Groundwater Supply Vulnerability Assessment for Whatì (NWT)

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Plain Language Summary

Overview

In the Northwest Territories, only three communities (Fort Liard, Nahanni Butte, and Whatì) use groundwater as their drinking water supply, while the remainder of the territory's population uses surface water sources such as lakes or rivers. In Whatì, the community well was drilled in the late 1980s because the adjacent Lac La Martre was considered too shallow to be a secure community surface water supply source. The community well was drilled near the point of the peninsula on which the community is located, at about 30 m from the shoreline of Lac La Martre and at a depth of 10-13 m (**Figure A1**). The well water comes from highly fractured bedrock (dolostone), which allows for a high-water pumping rate. Permafrost in the area has been reported to be discontinuous and covers about 50% of the area, though the well was drilled in an unfrozen soil region.

Figure A1. Satellite imagery of Whatì showing the location of the water well and water treatment facility (red star) (© Google Earth, 2023).

What is the water quality of the well?

The bedrock where the well is located is composed mainly of calcium and magnesium. We can find these elements in great quantities in the well water, making the untreated water in the well drinkable but with poor aesthetic (taste, smell, and colour) qualities. Treatment of the water greatly improves the taste of the water before consumption.

Chemistry and isotope data from multiple sources, including Lac La Martre, surface water features in the region, and the community well, suggest that the well is capturing a mixture of surface water (mostly from Lac La Martre) and groundwater. While traveling through the ground, the mineral content of the water from the lake changes as minerals from the soils and rocks dissolve along the groundwater flow system. The ground also acts as a filter for bacteria and microbes that could be present in surface water, preventing them from reaching the well. This is why groundwater is often viewed as a safer drinking water source, as long as it reaches quality standards for dissolved minerals. The tap water has a very different mineral content that clearly shows the impact of treatment by water softening.

Where is the water in the well is coming from?

Chemistry and isotope data can help us define the groundwater pathways around Whatì. Generally, groundwater would be hypothesized to flow from higher ground to lower ground. For Whatì, this would mean that local shallow groundwater flow would occur from the higher ground east of the community towards the west (lake), with deeper regional flow occurring in the opposite direction (**Figure A2**). Discontinuous permafrost complicates this flow system idea by providing a no-flow region wherever present. The presence of the well also changes the local flow system by capturing groundwater from the surrounding area and drawing it into the well. In our case, the chemistry and isotope data show that the groundwater extracted by the well is partially coming from the lake, even if the lake is downstream from the well.

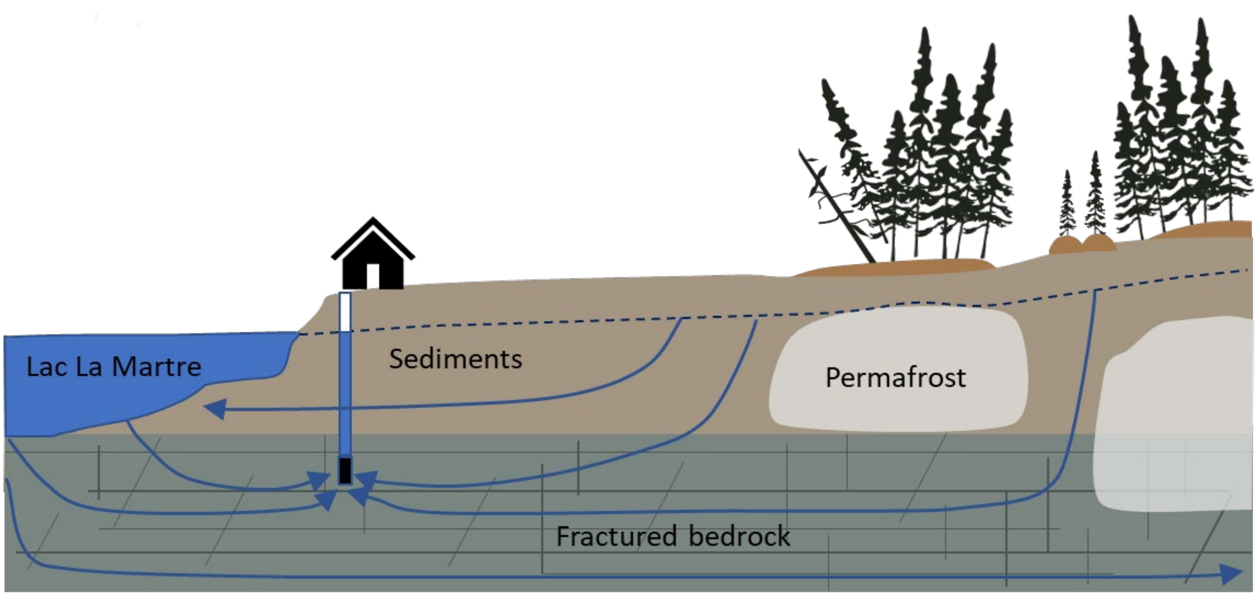

Figure A2. Conceptual model of groundwater flow directions (blue arrows) near Whatì (modified from Wright, 2022). The house represents the community of Whatì, the blue cylinder into the ground represents the community well and the black represents the well screen; finally, the blue dashed line represents the water table elevation (located at a depth of about 3 meters below ground surface).

What are the potential contamination sources for the water from the well?

While groundwater is often thought as being naturally protected and resilient, many elders in the community tend to distrust the treated groundwater from the community well based on its taste, colour, and the fact that pumping groundwater represents a change from traditional practices that was never fully explained to community members. Other community concerns for the water supply include the potential for contamination, the proximity of the cemetery to the well, and the extent to which permafrost degradation will occur and how this could impact water supply infrastructure.

The area around the well that supplies water to the well is referred to as the well capture zone. Two estimates were made of what the community well's capture zone area could look like. They suggest that the well may draw water from the lake and from under part of the peninsula where the community is located, though a better estimate of the locations and directions of fractures in the dolostone aquifer would be necessary to confirm the flow directions (**Figure A3**). Permafrost thaw may reduce how much lake water is drawn by the well and lead to more flow toward the well from the northeast, under the land (**Figure A4**).

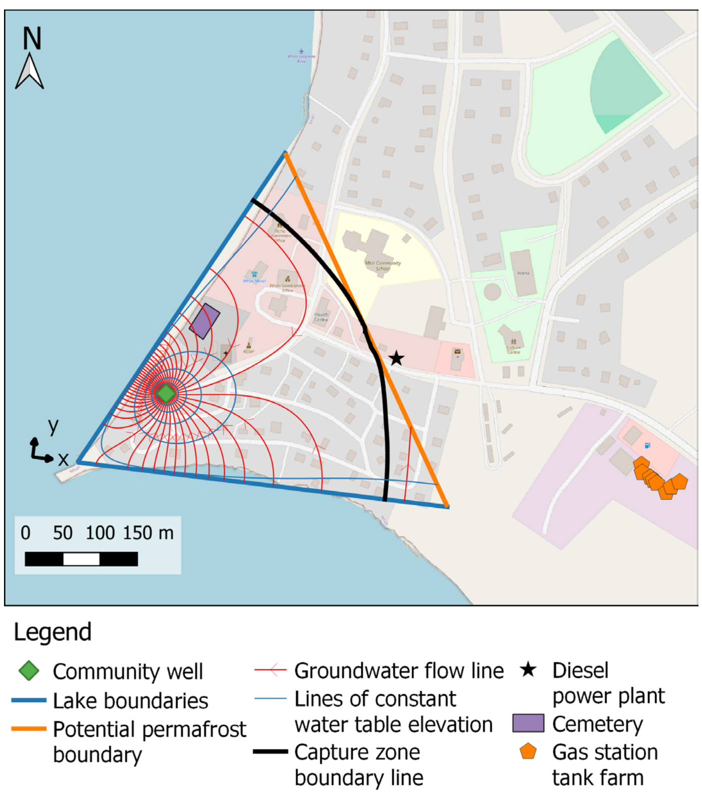

Figure A3. Possible current well capture zone and potential sources of contamination to the well water according to a probable scenario (© OpenStreetMap, 2023; Stanley Associates, 1987a; Wiebe *et al.*, 2024). Under this scenario, the capture zone is limited to the unfrozen region of the peninsula because of the presence of permafrost.

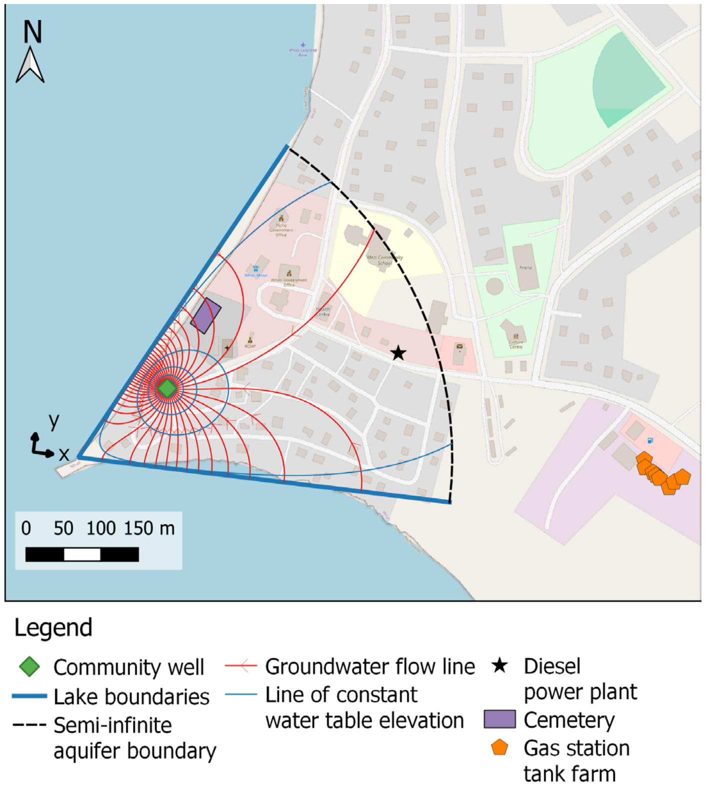

Figure A4. Possible future well capture zone and potential sources of contamination to the well water according to a probable future scenario where the permafrost is absent (© OpenStreetMap, 2023; Stanley Associates, 1987a; Wiebe *et al.*, 2024). Under these conditions, the capture zone extends from the peninsula toward the east.

According to the estimated well capture zones, some household heating fuel and wastewater tanks as well as the cemetery may have been potential threats to well water quality at first (**Figure A3**). However, as permafrost thaws and the capture zone size increases (**Figure A4**), other potential sources such as fuel spilling from the diesel power plant, more household heating fuel and wastewater tanks, and vehicle fuel likely represent the main threats to well water quality. It is also possible that a change in the water quality of Lac La Martre due to climate change could have an impact on the water quality of the well, but with lesser magnitude. In terms of water quantity, the well is screened in a highly productive aquifer that could likely support up to 800 people or more at the maximum pumping rate, with its current construction and average NWT or local per person water use.

Recommendations

The community well appears to be a relatively secure water supply for the near future, but three recommendations were made to improve the resilience and trust of the drinking water supply:

1. **Continue learning about groundwater and permafrost**
   Better knowledge of the bedrock properties, permafrost distribution, and groundwater levels across the community will better define the well's capture zone and could assist with answering the question of whether the cemetery is a potential contamination source, and will improve understanding of the impacts of permafrost degradation on the well water.

2. **Improve trust in the well water for drinking water**
   There is a level of distrust of the taste and colour of the water among some community members. Further conversations and illustrations of the story of how groundwater and observed processes and features of the landscape are connected may be one way to improve trust in the groundwater supply. Alternative sources of water such as lake and snow water are untreated and have unknown quality, and storing water for a long time may promote the growth of bacteria and viruses.

3. **Develop a source water protection plan**
   A source water protection plan is a plan for taking care of the area where water enters the ground before it is later captured by a well. This is a useful tool to address potential water security concerns and to ensure the future quality of the drinking water source. It could be developed as a community exercise that encourages reflection around best practices for fuel and household hazardous waste, for example.

Executive Summary

This report assesses the vulnerability of the groundwater supply for the community of Whatì, NT, (pop. ~ 500) located on the shore of Lac La Martre about 160 km northwest of Yellowknife. The approach involved: community conversations; developing a conceptual model of the groundwater flow system; evaluating hydrogeological, geochemical, and local factors to develop an initial vulnerability assessment; and consideration of possible effects of climate change on the groundwater supply. Available data for the area related to geology, permafrost, precipitation, groundwater flow and geochemistry, well construction, and potential contaminant sources were compiled. The report concludes by recommending considerations for a source water protection plan.

Whatì and the adjacent Lac La Martre are located within the Interior Platform geological province, where sedimentary bedrock is present regionally, with dolostone present locally. Overburden sediment thickness varies from 2 to 25 m in the area and is about 10 m beneath the community. Extensive discontinuous permafrost exists in the area, and the permafrost table was generally reported to be between 2 to 5 m below ground surface during geotechnical investigations related to building projects in Whatì in the 1980s and 1990s. Shallow groundwater may flow mostly within the weathered upper portion of the bedrock (dolostone) in areas with no permafrost, or within coarse-grained deposits when present. Average annual total precipitation for the area is around 349 mm. Accounting for evapotranspiration suggests that recharge rates are relatively low but mostly associated with the snowmelt period. The community relies on one production well that is screened in highly transmissive fractured dolostone at a depth of about 10 to 13 m below ground surface. The well is located about 30 m from the lake in a location where permafrost is not present. The bathymetry of the lake shows shallow depths (< 3 m) persisting for several hundred metres into the lake. The shallow nature of the lake was a main reason why groundwater was chosen over lake water for community supply in the 1980s. The water treatment plant removes hydrogen sulphide and decreases well water hardness in addition to chlorinating. Water is delivered by truck to the residents of the community, and wastewater is regularly removed from septic tanks and transferred by truck to a lagoon about 4 km from the community that drains to the outflow channel of the lake, downstream of the community.

Major ion geochemistry and stable isotopes suggest that the raw water captured by the community well has evolved somewhat from a surface water signature within the groundwater system. This suggests that the soil is filtering out possible disease-causing microbes and other pathogens that are commonly present in surface water. However, side effects of the travel time through the soil likely include the groundwater dissolving minerals from the soil, and the change in taste of the water.

Water security factors relate to trust of the treatment system, the potential for contamination, and uncertainty regarding local geology and permafrost. Elders in the community tend to distrust the treated groundwater from the community well based on its taste and colour. Pumping groundwater also represents a change from traditional practices that was never fully explained to the community members.

Concerns for the water supply include the potential for contamination, the proximity of the cemetery to the well, and the extent to which permafrost degradation will occur and how this could impact water supply infrastructure. The well's capture zone could not be estimated with certainty due to the unknown characteristics of the fractured rock aquifer and locations of permafrost, but it could include much of the region beneath the community. Two scenarios (with permafrost and without the presence of permafrost) were tested to see what the capture zone may look like under different conditions. Results suggest that the region that contributes groundwater to the well could increase considerably between a situation where permafrost prevents groundwater flow from the upland area and a future situation with no (or very little) permafrost. Considering that the present time constitutes an intermediate stage between the extremes represented by Scenario 1 (permafrost) and Scenario 2 (no permafrost), it may be reasonable to hypothesize that the well water quality would change slowly over time to become more like groundwater originating from recharge on land and less like lake water. Potential contamination threats include the cemetery, household heating and wastewater tanks and the diesel power plant.

Recommendations include the installation of additional observation wells, coupled with water level monitoring, which would assist with water table and permafrost mapping, and analysis of groundwater flow directions and the well's capture zone. A source water protection plan could be developed as a community exercise that encourages reflection around best practices for fuel and household hazardous waste. Finally, improved communication from stakeholders in charge of the drinking water management and from groundwater researchers is recommended to build trust in the groundwater resource and help community members to make informed decisions about their water consumption.

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Background and Objectives

In the Northwest Territories, only three communities (Fort Liard, Nahanni Butte, and Whatì) use groundwater as their drinking water supply, while the remainder of the territory's population uses surface water sources such as lakes or rivers. While groundwater is often thought of as being naturally protected and resilient, there are potential threats to these water supplies, including over extraction due to increased population and water demand, contamination, and secondary impacts from climate change. In the North, these issues are further complicated by the presence of relatively impermeable permafrost (ground that is perennially below 0 °C). With climate warming in the Arctic, permafrost is warming and thawing, leading to changes in groundwater systems (McKenzie *et al*., 2021). For communities that use groundwater as a water resource, it is important to think about how climate change will impact their water supply in the future.

The following report focuses on the community of Whatì, Northwest Territories (**Figure 1**; 117.274 °W, 63.144 °N), located on the eastern shore of Lac La Martre, approximately 160 km northwest of Yellowknife. The population of Whatì is around 519 (NWT Bureau of Statistics, 2021), and the community of about 128 dwellings (NWT Bureau of Statistics, 2017) uses groundwater for domestic water supply. The objectives of our study were to evaluate the vulnerability and sustainability of this water supply in terms of water quality and quantity, and with respect to future water demands and climate change.

Our approach included:

1. Gathering information regarding water, climate, and environment to guide, inform, and contextualize our study.
2. Developing a conceptual model of the Whatì groundwater system based on historical data and water chemistry.
3. Developing an evaluation of the vulnerability of the water system, including local factors such as contamination, increasing population, etc.
4. Evaluating the sustainability of the groundwater system with respect to a regime shift to a warmer and wetter climate.

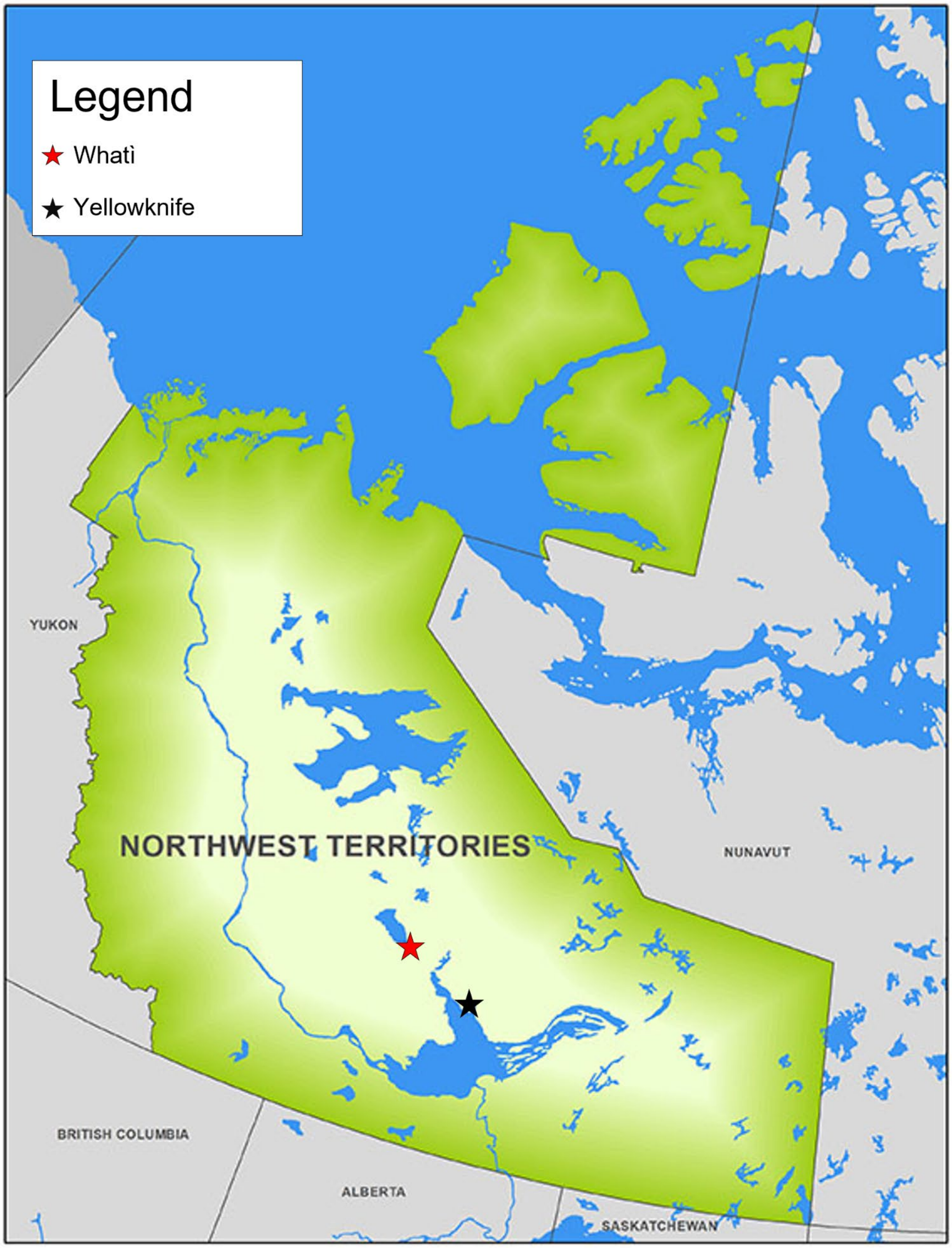

Figure 1. Location of Whatì, NWT (Source: Crown-Indigenous Relations and Northern Affairs Canada, available at: https://www.rcaanc-cirnac.gc.ca/eng/1100100022857/1617205117407).

Community Conversations related to Water, Permafrost, Landscape and Ecological Changes

Project participants initially met with community members in Whatì and Behchokǫ̀ and gained impressions from elders and others about the local groundwater in March 2018. One Elder, Mike Nitsiza, commented on the difference in taste between groundwater (treated) and lake water (likely untreated). Elders noted the staining of tea pots associated with groundwater use. They also questioned why lake water was no longer used. Other concerns were related to the possibility of contamination. The possibility for the cemetery to impact the groundwater well was suggested, and Elders wondered if the groundwater well would be a secure water source in the future because of the warming climate. This latter concern was related in part to the extent to which permafrost degradation will occur and how this could impact the groundwater supply. Field specialists from the Tłı̨chǫ Lands Department also indicated that there is extensive groundwater discharge within the watershed in winter, expressing a desire to understand potential contamination sources and risks related to development.

Project participants had a second opportunity to meet with Elders and community members in Whatì in August 2022 during the *What's Happening Under the Land?* workshop. Further observations were shared regarding observed changes related to wildlife, the landscape, water, and permafrost. Wildlife changes included that moose are moving north, there are fewer fish in Lac La Martre, fish meat is becoming softer, and the timing of the fish and caribou movements are less predictable. There is less trapping now, so the beaver population has increased in the watersheds of the creeks that flow into the lake. Beaver and muskrat populations seem to vary with water levels (higher levels means more of these species). There are fewer ducks now. Forest fires destroy plants and animals, and mines and road construction generate dust that is also destructive. Highways are associated with road salt, which attracts animals. Forest fires have also occurred, and ashes have entered the lake, negatively impacting the fish.

Observed hydrological changes that were shared included that snowmelt has been occurring faster in the past two years and there is more wind during the snowmelt season. The La Martre River now has consistently high water levels in spring. On the other hand, there are places nearby where Elders used to canoe where water courses have dried up. A creek historically flowed through the community (under the community hall) and into the lake. It was originally diverted but now no longer flows. Some lakes between Whatì and Yellowknife have dried up. People used to dry fish and clothes outside, but it is now too dusty to do so. Permafrost depth is changing. Permafrost thaw slumps at the lakeshore have been observed.

Many Elders and community members commented further on drinking water during the 2022 conversations. Elders again emphasized that they do not like the taste of the treated water that is distributed to their homes, and some shared that they did not understand why there was a change from traditional water sources (surface water and snow) to treated well water. Some collect lake or snow water to use as drinking water instead of the treated groundwater. The lake water is not considered as healthy as it used to be and is now darker in colour. Some still try to collect deeper lake water, which may still be of reasonable quality. More community members used to draw lake water for making tea, but now collecting snow and storing the melted snow water for making tea is a more common practice. Bubbles in the distributed tap water and the chemical taste of the treated water are concerns. Some community members have had to replace their household water pumps (e.g., two in eight years) and have hired contractors to clean sediments (possibly mineral precipitates from the hard groundwater) out of their household water tanks. Land disturbance near the cemetery and the community's diesel power plant were mentioned as concerns for drinking water quality.

Review and Analysis of Existing and Collected Regional Water Data

Geologic and Surficial Geology Setting

The community of Whatì is located on the eastern shore of Lac La Martre, within the Peace-Slave Lowland of the Interior Plains of Canada (Interior Platform geological province) and near the western margin of the Canadian Shield (SNC-Lavalin, 2012; **Figure 2**). Bedrock in this region is known to consist mostly of dolostone, shale, and sandstone units of the Ordovician Period (Stantec, 2017), as observed in outcrops along the La Martre River and through various geotechnical investigations conducted in the area over the past 40 years. Dolostone is a carbonate rock that is easily dissolved by rain and snowmelt over time, and it is susceptible to weathering and fracturing. Sandstone may transmit groundwater at reasonable but lower rates than dolostone, but shale is generally an aquitard that impedes groundwater flow where present.

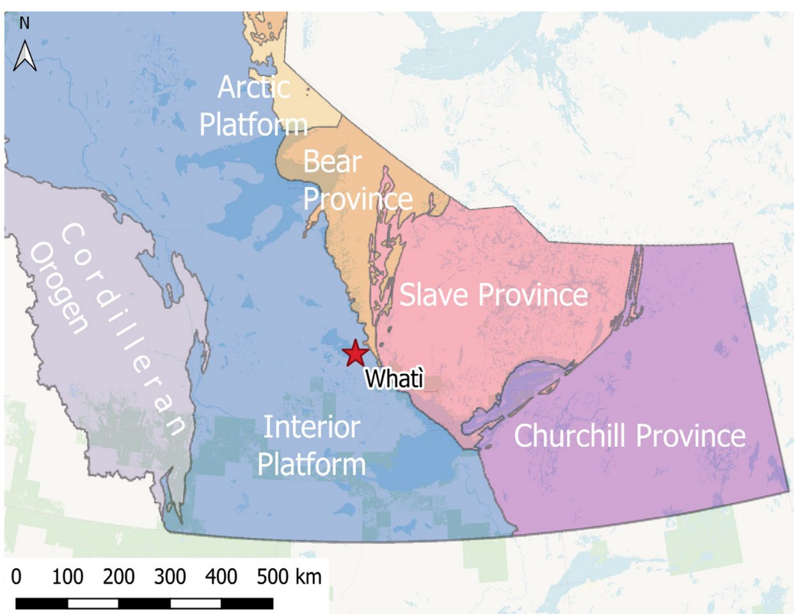

Figure 2. Bedrock geology of the region of the Northwest Territories near Whatì (GNWT, 2022; OSMF, 2023).

At the La Martre Falls, located approximately 20 km east of Whatì, the geology is composed of near horizontal, flat bedded, sedimentary rocks overlain by discontinuous glacial till deposits that thicken to the west (SNC-Lavalin, 2012; SNC Consultants, 1988). The dominant rock type is medium brown to grey, fine grained, massive to thickly bedded dolostone (SNC-Lavalin, 2012). Near ground surface, the dolostone has been weathered by annual freeze-thaw cycles resulting in rock that is characterized by numerous sub-vertical joints forming a columnar jointing pattern. At depth this rock unit is more competent. Underlying the dolostone is a weak, fissile sequence of red and green, iron-oxide rich shale that is also typically sub-horizontal (SNC-Lavalin, 2012). The contact between the soft, iron oxide rich shales and the dolostone is observed in outcrops downstream of La Martre Falls. The weathered upper part of the dolostone unit may provide a regional aquifer, with lower flow rates in the competent dolostone and very low flow rates in the underlying shale.

Overburden in the region has been broadly mapped as glacial till deposits that are typically thicker than 2 m and up to 25 m thick in places (Earth Tech, 2007). In the vicinity of La Martre Falls, the overburden varies from 0.3 to 1.2 m in thickness before reaching bedrock, and it is characterized by silt overlain by a thin layer of organics (SNC-Lavalin, 2012; Appendix A; **Figure 3**). Borehole records from geotechnical investigations along the proposed Tłįchǫ all-season access road show that the overburden varies in thickness from 0.3 to 8 m within 30 km of Whatì and that the thickness is highly variable, spatially (Stantec, 2017; Appendix A; **Figure 3**). Units of brown, silty or clayey sand with varying amounts of cobbles and boulders are common in the borehole logs (see Appendix C in Stantec, 2017). In many of the boreholes closest to Whatì (e.g., BH17-54 – BH17-81, i.e., within ~30 km; **Figure 3**) there is a layer of clay at or near the top of the sediment column. Borehole BH17-61 was an outlier, drilled in a low-lying area at an elevation of 257.5 m.a.s.l. (metres above sea level), and encountered a 2 m thick layer of peat. It is anticipated from the predictive surficial geology map that other low-lying areas would have similarly thick peat deposits. Borehole BH17-75 was also anomalous, as it was drilled at the edge of the La Martre River and encountered 7 m of gravel before auger refusal. This kind of complicated and spatially variable sediment stratigraphy is common for a proglacial environment.

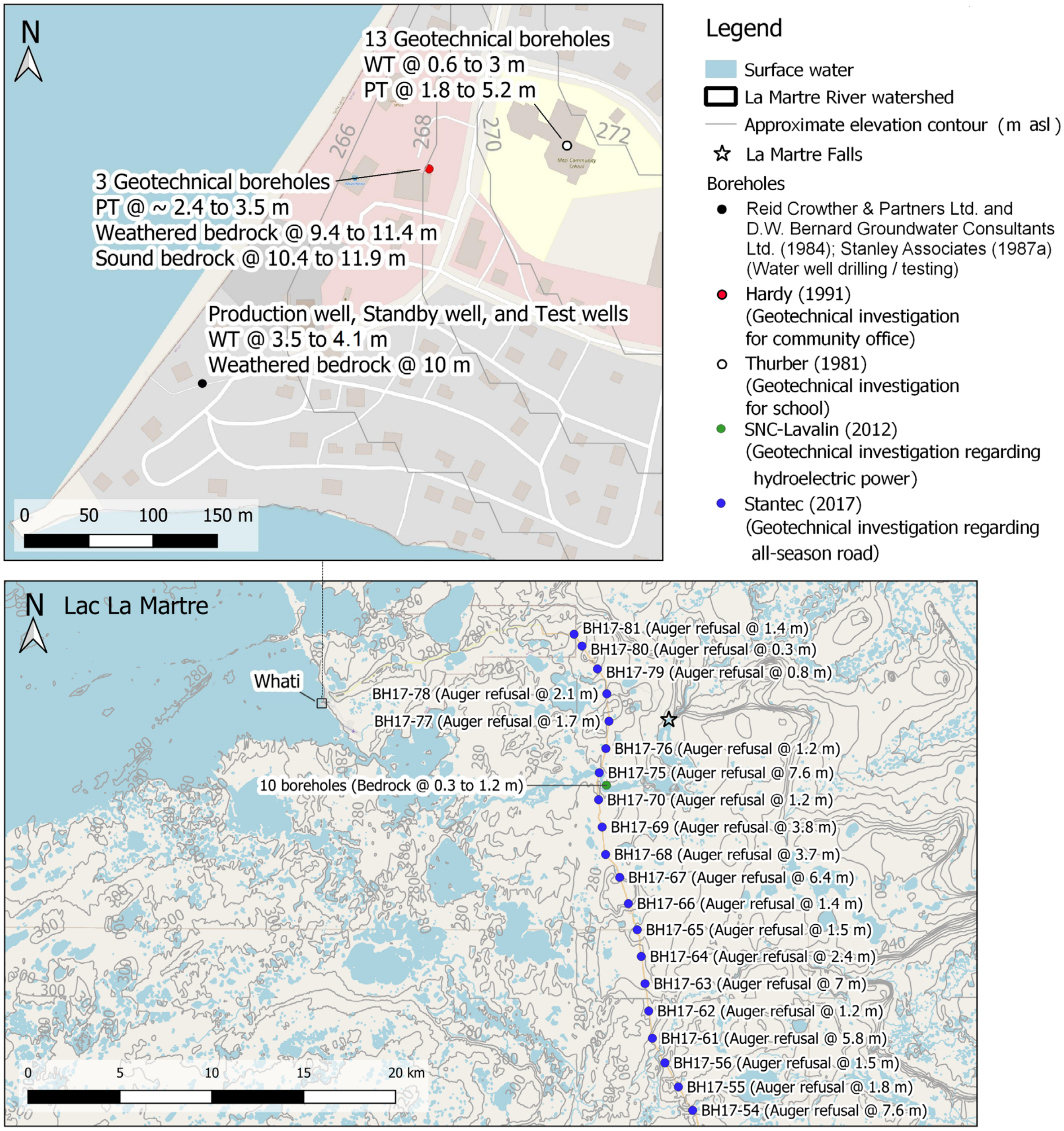

Figure 3. Borehole data for the Whatì area (Government of Canada, 2016, 2017; Hardy, 1991; NRC, 2016; © OpenStreetMap contributors – OSMF, 2023; Reid Crowther & Partners Ltd. and D.W. Bernard Groundwater Consultants Ltd., 1984; SNC-Lavalin, 2012; Stanley Associates, 1987a; Stantec, 2017; Thurber, 1981). Abbreviations: "asl" indicates *above sea level*, "WT" indicates *water table depth* and "PT" indicates *permafrost table depth*. "Auger refusal" was assumed to indicate the top of bedrock. The locations are approximate except for the Stantec (2017) boreholes.

Within the community of Whatì a variety of geotechnical investigations have occurred over the last 40 years, and these provide valuable subsurface information for this hydrogeological study of the area. The Lac La Martre School Investigation (Thurber, 1981) that occurred in 1980 and 1981 drilled four holes where bedrock was encountered between 8.5 – 11.2 m below surface (Appendix A; **Figure 3**); the bedrock was characterized as fine-grained, grey-brown, highly fractured dolostone. In the four drill holes (81-1, 81-2, 81-3, and 81-4), the quaternary geology was described as a thin, 0.05 m thick veneer of peat at surface, underlain by a 3 – 5 m thick unit of silty brown sand, which was followed by a 2 – 8 m thick sequence of silty, brown clay. Within some of the logs the clay unit contains thin (< 1 m thick) lenses of silt, sand, and gravel. This depositional environment is inferred to be of lacustrine origin and indicates the change from a low energy environment (clay unit) to a higher energy environment (sand unit), likely showing evidence of a receding Glacial Lake McConnell (Ednie *et al.*, 2014). A groundwater exploration and well development study was conducted in January 1984 (Reid Crowther & Partners Ltd. and D.W. Bernard Groundwater Consultants Ltd., 1984) in order to determine if a water well could be used as a community water source. For this project, a borehole was drilled at a location 3 m away from the current water production well, and the surficial geology was reported to comprise a layer of brown silty sand about 7 m thick overlying a 3 m-thick unit of clayey till. Gray fractured dolomite was encountered at a depth of 10 m.

A predictive surficial geology map of the area was produced by Ednie *et al.* (2014), using remote sensing datasets. The predictive model was then compared to the field data mentioned above to produce a more accurate regional surficial geology model (**Figure 4)**. It suggests that the community was built on a mix of glacial till, lacustrine sediments and organic deposits.

The implications of the bedrock and surficial geology are that groundwater may flow quickly in the fractured dolostone aquifer within shallow bedrock depths above the shale, which may act as an aquitard. This assumption was confirmed by Reid Crowther & Partners Ltd. and D.W. Bernard Groundwater Consultants Ltd. (1984) during their groundwater investigation. Glacial till and lacustrine sediments are likely associated with low flow rates, but higher rates would occur in the overburden where there are coarse sand and gravel deposits, if the soil is saturated. Thus, groundwater vulnerability may be most concerned with areas of coarse overburden sediments where higher recharge rates would transmit water to the weathered dolostone layer. Additionally, in a discontinuous permafrost environment, frozen ground is most likely to be found in organic or fine-grained deposits (Stantec, 2017) and could affect groundwater flow and pathways (see the Permafrost Setting section below).

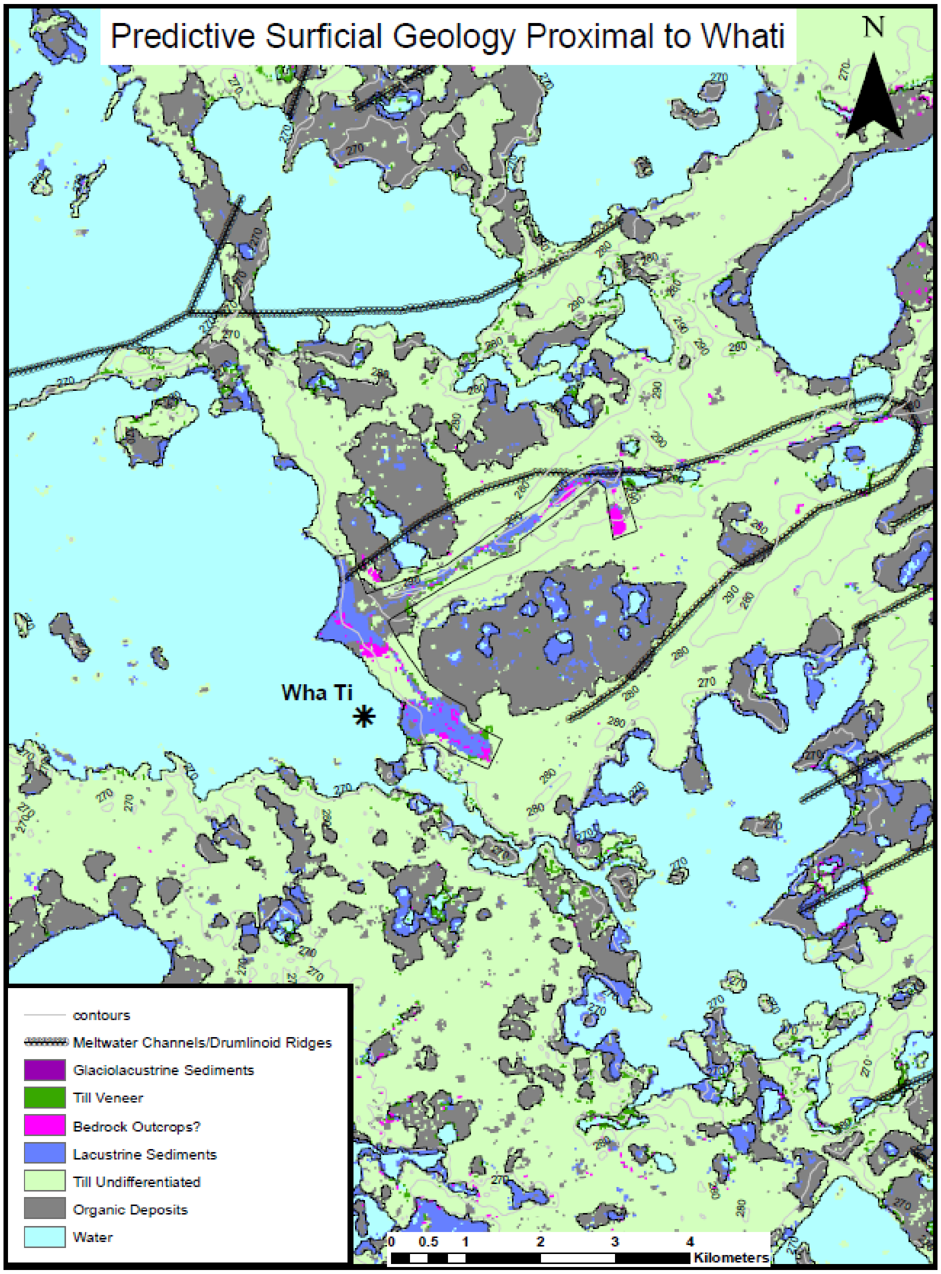

Figure 4. Predictive surficial geology of the Whatì area (modified from Ednie *et al.*, 2014).

Permafrost Setting

The Whatì area is located within a region classified as having extensive discontinuous (50 – 90% coverage area) permafrost with a low (< 10%) proportion of ground ice (Heginbottom *et al.*, 1995). Work by Daly *et al.* (2022) in the Whatì area suggests that only 50% of the area may be expected to have permafrost (**Figure 5**), much closer to the lower end of the extensive discontinuous range. The average annual daily air temperature at the Whatì Environment and Climate Change Canada weather station is approximately -4.7 °C, and permafrost is expected to be warm (> -2 °C) and associated with forested areas underlain by fine-textured soils in the area (Stantec, 2017) or low-lying peatland or wetland areas. The fact that the adjacent Lac La Martre is a relatively large lake (1,776 km^2; Herdendorf, 1982) suggests that the subsurface below (Rowland *et al*., 2011) or shoreline areas immediately bordering the lake may be consistently unfrozen as taliks (areas of unfrozen ground within permafrost) due to heat storage within the lake. The possibility for lake shoreline areas to be taliks has been suggested elsewhere in NWT by Wicke (2021), who found unfrozen soil adjacent to a small (~1.5 km^2) lake known to be associated with icings (Glass *et al*., 2020) in the Bogg Creek watershed near Norman Wells in western NWT. However, Lac La Martre is shallow (< 3 m deep within 500 m of Whatì; Stanley Associates, 1987b), so its heat storage capacity may not thaw extensive subsurface regions adjacent to or under the lake.

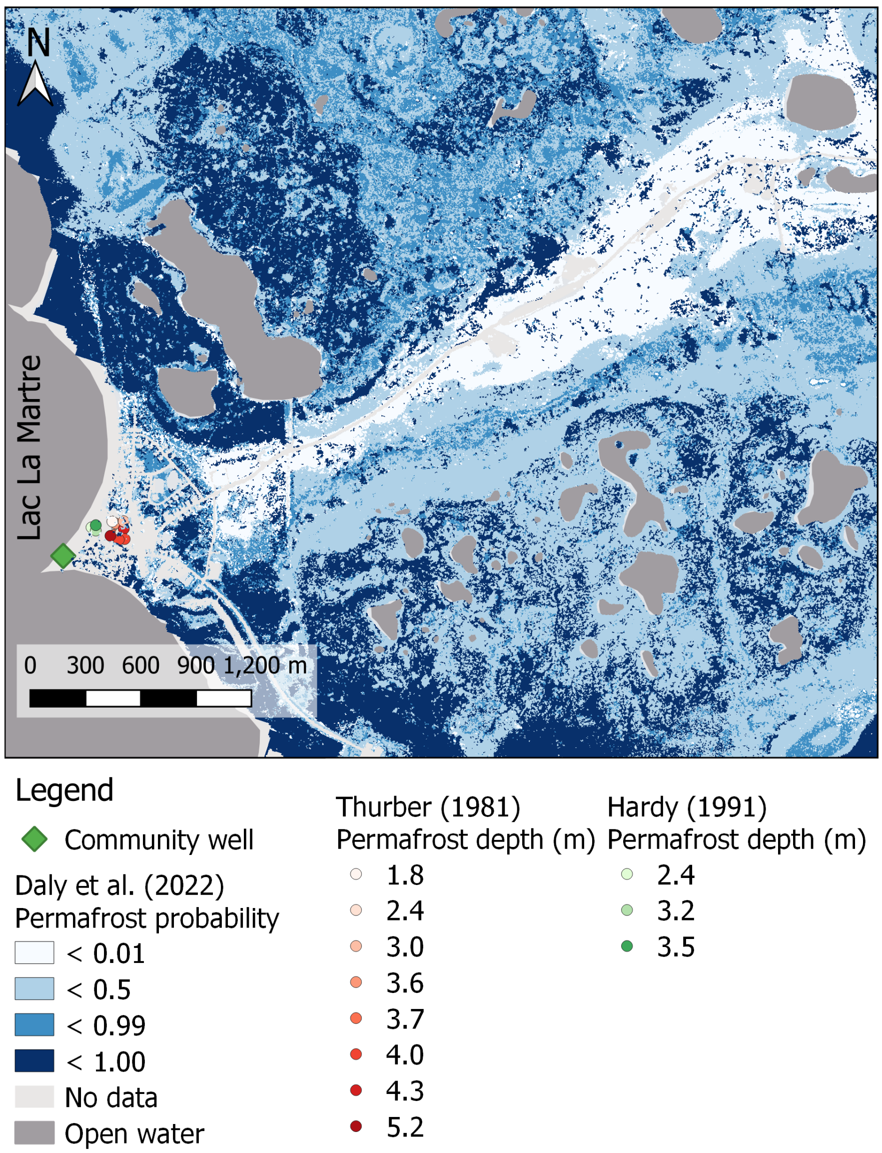

Figure 5. Estimated permafrost presence in the Whatì area (after Daly *et al.*, 2022; S.V. Daly, pers. comm., 2023; Hardy, 1991; Thurber, 1981; Wiebe *et al.*, 2024).

Geotechnical studies prior to building the Lac La Martre School (Thurber, 1981) observed warm (near 0 °C) permafrost below subsurface depths ranging from 1.8 to 5.2 m, and a supra-permafrost water table during drilling in Oct 1980 (Appendix A, **Figure 5**). Similarly, geotechnical investigations related to the community office building (Hardy, 1991; Appendix A; **Figure 5**) noted fragments of ice below depths of 2.4 to 3.5 m in the three boreholes drilled. The Hardy (1991) boreholes were drilled in Mar 1991 when active layer soils were frozen, so the upper depth of the ice-rich sediment was assumed to be an approximation for the permafrost table. It is therefore likely that permafrost was present at depths between 2 and 5 m below ground surface in at least some parts of the community in the 1990s. It is also likely that a talik or area without permafrost exists near the lakeshore. The report of the water well drilling by Stanley Associates (1987a) from 26 Feb to 5 Mar 1987 does not mention permafrost or ice and it notes groundwater levels at depths around 3.5 m below ground surface (Appendix A). In the Reid Crowther & Partners Ltd. and D.W. Bernard Groundwater Consultants Ltd. (1984) report, there was no mention of ground ice in the exploratory well (located 3 m away from the current production well), but liquid water was present starting at a depth of 4.15 m to the bottom of the hole (18.24 m) during a January investigation. This strongly suggests an absence of permafrost in the region of the community's production well (~30 m from the shoreline and near the point of the peninsula), or at least the presence of a thick talik at this location. From these reports, it seems that permafrost was present at least within a distance of 210 m of the groundwater well in the early 1990s. The more recent study by Daly *et al.* (2022) unfortunately does not contain an assessment of permafrost within the community itself. Permafrost provides protection to underlying groundwater by slowing recharge rates but may allow surficial contaminants to be conveyed laterally within the active layer and then migrate to the deeper groundwater system where permafrost is no longer present. Permafrost thaw would erode the vertical protection of groundwater at depth but also decrease the opportunity for contaminants to flow laterally within the active layer toward the well. Natural solutes such as salts trapped in the permafrost may also be mobilized by permafrost thaw in some places (Wicke, 2021).

Hydrology Data and Analysis

The community of Whatì is located on the southeast shore of Lac La Martre, near the outflow of the lake (**Figure 6**). The La Martre River flows southeast out of Lac La Martre into Marian River, a flow system that eventually discharges into the north arm of Great Slave Lake. The Water Survey of Canada (WSC) has operated a continuous stream discharge monitoring station (gauge 07TA001) on the La Martre River near the outflow of Lac La Martre since 1975 (**Figure 7**). Average total precipitation is approximately 349 mm per year (Hersbach *et al.*, 2017; based on the period 1975-2020).

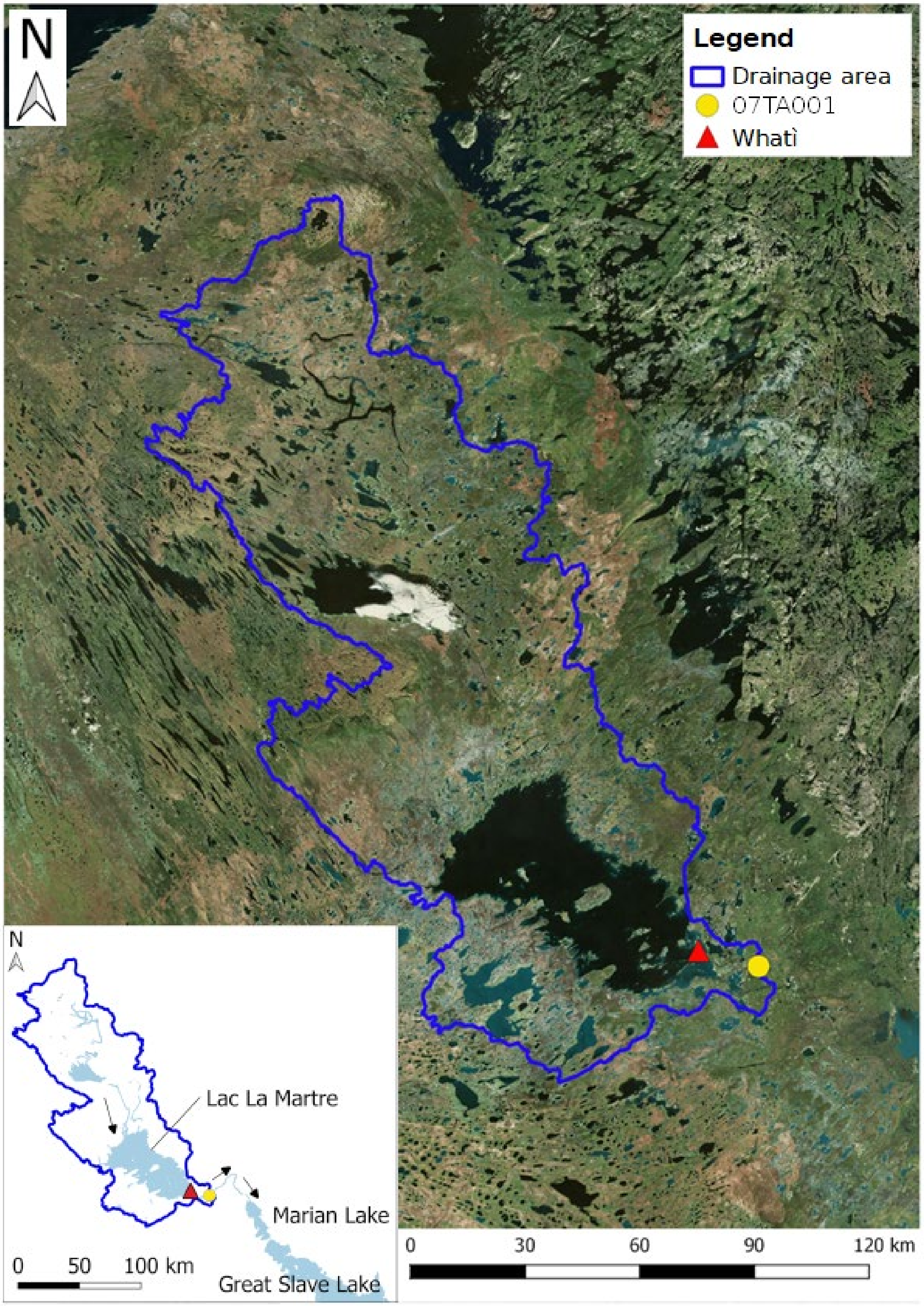

Figure 6. Map outlining the approximate drainage area for the Water Survey of Canada gauging station 07TA001 (Government of Canada, 2017; WSC, 2023; Z. Yang, pers. Comm., 2018; Bing Virtual Earth imagery – QGIS Project, 2018). The arrows show the general river flow directions.

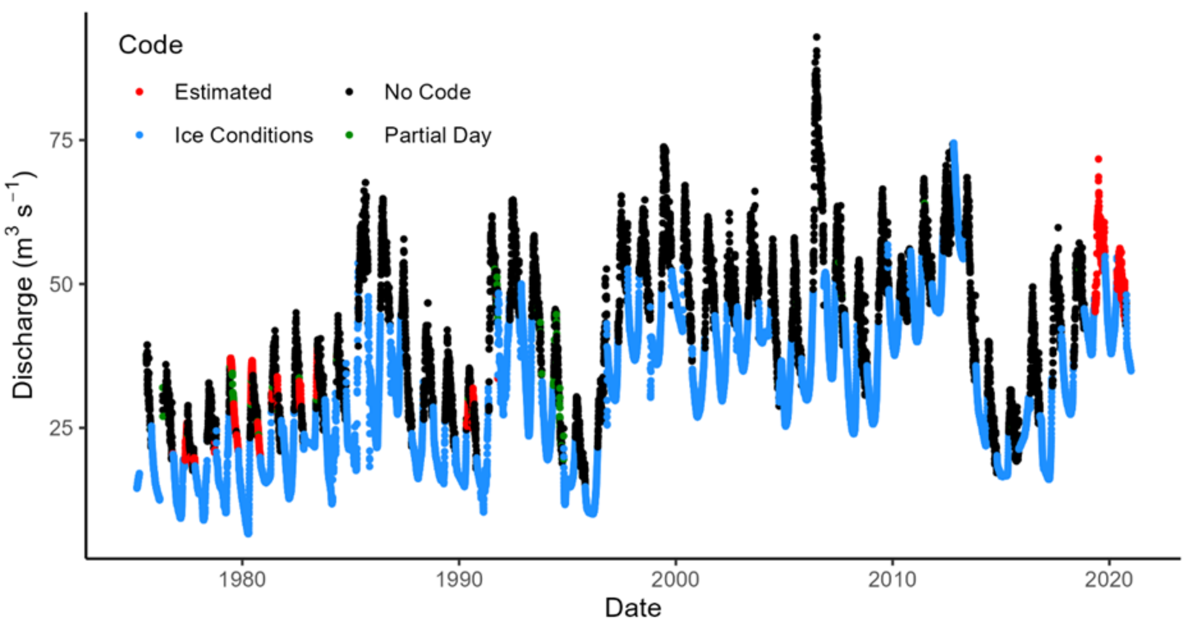

Figure 7. Historical discharge (WSC, 2023) from the Water Survey of Canada gauging station (07AT001) on the La Martre River near the outflow of Lac La Martre.

The analysis of historical streamflow records can provide important information on how watersheds are changing in response to climate change. Several recent studies have observed increasing trends in stream discharge in permafrost regions, with trends being more evident for low flow periods (Peterson *et al*., 2002; Walvoord & Striegl, 2007; St. Jacques & Sauchyn, 2009; Walvoord & Kurylyk, 2016). These trends have been linked to changes in large-scale climate patterns such as the North Atlantic Oscillation and the Arctic Oscillation, which respectively result in changes in precipitation patterns (Peterson *et al.*, 2002) and increased streamflow in NWT (St. Jacques & Sauchyn, 2009), and to increasing surface air temperatures, which have been linked to permafrost thaw and increased groundwater contributions (Walvoord & Striegl, 2007; St. Jacques & Sauchyn, 2009; Walvoord & Kurylyk 2016).

A 2012 report (SNC-Lavalin, 2012) noted an increase in annual discharge recorded at the WSC gauging station and suggested that this change can likely be attributed to permafrost thaw. An analysis of historical stream discharge records is presented below for the WSC gauging station (from 1975 to 2020) regarding trends in mean annual discharge and mean winter discharge. Trends in mean annual air temperature and annual precipitation that may play a role in changing river discharge are also discussed.

Discharge at the La Martre River gauging station is characterized by one large snowmelt driven peak occurring during the end of June or early July. After the peak, flows decline steadily to winter baseflow conditions (**Figure 8**). Minimum flows tend to occur in late February and early March. Over the period of record, discharge has ranged from 6.6 m^3/s on 10 Apr 1980 to 92.9 m^3/s on 1 Jul 2007 (WSC, 2023).

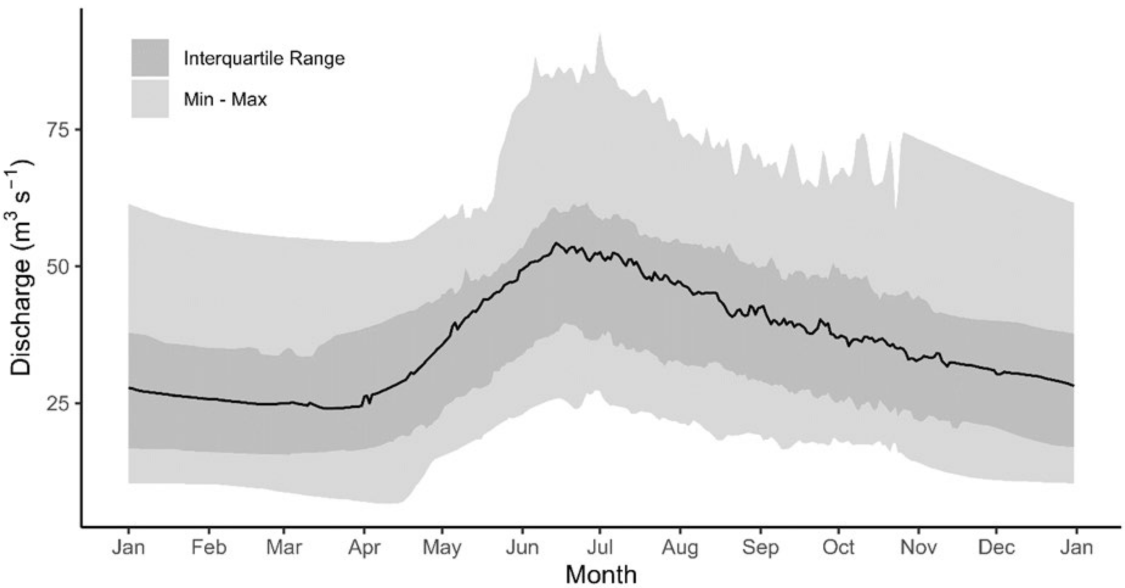

Figure 8. The hydrological regime of the La Martre River near the outflow of Lac La Martre, based on daily data from 1975 to 2020 (WSC, 2023).

The discharge record was analysed for trends in mean annual discharge (MAQ; **Figure 9**) and mean winter discharge (MWQ; **Figure 10**). MWQ was defined as the mean discharge for 1 January to 31 March. This period represents the lowest discharge period, during which surface water inputs (e.g., precipitation, runoff, and snowmelt) are negligible. Consequently, this period should be dominated by the release of water from lake storage and groundwater sources.

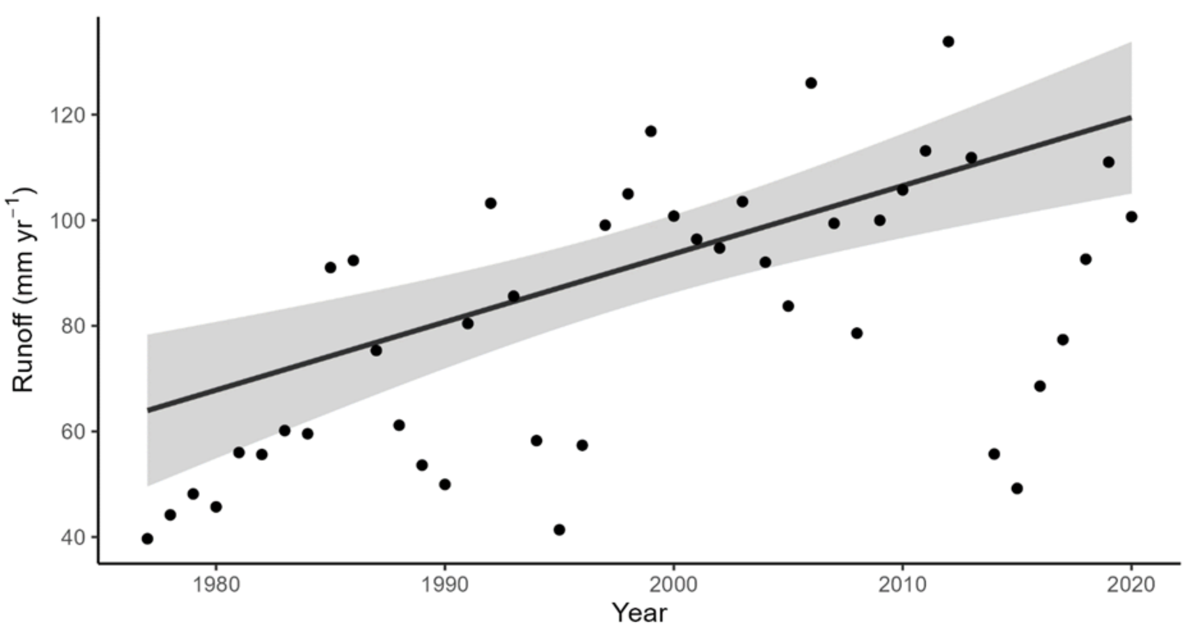

Figure 9. Total annual discharge (1975-2020) at the gauging station on the La Martre River near the outflow of Lac La Martre (WSC, 2023). The solid line shows the trend in the data, where $p < 0.01$ and the grey band represents the 95% confidence level interval.

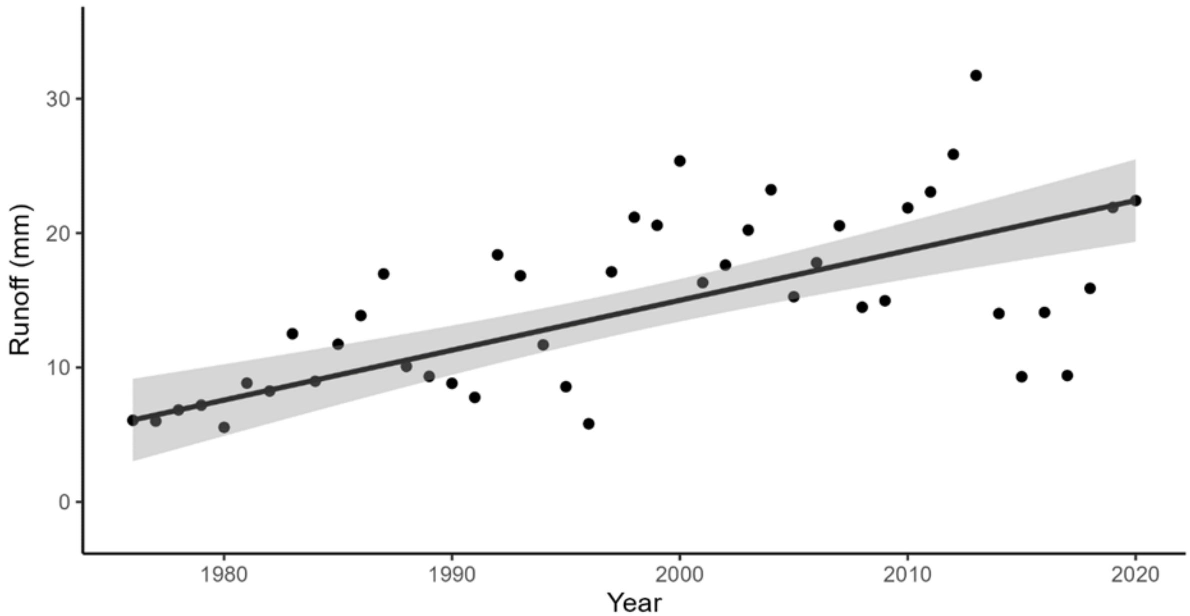

Figure 10. Mean winter (01 Jan – 31 Mar) discharge (relative to the gauged area) at the gauging station on the La Martre River near the outflow of Lac La Martre (WSC, 2023). The solid line shows the trend in the data, where $p < 0.01$ and the grey band represents the 95% confidence level interval.

Analysis of MAQ and MWQ show significant increasing trends in discharge. These trends show that average discharge nearly doubled over the 45 years of record (**Figure 9**). Given the proximity of the gauging station to Lac La Martre, and that there are no major surface water inputs between the lake outflow and the gauge, it is likely that discharge at the gauging station is controlled by the outflow of the lake and thus the lake water level. While increasing MAQ and MWQ are likely the result of an increase in lake water level, the cause of the increase requires further investigation.

Increases in MWQ and MAQ in permafrost regions have been linked to climate change (Rouse *et al.*, 1997; Arnell, 2005; St. Jacques & Sauchyn, 2009). Increasing temperatures leading to permafrost thaw have been hypothesized to induce an increase in groundwater discharge to streams, resulting in increased discharge and specifically winter discharge (St. Jacques & Sauchyn, 2009). Increased precipitation in some arctic regions has also been linked to increasing stream discharge (Peterson *et al.*, 2002).

To investigate the role of climate change on discharge for the La Martre River watershed, trends in historical temperature and precipitation estimates for the Whatì area were analyzed. Mean annual air temperature and total annual precipitation from 1975 to 2020 were downloaded for the Whatì region from the ERA5 reanalysis dataset (Hersbach *et al.*, 2017) at a spatial resolution of 0.5°. ERA5 data are generated from monthly observations at meteorological stations where available and interpolated using a general circulation model. Data from the grid cell containing Whatì and 07TA001 were used to compare trends in precipitation and air temperature to the observed trends in stream discharge. Increasing trends in both mean annual air temperature (**Figure 11**) and annual precipitation (**Figure 12**) were observed. It is difficult to quantify the effects of changing temperature and precipitation on watershed discharge without additional information regarding evapotranspiration, changes in permafrost distribution, and other changes in water storage within the watershed (e.g., groundwater and wetlands). A coarse water balance comparison can be made by comparing the increase in total annual specific discharge (stream discharge per square km of watershed area, expressed in mm) with the increase in precipitation over the same period of record (**Figure 13**).

The area topographically above the stream gauge at the La Martre River WSC station (WSC, 2023) is about 13,900 km^2. The trend in specific discharge indicates that it has increased by approximately 58 mm between 1975 and 2020. The trend in annual precipitation indicates that total annual precipitation has increased by approximately 76 mm over the same period. This suggests that increasing precipitation is likely an important component of the increase in discharge. Further research is required to elucidate the relationship between increasing precipitation and increasing discharge. For example, the ERA5 dataset suggests a general trend across the NWT of precipitation increases of this magnitude, but yet few other hydrometric gauges show similar trends. A proper evaluation of ERA5 performance is necessary, as well as a detailed water balance study to better understand the impact of how changing precipitation and increasing temperatures will impact the hydrology of the La Martre River watershed.

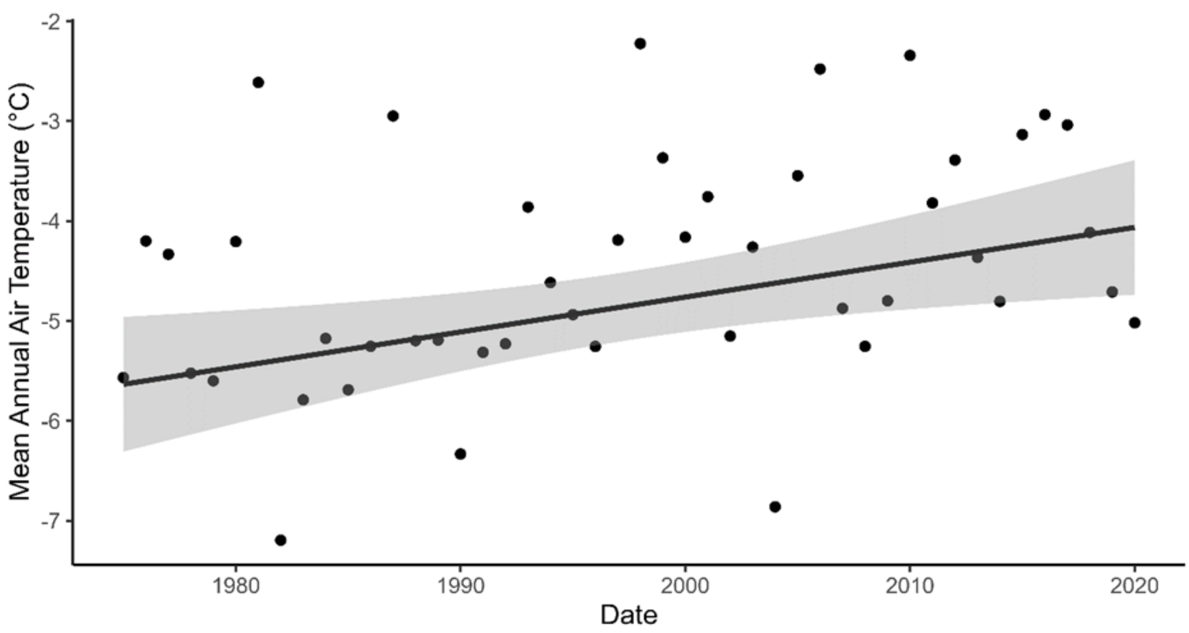

Figure 11. Gridded mean annual air temperature estimated for the Whatì area from ERA5 (Hersbach *et al.*, 2017). The solid line shows the trend in the data, where $p < 0.01$ and the grey band represents the 95% confidence level interval.

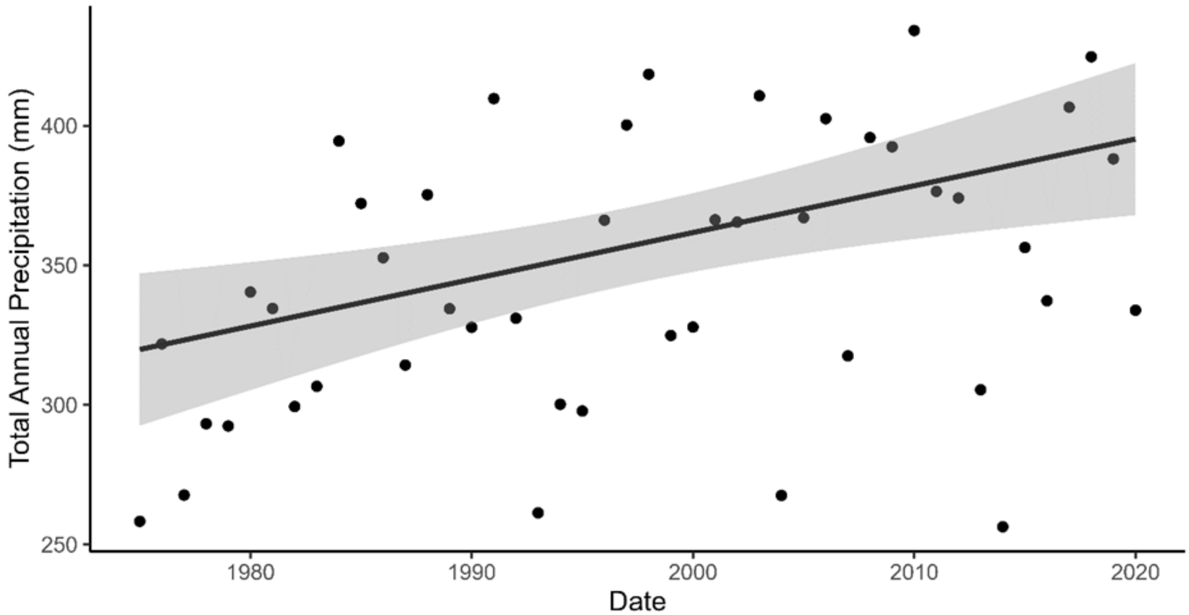

Figure 12. Gridded total annual precipitation estimated for the Whatì area from ERA5 (Hersbach *et al.*, 2017). The solid line shows the trend in the data, where $p < 0.01$ and the grey band represents the 95% confidence level interval.

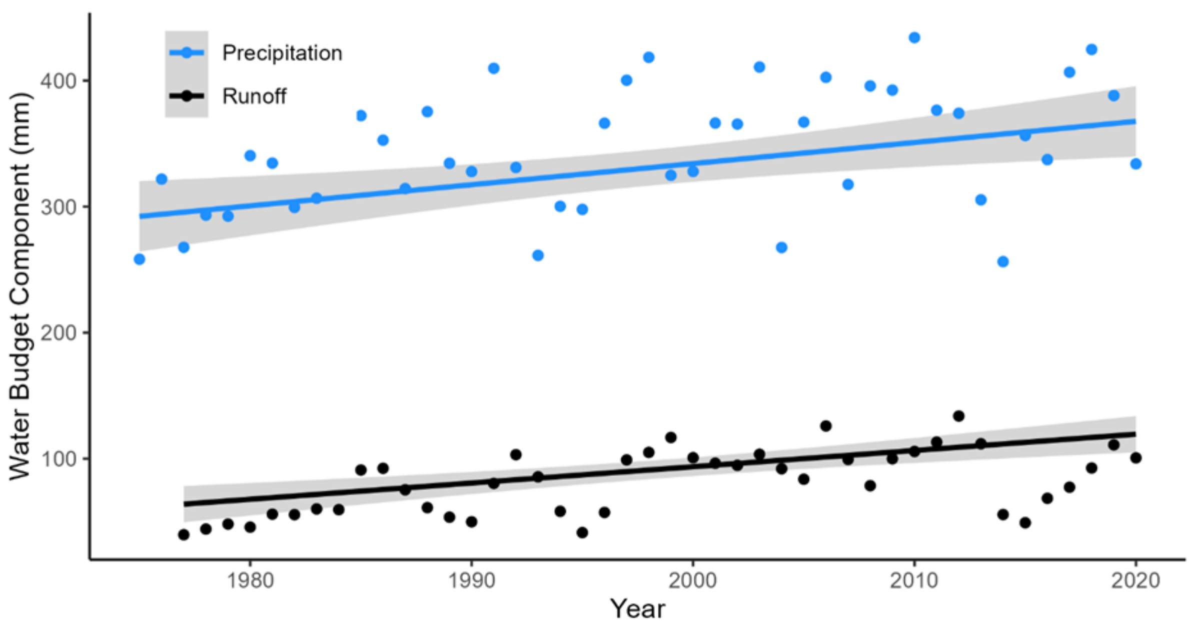

Figure 13. Total annual discharge ("Runoff") at the gauging station on the La Martre River near the outflow of Lac La Martre (WSC, 2023) and total annual precipitation estimates for the Whatì area (ERA5; Hersbach *et al.*, 2017). Solid lines indicate the trends for 1975 to 2020 and the grey bands represent the respective 95% confidence level intervals.

Overview of Water Supply and Wastewater Systems

Water pumped from a single production well provides the water supply for the community of Whatì. The water system was built in 1996 and updated in 2000 (GNWT Dept. of Public Works and Services, 2002). The single well predates the construction of the system and was constructed in 1987. Once treated in the plant, the water is stored below the plant in two cells. Water is then pumped into water distribution trucks from the storage cells via submersible pumps. The trucks, each with a capacity around 10,000 L, are responsible for the distribution of water to the community (GNWT Dept. of Public Works and Services, 2002).

Wastewater is stored in household tanks and routinely transported by truck to a sewage lagoon (Earth Tech, 2007) about 4 km from the community (Community Government of Whatì, 2017; **Figure 14**). The wastewater is then treated in a series of retention ponds before being discharged to the surface water system, the ultimate outflow of which is estimated to occur more than 3.5 km downstream from the community (Community Government of Whatì, 2017), along the outflow channel of Lac La Martre.

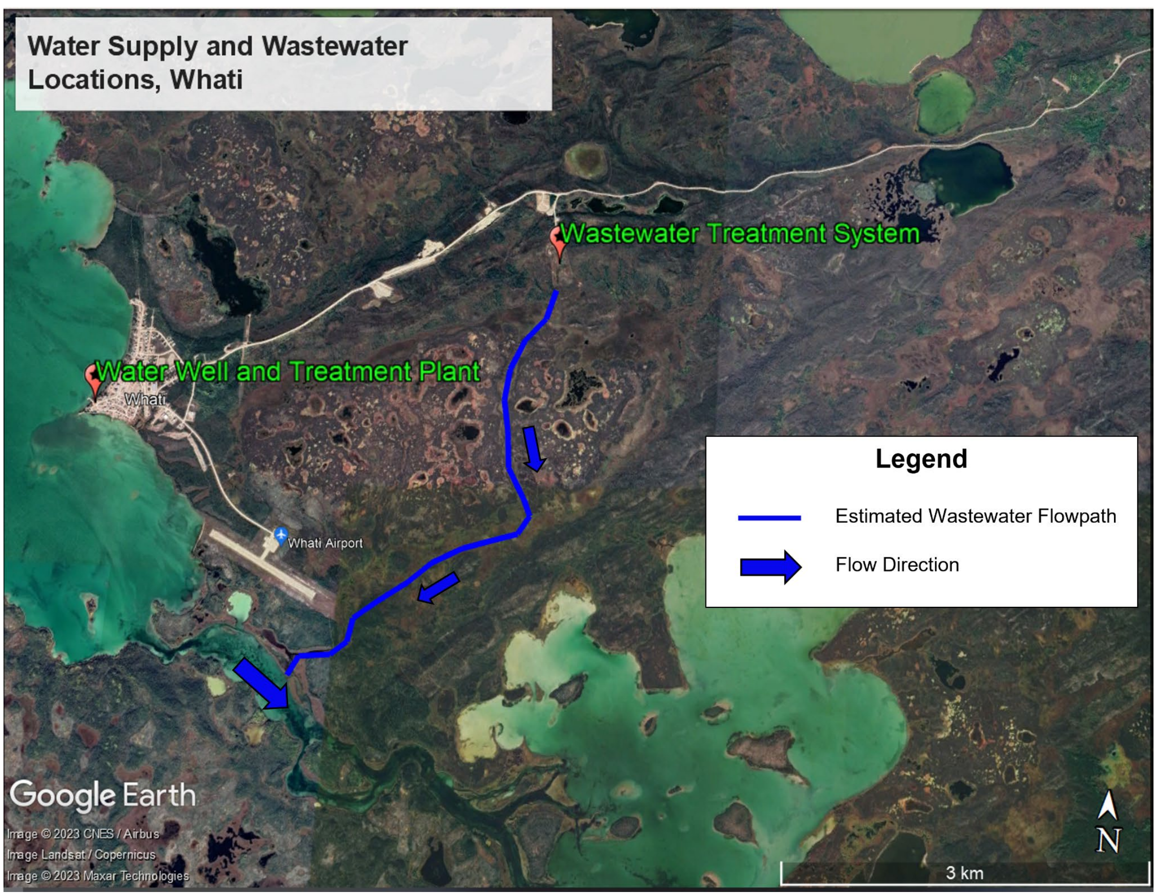

Figure 14. Locations of the community well, the wastewater lagoon, and the likely overland runoff flowpath for lagoon effluent (© Google Earth, 2022).

Well Construction and Hydrogeological Setting

Three wells (1-87, 2-87, and 3-87, or *test*, *production*, and *standby*, respectively) were installed and tested as part of the process of upgrading the water system in Whatì (Stanley Associates, 1987a) in the 1980s. Despite the need to treat hydrogen sulphide from well water, groundwater was identified as the preferred source at the time because the lake's shallow depth near the community precluded the economic installation of a surface water intake pipe at a desired lake depth of at least 4 m (Stanley Associates, 1987b). The production well is presently used to meet the water demands of Whatì residents and the hydrogeology of this well is discussed in greater detail below. The three wells were installed along a roughly east-west line with approximately 5 m spacing; their locations were slightly more than 30 m from sewage tanks associated with two existing buildings. The production well is approximately 30 m from the shoreline of the lake.

Figure 15 shows an overview of the well design (Stanley Associates, 1987a). The production well reaches a depth of 12.77 m, with a casing extending to 10.35 m depth. Neat cement surrounds the well casing, creating a seal. The top of the screen is located at 9.45 m depth, with spacing between slots of 1.27 mm. The aquifer is stabilized with a gravel pack to hold back finer sands from above, with frac sands surrounding the well screen. Fractured dolostone (likely mistaken as limestone in Stanley Associates (1987a), based on the other studies cited above) was encountered at a depth of around 10 m in all three wells.

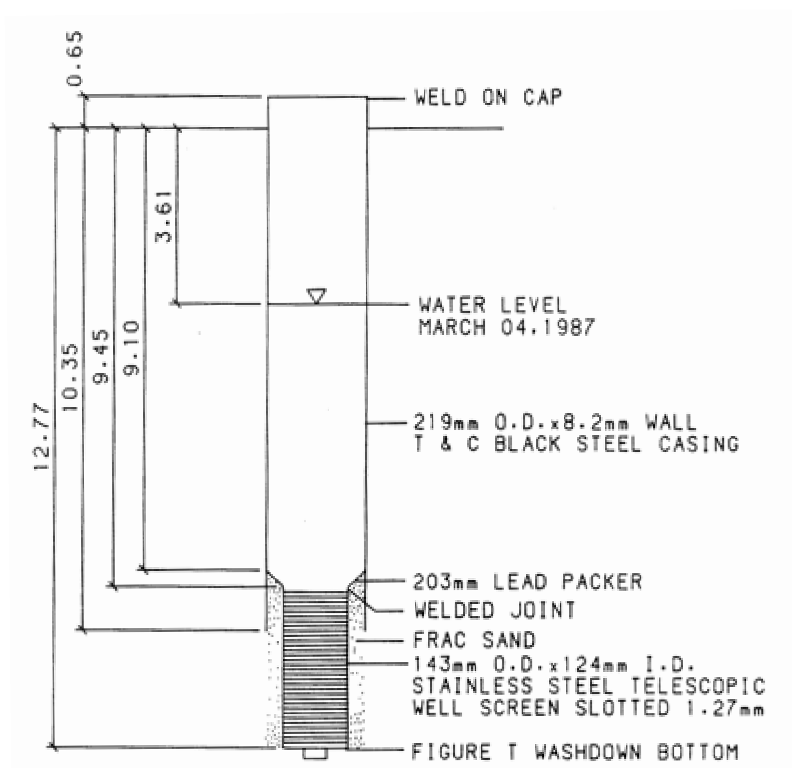

Figure 15. Production well design (Stanley Associates, 1987a). All depths in meters unless indicated.

As reported by Stanley Associates (1987a), aquifer tests (step-drawdown and constant rate) were performed during the initial assessment, each lasting 24 hours. Results of the step-drawdown tests projected that a drawdown of 0.89 m would be associated with a flow rate of 0.017 m^3/s at the pumping well. The constant rate aquifer test pumped water at a rate of 0.0154 m^3/s, though the well is designed to deliver up to 0.019 m^3/s based on the particular screen installed (Stanley Associates, 1987a). Recovery of the well following pumping was essentially instantaneous, with 95% recovery achieved within one minute following the end of testing; after 220 minutes the well had recovered within 0.03 m of the initial water level.

The aquifer tests were interpreted using the Cooper-Jacob method (Stanley Associates, 1987a), in which a straight line is matched to drawdown data plotted against the logarithm of time since pumping began. The Cooper-Jacob method can be used to determine hydrogeological properties, including transmissivity (T) and storativity (S). Transmissivity indicates the rate at which groundwater can flow through an aquifer section of unit width under a unit hydraulic gradient, while storativity represents the volume of water that is released from storage per unit surface area and per unit change in head (water level). Calculated transmissivity for the production well was reported as 0.19 m^2/s. The storativity of the well was estimated to be 0.001 (dimensionless). Applying the observations by Stanley Associates (1987a) and fitting on a Cooper-Jacob composite plot (drawdown vs the logarithm of t/r^2, i.e., time divided by the radius squared) suggests that the bulk transmissivity for the aquifer based on pumping at the production well and monitoring at the observation well is 0.15 m^2/s, and that the bulk transmissivity is 0.12 m^2/s for pumping at the standby well with observations at the observation well and production well. Thus, transmissivity seems to vary somewhat over short distances (10 m), possibly suggesting variability in the degree of weathering of the bedrock or a lack of fracture continuity in certain directions.

Overall, the maximum pumping rate of 0.019 m^3/s is sufficient for the current population. The well could support residential water use for up to 800 people at average water use rates for NWT (247 L/person/day; Statistics Canada, 2021). This would be equivalent to about 200 households, at the 2016 average occupancy rate (NWT Bureau of Statistics, 2017), after accounting for fire fighting capacity (60 m^3/hour; Stanley Associates, 1987a). Per capita water use rates in the community were around 100 L/person/day based on the 2020 annual water licence (Community Government of Whatì, 2021), which is much less than the NWT average. About 2.5 times as many people (~2000) could be supported at the current per capita water use rates.

Water Chemistry Data and Analysis

Water Chemistry – Untreated water

The Stanley Associates (1987a) well installation report indicated that the raw water quality at the well exceeds recommended hardness levels. Calcium carbonate hardness at the well was measured to be 300 mg/L, exceeding the contemporary aesthetic guideline of 120 mg/L (Stanley Associates, 1987a). The

Guidelines for Canadian Drinking Water Quality (GCDWQ; Health Canada, 1979) state that hardness levels above 200 mg/L pose no health risks, but the quality is considered poor.

Iron levels in the production well were initially measured to be 0.19 mg/L (Stanley Associates, 1987a), approaching the 0.3 mg/L recommended aesthetic guideline (e.g., Health Canada, 2020). Manganese levels were initially below (Stanley Associates, 1987a) but potentially close to the existing guideline amount of 0.05 mg/L (the aesthetic objective is now 0.02 mg/L; Health Canada, 2020). Stanley Associates (1987a) identified that hydrogen sulphide (0.44 mg/L) at the standby well greatly exceeded the recommended aesthetic objective (AO) of 0.05 mg/L, however the report did not specify the hydrogen sulphide level at the production well. A 2002 report on community water management and infrastructure indicated that the average hydrogen sulphide levels at the production well were 0.2 mg/L, rendering the untreated water unpalatable (GNWT Dept. of Public Works and Services, 2002).

Table 1 presents daily records from 2017 (L. Nitsiza, pers. comm., 2021) of raw water turbidity, and iron and manganese concentrations in the well. These three parameters were all quite consistent during 2017, with 95% of all iron concentrations between 0.2 and 0.4 mg/L, > 95% of all manganese concentrations between 0.03 and 0.1 mg/L, and > 95% of all turbidity readings between 0.07 and 0.3 NTU. The highest iron and turbidity readings occurred on the same day (4 Mar 2017). Samples of well water and lake water were collected during the present study (3 Mar 2018) and analyzed for a complete range of constituents, including hydrogen and oxygen isotopes (discussed below). All the other parameters measured were consistently below the Guidelines for Canadian Drinking Water Quality values.

Table 1: Selected water quality parameters for the Whatì production well (before water treatment) and Guidelines for Canadian Drinking Water Quality (Health Canada, 2020).

Parameter	**Lowest Value**	**Highest Value**	**Mean**	**Standard deviation**	**Guideline**
Turbidity (NTU)	0.06 (Dec)	1.00 (Mar)	0.14	0.08	≤ 1.0*
Iron (mg/L)	0.03 (Mar)	0.58 (Mar)	0.31	0.05	≤ 0.3†
Manganese (mg/L)	0.022 (Dec)	0.109 (Aug)	0.060	0.016	≤ 0.12‡

* For groundwater systems
† This is an aesthetic (taste) objective
‡ The aesthetic (taste) objective is ≤ 0.02

Water Treatment

The water treatment process includes chlorine and potassium permanganate to convert the dissolved iron, manganese, and sulphide gas into insoluble compounds. The water then passes through dual greensand filters, which remove sulphide from the water and decrease the turbidity levels. Although turbidity guidelines from the GCDWQ indicate that the groundwater source is not under the direct influence of surface water and can be exempt from related treatment recommendations, systems using groundwater should not exceed turbidity levels of 1 NTU (Nephelometric Turbidity Units). The greensand filters in the water treatment plant consistently maintain turbidity levels below 1 NTU (GNWT Dept. of Public Works and Services, 2013).

After passing through the greensand filters, the water passes through a water softening system. The softening system reduces the carbonate hardness, iron, and manganese in the water (GNWT Dept. of Public Works and Services 2002). The softening system was introduced in 2000 following complaints from community members regarding the aesthetic quality of the water. Softening is not applied to the entire treated volume; 70% of the treated water is softened and then mixed with the remaining 30% of un-softened water from the greensand filters. Water hardness following treatment is between 120-140 mg/L and manganese levels fall below the AO of 0.05 mg/L (GNWT Dept. of Public Works and Services, 2002, 2013). Community staff working at the water treatment plant indicated an improvement in water quality following the implementation of the softening system, noting that a film no longer formed on the surface of a cup of tea, but that the water was still darker than snow water (GNWT Dept. of Public Works and Services, 2002).

Water Chemistry – Inorganic Solutes

The major ion chemistry of available surface water and groundwater samples is presented on a Piper Plot in **Figure 16**. A Piper Plot is a graphical representation of major ion water chemistry, and it allows for easy comparison and classification of water samples. Context for the region is provided from the CIMP180 study data (Tank *et al*., 2017), which include surface water samples from Lac La Martre (LLM) and other lakes or ponds within 300 km of Whatì. The carbonate and bicarbonate concentrations for these samples were approximated from alkalinity and pH based on carbonate equilibria equations (constants based on 25 ^{o}C). The "Well" category (3 samples) includes two analyses by Stanley Associates (1987a) and one earlier result whose data are included in that report. Two samples (one from Lac La Martre and one from tap water at the Whatì motel; labelled as "McGill") were collected as part of the present study. Carbonate and bicarbonate concentrations were again calculated based on alkalinity and pH for these two samples.

The Piper Plot (**Figure 16**) shows a range of geochemical signatures related to surface water in the region around Whatì. This may be related to varying proportions of groundwater discharge and heterogeneities in terms of subsurface geology and groundwater flowpath length prior to discharge into surface water. The "Well" samples show a slightly increased amount of Sodium (Na^+) and Potassium (K^+) compared to the Lac La Martre (LLM) samples. This may be due to ion exchange occurring in the subsurface. The tap water sample clearly shows the impact of treatment by water softening (increasing Na^+ and K^+, and decreasing Calcium (Ca^{2+}) and Magnesium (Mg^{2+})).

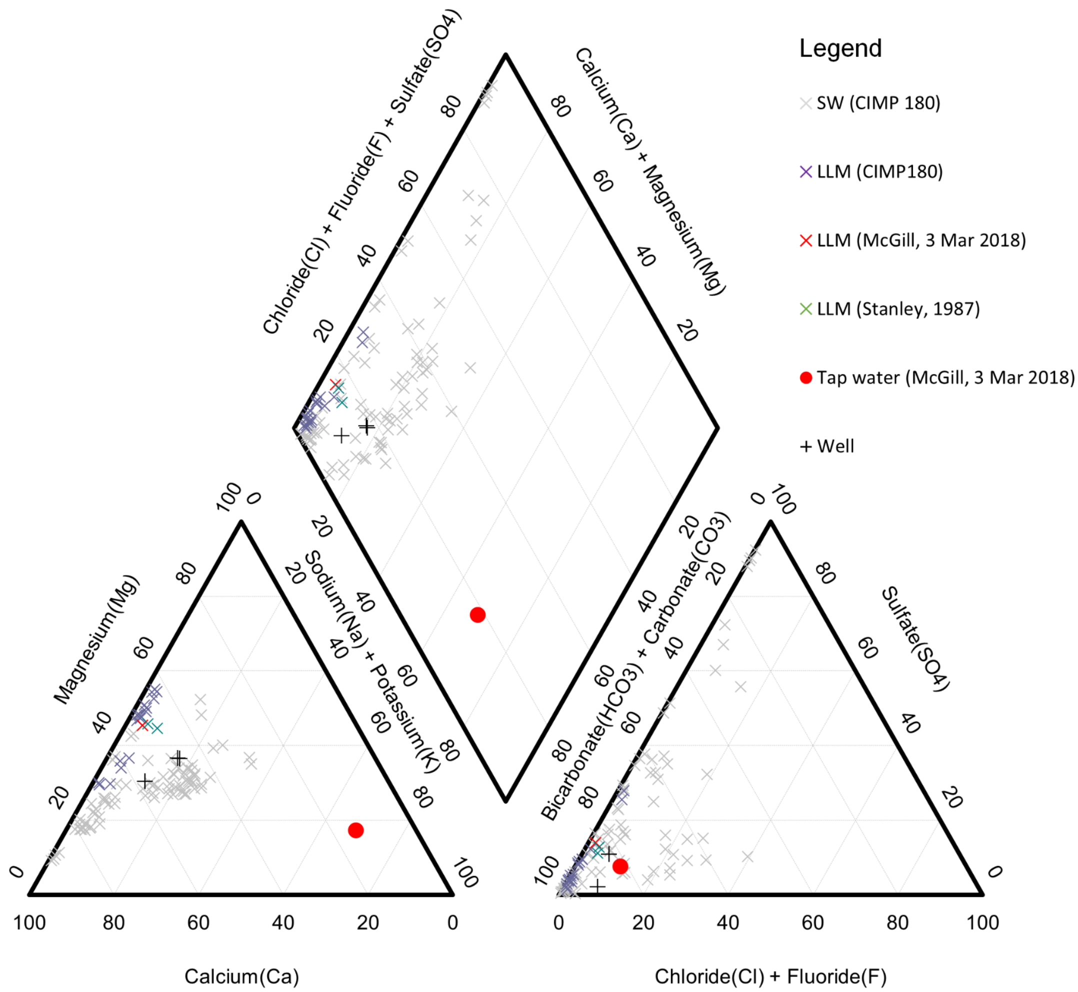

Figure 16. Piper Plot of major ion chemistry (Stanley Associates, 1987a; Tank *et al.*, 2017). Abbreviations: "SW" indicates *surface water*, "LLM" indicates *Lac La Martre*, and "McGill" indicates *McGill University researchers (present study)*.

Water Chemistry – Stable Isotopes

Isotopic analysis of water can assist in the identification of the likely water source and relationships between surface and subsurface sample locations. Rainfall typically has larger (less negative) δ^2H and δ^{18}O ratios than snow because rain has lighter isotopes. Also, groundwater usually has lower (more negative) δ^2H and δ^{18}O ratios than surface water because evaporation preferentially removes lighter isotopes. The three isotope samples (surface water from Lac La Martre, raw well water, and tap water at the Whatì motel) are plotted in **Figure 17**. The figure also shows a Canadian Meteoric Water Line (CMWL; Gibson *et al.*, 2020), which is derived from isotope results from rain and snow across Canada, and surface water samples from the Whatì area (CIMP180 Project; Tank *et al.*, 2017). The surface water sample falls along the estimated local evaporation line (LEL) for the area, a line that surface water results follow as they progressively experience evaporation. The well and tap water isotope results were nearly identical, and their points lie near the LEL and close to the point at which the LEL departs from the CMWL. This may suggest mixing within the groundwater system of surface water with a more pronounced evaporative signature (farther along the LEL toward the right side of the plot) and groundwater recharge of precipitation with heavier isotope signatures (i.e., snowmelt; assumed to have a signature near the lower left corner of the plot).

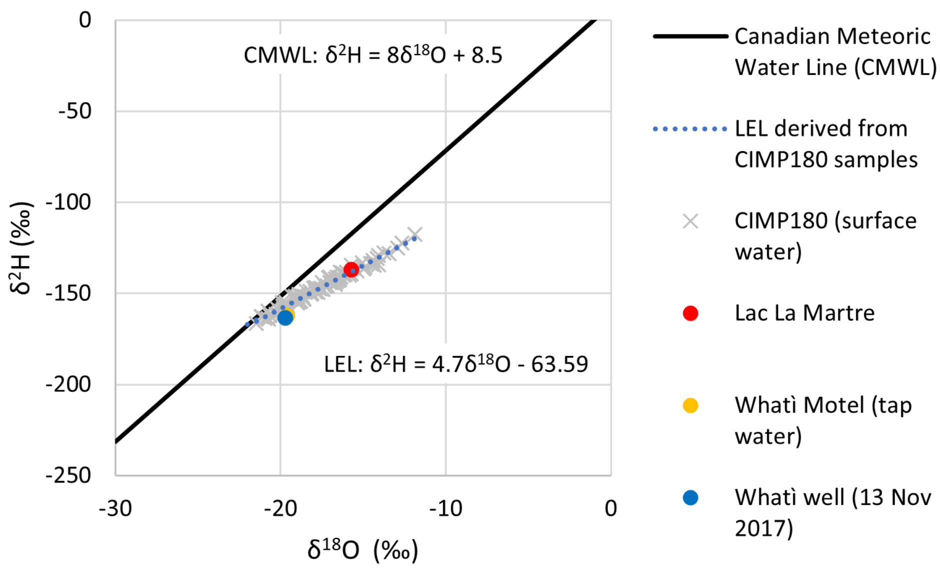

Figure 17. Isotope sampling results with the Canadian meteoric water line (CMWL; Gibson *et al.*, 2020) and surface water samples for the Whatì area (CIMP180 Project; Tank *et al.*, 2017). The y-axis represents the ratio of hydrogen with two neutrons to hydrogen with one neutron, compared to a standard. The x-axis represents the ratio of oxygen with 18 neutrons to oxygen with 16 neutrons, compared to a standard. The local evaporation line (LEL) was estimated based on the CIMP180 surface water samples.

Assessment of Groundwater System

Though there are relatively few details available regarding the hydrogeology of the region, a tentative conceptual model of the groundwater system may be developed based on the available data and general concepts. Groundwater and surface water generally form a continuum with flow from one to another. If groundwater levels reflect ground surface topography in a general way, the deeper regional groundwater flow is most likely to occur from the west to the east (from Lac LaMartre to Great Slave Lake - **Figure 18**). However, as Lac LaMartre is at a lower elevation than the Whatì community and as the local topography remains generally flat until it reaches the La Martre falls (about 20 km to the East), local shallow groundwater flow is likely to occur from the east to the West towards Whatì and the lake. Discontinuous permafrost complicates this hypothetical flow system by providing a no-flow region wherever present. **Figure 18** shows an example of what the flow system could look like along a cross-section from the lake toward the east, with local shallow groundwater flow occurring from the east to the west and with deeper regional flow occurring in the opposite direction. Also, the presence of the well changes the local hydrogeological dynamics by capturing groundwater from the surrounding area into the well.

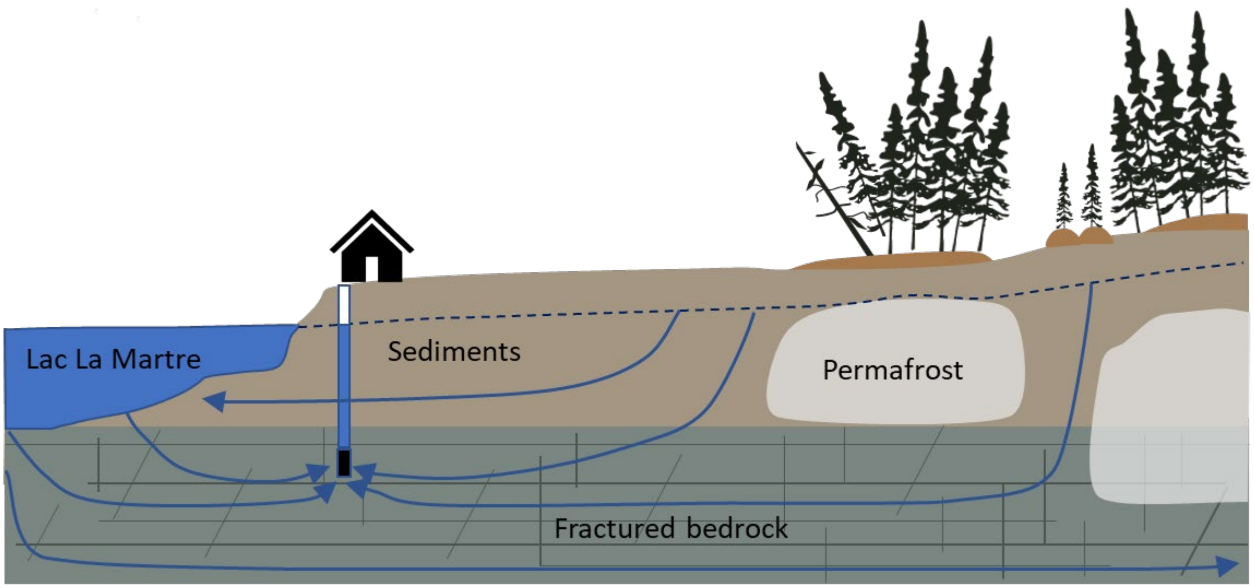

Figure 18. Diagram of possible flow from upland areas toward the community well and the lake near Whatì (modified from Wright, 2022). The gray-blue unit with lines represents the fractured dolostone, the beige unit represents unconsolidated sediments, the brown-orange unit represents peat plateaus and the white zones within the ground represent permafrost; the house represents the community of Whatì, the blue cylinder into the ground represents the community well and the black represents the well screen; finally, the blue dashed line represents the water table elevation (located at a depth of about 3 meters below ground surface) and the arrows represent the possible groundwater flow directions.

This conceptual model assumes that the production well is located within a talik, or perennially unfrozen ground, that exists beside the lake. In contrast to the essentially unlimited ("constant head") boundary represented by the lake, permafrost that potentially borders this talik would be (until it thaws) an impermeable boundary. In addition to the likely discontinuous nature of permafrost in the area, uncertainty regarding how much flow occurs through the shallow gravel, sand, silt, and clay sediments above the fractured rock aquifer in which the community well is screened also complicates the understanding of groundwater flow.

Lac La Martre is potentially the main source of water for the groundwater well. However, the available geochemistry and isotope data suggest that the groundwater extracted by the well has somewhat evolved from the signature of the lake. The geochemistry data on the Piper plot (**Figure 16**) suggest a slight evolution in water quality between the lake and the well, likely due to rock-water interactions. The isotope data also suggest the mixing of surface water and groundwater. The increase in iron concentrations of up to a factor of 6 between the lake and the well also suggests interaction with iron-bearing sediments or bedrock prior to capture by the well. Community conversations noted staining of tea cups when using well water, which may support this idea. However, minimum iron concentrations at the well (Table 1) are very similar to those in the lake. Seasonally high water levels experienced when the lake is unfrozen may lead to more rapid flowpaths from the lake to the well. This possibility should be investigated further.

Well Protection Area

Figure 19 shows a satellite imagery of the water well and treatment plant, community, and lake. For communities such as Whatì that rely on groundwater, well (or source water) protection plans are a useful tool for ensuring the safety and sustainability of the community's drinking water. Guidance for developing a well protection plan is provided by a number of agencies including the US Environmental Protection Agency (USEPA; Harvey and Linquiti, 1989), the British Columbia Ministry of the Environment (BCMOE, 2000), and, more recently, the Government of Northwest Territories (GNWT ECC, 2013a; GNWT ECC, 2013b).

Figure 19. Satellite imagery of Whatì showing the location of the water well and water treatment facility (red star) (© Google Earth, 2023).

A key step to developing a well protection plan is to define a well protection area. The well protection area (WPA) is the area around the well that should be managed and protected from potential contamination. There are a number of methods for defining the WPA, ranging from simply defining an arbitrary fixed radius (e.g., 300 m) around the well to defining the WPA based on the water contribution region (“well capture zone”) determined through computer modelling. When water is pumped from a well, groundwater from the surrounding aquifer is drawn into the well. The area around the well that contributes water to the well is referred to as the well’s capture zone (see **Figure 20**). The size and shape of a capture zone is determined by the hydrogeologic properties of the aquifer (e.g., hydraulic conductivity and porosity of the aquifer, whether the aquifer is confined or unconfined, etc.), the pumping rate or amount of drawdown in the well, and the shape of the water table (hydraulic gradient). The method used to define the WPA depends on the available information and resources. For Whatì, limited information regarding the water table, lake level, subsurface geology, and permafrost distribution hinder some types of analyses of the well capture zone.

Because the well is so close to the lake, simple capture zone estimation methods (such as the calculated fixed radius – e.g., BCMOE, 2000; or analytical boat-shaped approach – e.g., Ceric and Haitjema, 2005) that employ Darcy’s Law and ignore surface water features may be unreasonable. Surface water features represent “constant head” boundaries that may have a very large influence on nearby aquifers under the land. The method employed in the present study was an analytical approach outlined by Wiebe *et al.* (2024) – inspired by Nagheli *et al.* (2020). The method can represent aquifers as simple geometric shapes (wedge/triangle, square, etc.) and requires few parameters (well pumping rates, aquifer hydraulic conductivity and thickness, regional gradient magnitude and direction, and geometry of surface water features around the aquifer). An advantage of the method is its ability to incorporate surface water features into capture zone analysis without requiring a complex, fully distributed, three-dimensional modelling approach. Disadvantages of the method include the assumptions that hydraulic conductivity, aquifer thickness, and regional gradient are the same everywhere in the aquifer.

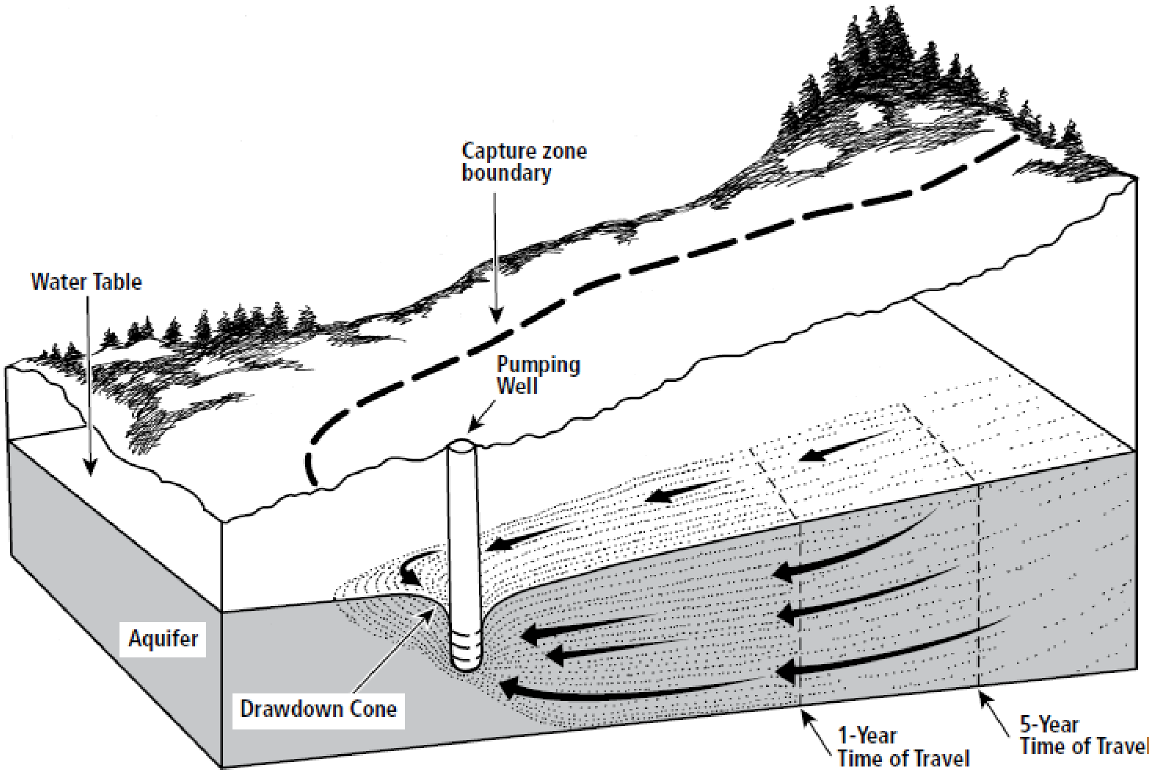

Figure 20. Illustration of a well capture zone for a sloping water table (BCMOE, 2000). Time of travel intervals indicate time required for contaminants to travel from the boundary line to the well, based on a specified pumping rate.

The Wiebe *et al.* (2024) approach involves solving equations to find the equipotential lines of constant hydraulic head and the streamlines showing flow directions within an aquifer of a specific geometric shape. The aquifer is bounded by a combination of constant head boundaries and infinite boundaries, though it can be modified to allow one side of the aquifer to be an impermeable boundary such as permafrost. The location of the community of Whatì on a peninsula within a lake lends itself to be represented as a wedge or triangle, where two sides are constant head boundaries and one side either extends infinitely or is bounded by a no-flow boundary representing permafrost. Including a permafrost boundary was attempted by using the common technique (Samani & Zarei Doudeji, 2012; Ferris *et al.*, 1962) of adding an image well at a location mirrored across a boundary line from the community well. A background flow field is assumed, with a water table that smoothly tapers down to the two lake boundaries from having a uniform slope at a distance of twice the aquifer wedge radius.

Two possible scenarios were simulated for the community well's aquifer (Wiebe *et al.*, 2024). The parameters used in the scenarios are listed in Table 2. Scenario 1 considered a situation with permafrost present about 500 m from the well as a rough approximation to the initial situation when the pumping well was installed, and Scenario 2 considered a situation with no (or very minor) permafrost presence, which may represent future conditions. Both scenarios used the same hydraulic conductivity for the aquifer, which was estimated based on pumping tests by Stanley Associates (1987a), and the current average pumping rate (0.59 L/s; Community Government of Whatì, 2021). Both scenarios assumed regional flow toward the tip of the peninsula, with the same tapering of the slope of the water table to zero at the lake boundaries. (**Figure 18**). The distance to permafrost in Scenario 1 was loosely based on geotechnical studies in the community (Thurber, 1981; Hardy, 1991) and represents conditions where unfrozen soil is present only near the tip of the peninsula. In Scenario 2, the (unfrozen) aquifer was considered to extend landward (eastward) and allow flow toward the well from a much larger area.

Table 2. Summary of well protection area scenarios.

Parameter	**Scenario 1**	**Scenario 2**
Pumping rate (L/s)	0.59*	0.59*
Hydraulic conductivity (m/s)	0.017†	0.017†
Aquifer thickness (m)	3†	3†
Magnitude of regional gradient (m/m)	1×10^{-5}	1×10^{-5}
Direction of regional flow (° clockwise from north, after shape rotation)	246 (west 24° south)	246 (west 24° south)
Aquifer radius from well or distance to permafrost along x-axis (m)	500‡	500
Aquifer triangle angle at point of peninsula (°)	63	63
Aquifer rotation angle to align x-axis with south side of peninsula (° clockwise 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 (1987a).
‡ Based on Thurber (1981) and Hardy (1991).

Scenarios 1 and 2 (**Figures 21 and 22**, respectively) suggest that the region that contributes groundwater to the well could increase considerably between a situation where permafrost prevents groundwater flow from the upland area and a future situation with no (or very little) permafrost. These figures show several of potential contaminant sources (cemetery, diesel power plant, gas station tank farm) along with the estimated capture zones, but do not include home heating fuel tank locations or septic tank locations.

Figure 21 shows the results of Scenario 1, which assumed a permafrost boundary located at x = 500 m. 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. This scenario suggests lake water from the northern shore of the peninsula flowing toward the well within the aquifer. The cemetery is located within the capture zone in this estimate.

Figure 22 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.

Considering that the present time constitutes an intermediate stage between the extremes represented by Scenario 1 (permafrost) and Scenario 2 (no permafrost), it may be reasonable to hypothesize that the well water quality would change slowly over time to become more like groundwater originating from recharge on land and less like lake water. Travel time in the aquifer along the flowpath from the lake to the well would still modify the lake water signature during ion exchange. Ultimately, however, due to the uncertainty of the aquifer properties, the exact contribution area for the well could look different than these estimates – especially for Scenario 2, where there is a larger region of the ground potentially available for groundwater flow.

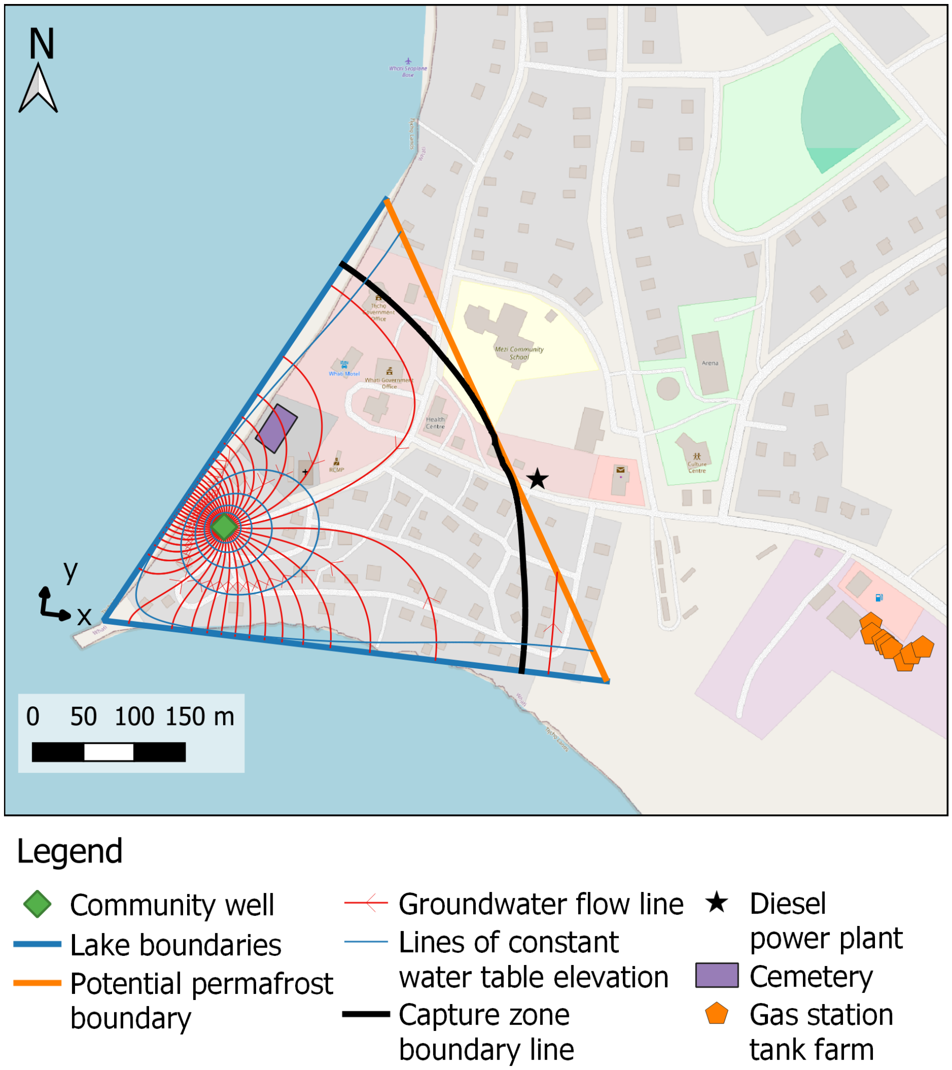

Figure 21. Possible steady state groundwater flow lines and equipotential lines for Scenario 1 (© OpenStreetMap contributors – OSMF, 2023; Stanley Associates, 1987a; Wiebe *et al.*, 2024). This scenario employed a pumping rate of 0.59 L/s, a homogeneous aquifer hydraulic conductivity of 0.017 m/s, a constant aquifer thickness of 3 m, a hydraulic gradient of 1×10^{-5} with groundwater flow toward the southwest, and permafrost present about 500 m from the tip of the peninsula. Under these conditions, the capture zone is present throughout nearly the entire unfrozen region of the peninsula.

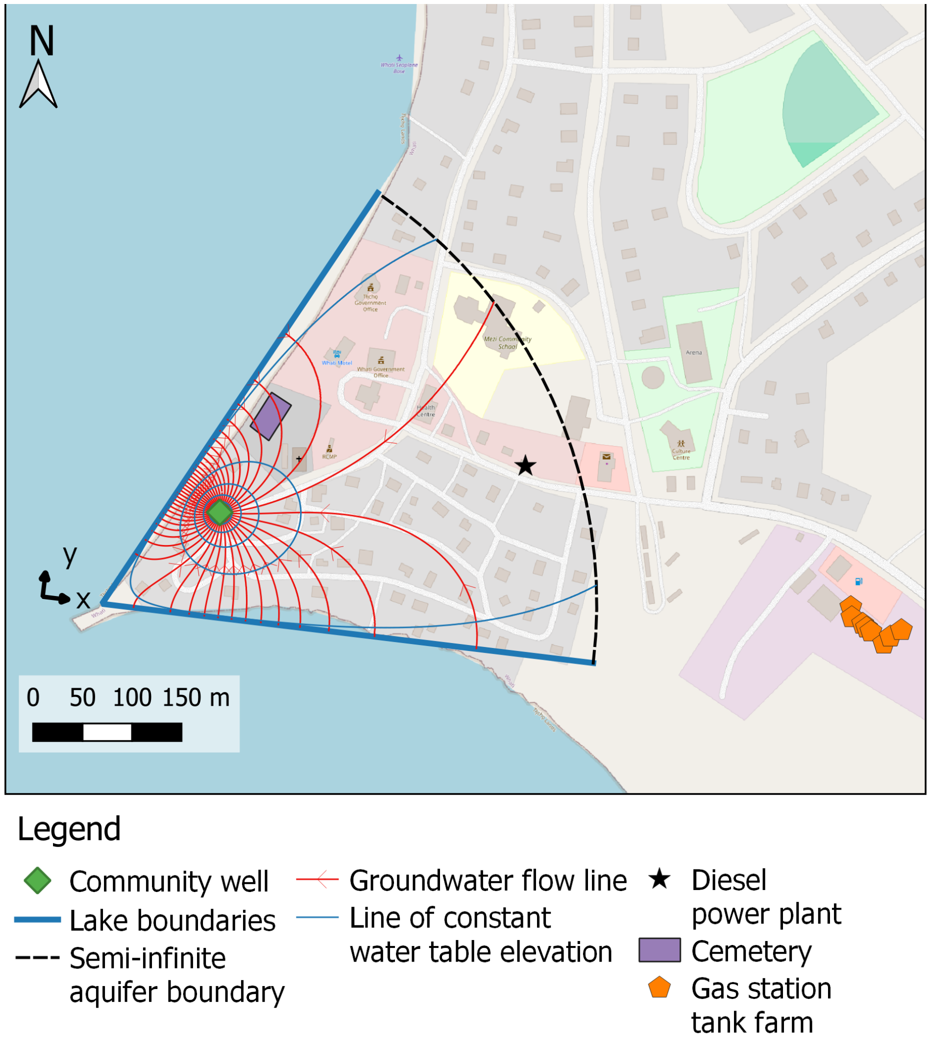

Figure 22. Possible steady state groundwater flow lines and equipotential lines for Scenario 2 (© OpenStreetMap contributors – OSMF, 2023; Stanley Associates, 1987a; Wiebe *et al.*, 2024). This scenario employed a pumping rate of 0.59 L/s, a homogeneous aquifer hydraulic conductivity of 0.017 m/s, a constant aquifer thickness of 3 m, a hydraulic gradient of 1×10^{-5} with groundwater flow toward the southwest, and no permafrost. Under these conditions, no capture zone boundary is present within the calculation region and the capture zone extends from the peninsula toward the east.

One issue and major unknown related to hydraulic conductivity is the continuity of the highly fractured bedrock aquifer from which the community well draws water. The scenarios illustrated here assumed that the aquifer is the same everywhere. Fractures could extend in certain directions, channeling flow preferentially along those lines rather than generally along the direction of the hydraulic gradient. This emphasizes the need for more information about the aquifer properties to assist future work.

Review of Climate Predictions for Whatì

Climate models predict that the Arctic will warm faster than the rest of the globe in response to increased greenhouse gas emissions (e.g., Bintanja & van der Linden, 2013). Indeed, observations from the last few decades have confirmed that this is happening (Serreze *et al*., 2009). Climate models also predict an increase in precipitation across the Arctic, with rain expected to be the dominant form of precipitation by the end of the century (Bintanja & Andry, 2017). These climatic changes are anticipated to have wide reaching impacts on the Arctic environment and on northern communities (Constable *et al.*, 2022; ACIA, 2004). Whatì is located just south of the Arctic circle and therefore likely to experience similar changes.

Dynamically-downscaled climate projections for Whatì were downloaded from the Canadian Climate Change Data Portal (resolution: 50 km x 50 km grid cells; Wang & Huang, 2017). Predicted trends in mean annual temperature are shown in **Figure 23**, and predicted trends in total annual precipitation are shown in **Figure 24**. The four projections (Precis_RCP4.5, Precis_RCP8.5, RegCM_4.5 and RegCM.8.5) were generated using the Precis and RegCM regional climate models under the Representative Concentration Pathway (RCP) 4.5 and 8.5 emission scenarios. The RCP 4.5 scenario is a scenario in which radiative forcing from greenhouse gases is stabilized at 4.5 W/m^2 before 2100. This stabilization assumes a range of technologies and strategies are employed to reduce and mitigate greenhouse gas emissions (Thomson *et al*., 2011). The RCP 8.5 scenario does not assume any measures are taken to reduce greenhouse gas (GHG) emissions. Under this scenario GHG emissions increase over time, leading to a radiative forcing of 8.5 W/m^2 by 2100 (Riahi *et al*., 2011). All projections were driven by the HadGEM2-ES coupled Earth Systems Model.

Linear trends for the downloaded climate projections suggest that mean annual surface temperature for Whatì (**Figure 23**) will increase by 2 ^oC (RegCM_4.5) to 7 ^oC (PrecisCM_8.5) by 2100. Note that while these trends are for mean annual temperature, climate models predict Arctic warming to have a strong seasonality with winter warming exceeding summer warming by at least a factor of 4 (Bintanja & van der Linden, 2013).

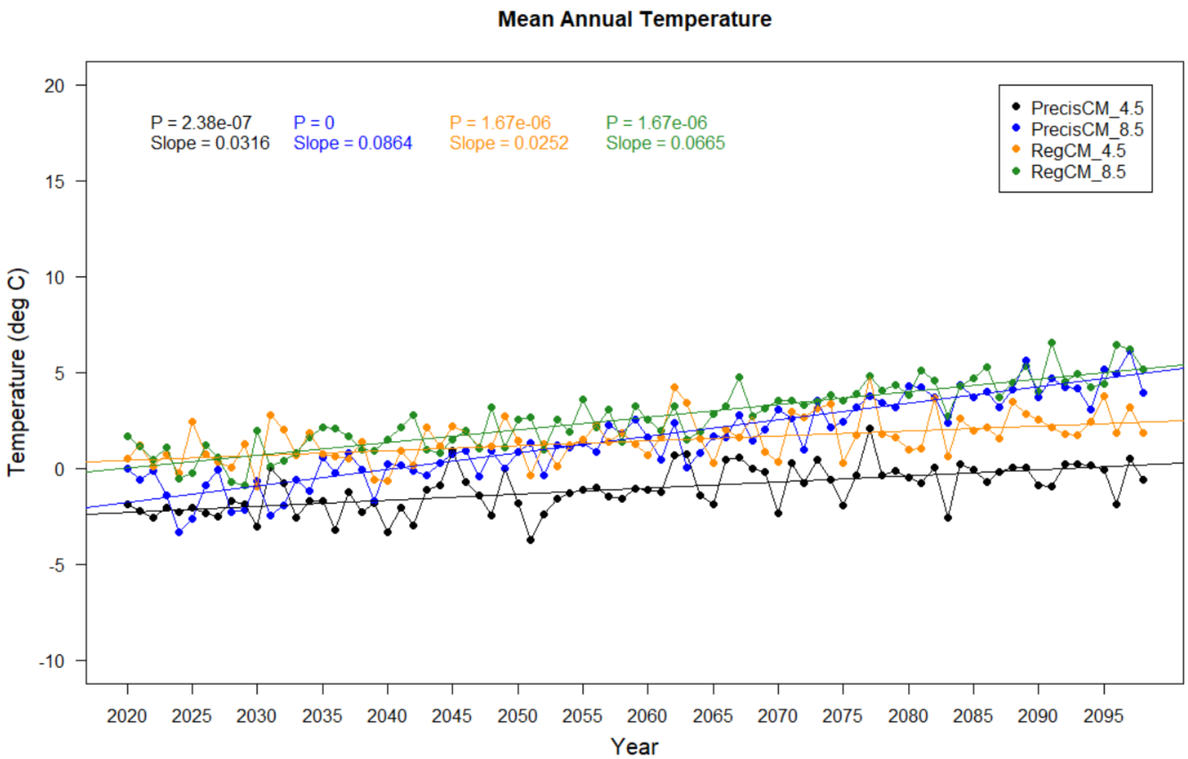

Figure 23. Predicted trends in mean annual temperature for the Whatì area (Wang & Huang, 2017). Solid lines show trends in the data.

Total annual precipitation (**Figure 24**) is also projected to increase by 17 mm (PrecisCM_4.5, not statistically significant) to 75 mm (PrecisCM_8.5) by 2100, overall. It is worth noting that in addition to an increase in annual precipitation, climate models predict an increase in extreme events and precipitation variability (Pendergrass *et al*., 2017). However, precipitation predictions are less well constrained than temperature predictions due the resolution of the downscaled models, which makes it difficult to account for the effects of landscape features as well as convective processes (Allen & Ingram, 2002; Kendon *et al*., 2012). Similarly, the daily time step of the downscaled models makes it difficult to capture localized extreme events that occur on time scales of less than 1 day (Lenderink & van Meijgaard, 2008). Despite the increased uncertainty in the predicted precipitation changes for Whatì specifically, the projections are consistent with other climate models, which predict increased precipitation across the Arctic. These changes need to be taken into consideration when assessing the water security of the community.

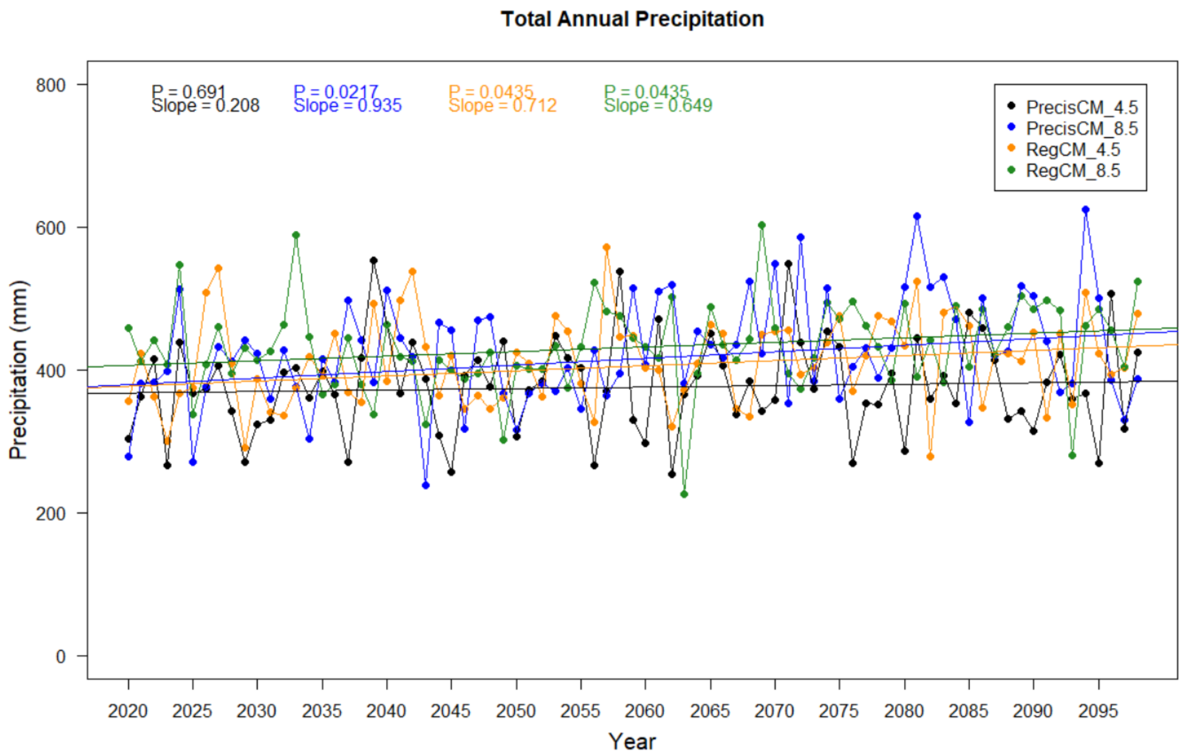

Figure 24. Predicted trends in total annual precipitation for the Whatì area (Wang & Huang, 2017). Solid lines show trends in the data.

Water Security

Potential Water Security Concerns

Water security could be defined as the capacity of a community to safeguard sufficient water quantity and water quality for human and ecosystem needs, including prevention of water pollution (based on the UN definition; UNU-INWEH, 2013). This section focuses on the water quality of the community well and discusses human and environmental factors. Water quantity is less of a concern due to the community's small population and low well pumping rates.

Based on conversations with Elders in Whatì, the water quality of the community well that was installed in the 1980s has not earned the trust of the community for direct drinking water uses. While the quantity of water pumped by the well is sufficient for the community and unlikely to have an impact on the local ecosystem, many community members are looking to other water sources such as the lake and snow because of the taste of the water (mineral hardness of the water and chlorine residual). This means that people often bypass the treatment processes in place at the water treatment plant and favour drinking water sources that are untreated and of unknown quality. Though the lake and snow water is often boiled for tea, this represents a concern from a microbial point of view because disease-causing organisms could be present in the raw water and/or grow when the water is stored for long periods of time, and a short boiling time may not inactivate them.

Considering the vulnerability of the community well itself and the different well protection area scenarios, the capture zone region that contributes water to the well appears to include part of the peninsula on which the community of Whatì is located, and may extend inland farther, depending on the presence of permafrost. This assumes that the highly fractured bedrock aquifer extends similarly in all directions. With permafrost present (**Figure 21**), the capture zone analysis suggested that possible contaminant sources would include the cemetery and household-related sources within the peninsula. Possible contaminant sources include petroleum hydrocarbons such as gasoline and heating oil, household hazardous waste, microbes such as bacteria and viruses in surface water that may cause illness, and household sewage tanks. With no permafrost to prevent groundwater flow toward the lake, the capture zone would extend from the peninsula towards the east. Under these conditions, more potential contamination sources would be of concern, including the diesel power plant, and most of the heating fuel and wastewater tanks in the community, in addition to the cemetery. **Figure 25** shows possible contaminant sources.

Petroleum hydrocarbons such as gasoline and heating oil represent a major threat in cold regions (Wiebe *et al.*, 2023; Treasury Board of Canada Secretariat, 2021). A small volume of these chemicals can potentially contaminate a large aquifer region. Accidental spills may occur when refuelling tanks or vehicles. Due to the potential for rapid flow from ground surface to the well, natural degradation of hydrocarbons may not occur prior to the capture of such contaminants by the well. The diesel power plant within the community (300 m from the well) may be the potential source of contamination of highest concern. Based on the transmissivity of the production well (0.19 m^2/s) estimated from the pumping test by Stanley Associates (1987a) and the fractured aquifer thickness, the hydraulic conductivity (K) of the fractured dolostone aquifer could be as high as 0.06 m/s. Because this is a fractured rock aquifer, the porosity (n) may be relatively high (Freeze & Cherry (1979) suggest a porosity range of up to 20% for limestone and dolostone). With a hydraulic gradient of 0.008 (0.25 m / 300 m, based on Stanley Associates, 1987b), and values of K = 0.06 m/s and n = 0.2, the average groundwater velocity could be 0.00026 m/s. With these estimates, a given contaminant could travel vertically downward through the ~ 10 m thick overburden's silty or clayey soil from the power plant to the fractured bedrock aquifer, then horizontally through saturated ground to the pumping well in a matter of weeks (assuming a direct flowpath from the power plant to the well). However, it is unknown whether the hydraulic conductivity is consistently high throughout the area, or whether the alignment of the bedrock fractures would allow the hydrocarbon contaminants to move toward the well or toward the lake in the case of a spill.

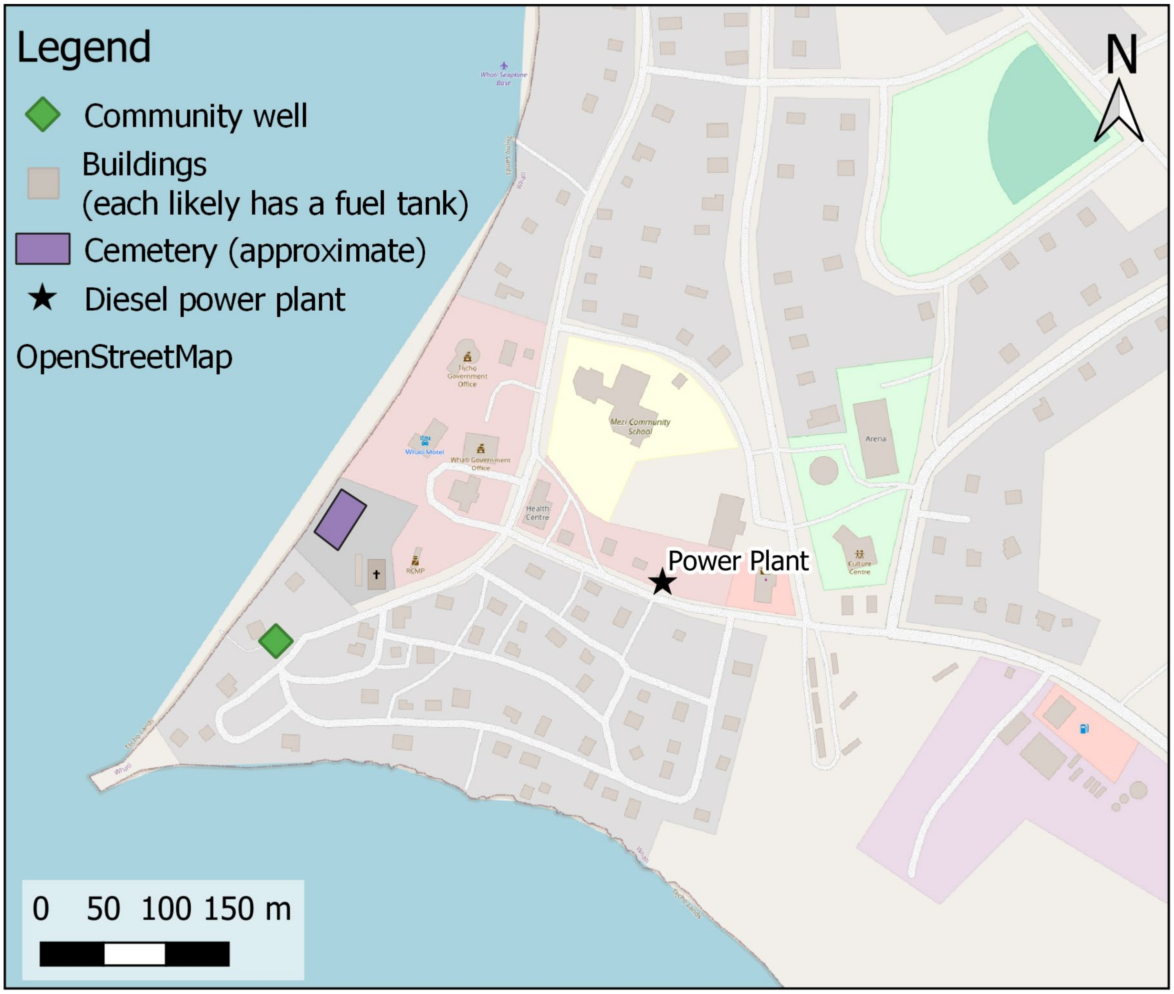

Figure 25. Potential contaminant sources near the Whatì community well (© OpenStreetMap contributors – OSMF, 2023; Stanley Associates, 1987a).

Another source of contamination is household hazardous waste. Harvey and Linquiti (1989) list several examples of such contaminants: solvents, septic systems (sewage tanks), chemicals, paint, and art supplies. Other examples could be items like batteries (a source of lead) and CFL light bulbs (a source of mercury). If such chemicals or items were disposed of into the environment within the community or at the landfill rather than shipped to a hazardous waste centre, they could potentially pose a greater threat to the well. Possible contaminant migration from the landfill is likely to migrate south along with the sewage lagoon runoff.

The short distance between the well and the lake has advantages and disadvantages. The lake offers essentially an unlimited quantity of water (compared to the current pumping rate), yet a contaminant entering the lake anywhere could theoretically reach the well at very small concentrations, if the lake is within the capture zone. The size of the lake suggests that any contaminants entering the lake are likely to undergo substantial dilution. Surface water is essentially always a threat to the microbial water quality at a well, though filtration through sediments offers protection by straining out microbes and allowing time for them to die off. It is unclear what the microbial quality of the raw water at the well is like on a regular basis, and it is also not known whether this may change due to extreme hydrological events (e.g., high water levels in the lake leading to shoreline flooding). Elevated lake water levels could result from permafrost thaw that increases groundwater contributions to the lake, and these could reduce the efficacy of subsurface sediments to filter water flowpaths from the lake to the production well by increasing the hydraulic gradient. The possibility for high lake levels to activate more rapid lateral flowpaths through permeable sediment layers typically above the water table is another concern.

The short distance between the production well and household sewage tanks is another concern. The use of sewage trucks to transport sewage out of the community is a related potential spill hazard. The silty sand soil could potentially have a moderate vertical hydraulic conductivity. The lateral distances between the well and any of the septic tanks in the community would not be a major buffer if there was a spill and sewage soaked into the ground and reached the water table because of the high hydraulic conductivity of the aquifer. The main issue related to contamination via sewage would be disease-causing microbes because a spill would lead to a pulse input of contaminants rather than a long-term legacy of contamination. The household sewage tanks are routinely emptied, implying at worst a potential short-term problem.

As mentioned above, the cemetery is another potential source of contamination. Despite the possible capture zones estimated in **Figures 21 and 22**, it is unknown what direction contaminants might move because, for example, ground surface topography suggests that groundwater flows from the cemetery more directly into the lake rather than toward the end of the peninsula where the well is located. Without additional data regarding the water levels beneath the community, the groundwater flow directions are uncertain.

As noted above, climate change is projected to increase average annual air temperatures by several degrees within the 21st Century and may lead to a slight increase in precipitation and more rain than snow due to warmer winters. Permafrost is already quite discontinuous (Daly *et al.*, 2022) around Whatì, so increased warming and permafrost thaw may result in little further change to the groundwater system. It is unclear whether changes in precipitation would lead to substantial changes in groundwater recharge rates that might affect the groundwater flow system. Because the community well likely receives water from both the lake and the groundwater system at present, there is not likely to be a change in the overall water quantity available. Possible changes in water quality in Lac La Martre from permafrost thaw throughout its large watershed could possibly have some effect on water quality at the well. Again, the mixture of groundwater and lake water within the soil may minimize water quality changes at the well.

Recommendations and proposed next steps

1. Continue learning about groundwater and permafrost

To better understand the potential for groundwater vulnerability, a more systematic vulnerability assessment could be conducted. This could include additional water sampling, and permafrost and aquifer data collection to provide more details on the local flow system around the well. The collection of groundwater samples across the Lac La Martre watershed could further inform the understanding of the groundwater system. The collection of additional water samples for isotopic analysis could also expand current understanding. Routine well water sample analysis, if it is not currently being conducted, would allow for potential microbial concerns to be detected. It is unclear whether the bacteriological water quality of the raw well water is being assessed. No coliform detections were found at the end of the initial 24-hour pumping test at the production well (Stanley Associates, 1987a), but few other sample results seem available. The timing of when iron levels are low in the well should be reviewed along with lake water level changes and iron concentrations during the weeks prior to well sampling. A greater similarity between lake and well iron concentrations could indicate more rapid groundwater recharge or lateral flow processes and therefore greater risk to the well water quality at such times.

A map of water table elevations would be useful for assessing the well's capture zone. A network of observation wells could be drilled in unfrozen soil and monitored, and a flow net (a map of water table elevation contours and flowlines; e.g., **Figures 21 and 22**) could be drawn to describe likely groundwater flow directions. As permafrost thaws in the future, more observation wells could be installed farther inland and farther from the well. Concerns about the cemetery and potential future concerns about the sewage lagoon and landfill could be addressed in this way. Geochemical analyses could also possibly be used to detect potential flowpaths from the cemetery. Any installed monitoring wells would need to be adequately secured (e.g., bentonite chips backfilled into the borehole annulus space; casing cemented in place; lock on the casing) to minimize the likelihood of these wells becoming pathways for contaminants from the surface. Monitoring water levels in an observation well network could become a community and educational activity to assess water flow directions at different times of year. A detailed survey of the ground surface topography within the community would be necessary to draw an accurate water table map.

Mapping of the permafrost table and bedrock would provide further information regarding the effective boundaries of the aquifer and may be useful for a more detailed evaluation of the drawdown cone of the well. The current limit of permafrost and the bedrock depth could potentially be mapped using geophysical techniques that scan underground soils and rock from the land surface. For instance, electrical resistance tomography (ERT; e.g., Salman, 2021; Hubbard *et al.*, 2013), and ground penetrating radar (GPR; e.g., Hubbard *et al.*, 2013; Langston *et al.*, 2011) have been used to estimate permafrost table depths. GPR has also been used to identify bedrock depths in a permafrost environment (e.g., Langston *et al.*, 2011).

2. Improve trust in the well water for drinking water

Groundwater is not a trusted source of drinking water for community members, who traditionally used surface water. The taste, color, and unknown origin and pathways of the water pumped into the well contribute to the mistrust of groundwater as a drinking water source. Improved communication from stakeholders in charge of the drinking water management and from groundwater researchers is essential to help community members to make informed decisions about their water consumption. For example, it may be helpful to provide further information to community members about why groundwater became the preferred source of drinking water, where the water from the well is likely coming from, what the role of the ground is in terms of filtering out harmful bacteria and viruses and in terms of minerals being added to the water, and how groundwater and surface water are closely connected despite their different flow rates. A large, illustrated information board could be created and installed near the water treatment plant to tell the story of the drinking water, from rain and snowmelt to the tap. Relating groundwater to well known processes and features of the landscape may improve trust in the community's groundwater supply. An initial attempt at telling these stories took place during the *What's Happening Under the Land?* workshop in August 2022, which gathered Elders from the community and participants from the Government of the Northwest Territories, Wilfrid Laurier University, and McGill University. Future conversations and events could build on this.

3. Develop a source water protection plan

The development of a source water protection plan would be a useful tool to address the potential water security concerns mentioned above regarding contamination risks. In order to be as meaningful as possible, it should ideally be developed by the community as an exercise of shared groundwater and drinking water protection. Such a plan could include best practices for gasoline, heating fuel tanks, septic tanks, and household hazardous substances and materials to minimize the potential for spills to occur. Petroleum hydrocarbons such as gasoline and heating fuel are common contaminants, and prevention of groundwater contamination by these substances is extremely important. Microbial threats to water quality from bacteria and viruses are also generally a major concern. Action plans should be put in place for what to do if a spill or detection of a contaminant occurs. The plan may also include a strategy to gather additional information about the aquifer and groundwater flow system that could assist in protecting well water quality and in identifying areas of higher and lower risk to groundwater due to potential ground surface contamination within the community. The *NWT Source Water Assessment and Protection (SWAP) Guidance Document* (GNWT ECC, 2013a)[1] and the *NWT Source Water Assessment and Protection (SWAP) Guidance Document - Workbook* (GNWT ECC, 2013b)[2] were developed to help communities with source water protection planning and would be useful tools to apply.

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[1]Available at: https://www.nwtwaterstewardship.ca/sites/water/files/resources/swap_guidance_web.pdf
[2]Available at: https://www.nwtwaterstewardship.ca/sites/water/files/resources/swap_workbook_web.pdf

Conclusions

This report reviewed the groundwater supply in the community of Whatì and considered community concerns, regional geology and permafrost, community water and wastewater systems, characteristics of the community well, hydrology data including watershed streamflow trends, water chemistry and treatment, what is known about the local groundwater system, what the contribution area for the well could look like, and climate predictions for the area. Community concerns in Whatì related to issues such as why groundwater was now used for the community's water supply, why the groundwater and lake water taste different, and what contamination concerns are present for the community well. The community well was drilled in the late 1980s because the adjacent Lac La Martre was considered too shallow to be a secure community surface water supply source. The community well was drilled near the point of the peninsula on which the community is located, and it was screened in a highly fractured dolostone aquifer at a depth of about 10 to 13 m below ground surface. The soils above the bedrock were noted as layers of silty sand and clay. Permafrost in the area has been reported to be discontinuous and cover about 50% of the area, though the well was drilled in an unfrozen soil region. Thawing permafrost may be leading to increased streamflow on average over time, and may allow previously immobile solutes (e.g., salts) to migrate through groundwater and surface water.

Chemistry data from multiple sources including Lac La Martre, surface water features in the region, and the community well suggest that the well is capturing a mixture of surface water and groundwater. The well water has more dissolved minerals than the lake, which would have an influence on the taste of the water. This also means that there has been time for potentially harmful microbes often present in surface water to be filtered out in the soils. Groundwater is often more protected from contamination than surface water by the soil's ability to filter out or absorb microbes or harmful substances.

Several estimates were made of what the community well's capture zone area could look like. These were rough estimates based on the limited measurements and data available regarding the extent and thickness of the fractured dolostone aquifer in which the well was screened. These estimates suggest that the well may transition over time to draw less water from the lake and more from recharge on land under the community as permafrost thaws, though a better estimate of the direction and extent of fractures in the dolostone aquifer would be necessary to confirm the flow directions.

The community well appears to be a relatively secure water supply for the near future, but there is a level of distrust of the taste and colour of the water among some community members. Alternative sources of water such as lake and snow water are untreated and have unknown quality, and storing water for a long time may promote the growth of bacteria and viruses. Further conversations and illustrations of the story of how groundwater and observed processes and features of the landscape are connected may be one way to improve trust in the groundwater supply.

It is important for the community to safeguard the well's water quality, especially because of observed changes in the lake water quality. The well is screened in a highly productive aquifer that could likely support up to 800 people or more at the maximum pumping rate, with its current construction and average NWT or local per person water use. Because the well receives water from Lac La Martre and from the groundwater system, changes in water quality to one of these sources due to climate change may be offset by the other source, leading to less impact. Helpful measures are currently being taken regarding planned shipping of household hazardous waste from the landfill to treatment facilities and the removal of household sewage tank waste to a lagoon several kilometres from the well. The diesel power plant, household heating fuel, and vehicle fuel likely represent the biggest threats to the well. Fuel spills are frequent contamination events in NWT. Careful refuelling and putting in place a water safety plan are necessary.

Future studies could evaluate bedrock depth below ground surface, water table elevations and groundwater flow directions, and aquifer properties. Such studies could assist with answering the question of whether the cemetery is a potential contamination source.

Acknowledgements

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Appendix A

Table A.1. Borehole data (Hardy, 1991; Reid Crowther & Partners Ltd. and D.W. Bernard Groundwater Consultants Ltd., 1984; SNC-Lavalin, 2012; Stanley Associates, 1987a; Stantec, 2017; Thurber, 1981).

Year	**Author**	**Borehole name**	**Permafrost table depth (m)**	**Initial water table depth (m)**	**Weathered bedrock depth (m)**	**Sound bedrock depth (m)**
1981	Thurber	Test hole 81-1	N/A	N/A	8.5	-
1981	Thurber	Test hole 81-2	N/A	N/A	10.6	-
1981	Thurber	Test hole 81-3	N/A	N/A	9.8	-
1981	Thurber	Test hole 81-4	N/A	N/A	11.2	-
1981	Thurber	Test hole 80-1	3.66	1	-	-
1981	Thurber	Test hole 80-2	3.6	0.6	-	-
1981	Thurber	Test hole 80-3	2.4	2 [*]	-	-
1981	Thurber	Test hole 80-4	4.3	1.2	-	-
1981	Thurber	Test hole 80-5	4	3	-	-
1981	Thurber	Test hole 80-6	4	2	-	-
1981	Thurber	Test hole 80-7	1.8	-	-	-
1981	Thurber	Test hole 80-8	3	1	-	-
1981	Thurber	Test hole 80-9	5.2	2.4	-	-
1984	Reid Crowther	Lac La Martre	-	4.15	10	N/A
1987	Stanley Assoc.	1-87	N/A	3.66	10 [‡]	N/A
1987	Stanley Assoc.	2-87	N/A	3.61	10 [‡]	N/A
1987	Stanley Assoc.	3-87	N/A	3.46	10 [‡]	N/A
1991	Hardy	BH-4	2.4 [†]	N/A	N/A	11.2
1991	Hardy	BH-5	3.2 [†]	N/A	9.4	10.4
1991	Hardy	BH-6	3.5 [†]	N/A	11.4	11.9
2012	SNC-Lavalin	C101	-	-	-	0.61
2012	SNC-Lavalin	C101A	-	-	-	0.61
2012	SNC-Lavalin	C102	-	-	-	0.3
2012	SNC-Lavalin	C103	-	-	-	0.91
2012	SNC-Lavalin	C104	-	-	-	0.61

Year	Author	Borehole name	Permafrost depth (m)	Initial water table depth (m)	Weathered bedrock depth (m)	Sound bedrock depth (m)
2012	SNC-Lavalin	C105	-	-	-	0.52
2012	SNC-Lavalin	D100	-	-	-	1.1
2012	SNC-Lavalin	D100A	-	-	-	0.91
2012	SNC-Lavalin	D100B	-	-	-	1.22
2012	SNC-Lavalin	D101	-	-	-	1.22
2017	Stantec §	BH17-54	-	0.9	-	7.6
2017	Stantec §	BH17-55	-	-	-	1.8
2017	Stantec §	BH17-56	-	-	-	1.5
2017	Stantec §	BH17-61	-	-	-	5.8
2017	Stantec §	BH17-62	-	-	-	1.2
2017	Stantec §	BH17-63	-	-	-	7
2017	Stantec §	BH17-64	-	-	-	2.4
2017	Stantec §	BH17-65	-	-	-	1.5
2017	Stantec §	BH17-66	-	-	-	1.4
2017	Stantec §	BH17-67	-	-	-	6.4
2017	Stantec §	BH17-68	-	-	-	3.7
2017	Stantec §	BH17-69	-	-	-	3.8
2017	Stantec §	BH17-70	-	-	-	1.2
2017	Stantec §	BH17-75	-	2.1	-	7.6
2017	Stantec §	BH17-76	-	-	-	1.2
2017	Stantec §	BH17-77	-	-	-	1.7
2017	Stantec §	BH17-78	-	-	-	2.1
2017	Stantec §	BH17-79	-	-	-	0.8
2017	Stantec §	BH17-80	-	-	-	0.3
2017	Stantec §	BH17-81	-	-	-	1.4

* Estimated
† Hardy (1991) boreholes were drilled in Mar 1991 during frozen soil conditions; permafrost depth approximated based on ice-rich soil.
‡ Estimated based on comments in the report.
§ Stantec (2017) boreholes were drilled until auger refusal (assumed to be bedrock depth).