Investigating Artificial Sweeteners As Groundwater Tracers Of Landfill Contamination In A Complex Landscape

By

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Contribution of Authors

This thesis is the result of my M.Sc. Research project in the Department of Earth and Planetary Sciences at McGill University. It consists of three chapters. Chapter 1 is a general introduction and literature review of a history of contamination in the NWT, a review of toxicity frameworks and groundwater vulnerability frameworks, a review of assessing baseline conditions, and a review of investigating groundwater contamination. Chapter 2 is a manuscript for subsequent submission, on which I am the first author and primary contributor to the data analysis and writing. Co-authors for the paper will include Jeffrey McKenzie and Isabelle de Grandpré. They helped define the research question of this thesis and assisted with field experiments. They contributed to funding the research, outlining the goals of this project, and proofreading the manuscripts. They were also essentials in the data collection and field work aspect of the project. Chapter 3 is a brief summary of the research and suggestions for directions of future work.

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Abstract

The Arctic and Subarctic are warming at twice the global average rate, leading to rapid changes in hydrologic systems, including a greater risk of contamination from anthropogenic and geogenic sources. The solid waste facility for Yellowknife, Northwest Territories, was unofficially opened in the 1970s and hazardous and nonhazardous waste was deposited on a site with little containment, leading to contamination of the surrounding groundwater. To understand how this leachate is entering the environment through groundwater, an uncontaminated baseline condition must be determined. Establishing baseline conditions in the region is complicated by the presence of geogenic groundwater contamination, nearby historic and current mining activities, and the lack of existing "natural" groundwater data. My MSc thesis research utilizes artificial sweeteners as an innovative tracer of landfill contamination to differentiate between local contamination sources and baseline groundwater conditions. Artificial sweeteners, whose approval in Canada coincides with the opening of the Yellowknife landfill, are an emerging tracer of landfill contamination that provide a unique fingerprint for leachate of different ages. In August 2022, a synoptic sampling of 25 samples of surface water and groundwater in and around the solid waste facility was undertaken. Samples were analyzed for artificial sweeteners, stable isotopes of water, major dissolved ions, and organic contaminants. The resulting data, analyzed with different geochemical and graphical methods, were compared to existing local datasets from nearby mines and historic data. Geospatial analysis was used to assess the leachate pathways. Three off-site leachate migration pathways through surface and groundwater were identified based on elevated sweetener concentrations and distinct ratios between sweetener types. The results show that a region to the northwest of the site appears to be unaffected by leachate and may be a potential location for background monitoring. The research results provide an improved understanding of hydrologic flow paths and benefit long-term monitoring of other sites such as mines, nuclear storage, and abandoned infrastructure in Arctic and Subarctic regions.

Résumé

Les régions arctique et subarctique se réchauffent deux fois plus vite que la moyenne planétaire, entraînant des changements rapides dans les systèmes hydrologiques, dont un risque accru de contamination de source humaine et géogène. La décharge de déchets solides de Yellowknife (Territoires-du-Nord-Ouest) a ouvert de manière non officielle dans les années 1970, et des déchets dangereux et non dangereux y ont été déposés dans un site peu confiné, entraînant la contamination de l'eau souterraine environnante. Pour comprendre comment ce lixiviat entre dans le milieu par le biais de l'eau souterraine, l'état non contaminé de référence doit être établi. L'établissement de conditions de référence dans la région est compliqué par la contamination géogène de l'eau souterraine, des activités minières passées et actuelles et l'absence de données sur l'eau souterraine « naturelle ». Dans mes travaux de maîtrise, des édulcorants artificiels sont utilisés comme traceurs novateurs de contamination de site d'enfouissement pour distinguer différentes sources locales de contamination et les conditions de référence de l'eau souterraine. Les édulcorants synthétiques, dont l'approbation au Canada coïncide avec l'ouverture de la décharge de Yellowknife, commencent à être utilisés comme traceur de contamination de site d'enfouissement pouvant fournir l'empreinte digitale de lixiviats de différents âges. Le prélèvement synoptique de 25 échantillons d'eau souterraine et de surface dans la décharge et ses environs a été réalisé en août 2022. Des analyses des édulcorants artificiels, de la composition d'isotopes stables de l'eau, des principaux ions dissous et des contaminants organiques ont été réalisées sur les échantillons. Les données produites ont été analysées par différentes méthodes géochimiques et graphiques et comparées à des ensembles de données locales existantes pour des mines à proximité, ainsi qu'à des données historiques. L'analyse géospatiale a été utilisée pour évaluer les voies empruntées par le lixiviat. Trois voies de migration hors site du lixiviat par le biais de l'eau souterraine et de surface ont été cernées sur la base de concentrations élevées d'édulcorants et des rapports de concentrations de différents édulcorants. Les résultats montrent qu'un secteur au nord-ouest du site ne semble pas contaminé par le lixiviat et pourrait constituer un site de surveillance des conditions de référence. Les résultats de ces travaux améliorent la compréhension des voies d'écoulement hydrologique et

seront utiles pour la surveillance à long terme d’autres sites, tels que des mines, sites de stockage de déchets nucléaires et infrastructures abandonnées, dans les régions arctique et subarctique.

1. Introduction and Literature Review

1.1. A History of Contamination in Northwest Territories

1.1.1. Colonialism and Resource Extraction

The first mining exploration in present-day Canada was to Baffin Island in 1577, resulting in Frobisher shipping back 200 tonnes of his "discovery" to England. The gold turned out to be 200 tonnes of pyrite (Rea, 2019). Frobisher was followed in his pursuit of minerals by Hearne in the 1770s. Hearne's search for the copper used by the Yellowknives Dene was the beginning of colonial resource extraction in the Northwest Territories (NWT). Since then, the current borders of NWT now encompass 1,665 federally recognized contaminated sites (Secretariat, 2022), many of the highest priority sites which are related to the long history of mining in the NWT. For instance, Giant Mine, within the municipal boundaries of Yellowknife, has enough arsenic trioxide stored under it to poison the entire population of the world 37 times over (Rea, 2019; Sandloss & Keeling, 2012). Although arsenic can chemically and biologically transform in the environment, it will continue to pose a threat to human and environmental health for thousands of years. The long-term persistence of contaminated sites makes it important to understand the history of socio-economic decisions that create contaminated lands and bodies and will continue to do so long after their economic lifetime is finished.

It is important to recognize that from 1870 to today, the colonial borders of the NWT have changed drastically. The socio-cultural context of contamination is a story of power, oftentimes expressed through borders. The shifting colonial borders of Canada reflect negotiations of power over land, people, and resources, and the legacy of these negotiations are the borders of today. The extent of the Northwest Territories has been largely a negative space drawn around provinces and divided based on changing needs for governance and resource discovery. Even the name, Northwest Territories reflects initial corporate interests rather than geophysical concerns (Rea, 2019). Similar to Rupert's Land, NWT was claimed by the North West Company, which later merged with the Hudson's Bay Company (Rea, 2019). In the age of militant geography (Nicol et al., 2016), lasting colonial Canadian place names and borders describe resource opportunities for exploitive industry (ex: Coppermine River), and the human resources attached to them (ex: Copper Inuit, Yellowknives Dene). In the distant heartland, the names of landmarks reference men who gained their wealth from controlling the Northwest Territories (ex: McTavish, Mackay, etc.).

The history of contamination in NWT follows patterns of human movement, economic interests, and changing geopolitical powers. Extractivism plays a large part in this timeline, as towns, roads, railroads, dams, and treaties are established to accommodate mining activities (Gobby, Temper, Burke, & von Ellenrieder, 2022; Rea, 2019; Sandlos & Keeling, 2016). For instance, the town of Pine Point is only on maps from 1974-1988, but the legacy contamination from the lead and zinc mine began in the 1920s, is currently the object of several environmental concerns (Sandloss & Keeling, 2012) and will continue to exist into the far future without any intervention (it can be seen on the map below as the blue point to the East of Hay River).

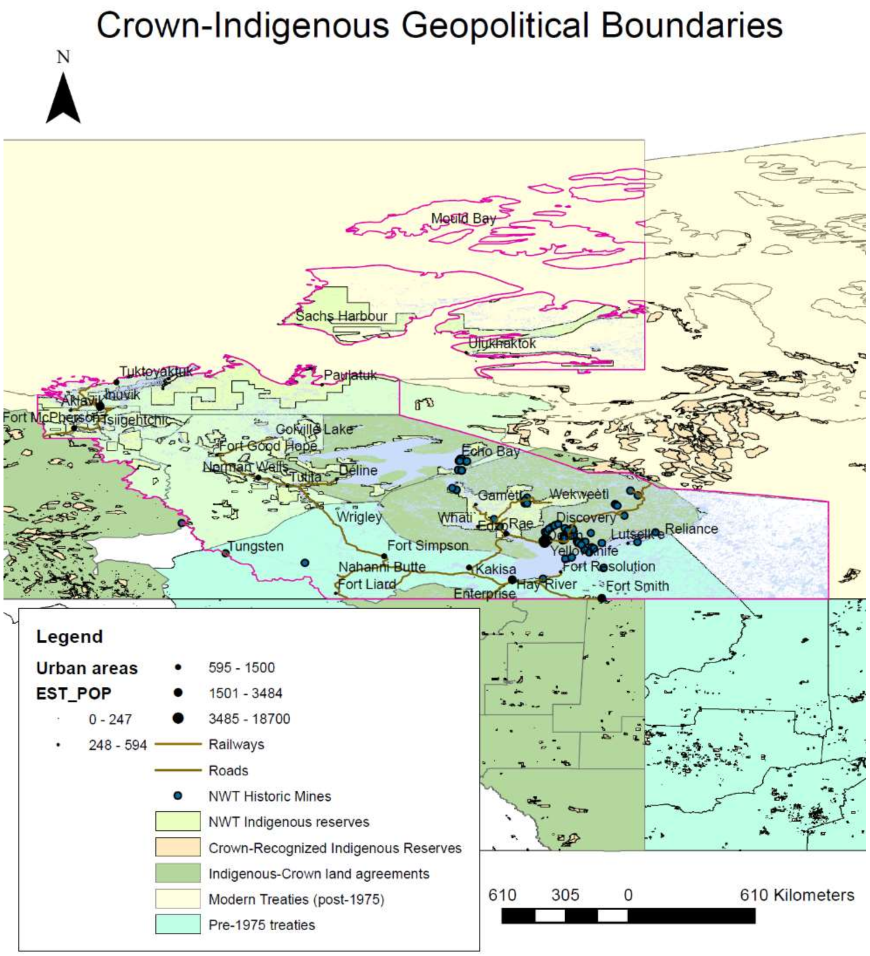


Figure 1. Crown-indigenous geopolitical boundaries on NWT.

Map created using data from Open Source Federal and Territorial Sources (G. o. Canada, 2023; Government, 2022; Secretariat, 2022; G. o. t. N. Territories, 2020)

Pine Point serves as a larger anecdote for the role of extractivisim in legacy contamination. Exploration activities in the 1920s around where Pine Point would eventually be locally precede Treaty #11 by only a year, as the Canadian government needed a way to maintain control over industry activities (Rea, 2019; Sandloss & Keeling, 2012). Exercising control through boundaries can be seen at many spatial scales; for instance, the Yellowknife municipal borders include 8 historic mine sites, with obvious taxation advantages for the city. Thirty years later, the newly renamed "Department of Northern Affairs and National Resources" (a telling name in itself) touted the Pine Point project as the centerpiece of its Northward expansion and "industrial modernization" agenda (Sandlos & Keeling, 2009, 2016; Sandloss & Keeling, 2012). CM & S, a subsidiary of Canadian Pacific Railway (CPR), which would later become Cominco (and the owner of 2 historic mine sites in Yellowknife), pressured the Canadian government for exclusive rights, and a lack of oversight which resulted in no consultation with Indigenous Nations in the area despite a large alienation of land within Treaty 8 (including preventing Indigenous trappers from accessing traplines in the newly alienated land) (Sandlos & Keeling, 2016; Sandloss & Keeling, 2012).

On the other hand, the Pine Point project was presented to Indigenous Dené and Métis people as an economic opportunity, as declining caribou and fur trading were ongoing concerns, yet the mine rarely employed any Indigenous people due to its lack of housing which would split up families (Sandloss & Keeling, 2012). Creating the Pine Point mine involved building a dam (which is still being fought as a socio-environmental disaster for Indigenous groups in the flooded area) to generate energy to build a railroad to move the ore to distant markets, and a road and townsite for workers and their families to arrive from the South (LeClerc & Keeling, 2015). The mine produced 82 million tons of tailings during its 28 years of operation, which remains as the only remnant of the town since every building and the railroad was removed or destroyed in its entirety upon closure of the mine (Abbate, Bortolotti, & Passerini, 1970; Sandloss & Keeling, 2012; Shoebridge & Simons, 2011). There were no environmental remediation requirements at the time and much of the tailings were released into Great Slave Lake (LeClerc & Keeling, 2015; Sandloss & Keeling, 2012).

Pine Point, besides acting as an anecdote for the workings of capitalist modernization agendas in the Canadian North, is also a story of contamination and people. Although there has been an award-winning media project about Pine Point from the residents' perspective, no one lives in Pine Point anymore, only contamination, and the people who continue to be affected by the legacy contamination are the Indigenous communities downstream of the tailings, within the flooded area from the dam, and who received no compensation or respect in the process of creating and closing this mine (Shoebridge & Simons, 2011).

1.1.2. Current Landscape and Calls to Action

The current and future landscape of contamination in the NWT is a patchwork of legacy and ongoing contaminated sites, increasing climate change, and ongoing geopolitical agreements, with many governing bodies involved in a single watershed. The future of these sites is debatable, but the recent Tlicho land agreement is a case study of ongoing dynamics surrounding contamination and points to a future of increased calls for remediation and accountability. The Tlicho Agreement (2005), which includes surface and subsurface rights, specifically excludes 9 contaminated areas from Tlicho Land and are instead designated as Crown Lands for investigation and remediation (C.-I. R. a. N. A. Canada, 2013). The Crown Lands are former mine sites for Uranium or Gold with additional contamination from hydrocarbons, asbestos, tailings, abandoned infrastructure, and dump sites (C.-I. R. a. N. A. Canada, 2013). In a few cases, new mineral claims and leases were given to mining corporations from the Government in exchange for remediation services on the territory (C.-I. R. a. N. A. Canada, 2013). No remediation or investigation activities have been reported since 2013 (Secretariat, 2022). The key point is that new land claims involve subsurface rights, but these land claims purposely avoid previously contaminated areas even though they are part of traditional lands. This puts the onus on the Canadian government for supervising remediation; however, it also allows the Canadian government to continue leasing the land to mining companies (as it is currently doing). This legacy contamination essentially functions to extend colonial control and corporate interests into the future. Contamination is therefore functioning as a border-controlling factor; whereas, initial treaties were used to secure Indigenous consent for mining operations to continue: the contamination these historic mines produced serves to exclude Indigenous governance and maintain extractive industry and Canadian control into the future.

The other point to be considered with this overlap of land claims and contamination is Article 29 outlined in United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) (which Canada legally singed onto in June 2021 (D. o. J. Canada, 2021) which stipulates: “2. States shall take effective measures to ensure that no storage or disposal of hazardous materials shall take place in the lands or territories of indigenous peoples without their free, prior and informed consent. 3. States shall also take effective measures to ensure, as needed, that programmes for monitoring, maintaining and restoring the health of indigenous peoples, as developed and implemented by the peoples affected by such materials, are duly implemented.” (Assembly, 2007). In this case, the Federal Contaminated Sites Inventory (FCSI) and the smaller subset of contamination outlined in the Wek’èezhìi land claim agreements both face a lack of data and monitoring of contaminated sites (C.-I. R. a. N. A. Canada, 2013; D. o. J. Canada, 2021). For instance, 73% of the licenses in the contaminated sites inventory are suspected sites or known sites with an unknown amount of risk (Secretariat, 2022). Additionally, the FCSI, which is organized through an economic framework, fails to account for environmental conditions, characteristics of specific contaminants, contaminators, the history of the contamination, or externalities within the economic costs (such as loss of habitat or human health) (Secretariat, 2022). In total, this dataset therefore fails to meet the conditions of UNDRIP through its incompleteness and narrow economic framework.

Table 1. Comparison of contaminated sites

Comparison of contaminated sites, as reported by the FCSI, and population, as reported by Statistics Canada. NWT is home to 1,665 contaminated sites total, or 405 /10,000 people, 68 times the national average (Secretariat, 2022; Statistics, 2020)

Province or Territory	Number of Sites	Population	Per 10,000 People
Alberta	1,141	4,262,635	2.68
British Columbia	4,819	5,000,879	9.64
Manitoba	1,426	1,342,153	10.62
New Brunswick	1,041	775,610	13.42
Newfoundland and Labrador	2,508	510,550	49.12
Northwest Territories	1,665	41,070	405.41
Nova Scotia	1,811	969,383	18.68
Nunavut	807	36,858	218.95
Ontario	3,935	14,223,942	2.77
Prince Edward Island	318	154,331	20.61
Quebec	2,491	8,501,833	2.93
Saskatchewan	1,739	1,132,505	15.36
Yukon	147	40,232	36.54
Total Canada	23,848	36,991,981	6.45

The ties between contamination and colonial power struggles are not subtle. The Federal Contaminated Sites Inventory lists the Department of Crown-Indigenous Relations and Northern Affairs as the reporting agency for roughly 32% of all the contaminated sites in the NWT, yet 51% of contaminated sites are within 10 km of Indigenous Reserve Land (G. o. Canada, 2023; I.

S. Canada, 2023; Secretariat, 2022). Additionally, of the 2212 contamination licenses on Indigenous Reserve Land, only 247 of them include any estimated amounts of contaminants (Secretariat, 2022). In the future, ensuring the rights of Indigenous people in Canada will include autonomy and information on contaminated sites.

1.2. Toxicity and Groundwater Vulnerability Frameworks

Groundwater vulnerability frameworks are used to identify and weight aspects of an aquifer system that allow for susceptibility to changes and contamination. These frameworks exist in many formats based on their use, which creates a lack of consistency across vulnerability literature (Alessa et al., 2008; Elshafei, Sivapalan, Tonts, & Hipsey, 2014; Hynds et al., 2018). Three key categories of frameworks have been developed to assess aquifer vulnerability, socio-environmental concerns, and climate change impacts (Alessa et al., 2008; Mark et al., 2017; Nadiri, Gharekhani, Khatibi, Sadeghfam, & Moghaddam, 2017; Srinivasan, Lambin, Gorelick, Thompson, & Rozelle, 2012). However, rarely are all aspects combined, and even less reflect cold regions-specific concerns such as heightened seasonality, slope aspect, and permafrost (Wiebe et al., 2023). Additionally, there is a pedagogical disconnect between these mainly Western frameworks and Indigenous relational approaches to environmental management that allows for connections between human decision-making, natural conditions, and the diverse feedbacks on both to be understood in a systematic way (Castleden, Hart, Cunsolo, Harper, & Martin, 2017; Wilson, 2020; Wilson, Harris, Joseph-Rear, Beaumont, & Satterfield, 2019; Wilson, Montoya, Arseneault, & Curley, 2021). Even within earth science literature, vulnerability is often contained within one earth system component (i.e. groundwater) rather than assessing the health of an area as a whole, and when connectivity is considered, it is rarely defined in a consistent way (Ali, Oswald, Spence, & Wellen, 2018).

Contamination itself is also difficult to quantify. Contamination and contaminants are determined by limits set by human actors and enforced differently across spatial and temporal scales. Regulations on the definition of “contamination” can be set based on human health, environmental health, and technical ability, which result in many different limits set in overlapping areas. In Yellowknife, a key example is the regulation of arsenic. The arsenic standard (goal) is a total concentration in soil of 340 ppm for non-urban and 160 ppm for residential areas, whereas the average natural background is 150 in Yellowknife (Bromstad, Wrye, & Jamieson, 2017; Jamieson, 2014; Palmer et al., 2021). In comparison, the Canadian standard is 12 ppm (Environment, 2023). With remediation beginning at Giant Mine, water quality guidelines set by the GNWT currently consider > 52 ppb total concentration of arsenic an "elevated" amount (GNWT, 2023). In this example, arsenic regulation is determined by technical ability for remediation and natural background conditions, since the human body is negatively impacted by any amount of arsenic and can cause generational impacts even without continued exposure (Guo et al., 2018; Mohammed Abdul, Jayasinghe, Chandana, Jayasumana, & De Silva, 2015).

In addition, the timescales of contamination must be accurately reflected. What does it mean to live in a permanently contaminated environment? What are the consequences for the future of epigenetic changes after remediation? This longevity of toxicity has concretely changed the way contamination is viewed (Liboiron, Tironi, & Calvillo, 2018). Spatially, removing the dimension of time creates a visual landscape where collections of actions are flattened into an array of features (Hadjikyriacou, 2021; Harris, 2021; Lawson, Bavaj, & Struck, 2022). Contamination being the main feature created by the actions of colonialism and extraction across time. Practically, in Canada, proving the timeline of contamination is also necessary for allocating remediation funding and identifying the responsible parties (I. S. Canada, 2023).

Quantifying the histories of contamination is essential for a holistic framework that incorporates timelines of contamination, including their futures. The legacy of contamination is guided by human decision-making, therefore reflecting the values, politics, and scientific climate of the time. Especially in the Canadian territories, changes in access, and the power it entails, are displayed in the distribution of contaminated sites (Nicol et al., 2016; Robards & Alessa, 2004). Access is moderated by transportation, electricity, political agreements and borders, industrial demands and geography. Access Theory points to the definition of access as opposed to property as the ability to derive a benefit rather than a right to it (Ribot & Peluso, 2009). In this thesis, one of these abilities is the ability to derive the benefit of contaminating. For a landfill, its presence becomes a contaminant in the environment, but the economic, hygienic, and aesthetic benefit of choosing this contamination to the people of a municipality and the local government cannot be overstated. In Yellowknife uniquely, scavenging at the landfill is a normal practice and residents have fought to keep that ability (Elliot, 2019).

In fact, there is a congruency between the timelines of environmental impacts, social legacy, and accessibility of the Yellowknife Solid Waste Facility (SWF) compared to the legacy mine sites in the area. Whereas the legacy of the landfill is one of communal decision-making, is equally accessible to all residents for a variety of purposes, and is exclusively locally beneficial; the legacy mines are rooted in the decisions of distant national, economic, and industrial powers, are inaccessible to the community (and has created inaccessibility of food and water resources from legacy contamination), and have created benefits for distant actors while disadvantages local actors (Sandlos & Keeling, 2016). This is called "wastelanding" where a place considered wasteland by the powers at play because it is not useful to them and turned into wasteland by these same powers for locals for whom it was never wasteland (Liboiron et al., 2018).

1.3. Baseline Conditions

1.3.1. Cold Region Variables

Groundwater vulnerability frameworks are largely developed in and for temperate climates. It is important to recognize the variables that are essential for understanding cold region hydrogeology and how these variables differ from traditional parameters in vulnerability frameworks. Permafrost, heightened seasonality, and rapid climate change resulting in intensified hydrology are some of the factors that make Arctic and Subarctic regions unique from their southern counterparts (Alessa et al., 2008; Bakker, 2012; Branch, 2019; Cochand, Molson, & Lemieux, 2019; Gorelick & Zheng, 2015; Goulding, 2011; Hjort et al., 2018; Jasechko et al., 2014). Permafrost (i.e. perennially frozen ground) acts as a barrier or aquitard to groundwater flow within hydrogeologic systems (Walvoord & Kurylyk, 2016). Due to rapid Northern warming and thawing permafrost, contamination that was previously frozen or that had limited mobility, may now become more mobile (McKenzie et al., 2021).

1.3.2. Geogenic Hazards

Constituents that naturally occur in toxic levels in the environment are called geogenic contaminants. In the Canadian north, the key geogenic contaminants are arsenic, mercury, and uranium (Medeiros, Wood, Wesche, Bakaic, & Peters, 2017; Palmer et al., 2021; Pelletier et al., 2020; Survey, 2022). At the regional scale, deeper groundwater hydrochemistry in cold regions behaves similarly to confined aquifer units due to being isolated by permafrost (Cochand et al., 2019; Doré, Niu, & Brooks, 2016; Hjort et al., 2018; Langer et al., 2023; O'Neill et al., 2020; Edward A. G. Schuur & Abbott, 2011; E. A. G. Schuur et al., 2015; Teufel & Sushama, 2019; Walvoord & Kurylyk, 2016; Whiteman, Hope, & Wadhams, 2013; Zipper, Lamontagne-Hallé, McKenzie, & Rocha, 2018). With changing and diminishing permafrost extent, these isolated waters are now able to mix between aquifers and surface water. For example, Skierszkan et al. (Skierszkan, 2019) found that 39% of wells in the Dawson Range had uranium concentrations exceeding drinking water guidelines. In cold regions, uranium and arsenic mobilization may be enhanced by thawing of permafrost, which leads to changes in redox potential, increased chemical weathering, more groundwater flow, and greater microbial activity (Skierszkan, 2019). The toxicity of these constituents depends on conditions such as redox potential, presence of other ions, and mobility in water sources.

1.3.3. Legacy Contamination

The Northwest Territories is home to 105 historical mine sites in varying stages of remediation. Within the Yellowknife municipal border itself there are eight historical mines. One of these mine sites, Giant Mine, stores 237,000 tonnes of arsenic dust in its underground chambers, not including the arsenic dust released into the air and deposited in the soils 15 km around the city which led to the deaths of 2 people in the 1950s (Sandlos & Keeling, 2016). It also doesn't include the arsenic stored in tailings ponds on the property, nor the contributions of the other 2 historic gold mines in the city limits (Bromstad et al., 2017; Ferguson, 2016; Jamieson, 2014; Pelletier et al., 2020; Sandlos & Keeling, 2016). Many studies have quantified the amount of arsenic contributed to the soils, waters, animals, plants, and people from the mine sites, but some uncertainty still exists in the severity of long-term effects (Bromstad et al., 2017; Jamieson, 2014; Nasser et al., 2016; Palmer et al., 2021; Wang & Mulligan, 2006).

Although the Giant Mine site closed in the 1990s, no remediation has been attempted on the site (Beckett, 2021; Zueter, Newman, & Sasmito, 2021). Currently, there are plans to install “hockey rink technology” to freeze the arsenic dust in place and prevent infiltration into groundwater (Zueter et al., 2021). Five billion CAD is currently budgeted to begin remediation on this site, however there is a suggestion that this would only cover eight years of operating the equipment to keep the arsenic frozen after an initial one billion dollars installation (C.-I. R. a. N. A. Canada, 2023). The mine itself only made four billion CAD over its 50-year operation (Jamieson, 2014).

1.4. Investigating Groundwater Contamination

1.4.1. Tracers

Artificial sweeteners (acesulfame, cyclamate, sucralose, and saccharin) are an emerging tracer of groundwater contamination from anthropogenic sources (Chattopadhyay, Raychaudhuri, & Chakraborty, 2014; James W. Roy, Van Stempvoort, & Bickerton, 2014; Van Stempvoort, Roy, Brown, & Bickerton, 2011). Sweeteners have several advantages over other tracers since they are abundant, non-toxic, solely from anthropogenic activities, and temporally constrained. When analyzing a suite of sweeteners, a signature can be used to distinguish different contamination sources. Acesulfame was approved for use in Canada in 1988 and sucralose in 1992, whereas saccharin and cyclamate were both in use during the 1960s (Chattopadhyay et al., 2014). Sorption and biodegradation of saccharin and acesulfame may be possible under certain groundwater conditions, but this still requires more research (Luo et al., 2019; Propp, Brown, Collins, Smith, & Roy, 2022). There is also conflicting evidence on sweeteners’ persistence in soil and under different microbial activity (James W. Roy et al., 2014). The use of sweeteners as a tracer is best applied for current contamination issues since they are limited to an approximate 30-year window (Van Stempvoort et al., 2011). Sweeteners have been used as tracers of urban contamination along streams (James W Roy & Bickerton, 2010), surface water –groundwater interaction (Van Stempvoort et al., 2011), leachate influence on groundwater (Roy et al., 2014), distinguishing contamination sources in groundwater (Khazaei & Milne-Home, 2017), and mining waste in groundwater (Liu, Ptacek, Groza, Staples,

& Blowes, 2022). Environmental isotopes are useful as a co-tracer with sweeteners to help constrain water source, age, and mixing. Especially when combined with an analysis of major ions, isotopes are instrumental in distinguishing between different ages of groundwater in fractured bedrock aquifers (Douglas, Clark, Raven, & Bottomley, 2000).

1.4.2. Synoptic Sampling

Cold regions present a variety of challenges with groundwater data collection such as a short window of unfrozen ground, lack of groundwater wells, and remote access. One tool to overcome these limitations is synoptic sampling where samples are taken from a variety of sources over a short time period (Baraer et al., 2015). This method creates a snapshot of the hydrological system where groundwater and surface water interactions are studied co-currently. This approach aligns with the conceptual holistic approach to monitoring environmental vulnerability, and it also functions practically to reduce costs associated with groundwater well installation. Synoptic sampling regimes have been used mainly for acid mine drainage when combined with tracer injection (Briant A. Kimball, Runkel, Walton-Day, & Bencala, 2002; Briant A Kimball, Walton-Day, & Runkel, 2007; Robert L Runkel, Verplanck, Walton-Day, McCleskey, & Byrne, 2023; Robert L. Runkel, Walton-Day, Kimball, Verplanck, & Nimick, 2013), but they have also been successful in high altitude glacier hydrology without tracer injection (Baraer et al., 2015; Mckenzie, Mark, Thompson, Schotterer, & Lin, 2010). Isotopic and source-dependent geochemical analysis are useful in synoptic sampling for determining mixing and source type. Classic geochemical groupings of groundwater from piper plot analysis are also useful in this case (Tóth, 1999). They serve a similar practical use where areas with limited data or a lack of existing models can be investigated using traditional graphical methods which require a limited analytical suite (Wiebe et al., 2023). Additionally, a synoptic sampling approach is usually paired with a spatial model to infer relative contributions from a variety of sources or catchments.

1.5. Objectives

The overarching objective of my MSc research is to investigate the transport and fate of contamination from the Yellowknife SWF, including evaluating the use of artificial sweeteners (a food additive) as a tracer of contaminant pathways.

The sub-objectives of my MSc research project are to: 1) contribute to the NWT territorial government's groundwater monitoring plan by establishing baseline water quality conditions for local groundwater around the SWF, 2) improve current groundwater vulnerability frameworks to account for anthropogenic sources of contamination under changing environmental conditions, and 3) investigate the wider temporal and spatial concerns presented by a constant influx of non-degradable contaminants into water resources.

Context of Chapter 2 Within Thesis

Chapter 2 is a manuscript describing the methodology, results, and interpretation of fieldwork to understand the interaction between leachate from the Yellowknife SWF and regional background groundwater.

2. Sweeteners as groundwater tracers of landfill contamination in a complex landscape

2.1. Introduction

Climate change is rapidly reshaping the landscape of the Arctic and Subarctic as the circumpolar North has already experienced up to 6°C of warming in the past 50 years (Ballinger et al., 2020; Monitoring, 2017).The interrelated effects of surface air temperature warming, including associated increased flooding, increased forest fires, intensified permafrost thaw, and decreased snowmelt are diverse, widespread, and only beginning to be identified (Goulding, 2011; Macfarlane, 2020; E. A. G. Schuur et al., 2015; Thoman, Richter-Menge, & Druckenmiller, 2020; Zipper et al., 2018). Groundwater, water that is stored in and flows through the ground, connects this complicated and changing landscape at the intersection between soil, surface water, permafrost, and people (McKenzie et al., 2021). Additionally, the number of people and industries relying on this rapidly changing environment is increasing, and to varying extents, water consumption demands are being met by using groundwater resources (Goulding, 2011). However, Northern development has also led to a legacy of contaminated sites that are being exasperated by warming and permafrost thawing (Langer et al., 2023; Wiebe et al., 2023). For example, historical decisions on solid waste storage and containment have failed to account for increasing population and environmental changes.

In the Northwest Territories, Canada (NWT), there are 1,665 federally recognized contaminated sites. This is the sixth highest number of contaminated sites or 7% of all sites in Canada despite a population representing only 0.12% of the total population (S. Canada, 2016; Secretariat, 2022). For additional comparison, Nunavut and the Yukon (YK) have 954 contaminated sites, combined (Secretariat, 2022). Additionally, there are 49 contaminated sites in the NWT and YK exclusively from municipal landfills (Figure 2) (Government, 2022; Yukon, 2014). Many landfill contaminants pose a threat to groundwater, the environment, and people; these include hydrocarbons, metals and cations, toxic nonmetals, microorganisms, radionuclides, and volatile organic compounds (Abiriga, Vestgarden, & Klempe, 2020; Fetter, Boving, & Kreamer, 1999).

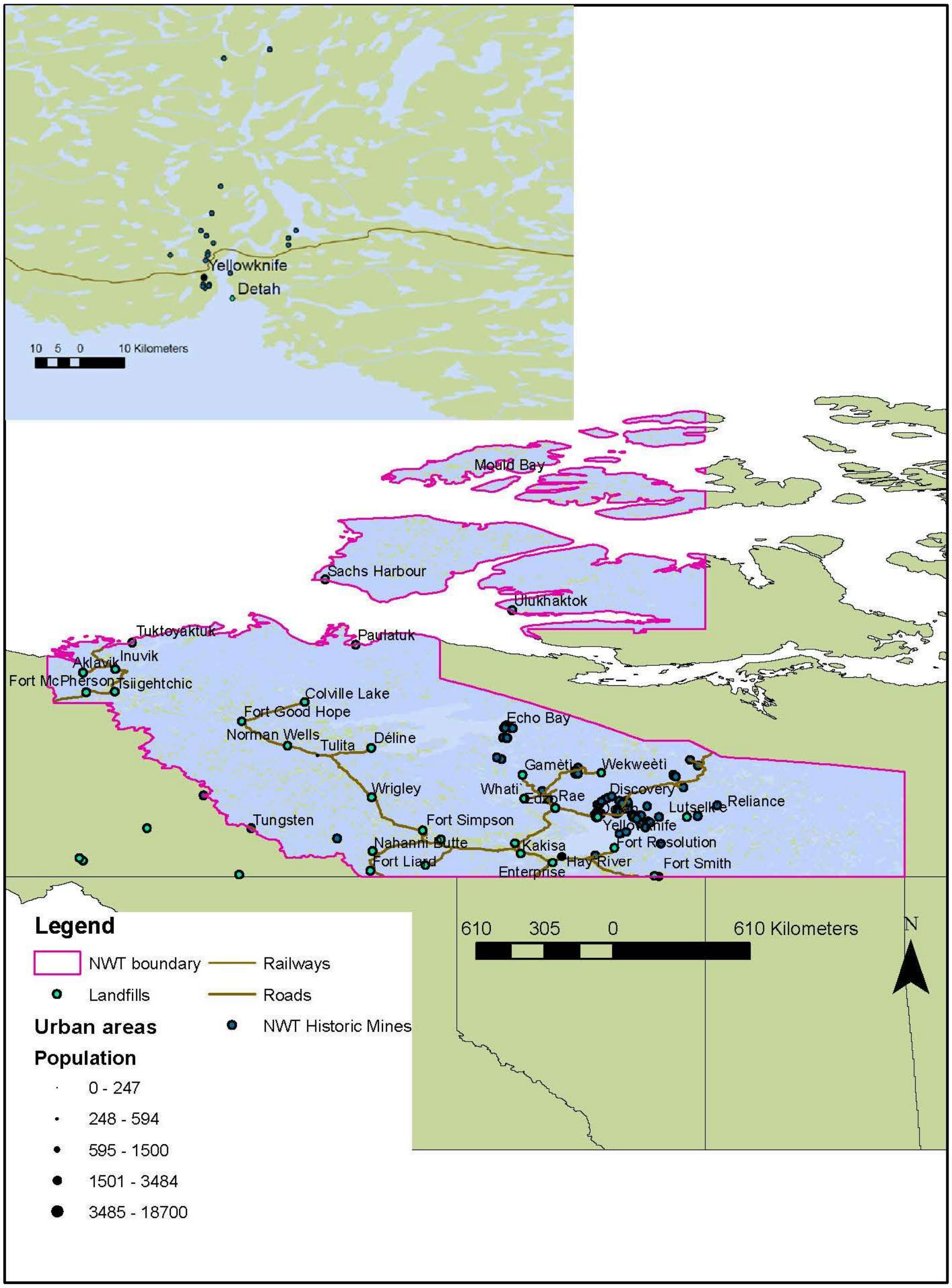


Figure 2. Contamination Sources in the NWT.

Map of overarching contamination sources in the NWT and Yellowknife area, including historic mine sites and landfills (data sourced from federal and territorial open data (G. o. Canada, 2023; Government, 2023; G. o. N. Territories, 2020))

Groundwater contamination itself presents a unique environmental challenge due to its relatively long residence times, difficulty in characterization, and allowing for long-term contaminant storage and migration. Groundwater, due to its long-term contact with surrounding natural rocks, can also have a high dissolved solid content, some of which can be toxic geogenic contaminants (e.g., Skierszkan et al, 2020). Sources of contamination to groundwater in NWT include mines, pipelines, landfills, roads, chemical spills, sewage tanks, and abandoned infrastructure. Additionally, there are many pathways for contaminants to enter groundwater systems and their associated mobilization mechanisms.

Due to the local geology in NWT, several heavy metals in groundwater are above generally accepted standards for the protection of aquatic life and drinking water. The bedrock and soils naturally contain arseno-sulfides, and the local background concentration for natural arsenic concentrations is 150 ppm, which is 12.5 times the Canadian standard (Jamieson, 2014). However, the current level of arsenic in the Yellowknife area is much higher in soils, organisms, surface water, and groundwater (Bromstad et al., 2017; Jamieson, 2014; Nasser et al., 2016; Palmer et al., 2021). Additionally, the changes to groundwater associated with landfill leachate (such as changes in pH, introduction of cations, and reducing conditions) may lead to mobilization of otherwise immobile elements, such as arsenic (As). Therefore, geogenic contamination is considered a major factor in determining a geochemical baseline for groundwater and asserts that the baseline cannot simply follow a standard threshold for all hazardous parameters. The quantification of the effect of geogenic contamination within contaminated areas has been explored in several studies, but their methods have yet to be applied to a landfill context (Grande et al., 2005; Nordstrom, 2009; Palmer et al., 2021; Skierszkan, 2019).

Mining and related activities are a major part of the NWT economy. In Yellowknife there are eight historic mines within the city limits that were in operation from the 1930s until the 2000s (Bromstad et al., 2017). Giant Mine is the largest in terms of legacy contamination, with 237,000 tonnes of arsenic trioxide dust stored under the mine (Jamieson, 2014). For reference, this is enough As to provide a lethal dose to the entire world population 37 times over. This number does not include the first five years of operations where roaster-generated As was released, unfiltered, into the air and now is incorporated into the regional soils, biology, and waters (Bromstad et al., 2017). Given this history within Yellowknife, prior mining activity introduces another layer of complexity in determining the natural or anthropogenic origins of contaminants in the soil infiltrating groundwater. The contamination of the mines in Yellowknife is a tangible legacy of social injustice caused by settler-colonialism and capitalism. This level of mining-driven contamination is not unique to Yellowknife, as much of the Northwest Territories faces similar challenges.

Within the landscape of highly contaminated sites in NWT, there are also many smaller legacy contamination issues. For example, in the municipality of Yellowknife, there is the Yellowknife Solid Waste Facility (SWF), also known as the Yellowknife Landfill. Previous environmental monitoring at the SWF has encompassed surface water, soil, and groundwater monitoring, with a specific focus on understanding the interactions between the SWF and nearby contaminated sites, such as the Giant Mine legacy site. While previous investigations have focused on the SWF specifically, results have been limited in scope and temporal comparisons.

The overarching objective of my MSc research is to investigate the transport and fate of contamination from the Yellowknife SWF, including evaluating the use of artificial sweeteners (a food additive) as a tracer of contaminant pathways.

The sub-objectives of my MSc research project are to: 1) investigate the applicability of artificial sweeteners as tracers of leachate contamination in a Northern setting, 2) in regions with complex water chemistry, establish baseline groundwater water quality, and 3) investigate the wider temporal and spatial concerns presented by a constant influx of non-degradable contaminants into water resources.

2.2. Study Site

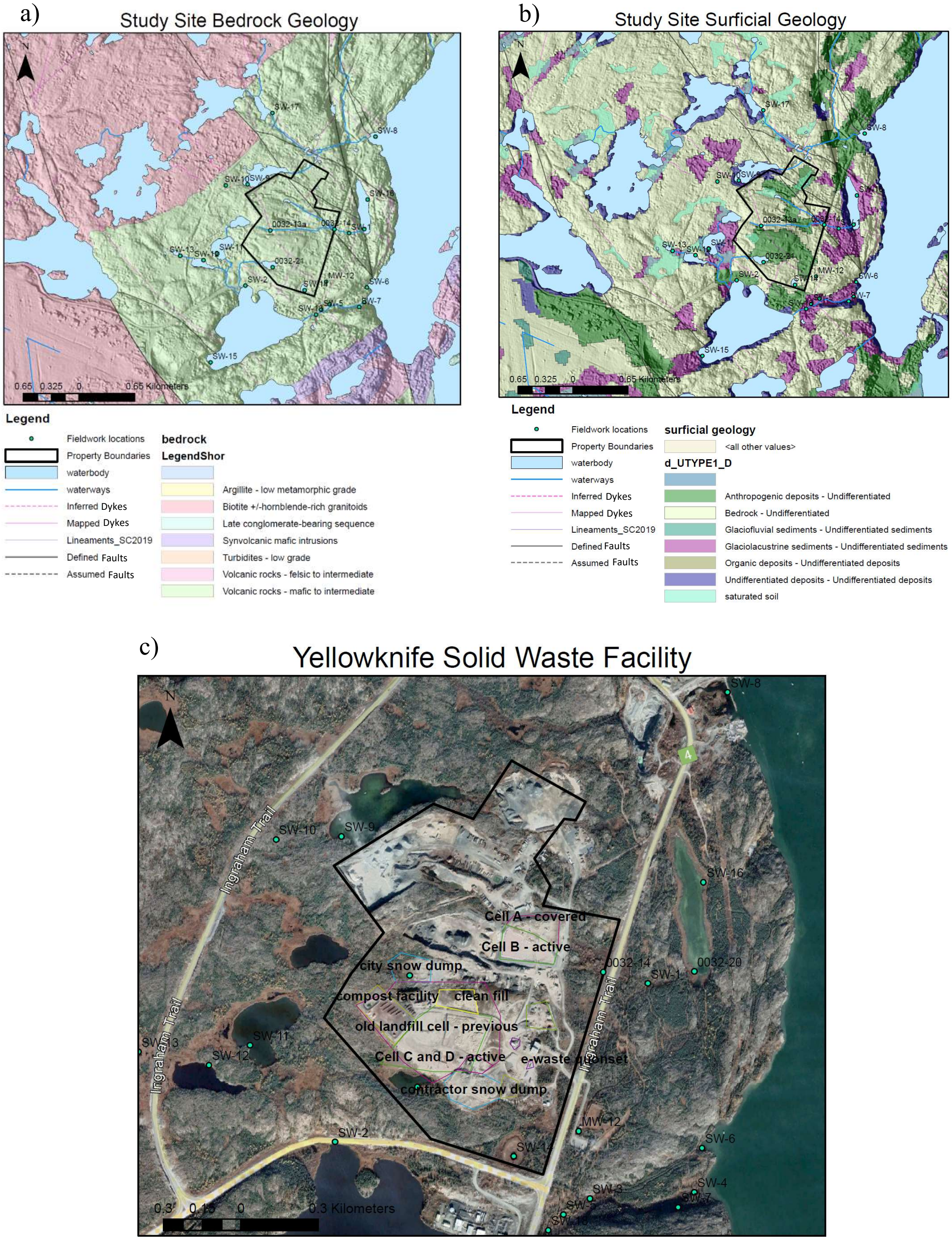


Figure 3. Study Site. Site overview of the a) bedrock geology, b) surficial geology, and c) Solid Waste Facility cells on an aerial map of the SWF (Survey, 2022; Yellowknife, 2021).

Yellowknife is situated on Chief Drygeese Territory, home of the Wiliideh Yellowknives Dene (Yellowknife, 2023), and the traditional lands of the Tłı̨chǫ Ndè, Akaitcho, Denendeh (Dënësųłinế Nëné), Michif Piyii (Métis), and Dënéndeh (Land, 2023). Yellowknife is on the shores of Yellowknife Bay on Great Slave Lake and is part of the Mackenzie Valley watershed. The Mackenzie Valley watershed drains 20% of Canada's total surface area, including the two largest lakes in Canada, Great Bear Lake and Great Slave Lake (Abdul Aziz & Burn, 2006). In 2003, 75% of the drainage basin was underlain by continuous or discontinuous permafrost (Abdul Aziz & Burn, 2006; Board, 2003; M. R. B. Board, 2023). Yellowknife is in the Great Slave sub-basin within the Mackenzie Valley watershed (Board, 2003; M. R. B. Board, 2023).

Average monthly temperatures in Yellowknife vary between -29.5 and 17 °C, with an annual temperature average of -4.6 °C. Monthly precipitation varies between 11.3 mm and 40.8 mm, with a total annual average of 288.6 mm, with 65% falling as snow (Resources, 2023). Being the second largest watershed in North America, there are many monitoring agencies and governments involved in the health of the drainage basin, the most prominent being the Mackenzie Valley Land and Water Board, who are made up of members appointed by Indian and Northern Affairs and the Tłı̨chǫ Government (M. V. L. a. W. Board, 2023).

This study focuses on the Yellowknife Solid Waste Facility (SWF). The SWF was an unofficial dumping area from the 1950s, with new cells not constructed until 2011 (Yellowknife, 2012). The SWF continues to be the official landfill for the Yellowknife municipal area. The SWF was to be closed in 2010, but has continued to operate continuously with some re-structuring of landfill cells and opening of new lined cells (Yellowknife, 2017). Waste deposited in the Yellowknife SWF includes scrap vehicles, metals, construction and commercial waste, and waste from surrounding mines (Dillon, 2006, 2012). The site currently contains asbestos, glycols, household hazardous waste, CFCs, propane tanks, batteries, heating oil tanks, paint, and other hydrocarbon sources (Yellowknife, 2021). There are four main cells of the SWF, with two new cells (one of which covered), and two uncovered cells on the historic landfill area (Yellowknife, 2021). The lack of covering allows for precipitation and snowmelt infiltration, which can generate potential leachate. A previous assessment of the SWF in 2012 confirmed leachate infiltrating the soils and bedrock; however, no extensive study has been completed since this time (Dillon, 2012).

Several monitoring wells and surface water sampling stations were installed within the SWF during surveys to prepare for the potential closure in 2010. Since 2012, reconstruction at the SWF has buried some of the pre-existing monitoring wells, and new wells have been added (Dillon, 2017; Yellowknife, 2021). The lack of continuity in monitoring presents issues with quantifying changes in leachate during the past 10 years. In the most recent report (Yellowknife, 2021), the leachate signature included Cl, F, N, Al, As, B, Cr, Cu, Fe, Pb, Hg, Se, Ag, and U above the Canadian thresholds for human health (Dillon, 2017; Yellowknife, 2017). Additionally, there is a lack of groundwater monitoring outside the extent of the leachate, and therefore a clear baseline groundwater quality is not well understood. Establishing baseline conditions is compounded by a lack of any region-specific standards or policies for water quality. There are predicted faults and fractures in the bedrock under the north side of the SWF, where there are no monitoring wells; these faults and fractures may be high permeability pathways for leachate since the bedrock itself is a low porosity igneous composition (Dillon, 2012). The regional groundwater flow was identified to be eastward from the SWF towards Yellowknife Bay, part of Great Slave Lake (Dillon, 2012).

The SWF sits in a bedrock bowl of mafic volcanic, gabbro, and diorite of the Kam Group (Yellowknife Bay Fm.) with depth to bedrock between surface level and 40 m below ground surface (170-200 m.a.s.l.) within the SWF area (Yellowknife, 2021). Giant Mine, Con Mine and Negus Mine exploited the same bedrock unit within a 3 km radius of the SWF (Douglas et al., 2000; Jamieson, 2014; Palmer et al., 2021). The western and northern perimeters of the SWF are underlain by shallow bedrock (5-10 m below ground surface) and the southeastern side is characterized by an “L-shaped” depression (bedrock >35 m below ground surface) (Dillon, 2017). Faults in the area trend generally NW-SE and dykes/intrusions form two series, one trending NW-SE and the other NE-SW. There is a major fault to the east of the SWF, West Bay Fault, which has been geochemically characterized by a study at Con Mine (Douglas et al., 2000). Overburden at the site is composed of glacial till and peat (Dillon, 2012). No permafrost has been observed the site for as long as monitoring has occurred.

The general topography of the SWF slopes southeast toward both Yellowknife Bay and Jackfish Lake (Figure 3). The surface hydrology of the site is subdivided into 7 sub-catchments of which it is estimated 50% of runoff through two sub-catchments drain into Fault Lake to the east, 33% through three sub-catchments drain into Jackfish Lake to the south, and 16% through two sub-catchments drain into Back Bay on Great Slave Lake to the southeast (Yellowknife, 2021). The site is ringed by several small ponds and wetlands to the north, west, and south and culverts to the east.

The hydrogeology of the SWF is not well understood. Due to the low permeability of the metamorphic igneous bedrock, it is expected that groundwater flow is through fractures. However, a previous report found no correlation with groundwater flow and known faults and dykes (Yellowknife, 2017). The regional groundwater flow has been found to generally flow in a southeast direction toward Jackfish Lake and Great Slave Lake, with some local flow to the west (Dillon, 2012). Parameters consistent with leachate have been observed in all functional monitoring wells and are present in several surface water monitoring locations over the last decade of monitoring.

Other sources of contamination of anthropogenic and geogenic nature are legacy mine sites, soil and water contamination widely released from the mine sites, the city center, the arsenic-bearing bedrock. Of the eight historic mines within the Yellowknife municipal boundaries, Giant Mine is situated 2.5 km north of the SWF, while Con Mine and Negus Mine are the next closest at just under 5 km to south of the SWF. Yellowknife's city center is 2.5 km to the south of the SWF property. Additionally, the mafic volcanic bedrock unit underlying the SWF and the legacy mines extends in a narrow faulted zone north and south of the SWF, and is considered to have a background of approximately 30 ppm arsenic (Bromstad et al., 2017; Palmer et al., 2021).

2.3. Methods

2.3.1. Data Collection

From August 15 to August 22, 2022, 25 water samples were collected for analysis of dissolved solute geochemistry, stable isotopes in water, and dissolved artificial sweeteners as well as *in situ* physiochemical measurements. The procedures for duplicates and blanks follow the quality assurance and quality control (QA/QC) guidelines set by the 2021 Yellowknife SWF Interim Groundwater Monitoring Plan (Yellowknife, 2021). Samples were taken from surface water (n=19), groundwater springs (n=5), and one groundwater well (n=1) (Figure 3). Sampling locations are divided into 3 categories: 1) SWF surface water monitoring locations, 2) surface water and groundwater springs, and 3) surface water locations based on their potential as upgradient baseline water quality sites. The samples were taken within a radius of 2 km around the SWF and follow a synoptic sampling approach. Sampling procedures for surface water and groundwater springs are based on the standards of the GNWT Surface Water Sampling Procedures whereas the groundwater well was sampled according to the procedures outlined by the Yellowknife Government in their SWF Interim Groundwater Monitoring Plan from 2021 (Yellowknife, 2021).

In situ parameter measurements included water temperature, dissolved oxygen (DO), conductivity (SPC), pH, redox potential (ORP), and turbidity (NTU), and were measured using a YSI EXO1 sonde. A general description at each site was recorded, including weather, vegetation, and any other notable factors. Geochemistry samples were collected based on Taiga Environmental Laboratory procedures and then transported in a cooler to the Laboratory each day for analysis. Taiga Environmental Laboratory is a Yellowknife based analytical laboratory that performs a wide range of organic and inorganic chemical analyses on numerous materials, including freshwater, groundwater, drinking water, and industrial effluents. A complete list of measured parameters and procedures is in Supplementary Materials 1. Samples for hydrogen and oxygen (^{2}H and ^{18}O) isotopes were taken at every sampling location and analyzed at McGill University using VSMOW standards. No filtration or preservation beyond refrigeration is required for isotopic sampling. Samples collected for sweetener analysis were filtered in the field using a 0.22-µm filter, after 30 mL of water was flushed through the filter to dissolve and remove any saccharin coating and avoid false positives. The sweetener samples were collected in 30 mL HDPE bottles, refrigerated, and analyzed at the Environment and Climate Change Canada laboratories in Burlington, Ontario. Each sample was analyzed for 4 sweeteners, cyclamate, acesulfame, saccharin, and sucralose. The sampling and analysis procedures follow those described in Van Stempvoort et al. (2011) and Roy and Bickerton (2010).

2.3.2. Data Analysis

Results are combined and standardized for trend and spatial analysis. ArcGIS is used for spatial analysis. Results are compared to historical geochemistry data sourced from the 2010-

2021 Yellowknife SWF water license reports for surface water and 2016-2021 license reports for groundwater. Additional groundwater geochemistry data was sourced from a preliminary groundwater monitoring plan that encompassed data from 2010-2012 (Dillon, 2012). Collected and pre-existing data was integrated as separate layers in ArcGIS and then several spatial models were built in arcModelBuilder to analyse spatial statistics and changes over time.

Major ion analysis is largely based on sample grouping on a Piper Plot (Piper, 1944). A Piper Plot is a graphical representation of the major ion chemistry of water samples, in which major cations (Ca, Mg, Na, K) and major anions (Cl, SO_4, CO_3, HCO_3) are plotted on separate ternary diagrams, and then projected onto the Piper Diamond. According to the location of the sample on the diamond, the hydrochemical facies of the water sample is identified, and is diagnostic of chemical aspect of samples and may indicate mixing relationships. 2022 data was compared to the past decade of data from SWF water licenses; however, inconsistencies in historical sampling regimes due to reorganization at the solid waste facility make direct temporal comparison challenging. Several additional constituents were compared, such as Cl-/Br- ratios and Nitrogen source types. These measurements were included due to their common usage to identify pollution source types, such as leachate (Kjeldsen et al., 2002).

2.4. Results

The results and summary statistics for artificial sweetener sampling results are presented in Table 2**Error! Reference source not found.**. Total sweetener concentrations ranged from below the detection limit (< 2 to 20 ng/L, depending on sweetener type) to over 3700 ng/L. Of the 25 sample sites, cyclamate was present at 3 sites, sucralose was present at 6 sites, saccharin was present at 14 sites, and acesulfame was present at 22 sites. Of the 4 sweetener types measured, sucralose was the most abundant by sum-total of all concentrations, while acesulfame was the dominant sweetener at the majority of the sites. Most sites had more than one sweetener type present; two sites (0032-21 and MW-12) had all 4 sweetener types, and one site (SW-17) had no sweeteners present.

Table 2. Artificial Sweeteners Results

Artificial sweeteners concentrations from 2022 sampling regime and associated statistics. *Statistical measurements calculated using an average for sites with field and lab duplicates.

	ng/L	ng/L	ng/L	ng/L	ng/L
Minimum detection limit	2	2	3	20	1
Practical quantitation limit	6	6	8	60	3

Sample Name	Location Description	Acesulfame	Saccharin	Cyclamate	Sucralose	Total
0032-13a	Snow dump in SWF	461	420	324	n.d.	1205
0032-14	SWF culvert	771	12	n.d.	573	1356
0032-14	SWF culvert (lab duplicate)	807	13	n.d.	707	1527
00-32-14-1	SWF culvert (field duplicate)	802	n.d.	n.d.	993	1795
0032-20	Fault lake (input)	548	37	n.d.	1783	2368
0032-21	Lake in SWF	1466	222	427	1602	3718
MW-12	Well SE of SWF	17	38	9	731	795
SW-1	Spring into fault lake	447	232	n.d.	1947	2626
SW-2	Jackfish lake (N input)	64	26	n.d.	n.d.	90
SW-3	Wetlands into creek into back bay	25	n.d.	n.d.	n.d.	25
SW-4	Creek into back bay (by old cemetery)	23	n.d.	n.d.	n.d.	23
SW-4	Creek into back bay (by old cemetery)	25	n.d.	n.d.	n.d.	25
SW-5	Anoxic spring into creek into back bay	32	7	n.d.	n.d.	39
SW-6	Bay N of Back Bay	9	n.d.	n.d.	n.d.	9
SW-7	Ice falls	16	7	n.d.	n.d.	23
SW-8	Great Slave Lake (S of GM)	39	5j	n.d.	n.d.	39
SW-9	Joe Lake (N of SWF)	36	n.d.	n.d.	n.d.	36
SW-10	Fault NW of SWF	134	6	n.d.	n.d.	141
SW-11	Middle small lake (W of SWF)	723	37	n.d.	1077	1836
SW-12	Southeast small lake (W of SWF)	142	49	n.d.	n.d.	191

		ng/L	ng/L	ng/L	ng/L	ng/L
	Minimum detection limit	2	2	3	20	1
	Practical quantitation limit	6	6	8	60	3
Sample Name	**Location Description**	**Acesulfame**	**Saccharin**	**Cyclamate**	**Sucralose**	**Total**
SW-13	Lake other side of highway from SW-12	22	5j	n.d.	n.d.	22
SW-14	Small lake outside SWF to SE	18	n.d.	n.d.	n.d.	18
SW-15	Jackfish lake (by cemetery)	47	31	n.d.	n.d.	78
SW-15	Jackfish lake (by cemetery, lab duplicate)	49	34	n.d.	n.d.	83
SW-15-1	Jackfish lake (by cemetery, field duplicate)	51	7	n.d.	n.d.	58
SW-16	Fault lake (output)	66	14	n.d.	n.d.	80
SW-17	Lake farthest North, background	n.d.	n.d.	n.d.	n.d.	0
SW-18	Culvert from jackfish lake to back bay creek	36	3j	n.d.	n.d.	36
TB	Trip Blank	4j	9	n.d.	n.d.	9
FB	Field Blank	4j	7	n.d.	n.d.	7
	Maximum	1466	420	427	1947	3718
	Minimum	n.d.	n.d.	n.d.	n.d.	0
	Total*	5167	1158	760	7897	14966
	Average*	246	43	27	336	652

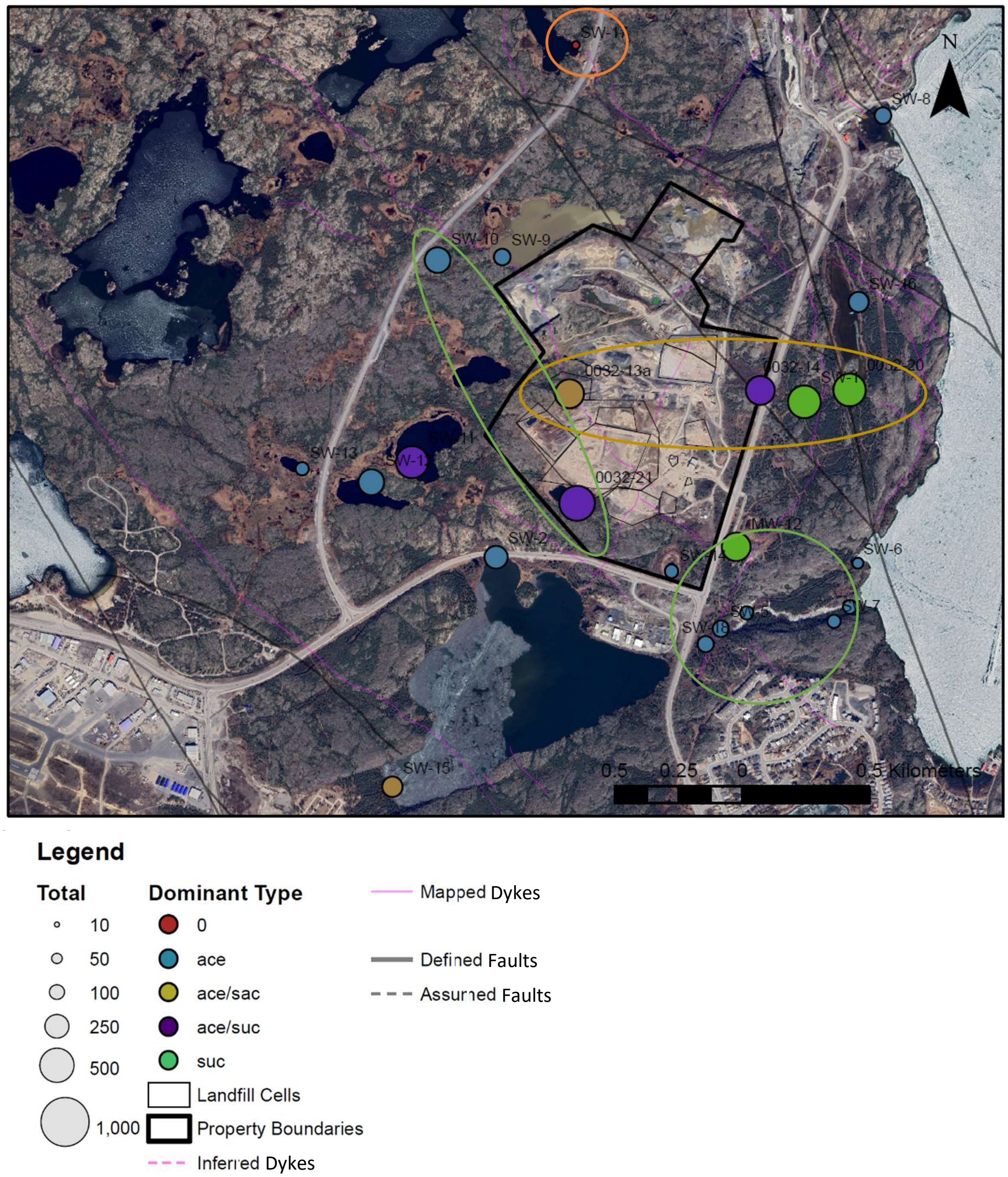


Figure 4. Sweetener and isotopic results

Sweetener concentrations are presented sized by total concentration and colour by dominant sweetener type. Purple is sucralose/acesulfame-dominated, brown is acesulfame/saccharin, green is sucralose, and blue is acesulfame. Isotopic groupings are presented by circled area and are colour-coded with data presented in Figure 5. Figure 5 also has blue-circled data which is not shown on this map, but it encompasses all sites outside the circled areas.

Isotopic and general geochemistry results are presented in Table 3 and 4 respectively. Isotopic values for the water samples collected in 2022 had $\delta^{18}O$ values between -24.9 and -9.4‰ VSMOW (Vienna Standard Mean Ocean Water) and $\delta\,^{2}H$ values between -193.9 and -108.9‰ VSMOW. All the measured stable isotope samples were below the Yellowknife local meteoric water line, Figure 5(Frape, Fritz, & McNutt, 1984). These results were compared to historical local data from nearby mines for consistency and to identify any overarching patterns.

Geochemical results were assessed for major ion concentrations, Cl^{-}/Br^{-}, and total Nitrogen by source types and the ratios between source types. These results (Table 4) were also compared to historical data from the past decade of water licenses for the solid waste facility to assess changes in distribution and leachate signature.

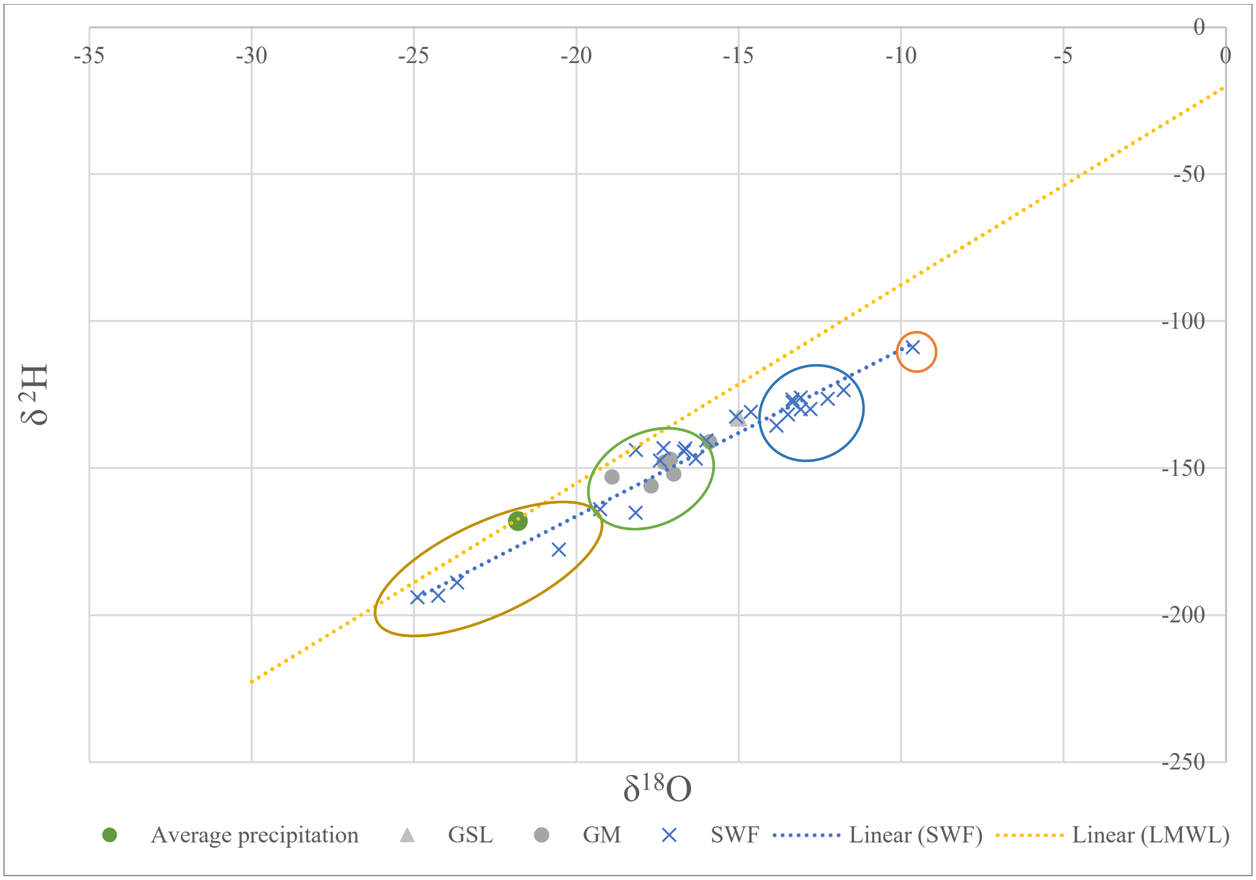


Figure 5. Isotopic Results

Isotopic data for 2022 samples (SWF), average precipitation for Yellowknife, Great Slave Lake (GSL) (Clark & Raven, 2004), Giant Mine (GM) (Clark & Raven, 2004), and the local meteoric water line for Yellowknife $\delta^{2}H = 6.75\ \delta^{18}O - 20.1$ (Frape et al., 1984). Circled data on the graph corresponds to circled points in Figure 4. LMWL is the local meteoric water line.

Table 3. Isotopic Data

Isotopic data from 2022 samples (SWF), average precipitation for Yellowknife, Great Slave Lake (GSL) (Clark & Raven, 2004), and Giant Mine (GM) (Clark & Raven, 2004).

Sample Name	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
0032-13a	-20.5	-177.8
0032-14	-24.3	-193.4
0032-14-1	-24.9	-193.9
0032-20	-19.3	-164.0
0032-21	-18.2	-165.2
MW-12	-18.2	-143.8
SW-1	-23.7	-189.0
SW-2	-13.3	-127.6
SW-3	-16.7	-144.3
SW-4	-16.6	-143.3
SW-5	-16.0	-140.6
SW-6	-15.1	-132.5
SW-7	-17.3	-143.2
SW-8	-14.6	-130.8
SW-9	-11.8	-123.5
SW-10	-16.3	-146.8
SW-11	-12.3	-126.5
SW-12	-13.5	-131.7
SW-13	-12.8	-130.0
SW-14	-13.1	-130.1
SW-15	-13.3	-126.6
SW-15-1	-13.1	-125.9
SW-16	-13.8	-135.6
SW-17	-9.6	-108.9
SW-17	-9.4	-110.4
SW-18	-17.4	-147.4
T.B.	-6.6	-48.9
F.B.	-14.0	-127.3
error (‰)	0.2	1.2
Avg precipitation	-21.8	-168.0
GSL	-15.0	-133.0
GM - chamber	-17.0	-152.0
GM - chamber	-17.7	-156.0
GM - local low As	-18.9	-153.0
GM - local low As	-17.3	-148.0
GM - tailings pond	-15.9	-141.0

GM - mine discharge	-17.1	-147.0

Table 4. Geochemistry Results
All concentrations in mg/L

Sample Name	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	TDS	Br	Cl^-/Br^-
0032-13a	38.8	5.3	37.1	8.3	0.1	117	45.7	10	280	0.04	1143
0032-14	166	23.6	81.8	15.9	0.1	272	92.9	250	814	0.17	546
0032-14-1	158	22.7	78.5	15.1	0.1	273	93.3	251	822	0.16	583
0032-20	180	40.6	129	19.2	0.1	155	168	505	1150	0.25	672
0032-21	19.8	21.5	92.9	19.5	34.1	113	111	29	416	0.05	2220
SW-1	199	30	90.7	16.7	0.1	272	102	382	1010	0.15	680
SW-2	40.8	12.9	33.3	4.3	25.7	79.9	60.8	27	288	0.05	1216
SW-3	70.9	17.7	81.8	5.2	0.1	155	170	43	562	0.03	5667
SW-4	58.3	16.1	29	4.3	0.1	145	67.5	40	360	0.05	1350
SW-5	47.6	13.9	17.5	4.2	0.11	130	42.9	29	266	0.05	858
SW-6	15.2	4.2	5.2	1.5	0.1	43.2	5.7	15	102	0.16	36
SW-7	60.1	15.6	29.2	2.9	0.1	154	59.9	42	354	0.02	2995
SW-8	28.7	7.2	10.2	1.6	0.1	38.4	18.7	55	174	0.20	94
SW-9	57.4	18.4	35.1	5.5	1.2	87.2	37.9	120	364	0.02	1895
SW-10	22.8	1.5	1.6	0.9	0.1	49.9	1.6	9	88	0.01	160
SW-11	30.1	9.5	52.1	4	0.1	63.9	91	23	322	0.04	2275
SW-12	22.2	6.6	16.7	1.6	0.1	45.1	27.3	20	196	0.01	2730
SW-13	17.9	5.8	4.3	0.4	0.1	29.5	3	29	162	0.01	300
SW-14	37.9	8	22.1	5.8	0.1	71.9	29	30	256	0.02	1450
SW-15	40.5	13	33.3	4.2	20.4	82.8	61.3	28	305	0.07	876
SW-15-1	40.4	12.9	33.3	4.2	22.6	80.7	61.2	27	296	0.06	1020
SW-16	164	50	165	22	0.1	60	235	569	1310	0.38	618
SW-17	26.7	14.3	9	4.7	8.9	112	5.9	6	214	0.04	148
SW-18	70.4	18.2	36	4.9	0.1	141	91.2	72	440	0.03	3040
*MW-10	192	49.7	66.7	2.57	<1.0	232	77.9	440	982	0.115	677
*MW-11	244	76.3	167	6.86	<1.0	352	445	190	1620	0.249	1787
*MW-12	33.7	19.1	61.0	6.22	3.3	191	9.62	88.8	341	0.05	192

Organic contaminants and microbiological pathogens were also measured for all of the sampled sites, however only the microbiological pathogens were included in further analysis due to the lack of detection of any significant organic contamination attributable to the SWF. The only site with any detectable organic contamination was SW-6, a site on Great Slave Lake, which had 2.4 mg/L of hexane extractable material. The microbiology results are presented in

Table 5. The microbiological results were the most correlated with sweetener concentration out of all parameters studied, however it was still relatively low and required the removal of an outlier, 0032-13a, which had uncountably high results.

Table 5. Microbiology Results

CFU, colony-forming unit, is a unit of grouped microbial life, rather than a single microbe; and MPN, most probable number, is a unit of estimated individual microbes.

Sample Name	CFU/100ml Coliforms, Fecal	MPN/100ml Enterococci
0032-13a	>2419.6	>2420
0032-14	23	43.5
0032-14-1	23	48.2
0032-20	38	46.5
0032-21	57	122
SW-1	10	178
SW-2	2	37.7
SW-3	<1	5.2
SW-4	<1	42.6
SW-5	<1	<1
SW-6	<1	42.8
SW-7	<1	2
SW-8	6	5.2
SW-9	15	19.9
SW-10	2	4.1
SW-11	40	20.1
SW-12	3	2
SW-13	4	1
SW-14	20	214
SW-15	1	33.2
SW-15-1	1	17.3
SW-16	19	39.7
SW-17	<1	23.1
SW-18	<1	75.4

2.5. Discussion

The discussion is organized to address the three main sub-objectives of this research within the broader aim to evaluate the transport and fate of contaminants originating from the

Yellowknife SWF. The first objective is to improve current groundwater vulnerability frameworks to account for anthropogenic sources of contamination under changing environmental conditions. Second, to investigate the temporal and spatial concerns presented by a constant influx of non-degradable contaminants into water resources from the SWF, including leachate migration pathways. Third, is to contribute to the NWT territorial government's groundwater monitoring plan by establishing baseline water quality conditions for local groundwater around the SWF.

2.5.1. Groundwater vulnerability and a rapidly changing climate

This case study demonstrates groundwater vulnerability in a changing climate. Contaminated sites in Yellowknife initially relied on permafrost to contain hazardous components such arsenic (Jamieson, 2014). By the late 1990s, there was little evidence of permafrost around Yellowknife (Jamieson, 2014), and no permafrost has been documented around the SWF in recent years (Yellowknife, 2012), although, little was done to adjust for this thaw. The geochemical and isotopic results (Figure 5, Table 3, and Table 4) demonstrate interaction between deep and shallow groundwater and surface water sources and heterogeneous levels of metal contamination (Figure 6). Permafrost thaw removes barriers to contamination dispersion and an intensifying hydrological system can synergize this feedback by increasing infiltration and carrying surface-level contamination to greater depths. Investigating pre-climate change conditions at this site are outside the scope of this research, however novel tracers, such as sweeteners, could provide temporally-constrained information for other locations beginning to experience permafrost thaw.

Increased wildfires are another symptom of rapid climate change in the Arctic and Subarctic. Extremely dry, wildfire conditions during 2022 sampling and a groundwater-dominated pathway for leachate migration into the environment (Figure 10) overall could correlate. This could explain differences between past predictions for leachate migration (see 2.2 Study Site for sub-catchment predictions), due to their focus on runoff during comparatively wetter conditions (Dillon, 2017). In the future, continuous long-term monitoring of leachate pathways from the SWF could help increase the accuracy of predicting contamination changes from seasonal and climatic effects.

2.5.2. Contaminant transport and fate

Total and dissolved metal concentrations in the samples were screened for water quality guideline exceedances and compared to historical water quality data. Screened water quality parameters were selected based on consistent exceedances at the Yellowknife SWF over the past decade and are presented in Table 6, and the guideline data for all sites and exceedance percent are in Table 7 and Table 8 in the Appendix. The sites with the most parameters with exceedances are the wetland site southeast of the SWF (SW-14), a groundwater spring southeast of the SWF (SW-7), and the SWF municipal snow dump (0032-13a). These three sites also have the highest values for the sum of all parameters by percentage over the local guidelines (Figure 6). Assessing exceedances by percentage over local guidelines is based on a simplified version of a Heavy Metal Pollution Index (HPI) (Kumar et al., 2019), in which the relative amount over the guideline is also weighted by severity of the contaminant before being totaled to estimate the cumulative effect of the pollution. The two sites within the SWF had high exceedances of zinc and iron compared to sites outside the SWF. Some sites outside the SWF also had high metal exceedances, but low sweetener concentrations (as described below). All sites studied exceeded the CCME, Alberta, and BC government regulations for Arsenic (<5 µg/L) (Figure 7) , although the Yellowknife local limit of < 52 µg/L for residential areas was exceeded at only fourteen sites (GNWT, 2023) (Figure 6).

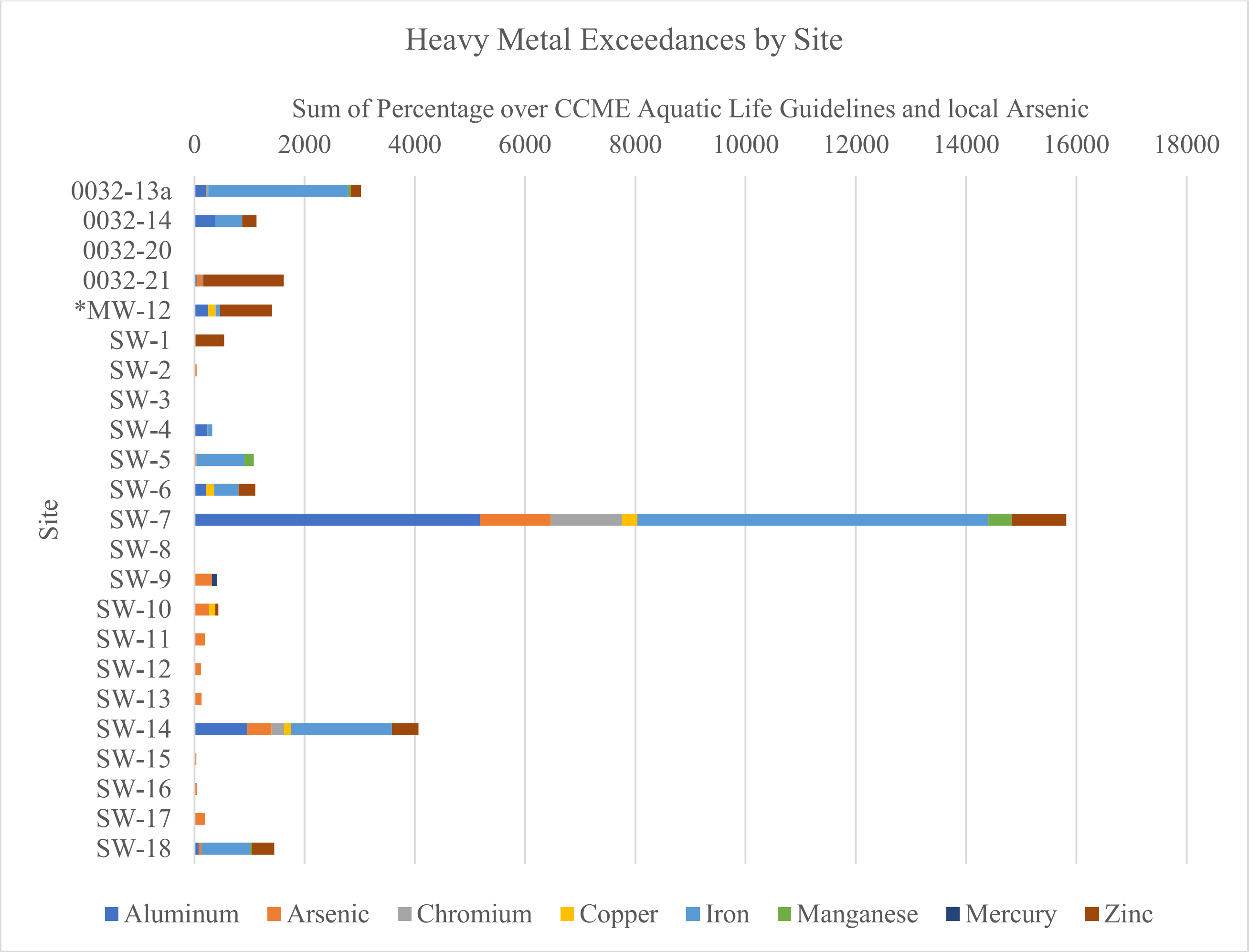


Figure 6. Heavy Metal Exceedances relative to local guidelines

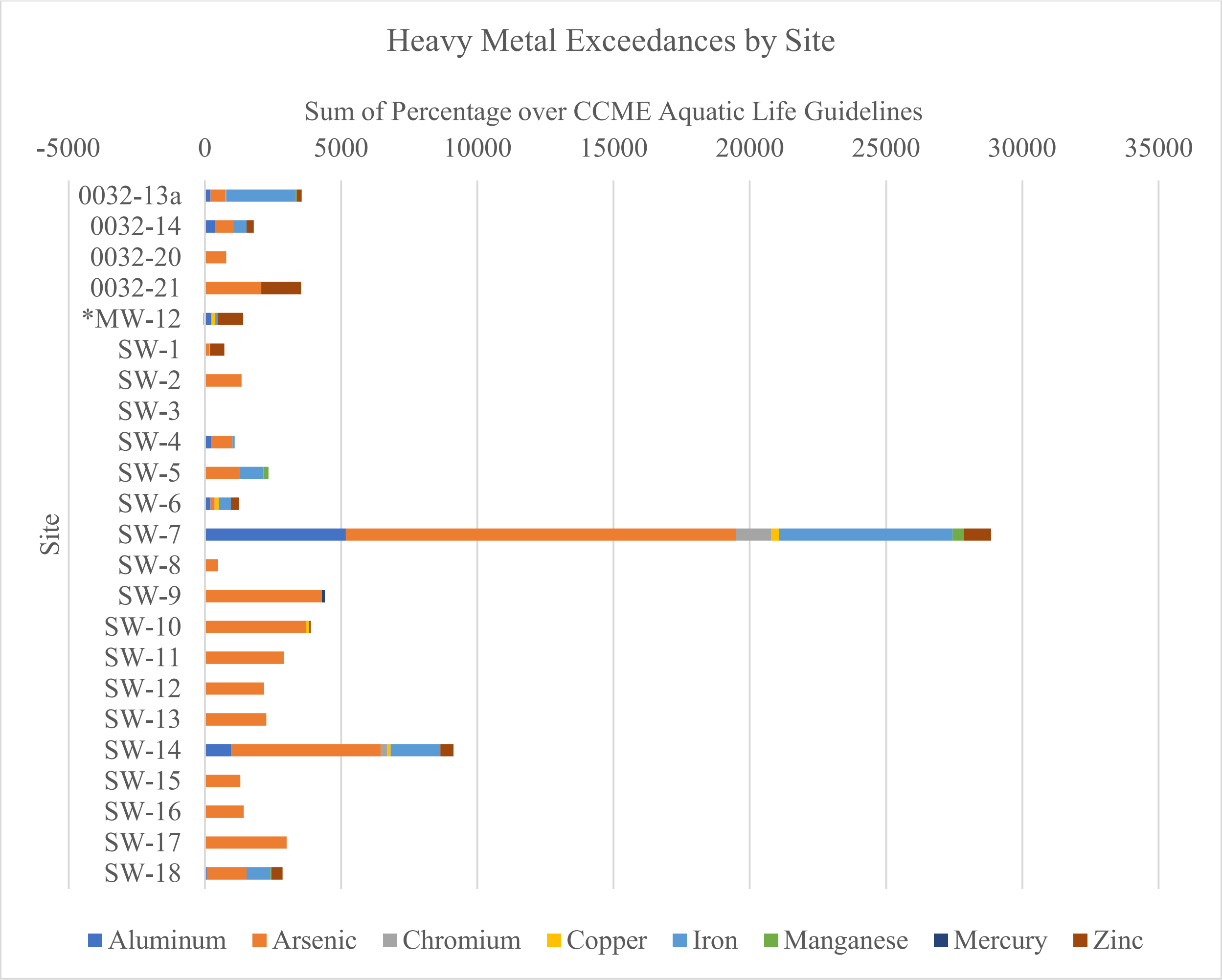


Figure 7. Heavy Metal Exceedances relative to national standards

Geochemical data from the SWF water licenses between 2017-2022 from surface water sites, and data from the past year for groundwater sites, all within the SWF, have heavy metal exceedances that are within a similar range to the 2022 samples, including exceedances for similar parameters (Yellowknife, 2017, 2021). This similarity is indicative that the data collected for this study are representative of recent years' data and are applicable for this study.

Table 6. Heavy Metals Totals

Results are all presented in µg/L. Highlighted cells exceed CCME Guidelines for the Protection of Aquatic Life, except for As, which is assessed by local guidelines. The MW-12 data is sourced from the Fall 2021 SWF water license.

Site	Sweeteners	Al	As	Cr	Cu	Fe	Mn	Hg	Zn
0032-13a	1205	312	31.8	1.4	2.7	7900	557	0.01	5.8
0032-14	1527	477	38.4	0.8	3.8	1770	141	0.01	11.8
0032-20	2368	29.7	44.1	0.3	1.5	68	30.6	0.01	2.6
0032-21	3718	141	106	0.6	1.7	329	129	0.01	12.4
*MW-12	795	350	2.58	0.6	8.52	525	17.7	0.005	12.8
SW-1	2626	92.2	13.8	0.4	4.7	115	19.6	0.01	20.9
SW-2	90	9.2	72.3	0.1	1.8	29	21.8	0.01	0.5
SW-3	25	8.2	6.3	0.3	0.5	71	25.9	0.01	0.4
SW-4	25	334	43.9	1	1.5	568	67.8	0.01	1.2
SW-5	39	3.1	69.5	0.2	0.3	2900	1510	0.01	0.4
SW-6	9	309	12.7	0.8	3.5	1640	54.1	0.01	7.1
SW-7	23	5280	721	13.9	15.2	19400	1410	0.01	20.8
SW-8	39	75.2	29.6	0.2	1.7	162	19.8	0.01	1.2
SW-9	36	31.4	220	0.1	0.6	13	5.5	0.05	0.8
SW-10	141	13.3	191	0.3	3.4	228	62.8	0.01	2.2
SW-11	1836	45.7	150	0.3	0.7	65	58.5	0.01	0.8
SW-12	191	30.5	114	0.2	0.9	46	29.3	0.01	2
SW-13	22	32.3	118	0.2	1	37	14	0.01	2.7
SW-14	18	1060	280	3.3	6.6	5780	453	0.02	27.3
SW-15	83	21.9	70.3	0.1	1.6	44	45.3	0.01	0.4
SW-16	80	47.2	76.8	0.4	0.5	66	19.6	0.01	1
SW-17	0	24.7	155	0.3	0.5	103	144	0.01	0.7
SW-18	36	180	77.7	0.8	1.6	2930	581	0.01	12.2

The geochemistry results, including major dissolved ions and common leachate contaminants, are also compared to historical data from nearby mines and historic SWF monitoring results. Major ion results were plotted in Figure 8. Sites within the landfill and a monitoring well to the southeast of the SWF (0032-13a, 0032-21, and MW-12) plot in the center of the Piper Diamond, and are closest to the commonly recognized major-ion signature of leachate (bottom quadrant). The two samples (SW-17, SW-10), which plot towards the left quadrant of the diagram, which aligns with their position on the diagram commonly associated with crystalline rock. These samples are located near the geologic contact between the mafic volcanic geologic units to the east, and a more felsic granitic unit to the west. The majority of the samples plot in the upper quadrant, reflecting mixing between surface water, leachate, and groundwater of different compositions. The upper quadrant is commonly associated with gypsiferous rock types. This rock type has been noted in studies from both the Con and Giant Mine, near to the SWF (Douglas et al., 2000; Palmer et al., 2021). One sample, taken from Fault Lake which sits along West Bay Fault, plots on the furthest right edge of the Piper Diagram and aligns with a mix of shield brine and glacial meltwater found along faults (approximately 1372 meters below ground surface) at Con Mine (Figure 9).

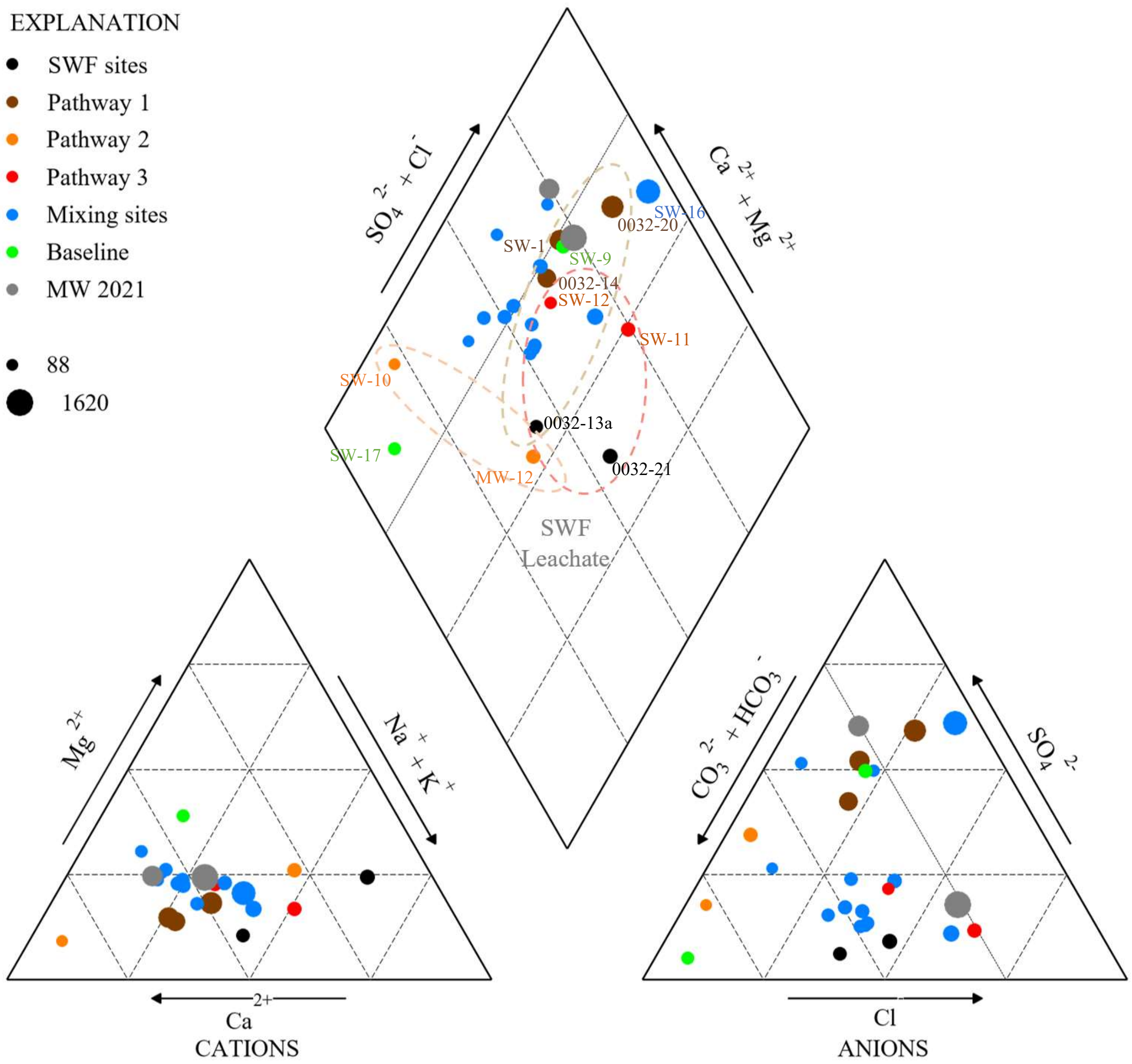


Figure 8. Piper Plot of 2022 Samples

Sites from 2021 groundwater monitoring wells were included for comparison and further discussion. Pathways and interpretations in this figure are linked to Figure 10. Sizes determined by TDS (mg/L).

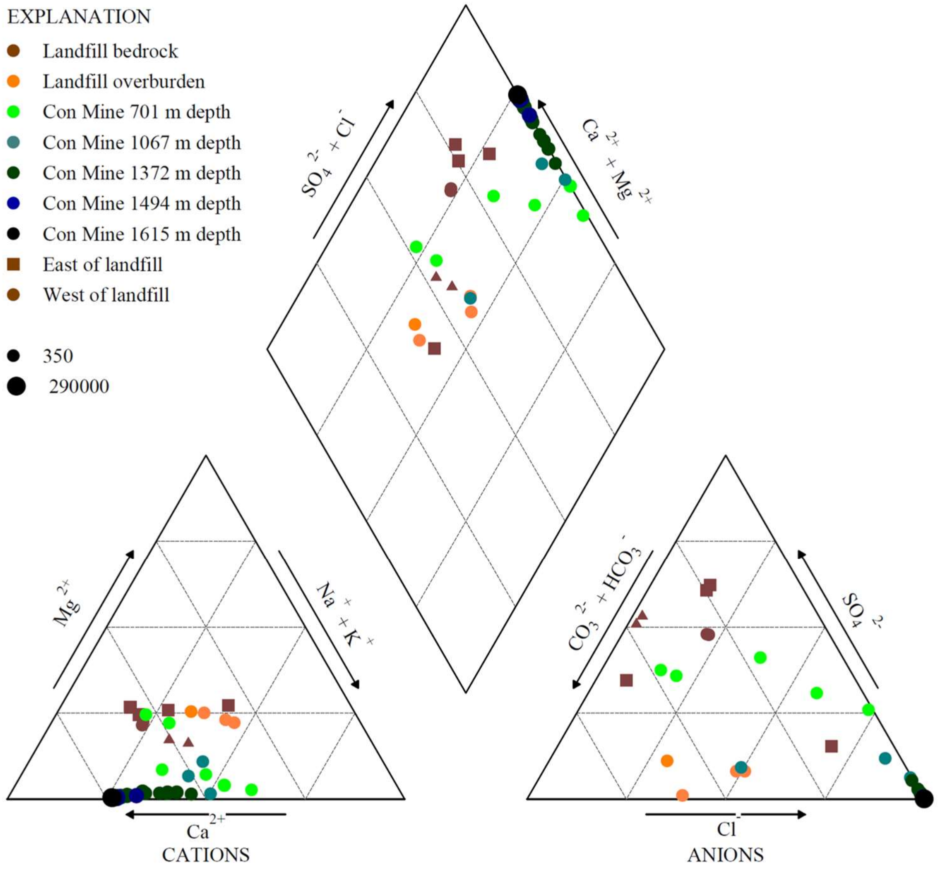


Figure 9. Piper Plot of Con Mine and 2021 Groundwater Sampling

Data for this diagram was sourced from Douglas, 2000 and The Groundwater Interim Monitoring Plan (Douglas et al., 2000; Yellowknife, 2021). Sizes determined by TDS (mg/L).

2.5.3. Pathways

Data from sweeteners, hydrochemistry, and isotopic results are used to identify different sources and pathways of water in and around the Yellowknife Solid Waste Facility. The following discussion describes how these results both differentiate different water sources, and pathways of landfill leachate.

As discussed in the introduction, previous research has highlighted the effectiveness of sweeteners in identifying leachate and wastewater signatures within groundwater, streams, and surface water, and this appears to be true in Yellowknife as well (Khazaei & Milne-Home, 2017; Liu et al., 2022; Propp et al., 2022; James W. Roy et al., 2014; Van Stempvoort et al., 2011).

The highest total concentration of artificial sweeteners was found in the lake downhill from the main active landfill cell (0032-21). The other sample within the solid waste facility property, the municipal snow dump, also had elevated sweetener concentrations, although there were higher sweetener concentrations for sites which were in closer proximity to active and inactive general SWF cells and compost facilities (Figure 10). Based on the location of the elevated sweetener sites (Figure 4Figure 10), the SWF is an appreciable source of the measured artificial sweetener types. Based on the spatial pattern and concentrations of sweeteners in the samples, there are 3 potential leachate pathways (Figure 10). Changes in leachate discharge quantity and directional changes due to seasonal and climatic conditions may be responsible for deviations from previous estimations of leachate migration pathways due to their focus on runoff (Dillon, 2012).

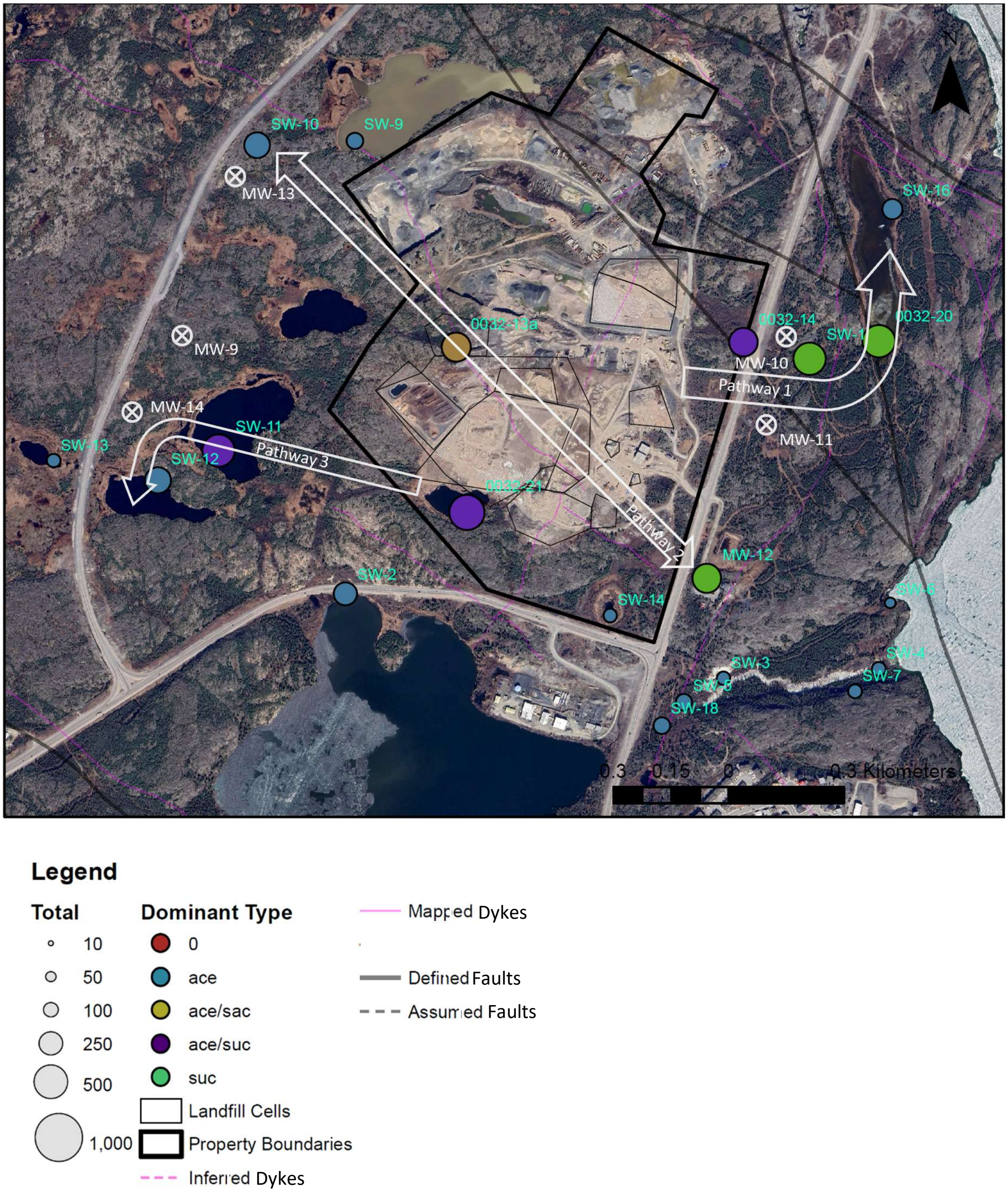


Figure 10. Sweeteners pathways

Sweeteners pathways migrating off the solid waste facility property. Monitoring wells that were not sampled in 2022 but referenced in the discussion are included as circles with an x. Dykes are delineated by magenta solid and dashed lines and faults are delineated by grey solid and dashed lines.

Pathway 1. The most prominent pathway from the SWF flows eastward from the NE corner of the property into Fault Lake (Figure 10). This pathway flows through the culvert leading off the SWF property (Site 0032-14), where it is joined by the outflow from a groundwater-fed wetland (SW-1), the combined flow which then enters Fault Lake (0032-20). There was no surface outflow from the lake, and a sample on the side of the lake opposite the inflow (SW-16) had a sweetener concentration 2 orders of magnitude lower than the inflow sample.

Differences in the ratios between sweetener types and overall concentrations between the culvert and the groundwater-fed wetlands indicate that there are separate surface water and groundwater inputs along this transect. The groundwater site (SW-1) has double the total concentration of sweeteners as the culvert site (0032-14) and has an appreciable amount of saccharin, which is negligible in the culvert site. Saccharin is an older sweetener type, first used in food in 1968, and declined in usage with the availability of newer artificial sweeteners, which may indicate that this is older compared to the runoff-fed culvert. The sweeteners entering Fault Lake from the creek (0032-20) fed by both SW-1 and 0032-14 are similar in ratio and total concentration to the groundwater-fed wetland (SW-1), whereas the other side of the lake has a similar amount of saccharin but much lower concentrations of the other two sweeteners.

Fault Lake (SW-16) has a similar geochemical signature to samples taken from groundwater in Con Mine (just over 4 km south of the SWF), between 1067-1372m in depth. This similarity is interpreted to indicate that the lake is receiving a large influx of deeper groundwater (not from the SWF), and that this deeper groundwater significantly dilutes the entering leachate. Isotopically, the 3 sites contributing to Fault Lake inflow are similar to both the SWF snow dump and larger SWF lake. From major ion analysis (Figure 8, Table 4), the groundwater-fed wetlands (SW-1), the culvert (0032-14), and the lake inflow (0032-20) plot near the groundwater well site (MW-10) that is within 100 m of SW-1. This well is screened at a depth of 8.1 to 11.1 m below ground surface in bedrock. These data verify that the wetland is receiving groundwater discharge and distinguishes it from the other groundwater signature of the shallower groundwater well to the south (MW-12). Further, on the Piper Plot (Figure 8), SW-1 and MW-10 also plot in the same geochemical location as SW-9, which is a lake NW of the SWF.

Sites SW-1, MW-10, and SW-9 are located on the Martin Fault, a major sinistral strike-slip fault in the area. Fault Lake sits on the West Bay Fault, although these 2 faults are connected by a shorter E-W trending fault (Figure 10). Overall, the sweetener distribution along this pathway demonstrates eastward leachate transport through deeper groundwater in the area along the Martin Fault, with no transport towards the northwest. The SW-9 site presents a baseline composition for sites along this fault whereas SW-1 and 0032-20 have a similar geochemical composition but with high quantities of sweeteners indicating the effect of the landfill leachate on this groundwater.

Pathway 2. Pathway 2 flows from the south side of the solid waste facility to the east and potentially west through shallow groundwater. Evidence for Pathway 2 is based on elevated total concentration of sweeteners in the well SE of the SWF (Site MW-12). It is one of two sites with all four types of sweeteners present, the other being the lake within the SWF property (0032-21). These two sites are also geochemically similar (Figure 8), however, the other sites around the monitoring well did not have heightened levels of sweeteners. The sampled well is screened between 3.4 to 6.4 m below ground surface (190.9-187.9 m.a.s.l.) in bedrock (Yellowknife, 2021). Although the well has similar isotopic values as the other sites, the geochemical signature and Cl^-/Br^- ratio of the well is dissimilar to the other nearby groundwater sites, indicating potentially different groundwater sources. The MW-12 groundwater site is similar isotopically and in Cl^-/Br^- ratio to a sample taken northwest of the SWF along a known geologic contact (SW-10). The heightened sweeteners in SW-10 are four times higher than a surface water sample (SW-9) which is geographically closer and downhill from the SWF. This spatial pattern may imply groundwater transport of leachate through shallow groundwater exclusively to the NW and SE of the SWF. Pathway 2 is important to note for future landfill leachate monitoring plans since a baseline well was recently installed within 200 meters of this site (MW-13) (Yellowknife, 2021). The other nearby sites to MW-12 have a Cl^-/Br^- ratio and geochemical signature similar to a well north of MW-12 (MW-11) that is screened 15 meters deeper. Well MW-11 was not sampled as part of this project; in the future, an artificial sweetener sample at MW-11 would help confirm any leachate transport through deeper groundwater to the east.

Pathway 3. Pathway 3 flows from the compost facility and active landfill cell in the southwest of the solid waste facility to the west through runoff and groundwater discharge to three small lakes. Pathway 3 is to the west of the SWF where there is an elevated total concentration of sweeteners in the lake nearest to the food compost facility within the SWF (SW-11). Previous reports have suggested that a small amount of surface runoff from the SWF could be flowing into this lake (Dillon, 2012), however the substantial concentration of sweeteners implies that there may also be groundwater transport into these lakes. This site has a slightly higher concentration of sweeteners than the culvert running off the SWF to the northeast (0032-14), including a higher ratio of sucralose to acesulfame and double the saccharin compared to the northwest site. This sweetener ratio fingerprint is more similar to groundwater samples (MW-12, SW-1) with heightened sweetener concentrations. The two small nearby lakes (SW-12 and SW-13) have decreasing total concentrations of sweeteners with distance from SW-11, indicating flow westward and dilution. The sucralose is absent in the two receiving lakes, saccharin is present only in the closer lake, and acesulfame is the only component left in the furthest lake. These changes in relative concentrations and ratios of sweeteners with distance from the SWF are the same as the changes observed with Pathway 1, and may be indicative of the relative degradability of different sweetener types (Van Stempvoort et al., 2011). Pathway 3 is important to note for future landfill leachate monitoring plans since baseline wells have been recently installed within 200 meters of this site (MW-14, MW-9) (Yellowknife, 2021).

2.5.4. Baseline Conditions

In this research, baseline conditions are sought rather than natural background conditions. The legacy contamination in the area unconnected to the landfill is an overarching condition that, although a potential contaminant of groundwater in the study area, is considered part of the baseline conditions for distinguishing only the effect of the SWF. It is a bias in geoscience to separate all contamination from a “natural” state, but in an urban area with both geogenic and anthropogenic sources of constituents that are hazardous to biological life, a baseline condition seeks to reflect source-specific changes rather a virtual uncontaminated state. With this in mind, elevated artificial sweetener content separates the leachate-contaminated water sources, from an ambient baseline that exceeds national guidelines for heavy metals and other toxins. It is useful to introduce the idea of a toxin compared to a toxicant in this case study, where a toxin is naturally occurring opposed to a toxicant which is part of human systems of industry, capitalism, and colonialism, and dwarf natural toxins in temporal and spatial scale (Liboiron et al., 2018). In this case, sweeteners are a toxicant and are used to trace other toxicants in leachate that have a similar toxin (bedrock arsenic) or differently sourced toxicant (legacy mining arsenic) that bury the leachate signature.

Surface and groundwater sites in this study with <50 ng/L of total sweetener concentration appear to have minimal contamination from landfill leachate, this included samples taken from Great Slave Lake (SW-6, SW-8), a groundwater-fed creek system in the southeast of the study area (SW-3, SW-4, SW-5, SW-7, SW-18), and a lake (Joe Lake) to the northwest of the SWF (SW-9). Site SW-17 contained no measurable sweeteners and could be a valuable baseline monitoring site for surface water within a crystalline rock geochemical facies (see Figure 8). Site SW-9 also to the north of the SWF is a valuable potential baseline groundwater site since it geochemically and isotopically is similar to a sweetener contaminated site (SW-1) and an existing monitoring well (MW-10) representing a more gypsiferous geochemical facies. The groundwater sites along the creek (SW-3, SW-5) could also serve as a baseline deep groundwater monitoring site, these sites are within 200 m of a shallow groundwater sample that had high concentrations of sweeteners (MW-12), yet their lack of sweeteners demonstrates the leachate's confinement to a shallow aquifer. SW-7, although having limited sweeteners, is hydrologically disconnected from any effect of the SWF and therefore would be a poor baseline monitoring site. Overall, the many different water types and fractured bedrock aquifer make predictions on baseline groundwater chemistry and flow complex, but sweeteners are a useful tool in distinguishing leachate contamination against a background of many contamination sources.

Standard geochemical delineation methods for leachate contamination (e.g., elevated chloride, organic chemicals, heavy metal contamination, etc.) are difficult to apply at the Yellowknife SWF due to the existing complex hydrochemical groundwater and pre-existing anthropogenic conditions (e.g., the Giant Mine stie). The findings from this research show that total and dissolved metal concentrations do not correlate well with sweetener concentrations. The high geogenic concentrations of heavy metals and legacy mining in the area have historically made monitoring the proportionally minimal metal contamination from the Yellowknife SWF difficult. Additionally, using elevated chloride concentration as a tracer of landfill leachate is ineffective due to the naturally occurring high chloride concentrations in Canadian shield brines in the area.

For example, Site SW-7, a groundwater spring on the eastern edge of the study area, had the highest number of drinking water quality exceedances for metals, and sites downstream of SW-7 (SW-4 and SW-6) also exceeded standards for similar parameters (Figure 6). SW-14, although very close to the SWF, is topographically isolated from the SWF. SW-7 and SW-14 are very similar in major ion concentration (plotting next to each other on the piper plot, Figure 8, and the two sites also have similar relative proportions of metals (Figure 6). These results demonstrate the difficulty in using trace metals as tracers of groundwater contamination from the SWF at this site.

Microbiological pathogens (i.e., fecal coliforms) were found to generally correlate with sweetener concentration, with the two sites within the SWF having the highest concentrations of pathogens and one of these sites (0032-13a) exceeding the national guidelines for the protection of aquatic life by 1105%. However, this may be more representative of increased animal activity, particularly birds, within the SWF rather than reflecting waste composition. The site with the least correlation was SW-1, which had elevated sweetener concentration but low pathogen concentration, potentially demonstrating the degradation of organic pollutants in groundwater with travel distance.

2.6. Conclusion

In conclusion, artificial sweetener concentrations are an effective tracer of landfill contamination in a landscape dominated by geogenic and industrial contamination. Three conclusions can be drawn from the isotopic, geochemical, and artificial sweetener results: 1) The Yellowknife SWF is a significant source of sweeteners, particularly from the general landfill cells and the compost facility. 2) Three distinct leachate pathways flowing to the SE, NE and SW from the SWF property were identified and are composed of mainly shallow groundwater transport. 3) Baseline measurements for surface and groundwater can be identified to the northwest of the SWF, further north of proposed monitoring sites where the presence of leachate was identified through elevated sweetener concentrations. The use of artificial sweeteners makes a baseline site to the north of the SWF newly feasible since the sweeteners allow distinction between the landfill-derived leachate and legacy mine site contamination.

2.6.1. Social Framework of Results

Within a framework of groundwater vulnerability and legacy contamination, the unique interaction of geogenic contamination, mining contamination, and lack of applicable standards for protection of the environment and people, is a case study for a future in the Anthropocene. Accountability, remediation, and autonomy are challenging topics in a permanently contaminated world. Being able to separate SWF leachate contamination from a baseline that includes chronically toxic levels of heavy metals pollution demonstrates the value of sweeteners as a tracer for source-specific accountability. Artificial sweeteners allow for autonomy in regulating the communally beneficial landfill amidst a landscape of contamination and rapid climate change that strips autonomy from local actors in favour of international economies. Contamination is a form of dispossession as a symptom of colonial-capitalism, and strengthening local regulations on cumulative and parameter-based contamination through the use of novel tracers is a tool for strengthening local power over environmental and human health.

The long-term impact of legacy contamination is best connected to groundwater where time capsules of contamination will be present on scales across human generations. Sweeteners again align temporally with elevated anthropogenic contamination and are useful in areas where geogenic contamination has existed long before human influence. The 1,665 contaminated sites in the NWT, combined with climate change-driven intensification of hydrology for Northern regions, presents critical social and technical challenges. Symptomatic solutions, that fail to address the capitalist colonial origins of many of these sites, will only undermine environmental justice and the systematic prevention of future contamination.

2.7. Acknowledgement

We would like to thank the GNWT, and in particular the staff at ENR. The project is supported by grants from NSERC and the NSTP. Additional thanks to McGill University for additional support. Please contact the corresponding author for use of published data.

2.8. Appendix

Table 7. CCME Guidelines for the Protection of Aquatic Life (2023)

Values are calculated for individual sites due to guidelines being determined by hardness, DOC, and pH. Arsenic values are set to local guidelines. All values are in µg/L.

Site	Aluminum	Arsenic	Chromium	Copper	Iron	Manganese	Mercury	Zinc
0032-13a	100	52	1	2.743743	300	370	0.026	2.004535
0032-14	100	52	1	4	300	480	0.026	3.296457
0032-20	100	52	1	4	300	300	0.026	3.097983
0032-21	100	52	1	3.113976	300	120	0.026	0.795652
*MW-12	100	52	1	3.59	300	260	0.026	1.223644
SW-1	100	52	1	4	300	480	0.026	3.361362
SW-2	100	52	1	3.362981	300	130	0.026	0.768649
SW-3	100	52	1	4	300	270	0.026	2.023863
SW-4	100	52	1	4	300	270	0.026	1.546918
SW-5	100	52	1	3.833356	300	540	0.026	2.216766
SW-6	100	52	1	1.416619	300	430	0.026	1.759992
SW-7	100	52	1	4	300	270	0.026	1.899094
SW-8	100	52	1	2.326322	300	350	0.026	1.469744
SW-9	100	52	1	4	300	270	0.026	1.849728
SW-10	100	52	1	1.59124	300	320	0.026	1.409525
SW-11	100	52	1	2.644928	300	370	0.026	1.861611
SW-12	100	52	1	1.958419	300	440	0.026	2.371988
SW-13	100	52	1	1.666599	300	430	0.026	2.86452
SW-14	100	52	1	2.920112	300	710	0.026	4.687358
SW-15	100	52	1	3.362981	300	130	0.026	0.842318
SW-16	100	52	1	4	300	300	0.026	3.676919
SW-17	100	52	1	2.881079	300	180	0.026	1.183113
SW-18	100	52	1	4	300	430	0.026	2.397324

Table 8. Percentage over the CCME Guidelines

Percentage over each parameter's guideline, sum-total of percentage over the guideline for all parameters listed, and total number of parameters that had an exceedance (Number Exceedances = N.E.). Sites marked with an asterisk are from 2021 data.

	% over									
Site	Al	As	Cr	Cu	Fe	Mn	Hg	Zn	Total	N. E.
0032-13a	212	0	40	0	2533	51	0	189	3025	5
0032-14	377	0	0	0	490	0	0	258	1125	3
0032-20	0	0	0	0	0	0	0	0	0	0
0032-21	41	104	0	0	10	8	0	1458	1517	4
*MW-12	250	0	0	137	75	0	0	946	1408	4
SW-1	0	0	0	18	0	0	0	522	539	2
SW-2	0	39	0	0	0	0	0	0	0	0
SW-3	0	0	0	0	0	0	0	0	0	0

SW-4	234	0	0	0	89	0	0	0	323	2
SW-5	0	34	0	0	867	180	0	0	1046	2
SW-6	209	0	0	147	447	0	0	303	1106	4
SW-7	5180	1287	1290	280	6367	422	0	995	14885	7
SW-8	0	0	0	0	0	0	0	0	0	0
SW-9	0	323	0	0	0	0	92	0	130	2
SW-10	0	267	0	114	0	0	0	56	189	3
SW-11	0	188	0	0	0	0	0	0	0	0
SW-12	0	119	0	0	0	0	0	0	0	0
SW-13	0	127	0	0	0	0	0	0	0	0
SW-14	960	438	230	126	1827	0	0	482	3700	6
SW-15	0	35	0	0	0	0	0	0	0	0
SW-16	0	48	0	0	0	0	0	0	0	0
SW-17	0	198	0	0	0	0	0	0	0	0
SW-18	80	49	0	0	877	35	0	409	1401	4

3. Final Remarks

3.1. Research Summary and Conclusions

Legacy contamination sources in the Arctic and Subarctic pose an increasing hazard to water resources and the people who rely on them. In regions where there are multiple contamination sources, including both anthropogenic and geogenic sources, the accountability and remediation measures become complex to quantify. Although groundwater contamination concerns from multiple sources have been studied using various methods, there are still gaps in the literature regarding the unique circumstances of Northern communities, such as holistic frameworks incorporating past and future timelines of contamination to provide the data necessary for remediation, in addition to incorporating the ongoing effects of climate change. Holistic frameworks that incorporate connectivity between earth system components are also necessary for defining the cumulative effects of contamination and biogeochemical changes across long time spans (Ali et al., 2018). This structural lack of information is due to a lack of cross-disciplinary research, minimal historical groundwater monitoring in remote regions, and ever-changing definitions of contamination.

The goal of this research is to test the effectiveness of artificial sweeteners in tracing groundwater contamination from a landfill setting in an urban area that is also impacted by influenced by legacy mining and geogenic contamination. I demonstrate that artificial sweeteners can be used to track leachate of different ages (< 60 years old) through surface and groundwater migration pathways and assert a baseline condition for water uncontaminated by leachate. Sweeteners, when combined with isotopic and geochemical data, are demonstrated to overcome the limitations of a lack of pre-contamination data and provide evidence for source-specific contamination in a permanently contaminated landscape.

In this research, the artificial sweetener concentrations, obtained through a synoptic sampling campaign, are compared between sites based on total sweetener concentration and ratios between sweeteners. The results show that the Yellowknife solid waste facility is a significant source of sweeteners and contributor to elevated concentrations along three distinct leachate migration pathways. Mainly, shallow groundwater was the most common transport avenue, with mixing from surface water and deeper groundwater eventually diluting the sweeteners. These shallow groundwater pathways flow to the southwest and northwest of the SWF, as well as the expected southeast and northeast directions. These results are essential information for planning locations of future monitoring and baseline wells.

Artificial sweeteners, as a non-toxic, temporally distributed tracer of groundwater contamination, have the potential to be a tool for Northern communities in monitoring the health of their water resources and imposing responsibility onto polluters. Legacy contamination functions as a form of dispossession in ongoing colonial-capitalist history, and tracers that can prove (in any capacity) what an uncontaminated landscape should be, regardless of existing baseline data, are powerful in working towards remediation and local autonomy over the environment.

3.2. Future Directions

Using artificial sweeteners as a tracer of groundwater contamination would be improved if the degradation rates for different sweeteners were better understood, including under different conditions, potential effects on organisms, and timelines of local use. These factors would allow for improved models of temporal distributions of artificial sweeteners and could further pinpoint timelines of contamination. This is particularly relevant for future research if it is to connect sweeteners to older contaminant sources; the combined use could extend the range of contamination fluxes able to be studied greater than 60 years. Additionally, this research leaves some questions, such as the effectiveness of sweeteners as a tracer of all contaminants produced by a landfill rather than just compost and general composition landfill cells. Additionally, expanding the range of contamination sources, such as cemeteries, agriculture, and different types of industry, and the setting of sweeteners, such as soil, sediment, and water vapour, could help broaden the scope of sweeteners as a tracer.

Theoretically, there is a need for more research to identify tracers that can uncouple contamination from geogenic from anthropogenic sources and provide histories of contamination. This is essential for addressing the 1665 contaminated sites in the NWT, and 2,619 contaminated sites across all Canadian territories. One of the key requirements for Indigenous nations to receive funding for contaminated site remediation is establishing a history of contamination, which is impossible in most locations due to lack of historical monitoring.

Making the sampling and testing process for these tracers accessible to citizen scientists would significantly aid in promoting local autonomy and sovereignty.

4. References

Abbate, E., Bortolotti, V., & Passerini, P. (1970). Olistostromes and olistoliths. *Sedimentary Geology, 4*(3), 521-557. doi:https://doi.org/10.1016/0037-0738(70)90022-9

Abdul Aziz, O. I., & Burn, D. H. (2006). Trends and variability in the hydrological regime of the Mackenzie River Basin. *Journal of Hydrology, 319*(1), 282-294. doi:https://doi.org/10.1016/j.jhydrol.2005.06.039

Abiriga, D., Vestgarden, L. S., & Klempe, H. (2020). Groundwater contamination from a municipal landfill: Effect of age, landfill closure, and season on groundwater chemistry. *Science of The Total Environment, 737*, 140307. doi:https://doi.org/10.1016/j.scitotenv.2020.140307

Alessa, L., Kliskey, A., Lammers, R., Arp, C., White, D., Hinzman, L., & Busey, R. (2008). The Arctic Water Resource Vulnerability Index: An Integrated Assessment Tool for Community Resilience and Vulnerability with Respect to Freshwater. *Environmental Management, 42*(3), 523-541. doi:http://dx.doi.org/10.1007/s00267-008-9152-0

Ali, G., Oswald, C., Spence, C., & Wellen, C. (2018). The T-TEL Method for Assessing Water, Sediment, and Chemical Connectivity. *Water Resources Research, 54*(2), 634-662. doi:https://doi.org/10.1002/2017WR020707

Assembly, U. G. (2007). United Nations declaration on the rights of indigenous peoples. *UN Wash, 12*, 1-18.

Bakker, K. (2012). Water Security: Research Challenges and Opportunities. *Science, 337*(6097), 914-915. doi:10.1126/science.1226337

Ballinger, T. J., Overland, J. E., Wang, M., Bhatt, U. S., Hanna, E., Hanssen-Bauer, I., . . . Walsh, J. E. (2020). Arctic Report Card 2020: Surface Air Temperature. doi:https://doi.org/10.25923/gcw8-2z06

Baraer, M., McKenzie, J., Mark, B. G., Gordon, R., Bury, J., Condom, T., . . . Fortner, S. K. (2015). Contribution of groundwater to the outflow from ungauged glacierized catchments: a multi-site study in the tropical Cordillera Blanca, Peru. *Hydrological Processes, 29*(11), 2561-2581. doi:https://doi.org/10.1002/hyp.10386

Beckett, C. (2021). Beyond remediation: Containing, confronting and caring for the Giant Mine Monster. *Environment and Planning E: Nature and Space, 4*(4), 1389-1412.

Board, M. r. B. (2003). *Mackenzie River Basin - State of the Aquatic Ecosystem Report 2003*. Retrieved from https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/water-planning/mackenzierbb_cov_let_contents_pref.pdf

Board, M. R. B. (2023). Basin Maps. Retrieved from https://www.mrbb.ca/resources/basin-maps

Board, M. V. L. a. W. (2023). Who We Are. Retrieved from https://mvlwb.com/who-we-are

Branch, W. R. (2019). *Yukon Observation Well Network - 2017 Report*. online: Yukon Government Retrieved from https://yukon.ca/sites/yukon.ca/files/env/env-yukon-observation-well-network-2017-report.pdf

Bromstad, M. J., Wrye, L. A., & Jamieson, H. E. (2017). The characterization, mobility, and persistence of roaster-derived arsenic in soils at Giant Mine, NWT. *Applied geochemistry, 82*, 102-118. doi:https://doi.org/10.1016/j.apgeochem.2017.04.004

Canada, C.-I. R. a. N. A. (2013). Wek'èezhìi Area. Retrieved from https://www.rcaanc-cirnac.gc.ca/eng/1100100026707/1618000935787

Canada, C.-I. R. a. N. A. (2023). Giant Mine Remediation Project. Retrieved from https://rcaanc-cirnac.gc.ca/eng/1100100027364/1617815941649

Canada, D. o. J. (2021). Implementing the United Nations Declaration on the Rights of Indigenous Peoples Act. Retrieved from https://justice.gc.ca/eng/declaration/index.html

Canada, G. o. (2023). Open Government Portal. Retrieved from https://search.open.canada.ca/opendata/?page=1&sort=score+desc&collection=fgp&_ga=2.146792179.655416100.1681828335-565365684.1655151843&search_text=population+. from Open Government https://search.open.canada.ca/opendata/?page=1&sort=score+desc&collection=fgp&_ga=2.146792179.655416100.1681828335-565365684.1655151843&search_text=population+

Canada, I. S. (2023). Contributions to First Nations for the Management of Contaminated Sites. Retrieved from https://www.sac-isc.gc.ca/eng/1386010106915/1615723093657

Canada, S. (2016). Census Profile, 2016 Census: Yellowknife [Census agglomeration]., Northwest Territories. Retrieved from https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/details/page.cfm?Lang=E&Geo1=CMACA&Code1=995&Geo2=PR&Code2=61&SearchType=Begins&SearchPR=01&B1=All&type=0. Retrieved February 25, 2022, from Statistics Canada https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/details/page.cfm?Lang=E&Geo1=CMACA&Code1=995&Geo2=PR&Code2=61&SearchType=Begins&SearchPR=01&B1=All&type=0

Castleden, H., Hart, C., Cunsolo, A., Harper, S., & Martin, D. (2017). Reconciliation and relationality in water research and management in Canada: Implementing indigenous ontologies, epistemologies, and methodologies. In *Water policy and governance in Canada* (pp. 69-95): Springer.

Chattopadhyay, S., Raychaudhuri, U., & Chakraborty, R. (2014). Artificial sweeteners – a review. *Journal of Food Science and Technology, 51*(4), 611-621. doi:10.1007/s13197-011-0571-1

Clark, I. D., & Raven, K. G. (2004). Sources and circulation of water and arsenic in the Giant Mine, Yellowknife, NWT, Canada. *Isotopes in Environmental and Health Studies, 40*(2), 115-128. doi:10.1080/10256010410001671014

Cochand, M., Molson, J., & Lemieux, J. M. (2019). Groundwater hydrogeochemistry in permafrost regions. *Permafrost and Periglacial Processes, 30*(2), 90-103.

Dillon, C. L. (2006). *City of Yellowknife Solid Waste Facility – Drainage Study* (Reference File No. 06-6460). Retrieved from https://registry.mvlwb.ca/Documents/MV2009L3-0007/MV2009L3-0007%20-%20City%20of%20Yk%20-%20Landfill%20Drainage%20Study%20(LDS)%20-%20Mar8-12.pdf

Dillon, C. L. (2012). *Yellowknife Solid Waste Facility Leachate Modeling and Groundwater Study – Yellowknife, NT. Final Report* (Project No. 10-3478). Retrieved from

Dillon, C. L. (2017). *City of Yellowknife Groundwater Monitoring Plan Review –City of Yellowknife Landfill* (Project No. 17-5937). Retrieved from

Doré, G., Niu, F., & Brooks, H. (2016). Adaptation Methods for Transportation Infrastructure Built on Degrading Permafrost. *Permafrost and Periglacial Processes, 27*(4), 352-364. doi:https://doi.org/10.1002/ppp.1919

Douglas, M., Clark, I., Raven, K., & Bottomley, D. (2000). Groundwater mixing dynamics at a Canadian Shield mine. *Journal of Hydrology, 235*(1-2), 88-103.

Elliot, A. C. (Writer). (2019). Salvage. In E. Donius (Producer). United States.

Elshafei, Y., Sivapalan, M., Tonts, M., & Hipsey, M. R. (2014). A prototype framework for models of socio-hydrology: identification of key feedback loops and parameterisation approach. *Hydrol. Earth Syst. Sci., 18*(6), 2141-2166. doi:10.5194/hess-18-2141-2014

Environment, C. C. o. M. o. t. (2023). Water - Aquatic Life. Retrieved from https://ccme.ca/en/resources/water-aquatic-life

Ferguson, C. (Writer). (2016). Shadow of a Giant. In L. Johnson & C. Ferguson (Producer). Canada.

Fetter, C. W., Boving, T. B., & Kreamer, D. K. (1999). *Contaminant hydrogeology* (Vol. 500): Prentice hall Upper Saddle River, NJ.

Frape, S. K., Fritz, P., & McNutt, R. H. (1984). Water-rock interaction and chemistry of groundwaters from the Canadian Shield. *Geochimica et Cosmochimica Acta, 48*(8), 1617-1627. doi:https://doi.org/10.1016/0016-7037(84)90331-4

GNWT. (2023). Arsenic in Lake Water Around Yellowknife. Retrieved from https://www.hss.gov.nt.ca/en/newsroom/arsenic-lake-water-around-yellowknife

Gobby, J., Temper, L., Burke, M., & von Ellenrieder, N. (2022). Resistance as governance: transformative strategies forged on the frontlines of extractivism in Canada. *The Extractive Industries and Society, 9*, 100919.

Gorelick, S. M., & Zheng, C. (2015). Global change and the groundwater management challenge. *Water Resources Research, 51*(5), 3031-3051.

Goulding, H. (2011). Yukon water: An assessment of climate change vulnerabilities. *Yukon EY (ed)*.

Government, Y. (2022). Contaminated Sites. Retrieved from https://yukon.maps.arcgis.com/apps/webappviewer/index.html?id=d331e96802054e6aabc8f0d8ed61311a. Retrieved January, 2022, from Yukon Government https://yukon.maps.arcgis.com/apps/webappviewer/index.html?id=d331e96802054e6aabc8f0d8ed61311a

Government, Y. (2023). Contaminated Sites. Retrieved from https://yukon.maps.arcgis.com/apps/webappviewer/index.html?id=d331e96802054e6aabc8f0d8ed61311a. Retrieved 2022 https://yukon.maps.arcgis.com/apps/webappviewer/index.html?id=d331e96802054e6aabc8f0d8ed61311a

Guo, X., Chen, X., Wang, J., Liu, Z., Gaile, D., Wu, H., . . . Ren, X. (2018). Multi-generational impacts of arsenic exposure on genome-wide DNA methylation and the implications for arsenic-induced skin lesions. *Environment International, 119*, 250-263. doi:https://doi.org/10.1016/j.envint.2018.06.024

Hadjikyriacou, A. (2021). Economic geographies. In *Doing Spatial History* (pp. 252-273): Routledge.

Harris, M. (2021). Rivers. In *Doing Spatial History* (pp. 154-170): Routledge.

Hjort, J., Karjalainen, O., Aalto, J., Westermann, S., Romanovsky, V. E., Nelson, F. E., . . . Luoto, M. (2018). Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nature Communications, 9*(1), 5147. doi:10.1038/s41467-018-07557-4

Hynds, P., Regan, S., Andrade, L., Mooney, S., O'Malley, K., DiPelino, S., & O'Dwyer, J. (2018). Muddy Waters: Refining the Way forward for the "Sustainability Science" of Socio-Hydrogeology. *Water, 10*(9), 1111. Retrieved from https://www.mdpi.com/2073-4441/10/9/1111

Jamieson, H. E. (2014). The legacy of arsenic contamination from mining and processing refractory gold ore at Giant Mine, Yellowknife, Northwest Territories, Canada. *Reviews in Mineralogy and Geochemistry, 79*(1), 533-551.

Jasechko, S., Birks, S. J., Gleeson, T., Wada, Y., Fawcett, P. J., Sharp, Z. D., . . . Welker, J. M. (2014). The pronounced seasonality of global groundwater recharge. *Water Resources Research, 50*(11), 8845-8867. doi:https://doi.org/10.1002/2014WR015809

Khazaei, E., & Milne-Home, W. (2017). Applicability of geochemical techniques and artificial sweeteners in discriminating the anthropogenic sources of chloride in shallow groundwater north of Toronto, Canada. *Environmental Monitoring and Assessment, 189*(5), 218. doi:10.1007/s10661-017-5927-1

Kimball, B. A., Runkel, R. L., Walton-Day, K., & Bencala, K. E. (2002). Assessment of metal loads in watersheds affected by acid mine drainage by using tracer injection and synoptic sampling: Cement Creek, Colorado, USA. *Applied geochemistry, 17*(9), 1183-1207. doi:https://doi.org/10.1016/S0883-2927(02)00017-3

Kimball, B. A., Walton-Day, K., & Runkel, R. L. (2007). Quantification of metal loading by tracer injection and synoptic sampling. *Integrated investigations of environmental effects of historical mining in the Animas River Watershed, San Juan County, Colorado, 1*, 417.

Kjeldsen, P., Barlaz, M. A., Rooker, A. P., Baun, A., Ledin, A., & Christensen, T. H. (2002). Present and Long-Term Composition of MSW Landfill Leachate: A Review. *Critical Reviews in Environmental Science and Technology, 32*(4), 297-336. doi:10.1080/10643380290813462

Kumar, V., Parihar, R. D., Sharma, A., Bakshi, P., Singh Sidhu, G. P., Bali, A. S., . . . Rodrigo-Comino, J. (2019). Global evaluation of heavy metal content in surface water bodies: A meta-analysis using heavy metal pollution indices and multivariate statistical analyses. *Chemosphere, 236*, 124364. doi:https://doi.org/10.1016/j.chemosphere.2019.124364

Land, N. (2023). Native Land Digital. Retrieved from https://native-land.ca/

Langer, M., von Deimling, T. S., Westermann, S., Rolph, R., Rutte, R., Antonova, S., . . . Grosse, G. (2023). Thawing permafrost poses environmental threat to thousands of sites with legacy industrial contamination. *Nature Communications, 14*(1), 1721. doi:10.1038/s41467-023-37276-4

Lawson, K., Bavaj, R., & Struck, B. (2022). *A Guide to Spatial History: Areas, Aspects, and Avenues of Research*: Olsokhagen.

LeClerc, E., & Keeling, A. (2015). From cutlines to traplines: Post-industrial land use at the Pine Point mine. *The Extractive Industries and Society, 2*(1), 7-18.

Liboiron, M., Tironi, M., & Calvillo, N. (2018). Toxic politics: Acting in a permanently polluted world. *Social Studies of Science, 48*(3), 331-349. doi:10.1177/0306312718783087

Liu, Y., Ptacek, C. J., Groza, L. G., Staples, R., & Blowes, D. W. (2022). Occurrence and distribution of emerging contaminants in mine-impacted lake water and potential use as co-tracers of anthropogenic activity in the subarctic region, Northwest Territories, Canada. *Environmental Research, 207*, 112034. doi:https://doi.org/10.1016/j.envres.2021.112034

Luo, J., Zhang, Q., Cao, M., Wu, L., Cao, J., Fang, F., . . . Feng, Q. (2019). Ecotoxicity and environmental fates of newly recognized contaminants-artificial sweeteners: A review. *Science of The Total Environment, 653*, 1149-1160.

Macfarlane, R. (2020). *Health Effects of Extreme Weather Events and Wildland Fires*. Online: Yukon Government Retrieved from https://yukon.ca/sites/yukon.ca/files/hss/climate_change_report_web_feb.2020_0.pdf

Mark, B. G., French, A., Baraer, M., Carey, M., Bury, J., Young, K. R., . . . Lautz, L. (2017). Glacier loss and hydro-social risks in the Peruvian Andes. *Global and Planetary Change, 159*, 61-76. doi:https://doi.org/10.1016/j.gloplacha.2017.10.003

McKenzie, J. M., Kurylyk, B. L., Walvoord, M. A., Bense, V. F., Fortier, D., Spence, C., & Grenier, C. (2021). Invited perspective: What lies beneath a changing Arctic? *The Cryosphere, 15*(1), 479-484.

Mckenzie, J. M., Mark, B. G., Thompson, L. G., Schotterer, U., & Lin, P.-N. (2010). A hydrogeochemical survey of Kilimanjaro (Tanzania): implications for water sources and ages. *Hydrogeology Journal, 18*(4), 985.

Medeiros, A. S., Wood, P., Wesche, S. D., Bakaic, M., & Peters, J. F. (2017). Water security for northern peoples: review of threats to Arctic freshwater systems in Nunavut, Canada. *Regional Environmental Change, 17*(3), 635-647.

Mohammed Abdul, K. S., Jayasinghe, S. S., Chandana, E. P. S., Jayasumana, C., & De Silva, P. M. C. S. (2015). Arsenic and human health effects: A review. *Environmental Toxicology and Pharmacology, 40*(3), 828-846. doi:https://doi.org/10.1016/j.etap.2015.09.016

Monitoring, A. (2017). Snow, Water, Ice and Permafrost in the Arctic (SWIPA); Summary for Policy-makers.

Nadiri, A. A., Gharekhani, M., Khatibi, R., Sadeghfam, S., & Moghaddam, A. A. (2017). Groundwater vulnerability indices conditioned by supervised intelligence committee machine (SICM). *Science of The Total Environment, 574*, 691-706.

Nasser, N. A., Patterson, R. T., Roe, H. M., Galloway, J. M., Falck, H., Palmer, M. J., . . . Neville, L. A. (2016). Lacustrine Arcellinina (Testate Amoebae) as Bioindicators of Arsenic Contamination. *Microbial Ecology, 72*(1), 130-149. doi:10.1007/s00248-016-0752-6

Nicol, H., Weber, B., Barkan, J., Steinberg, P., Tasch, J., & Gerhardt, H. (2016). Contesting the Arctic: Politics and Imaginaries in the Circumpolar North. *The AAG Review of Books, 4*(3), 170-178. doi:10.1080/2325548X.2016.1187510

O'Neill, H. B., Burn, C. R., Allard, M., Arenson, L. U., Bunn, M. I., Connon, R. F., . . . Smith, S. L. (2020). Permafrost thaw and northern development. *Nature Climate Change, 10*(8), 722-723. doi:10.1038/s41558-020-0862-5

Palmer, M. J., Jamieson, H. E., Borčinová Radková, A., Maitland, K., Oliver, J., Falck, H., & Richardson, M. (2021). Mineralogical, geospatial, and statistical methods combined to estimate geochemical background of arsenic in soils for an area impacted by legacy mining pollution. *Science of The Total Environment, 776*, 145926. doi:https://doi.org/10.1016/j.scitotenv.2021.145926

Pelletier, N., Chételat, J., Cousens, B., Zhang, S., Stepner, D., Muir, D. C. G., & Vermaire, J. C. (2020). Lead contamination from gold mining in Yellowknife Bay (Northwest Territories), reconstructed using stable lead isotopes. *Environmental Pollution, 259*, 113888. doi:https://doi.org/10.1016/j.envpol.2019.113888

Piper, A. M. (1944). A graphic procedure in the geochemical interpretation of water-analyses. *Eos, Transactions American Geophysical Union, 25*(6), 914-928. doi:https://doi.org/10.1029/TR025i006p00914

Propp, V. R., Brown, S. J., Collins, P., Smith, J. E., & Roy, J. W. (2022). Artificial Sweeteners Identify Spatial Patterns of Historic Landfill Contaminated Groundwater Discharge in an Urban Stream. *Groundwater Monitoring & Remediation, 42*(1), 50-64.

Rea, K. J. (2019). The political economy of the Canadian North. In *The Political Economy of the Canadian North*: University of Toronto Press.

Resources, E. a. N. (2023). Canadian Climate Normals 1981-2010 Station Data. Retrieved from https://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?searchType=stnProv&lstProvince=NT&txtCentralLatMin=0&txtCentralLatSec=0&txtCentralLongMin=0&txtCentralLongSec=0&stnID=1706&dispBack=0. from Government of Canada https://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?searchType=stnProv&lstProvince=NT&txtCentralLatMin=0&txtCentralLatSec=0&txtCentralLongMin=0&txtCentralLongSec=0&stnID=1706&dispBack=0

Ribot, J. C., & Peluso, N. L. (2009). A Theory of Access*. *Rural Sociology, 68*(2), 153-181. doi:10.1111/j.1549-0831.2003.tb00133.x

Robards, M., & Alessa, L. (2004). Timescapes of community resilience and vulnerability in the circumpolar North. *Arctic, 57*, 415+. Retrieved from https://link-gale-com.proxy3.library.mcgill.ca/apps/doc/A126852887/GRNR?u=crepuq_mcgill&sid=GRNR&xid=b9d0da19

Roy, J. W., & Bickerton, G. (2010). Proactive screening approach for detecting groundwater contaminants along urban streams at the reach-scale. *Environmental Science & Technology, 44*(16), 6088-6094.

Roy, J. W., Van Stempvoort, D. R., & Bickerton, G. (2014). Artificial sweeteners as potential tracers of municipal landfill leachate. *Environmental Pollution, 184*, 89-93. doi:https://doi.org/10.1016/j.envpol.2013.08.021

Runkel, R. L., Verplanck, P. L., Walton-Day, K., McCleskey, R. B., & Byrne, P. (2023). The truth is in the stream: Use of tracer techniques and synoptic sampling to evaluate metal loading and remedial options in a hydrologically complex setting. *Science of The Total Environment, 876*, 162458.

Runkel, R. L., Walton-Day, K., Kimball, B. A., Verplanck, P. L., & Nimick, D. A. (2013). Estimating instream constituent loads using replicate synoptic sampling, Peru Creek, Colorado. *Journal of Hydrology, 489*, 26-41. doi:https://doi.org/10.1016/j.jhydrol.2013.02.031

Sandlos, J., & Keeling, A. (2009, 04 March 2015). Mining. Retrieved from www.thecanadianencyclopedia.ca/en/article/mining

Sandlos, J., & Keeling, A. (2016). Toxic legacies, slow violence, and environmental injustice at Giant Mine, Northwest Territories. *Northern Review*(42), 7–21-27–21.

Sandloss, J., & Keeling, A. (2012). Claiming the new north: development and colonialism at the Pine Point mine, Northwest Territories, Canada. *Environment and History, 18*(1), 5-34.

Schuur, E. A. G., & Abbott, B. (2011). High risk of permafrost thaw. *Nature, 480*(7375), 32-33. doi:10.1038/480032a

Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., . . . Vonk, J. E. (2015). Climate change and the permafrost carbon feedback. *Nature, 520*(7546), 171-179. doi:10.1038/nature14338

Secretariat, T. B. o. C. (2022). Federal Contaminated Sites Inventory. Retrieved from https://www.tbs-sct.gc.ca/fcsi-rscf/numbers-numeros-eng.aspx?qid=687244. Retrieved

February 10, 2022, from Treasury Board of Canada Secretariat https://www.tbs-sct.gc.ca/fcsi-rscf/numbers-numeros-eng.aspx?qid=687244

Shoebridge, P., & Simons, M. (2011). Welcome to Pine Point [Web Documentary]. Online: National Film Board of Canada.

Skierszkan, E. (2019). *Uranium and Arsenic in the Baseline Environment, Dawson Range, Yukon*. Government of Yukon Retrieved from https://yukon.ca/sites/yukon.ca/files/env/env-uranium-arsenic-baseline-environment-dawson-range-yukon.pdf

Srinivasan, V., Lambin, E. F., Gorelick, S. M., Thompson, B. H., & Rozelle, S. (2012). The nature and causes of the global water crisis: Syndromes from a meta-analysis of coupled human-water studies. *Water Resources Research, 48*(10). doi:https://doi.org/10.1029/2011WR011087

Statistics, Y. B. o. (2020). *Population Report First Quarter, 2020*. Online: Yukon Government Retrieved from https://yukon.ca/sites/yukon.ca/files/ybs/populationq1_2020.pdf

Survey, N. T. G. (2022). Northwest Territories Geological Survey Open Data. Retrieved from https://ntgs-open-data-ntgs.hub.arcgis.com/. Retrieved February 12, 2022, from Northwest Territories Geological Survey https://ntgs-open-data-ntgs.hub.arcgis.com/

Territories, G. o. N. (2020). *Environmental Liabilities*. online: Government of Northwest Territories Retrieved from https://www.fin.gov.nt.ca/sites/fin/files/resources/environmental_liabilities_2020.pdf

Territories, G. o. t. N. (2020). *Environmental Liabilities*. Retrieved from https://www.fin.gov.nt.ca/sites/fin/files/resources/environmental_liabilities_2020.pdf

Teufel, B., & Sushama, L. (2019). Abrupt changes across the Arctic permafrost region endanger northern development. *Nature Climate Change, 9*(11), 858-862. doi:10.1038/s41558-019-0614-6

Thoman, R. L., Richter-Menge, J., & Druckenmiller, M. L. (2020). NOAA Arctic Report Card 2020 Executive Summary. doi:https://doi.org/10.25923/mn5p-t549

Tóth, J. (1999). Groundwater as a geologic agent: An overview of the causes, processes, and manifestations. *Hydrogeology Journal, 7*(1), 1-14. doi:10.1007/s100400050176

Van Stempvoort, D. R., Roy, J. W., Brown, S. J., & Bickerton, G. (2011). Artificial sweeteners as potential tracers in groundwater in urban environments. *Journal of Hydrology, 401*(1), 126-133. doi:https://doi.org/10.1016/j.jhydrol.2011.02.013

Walvoord, M. A., & Kurylyk, B. L. (2016). Hydrologic impacts of thawing permafrost—A review. *Vadose Zone Journal, 15*(6).

Wang, S., & Mulligan, C. N. (2006). Occurrence of arsenic contamination in Canada: Sources, behavior and distribution. *Science of The Total Environment, 366*(2), 701-721. doi:https://doi.org/10.1016/j.scitotenv.2005.09.005

Whiteman, G., Hope, C., & Wadhams, P. (2013). Vast costs of Arctic change. *Nature, 499*(7459), 401-403. doi:10.1038/499401a

Wiebe, A. J., McKenzie, J. M., Hamel, E., Rudolph, D., Mulligan, B., & de Grandpré, I. (2023). *Groundwater vulnerability in the Yukon and Northwest Territories, Canada*. Under Review.

Wilson, N. J. (2020). Querying water co-governance: Yukon First Nations and water governance in the context of modern land claim agreements. *Water Alternatives, 13*(1), 93-118.

Wilson, N. J., Harris, L. M., Joseph-Rear, A., Beaumont, J., & Satterfield, T. (2019). Water is medicine: Reimagining water security through Tr'ondëk Hwëch'in relationships to treated and traditional water sources in Yukon, Canada. *Water, 11*(3), 624.

Wilson, N. J., Montoya, T., Arseneault, R., & Curley, A. (2021). Governing water insecurity: navigating indigenous water rights and regulatory politics in settler colonial states. *Water International, 46*(6), 783-801.

Yellowknife, C. o. (2012). *Yellowknife Solid Waste Facility Leachate Modeling and Groundwater Study -Yellowknife, NT* (10-3478). City of Yellowknife

Yellowknife, C. o. (2017). *Solid Waste Facility Interim Groundwater Monitoring Plan*. Mackenzie Valley Land and Water Board

Yellowknife, C. o. (2021). *Solid Waste Facility Interim Groundwater Monitoring Plan*. online: City of Yellowknife Retrieved from https://registry.mvlwb.ca/Documents/MV2021L3-0003/City%20of%20YK%20-%20Type%20A%20Water%20Licence%20-%20Renewal%20Application%20-%20Solid%20Waste%20Facility%20Interim%20Groundwater%20Monitoring%20Plan%20-%20Feb5_21.pdf

Yellowknife, C. o. (2023). Indigenous Peoples. Retrieved from https://www.yellowknife.ca/en/living-here/indigenous-peoples.aspx

Yukon, E. (2014). *Water for Nature, Water for People: Yukon Water Strategy and Actions Plan*. Canadian Electronic Library/desLibris: Yukon Government

Zipper, S. C., Lamontagne-Hallé, P., McKenzie, J. M., & Rocha, A. V. (2018). Groundwater Controls on Postfire Permafrost Thaw: Water and Energy Balance Effects. *Journal of Geophysical Research: Earth Surface, 123*(10), 2677-2694. doi:https://doi.org/10.1029/2018JF004611

Zueter, A. F., Newman, G., & Sasmito, A. P. (2021). Numerical study on the cooling characteristics of hybrid thermosyphons: Case study of the Giant Mine, Canada. *Cold Regions Science and Technology, 189*, 103313.

5. Supplementary Materials 1

5.1. Yellowknife Field Plan

5.1.1. Sampling Area Overview

Yellowknife Field Plan overview:

Roughly 50 sample kits will be collected over a week-long period at the end of August (14-22) from the waters surrounding the landfill. These samples will be used to verify background geochemical concentrations and spatial changes in contaminants from the landfill and well as track flowpaths of groundwater around the landfill. The 50 sample kits are broken down into: 44 regular sample collections + 4 duplicates + 1 field blank + 1 trip blank. The number of duplicates and blanks follows the QA/QC guidelines set by the Yellowknife SWF Interim Groundwater Monitoring Plan. The samples, divided by type will be: 11 groundwater wells +1 duplicate, 23 surface water sites (7 SWF sampling sites, 8 recommended by Isabelle) +2 duplicates, 10 near-surface groundwater sites + 1 duplicate.
This field plan is organized by sampling media protocols and then sample type:

Part A: Sampling Area Overview
Figure 1) Satellite Imagery and Sampling Locations
Figure 2) Surficial Geological Setting
Figure 3) Bedrock Geological Setting
Figure 4) Hydrogeologic Setting of SWF

Part B: Sampling Media
1) groundwater (wells)
2) surface water (streams and lakes)
3) near-surface groundwater (drive point)

Part C: Sampling Types
1) on-site physicochemical measurements (field)
2) general geochemistry (Taiga Labs)
3) sweeteners (ECCC)
4) isotopes (McGill)

Part D: Itinerary and Gear List

Part A: Sampling Area Overview
Figure 1) Satellite Imagery and Proposed Sampling Locations

Sampling Locations around SWF

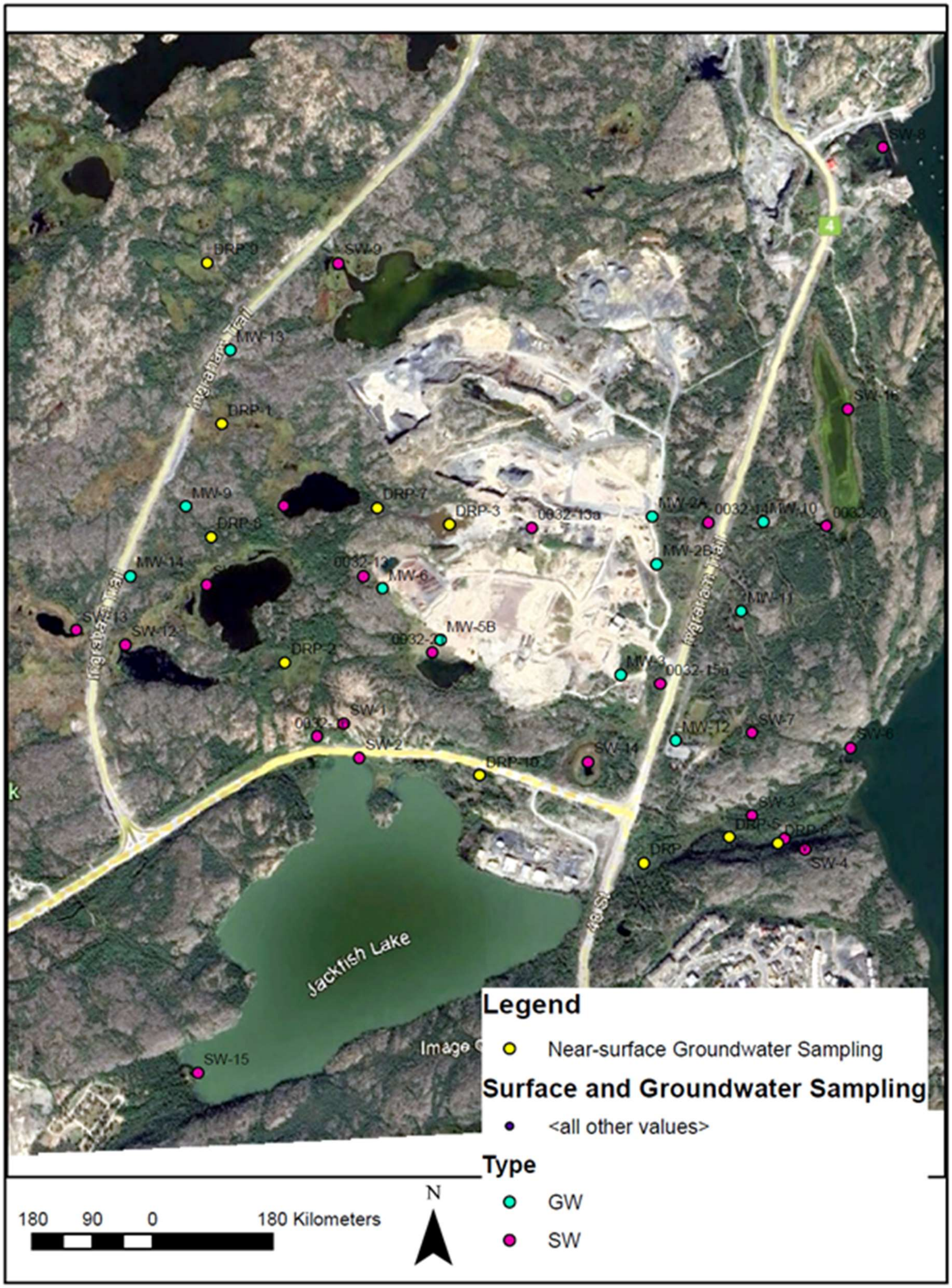


Figure 2) Surficial Geological Setting

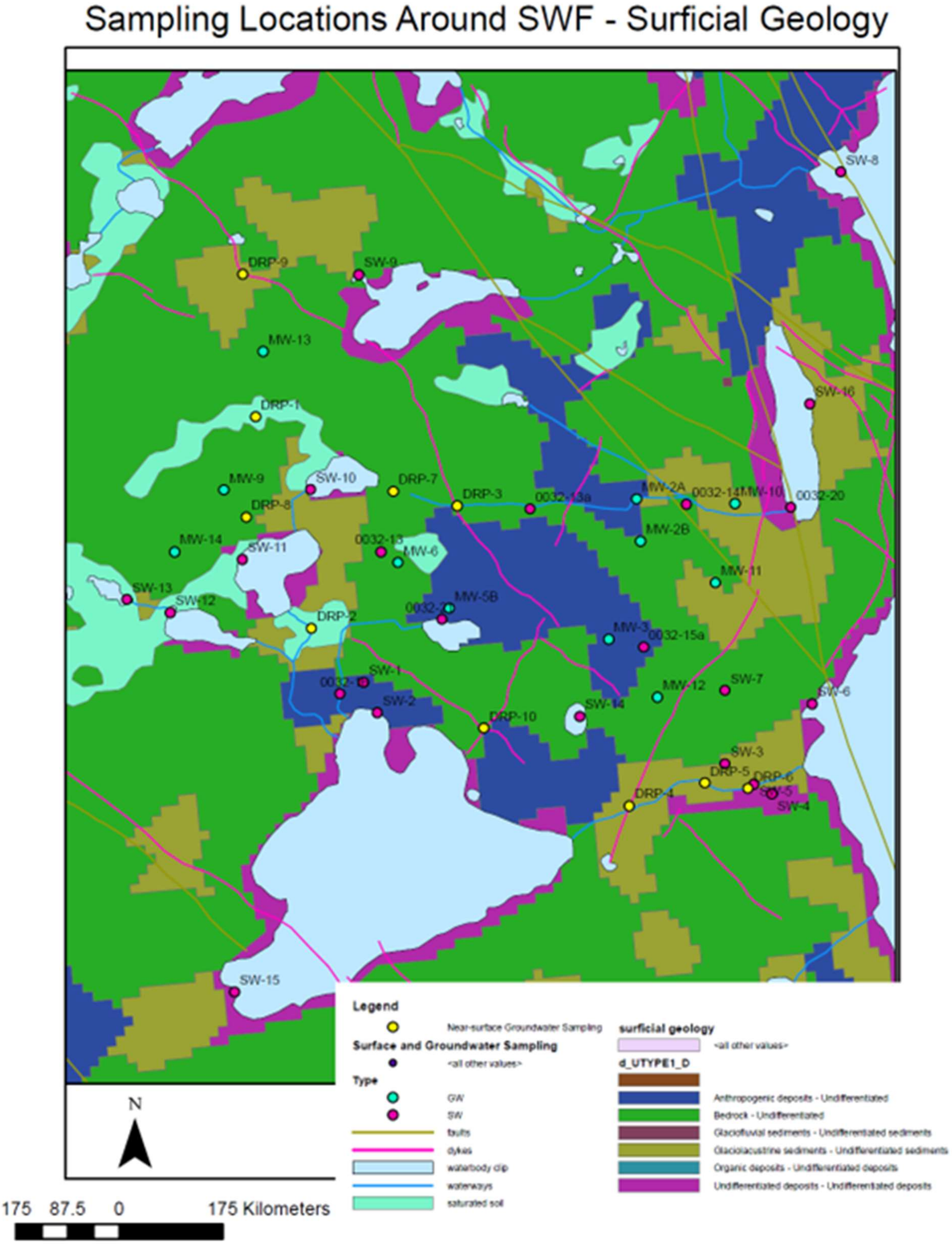


Figure 3) Bedrock Geological Setting

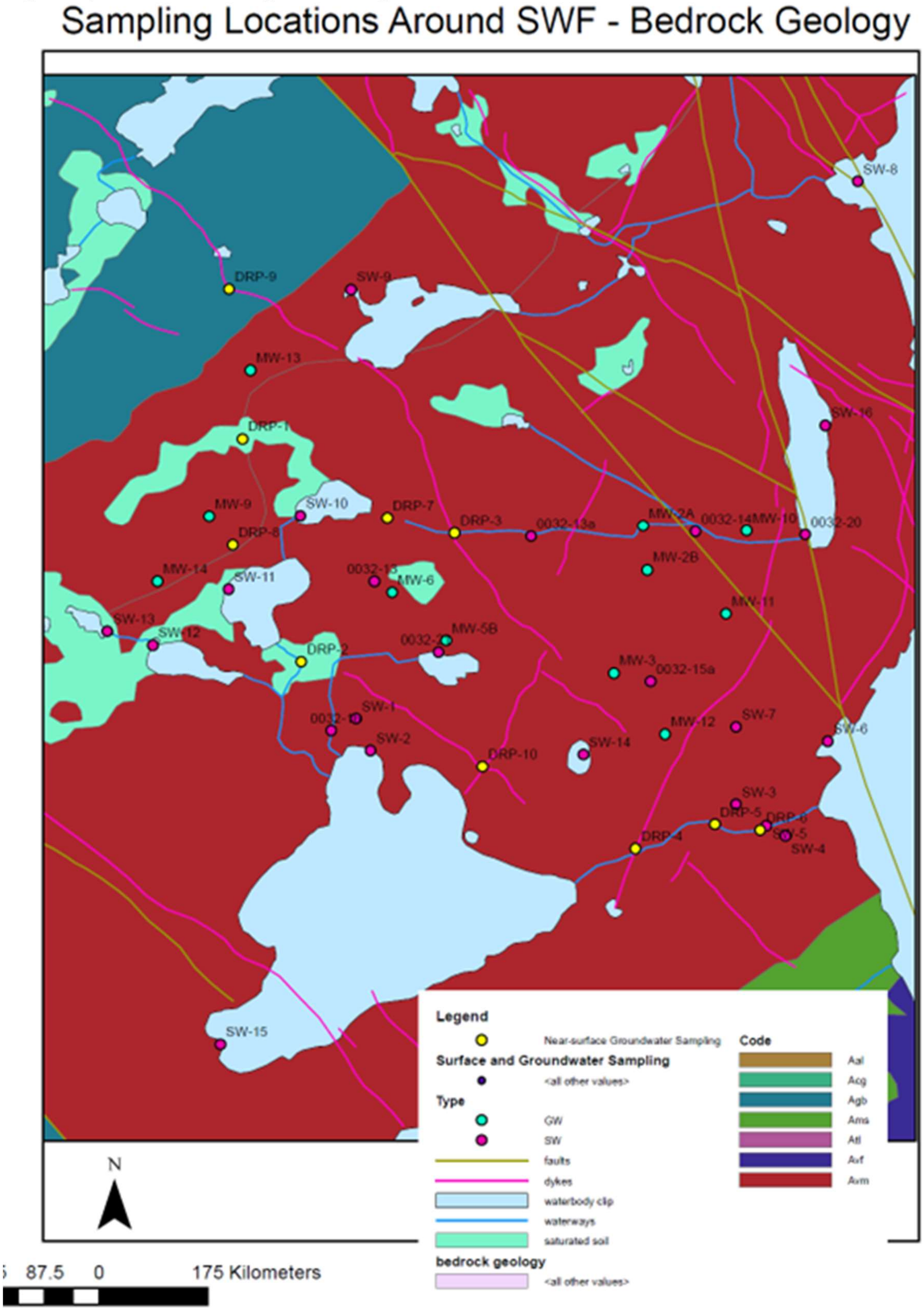
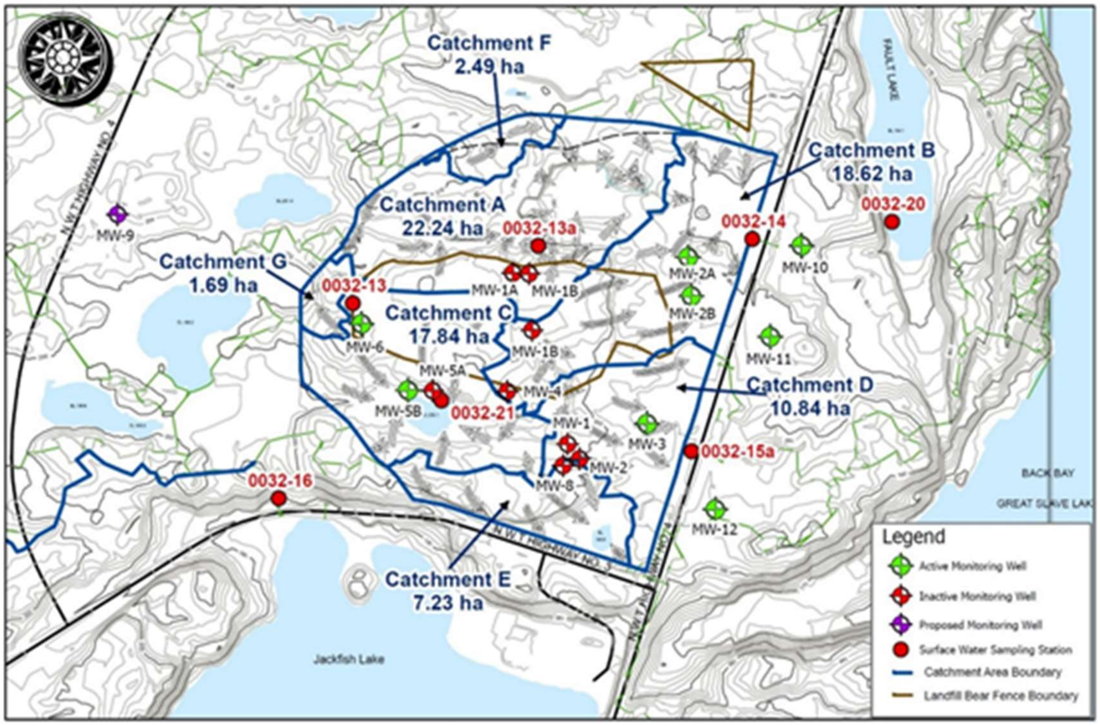


Figure 4) Hydrogeological Setting around SWF (from the SWF Interim Groundwater Monitoring Plan)

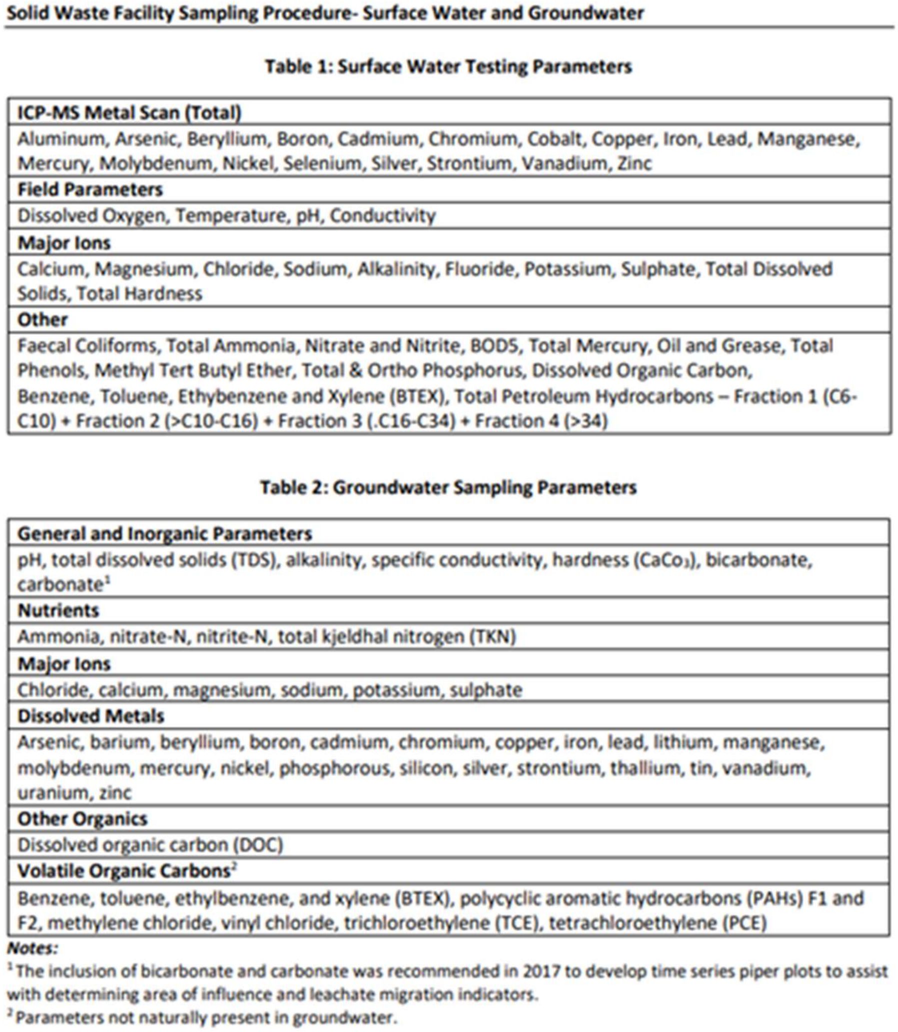


5.1.1. Sampling Media

Part B: Sampling Media
Groundwater
Sampling of the groundwater wells located on and around the landfill will follow the procedures outlined by the Yellowknife government in their SWF Interim Groundwater Monitoring Plan from 2020. The QA/QC procedures are as follows:
Duplicate Sample: Two samples will be collected from a sampling location using identical sampling procedures. Both samples will be labelled and preserved individually and submitted to the laboratory for analyses (not marked duplicate or the same as the sample ID). Approximately, one sample for every ten (10) sampling locations will be collected as a duplicate and submitted to the laboratory for analyses. For smaller sampling events (less than 10), at least one duplicate will be collected and submitted for analysis.
Field Blank: A sample will be collected in the field using identical sampling methods, equipment and preservatives; however, the water used for the field blank sample will be laboratory-provided deionized water instead of water from a groundwater monitoring well. The field blank will then be submitted to the laboratory for the same analysis as other groundwater samples. One field blank will be submitted to the laboratory for analysis per sampling event
Trip Blank: A sample using laboratory-provided deionized water will be prepared and preserved by the laboratory prior to the sampling event. The sample will remain unopened throughout the duration of the sampling trip and will then be submitted to the laboratory for the same analysis as other groundwater samples collected during the same sampling event. One trip blank sample will be submitted to the laboratory for analysis per sampling event.

In total: this field work will require, 1 duplicate sample, 1 field blank, and 1 trip blank

A note about sampling: calibration is done each done at the start of each day for the physicochemical measurements tool
The items to complete before going to site are related to pick-up of sampling bottles and supplies from the lab, preparing equipment, and notifying relevant personnel, as well as purging the wells at least 1 week before (usually routine sampling happens last week of July, so should be good when I get there)
-not going to purge any wells that have already been sampled in the weeks prior
contacting the lab: bottles and supplies should be ordered weeks ahead. The week before sampling, an email must also be sent specifying the date of sampling, type of samples taking place (sw/gw), and a chain of custody form (do I need this?), also the pick-up time. Samples that are usually sent to this lab are:



Solid Waste Facility Sampling Procedure- Surface Water and Groundwater

Table 1: Surface Water Testing Parameters

ICP-MS Metal Scan (Total)
Aluminum, Arsenic, Beryllium, Boron, Cadmium, Chromium, Cobalt, Copper, Iron, Lead, Manganese, Mercury, Molybdenum, Nickel, Selenium, Silver, Strontium, Vanadium, Zinc
Field Parameters
Dissolved Oxygen, Temperature, pH, Conductivity
Major Ions
Calcium, Magnesium, Chloride, Sodium, Alkalinity, Fluoride, Potassium, Sulphate, Total Dissolved Solids, Total Hardness
Other
Faecal Coliforms, Total Ammonia, Nitrate and Nitrite, BOD5, Total Mercury, Oil and Grease, Total Phenols, Methyl Tert Butyl Ether, Total & Ortho Phosphorus, Dissolved Organic Carbon, Benzene, Toluene, Ethybenzene and Xylene (BTEX), Total Petroleum Hydrocarbons – Fraction 1 (C6-C10) + Fraction 2 (>C10-C16) + Fraction 3 (.C16-C34) + Fraction 4 (>34)

Table 2: Groundwater Sampling Parameters

General and Inorganic Parameters
pH, total dissolved solids (TDS), alkalinity, specific conductivity, hardness ($CaCo_3$), bicarbonate, carbonate[1]
Nutrients
Ammonia, nitrate-N, nitrite-N, total kjeldhal nitrogen (TKN)
Major Ions
Chloride, calcium, magnesium, sodium, potassium, sulphate
Dissolved Metals
Arsenic, barium, beryllium, boron, cadmium, chromium, copper, iron, lead, lithium, manganese, molybdenum, mercury, nickel, phosphorous, silicon, silver, strontium, thallium, tin, vanadium, uranium, zinc
Other Organics
Dissolved organic carbon (DOC)
Volatile Organic Carbons[2]
Benzene, toluene, ethylbenzene, and xylene (BTEX), polycyclic aromatic hydrocarbons (PAHs) F1 and F2, methylene chloride, vinyl chloride, trichloroethylene (TCE), tetrachloroethylene (PCE)

Notes:

[1] The inclusion of bicarbonate and carbonate was recommended in 2017 to develop time series piper plots to assist with determining area of influence and leachate migration indicators.

[2] Parameters not naturally present in groundwater.

- sample pick-up/drop off: sample kits can be picked up in the morning (latest 8:30 am, call to check the hours). They will come in coolers with ice, and each cooler contains no more than 4 sample kits. Kits should be returned the same day.
- gear to be collected:

Gear Type	Gear List	Where to get?
PPE	-disposable gloves (need to be switched between samples) -safety glasses -high vis -steel toed boots -bangers, bells, spray -bug spray (can't use when sampling) -sunscreen -phone/radio	
General sampling items	-Sondes (YK uses Hanna probe) -20L bucket -map (paper!!) of sampling sites -field notebook -pen/permanent marker	-GNWT
GW -specific items	-keys for wells located at the Ski Club -measuring tape -water level meter -hydrolift (generator, gas, extension cord) -extra waterra tubing -extra waterra tubing foot valves -duct tape, rope, needle nose pliers -step stool for tall well casings -storage tank (for purged water)	-in Engineer's office -hydrolift at city hall basement, but rest in SWF

people to notify: the SWF manager (Wendy Newton), and the Ski Club Manager
Once at the sampling site, stop by the office to check in with the SWF Manager, they may provide a radio to keep in contact with them. Check back in with them upon departure. Pick up a jerry can of gas, generator, extension cord; the SWF Manager can communicate the location of these items, usually in the gatehouse or bailing facility. Return these items at the end of the day, every day. Use map to find sampling locations. Sampling kit bags need to be labelled before starting the sampling kit. Each bottle does not need to be labeled if the bag itself is labelled with date, time, location/ well number. Do not misplace bottles that are unlabelled.
Sampling Procedure:
Preparing the Well:
1) open well top cover, pull out all the tubing inside the well to check for damage/blockages,
2) while tubing is out of the well use the water level meter to record water level and well depth, use a measuring tape to measure how much of the well casing is above-ground

3) calculate well volume (V) based on column of water in well, prepare to purge 3-5 times the V of the week (estimated V are included in well descriptions), purging allows accurate measures of water quality without standing water.
4) put tubing back into well, if tubing was damaged, replace with new tubing and ensure foot valve is attached, leave enough tubing out of the well to reach the bucket with straining the tube.
DO NOT MOVE TUBING BETWEEN WELLS
Hydrolift Set-up:
1) use the hooks on the hydrolift to latch onto the metal (NOT PLASTIC) well casing, use the ratchet strap to latch the hydrolift to the metal well casing.
2) clamp the plastic tubing to the clamp arm, ensure that it will move only up/down with clamp arm to avoid tubing at an angle that could rub against the well piping or bend.
3) start the generator by turning it on, turn on the choke (right), and pulling cord, slowly turn down choke once started.
4) make sure hydrolift is off with speed turned to the minimum, connect hydrolift to extension cord attached to generator.
5) turn on the hydrolift, slowly turn speed knob to a very slow pump, ensure clamp arm doesn't hit the well, readjust hydrolift as necessary (turn off and unplug before moving)

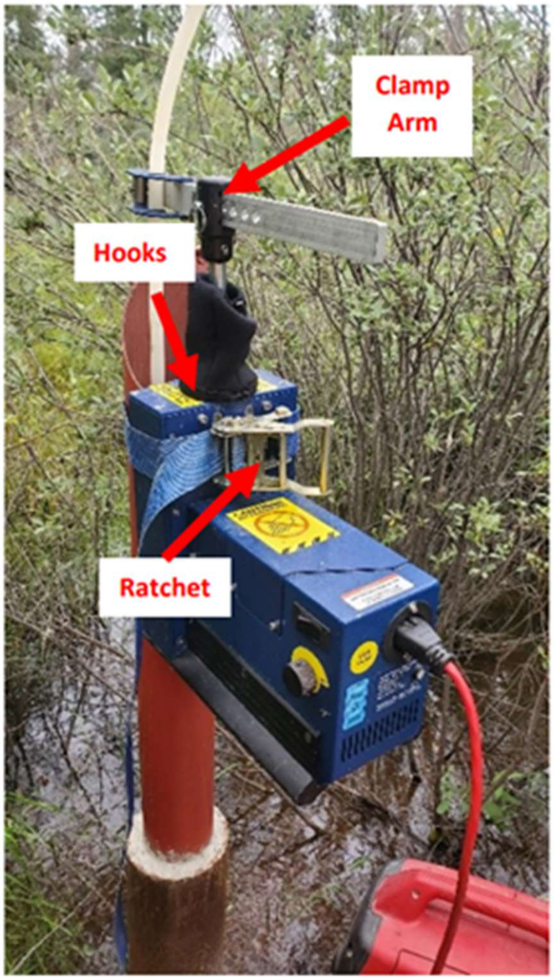


Figure 5) Hydro-lift Set-up for well purging and sampling

Well Purging:

1) once hydrolift is properly positioned and the 20L bucket is placed to collect water, slowly turn speed to max., water should start coming out of the tubing.

2) once the 20 L is full, shut off the hydrolift and drain bucket into storage barrel in truck (MIGHT NEED THIS IN GEAR LIST), record number of buckets removed from each well in notebook.

3) once storage barrel is full, drive to landfill cell and empty it completely.

4) purge 3-5 times the volume of the water column, if not possible and well is pumped dry before this occurs, then this is good enough

Location Specifics:

Name	Approx. Depth	Purge V	Coordinates	Description
MW-2A	25 m	100 L	Easting: 635349.78 Northing: 6930161.81	Fastest recharging well, will recharge as fast as purged, water height will remain unchanged, can be purged and sampled immediately, easy to use as duplicate because of fast recharge
MW-2B	4 m	10-15 L	Easting: 635362.79 Northing: 6930027.41	Top of well is high, requires a step stool for access, purge and then return ½ day later to sample
MW-3	43 m	100 L	Easting: 635260.54 Northing: 6929713.59	Located a bit into the bush, purge and then return ½ day later to sample.
MW-5B	9 m	20 L	Easting: 634749.96 Northing: 6929812.02	Located right beside defunct MW-5A, purge then return 1 day later to sample, lots of sediments in this well so tube will likely be plugged and need to be cleared
MW-6	8 m	5-10 L	Easting: 634586.71 Northing: 6929958.29	Located beside compost pond, after purging well does not significantly recharge even after 3 days (maybe sample without purging?)
MW-9			Easting: 634028.96 Northing: 6930190.54	Located off the Ingraham Trail, can park by Prospector Trail Scenic Viewpoint and then walk in, might be bushwhacking, may be dry
MW-10	12 m	40 L	Easting: 635665.02 Northing: 6930147.28	Located off Hwy 4, slightly after gravel turnout section towards Giant Mine, there is path leading off highway, park at start of path and carry equipment, well is on Ski Club Trail overlooking Fault Lake, recharge can take between 1-3 days

MW-11	22m	60 L	Easting: 635602.33 Northing: 6929893.47	Located off Hwy 4, park truck and carry equipment needed down Ski Club Trail, recharge usually takes 1 day
MW-12	8 m	60 L	Easting: 635417.03 Northing: 6929527.90	Located in the ski club parking lot, truck can be parked right beside well, recharge can take between 3-7+ days
MW-13	30m		Easting: 634155 Northing: 6930635	Located off Ingraham Trail to the W of the SWF, N of MW-9 may be dry.
MW-14	9m		Easting: 633871 Northing: 6929993	Located off Ingraham Trail to the W of the SWF, S of MW-9

Images of well locations and how to get there:

Figure 6) MW-2A and MW-2B

Figure 7) MW-3

Figure 8) MW-5B

Figure 9) MW-6

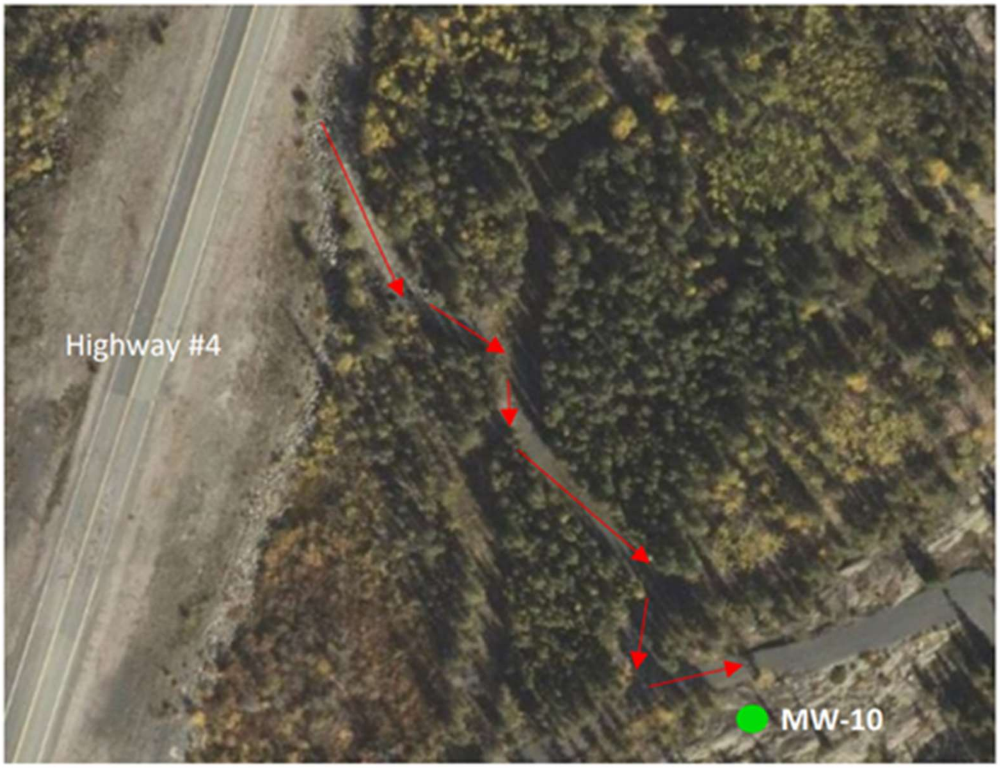


Figure 10) MW-10

Figure 11) MW-11

Figure 12) MW-12

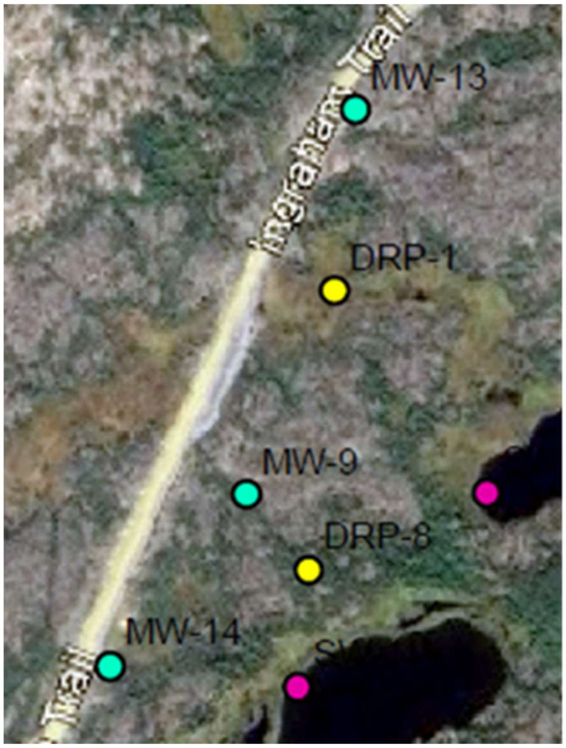


Figure 13) MW-9, MW-13, MW-14

Surface Water

Surface Water samples are divided into 3 categories: 1) SWF surface water monitoring locations, to be used for historical comparison, 2) surface water and potential groundwater springs recommended by local hydrogeologist (Isabelle de-Grandpré), sites SW-1-8, 3) surface water locations chosen based on their ability to act as upgradient baseline sites, identify flow paths downgradient, or identify alternate contaminant sources (SW Jackfish Lake). There are 23 surface water sampling locations.

Location Specifics:

Name	Location	How to get there	Coordinates
0032-13	Approx. 400 m NW of SWF above the confluence of unnamed feeder creek	Go through the gate to the composting retention pond and drive around the pond to SW end, go up steep incline to MW-6, sampling location is nearby pond, location full of debris which should not be included in sample	Easting:634532.09 Northing: 6929993.33
0032-13a	Approx. 400 m NW of SWF that captures the drainage from the SWF and drains from the snow disposal area	Access through the NWT quarry, sign logbook at front gate, then go to snow dump area, goes further W every year, likely dry in fall	Easting: 635008.97 Northing: 6930130.05
0032-14	Upstream of culvert location on Hwy 4, upstream of fault and	More or less opposite of the start of the trail leading to 0032-	Easting: 635509.98 Northing: 6930144.84

	downstream of confluence of unnamed feeder creek	39, small and steep incline to the sampling point	
0032-15a	W side of Hwy 4, across from SNP 0032-15	Before entrance to SWF on Hwy 4 leading to Giant Mine	Easting: 635372.59 Northing: 6929688.00
0032-16	Upstream of culvert on Hwy 3, opposite of Jackfish Lake	Double culvert at this location, flow may be leading to one or both of them, this is a busy highway so take precautions parking on side of road	Easting: 634400.90 Northing: 6929539.15
0032-20	S end of Fault Lake where the run-off enters the lake	Vehicle can be parked along side of Hwy 4 to Giant Mine, use the ski club trails to reach sampling location, trail is called "Otter Slide", lots of mosquitoes and marshy conditions (where rubber boots maybe)	Easting: 635843.85 Northing: 6930134.91
0032-21	Located at Vicinity Lake 3 within the borders of the SWF	Located near GW well 5A and 5B, take access road near Compost Facility to go S of the old landfill cell, sample from the edge of the lake	Easting: 634727.24 Northing: 6929776.63
SW-1	Cliff with potential springs to S of landfill	Located on N side of Hwy 3 directly above Jackfish Lake, a little way past station 0032-16. Parking pull out on S side of Hwy beside Jackfish Lake	Easting: 634475.39 Northing: 6929574.40
SW-2	N end of Jackfish Lake	Located to the S of Hwy 3, directly opposite SW-1, this lake has recently been getting algal blooms in spring. Parking pull-out on S side of Hwy beside Jackfish Lake	Easting: 634520.41 Northing: 6929478.38
SW-3	Cliff with potential springs leading to creek	Located in the Ski Club Trails area, park in the ski club parking lot and walk S on "Rollaway: and then head E on "The Ravine", the cliffs are on the N side of the creek.	Easting: 635633.22 Northing: 6929314.57
SW-4	Back Bay Ice Falls	Located in the Ski Club Trails area, park at the Back Bay trailhead and walk E until there is a trail heading N, the icings are on the S side of the creek	Easting: 635782.43 Northing: 6929219.64

SW-5	Creek between Jackfish Lake and Back Bay	Located in the Ski Club Trails area, park at the Back Bay trailhead and walk E until there is a trail heading N	Easting: 635725.35 Northing: 6929249.49
SW-6	Back Bay	Located in the Ski Club Trails area, park in the ski club parking lot and walk S on “Rollaway: and then head E on “The Ravine”, the trail follows the edge of the lake and has access to Back Bay	Easting: 635912.04 Northing: 6929506.66
SW-7	Winter Icing features	Located in the Ski Club Trails area, park in the ski club parking lot, and walk E onto the “Lynx Loop”	Easting: 635632.80 Northing: 6929548.95
SW-8	Public boat launch on Great Slave Lake, E of SWF	Located N of Ski Trails and E of SWF, continue on Hwy 4 and turn right onto Giant Mine Twp Rd. Park at the boat launch and sample on the inland side of the pier (it might be a wave-break)	Easting: 636003.37 Northing: 6931209.57
SW-9	Joe Lake, NW of SWF	Located N of SWF, take the Ingraham trail past the scenic trail viewpoint and park at small pullout on side of road, sample at NW side of lake closest to road	Easting: 634460.59 Northing: 6930881.34
SW-10	Small Lake #1, W of SWF	Located W of SWF, this is the most North of the small lakes, park on the side of the Ingraham trail at the Prospector trail viewpoint and walk in	Easting: 634306.62 Northing: 6930192.88
SW-11	Small Lake #2, W of SWF	Located W of SWF, this is between the 2 other small lakes, park on the side of the Ingraham trail and walk in	Easting: 634087.97 Northing: 6929968.17
SW-12	Small Lake #3, SW of SWF	Located W of SWF, this is the most South of the small lakes, park on the side of the Ingraham trail and walk in	Easting: 633856.81 Northing: 6929798.88
SW-13	Fred Henne Territorial Park small lake, SW of SWF	Located SW of the SWF, this is across from SW-12 on the W side of the HWY, park on the side of the Ingraham trail and walk in	Easting: 633718.72 Northing: 6929840.34

SW-14	Small Lake #4, S of SWF	Located SE of the SWF, park on Hwy 3 right before the turn off to Hwy 4 and this point is on the N side of the road, S of MW-3	Easting: 635167.51 Northing: 6929465.85
SW-15	S end of Jackfish Lake	Drive into Lakeview Cemetery and park at the most E end, walk along path to lake lookout on S end of Jackfish Lake	Easting: 634062.43 Northing: 6928584.66
SW-16	NE end of Fault Lake	Drive past the ski trails and turn right off Hwy 4, drive S until lake is in sight and park, sample on edge of lake (hopefully near outflow)	635904.28 6930468.44

GNWT -Surface Water Sampling Procedures

Bottle prep:
Coolers
Frozen ice packs
Powder-free vinyl gloves
Labels
Bottle and preservative sets:

	Ultra-low dissolved mercury and total mercury	Two small clear glass vials that come in pairs in clear Ziploc bags and bubble wrap.
	Total metals and dissolved metals	Two skinny bottles with a red dot on lid, one will be marked with a 'T' and will need to be preserved with HNO3
	HNO3 preservative	One small vial with a red dot on the cap. Add to the total metal sample once collected.
	Nutrients	One bottle with a black dot on lid
	Routine parameters	One bottle with a green dot on lid.
	Chlorophyll	One tall bottle with no dot on lid.

Best practice is to bring an extra bottle set to replace any dropped/contaminated/damaged bottles.

On Site Arrival
Record site information in field notebook
Date, site name, sample time
Staff involved in sampling
Weather conditions and temperature
Record any situation that might contaminate the sample, ie:
Oil or gasoline on the water surface
Forest fire smoke in the air
Dirty equipment

Dirty hands that touched sample

Label bottles while dry including Site Name, Date, and Sampler's name

It is important that you do not smoke for a minimum of 4 hours before working with the samples: please plan accordingly. Also, make sure everyone involved, even those not handling the samples (if there's more than two people), does not smoke while samples are being taken. The smoke in the air can contaminate samples.

Do not use bug spray before or during sampling. The chemicals could contaminate the samples. A bug jacket is a good alternative.

Working in pairs

One person will be Support Sampler: After putting on your gloves, take the empty sampling bottles out of the cooler, finish labelling them with a marker, and hand the labelled bottle to the Main Sampler.

The second person is Main Sampler: This person will collect the water sample. Try not to touch anything other than the sampling bottles and site water once you have put on your gloves.

Do not put anything inside your sample bottle except the water you are sampling and, if needed, preservative. Usually, the water you are sampling is site water; however, if you are taking a field blank, only deionized water should be in the sample bottle.

Collect Surface Water Grab Samples

Main Sampler: Triple Rinse each sample bottle before collecting sample:

Take the cap off, fill the bottle ¼ full of water you are sampling, replace the cap, and shake the partially filled bottle. Remove the cap and empty bottle contents downstream.

Do this three times for each sample bottle.

Never touch the inside of a cap or bottle when handling sample bottles.

After rinsing three times, insert the bottle upside down and hold the sample bottle under the water surface approximately 15-30 cm (6-12 inches). Tip sample bottle upward, allowing air to exit and the bottle to fill to the top with your sample water.

Cap the sample under water if possible.

If the sample needs to be preserved (total metal sample), pour a small amount of the water out of sample bottle (red dot on lid) and add preservative (small vial with red dot). Cap the sample.

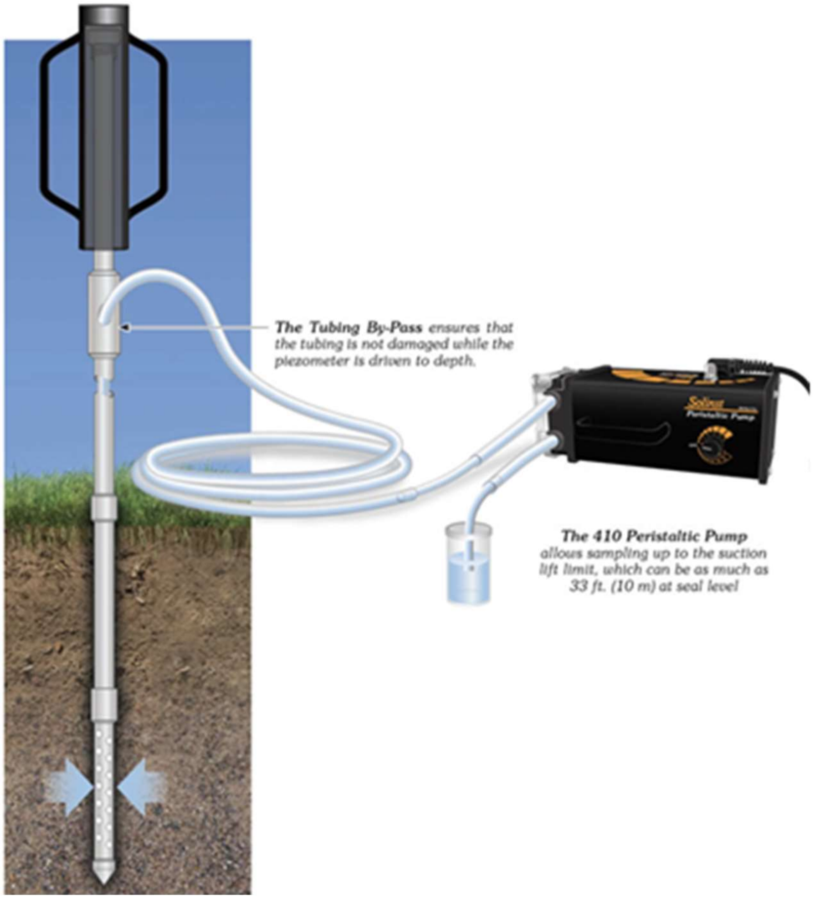
Invert the bottle once or twice to mix in preservative.

Hand completed sample back to Support Sampler.

Support Sampler: Put completed sample into a cooler with frozen ice packs.

Near-Surface Groundwater

In the areas without accessible surface water or groundwater wells, drive-point piezometers will be used to sample near-surface groundwater. This will enable measurements in areas of high uncertainty when existing measurements are extrapolated, and overall lower uncertainty across the study area. All the same parameters will be sampled across the groundwater wells, surface water, and near-surface groundwater stations. There are 10 drive-point piezometers available for use.



The Tubing By-Pass ensures that the tubing is not damaged while the piezometer is driven to depth.

The 410 Peristaltic Pump allows sampling up to the suction lift limit, which can be as much as 33 ft. (10 m) at seal level

Figure 14) Drive-point piezometer pumping and sampling set-up

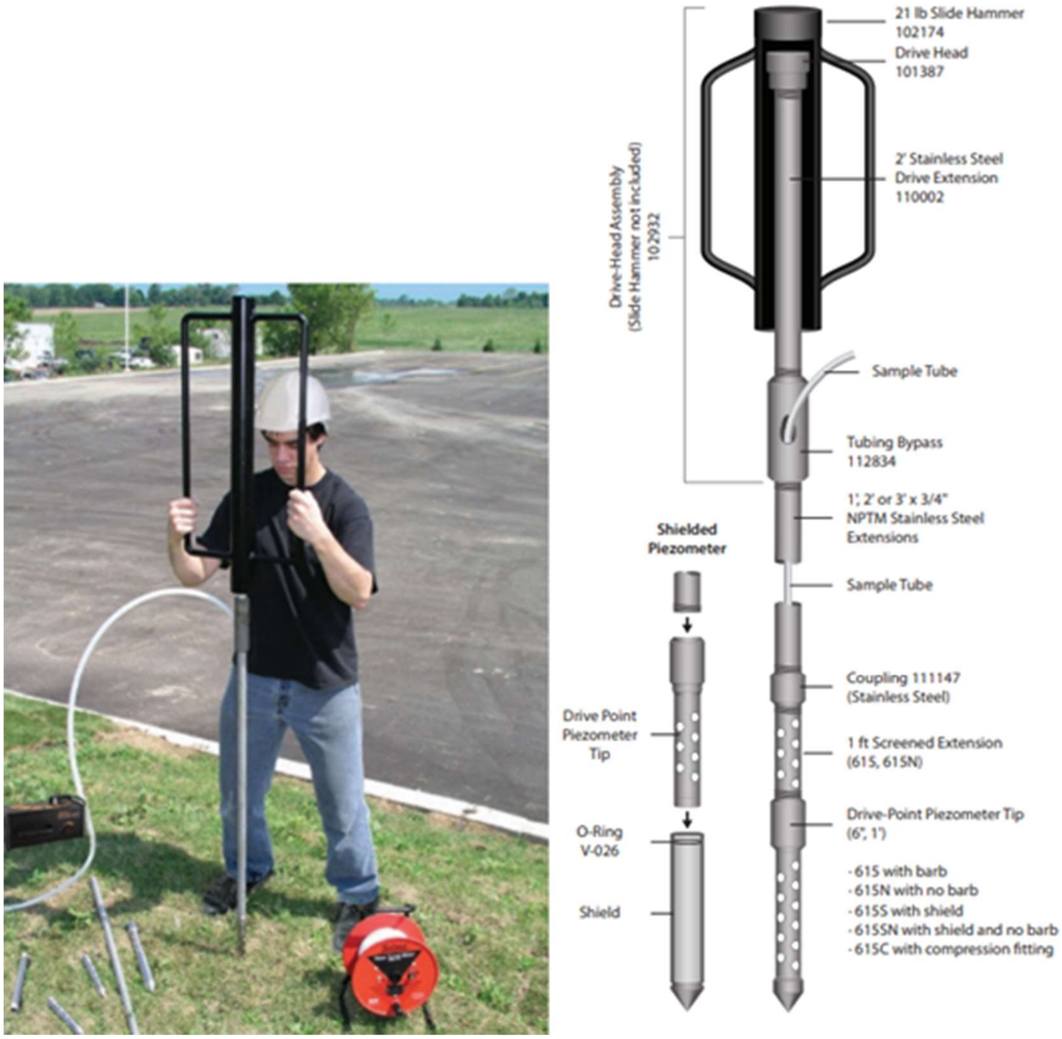


Figure 15 and 16) left: drive-point piezometer components and set-up, right: drive-hammer operation

Sampling Procedure (from https://www.solinst.com/products/direct-push-equipment/615-drive-point-piezometers/sampling-groundwater-using-drive-points.pdf and https://www.solinst.com/products/direct-push-equipment/615-drive-point-piezometers/operating-instructions/drive-point-piezometer-instructions/615-drive-point-piezometer-instructions.pdf):

Install the drive-point piezometer

1) cut piezometer tubing to length (desired depth + 1.5m) and push into barbed fitting on drive-point tip by pushing firmly until it reaches base of fitting (if using 615C, loosen compression fitting and insert ¼" piezometer tubing and then tighten 1 + ¼ times past finger tight to secure tubing) NOT REQUIRED FOR MODELS 615N OR 615SN

2) slide extension pipe over the tubing and thread onto the drive-point tip, tighten with a pipe-wrench

3) slide tubing by-pass over tubing and tighten, tubing end is then extended through the side hole in the tubing bypass and out of the way NOTE: make sure tubing does not turn during connecting tubing bypass by holding firmly

4) use the manual slide hammer to hammer the drive-point until 6” of extension pipe below tubing bypass are visible (as can be seen in picture above)
5) remove hammer and (while holding tubing) remove drive head assembly, slide a coupling over the tubing and tighten firmly onto the previous extension pipe, slide the next extension pipe over the tubing and tighten securely
6) repeat steps 1-5 for increasing depth using extension pipes

- Insert sampling tubing

1) Insert sample tubing inside the Peristaltic pump tubing and insert the other end into the drive-point piezometer tubing, the tubing should be held together with friction (as can be seen in picture above)

- Pumping

1) attach extension cord from generator to peristaltic pump
2) start generator (specific instructions in groundwater sampling procedure)
3) slowly turn on pump
4) monitor water quality using sondes until the DO and electrical conductivity stabilize before sampling

[Text Wrapping Break]Gear List:
-10 drive-point piezometers are available for single-use sampling (components include: drive-point tip, screened extensions, extensions, couplings for extensions, manual slide hammer, piezometer tubing, delrin cap, drive head assembly – drive head, drive extension, tubing bypass)
-1/2” sampling tubing
-peristaltic pump
-generator
-extension cord
-knife
-pipe-wrench

Groundwater sampling procedure (under streambed) in sweeteners paper:
“Shallow groundwater samples were collected from 30 mini-piezometers installed 15 cm below the streambed in five transects of three mini-piezometers at each of Stretch B and Stretch C (Figures 2A and 3A). The mini-piezometers consisted of 2.5 cm drive-point stainless steel screened tips (Gas Vapor Tip, AMS) connected to 1/4″ polyethylene tubing. Samples were collected using a peristaltic pump, after which the tubing was clamped and attached to a stake driven into the streambed, to avoid the piezometers continually discharging to the stream, filling with surface water or sediment, or being pulled out by passing debris.”
“Dissolved oxygen and electrical conductivity of pumped water were monitored using hand-held meters to help identify the contribution of stream water (due to hyporheic exchange or short-circuiting along the profiler). When surface water influences were suspected, the profiler was driven deeper into the sediments, if possible, prior to sampling.”
Near-surface groundwater sampling locations:

Name	Location	How to get there	Coordinates
DRP-1	Saturated soil suspected upgradient of SWF	N on Ingraham Trail, park at Prospectors Trail Scenic viewpoint and walk in	Easting:634130.66 Northing: 6930426.60

DRP-2	Saturated soil suspected upgradient of SWF	Hardest spot to get to, park along Hwy 3, S of SWF and walk in, steep uphill and swampy	Easting: 634309.93 Northing:6929747.72
DRP-3	Saturated soil within boundaries of SWF, along NW-SE dyke (downgradient from DRP-9)	Located within the SWF border, neat sampling station 0032-13a	Easting:634775.79 Northing: 6930139.85
DRP-4	Streambed downgradient of SWF (groundwater plume) along NE-SW dyke	Park on 48 St before it becomes Hwy 4, and walk into ravine and sample in streambed	Easting: 635326.96 Northing: 6929180.17
DRP-5	Streambed downgradient of SWF (groundwater plume)	Continue past DRP-5 and sample in streambed	Easting: 635568.12 Northing: 6929253.36
DRP-6	Streambed downgradient of SWF (groundwater plume), paired with SW-3,4,5	Close to SW-5, park at Back Bay trail head and follow trail N until reach creek, sample beneath streambed	Easting: 635706.77 Northing: 6929235.69
DRP-7	Streambed upgradient of SWF, outflow of small lake #1, upstream of DRP-7	Just outside boundaries of SWF in creek/saturated outflow from small lake #1, park in SWf and walk past DRP-3	Easting:634570.86 Northing: 6930186.30
DRP-8	Upgradient of SWF, paired with MW-9 and SW-11	Park on Ingraham Trail at Prospectors Trail Scenic Viewpoint, Located downgradient from MW-9, may be quite dry so keep walking downhill toward area between 2 small lakes until reach viable spot	Easting: 634100.96 Northing: 6930103.75
DRP-9	Upgradient of SWF along NW-SE dyke, upgradient from DRP-3, in different bedrock geology	Park in same spot as in SW-9 on Ingraham Trail, and walk W of Hwy into swamp	Easting: 634090.02 Northing: 6930882.62
DRP-10	Downgradient of SWF, on intersection of both dyke systems	Park along Hwy 3 S of SWFand sample on S side of road, may be dry, so N side of road	Easting: 634861.16 Northing: 6929428.74

		near small lake #4 also an option	

5.1.1. Sampling Types

Part C: Sampling Types
On-Site Physicochemical Measurements
Several field parameters will be measured on-site prior to sampling for other parameters and will be recorded in the field notebook. These are: water depth measurement (dependent on sampling media), conductivity, temperature, pH, dissolved oxygen, and turbidity. The tools list and sampling procedure have been sourced from the link below:
http://www-naweb.iaea.org/napc/ih/documents/other/Sampling%20booklet%20web.pdf
Sampling Procedure:
-water depth: self-explanatory
-temperature: self-explanatory
-conductivity: The conductivity meter must be calibrated following the manufacturer's instructions. Normally, a calibration standard with a conductivity of 1413 µS/cm at 25°C is used. The conductivity meter should be calibrated before use. Make sure that the electrode is rinsed with distilled or well water before measurements are made. To measure sample conductivity, the sample is poured into a beaker or into a flow through cell and the conductivity electrode is inserted. Once the readings have stabilized, record the temperature and conductivity of the water sample.
-pH: Operate the pH meter according to the manufacturer's instructions and calibrate the meter accordingly. Two or three standard solutions or pH buffers are used for this calibration. Commercially available pH buffers may be found in different forms, including tablets, colour-coded solutions, or disposable packs. Set the pH meter to calibration mode. Insert the electrode into the first buffer of higher pH, for example pH7. When the correct pH display is seen, store the reading in the unit by pressing the appropriate key. Remove and rinse the electrode. Place the electrode into the second buffer solution of lower pH, e.g. pH4. When the reading stabilizes and the correct pH display is seen, the pH meter is calibrated and ready for measuring. Switch to measurement mode. To measure the pH of a sample, insert the electrode into the sample (beaker or flow though cell), press the appropriate key, and wait for the reading to stabilize. Do not stir the electrode as vigorous stirring may change the sample pH through degassing of carbon dioxide. After measurements have been made, clean the electrode and store in the storage solution.
-dissolved oxygen: Dissolved oxygen is measured either by using a meter with a dedicated submersible probe, or with the spectrophotometric method described below, using vacu-vials and a field spectrophotometer. Using this second method, insert the sealed zero-oxygen blank ampoule into the sample slot aligning the marks on the meter and the ampoule. This calibrates the spectrophotometer. Fill the sample container (beaker) with well water. Insert the vacu-vial filled with the necessary reagents into the water and break the tip of the vial. Water is sucked into the vial and a blue colour develops depending on the concentration of dissolved oxygen. Clean the vial using tissue paper and depress into the sample slot, aligning the marks on the spectrophotometer. Record the dissolved oxygen value of the sample, usually expressed in milligrams per litre or parts per million. NOT USING SPECTROPHOTOMETER METHOD
Tools required:

-gloves, labels, sharpies/water-proof pens, thermometer, GPS, field notebook
-water depth: measuring tape or electrical sounder (sondes has depth sensor)
-temperature: sondes
-conductivity: conductivity meter (sondes), flow cell (gw), beaker (surface water/soil water)
-pH: pH meter (sondes), calibration solutions, beakers (*calibrate before leaving at start of day, but keep calibration solutions in field in case), flow through cell (gw), beaker (sw, soil water), storage solution
-dissolved oxygen: meter with submersible probe (sondes)
-turbidity: sondes (don't know what else is needed)

General Geochemistry

Geochemical analysis of all the samples will be completed using the protocols and tools provided by Taiga Labs in Yellowknife. The constituents to be analyzed are:

Category/Bottle Colour	Constituents
Routine	-pH, conductivity, alkalinity -individual anions (Cl, SO4, F, NO2-N, NO3-N) -total nitritie + nitrate (NO2-N + NO3-N) -individual cations (Ca, Mg, Na, K) -hardness (calculated) -reactive silica (SiO2) -colour (apparent, true)
Nutrients	- chlorine: total, residual -chemical oxygen demand (COD) -turbidity -total suspended solids, dissolved solids (TSS,TDS) -ammonia (NH3-N) -phosphorus: total, dissolved, ortho (TP, DP, OP) -carbon: total, dissolved (TOC, DOC) -nitrogen: total, dissolved -visible oil and grease
Sterile	-fecal coliforms -total coliforms, e. coli -enterococci (EN)
BOD	-biochemical oxygen demand (BOD) -carbonaceous BOD (CBOD)
Metals*	-ICP-Ms(1): total, dissolved (Cd, Cr, Cu, Co, Mn, Ni, Pb, Zn, Fe) -ICP-MS(2): total, dissolved (25 element scan includes As (not included: B, Bi, Hg, Sn) -individual metals by ICP-MS (Ag, Al, As, B, Ba, Be, Bi, Cd, Co, Cr, Cs, Cu, Fe, Hg, Li, Mn, Mo, Ni, Pb, Rb, Sb, Se, Sn, Sr, Ti, Tl, U, V, Zn)
Hexane	-hexane extractable material (O&G)
Misc.	-BTEX, Purgeable HC (40 mL x 2 vials) -Extractable HC (1 L amber glass bottle) -Trihalomethanes (40 mL x 2 vials)

Other	-bicarbonate -carbonate -total kjendhal N (TKN) -PAHs F1 and F2 -methylene chloride, vinyl chloride, TCE, PCE

*metals sampled in the 2021 groundwater sampling: aluminum, total; antimony, total; arsenic, total; barium, total; beryllium, total; bismuth, total; boron, total; cadmium, total; calcium, total; cesium, total; chromium, total; cobalt, total; copper, total; iron, total; lead, total; lithium, total; magnesium, total; manganese, total; mercury, total; molybdenum, total; nickel, total; phosphorus, total; potassium, total; rubidium, total; selenium, total; silicon, total; silver, total; sodium, total; strontium, total; sulfur, total; tellurium, total; thallium, total; thorium, total; tin, total; titanium, total; tungsten, total; uranium, total; vanadium, total; zinc, total; zirconium, total

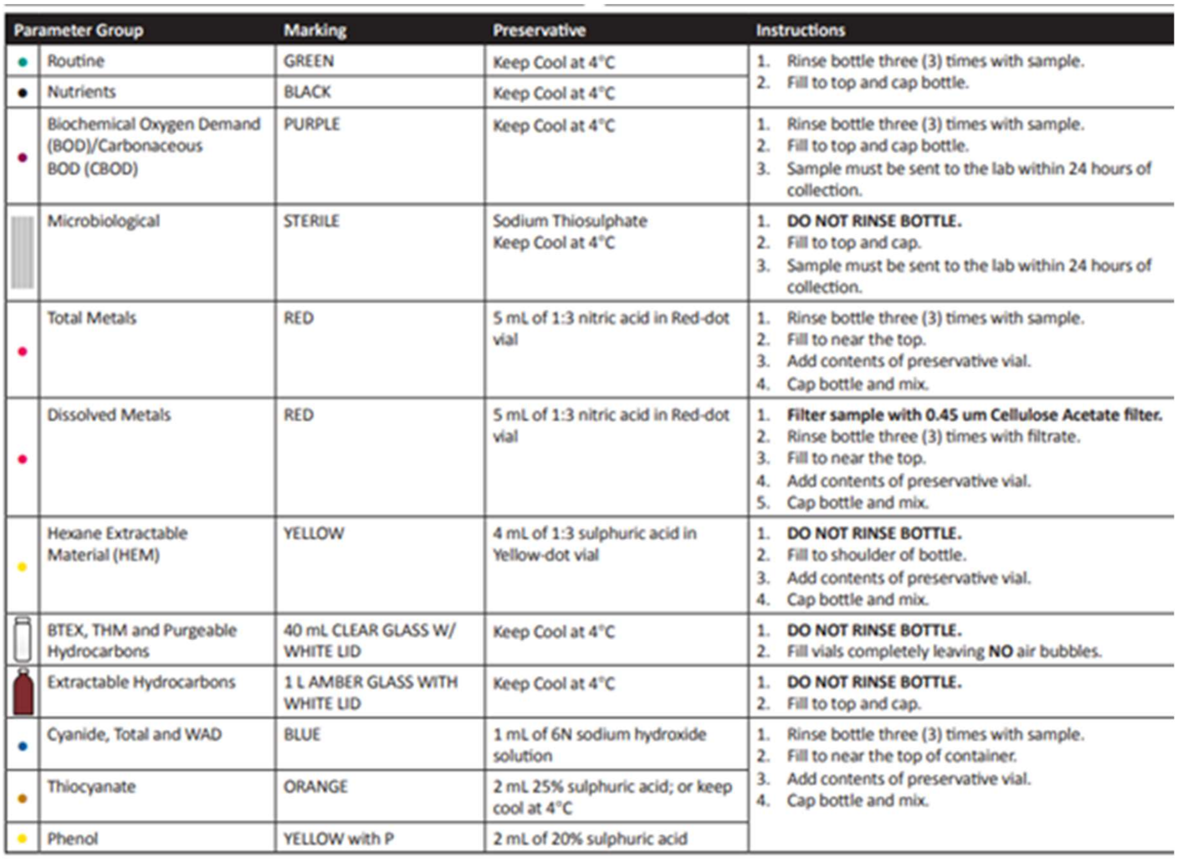
Sampling Procedure by bottle (ALS Environment used for YK sampling, Taiga Procedure below is slightly different and should be followed where guidelines differ)

Routine/BOD: General water quality and biochemical oxygen demand, no preservatives, can be submerged in water to fill, used to pour water into other bottles that cannot be submerged.

Metals: Used to test for trace metals, contain a preservative (CANNOT BE SUBMERGED AND CANNOT BE FILLED MULTIPLE TIMES I.E. FLUSHED), fill using the routine bottles and then leave a tiny amount of air at the top.

Bacteria: Used to test for fecal coliforms, contains a preservative (CANNOT BE SUBMERGED AND CANNOT BE FILLED MULTIPLE TIMES I.E. FLUSHED), fill to the indicator line at top of bottle using the routine bottle.

Major analytes, Hg, total nutrients, hydrocarbons: All must be filled to the top with NO air trapped inside, contains a preservative (CANNOT BE SUBMERGED AND CANNOT BE FILLED MULTIPLE TIMES I.E. FLUSHED). Filling instructions: place bottle on level surface, slowly pour sample water into bottle and cap, should look concave (bubbled up), quickly place cap on, check for air bubbles (if none observed, then turn bottle upside down and tap it, if still no bubbles are observed then it is ready), if there are bubbles, then repeat by adding water and following all successive steps.



Parameter Group		Marking	Preservative	Instructions
●	Routine	GREEN	Keep Cool at 4°C	1. Rinse bottle three (3) times with sample. 2. Fill to top and cap bottle.
●	Nutrients	BLACK	Keep Cool at 4°C	
●	Biochemical Oxygen Demand (BOD)/Carbonaceous BOD (CBOD)	PURPLE	Keep Cool at 4°C	1. Rinse bottle three (3) times with sample. 2. Fill to top and cap bottle. 3. Sample must be sent to the lab within 24 hours of collection.
▨	Microbiological	STERILE	Sodium Thiosulphate Keep Cool at 4°C	1. **DO NOT RINSE BOTTLE.** 2. Fill to top and cap. 3. Sample must be sent to the lab within 24 hours of collection.
●	Total Metals	RED	5 mL of 1:3 nitric acid in Red-dot vial	1. Rinse bottle three (3) times with sample. 2. Fill to near the top. 3. Add contents of preservative vial. 4. Cap bottle and mix.
●	Dissolved Metals	RED	5 mL of 1:3 nitric acid in Red-dot vial	1. **Filter sample with 0.45 um Cellulose Acetate filter.** 2. Rinse bottle three (3) times with filtrate. 3. Fill to near the top. 4. Add contents of preservative vial. 5. Cap bottle and mix.
●	Hexane Extractable Material (HEM)	YELLOW	4 mL of 1:3 sulphuric acid in Yellow-dot vial	1. **DO NOT RINSE BOTTLE.** 2. Fill to shoulder of bottle. 3. Add contents of preservative vial. 4. Cap bottle and mix.
▯	BTEX, THM and Purgeable Hydrocarbons	40 mL CLEAR GLASS W/ WHITE LID	Keep Cool at 4°C	1. **DO NOT RINSE BOTTLE.** 2. Fill vials completely leaving **NO** air bubbles.
▮	Extractable Hydrocarbons	1 L AMBER GLASS WITH WHITE LID	Keep Cool at 4°C	1. **DO NOT RINSE BOTTLE.** 2. Fill to top and cap.
●	Cyanide, Total and WAD	BLUE	1 mL of 6N sodium hydroxide solution	1. Rinse bottle three (3) times with sample. 2. Fill to near the top of container. 3. Add contents of preservative vial. 4. Cap bottle and mix.
●	Thiocyanate	ORANGE	2 mL 25% sulphuric acid; or keep cool at 4°C	
●	Phenol	YELLOW with P	2 mL of 20% sulphuric acid	

Sampling Procedures can be found here:
https://www.enr.gov.nt.ca/en/services/taiga-environmental-laboratory/supplies-and-sampling
^ Taiga Lab sampling procedures, order form, collection protocol
Field Sheet to be included in cooler that is given to Taiga with samples:
https://www.enr.gov.nt.ca/sites/enr/files/resources/taiga_environmental_laboratory_field_sheet_-_nwt9037.pdf
^ Taiga field sheet (has sample parameters, bottle identification guide for each sample type, and instructions for how to take sample, this form is used to figure out how many/what type of bottles are required for each site
Bottle order request form, to be completed prior to sampling:
https://www.enr.gov.nt.ca/sites/enr/files/bottle_order_request_form.pdf
^Bottle order request form, need to know # field blanks, # travel blanks, # bottles for samples, # of preservatives. Options for sample type: routine (full list on field sheet), nutrients, bacti, BOD, total metals, dissolved metals, arsenic speciation bottle, cyanide, thiocyanate, hexane extractable material, phenol, sulphide, radionuclide, chlorophyll A, extractable hydrocarbons, BTEX, THM, +sediment samples. ALSO HAVE ANY OTHER FIELD SUPPLIES SECTION – CAN I ASK FOR GLOVES AND LABELS?
After sampling, the filled bottles need to be placed in a cooler with ice and immediately given to Taiga Labs for analysis.

Sweeteners

Sweeteners will be sampled at every sampling location and then sent to the ECCC labs in Burlington, ON for analysis. 1 sample will be analyzed for 4 sweeteners (cyclamate, acesulfame, saccharin, sucralose). There are no differences when sampling groundwater and surface water. The sampling procedure will follow the procedures outlined in personal correspondence with researchers at ECCC and these 2 reports: Van Stempvoort et al., 2011 and Roy and Bickerton, 2010. The procedure will be as follows:

1) Sample bottles for sweeteners will be marked with a light blue sticker on the cap and labelled with date, time, location
2) Pre-condition the filter by passing 10-30 mL of on-site water through the filter to dissolve any saccharin coating and avoid a false positive
3) Triple rinse the sample bottle (as per GNWT water sampling procedure)
4) Samples will be collected in 30 mL high-density polyethylene (HDPE) bottles after being filtered in the field using a 0.22-µm filter
5) Place sample in cooler with ice and keep out of sunlight while in the field
6) freeze ASAP
7) Contact Greg Bickerton (greg.bickerton@ec.gc.ca) when samples are being shipped

ECCC lab address:
Sue Brown / Greg Bickerton
867 Lakeshore Rd., Burlington ON
L7S 1A1

Gear List:
-30 mL HDPE bottles
- 0.22-µm filters
-coolers, ice
- syringe
-tubing?

Other useful papers with sweeteners used in groundwater/landfill settings:
https://www.sciencedirect.com/science/article/pii/S0956053X19303885?casa_token=2sMpjlTYpnkAAAAA:S06NisAbxKObzM8nQAUdbaMvp5IZbrCQwaZAVDC2X1obVab4D0k5DC-jlfu4OCfksgtbWERt
^Identification of groundwater pollution sources in a landfill site using artificial sweeteners, multivariate analysis and transport modeling (Stefania et al., 2019)
https://ngwa.onlinelibrary.wiley.com/doi/full/10.1111/gwmr.12483?casa_token=f_GooDprmMwAAAAA%3ARqaQItOUi5oU686xds8gJb_tWE9w1ibjfZYp5-_71xJ_48jTdJOYn7ZhL2mlNl3i4DnyXRqyIWrF
^Artificial Sweeteners Identify Spatial Patterns of Historic Landfill Contaminated Groundwater Discharge in an Urban Stream (Propp et al., 2021)

“Roy et al. (2014) showed that old landfills (those closed 1960s to early 1990s) only contained saccharin (SAC) and, less frequently, cyclamate (CYC), whereas modern landfills also contained acesulfame (ACE) and sucralose (SUC). These four AS are generally poorly degraded in anaerobic conditions (e.g., Biel-Maeso et al. 2019), as predominates in most landfills and their plumes, and are fairly conservative in groundwater systems (Luo et al. 2019). This temporal

series occurs because SAC and CYC have been commercialized for many decades, whereas ACE and SUC only became commercially available in the early 1990s.”
https://pubmed.ncbi.nlm.nih.gov/30759555/
^Ecotoxicity and environmental fates of newly recognized contaminants-artificial sweeteners: A review (Luo et al., 2018)
-for groundwater sampling
techniques: https://books.google.ca/books?hl=en&lr=&id=5fL4WmUxBhYC&oi=fnd&pg=PP1&dq=The+Essential+Handbook+of+Ground-water+Sampling&ots=VmqbI3oeGE&sig=ZU4fxekkDjDAhpP8YT7_EePhkCU&redir_esc=y#v=onepage&q=The%20Essential%20Handbook%20of%20Ground-water%20Sampling&f=false

3. Methods

3.1. Sample collection

Groundwater was collected from twelve monitoring wells at the Hamilton site using a Teflon®-lined bladder pump and low-flow sampling and purging techniques (e.g., Neilsen and Neilsen, 2007). These wells were completed in surficial sand (native or fill) and/or the underlying silty clay till. Typically these wells had intake screens from 1.5 to 4.5 m below ground. The screen interval of the deepest well was completed in the silty clay till from 7.6 to 9.1 m below ground. Groundwater was collected from six monitoring wells near wastewater ponds at Whitehorse; these wells had screens at depths (mid-screen) ranging from 1 to 45 m below ground. Here the surficial sediments are dominated by glaciolacustrine silt and fine sand, with some sand and gravel units. The Whitehorse groundwater samples were obtained using dedicated inertial-lift pumps or bailers. Prior to sampling, the wells at both the Hamilton and Whitehorse sites were purged until indicator parameters (i.e., dissolved oxygen and electrical conductivity) stabilized. Monitoring wells with low recovery rates (e.g., >24 h) were purged to dryness and sampled when an adequate volume of groundwater had recharged the well (e.g., in 1–3 days).

Groundwater collection along the six stream reaches (Table 1) followed the screening approach outlined by Roy and Bickerton (2010). Water samples were collected at depths generally between 0.25 and 0.75 m below the stream beds using a temporary drive-point profiler connected to a peristaltic pump. Sampling stations along each stream reach were spaced about 10–15 m apart. Dissolved oxygen and electrical conductivity of pumped water were monitored using hand-held meters to help identify the contribution of stream water (due to hyporheic exchange or short-circuiting along the profiler). When surface water influences were suspected, the profiler was driven deeper into the sediments, if possible, prior to sampling.

At two of the sites, Jasper and Whitehorse, where exfiltration of treated municipal wastewater to the subsurface is practiced, samples of wastewater (at various stages of treatment) were collected for sweetener analyses.

All water samples were collected in high-density polyethylene or glass bottles/vials, filtered in the field using a 0.22-µm filter, and either refrigerated or frozen prior to analyses. Details regarding timing and storage of samples are indicated in Table S1 of Supporting information. Sample storage criteria were based, in part, on the results of a parallel study by Van Stempvoort et al. (submitted for publication), who analyzed duplicate (sequential) samples of groundwater impacted by a septic system that had been stored for 13.5 months under (i) refrigerated and (ii) frozen conditions. They found no perceptible differences in the concentrations of acesulfame and sucralose for these two different storage conditions, but observed losses of both cyclamate and saccharin in the refrigerated samples, compared to the frozen samples. Additionally, analyses of some samples of treated wastewater and groundwater in this study showed that cyclamate declined in refrigerated samples over 3 weeks, whereas acesulfame and saccharin appeared to be stable over this time period. Accordingly, for this study, analyses for saccharin and cyclamate that were stored under refrigerated conditions (~5 °C) for periods >15 days for cyclamate or >30 days for saccharin were omitted. Using this criterion, data from all eight sites were included for acesulfame, sucralose and saccharin, and data from seven sites were included for cyclamate. See Table S1 in Supplementary materials for more details regarding sample storage for each site.

Isotopes

Hydrogen and Oxygen (2H and 18O) isotopes will be sampled at every sampling location and then sent to the analytical facilities at McGill University in Montreal. These samples will be analyzed using a Picarro cavity ring-down spectrometer. Only 2 mL is required, but samples will be taken in a 10 mL HDPE as per the sampling instructions in this reference guide http://www-naweb.iaea.org/napc/ih/documents/other/Sampling%20booklet%20web.pdf. No filtration or preservation is needed for isotopic sampling. Evaporation from the sample is to be avoided. Sample bottles for isotopes will be marked with a light green sticker on the cap. Only 1 bottle is required for each sample site. The sampling procedure will be as follows:

1) Mark the bottle with a light green sticker on the cap and label it with the date, time, location of sample
2) Triple-rinse the bottle (as per GNWT sampling procedures)
3) Fill 10 mL HDPE bottle and cap
4) Keep cool and out of the sunlight
5) Samples will be personally transported back to Montreal at the end of the fieldwork

Gear List:
-light green stickers
-labels
-10 mL bottles
-cooler (ice if hot out)
http://www-naweb.iaea.org/napc/ih/documents/other/Sampling%20booklet%20web.pdf

Part D: Itinerary and Gear List

Shopping List:
-55 x 30 mL HDPE bottles (sweeteners) – 5 for redundancy
-55 x 30 mL HDPE bottles (isotopes) – 5 for redundancy
-55 x 0.22 µm filters (sweeteners) – 5 for redundancy
-55 x 0.45 µm cellulose acetate filters (dissolved metals) -5 for redundancy
-1 L deionized water (2 trip and field blanks, 1 for isotopes, 1 for sweeteners)
-100 pairs of nitrile gloves
-110 labels
-55 light blue stickers
-55 light green stickers
-5 waterproof pens

Taiga Bottle List:
-routine 1 field, 1 trip, 48 sampling
-nutrients: 1 field, 1 trip, 48 sampling
-bacti: 0 field, 0 trip, 48 sampling
-BOD: 0 field, 0 trip, 48 sampling

-total metals: 1 field, 1 trip, 48 sampling
-dissolved metals: 1 field, 1 trip, 48 sampling (FILTERS)
-arsenic speciation: 0 field, 0 trip, 48 sampling
-*cyanide: 0 field, 0 trip, 0 sampling
-thiocyanate: 0 field, 0 trip, 0 sampling
-HEM: 1 field, 1 trip, 48 sampling
-phenol: 1 field, 1 trip, 48 sampling
-sulphide: 1 field, 1 trip, 48 sampling
-radionuclide: 0 field, 0 trip, 0 sampling
-chlorophyll A: 0 field, 0 trip, 0 sampling
-extractable hydrocarbons: 1 field, 1 trip, 48 sampling
-BTEX/Purgeable HC: 2 field, 2 trip, 96 sampling
-THM: 2 field, 2 trip, 96 sampling
-labels: 1 for each kit: 50 +5 for redundancy
(=12 trip blanks, 12 field blanks total + 15 samples per site)

-OTHER THINGS: syringes, flow-through cell, pH calibration solutions, thermometer, cooler, waders, safety goggles, measuring tape, beakers/bucket, high vis, bangers, bells, bear spray, duct tape, needle nose pliers, step stool for tall well casings, storage tank (like a big cooler that's sealable would work perfect + tarp, only if I need to purge wells), clipboard
THINGS I HAVE: steel-toes, compass, GPS, field notebook, bug spray, sunscreen, phone, Sondes (GNWT), map (I will print out before leaving + field plan), keys for wells (pick up Ski Club manager), rope, first aid kit, other field things (rain gear, hat, gaiters, long sleeve field shirt, buff, 3 L water for personal use, snacks, etc.)
EXTRA GEAR FROM GNWT
-10 drive-point piezometers https://www.solinst.com/products/direct-push-equipment/615-drive-point-piezometers/?utm_source=GA-&utm_medium=Search-&utm_campaign=615-GA-615-search-na&utm_term=DP-USA-Canada&utm_content=responsivetextad-3&gclid=Cj0KCQiA3rKQBhCNARIsACUEW_bDFZxCNDCXK8v2fPjTZ6cll0mOFAqLJDnUJyVlq5RhUwz0zSUFWvkaAtAJEALw_wcB
-YSI EXO1 sondes https://www.ysi.com/exo1 (TOO BIG TO FIT IN DRIVE POINTS THOUGH, SO WOULD NEED TO ORDER SMALLER ONES / can use a Nalgene/bucket to sample if too small)
- Flow cell https://www.ysi.com/accessory/id-599080/exo1-and-prodss-flow-cell (potentially also has this, but not sure if it was ever purchased)
-talked about foot valves (but also decided not to order them at that time because wasn't sure exactly what was needed)

5.1.2. Field Measurements

Name	Type	Latitude	Longitude	Temp	DO %	DO mg/L	SPC (-um/cm)	pH	ORP (mV)	NTU	Date	Time
SW-17	SW	62.490196	-114.383914	22.591	127.2	10.99	264.5	8.53	113.1	2.22	8/19/2022	13:02

0032-13a	SW	62.477801	-114.385118	18.914	7.94	7.36	452.7	6.91	184.4	26.52	8/19/2022	10:22
0032-14	SW	62.477661	-114.37133	14.381	59	6	1208	7.3	49.7	0.25	8/18/2022	11:50
0032-14-1	SW	62.477661	-114.37133	14.381	59	6	1208	7.3	49.7	0.25	8/18/2022	11:50
SW-10	SW	62.482872	-114.394973	16.181	88.1	8.66	125.6	6.94	154.6	17.1	8/19/2022	11:21
SW-18	SW	62.468736	-114.376073	6.722	24.1	2.93	699	7	-65.8	0.44	8/19/2022	16:20
0032-20	SW	62.47716	-114.364183	19.613	154	14.05	1564	7.7	57.3	287.55	8/18/2022	14:07
0032-21	SW	62.473994	-114.385151	16.988	83.1	8.01	669	6.56	-46.6	28.8	8/19/2022	10:18
SW-1	SW	62.477136	-114.36775	14.119	62.1	6.35	1429	7.33	198.7	0.58	8/18/2022	14:36
SW-2	SW	62.472146	-114.39158	23.025	125.7	10.75	453	8.66	169.2	8.29	8/17/2022	14:39
SW-3	SW	62.469816	-114.372386	16.92	76.1	7.37	912	7.25	92.7	0.68	8/19/2022	15:47
SW-4	SW	62.469913	-114.364846	12.386	103	10.98	556		-13.5	11.65	8/19/2022	15:15
SW-4*	SW	62.469913	-114.364846	9.633	89.5	10.17	562	7.32	-0.8	7.69	8/22/2022	9:45
SW-5	SW	62.469427	-114.374771	3.575	-2.4	-0.34	448	6.9	-85.8	0.48	8/19/2022	15:12

SW-5*	SW	62.469427	-114.374771	3.577	-0.4	-0.05	446.2	6.75	-66.4	0.22	8/19/2022	16:00
SW-6	SW	62.471314	-114.36463	20.55	96.9	8.71	136.9	6.92	106.7	15.6	8/19/2022	14:07
SW-7	SW	62.469581	-114.36608	7.365	70.4	8.42	571	7.28	44	1.68	8/19/2022	14:25
SW-8	SW	62.487203	-114.360706	22.576	109.5	9.46	258.1	7.35	238	1.13	8/17/2022	16:03
SW-9	SW	62.482662	-114.390422	22.327	89.2	7.74	535	7.89	152.6	0.77	8/17/2022	10:37
SW-11	SW	62.474967	-114.397133	20.917	97.6	8.7	495	7.48	158.1	2.02	8/19/2022	11:23
SW-12	SW	62.475169	-114.401558	23.145	99	8.47	235.5	7.03	186.5	0.84	8/17/2022	12:10
SW-13	SW	62.47588	-114.406346	23.906	94	7.92	139.7	6.6	196	0.49	8/17/2022	12:37
SW-14	SW	62.471311	-114.378434	17.555	58.5	5.58	315.5	6.17	-84	97.47	8/18/2022	15:24
SW-15	SW	62.464125	-114.400153	20.499	124	11.12	444.9	8.75	158.7	10.3	8/17/2022	13:31
SW-15-1	SW	62.464125	-114.400153	20.499	124	11.12	444.9	8.75	158.7	10.3	8/17/2022	13:31
SW-16	SW	62.480721	-114.363342								8/18/2022	10:55
FB	SW										8/19/2022	
TB	SW										8/15-19/2022	
MW-12	GW	62.472103	-114.373266								8/19/2022	8:10

Site Description

SW-17 sampled off fine grained basaltic volcanic?, can see felsic cliffs at W side of lake, smoky from wildfires, hot, slight breeze from S, jackpine, potentilla, poplar, cattails, alder, willow, calm, slightly green water, shallow lake

0032-13a fireweed, jackpine, dead trees, snow dump puddles with gravel bottom (from snow/ice removal), no wind, wildfire smoke, hot

0032-14 potentilla, willow, grasses. fireweed, tamarack, hot, breeze, culvert right beside highway

0032-14-1 potentilla, willow, grasses. fireweed, tamarack, hot, breeze, culvert right beside highway

SW-10 fault in meta-basalt, fine-grained volcanic trending N/S, 4 ft wide, birch, jack pine, black spruce, fault trench continues at least 100m

SW-18 organic oil-slick surface, cooling off, no breeze, sampling downstream of culvert, sloght sulfur smell, no orange algae on downstream side of culvert but present on upstream side of culvert, alder, willow, poplar, beside gravel path

0032-20 creek into swampy lake, inflow of fault lake inflow, grasses, cattails, willows, poplar, black spruce, hot, sunny, breeze from W

0032-21 grass, ferns, algae, small shallow lake near landfill, outside active cell, downhill from landfill, smoky, slight breeze, hot

SW-1 hot, muggy, spring, grasses, black spruce, roses, horsetails, labrador tea, willow, birch, strawberries, apparent spring down-gradient of landfill and upstream of 0032-20

SW-2 hot, still, grasses, willow, pebble shore on Jackfish Lake, downhill from highway, very green lake

SW-3 organic oil-slick surface, wetlands, grasses, no iron staining, black spruce, willows, alder, flowing maybe from under cliff nearby, smoky, hot, calm, in ski trails

SW-4 grass, willows, muddy creek in gully beside back bay cemetery, under bridge, smoky, no wind

SW-4* less smoky, warm, no breeze, muddy creek bed with fast flow, small stream, coyote followed off site, not resampled, just sondes

SW-5 spring! bubbling up from ground and flowing downhill through grassy area, staining orange algae, and organix oil-slick surface, no orange sstaining in any other puddles uphill, labrador tea, moss, horsetails, tamarack, black spruce, willow, forest fire smoke, hot but cold water, sulfuric smelling, hot, calm

SW-5* not resampled, just sondes

SW-6 muddy, swampy bay, appears flooded, dead trees, grasses, slight breeze, smoky, bay on Great Slave Lake, near ski trails

SW-7 rock cliff, ice falls, fine-grained basalt, thick vertical cracks and overall horizontal foliation, moss, black spruce, green water, cool beside rocks, water leaking through rocks, rusty water

SW-8 hot, breeze from S, abandoned train tracks in water, dead trees, foxtails, sampled from rocky pier on inland side

SW-9 hot, still, shallow lake, green, calm, off meta-sed? outcrop, jackpine, grasses, juniper

SW-11 very smoky from wildfires, slight breeze, black spruce, polar, thin mossy soil, off outcrop (indeterminate)

SW-12 hot, slight breeze from W, off meta-basalt outcrop, black spruce, jackpine, grasses, poplar, cattails, dwarf birch

SW-13 hot, slight breeze from W, off moss pile, swamp, dwarf birch, poplar, blackspruce, lots of grasses, cat tails, labrador tea

SW-14 cattails, swampy puddle in overall depression, downgradient of landfill, visible fuel on surface of water, very muddy/swampy and full of plants/bugs

SW-15 hot, still, calm, willow, poplar, felsic outcrop, very green lake, beside modern cemetery

SW-15-1 hot, still, calm, willow, poplar, felsic outcrop, very green lake, beside modern cemetery

SW-16 swamp, warm, breeze, cattails, grasses, very sludgy bottom, tall trees beside shore, nearby cliffs

FB taken at site SW-5

TB

MW-12 lots of smoke in air, cool, no breeze, black spruce, poplar, willow, juniper, thin to no soil, bedrock has foliations 014/10/W, well sits in local strech in rock, running parallel to foliations but more stressed, only isotope and sweetener sample

6. Supplementary Materials 2

6.1. Contamination Guidelines

6.1.1. Highlighted Parameters CCME Protection for Aquatic Life

Highlighted Parameters Alberta - Environmental Quality Guidelines for Alberta Surface Waters Surface Water Quality Guidelines for the Protection of Aquatic Life
https://open.alberta.ca/dataset/5298aadb-f5cc-4160-8620-ad139bb985d8/resource/38ed9bb1-233f-4e28-b344-808670b20dae/download/environmentalqualitysurfacewaters-mar28-2018.pdf

Parameter	Long-Term (Chronic) Guidelines	Units
Hardness ($CaCO_3$)	> 20	mg/L
Aluminum	Variable by pH pH < 6.5 = e(1.6 – 3.327 (pH) + 0.402 (pH) ^2) x 1000	µg/L

	PH > 6.5 = 50	
Arsenic (total)	5	µg/L
Boron (total)	1.5	mg/L
Cadmium	Variable by Hardness Hardness ≥ 17 mg/L and ≤ 280 mg/L = 100.83(log10[hardness]) – 2.4 Hardness > 280 = 0.37	µg/L
Chloride	120	mg/L
Chromium	Cr VI = 1 Cr III = 8.9	µg/L
Cobalt	Variable by Hardness Hardness ≥ 52 mg/L and ≤ 396 mg/L, = e(0.414[ln(hardness)] - 1.887 Hardness > 396 = 1.8	µg/L
Copper (total)	7	µg/L
Iron (dissolved)	300	µg/L
Mercury (total)	0.005	µg/L
Lead (total)	Variable by Hardness Hardness > 60 mg/L and ≤180 mg/L, = e1.273[ln(hardness)] -4.705 Hardness > 180 = 7	µg/L
Nickel (total)	Variable by Hardness = e0.846 [ln(hardness)]+0.0584 Undefined above hardness > 400, Ni = 170	µg/L
Uranium (total)	15	µg/L
Zinc (total)	30	µg/L
Selenium (total)	1 (alert) 2 (exceedance)	µg/L
Silver (total)	0.25	µg/L
*Manganese	200	µg/L
**Fecal Coliforms	10	CFU/100 ml
***Enterococci	35	CFU/100 ml

*Only regulated for Agricultural Uses
**Only regulated for Drinking Water
***Only regulated for Recreational Uses

6.1.1. Highlighted Parameters BC Water Quality Guidelines

British Columbia Water Quality Guidelines – Freshwater Aquatic Life
https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-quality/water-quality-guidelines/approved-water-quality-guidelines
https://bcgov-env.shinyapps.io/bc_wqg/

Parameter	Long-Term (Chronic) Guidelines	Units
Hardness (CaCO3)	Variable by Calcium Ca (dissolved) <=4 =< 10 Hardness Ca (dissolved) >5 =< 20 Hardness	mg/L
Aluminum (dissolved)	Variable by pH PH < 6.5 = e(1.6 - 3.327 (median pH) + 0.402 K) where K = (median pH)^2 PH > 6.5 = 0.05	mg/L
Arsenic (total)	5	µg/L
Boron (total)	1.2	mg/L
Cadmium	Variable by Hardness Hardness ≥ 3.4 mg/L and ≤ 285 mg/L = = e[0.736 * ln(Hss) - 4.943] where Hss is site-specific water hardness Hardness > 285 = 0.46 (site-specific)	µg/L
Chloride	150	mg/L
Chromium	Cr VI = 1 Cr III = 8.9	µg/L
Cobalt	4	µg/L
Copper (dissolved)	Variable by Temperature, Hardness, DOC, and pH * https://bcgov-env.shinyapps.io/bc_wqg/	µg/L
*Iron (dissolved)	0.35	mg/L
*Iron (total)	1	mg/L
Mercury (total)	Variable by percentage methyl mercury to mercury total At 0 methyl mercury, the limit is <= 0.02 At 0.01 methyl mercury, the limit is <= 0.0001	µg/L
Lead (total)	Variable by Hardness Hardness > 8 >= 3.31 + e(1.273 ln (mean hardness) - 4.704)	µg/L
Nickel (total)	Variable by Hardness Equation unavailable, range from hardness 55-500 = 25 -150	µg/L
Uranium (total)	8.5	µg/L
Zinc (total)	Variable by Hardness For hardness 0-400 = 7.5 + 0.75 x (hardness - 90)	µg/L
Selenium (total)	2	µg/L
Silver (total)	Variable by Hardness For hardness <= 100, <= 0.05 For hardness > 100, <= 1.5	µg/L
Manganese	Variable by Hardness >= 0.0044 hardness + 0.605	µg/L

**Fecal Coliforms	10	CFU/100 ml
***Enterococci	35-70	CFU/100 ml

*Only available for short-term (acute) guideline
**Only available for drinking water guidelines
***Only available for recreation use guidelines

6.1.1. Highlighted Parameters Alberta Water Quality Guidelines

CCME –Water Quality Guidelines for the Protection of Aquatic Life, Freshwater, Marine
https://ccme.ca/en/summary-table
https://ccme.ca/en/resources/water-aquatic-life#
https://ccme.ca/en/res/keyelementstoguidegovernanceforceamm-secured.pdf
https://ccme.ca/en/res/ncscs_guidance_e.pdf

Parameter	Long-Term (Chronic) Guidelines	Units
Hardness (CaCO3)	None	mg/L
Aluminum (dissolved)	Variable by pH PH < 6.5 = 5 PH >= 6.5 = 100	µg /L
Arsenic (total)	5	µg/L
Boron (total)	1.5	mg/L
Cadmium	Variable by Hardness Hardness < 17 mg/L = 0.04 Hardness >=17 to <= 280 = $10^{0.83(\log[\text{hardness}]) - 2.46}$ Hardness > 280 = 0.37	µg/L
Chloride	120	mg/L
Chromium	Cr VI = 1 Cr III = 8.9	µg/L
Cobalt	None	µg/L
Copper (dissolved)	Variable by Hardness Hardness < 82 mg/L = 2 Hardness >= 82 to <= 180 is $= 0.2 * e^{0.8545[\ln(\underline{hardness})]-1.46\}}$ Hardness > 180 = 4 Unknown hardness = 2	µg/L
Iron (total)	0.3	mg/L
Mercury (total)	0.026	µg/L
Lead (total)	Variable by Hardness Hardness <= 60 mg/L = 1 Hardness >60 to <= 180 = $e^{1.273[\ln(\underline{hardness})]-4.70}$ Hardness > 180 =7 Unknown hardness =1	µg/L
Nickel (total)	Variable by Hardness Hardness <= 60 = 25	µg/L

	Hardness > 60 to <= 180 = $e^{0.76[\ln(\underline{hardness})]+1.06}$ Hardness > 180 = 150 Unknown hardness = 25	
Uranium (total)	15	µg/L
Zinc (dissolved)	Variable by Hardness, pH, DOC Valid for hardness 23.4- 339 mg/L, pH 6.5-8.13, and DOC 0.3- 22.9 mg/L $= \exp(0.947[\ln(\text{hardness mg}\cdot \text{L}^{-1)}] - 0.815[\text{pH}] + 0.398[\ln(\text{DOC mg}\cdot \text{L}^{-1})] + 4.625)$	µg/L
Selenium (total)	1	µg/L
Silver (total)	0.25	µg/L
Manganese	Variable by hardness and pH using reference table *https://ccme.ca/en/chemical/129#_aql_fresh_concentration	µg/L
*Fecal Coliforms	100	CFU/100 ml
Enterococci	None	CFU/100 ml

*Only available for irrigation