Climate warming and the progression of winter road degradation in northern Canada

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ABSTRACT

Winter roads have been the lifeline for remote northern communities in Canada for decades. The historical method of winter road building on flat terrain such as muskeg (peat) and lakes has become less effective as the climate warms and winter road seasons become shorter. The immediate concern is the reduction in serviceability of historically constructed winter roads, due to the drastically diminishing winter road seasons. This paper details the progression of climate change and subsequent consequences for our winter road networks in Canada's central provinces of Ontario and Manitoba. Nearly 6000 km of winter roads exist in Manitoba and Ontario, servicing a total of 54 separate communities, to supply food, fuel, school, medical, and construction supplies each year. Regional climate data, research, and first-hand accounts suggest that new solutions and strategies are required to maintain seasonal access for northern remote communities.

This paper presents the case study of the Fort Severn First Nation Winter Road, part the longest winter road in the world, where the continued degradation and reduced operating seasons have resulted in significant socio-economic repercussions for the community. A helicopter reconnaissance of the existing Fort Severn Winter Road alignment versus potential alternative routes revealed widespread permafrost degradation and significant ground warming. Options for relocating the existing winter road to higher and more favourable ground is detailed, while some level of permanent embankment construction is suggested through muskeg terrain. This strategy also offers the potential for future all season road development, reducing our overall environmental footprint. Adopting climate resilient winter road principles is required to maintain access to northern communities while protecting the environment and promoting sustainable and reliable infrastructure.

1 INTRODUCTION

Climate change has evolved into a climate crisis in northern Canada. Increasingly warmer mean annual temperatures have resulted in extreme changes to the environment and subsequently, the socio-economic normality of the North. The engineering profession has been challenged in recent decades to maintain or upgrade established infrastructure as the environment adjusts to a rapidly changing climate.

An immediate concern for remote communities in northern Canada is the sustainability of winter road infrastructure. Winter roads in Canada have provided essential seasonal access to fly-in only locations, typically remote northern communities and mining infrastructure, since the early 20th century (Kuryk, 2003; Sigfusson, 1992). Accounting for over 50% of Canada's winter roads, Manitoba and Ontario have a combined winter road network of approximately 5660 km, servicing 54 First Nation communities.

Conventionally constructed through low-lying terrain, winter roads have historically been routed across lakes, rivers, muskeg, and permafrost terrain. The routing process was undertaken without consideration for the characteristics of the underlying soils, leading to poor winter road performance as warmer winter season temperatures are recorded.

As the operating window of winter roads continues to shorten, First Nation communities in Canada are searching for a more reliable and permanent solution. In conjunction with the engineering profession, many First Nation communities have been able to improve accessibility by re-routing their winter road alignments to more stable higher ground. However, there are northern communities where an all-season road is not considered to be a feasible solution from a costing perspective. Construction costs for northern all-season roads can range from $2 million to $5 million per kilometer depending on terrain, topographic conditions, water crossings, borrow sourcing, and the design level of service. By using a transitional approach that improves our winter roads in the interim, engineers can plan for future all-season road development by applying a staged construction strategy. This paper presents the case study of the Fort Severn First Nation Winter Road, which is located in one of Canada's most sensitive and challenging areas, the Hudson Bay Lowlands.

1.1 Regional Climate Data

The progression of climate change has resulted in observed and projected mean annual average temperatures (MAAT) across northern Canada increasing at twice the rate of the global mean annual temperatures. The greatest increases in MAAT have been observed in the winter season, a trend projected to continue as fewer Freezing Degree Days (FDD) are observed each year (Bush et al. 2019). As shown on Figure 1, historical temperature data from four northern communities located in the Hudson Bay Lowlands region show that MAAT have increased by approximately 1.98 °C since 1935, 2.5 times the global average.

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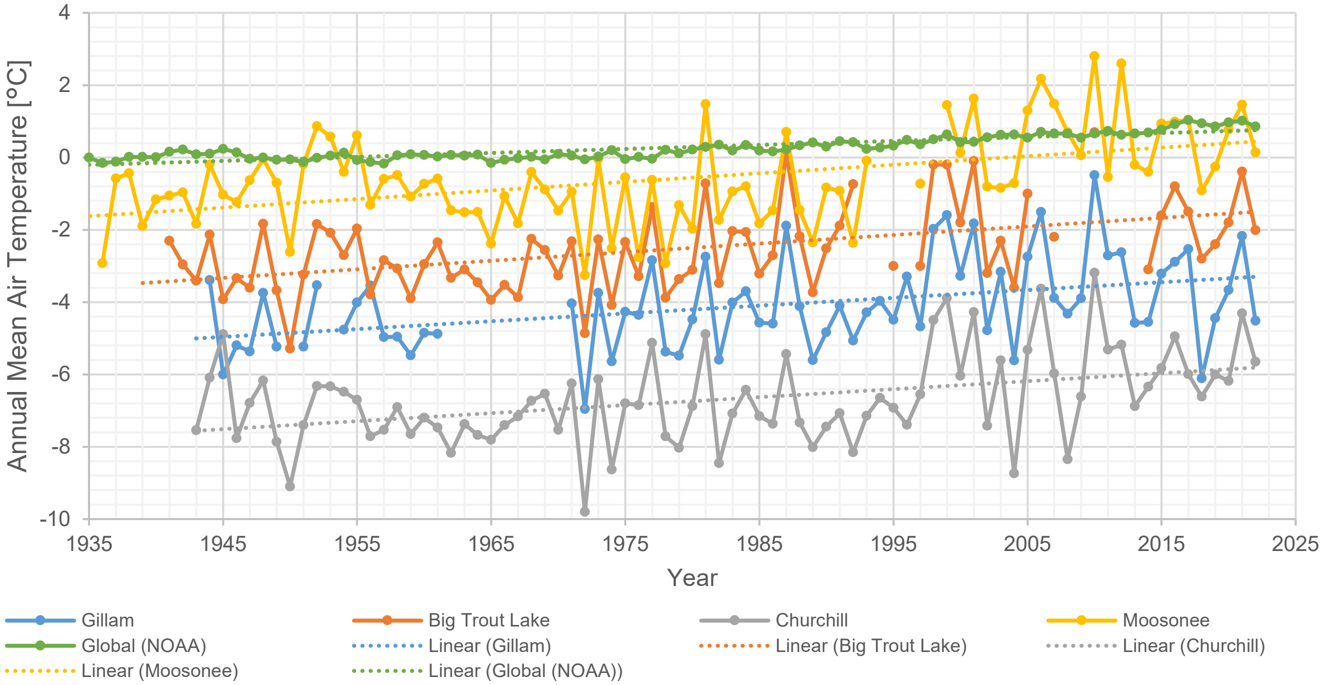

Figure 1. Annual mean air temperatures of four communities in the Hudson Bay Lowlands compared to global mean temperatures since 1935 (Government of Canada 2023; NOAA 2023).

Regional temperature forecasting based on 24 climate models in the area of the case study predict that the MAAT in the region of Fort Severn First Nation will increase by as much as 2.6 °C by 2050, as shown in Figure 2. The predicted warming trends will result in the reduction of observed annual FDD and require more effort on the winter road pre-conditioning period as more energy is required to freeze the warmer subsurface and water bodies. (Hori et al. 2017, 2018).

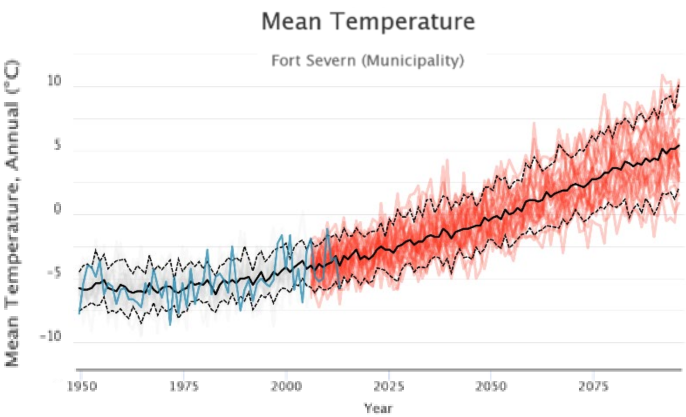

Figure 2. Mean annual temperature forecasting based on 24 climate models for Fort Severn, Ontario (Prairie Climate Center 2019).

1.2 Muskeg Terrain, Water Crossings, and Permafrost

Muskeg has become increasingly difficult to construct winter roads through despite historically being considered an economically viable winter subgrade. Insulative properties, heat generation, and high moisture contents associated with the chemical and thermal properties of muskeg contribute to its progressive inability to freeze through natural climatic processes, as more heat is transferred into the peat in the summer months (Phukan 1982).

In the northern regions of Canada, muskeg terrain is also associated with underlying permafrost as the high void ratio in peat deposits naturally insulates the perennially frozen ground against surface air temperatures. However, the insulative properties of peat are now not enough to prevent active permafrost warming and thaw in most regions of Canada, posing a greater risk to winter roads.

Water crossings have also become increasingly problematic due to late ice freezing in the fall and early thawing in the spring. Relying on ice formation to naturally bridge water bodies requires significant maintenance efforts to build ice in early winter and maintain access during warmer weather conditions. As winter road networks generally do not have built in redundancies, system functionality can rely entirely on the water crossing maintenance. In cases where a water crossing fails or becomes increasingly problematic, the entire system fails.

The increase in MAAT has resulted in long term changes to the ground temperature regime and a gradual expansion of the active zone of influence. In northern regions of Canada, the thawing of permafrost is irrevocably changing the environment through ground subsidence, slope and erosional failures, thermal regime of the subsurface, and increased saturation of soils. Terrain and landform changes (such as bog turning into fen as the groundwater table rises) are directly connected to the increased challenges of our winter road systems.

1.3 Climate Sensitive Winter Road Strategy

Incremental re-routing solutions along shorter sections of existing alignments are no longer sufficient to maintain access along winter roads. In response, a climate sensitive winter road routing and ground improvement strategy has been developed that suggests re-routing the entire winter road system and applying fundamental all-season road routing and construction principles. The basis of the strategy is to minimize traversing organic deposits and poorly draining terrain, avoid ice rich ground, reduce or eliminate water crossings, and re-route along geological features of higher local relief (such as beach ridges, eskers, moraines, and outwash deposits) with stable subsurface characteristics that promote hard freezing.

Not only will the re-routing and ground improvement strategy aid in extending the winter road season, but this strategy provides the first step for potential future all-season road (ASR) alignments. Soon, ASR development will become a requirement to keep these remote communities connected by ground.

1.3.1 Muskeg Ground Improvement Technique

Segments of most winter roads in Canada will inevitably cross areas of muskeg terrain. The construction of a permanent shallow embankment floated on organic deposits (muskeg) offers a solution for hard freezing and potential year-round access. The synthetic embankment can be constructed by placing a thick granular layer over a swamp rated geogrid/geotextile composite to float the road on the peat, as shown in Figure 3. Alternatively, a classic corduroy road could be constructed by placing the granular fill over a mattress of tightly spaced logs.

The success of the floating road strategy relies on ability of peat to act as a foundation material, whose characteristics are highly variable based on formation, humification, and moisture content. Shear strength, which is a critical parameter to this methodology, is a function of the structure and moisture content of the peat. Peat of higher fibrosity, lower moisture contents, and lower degree of decay has greater shear strengths than less fibrous peat with a higher moisture content and level of decay (Forestry Civil Engineering 2010; Hobbs 1986; Munro 2004). The shear strength profile will typically decrease with depth as the peat loses fibrosity and becomes more amorphous. Therefore, the depth of the synthetic embankment will vary based on the shear strength of the peat. When considering constructability, the establishment of a floating embankment is more suited to winter construction to maintain the natural tensile forces in peat fibers and to reduce the risk of excessive tearing/shearing. Winter construction will also allow for gradual compression of the peat layer as it naturally thaws during the spring.

The muskeg ground improvement technique of constructing a floating embankment through muskeg terrain is typical practice for all-season road development. However, the same principle should also be applied to winter road construction to maintain serviceability along alignments where there is a risk for non-freezing muskeg or melting permafrost.

1.3.1 Water Crossing Upgrades

A crucial factor to winter road functionality is the water crossings. Winter road seasons can be extended when winter road alignments are more strategically routed to avoid or limit the number of water bodies crossed. The location of a winter water crossing should be routed in areas that promote ice generation (e.g., straight sections, low water velocities), which is quite often in conflict with the preferred crossing location for a permanent bridge structure. In areas where water crossings cannot be avoided, risk can be minimized by installing culverts, or temporary or permanent bridge structures. As a preventative measure, several provincial and territorial government bodies are currently installing permanent bridge structures.

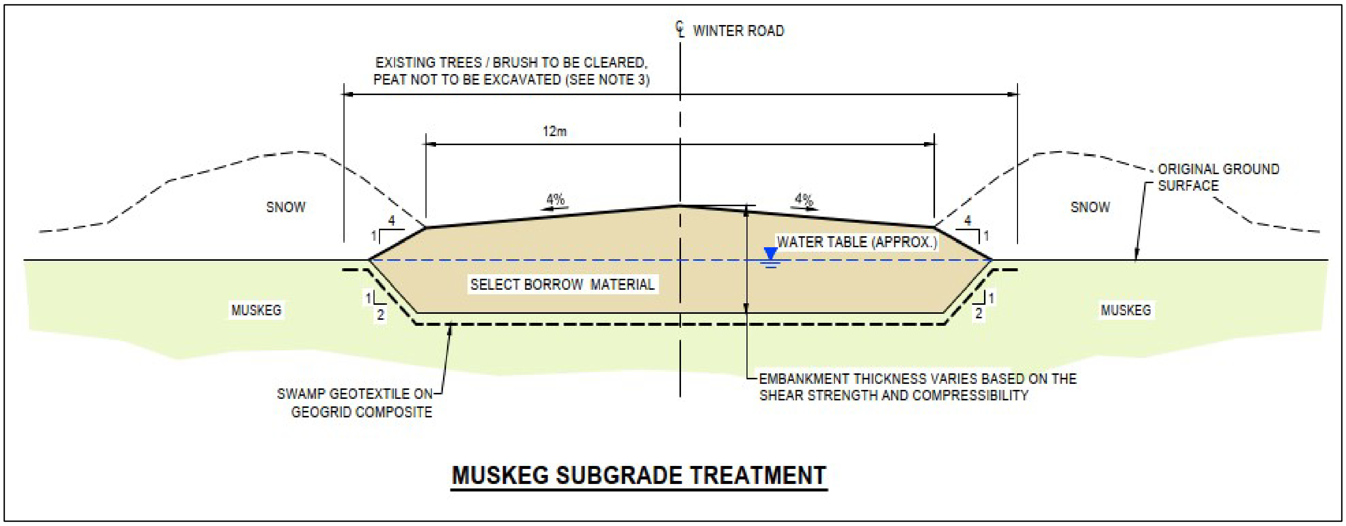

Figure 3. Example of a synthetic floating embankment as a ground improvement technique for winter roads over muskeg.

2 Fort Severn First Nation Winter Road

The existing winter road for Fort Severn, ON is part of the longest winter road in the world, the Wapusk Trail, at 752 km in length, beginning in Gillam, MB and ending in Peawanuck, ON, as shown in Figure 4. Fort Severn First Nation (FSFN) is responsible for the construction and maintenance of a 305 km section that runs east–west between FSFN and Shamattawa First Nation, MB. The winter road continues beyond Shamattawa First Nation for approximately 200 km to Gillam, MB until it connects to the Manitoba provincial all-season road network.

Figure 4. The Wapusk Trail, approximately 752 km in length, between Gillam, Manitoba and Peawanuck, Ontario.

The entire length of the winter road is located within a unique and complex region known as the Hudson Bay Lowlands, the largest wetland in Canada. The surficial geology is dominated by poorly draining organic deposits of muskeg (peat) that are typically underlain by fine-grained glacio-lacustrine clays and silts (Ontario Geological Survey 2016). Terrain within the Hudson Bay Lowlands is also heavily influenced by areas of discontinuous and continuous permafrost. The frozen soils are currently melting at an accelerated rate, posing considerable risk for winter road infrastructure.

Originally routed using the historic conventional method of winter road routing, over 90% of the current FSFN winter road route traverses flat organic terrain and lakes with limited high ground options. In recent years, the winter road season has shortened to as little as two weeks, and it was open for light traffic only, having significant socio-economic repercussions for the community. Reduced weight capacities and short winter road seasons that limit the delivery of essential supplies have major negative impacts on the community in the form of fuel shortages, inflation, and decreased economic development and growth. It has become critical for FSFN to find an adaptative and sustainable solution to maintain roadway access while preserving their culture and way of life.

2.1 Regional Surficial Geology

The Hudson Bay Lowlands is one of the most difficult settings for road building (winter road and all-season) as the low-lying terrain is poorly draining, consists of variable depths of peat deposits, and has limited high ground options and conventional borrow sourcing. Surficial geology was reviewed to assess the terrain, topography, and geological features to assess potential new routing options.

Along the Hudson Bay coastline there exists a series of historical beach ridges as long linear features with shallow relief above the neighbouring muskeg terrain, as shown in Figure 5. The beach ridges are historical marine shorelines, deposited by the Tyrell Sea as the Laurentide ice sheet retreated. Within the limits of the Hudson Bay Lowlands, glacial fluvial and alluvial deposits along the Severn River also provide some low-lying relief through the muskeg, including potential borrow sources (Ontario Geological Survey 2016). Beyond the limits of the Hudson Bay Lowlands, the surficial geology maps indicate some high ground options and aggregate resource potential that exists in the form of moraines and eskers.

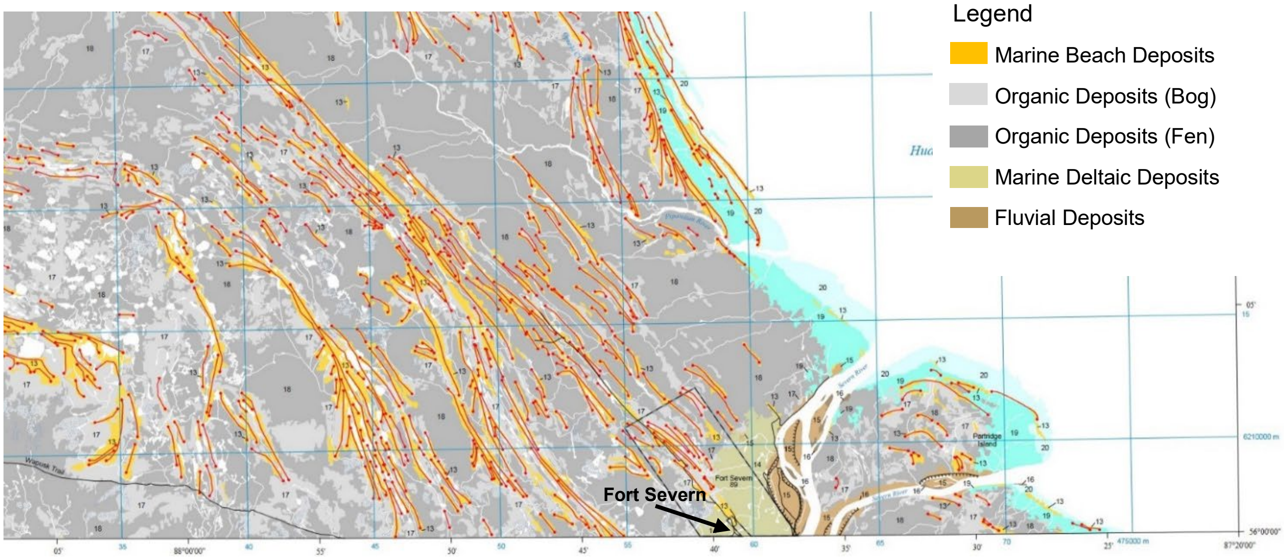

Figure 5. Surficial geology map of Fort Severn, Ontario at a scale of 1:100,000 (Ontario Geological Survey 2016).

2.2 Alternative Route Development

There are significant construction challenges and costing implications linked to the design and construction of a route through the Hudson Bay Lowlands. The length of any route examined spans a large region and the terrain characteristics change drastically along the alignment in terms of vegetation, material composition, and variable permafrost conditions. The region also has numerous environmentally sensitive areas and species at risk that further complicates the routing process. A climate sensitive routing strategy was used to focus on high ground options, minimize areas of high risk, and limit the traversing of environmentally and culturally sensitive areas.

Figure 6. Existing FSFN winter road route through muskeg terrain and across lakes.

Development of several alternative route options along the existing alignment were considered in the initial stages of the project. However, it was found that no re-alignment option had measurable improvement over the existing alignment. The beach ridges that exist become less prominent farther away from the coastline and the existing route mainly runs perpendicular to the ridges and does not provide the opportunity to route long sections directly on the ridges (Figure 6). Furthermore, the cost and construction of ground improvements would be expensive and challenging due to long sections of muskeg terrain that could not be avoided and the limited borrow sources that exist near the alignment.

Therefore, three new alternative routes were developed. The route alternatives are depicted in Figure 7 and include the following:

- Alternative Route 1 – Southern Coastal Route to Gillam, MB
- Alternative Route 2 – Northern Coastal Route to Gillam, MB
- Alternative Route 3 – Ontario Route to Bearskin Lake FN, ON

Alternative Route 1 and 2 follow along the coastline of Hudson Bay to utilize the beach ridges that can provide a favorable running surface and tree cover. The beach ridges provide numerous options for potential alignments along the coast; however, two main alternative routes were identified along the more prominent and continuous beach ridge features.

Alternative Route 3 was developed along the Severn River to take advantage of potential fluvial deposits and tree cover along the river system. Where the alignment was routed along the Severn River, it was important to remain close to the top of the bank to capture potential fluvial deposits and tree cover but offset far enough to reduce the risk of slope instabilities and natural riverbank erosional processes.

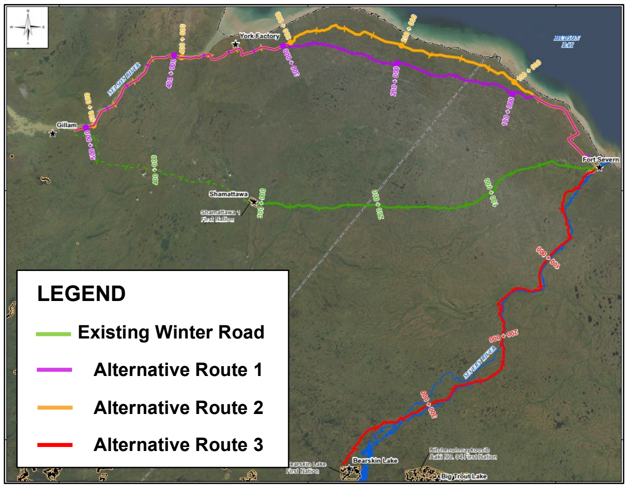

Figure 7. Alternative route options and the existing FSFN winter road alignment.

2.3 Desktop Assessment of Route Options

The alternative route options were evaluated based on the following general criteria:

- Design and Construction Challenges
- Operation and Maintenance
- Safety
- Cost
- Community Preference

The general criteria outlined above can be further defined by specific characteristics along each route alternative. A summary of key routing characteristics for each alternative route are shown in Tables 1, 2, and 3. These characteristics were used as part of the evaluation of each alternative.

Table 1. Percentage of terrain type crossed by each alternative route.

Terrain Type [%]	Route 1	Route 2	Route 3
Beach Ridges[1]	53	56	0
Forested Area[2]	32	31	71
Muskeg[3]	16	13	29

[1]Has light grading and light brushing clearing requirements.
[2]Has medium grading and tree clearing requirements.
[3]Requires the muskeg subgrade treatment (Figure 3)

Table 2. Water crossings along each alternative route.

Characteristic	Route 1	Route 2	Route 3
Creeks	221	216	172
Minor Water Crossing[1]	35	45	9
Major Water Crossing[2]	9	11	3
Ponds and Lakes	0	0	3

[1]defined as 5 to 40 m wide from shoreline to shoreline
[2]defined as greater than 40 m wide from shoreline to shoreline

Table 3. Constructable length of each alternative route

Characteristic	Route 1	Route 2	Route 3
Total Length[1]	509 km	515 km	392 km
Est.Travel Time[2]	18.5 hr	18.5 hr	23 hr

[1]Total length of a newly constructed winter road
[2]Estimated travel time to FSFN's preferred destination of Winnipeg, MB

2.4 Field Assessment of Terrain Suitability and Risk Along Alternative Routes

Following a review of aerial imagery based surficial mapping, a helicopter reconnaissance, with limited ground truthing, was conducted to assess the suitability of the terrain from a field perspective and outline potential risks of constructing a winter road along each alternative route.

The reconnaissance confirmed that the beach ridges were abundant throughout the initial 330 km of Alternative Routes 1 and 2 and offer an effective option for a new winter road alignment. It was confirmed through ground truthing that the beach ridges were composed of dry sand and gravel deposits with minimal fines content. These soils will freeze more readily than the neighboring organic terrain which was saturated at or near the ground surface.

The beach ridges also had sufficient tree cover to act as a windbreak against snow drifting when offset a minimum of 20 km from the coastline (Figure 8). The risk of putting a new winter road alignment on the existing ridges is low given that their material composition is ideal for hard freezing conditions and the community has demonstrated that all-season roads on the ridges are functional and require minimal operation maintenance (Figure 9 and 10). The beach ridge material is also suitable as borrow for the muskeg ground improvement. Using these ridges sets up the project for a future all season road which will be required at some point as climate change progresses.

It was determined during the helicopter reconnaissance that Alternative Route 2 would not be considered a feasible route in comparison to Alternative Route 1 due to the lack of tree coverage near the coastline (Figure 11) and because the ridges were smaller in width and height. Tree cover was an important safety consideration for the community as it will provide improved driving visibility and some protection from the coastal winds.

Figure 8. Beach ridges near the Hudson Bay coastline with tree cover along Alternative Route 1.

Figure 9. Existing FSFN community road located on a beach ridge north of the airport.

Figure 10. Aerial view of existing FSFN community road north of airport located on a beach ridge.

Figure 11. Beach ridges without tree cover near the Hudson Bay coastline on Alternative Route 2.

Areas routed along major river systems, such as the Nelson River and Severn River, were targeted for the moderate tree cover present and borrow potential. However, the helicopter reconnaissance proved that these areas are complex in terms of major permafrost thaw, riverbank instability, the presence of organic terrain near the top of the riverbank, and steep grades at water crossings. The helicopter reconnaissance also determined that a greater offset from riverbanks will be required to avoid slope instability and permafrost thaw slumps. However, this will require the alignment to traverse longer, and most likely deeper, sections of organic terrain as shown in Figure 12, where the organic terrain is immediately adjacent to the top of bank.

Figure 12. Muskeg terrain along Alternative Route 3 directly adjacent to the Severn River, Ontario.

One challenge to constructing a permanent embankment in the organic terrain will be navigating the widespread permafrost thaw that was observed across the entire project area, as shown in Figure 13. It became clear over the course of the helicopter reconnaissance that, although engineers have historically built our infrastructure to preserve and maintain permafrost soils, it has now become clear that the design and construction of infrastructure should consider the inevitable thawing of permafrost.

Figure 13. Widespread permafrost thaw (thermokarst) along the Nelson River in Manitoba.

2.5 Evaluation of Route Options

Alternative Route 1 was determined to be the most economical route option while carrying the least amount of long-term risk for a winter road, despite the route having one of the longer constructable lengths in the study. The route will still traverse some difficult areas. Although comparatively feasible from an engineering perspective, Alternative Route 2 was not considered to be a suitable alternative with the increased safety hazard of coastal proximity and limited tree cover. Alternative Route 3 was deemed to be high risk and did not result in a measurable improvement over the existing winter road route, as a majority of the route would require extensive construction of ground improvement techniques while avoiding riverbank instability and permafrost thaw slumps. Based on the feasibility study results, it was concluded that Alternative Route 1 poses the least risk for a potential winter road relocation, a conclusion that was supported by the FSFN community from their personal experience.

The helicopter reconnaissance confirmed that permafrost degradation poses the highest long-term risk to the region as the ever-changing subgrade conditions will affect the way northern infrastructure is designed and maintained. Therefore, the current extent of permafrost, temperature profiles, percentages of ice content and related anticipated ground subsidence must all be taken into consideration in the muskeg ground improvement design. All these factors contribute to the complexity of the terrain as the region is constantly changing due to climate warming. The next project stages will be to conduct additional geotechnical investigations and temperature instrumentation, ground ice mapping and monitoring, thermal modelling, and the construction of a ground improvement test section to assess the short- and long-term performance of the muskeg subgrade treatment.

3 Conclusions

Inaccessible by permanent or all-season road networks, remote First Nation communities rely on winter roads as a cost-effective means of ground transportation for goods and services such as the delivery of fuel, food, construction materials and equipment. The case study examined in this paper is characteristic of the ongoing problems facing the entirety of the Canadian winter road network; diminishing serviceability, reduced operating windows, and increasing maintenance efforts. Historically routed through flat terrain such as muskeg and lakes, these conventional routes are no longer considered to be sustainable with a warming climate. Areas of permafrost are continuing to warm and melt, creating additional engineering challenges that change our traditional permafrost engineering methodology, which was once to preserve perennially frozen ground.

The case study applied climate sensitive routing strategies to determine the feasibility of the relocation and redesign of the Fort Severn First Nation Winter Road. Alternative alignment options that were adaptive to climate warming and minimize overall environmental impact were selected to provide a sustainable and cost-effective route option. In areas of muskeg, it is recommended that ground improvement techniques be implemented along winter road alignments in anticipation of a warming climate, recognizing that areas of muskeg within the Hudson Bay Lowlands cannot be avoided. Permanent crossing structures should be considered where water crossings are unavoidable to increase the longevity of a winter road season. It was determined that Alternative Route 1 along the beach ridges was the most economical option while providing the least engineering and climate-based risk.

It is now becoming crucial to relocate existing winter road systems to areas where alignments will be more resilient to climate change. Innovative and adaptive solutions will be required to maintain access to remote communities as climate change will eventually eliminate these seasonal roads on their present alignments.

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