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Groundwater vulnerability in the Yukon and Northwest Territories, Canada

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Abstract

Groundwater is a valuable resource in northern Canada, which is used as a primary drinking water source for many residents and ensures the health of ecosystems. However, no groundwater vulnerability assessment methods have been specifically developed for these cold regions. The extreme seasonal climate and frozen ground conditions present unique challenges in assessing groundwater and well vulnerability. Climate warming and permafrost thaw, population density, contaminant threats, and Indigenous knowledge are key features to integrate within adapted assessment approaches.

Introduction

Groundwater is a valuable resource in northern Canada (Fig. 1). In addition to its use as a primary source of drinking water, groundwater plays an important role in the health of ecosystems. In the Yukon, 97% of the population has access to groundwater as a domestic water source (Yukon Government, 2017). However, access to potable water can be problematic, particularly for Indigenous communities due to inadequate infrastructure and/or a perception of poor water quality (e.g., Ratelle et al., 2022). Access to potable water is further complicated as water demands are higher in some regions. For example, the average daily residential use per capita is 385 L/day in the Yukon, versus a Canadian average of 215 L/day (Statistics Canada, 2019), likely due in part to the need to use recirculating pumps or bleeders in winter to prevent pipes from freezing in communities such as Dawson City (Tetra Tech, 2017b). While groundwater use in the Northwest Territories (NWT) is lower (only three communities or 3% of the population use wells; Northwest Territories Bureau of Statistics, 2020), the population relies heavily on clean groundwater to maintain healthy ecosystems, on which their traditional lifestyle depends.

Despite this groundwater reliance, methods for groundwater vulnerability assessment (broadly defined here as either aquifer or well susceptibility to contamination) have not been developed for this

type of cold regions setting. Most existing methods (e.g., DRASTIC – Aller et al., 1987; GOD – Foster, 1987; Aquifer Vulnerability Index – Van Stempvoort et al., 1992; Weights of Evidence – Sorichetta et al., 2011; Logistic Regression – Tesoriero and Voss, 1997; groundwater age via lumped parameter models – Eberts et al., 2012) have been developed in warmer southern regions, and the degree to which these methods are transferable to cold regions is poorly understood. This essay outlines issues related to groundwater vulnerability in cold regions and makes recommendations for future research and assessment.

Features related to groundwater vulnerability

Climate change and permafrost thaw may increase groundwater vulnerability in northern regions in the future. The Yukon and NWT experience the unique climatic conditions of long and very cold winters, including five to nine months with average air temperatures below 0 °C (Government of Canada, 2022a,b), snowfall as a substantial portion of total precipitation and recharge, and the occurrence of perennially frozen ground (permafrost) that can act as an aquitard to groundwater flow. Northern Canada is now experiencing rapid climate change, with warming at a rate of about two to three times the global average (IPCC, 2022; Zhang et al., 2019). As in other parts of the world, there is an expected intensification of the hydrological cycle because of changing climatic conditions (Box et al., 2019). The occurrence of more frequent large rainfall events could increase the potential for out-of-bank flows and episodic recharge events. As an example of intense conditions, earlier and more rapid melting of record snowpacks in recent years in the Yukon has caused high-water events in the Yukon River (and other surface water bodies), leading to increased microbial contamination threats to wells and triggering boil-water advisories in flooded downstream communities (e.g., Henney, 2022).

Permafrost thaw may have several indirect influences on groundwater vulnerability. As frozen ground within the shallow subsurface begins to thaw, the connectivity between surface water and

groundwater systems may increase (Lamontagne-Hallé et al., 2018), thus increasing solute transport rates (Mohammed et al., 2021) and potentially mobilizing previously isolated natural solutes (McKenzie et al., 2021), anthropogenic contaminants (Colombo et al., 2018), and organic carbon (Connolly et al., 2020; Mohammed et al., 2022). Elsewhere, naturally occurring geogenic contaminants (e.g., Uranium and Arsenic – Skierszkan et al., 2020; and Mercury – Schuster et al., 2018) could also become mobilized by permafrost thaw and travel to wells or surface water bodies used for drinking water. Further, researchers have speculated that groundwater availability and extraction in cold regions may increase as permafrost thaws (Cochand et al., 2019), highlighting the need for well vulnerability assessment methods capable of addressing northern conditions.

Contaminant threats in cold regions are dominated by petroleum hydrocarbons (Treasury Board of Canada Secretariat, 2021). Around 95% of the > 500 contamination incidents reported in the Yukon involve petroleum hydrocarbons (Yukon Government, 2022). Industries such as mining, and oil and gas development in northern regions represent particular contamination concerns. There are 105 legacy mine sites in NWT (Treasury Board of Canada Secretariat, 2021, 2022), suggesting the potential for local impacts on ecosystem health in many areas. About 72% of the contaminated sites in the Yukon are on or within 10 km of First Nations settlement lands (Yukon Government, 2015, 2022; Treasury Board of Canada Secretariat, 2021, 2022). Further, two of the four contaminated sites reported to have the highest financial liabilities in Canada in 2012 are in the territories (Faro Mine in the Yukon, and Giant Mine in NWT; Auditor General of Canada, 2012). The Yukon and NWT have a disproportionately high burden of contaminated site remediation costs per capita, compared to other Canadian jurisdictions (Fig. 2; ECCC, 2022; Government of Canada, 2021). Additional contaminants include geogenic metals and metalloids (Skierszkan et al., 2020) and pathogenic microbes (Roach et al., 1993; Tetra Tech, 2017a), though little research has addressed the latter topic.

Another threat to groundwater resources is contamination related to waste management for landfills, mine tailings, and sewage, which historically often relied on frozen soil associated with stable

permafrost rather than engineered liners to minimize the release of contaminants (e.g., INAC, 2007; Kent et al., 2003). Permafrost thaw due to climate change is opening subsurface flow pathways (McKenzie et al., 2021) and potentially exposing receptors to previously entombed waste. As in many other regions, but likely enhanced by climate change, microbial contamination threats represent an important concern for human health, especially where private wells are untreated and located near surface water features. Surface water is prominent within the landscape and communities are often located beside rivers or lakes. Groundwater flow systems related to wells are more likely to be shallow, "bank-filtration" type systems adjacent to surface water, in contrast to the more extensive and deeper aquifer sources exploited elsewhere in southern regions. For instance, aquifers used in the Yukon and NWT tend to be shallow, unconfined, fluvial and glaciofluvial, often in direct connection with surface water, and potentially in connection with adjacent bedrock aquifers (Tetra Tech, 2017b; Reid Crowther and Bernard, 1984). The potential for pathogenic microbes to enter the subsurface closer to wells than otherwise due to hydrological events (Wiebe et al., 2021), or be transported more rapidly due to higher soil permeability associated with permafrost thaw, and subsequently cause illness, may increase with flood frequency due to climate warming and associated glacier and permafrost thaw.

Discussion and recommendations

Northern regions have relatively sparse populations, and technical hydrogeology capacity, including monitoring infrastructure, is not broadly available when compared to respective southern regions (e.g., Canadian northern territories vs. southern provinces). This has an impact on the amount of hydrogeological data collected. Very few monitoring wells exist to provide groundwater level observations, water quality data, and estimates of subsurface properties, hindering understanding of groundwater flow systems. Therefore, it will be useful to adapt some easily implemented hydrogeology methods and tools. Vulnerability assessment typically requires a general understanding of regional and

local groundwater flow, such as identification of recharge areas and discharge areas. Conceptual diagrams related to Tóthian flow system analysis (Tóth, 1963) or flow nets (e.g., Freeze and Cherry, 1979) can generate an initial estimate where data are scarce. Such diagrams should be adapted to be regionally appropriate; permafrost (and permafrost thaw) should be included – for instance, as a low-permeability unit with different cases for evolving thickness and extent. Water-table depth estimates based on surface topography can be used to draw initial flow nets. A tentative understanding can be enhanced by the identification of types of information or borehole locations suitable for distinguishing between conceptual models (Ferré, 2017). In the relatively data-scarce context of northern Canada, simple vulnerability approaches should be attempted and updated as more data are collected.

Indirect methods such as geochemistry, geophysics, and remote sensing are useful for inferring groundwater flow, especially where site access and the collection of subsurface data are challenging. Geochemistry can integrate and extract hydrogeologic information in lieu of traditional groundwater methods. For example, Piper diagrams (e.g., Piper, 1944; Appelo and Postma, 2005) can be helpful in tracking groundwater mixing/evolution from different flow sources. Mixing and mass balance approaches can also elucidate groundwater exfiltration processes in cold regions (e.g., Lapp et al., 2017). Obtaining end member concentrations for different aquifer/aquitard units will be necessary to evaluate flow paths (e.g., Wicke, 2021). For example, distinct end members are necessary for the vulnerability method proposed by Meyzonnat et al. (2016), which has been applied in a glaciated watershed in Quebec with underlying sedimentary bedrock to map estimates of relative aquifer vulnerability. Geophysical techniques represent another category of indirect methods that can be useful for delineating permafrost presence and depth (Hubbard et al., 2013), as well as bedrock depths (Langston et al., 2011). Geochemical and geophysical data are often available from private industry, and any data related to groundwater should be accessed and/or made public whenever possible. Further, remote sensing can be used to infer groundwater flow. For example, Glass et al. (2021) used thermal and optical remote sensing

data to identify icings (aufeis), which are locations of winter groundwater discharge on river ice or at the land surface.

Groundwater vulnerability tools have been built around Western science. The integration of Indigenous knowledge would be highly beneficial in the development of northern methods. Hydrogeologists working in the north, like all natural scientists working in Canada, should take up the ten calls to action articulated by Wong et al. (2020). This includes valuing Indigenous knowledge on equal terms with Western scientific knowledge, an approach that has been framed as "Two-Eyed Seeing" (Bartlett et al., 2012; Wilson et al., 2019) and which is necessary to holistically assess northern groundwater vulnerability. Indigenous knowledge is critical for understanding and relating to the environment (e.g., Woo et al., 2007). Locations of bedrock outcrops or springs may assist conceptual flow system understanding (for instance, groundwater flow directions toward wells and streams) in a data-scarce environment. Indigenous knowledge systems tend to holistically consider climate, land, water, and human and natural ecosystems (Ban et al., 2018; Wilson et al., 2019; Woo et al., 2007), offering perspectives that could be integral to understanding groundwater flow systems (Rudolph, 2022) and vulnerability.

Groundwater in northern Canada is vulnerable because of many factors, including its importance for sustaining healthy ecosystems and communities that depend on it for drinking water, water distribution and waste disposal practices, frequent contamination occurrences in addition to natural resources industries, and the presence of permafrost and hydrogeological changes due to permafrost thaw. These factors, combined with the sparsity of data and the availability of technical hydrogeological expertise, highlight the necessity to develop groundwater vulnerability tools adapted for northern environments. Recommendations for groundwater vulnerability research in northern Canada include: 1) valuing both Indigenous knowledge and Western science; 2) employing indirect methods such as geochemistry, geophysics, and remote sensing to make inferences about groundwater flow systems; and

3) implementing simple and conceptual approaches while incorporating new data as they become available.

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Figures:

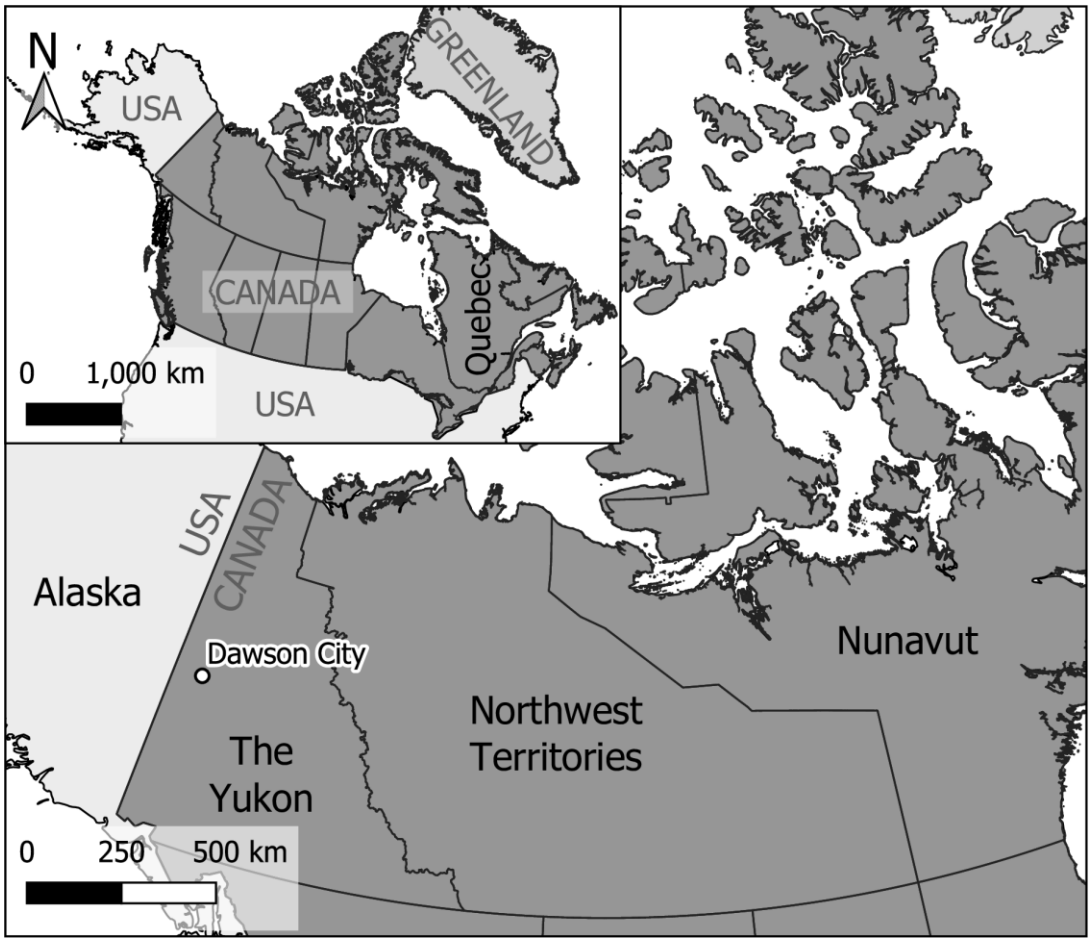


Fig. 1. Northern Canada (Sandvik, 2009; Statistics Canada, 2017).

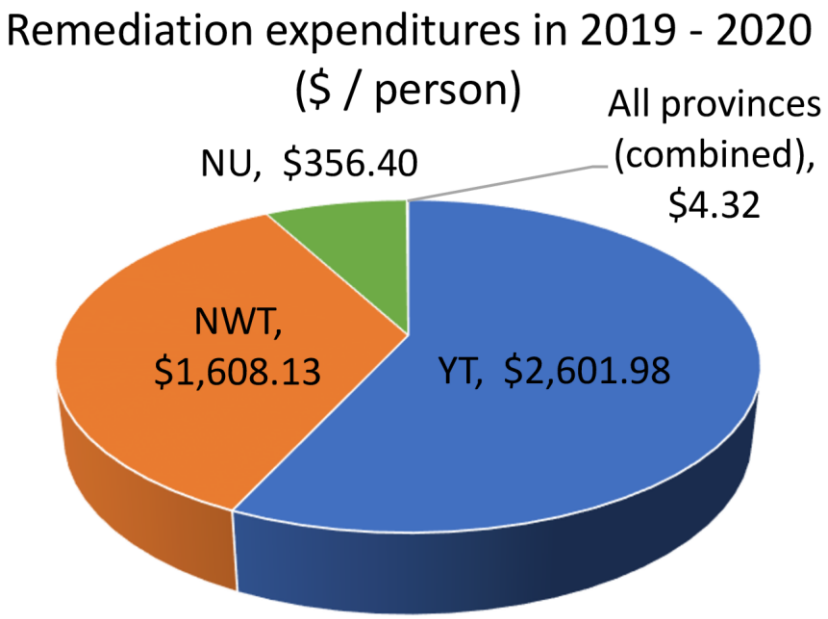


Fig. 2. Example of federal remediation expenditures per person for fiscal year 2019-2020 (ECCC, 2022; Government of Canada, 2021). Territory abbreviations: YT – the Yukon; NWT – Northwest Territories; and NU – Nunavut.