Vulnerability assessment of the Hudson Bay Railway for permafrost thaw and flooding hazards

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ABSTRACT

Due to Arctic amplification, the impact of climate change effects on infrastructure, ecosystems and way of life is significant in Arctic and sub-Arctic regions of the world. In Canada, the first major transportation facility to be built over permafrost was the 821 km long Hudson Bay Railway (HBR) in 1929. Over time, the railway has required recurrent maintenance due to subsidence resulting from the thawing of ice-rich permafrost beneath its embankment. In 2017, the railway also experienced damage due to flooding and washouts. These events impact cost and serviceability, and potentially integrity of the railway and safety. Conducting a vulnerability assessment of the HBR to permafrost thaw potential and flood hazards is an important action to support informed decision making on planning maintenance activities and developing adaptation strategies addressing climate change effects. This study addresses the vulnerability of the HBR to flood events. The regional watersheds are evaluated with respect to the land-cover type, drainage density, and ground ice content on the hydrological function, and impact on surface runoff dynamics. Consistent with past events, higher vulnerability was predicted in the northern track sections, in the Herchmer subdivision, in comparison with sections south of Gillam. The analysis highlighted the need for focused flood risk assessment, particularly between O'Day (KP 685.9) and Belcher (KP 725.8). Previous investigations on problematic areas experiencing thaw subsidence, and records of washouts during the 2017 flood event are also integrated within the GIS-based vulnerability framework. The results will guide future hydrological modelling studies and support decision-makers to assess vulnerabilities, quantify risks, and formulate maintenance and adaptation strategies for the railway.

1 INTRODUCTION

The accelerated rate of climate change in Arctic and sub-Arctic regions of the world has increased concerns about the construction and maintenance of linear transportation infrastructure in these areas. Studies have shown the annual surface air temperature of Arctic regions is persistently higher than temperate zones, which is associated with the phenomenon of Arctic amplification, and is warming at a rate of four times the global average (Arctic Council and the International Arctic Science Committee 2004; Rantanen et al. 2022, Thoman et al. 2023). Consistent with the warming trend, there is an increase in the mean annual precipitation magnitude. Climate change affects have been attributed to natural disasters, including thawing of permafrost, that has presented significant obstacles to the development and maintaining of infrastructure (Hjort et al. 2022).

In Canada, the first major transportation facility to be built over permafrost was the Hudson Bay Railway (HBR) in 1929 (L'Hérault et al. 2024). The 821-km railway in Northern Manitoba provides a land transportation route to the seaport at Churchill for the global export of grain products from the Prairie Provinces (Miller 1958; EBA 1979). Maintenance of the railway is challenged by it's the remote location and extensive peatland along the route, which is now further impacted by climate change effects due to permafrost thaw (EBA 1990). As a result of gradual thaw settlement of subgrade permafrost and recurrence of sinkholes, the railway has always required both track lifting and bank widening by placement of new granular fill (EBA 1982). Moreover, increasing occurrences of flooding and intense precipitation due to climate change have increased railway maintenance costs in recent decades. Washouts, triggered by a flooding event in 2017, highlight the significance of hydrological processes that impact railway performance and integrity, which may be influenced by permafrost thaw and climate change effects.

There is now an urgent need to improve the current understanding of the HBR railway vulnerability to natural hazards and climate change effects. While the degradation of permafrost along the railway has been extensively studied (e.g., Michigan Technological University, 2017; EBA Consultant Ltd, 1976–1998), little is known about resilience of the railway to hydrological processes and flood events. Although comprehensive knowledge base exists (Mathias 2023) on fluid mechanics (e.g., open channel flow), and hydrology (e.g., water balance, vadose zone, flood frequency), there is a lack of region-specific knowledge (e.g., field measured precipitation, river flow rates, water heights) to improve confidence in predictable outcomes (e.g., flood frequency). In this environment, distinct physiographic features (e.g., low topographic gradients, peat, fen) influence hydrological characteristics that add complexity to the evaluation process. For example, some models are better suited to the evaluation of hydrological cryosphere processes in permafrost dominated regions (Bui et al. 2020; Stuurop et al. 2021). Furthermore, the presence of permafrost influences the soil material state (i.e., frozen, unfrozen), cryosuction processes, and active layer thickness that can have substantial impact on hydrological processes such as surface water runoff pathways and water storage (Hayashi et al. 2004; McLaughlin and Webster 2014; Woo 2012).

GIS-based spatial analysis can be used to identify areas that are vulnerable and makes it easier to conduct focused flood risk assessment in future studies. GIS supports the visualization of spatially distributed features (e.g., surface water, vegetation, forest fires) and data (e.g., meteorological conditions, active layer thickness, ground ice content) along the Hudson Bay Railway that may influence flood events or other geohazards.

This study addresses the vulnerability of the HBR to flooding and permafrost thaw hazards. The regional watersheds are evaluated with respect to the land-cover type, drainage density, permafrost, and ground ice content on the hydrological function, and impact on surface runoff dynamics. Previous investigations on problematic areas experiencing thaw subsidence (EBA 1976; Michigan Technological University 2017), and records of washouts during the 2017 flood event are also integrated within the GIS framework. The results will support hydrological modeling and assist decision-makers in assessing vulnerabilities, quantifying risks, and formulating maintenance and adaptation strategies for the railway, including water management strategies.

2 OVERVIEW OF THE STUDY AREA

The main line of the HBR connects The Pas (53° 48′N, 101°12′W), at KP 0, with the port of Churchill (58°45'N, 94° 10′W) at KP 820.4. The rail is a vital link for the transport of goods in northern Manitoba and provides access for passenger rail service (VIA Rail Polar Bear Express) to Churchill. For this study, the region of interest is north of the Pas and onward to Churchill.

Near Gillam (KP 524.8), the surficial geology can be classified as proximal glaciofluvial (sand and gravel), and offshore glaciolacustrine (clay, silt, and minor sand) with thickness of 1 m to 20 m (Matile and Keller 2006). The northern HBR section, onward to Churchill, is predominantly offshore glaciomarine sediments (clay, silt, and minor sand) with laminated deposits, of 1 m to 20 m thickness, overlain by peat (Matile and Keller 2006). The northern section of the HBR is along the southwestern limits of the Tyrell Sea (ca. 10,000-8,000BC).

The Hudson Plains ecosystem zone is largely treeless in the north with southern locations populated by willow, tamarack, and black spruce. From Gillam north to Churchill, the vegetation zones exhibit a transition from West-Central Boreal Forest to Northern Boreal Woodland and Subarctic Woodland-Tundra (Baldwin et al., 2019). Representative sections along the HBR, within the Herchmer subdivision, are shown in Figure 1.

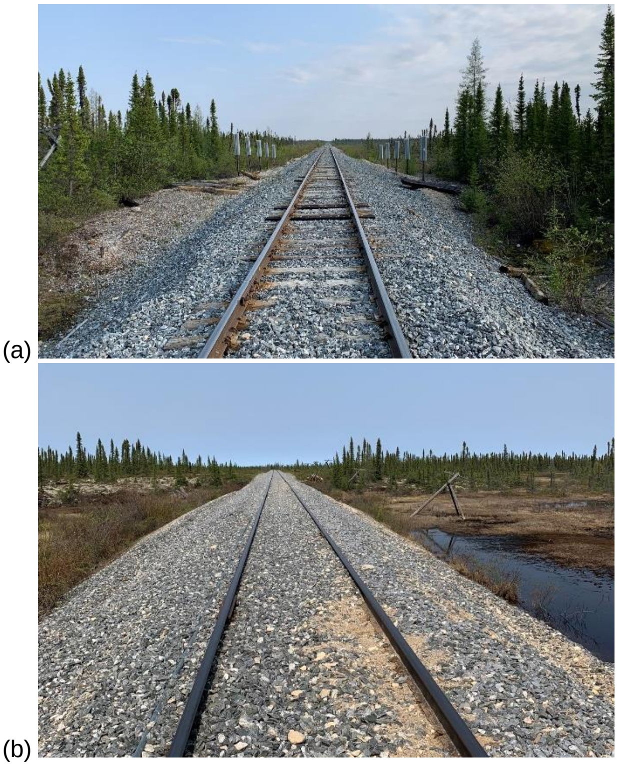

Figure 1. The Hudson Bay Railway at (a) Charlebois (KP 586.3) and (b) near Belcher (KP 725.8).

A peat plateau bordering fens and surface water bodies exist along the HBR (Dyke and Sladen 2010). When underlain by permafrost, peatlands can form complexes of elevated palsas and peat plateaus, which typically have a dry surface and covered with dense to scattered stands of black spruce. The ground has a thick forest peat cover consisting of Sphagnum mosses and lichens that are usually interspersed with low shrubs (EBA 1982). The fen exhibits little or no tree growth, are invariably wet, and are predominated by marsh sedges and thin, non-Sphagnum mosses.

A frozen peat plateau complex, running northwest to southeast, provides a habitat for local wildlife (e.g., polar bear, caribou) and influences natural processes related to permafrost integrity and hydrological processes (Dyke and Sladen 2010). The permafrost transitions from sporadic discontinuous south of Gillam to extensive discontinuous north to approximately Belcher (KP 725.8) with continuous permafrost distribution north to Churchill.

Across the study region there are two major drainage basins (i.e., Churchill River and Nelson River) and, as shown in Figure 2, 15 wetland-dominated watershed basins (National Hydro Network - NHN - GeoBase Series - Open Government Portal 2024; O'Neill et al. 2020). The 7 basins north of Pit Siding Station (KP 412.3) had wetlands (i.e., peatland and mineral wetland) covering greater than 50 percent of the enclosed area (Pontone et al. 2024). Boundary lines differentiating permafrost zones are also shown, where the volume of permafrost increases northward along the HBR.

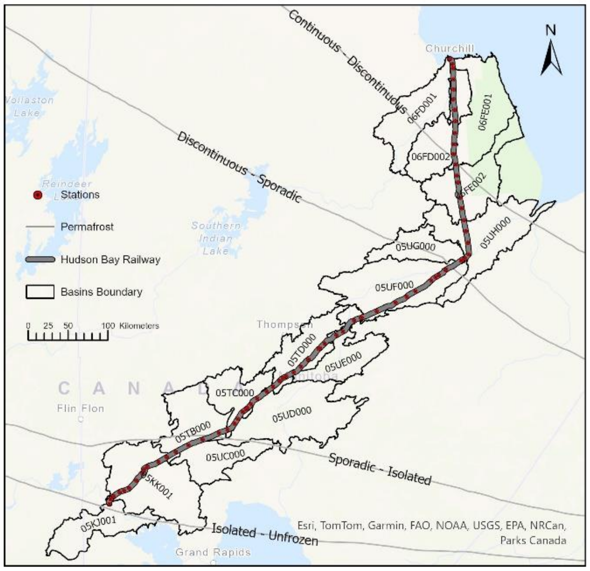

Figure 2. Hudson Bay railway and surrounding environment.

To better understand the historical and expected future climate conditions within the study area, data from four weather stations, including The Pas, Thompson, Gillam, and Churchill, have been analyzed. The data analyzed included daily average temperature, rainfall, snowfall, and snow depth at the end of the month for the climate normal 1961-1990, 1971-200 and 1981-2010 (ECCC 2024). The expected impact of climate change effects for the Low (RCP 4.5) and High (RCP 8.5) emissions scenarios was also analyzed (Prairie Climate Centre 2019).

Historically, based on the 1976-2005 climate normals, across the study region (Prairie Climate Centre 2019), from The Pas to Churchill, summer temperatures are relatively cool (10.8 °C to 16.6 °C) with colder winter temperatures (-18.1 °C to -24.4 °C) and low annual mean temperatures (0.3 °C to -6.4 °C). The mean annual temperatures decreased with increasing distance northward from The Pas to Churchill. There is a warming trend with successive climate normals where The Pas, Thompson, and Gillam may experience positive mean annual air temperatures by 2051-2080. For example, Churchill may experience warming from a mean annual temperature of -7.1 °C to -1.0 °C by 2051-2080. In the longer term, increasing mean annual temperatures above freezing will have a negative impact on permafrost integrity, which may influence hydrological processes and HBR embankment stability.

There are regional differences in total annual precipitation with the historical total annual precipitation between 400 mm and 535 mm for the four stations. The highest monthly value (90.5 mm) was reported for Thompson station in July. The maximum monthly values for The Pas, Gillam and Churchill stations are 80.1 mm (June), 78.6 mm (July) and 80.5 mm (August), respectively. The water flow in northern wetlands is extremely responsive to rainfall due to the presence of highly permeable soil layers and a shallow active layer (i.e., presence of an impermeable frost table) (Wright et al. 2008).

3 CONCEPTUL FRAMEWORK

Understanding the landforms and land cover along the HBR provides insight on the hydrological processes that may influence flooding events. Provided storage capacity is available, wetlands can reduce peak flows by collecting and temporarily holding runoff water. However, when the storage capacity is exceeded, discrete wetland areas merge to form a flow system. (Price and Maloney 1994; Quinton and Roulet 1998).

In the Hudson Bay Lowlands (HBL), which includes the northern Herchmer Subdivision of the HBR, wetlands are a dominant feature. This region can be characterized by bogs, fens, and open water bodies (Dredge and Dyke 2020). Bogs generally lie above the water table and are recharged through precipitation. Along the HBR, the bogs may be open, forested or coalesced peat plateaus with local relief of 1 m to 3 m, and variable peat thickness (1 m to 5 m). Marginal collapse along the edges of a peat plateau may result in its transformation into a fen. The surrounding fen, located within local depressions that often contain standing water, are primarily recharged by the ground water table with surface land cover comprising sedges or trees and relatively thin peat layers less than 2m in thickness (Dredge and Dyke 2020, Dyke and Sladen 2022). Conversely, internal degradation processes may lead to collapse within the peat plateau and form bogs. The collapsed bog may be surrounded by permafrost, with the water table typically situated at least 25 cm below the peat surface (Robinson and Moore 2000).

The hydrological response of wetland-dominated zones, particularly in areas with underlying permafrost, is not well understood (Dyke and Sladen 2010; Quinton et al. 2003). Peat plateaus have unique drainage characteristics whereby water can be efficiently store within adjacent bogs or redirect flow towards the fens due to the relative higher topography (Quinton et al. 2003). Additionally, the movement of water beneath the surface is typically confined to the area between the water table and frost table, known as the saturated zone. The rate of lateral subsurface drainage is significantly affected by the vertical position of the saturated zone due to the considerable reduction in permeability as depth increases (Quinton et al., 2000; Hoag and Price, 1997). As a result, they can produce substantial snowmelt runoff in the early spring, which accumulates in nearby flat bogs and channel fens (Hayashi et al. 2004)., The surface and groundwater flow may be influenced by the presence of permafrost that impacts the active layer thickness, hydraulic conductivity, and depth to the impermeable permafrost table.

The absence of permafrost under channel fens and flat bogs allows for different hydrological dynamics. Bogs typically occur within depressions, with the water table commonly positioned below the surface (NWWG, 1988), thereby facilitating subsurface flow as the primary lateral conveyance pathway (Quinton and Marsh 1999). Bogs have the capacity to receive drainage from adjacent landscapes and precipitation inputs yet seem incapable of discharging water to neighboring regions (Zoltai and Vitt, 1995). Thus, they function as storage areas that mitigate runoff generation. Like bogs, fens occupy a relatively low topographic elevation and are an integral part of the basin drainage network that serve as conveyors of flow (Quinton et al., 2003).

Along the HBR, the peat plateaus may be interspersed with open water bodies, which are hydraulically connected through the active layer. Climate change effects may be a driving force for the accelerated transition in the landscape from peat plateaus to fens. This will have an impact on the surface and ground water flow regime.

4 ANALYSIS AND RESULTS

Conducting a vulnerability assessment of the HBR to permafrost thaw potential and flood hazards is an important process to support informed decision making on planning maintenance activities and developing adaptation strategies addressing climate change effects. The assessment integrates federal and provincial datasets, public domain literature, and HBR records and knowledge. The analysis considers the relationship with surficial geology, soil type and stratigraphy, mean air temperature and river flow rates. Studies have shown, particularly during wetter periods, surface runoff is positively correlated with the drainage density, basin slope, and the percentage of basin area covered by channel fens, while negatively correlated with the percentage of basin area covered by flat bogs (Richardson et al. 2012, Quinton et al. 2003). The presence of permafrost is also an important parameter, which can influence the surface runoff due to a thinner active layer and impermeable permafrost table boundary.

The vulnerability assessment integrates four main layers within ArcGIS Pro tool including percentage area of land cover type such as (1) fen and (2) bog, (3) drainage density, and (4) ground ice type and distribution.

The ground-cover classification scheme distinguished among different organic terrain types. A 30 m special resolution map of peatland sub-classes for the Canadian boreal forest by Pontone et al. (2024) is been used for calculating percentage area of different land types in each basin. The dataset contains seven land cover classes, bog, rich fen, poor fen, peatland permafrost complex, mineral wetlands upland and water.

To determine drainage density, the National Hydro Network (NHN) is used, which provides a quality geometric description and a set of basic attributes describing Canada's inland surface waters.

The Ground Ice Map developed by O'Neill et al. (2020) is used to account for the impact of ground ice. This map provides a broad assessment of ground ice conditions across Canada. It highlights the volumetric percentage of excess ice derived from segregated, wedge, and relict ice types within the top 5 meters of permafrost. A customized layer was created by merging the ice wedges and segregated ice maps from this dataset.

The basin-specific results were reclassified within the ArcGIS Pro environment to transform them into an index ranging from 1 to 5, where the vulnerability severity is ranked from the lowest (1) to highest (5) value. In the reclassification process, a higher percentage of bog area was assigned lower a vulnerability class, whereas increasing fen area, drainage density or ground ice content was associated with increasing vulnerability severity. The vulnerability severity across all classes for all criteria is summarized in Table 1.

In the HBL, the local relief is typically less than 2 m and the general gradient is less than 2 m per kilometre distance. The area is relatively flat, and the effect of basin average slope is not considered in this analysis. Figure 3a illustrates the reclassified layer, on a scale of 1 to 5 as summarized in Table 1, for the bog percentage area within each basin. Among the four basins within the Churchill watershed, including the section north of Lawledge (KP 614.9), higher distributions of bogs are evident, with all basins having greater than 11 percent area coverage of bog with indices of 1 or 2. Figure 3b displays the distribution of five classes of fen percentage area within the basins. The analysis indicates basins with fen coverage exceeding 41% (Class 5) include the segment between O'Day (KP 685.9) and Back (KP 699.1), as well as small sections around The Pas (KP 0) and Wekusko (KP 130.7). Figure 3c depicts the spatial distribution of five indices for drainage density within each grid. The analysis shows that the portion of the HBR between Lawledge (KP 614.9) and Chesnaye (KP 755.3) is in an area with a drainage density of more than 1.6 kilometers per square kilometer. Figure 3d illustrates the distribution of ground ice along the HBR. Significantly, every track segment to the north of Gillam (KP 524.8) is located on a terrain with high to very high levels of ground ice.

Subsequently, the reclassified layers, with equal weighting, were overlaid to generate the final spatial distribution of the vulnerability index. Equal weighting is used due to the lack of similar studies in these basins or comparable regions that establish the relative significance of these factors. This approach is a starting point for further research. Future studies can focus on integrating more layers, conducting sensitivity analyses to assess the influence of each layer, and validating the final vulnerability index using observed flow data.

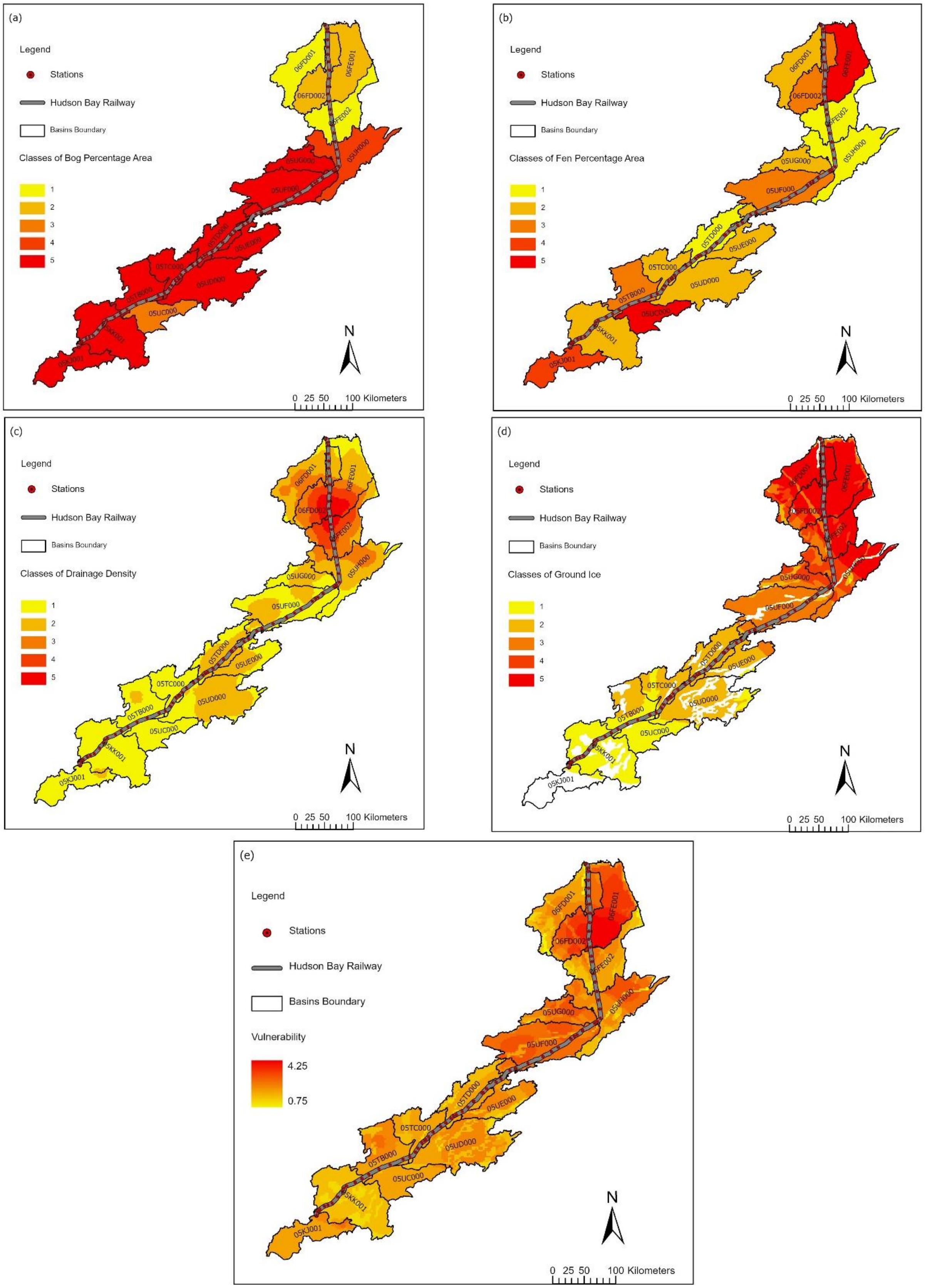

Figure 3. Reclassified flood vulnerability criteria a) Percentage area of bogs b) percentage area of fens c) drainage density d) ground ice and e) final vulnerability map.

As shown in Figure 3e, the highest vulnerability index, exceeding 4, is observed along the track section between O’Day (KP 685.9) and Belcher (KP 725.8). Additionally, the map highlights a comparatively higher vulnerability north of Boyd (KP 401.9) in comparison to the southern portion of this station.

Table 1. Classes of criteria that contribute to flooding vulnerability.

Class	Bog Percentage Area	Fen Percentage Area	Drainage Density $(\mathrm{Km/km^2})$	Ice Map Content Class
5	< 3.7	41.2 - 48.8	3.3 – 4.2	Very High
4	3.7 - 7.4	33.6 - 41.2	2.5 – 3.3	High
3	7.4 - 11.2	26 - 33.6	1.6 – 2.5	Medium
2	11.2 - 14.8	18.4 - 26	0.8 – 1.6	Low
1	14.8 - 18.6	< 18.4	<0.8	Negligible

5 DISCUSSION

The analysis revealed that the railway segment spanning from O’Day (KP 685.9) to Belcher (KP 725.8) stations, exhibits the highest vulnerability to flooding. This observation aligns with the documented occurrences of washouts and unstable areas reported by the railway owner following the 2017 flooding, as illustrated in Figure 4. Although there are many reported problematic areas along the track section between Lawledge (KP 614.9) and O'Day (KP 685.9), the calculated vulnerability indexes for this section range between 2 and 3. This is likely due to the high percentage of bogs and low percentage of fens in the surrounding basins. The vulnerability index increases from 2.75 south of Lawledge (KP 614.9) to 3 near Gillam (KP 524.8).

This section of the railway has also been the study area for previous investigations addressing drainage and water management along the HBR. EBA Consultant Ltd (1989) investigated 145 km section of HBR from Gillam (KP 524.8) to McClintock (KP 711.7), with objectives including identifying areas where the railway grade obstructs natural drainage, assessing culverts and ditches, and proposing solutions to mitigate ponding issues. Their findings revealed that while culverts were generally effective in handling peak flows, issues such as permanent ponding, deterioration of ditches, and obstructions like beaver dams were identified.

Moreover, the HBR operators has championed over two decades of extensive studies on the nature of sinkholes and assessment of adaptation strategies to address degrading permafrost (e.g., thermosyphons). Their reports indicate that the extensive discontinuous permafrost region in this section of the railway (between Gillam and McClintock) is the most problematic segment of the HBR, and interviews with OmniTRAX personnel confirmed that this section remains the most problematic, depicting increasing structural instability (Addison et al 2015a; Addison et al 2016a; Addison et al 2016b).

Addison et al (2016b) compared number of track geometry exceptions with vegetation indices. They established a link between track quality and vegetation density to characterize permafrost degradation susceptibility along the railway. High track geometry exceptions correlated with thawing permafrost and low NDVI values, while low exceptions indicated permafrost absence. Also, photo surveys taken at the study site revealed that low NDVI does not only shows the typical interpretation of low vegetation density, but more importantly, indicate an accumulation of ponded water close to the embankment shoulders which can lead to permafrost degradation. Their results showed susceptibility to degradation, predicted at Kilometers 655 to 761, featured sparse vegetation, ponded water, and low NDVI, indicating active permafrost thawing and transition zones. This section includes the area with highest vulnerability in the recent map with the indexes equal or above 3.

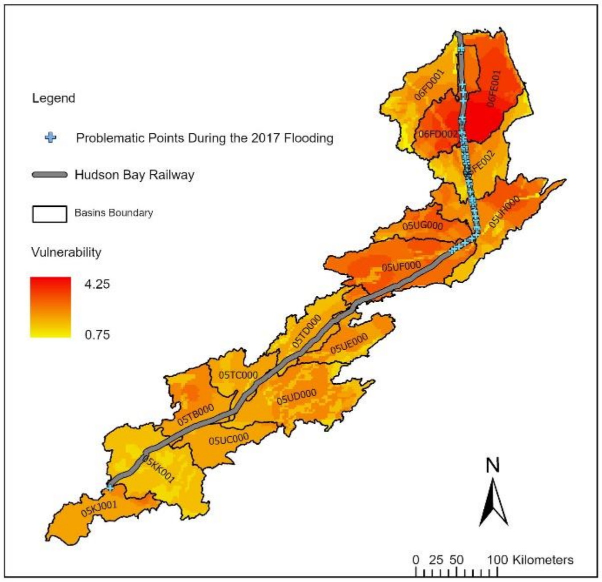

Figure 4. Washouts and unstable areas after 2017 flooding

Addison et al. (2015b) also examined fire history using satellite image analysis, revealing significant wildfires near the railway over the years. Fire removes the insulating organic layer of permafrost, exposing mineral soil, leading to increased active layer depth and subsidence. Temperature data from Landsat 5 TM band-6 detected a total of 18 wildfire events in the vicinity of the HBR between 1984 and 2010, notably including a significant fire in July 2003 that impacted the railway section between KP 606.7 and KP 646.9. This highlights the susceptibility of the area to permafrost degradation triggered by forest fires. The vulnerability map generated in this study reveals varying vulnerability levels, ranging from 2.25 to 3, across the affected region with the higher vulnerability of 3 in the first 10 kilometers south of Lawledge (KP 614.9).

6 CONCLUSION

The gradual thaw settlement of subgrade permafrost, recurrent sinkholes, and recent flooding events underscore the imperative to better understand the Hudson Bay Railway's vulnerability to natural hazards and climate change impacts. This study implemented ArcGIS Pro to develop a flood vulnerability map, considering key factors affecting runoff, including land cover types (such as fen and bog), drainage density, and ground ice distribution. By superimposing these layers with equal weights, the vulnerability map identified a higher vulnerability in the northern track sections compared to the southern parts, emphasizing the need for focused flood risk assessment, particularly between O'Day (KP 685.9) and Belcher (KP 725.8). When compared to historical flood data and previous studies on thaw settlement and permafrost degradation, specific sections were highlighted, particularly between kilometers 655 to 761 and 606.7 to 614.9.

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