Capture zone uncertainty and the dynamics of well vulnerability as permafrost thaws – Whatì, NWT, Canada

Andrew J. Wiebe[1], Isabelle de Grandpré[2] & Jeffrey M. McKenzie[3]

[1]*Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, Ontario, Canada*

[2]*Water Monitoring and Stewardship Division, Government of Northwest Territories, Yellowknife, Northwest Territories, Canada*

[3]*Department of Earth and Planetary Sciences, McGill University, Montreal, Québec, Canada*

ABSTRACT

Thawing permafrost modifies the conditions of the ground and can impact groundwater connectivity, quantity, and quality. These changes may increase the contaminant threats to drinking water for communities relying on nearby production wells. This study evaluated possible changes in vulnerability for a community well in Whatì (Northwest Territories, Canada), located in a discontinuous permafrost region beside Lac La Martre, the third largest lake of the Northwest Territories. The community well was installed in a talik at a depth of around 12 m. Where present, the permafrost in the area is warm (> -2 °C) and can be found starting at depths between two and five meters. A two-dimensional analytical method was used to visualize possible theoretical well capture zones for a wedge-shaped aquifer representing the peninsula on which the community is located. Average well pumping rates and aquifer hydraulic conductivity values were employed. Two scenarios simulated stages of likely permafrost thaw based on observations within the community in the 1980s and 1990s and recent field studies at the edge of the community. Results indicate that the well capture zone may initially have underlain a portion of community but that it has likely expanded due to permafrost thaw, now possibly including areas of the land surface with previously unlikely contaminant threats such as more heating fuel storage tanks, the landfill, and wastewater disposal sites. This study highlights the importance of assessing the vulnerability of wells located in permafrost zones in the context of climate change.

1 INTRODUCTION

Permafrost thaw due to climate change may increase the active layer thickness as well as the number and the size of taliks in discontinuous permafrost, thereby enhancing groundwater recharge and flow. This thaw may also increase threats of contamination to groundwater wells in permafrost regions by increasing the connectivity between surface water bodies and groundwater supply aquifers (Lamontagne-Hallé et al. 2018), by eroding the protective low-permeability permafrost layer beneath unlined landfills (INAC 2007; Kent et al. 2003; Wiebe et al. 2023), and by decreasing subsurface travel times during which contaminants might biodegrade or disperse. Climate change is occurring at a rapid rate at northern latitudes (warming at two to three times the global average – IPCC 2022; Zhang et al. 2019) and discontinuous permafrost regions are especially susceptible to thaw and progressive degradation over time (e.g., Devoie et al. 2019).

The use of groundwater as a drinking water source varies across northern Canada from greater than 90% in the Yukon (Government of Yukon 2017) to around 3% in the Northwest Territories (NWT Bureau of Statistics 2022) to ~0% in Nunavut. Groundwater use for drinking water is also common in Alaska, providing around 40% of the combined public and domestic supply (Dieter et al. 2018). Groundwater may be more protected than surface water from certain types of contaminants, especially where there exist low-permeability layers such as clayey confining units or permafrost to limit vertical flow within the footprint of a community. Three communities in the Northwest Territories (NWT; i.e., Fort Liard, Nahanni Butte, and Whatì) have groundwater wells that supply drinking water, and all three are located in the discontinuous permafrost region (Heginbottom et al. 1995). In addition to issues related to permafrost thaw, northern communities may face groundwater management challenges such as limited knowledge regarding their groundwater resources, subsurface properties, permafrost extent, and contamination occurrences (e.g., spills of gasoline and diesel heating fuel). A typical groundwater management approach to protecting wells from contamination is to delineate each well's groundwater contribution area ("capture zone") and then take subsequent steps to safeguard water quality and recharge rates in these areas.

1.1 Well capture zones

Delineating a well capture zone involves estimating the region of the subsurface that contributes water to a well within a specified amount of time (e.g., several decades). The delineation ranges in complexity from a simple calculated fixed radius approach (if the regional water table is relatively flat; BCMOE 2000) to approaches that include regional flow via Darcy's Law (e.g., Ceric and Haitjema 2005) to fully distributed numerical models that account for detailed stratigraphic information and regional boundary conditions (e.g., HydroGeoSphere – Aquanty 2015; Yin 2023). Capture zone delineation in northern Canada is complicated by the fact that many communities are located adjacent to surface water bodies. These pose a challenge for simple approaches because such methods do not account for surface water features. The application of fully distributed, three-dimensional (3-D) models is not always

https://doi.org/10.52381/ICOP2024.204.1

feasible because of data requirements, modelling expertise availability, and the time required to construct a site-specific model and perform simulations. Analytical models capable of accounting for surface water features offer a middle road in terms of model development and complexity while maintaining rapid run times.

1.2 Study site

The community of Whatì, NWT, Canada (117’16”19.9°W, 63’8”38.3°N; Figure 1) has a population of approximately 550 people (NWT Bureau of Statistics 2022) and the community’s drinking water supply system consists of one production well screened in highly fractured dolostone bedrock (Stanley Associates 1987). The well is located near the tip of the peninsula on which the community is located, adjacent to Lac La Martre, the third largest lake in the NWT.

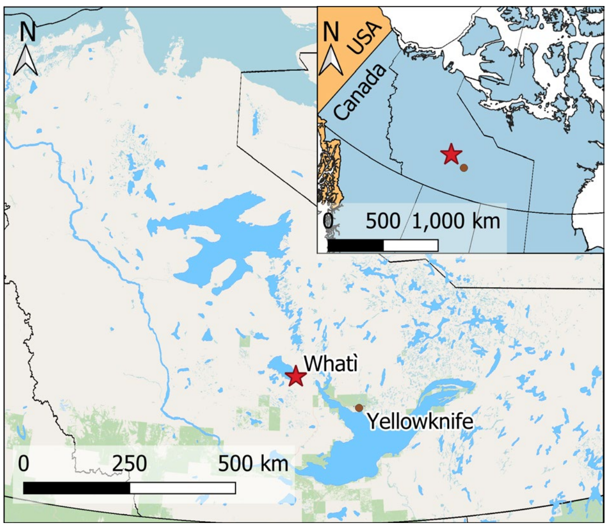

Figure 1. Location of Whatì, NWT (country boundaries: Sandvik 2009; province/territory boundaries: Government of Northwest Territories 2023; basemap: ©OpenStreetMap, 2023).

Whatì is located within a zone of discontinuous permafrost (Daly et al. 2022; Heginbottom et al. 1995), where permafrost is likely to be present in lower permeability soils underlying forests (Stantec 2017) and associated with low-lying peatlands or wetlands. Geotechnical studies (Hardy 1991; Thurber 1981) reported permafrost at depths between 2 and 5 m beneath the community in previous decades, while Daly et al. (2022) collected recent field data regarding permafrost presence or absence in areas largely outside the community (Figure 2). Permafrost thaw is evident from structural damage to some of the buildings within the community. It is likely that permafrost has thawed substantially due to climatic warming since measurements in the 1980s and 1990s.

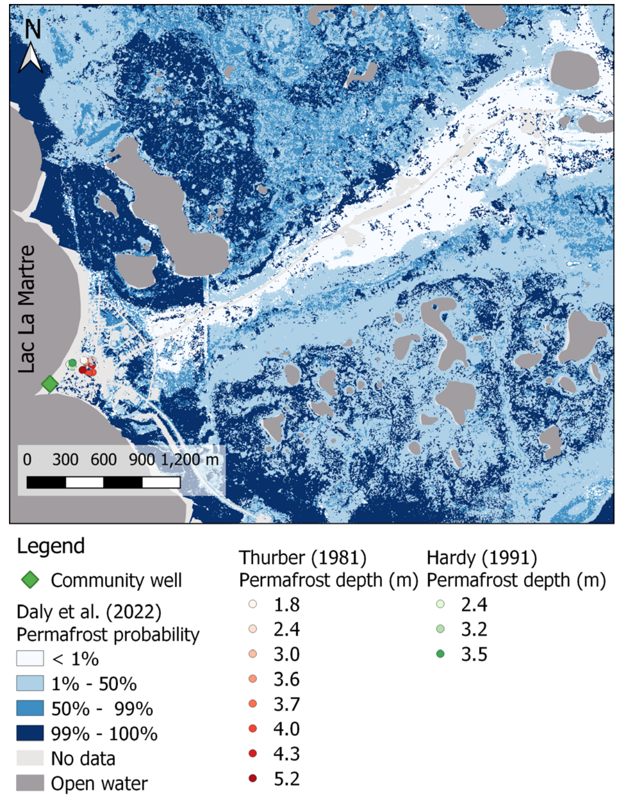

Figure 2. Estimates of permafrost presence (after Daly et al. 2022; S.V. Daly, pers. comm. 2023; Hardy 1991; Thurber 1981).

The local, near-surface geology of the Whatì area consists of glacial overburden and lacustrine sediments overlying dolostone bedrock, the upper surface of which is highly weathered and fractured (Reid Crowther and Bernard 1984). Bedrock has been encountered at depths of about 10 m in multiple boreholes within the community (Reid Crowther and Bernard 1984; Hardy 1991; Stanley Associates 1987; Thurber 1981). Till, lacustrine deposits, and organic deposits are present elsewhere nearby (Figure 3; Ednie et al. 2014).

The current conceptual model for groundwater flow at the site is that shallow, local flow is directed toward Lac La Martre from the upland area immediately east of the lake, but that deeper regional flow is toward the east. This is based on local scale (several hundred metres) and regional scale (tens of kilometres) topography. The land generally rises toward the east away from the lake for several kilometres, but there is a sharp decline in ground surface elevation of over 50 m near La Martre Falls (Natural Resources Canada 2017), which is located about 20 km east of Whatì. The relevant spatial scale of the flow system for the relatively small pumping rate at the community well is the local scale. The “regional” hydraulic gradient that is later discussed in association with the analytical solutions is in fact the shallow, local flow system discussed here.

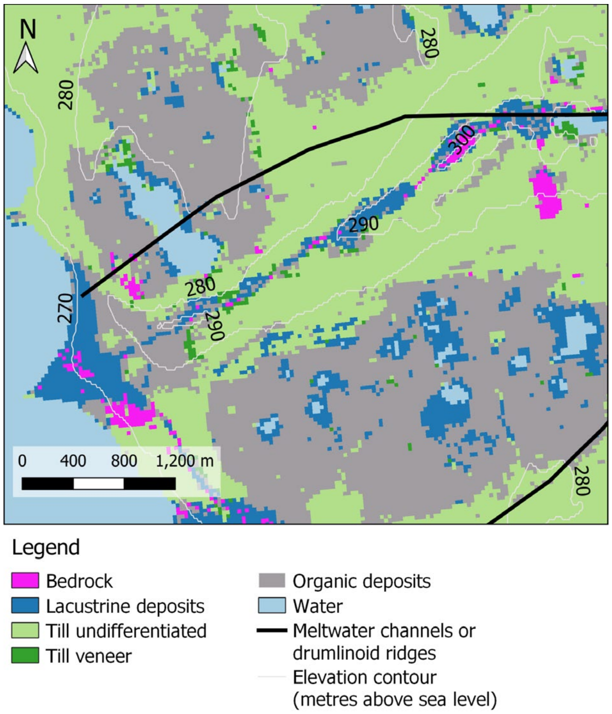

Figure 3. Surficial geology (after Ednie et al. 2014; Government of Canada 2017). The validity of the bedrock location predictions is unknown and may not be accurate for these predictions based on remote sensing.

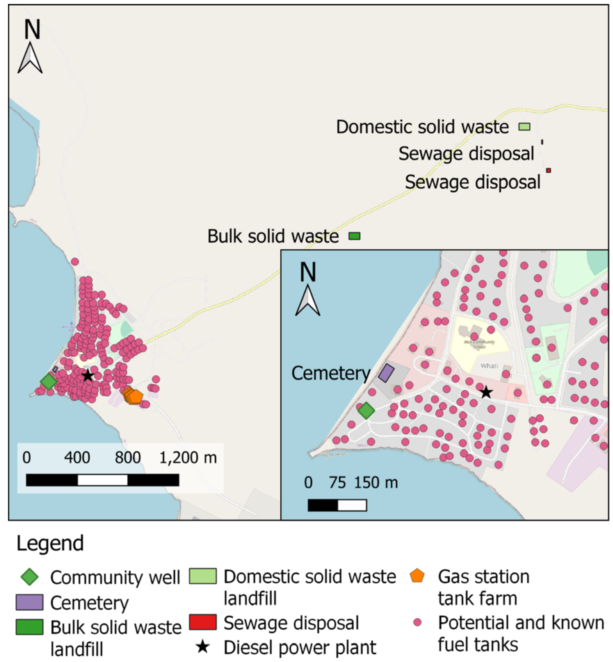

Figure 4. Potential contaminant sources (building locations and basemap: © OpenStreetMap 2023; solid waste disposal and sewage disposal locations: Community Government of Whatì 2017). Note: not all potential sources (fuel and wastewater tanks) may be identified at the eastern edge of the community.

Possible groundwater contaminants include petroleum hydrocarbons, landfill leachate, and wastewater. There is a diesel power plant within the community, and houses and buildings have fuel tanks for winter heating. The community's landfill locations are about 2 and 4 km NE from the well. Wastewater is stored in household tanks that are emptied regularly, and waste is transported by truck to a sewage lagoon that is about 4 km from the well (Community Government of Whatì 2017). Figure 4 shows the locations of potential contaminant sources. Each building on the map was assumed to have associated heating fuel and wastewater tanks.

The Whatì production well is located about 30 m from the lake and screened in fractured dolostone over an effective interval from 10.35 m to 12.77 m below ground surface (Stanley Associates 1987). A 24-hour pumping test by Stanley Associates (1987) at this well yielded a transmissivity estimate of 0.19 m^2/s, but a Cooper-Jacob composite analysis using the pumping test data from Stanley Associates (1987) for the production, test, and standby wells yielded a transmissivity of 0.15 m^2/s. The latter suggests a hydraulic conductivity of about 0.017 m/s, assuming an initial saturated aquifer thickness of 9 m.

1.3 Objectives

The objectives of this study are to investigate how the capture zone of the Whatì community well might change in response to progressive permafrost thaw, and whether this might increase threats to well water quality. Capture zone boundaries are calculated using an analytical approach that approximates constant head boundary conditions based on an imposed gradient. Threats to water quality are evaluated based on known potential sources of contamination within the community. The present study builds on unpublished work by the authors regarding a groundwater vulnerability assessment for the community of Whatì that is based on discussions with community members and review of relevant literature and available data.

2 Methodology

2.1 Analytical capture zone calculations

A 2-D analytical method inspired by Nagheli et al. (2020) and similar to the one by Holzbecher (2005) was used to estimate capture zone boundaries for the Whatì community well under steady-state conditions for two snapshots of permafrost thaw evolution. A 3-D numerical model was not used to estimate capture zones because uncertainty in the stratigraphy and boundary conditions due to data availability would greatly exceed the complex model's usefulness. Hydraulic heads have not been reported except in the immediate vicinity of the community well during initial aquifer tests (Stanley Associates 1987). The analytical method has the advantages of having short run-times and incorporating surface water features that can reasonably be represented as constant hydraulic head boundaries. The method is briefly outlined as follows.

A wedge aquifer shape was selected to represent the peninsula on which the community of Whatì is located. Parameters such as the saturated thickness and hydraulic conductivity of the aquifer underlying the community were obtained from borehole logs and pumping tests, respectively (Stanley Associates 1987). Hypothetical values were specified for the magnitude and direction of the regional hydraulic gradient because of insufficient data (discussed below). The location of the frozen/unfrozen soil interface was specified as explained below. The x and y axes of the coordinate system were rotated from east and north, respectively, to match the geometry of the Whatì peninsula more closely.

The method employed used image well theory (Strack 1989) and the complex potential for a system consisting of multiple wells and a regional gradient within a homogeneous unconfined aquifer with defined hydraulic conductivity. Superposition of the potentials related to recharge, a regional gradient, and real and image wells was accomplished by adapting the solution of Holzbecher (2005) for two-dimensional groundwater flow in the presence of two isopotential lines (lake shorelines, here) at an angle α, resulting in Eq. 1:

$$\Phi(z) = \Phi_{rech}(z) - (Q_{x0} - iQ_{y0})\,z + (Q_{well}/2\pi)\,[\ln(z^{\pi/\alpha} - z_{well}^{\pi/\alpha}) - \ln(z^{\pi/\alpha} - \mathrm{conj}(z_{well})^{\pi/\alpha}) - \ln(z^{\pi/\alpha} - z_{pf}^{\pi/\alpha}) - \ln(z^{\pi/\alpha} - \mathrm{conj}(z_{pf})^{\pi/\alpha})], \quad [1]$$

where $\Phi(z)$ is the complex discharge potential, z is the complex coordinate, $\Phi_{rech}(z)$ is the potential related to uniform recharge, $-(Q_{x0} - iQ_{y0})z$ is the complex potential for uniform flow related to the regional gradient (Strack 1989), Q_{well} is the pumping rate of the well, z_{well} specifies the real and imaginary coordinates of the well, $conj(z)$ is the complex conjugate of z, and z_{pf} specifies the coordinates for an optional image well (extraction) that enforces the permafrost boundary on the upland side of the aquifer. The image well was determined (through trial and error) to be located at a distance from the real well of 4 times the perpendicular distance between that well and the permafrost boundary line, along that line. Q_{x0} and Q_{y0} are the x and y- flow components per unit aquifer width, where Q_{x0} was calculated via Eq. 2 (Strack 2017):

$$Q_{x0}(z) = -\partial\Phi(z)/\partial x \approx -\Delta\Phi_{j,k}/\Delta x = -K(h^2_{j,k+1} - h^2_{j,k})/(2\Delta x), \quad [2]$$

where K is the hydraulic conductivity, h is the hydraulic head, and (j,k) specifies the cell coordinates – (imaginary, real) = (row, column). Q_{y0} was calculated similarly, except that the difference was between squared heads in adjacent rows rather than columns. The domain was divided into 0.5 m by 0.5 m grid cells for the calculations ($\Delta x = \Delta y$). Recharge was incorporated by solving the Poisson equation ($\nabla^2\Phi = -b$; e.g., Strack 2017) to represent shallow unconfined flow with a uniform recharge rate of b (50 mm/yr). This was accomplished using a numerical technique outlined by Barba and Forsyth (2017) to solve for the complex discharge potential at each cell within the wedge-shaped aquifer, with boundary conditions specifying a potential of zero along and outside the lake boundaries, and potential values at the inland edges of the aquifer set to adjacent values. Discharge potential for each grid cell (j,k) was calculated iteratively via Eq. 3 (Barba and Forsyth 2017):

$$\Phi^t_{j,k} = (2[\Delta x^2 + \Delta y^2])^{-1}([\Phi^t_{j+1,k} + \Phi^t_{j-1,k}]\Delta y^2 + ([\Phi^t_{j,k+1} + \Phi^t_{j,k-1}]\Delta x^2 - b^t_{j,k}\Delta x^2\Delta y^2) \quad [3]$$

where t is the timestep, and $b^t_{j,k}$ is the recharge rate (uniform in time and space, here). A total of 100 timesteps were employed to calculate the potential related to recharge.

Cubic Hermite interpolation (Van Loan 2000) was used to create a background regional flow field (in the absence of pumping and recharge) by specifying the gradient of the water table as zero at the lake boundaries and as a fixed vector at points along a radius of 1000 m from the peninsula tip. The resulting background flow field (Figure 5) was used for all simulations. Locations along curves starting at points along a radius of 1000 m from the origin that terminated at the lake boundaries, and associated hydraulic head values, were calculated for 21 splines, with one as the centreline bisecting the peninsula, and the other ten pairs of curves mirrored across it (Figure 5). Head values along the outer arc were also calculated with a spline. The head values were interpolated across the grid, subsampled, and then smoothed with a cubic interpolation method. The head values in adjacent cells were used to calculate Q_{x0} via Eq. 2, and Q_{y0} via an analogous equation.

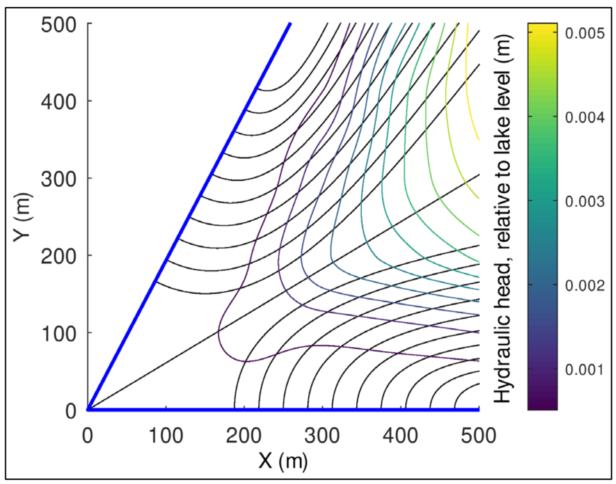

Figure 5. Contour map of background regional flow field hydraulic head (water table). The blue lines are the lake boundaries, and the black lines indicate the splines used to calculate the hydraulic head values.

A sequential contouring approach (Holzbecher 2018) was used to line up the streamlines on either side of a branch cut resulting from the discontinuity in the complex logarithm of the solution. Streamlines along the branch cut were manually removed in QGIS. Stagnation points were identified using a gradient ascent method search of the *real(Φ(z))* field. Hydraulic heads, $h_{j,k}$, were calculated from the complex potential via Eq. 4 (Strack 2017):

$$h_{j,k} = \text{sqrt}(\ 2\ [\text{real}(\Phi_{j,k}) - C_u]\ /\ K), \qquad [4]$$

where K is the hydraulic conductivity and C_u is a constant (a negative C_u was used to ensure real values of $h_{j,k}$). The sequential contouring step was performed using a modified version of the R (R Core Team 2022) code by Wiebe and McKenzie (2022). The remainder of the method was coded in the scientific computation program GNU Octave (Eaton et al. 2020). All code is available at https://github.com/ajwiebe77/ICOP24.

2.2 Scenario analysis

Two scenarios were employed to assess the changes in capture zone size and shape for the community at Whatì based on hypothesized locations of the interface between frozen and unfrozen soil beneath the community. Scenario 1 assumed that the presence of the interface was located 500 m away from the community well along the two arms of the wedge-shaped aquifer. This scenario sought to represent the interface as a continuous no-flow line, whereas the actual situation is likely more complex because of the discontinuous nature of the permafrost. The location of the permafrost boundary was based loosely on the results of Thurber (1981) and Hardy (1991) and represents conditions where unfrozen soil is present only near the tip of the peninsula. Both scenarios assumed regional flow toward the tip of the peninsula, with a tapering of the slope of the water table to zero at the lake boundaries (Figure 5).

Scenario 2 assumed no permafrost presence and simply employed a semi-infinite boundary along the third side of the wedge. This second scenario represents complete permafrost thaw at some point in the future, or at least such extensive thaw that permafrost does not represent a major barrier to groundwater flow. Table 1 lists the parameters employed during the scenario analysis.

3 Results

Figure 6 shows the results of Scenario 1, which assumed a permafrost boundary located at x = 500 m. The groundwater flow lines are essentially perpendicular to the lake boundaries, as expected for constant head lines. One flow line unrealistically shows flow from the lake around the outside of the capture zone, which is a byproduct of the image well used to represent the permafrost interface. The results visualize that the capture zone for the Whatì production well may initially have encompassed only part of the community footprint. Permafrost may thus have provided some initial protection to the well in terms of potential contamination by limiting the region from which groundwater recharge could convey pollutants, although the cemetery and approximately 50 heating fuel and wastewater tanks are within the capture zone.

Table 1. Summary of capture zone simulation parameters.

Parameter	Scenario 1	Scenario 2
Pumping rate, Q_{well} (L/s)	0.59*	0.59*
Hydraulic conductivity, K (m/s)	0.017	0.017
Saturated aquifer thickness (m)	9†	9†
Magnitude of regional gradient at radius of 1000 m (m/m)	1×10^{-5}	1×10^{-5}
Direction of regional gradient (° clockwise from north; after shape rotation)	246	246
Aquifer radius from well or distance to permafrost along x-axis (m)	500‡	500
Aquifer angle at point of peninsula (°)	63	63
Aquifer rotation angle to align x-axis with south side of peninsula (° counterclockwise from east)	-7	-7
Boundary type on inland side of aquifer	Impermeable	Semi-infinite

* Based on Community Government of Whatì (2021).
† Based roughly on Stanley Associates (1987).
‡ Based on Thurber (1981) and Hardy (1991).

Figure 7 shows the results of Scenario 2, which assumed no permafrost. The results suggest a larger capture zone area that extends throughout the aquifer wedge and beyond the 500 m radius of the calculation region. Most of the heating fuel and wastewater tanks in the community could potentially be within the well capture zone, in addition to the cemetery and the diesel power plant, although groundwater would be expected to flow into the lake rather than toward the well near shoreline areas at some point beyond the 500 m radius shown. The sewage lagoon and landfill are located outside of the community toward the east and may possibly also be within the capture zone for Scenario 2, although groundwater flow directions may be more nuanced with flow toward wetland areas south of these features rather than directly toward the peninsula.

4 Discussion

The results visualize an expansion of the capture zone as permafrost thaws. The diesel power plant is likely within the long term (no permafrost) capture zone, although it is uncertain whether the gas station tank farm is likely to be because of expected flow toward the lake farther from the well and near the shoreline. Additional data such as hydraulic head measurements would improve the analysis.

Limitations of the study include: 1) the use of steady-state snapshots instead of transient scenarios to explore changes in the capture zone, 2) the representation of permafrost as an impermeable region of the subsurface, 3) assumptions of homogeneous aquifer conditions and fully penetrating wells, 4) the assumption that the surface water boundaries continue beyond the calculation domain, 5) unknown bedrock topography, and 6) neglect of dispersion. Despite the capture zone illustrated for Scenario 1, overland flow downslope toward the lake or supra-permafrost groundwater flow within the active layer could convey contaminants from outside the estimated capture zone into the contributing recharge area. In terms of representing permafrost as an impermeable boundary resulting from an image well, this approach failed to generate a truly impermeable boundary because of the regional gradient, and conceptually does not incorporate the discontinuous nature of local permafrost. It is therefore somewhat unrealistic but conceptualizes the likely initial capture zone as restricted to the unfrozen region. The assumptions of the analytical approach limit the investigation to simplistic scenarios.

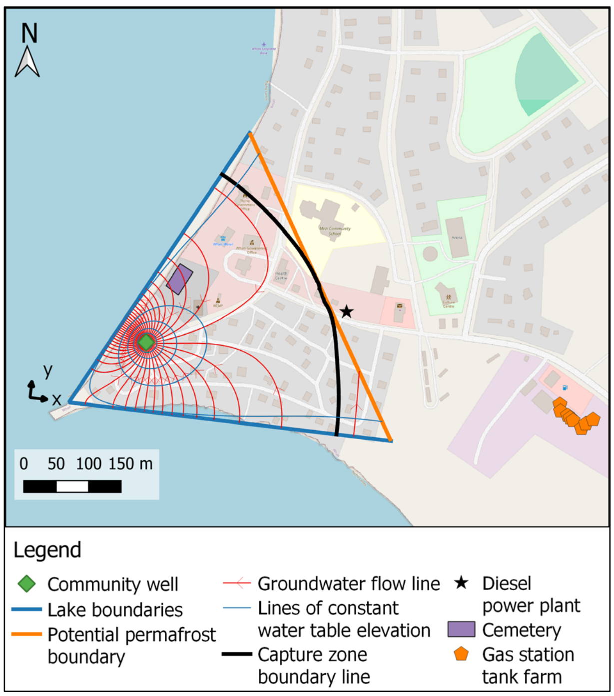

Figure 6. Possible steady-state capture zone for Scenario 1 (basemap: © OpenStreetMap 2023; well location: Stanley Associates 1987). Head contour interval (water table): 2×10^{-5} m; flow line contour interval: 1.31×10^{-5} m^3/s. The capture zone is present throughout nearly the entire unfrozen region of the peninsula.

Despite the limitations listed above, analytical solutions offer certain advantages to capture zone estimates for northern regions. Many wells in northern regions are located near surface water features, and permafrost boundaries may exist near some of these wells. The ability to incorporate surface water and permafrost features represents a distinct advantage over simpler capture zone estimation methods, and the rapid run times and ability to test different parameter combinations quickly has advantages over fully distributed, process-based models.

Analytical approaches could be helpful in assessing possible climate change impacts on well capture zones if boundary conditions can be represented reasonably.

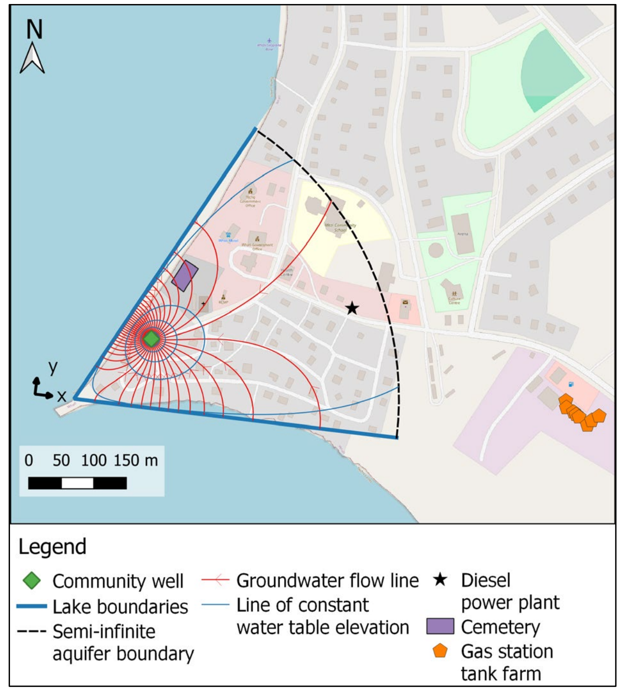

Figure 7. Possible steady-state groundwater flow lines and equipotential lines for Scenario 2 (basemap: © OpenStreetMap 2023; well location: Stanley Associates 1987). Head contour interval: 2×10^{-5} m; flow line contour interval: 1.31×10^{-5} m^3/s. No capture zone boundary is present within the calculation region and the capture zone extends from the peninsula toward the east.

5 CONCLUSIONS

The analytical simulations visualize the evolution of the capture zone shape and area for the Whatì community well over time due to permafrost thaw. The initial capture zone around the 1990s was likely small in extent and confined to the unfrozen region near the tip of the peninsula, due to the presence of permafrost within several hundred metres of the well. Such a capture zone would include multiple household fuel and wastewater tanks but not the diesel power plant, nor the gasoline tank farm, landfill, or sewage lagoon. If permafrost thaws completely, the capture zone could expand to include a larger area and many more potential contaminant sources. Additional data from an observation well network would assist vulnerability assessment and constrain the uncertainty, especially regarding groundwater flow near the lake shoreline. Analytical solutions may offer a relevant approach to estimate capture zones for other wells near surface water features and permafrost in northern regions in the context of climate change, but special care must be taken when representing boundary conditions.

6 ACKNOWLEDGEMENTS

Funding from the Canada First Research Excellence Fund (CFREF) Global Water Futures (GWF) program is gratefully acknowledged. The authors wish to thank the Elders, translator, and other community members from Whatì who participated in the 2022 *What's Happening Under the Land?* workshop. S.V. Daly kindly shared GIS files for the permafrost probability map.

7 REFERENCES

Aquanty Inc. (Aquanty). 2015. *HGS Reference Manual. Manual for HydroGeoSphere code*. Waterloo, Ontario, Canada: Aquanty, Inc. Available at: https://www.aquanty.com/ (Accessed: 12 February 2018).

Barba, L.A. and Forsyth, G.F. 2017. *12 Steps to Navier-Stokes*. Available at: https://nbviewer.org/github/barbagroup/CFDPython/blob/master/lessons/13_Step_10.ipynb (Accessed: 3 January 2024).

British Columbia Ministry of the Environment (BCMOE) 2000. *Well Protection Toolkit. Step 2: Define the Well Protection Area*. Available at: http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/wells/well_protection/wellprotect.html (Accessed: 22 July 2021).

Ceric, A. and Haitjema, H. 2005. 'On using simple time-of-travel capture zone delineation methods', *Groundwater* 43(3), pp. 408–412. doi:10.1111/j.1745-6584.2005.0035.x.

Community Government of Whatì 2017. *Sewage Disposal: Operation and Maintenance Manual, Version 1.1*. Whatì, Northwest Territories, Canada: Community Government of Whatì, Updated 26 June 2017. Available at: https://mvlwb.com/registry/W2017L3-0002 (Accessed: 7 July 2023).

Community Government of Whatì 2021. *Municipal water licence annual report. Reporting Year: 2020*. Whatì, Northwest Territories, Canada: Community Government of Whatì, Updated 16 Aug 2021. Available at: https://mvlwb.com/registry/W2017L3-0002 (Accessed: 6 March 2023).

Daly, S.V., Bonnaventure, P.P., and Kochtitzky, W. 2022. 'Influence of ecosystem and disturbance on near-surface permafrost distribution, Whatì, Northwest Territories, Canada'. *Permafrost and Periglacial Processes* 33(4), pp. 339–352. doi:10.1002/ppp.2160.

Devoie, E.G., Craig, J.R., Connon, R.F., and Quinton, W.L. 2019. 'Taliks: A tipping point in discontinuous permafrost degradation in peatlands', *Water Resources Research* 55, pp. 9838–9857. doi:10.1029/2018WR024488.

Dieter, C.A., Maupin, M.A., Caldwell, R.R., Harris, M.A., Ivahnenko, T.I., Lovelace, J.K., Barber, N.L., and Linsey, K.S. 2018. 'Estimated use of water in the United States in 2015', *United States Geological Survey* US Geological Survey Circular 1441.doi:10.3133/cir1441.

Eaton, J.W., Bateman, D., Hauberg, S., and Wehbring, R., 2020. *GNU Octave version 6.4.0 manual: A high-level interactive language for numerical computations*. Available at: https://docs.octave.org/v6.4.0/index.html (Accessed: 3 Jan 2024).

Ednie, M., Kerr, D.E., Olthof, I., Wolfe, S.A., and Eagles, S. 2014. 'Predictive Surficial Geology derived from LANDSAT 7, Marian River, NTS 85-N, Northwest Territories', *Geological Survey of Canada* Open File 7543, zip file. doi:10.4095/294923.

Government of Canada 2017. *Elevation in Canada - CanVec Series - Elevation Features*. Available at: https://open.canada.ca/data/en/dataset/64aad38d-f692-4ab6-bf2c-f938586c1249 (Accessed: 11 August 2021).

Government of Northwest Territories 2023. *Provincial Admin. Accessed within QGIS 3.16.9*. Available at: https://www.apps.geomatics.gov.nt.ca/arcgis/services/GNWT_Basemaps/GNWTBasemapLCC/MapServer/WMSServer.

Government of Yukon 2017. *Yukon Observation Well Network: 2017 Report*. Available at: https://yukon.ca/en/yukon-observation-well-network-2017-report (Accessed: 3 August 2023).

Hardy BBT Ltd. (Hardy) 1991. *Geotechnical investigation: Proposed Community Office, Lac La Martre, NWT*. Yellowknife, Northwest Territories, Canada: Government of Northwest Territories Department of Public Works, Architectural Division, March 1991.

Heginbottom, J.A., Dubreuil, M.A., and Harker, P.T. 1995. 'Canada, permafrost', in *The National Atlas of Canada, 5th edition*. Natural Resources Canada, Geomatics Canada, MCR 4177, 1 sheet. doi:10.4095/294672.

Holzbecher, E. 2005. 'Analytical solution for two-dimensional groundwater flow in presence of two isopotential lines', *Water Resources Research* 41, W12502. doi:10.1029/2005WR004583.

Holzbecher, E. 2018. 'Streamline visualization of potential flow with branch cuts, with applications to groundwater', *Journal of Flow Visualization and Image Processing* 25(2), pp. 119–144. doi:10.1615/JFlowVisImageProc.2018025918.

Indian and Northern Affairs Canada (INAC) 2007. *Giant Mine remediation plan.*, Yellowknife, Northwest Territories, Canada: Department of Indian Affairs and Northern Development Giant Mine Remediation Project, 260 p. Available at: http://reviewboard.ca/upload/project_document/EA0809-001_Giant_Mine_Remediation_Plan_1328900464.pdf (Accessed: 14 November 2022).

Intergovernmental Panel on Climate Change (IPCC) 2022. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Cambridge, United Kingdom and New York, New York, United States: Cambridge University Press, 755 p. doi:10.1017/9781009157964.

Kent, R., Marshall, P., and Hawke, L. 2003. *Background report for updating the guidelines for the planning, design, operations and maintenance of modified solid waste sites in the Northwest Territories*. Yellowknife, Northwest Territories, Canada: Department of Municipal and Community Affairs, Government of the Northwest Territories, prepared by FSC Architects & Engineers. Available at: https://www.enr.gov.nt.ca/sites/enr/files/reports/background_updating_the_solidwaste_guidelines.pdf (Accessed: 14 November 2022).

Lamontagne-Hallé, P., McKenzie, J.M., Kurylyk, B.L., and Zipper, S.C. 2018. 'Changing groundwater discharge dynamics in permafrost regions', *Environmental Research Letters* 13, 0840017. doi:10.1088/1748-9326/aad404.

Nagheli, S., Samani, N., and Barry, D.A. 2020. 'Capture zone models of a multi-well system in aquifers bounded with regular and irregular inflow boundaries', *Journal Hydrology X* 7, 100053. doi:10.1016/j.hydroa.2020.100053.

Natural Resources Canada 2017. *CanVec Elevation Features*. Available at: https://atlas.gc.ca/toporama/en/index.html (Accessed: 7 January 2023).

Northwest Territories (NWT) Bureau of Statistics 2022. *Population Estimates By Community*. Available at: https://www.statsnwt.ca/population/population-estimates/bycommunity.php (Accessed: 20 July 2023).

OpenStreetMap 2023. *Basemap*. Accessed within QGIS 3.1.2 software. Data available under Open Database License https://www.openstreetmap.org/copyright.

R Core Team 2022. *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Available at: https://www.R-project.org/ (Accessed: 17 March 2022).

Reid Crowther & Partners Ltd., and D.W. Bernard Groundwater Consultants Ltd. (Reid Crowther and Bernard) 1984. *Groundwater Exploration and Well Development Study - 4 Communities in Fort Smith Region, N.W.T.* Yellowknife, Northwest Territories, Canada: Department of Local Governments, Government of the Northwest Territories, March 1984.

Sandvik, B. 2009. *World borders dataset*. GIS digital mapping data. Available at: http://thematicmapping.org/downloads/world_borders.php (Accessed: 27 June 2022).

Stanley Associates Engineering Ltd. (Stanley Associates) 1987. *Lac La Martre - Well Construction, Draft Report*. Yellowknife, Northwest Territories, Canada: Government of Northwest Territories, Engineering Division, Department of Public Works and Highways, 23 March 1987.

Stantec Consulting Ltd. (Stantec) 2017. *Geotechnical report, road alignment, proposed Tlicho all-season road, Northwest Territories*. Ottawa, Ontario, Canada: Tlicho Engineering and Environmental Services Ltd., 10 November 2017.

Strack O.D.L. 1989. *Groundwater Mechanics*. Englewood Cliffs, New Jersey, United States: Prentice-Hall.

Strack, O.D.L. 2017. *Analytical groundwater mechanics*. Cambridge, United Kingdom: Cambridge University Press. doi:10.1017/9781316563144.

Thurber Consultants Ltd. (Thurber) 1981. *Lac La Martre School: Geotechnical Investigation*. Edmonton, Alberta, Canada: Department of Public Works, Government of the Northwest Territories, 9 March 1981.

Van Loan, C.F. 2000. *Introduction to Scientific Computing*. 2nd Edition. Upper Saddle River, New Jersey, United States: Prentice-Hall.

Wiebe, A.J. and McKenzie, J.M. 2022. 'An Open-Source Web Tool for Visualizing Estimates of Well Capture Zones Near Surface Water Features', in *AGU Fall Meeting 2022,* Poster presentation. Chicago, Illinois, United States: 12–16 December 2022. doi:10.22541/essoar.167267811.10671930/v1.

Wiebe, A.J., McKenzie, J.M., Hamel, E., Rudolph, R., Mulligan, B., and de Grandpré, I. 2023. 'Groundwater vulnerability in the Yukon and Northwest Territories, Canada', *Hydrogeology Journal*. doi:10.1007/s10040-023-02720-8.

Yin, H. 2023. *Influence of Dynamic River Stage on the Vulnerability of Water Wells and Structure Foundations in Cold Regions*. Waterloo, Ontario, Canada: MSc. Thesis, University of Waterloo. Available at: http://hdl.handle.net/10012/19605.

Zhang, X., Flato, G., Kirchmeier-Young, M., Vincent, L., Wan, H., Wang, X., Rong, R., Fyfe, J., Lil, G., and Kharin, V.V. 2019. 'Changes in Temperature and Precipitation Across Canada', in E. Bush and D.S. Lemmen (eds), *Canada's Changing Climate Report*, pp 112–193. Available at: https://changingclimate.ca/CCCR2019/ (Accessed: 16 August 2023).