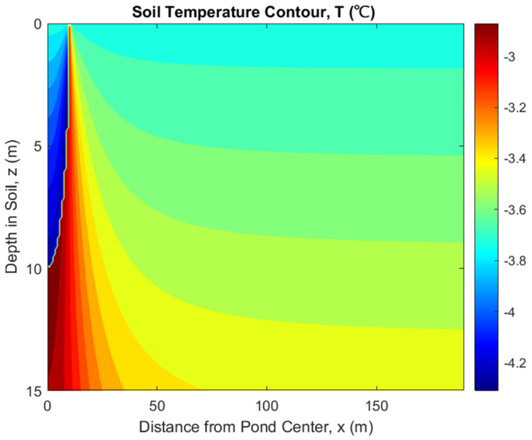


Figure 4. Soil temperature contours up to 200 m from the center of a pond with a radius of 10 m ($r = 10$).

The results presented in Figure 5 indicate that beyond 50 m from the pond center, the thermal influence of the pond becomes minimal, even in the presence of larger ponds. At distances of 500–1000 m (Figure 5g and 5h), the soil temperature profiles for all pond sizes nearly overlap, suggesting that pond size has a negligible effect on the surrounding soil temperature. However, at distances less than 50 m, the soil temperature profiles vary with pond size (Figure 5a–5d). Within this range, the results show that when the pond radius is approximately half the distance from pond center to the embankment, it can cause an increase in subsurface soil temperatures of up to 0.2 ℃. At intermediate distances of 100–200 m, the influence of pond size on soil temperature is minor, with observed differences generally less than 0.1 ℃ (Figure 5e and 5f).

In the second set of analyses, illustrated in Figure 6, each plot corresponds to a specific pond size. For each case, the normalized soil temperature profiles at varying distances from the pond center are compared relative to the temperature profile at a reference distance of 1000 m from pond center ($x = 1000$), where the thermal influence of the pond is considered negligible. This comparison allows assessment of the thermal impact of a given pond size, based on its proximity to the rail embankment. The results in Figure 6 indicate that small ponds, despite their size, can exert a more pronounced thermal influence on the adjacent ground than larger ponds located farther away. Specifically, for ponds with a radius of less than 10 m, the warming effect on subsurface soil temperatures is noticeable up to a distance of approximately twice the pond radius ($2r$) (Figure 6a-c). The analysis shows that this influence can result in temperature increases of approximately 0.2–0.25 ℃ for pond radius of 2.5, 5, and 10 m. However, as the pond size and distance increases, this thermal effect diminishes significantly (Figure 6d-g). For instance, as shown in Figure 6g, a 250 m radius pond, which can be considered representative of a small lake, results in only a slight increase in ground temperature at distances of 500–1000 m from the pond center. This temperature increase is minimal and can be considered negligible in terms of its impact on the surrounding soil thermal regime. In the case of moderately sized ponds, with radii ranging from 25 to 50 m, the thermal influence becomes noticeable only when the railway embankment is located within a distance equivalent to twice the pond radius from the pond center. Under these conditions, the presence of the pond can lead to an increase in subsurface soil temperatures beneath the embankment in the range of approximately 0.1–0.15 ℃, as illustrated in Figure 6d and 6e.

To enable a simultaneous comparison of the thermal effects of pond size and distance, 2D heat maps are presented in Figure 7. These color maps show the temperature difference (ΔT) relative to a reference point located 1000 m from the pond center ($x = 1000$), where the thermal influence of the pond is assumed to be negligible. The temperature difference is shown as a function of pond radius (r) and distance from the pond center (x). Figure 7a illustrates the thermal effect at a shallower depth (2 m), while Figure 7b shows the distribution at a deeper location (15 m). Both plots indicate that the thermal influence of the pond decreases with increasing distance from the pond center. Isotherms are overlaid as contour lines to highlight gradients more clearly. The plot reveals that distance from the pond plays a dominant role in controlling subsurface temperature variation, whereas increasing the pond radius leads to only a moderate increase in ΔT beyond a certain point. This indicates that proximity to the pond is more critical than pond size in influencing subsurface thermal conditions. A comparison of the two maps (Figure 7a and b) reveals that the thermal impact of the pond becomes more pronounced with depth, as the temperature differences at 15 m are greater than those at 2 m.

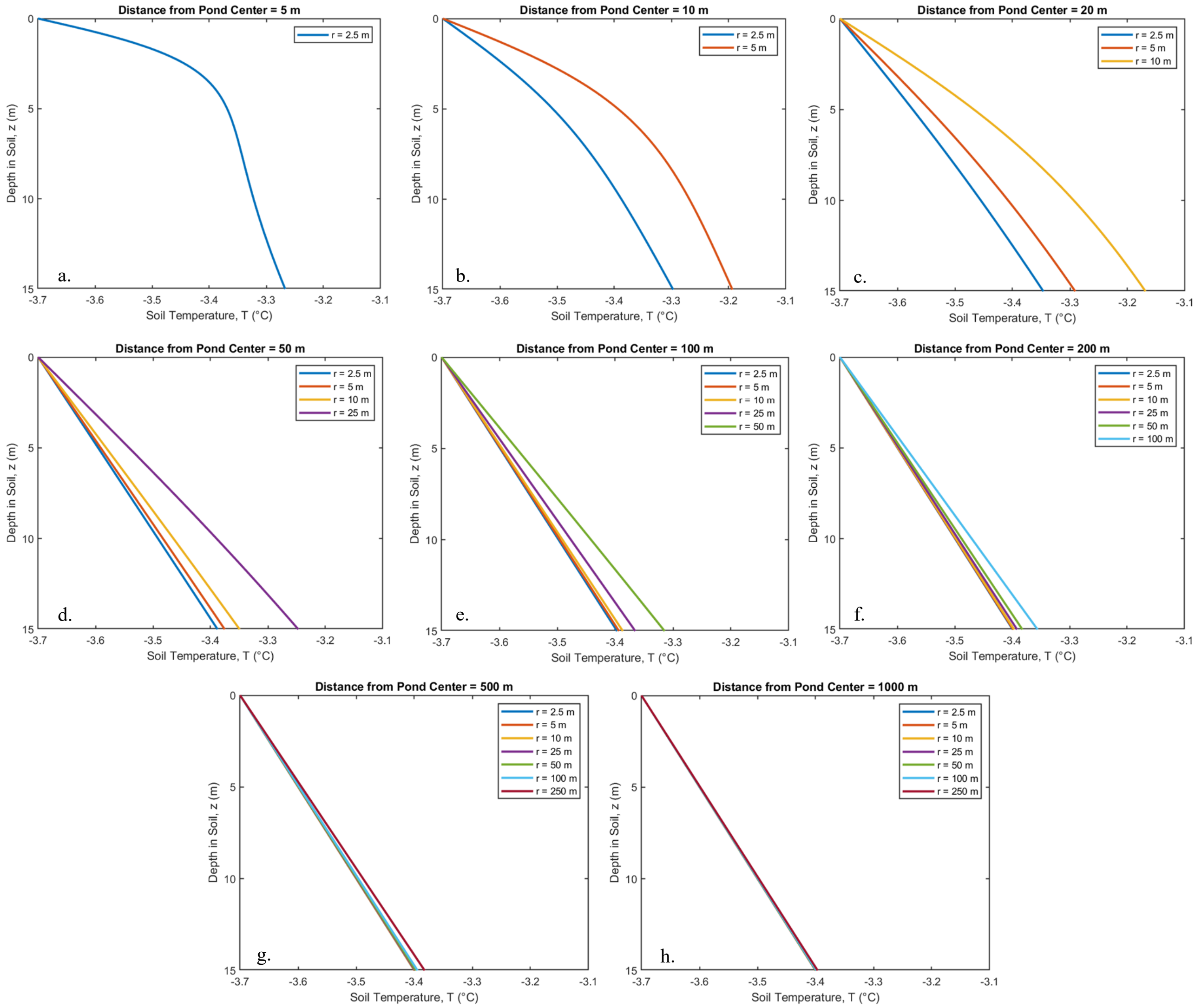


Figure 5. Soil temperature profiles at a given distance from pond center (x) with varying pond radius size (r).

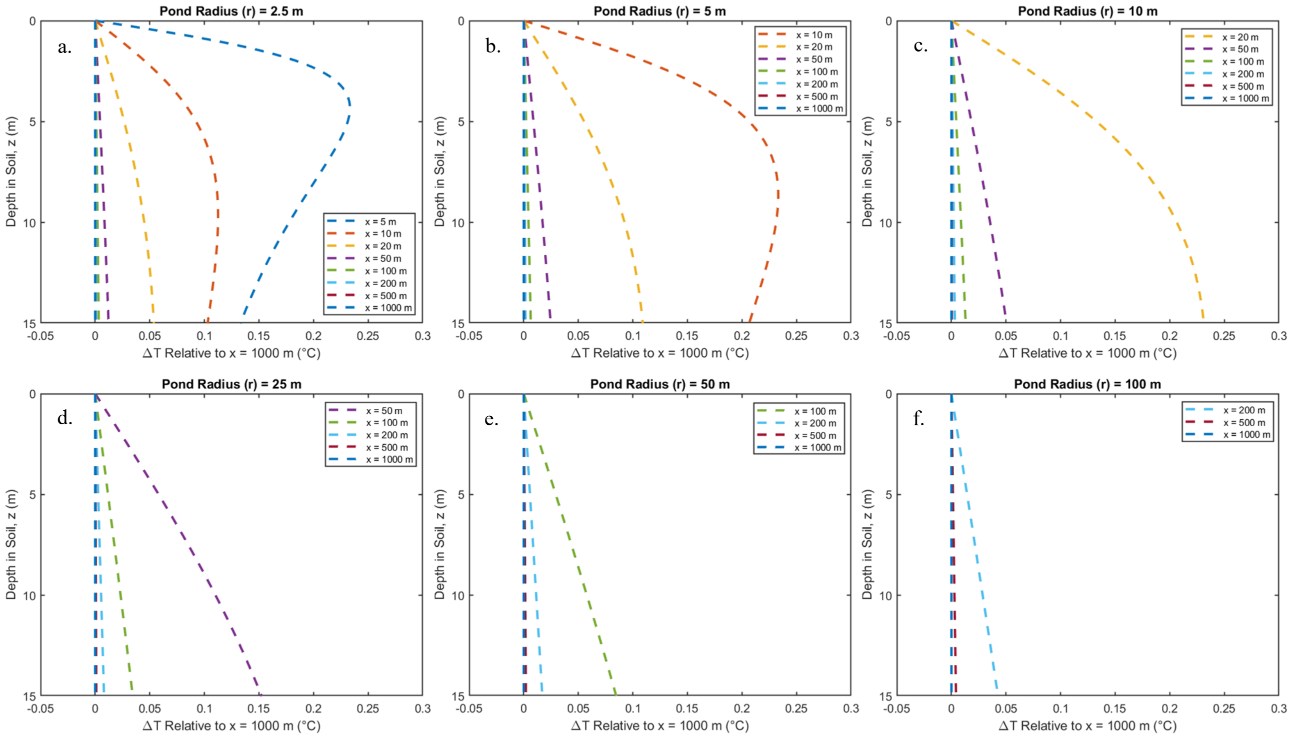
5 CONCLUSIONS

The effects of climate change are particularly severe in northern regions due to polar amplification. Infrastructure in these regions, much of which is constructed on permafrost, is increasingly at risk as thawing intensifies. The Hudson Bay Railway (HBR) in northern Manitoba is already experiencing the consequences of climate warming and permafrost degradation. Comprehensive and reliable investigations, supported by modeling data, are essential to help HBR policymakers make informed decisions regarding mitigation and adaptation strategies.

In thermal modeling of the soil beneath the railway embankment and its surrounding areas, it is crucial to consider variations in surface materials and boundary conditions. In the HBR region, numerous ponds exist, ranging from small ponds to larger ones comparable in size to small lakes. These surface water bodies can significantly alter the thermal regime of the surrounding ground by acting as either heat sources or sinks, depending on seasonal and environmental conditions. To estimate the thermal impact of these ponds on the soil beneath and adjacent to the railway embankment, a sensitivity analysis has been conducted in this study. Analytical solutions were implemented to evaluate the effects of pond size and its distance from the rail embankment on the ground thermal regime, by applying different surface temperature boundary conditions to the pond and adjacent ground areas. This analysis focuses solely on the surface size (radius) of the pond, neglecting its depth, whether shallow or deep.

The results indicate that the distance between the pond center and the railway embankment plays a more dominant role in thermal influence than the pond size itself. This conclusion is based on comparisons of soil temperature profiles extending to a depth of 15 m, evaluated at various distances and pond sizes. The findings confirm that even a relatively large pond, comparable in size to a small lake, has a negligible thermal effect if it is located 500–1000 m away from the railway. In contrast, small ponds with radius less than 10 m can raise subsurface soil temperatures by as much as 0.2–0.25 ℃ if they are located within 50 m of the embankment. For moderately sized ponds (with radius of 25–50 m), a positive thermal influence of 0.1–0.15 ℃ is observed in the soil beneath the railway embankment, provided that the embankment lies within a distance equivalent to twice the pond radius from the pond center.

These findings suggest that sections of the Hudson Bay Railway located within approximately 50 m of ponds are the most thermally vulnerable and should be prioritized for monitoring and maintenance. Snow accumulation near the embankment shoulders adjacent to ponds can further enhance ground warming and should be minimized through effective snow management or improved drainage. In areas where ponds cannot be avoided, mitigation strategies such as thermal insulation layers, shading, or culvert placement that enhances cold-air drainage could help reduce permafrost degradation risks. Future investigations incorporating transient heat transfer and hydrological processes are recommended to refine culvert spacing and assess long-term performance under evolving climatic conditions.



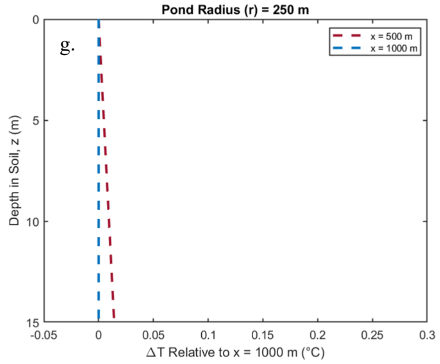


Figure 6. Normalized soil temperature values in different distances from the pond center (x) relative to x = 1000 m for each pond radius size (r).

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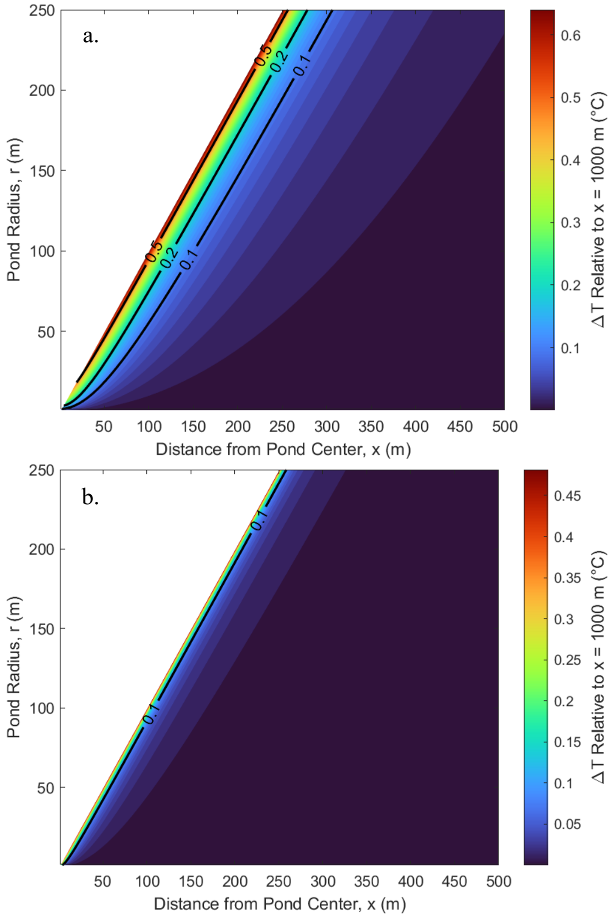

Figure 7. Heat map of soil temperature difference relative to distance of 1000 m from pond center at depth of a. 15 m, b. 2 m.

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