Hydrogeological Site Characterization Methods for Discontinuous Permafrost Terrain

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Executive Summary

A compilation of various hydrogeologic site characterization techniques for application in remote, discontinuous permafrost regions is presented. Methods prioritize a strategic approach to selecting field monitoring targets, primarily at areas of active groundwater flow such as springs or groundwater fed water bodies. It is understood that springs and surface water may represent areas of interaction between the suprapermafrost and subpermafrost groundwaters, potentially making these features of interest for detailed terrestrial monitoring. Initial identification of these priority monitoring sites can be aided through the use of Geographic Information Systems (GIS). The GIS tools can be applied to the mapping areas of potential groundwater discharge features identified through remote sensing methods and through analysis of regional geologic and hydrologic patterns based on available information from a specific site of interest. Airborne thermal infrared imagery surveys complement these methods by the determination of precise locations of potential groundwater discharge, guided by previous desktop site assessment. This is achieved by the combined usage of thermal infrared and visible light cameras to capture imagery of cold thermal anomalies, which in summertime indicate potential groundwater fed springs and other discharge features. After selection of priority monitoring sites, a number of terrestrial geophysical instruments can be utilized to map the permafrost table and active layer thickness in locations of interest, which can be complemented by physical depth sounding of permafrost using probes. Groundwater sampling and hydraulic parameter estimates at priority monitoring sites can be conducted using lightweight, inexpensive and portable instruments. Vertical gradients can be determined by hydraulic head and temperature measurements, while sampling for particular geochemical and isotopic species provides insight into groundwater sources, contributions, flowpaths, and residence times. These tracer methods are limited in that different conclusions can be drawn from the same lines of evidence, but they provide a first step in understanding behavior of both the shallow and deep groundwater flow systems. Future monitoring decisions can be guided by these approaches, which may evolve moving forward.

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1.0 Introduction

The principle objective of this methods review document is to present and briefly discuss a suite of hydrogeologic field tools and strategies that can be used within remote terrain characterized by discontinuous permafrost to document groundwater flow phenomena. Permafrost development and maintenance requires an energy balance where more heat energy is lost in the winter than is gained in the summer (Woo, 2012). With climate warming trends, this balance may reverse and result in the degradation of the permafrost. Due to the heat capacity of water, this energy balance may be significantly disrupted below surface water bodies such that there could be an exaggerated influence on permafrost occurrence and continuity. Permafrost may therefore be thinner or absent entirely below a surface water body such as a river or lake, which may become exacerbated from climate warming (Woo, 2012). As such, the investigation of groundwater flow in the vicinity of surface water bodies may be of significant importance in these types of environments, which will influence the type of monitoring approach employed in these areas.

Upon freezing, unconsolidated sediment with high soil water content may lose much of its ability to transmit water. Hydraulic conductivity may decrease by 4-5 orders of magnitude as temperature decreases from 0°C to -0.5°C (Burt & Williams, 1976). If pores or fractures in rock and soil are saturated upon freezing, the ability to conduct water may cease, effectively causing the aquifer to behave as an aquitard. This means that in continuous and discontinuous permafrost regions, groundwater is partitioned within unfrozen geologic materials above (in the seasonal active zone) or below the permafrost. These groundwater systems are termed *suprapermafrost* if positioned above the permafrost table, and *subpermafrost* if below the permafrost. Suprapermafrost groundwater is typically younger, takes a shorter flowpath from infiltration to discharge, and can be more dilute than subpermafrost groundwater (Woo, 2012). Due to the longer residence time of the deeper subpermafrost groundwater, it tends to be much older and can be more solute-rich as a result of extensive interaction with subsurface materials. The nature of the groundwater geochemistry and isotopic composition can be used to interpret its source and age. Areas within permafrost terrain that remain devoid of permafrost year-round are known as *taliks* (Woo, 2012). Taliks that penetrate completely through permafrost can connect surface water with groundwater in the suprapermafrost zone and the subpermafrost zone; they create “hydraulic windows” through permafrost, allowing exchange between the different groundwater systems (Woo, 2012). As conventional groundwater monitoring wells require unfrozen conditions to function properly, the occurrence and persistence of the permafrost within the subsurface significantly influences their utility.

In developing this methods document, it was anticipated that through the use of novel groundwater monitoring and sampling techniques, some aspects of the groundwater flow systems within remote, discontinuous permafrost environments could be characterized without the need for conventional methods that require road site access and are prohibitively expensive. This includes approaches such as standard drilling and monitoring well installation. The suprapermafrost zone can be characterized through direct measurements while the subpermafrost zone behavior can be characterized indirectly from data collected in the vicinity of areas of groundwater discharge such as surface water and springs. Essentially, by finding evidence for subpermafrost groundwater in springs or surface water, it is possible to infer that the deeper groundwater flow systems are active and contributing to the shallow, suprapermafrost groundwater and surface water bodies. It is also anticipated that these combined groundwater characterization methods may provide insight into the interaction of deeper aquifers with the near surface environment and potentially assist in understanding how the overall hydrologic system is changing over time.

A variety of physical, geochemical and isotopic-based methods were explored in developing this report and it is anticipated this this will be a living document that will be updated as experience is derived from additional field testing. The methods include:

- Geographical Information Systems (GIS)
- Remote sensing
- Terrestrial and Air borne Geophysics
- Thermal infrared imagery
- Measurement of physical hydrogeological parameters
- Analysis of water geochemistry and isotopes

Geochemical species and isotopes are used primarily as "environmental tracers" which reflect information about the groundwater flowpaths, age, and source. For demonstration purposes, this document outlines the different methods as they were utilized to characterize hydrologic baseline conditions within a small watershed in the Central Mackenzie Valley, near Norman Wells, NWT. The field area is referred to as the Bogg Creek watershed (Figure 1). Emphasis is placed on how a strategic approach can be taken to determine how and where monitoring and sampling should occur a priori by initial identification of priority monitoring sites. We define priority monitoring sites as locations of potential groundwater discharging conditions or those under influence of groundwater that may provide insight into local and regional groundwater flow phenonena.

This document is intended as a guideline for characterizing groundwater flow phenomena in this specific environment and is not intended to be an exhaustive list of all methods and techniques that may be viable. Future updates to this document will be made as new information becomes available.

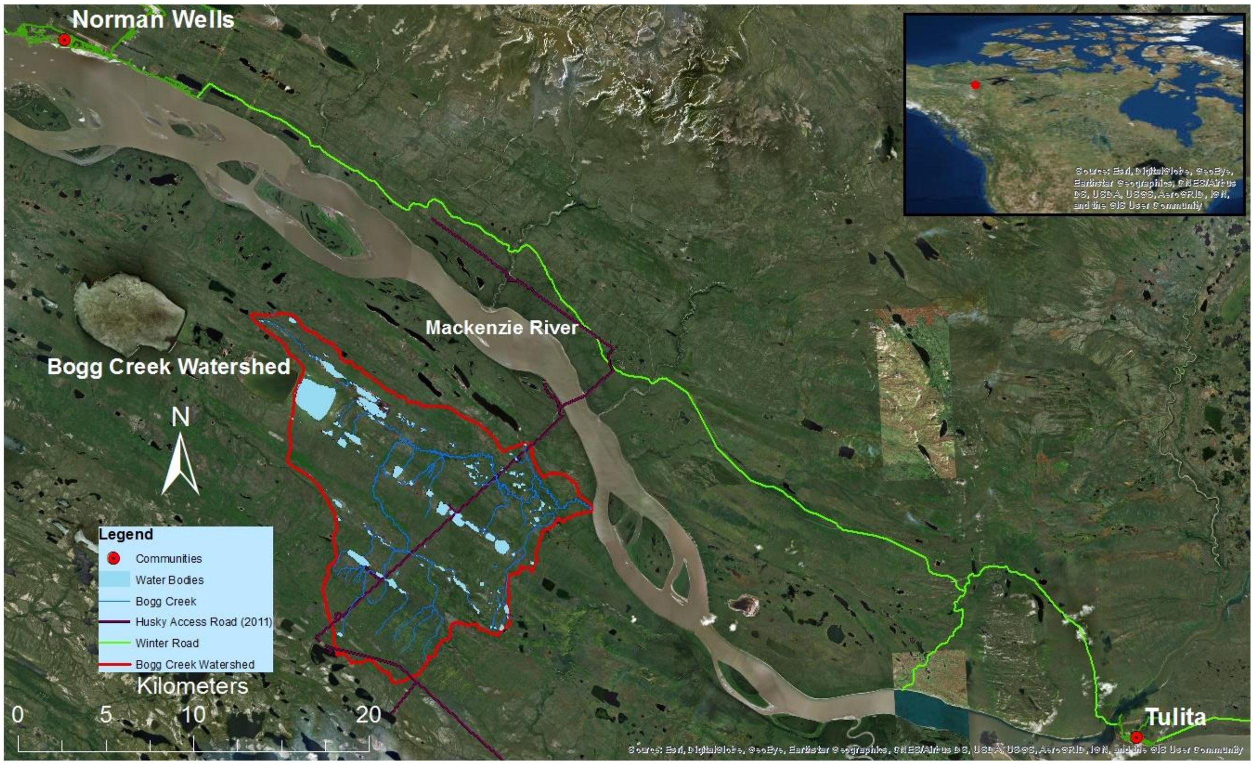

Figure 1: Map of study area and regional context. The Bogg Creek watershed is shown as a red outline and nearby communities as red dots. Winter and all-weather roads in the watershed provide access to several monitoring sites (Wicke, 2020)

2.0 Methods

2.1 Selection and Screening of Priority Monitoring Sites

Prior to consideration of a field site visit and specific terrestrial monitoring activities, it may be possible to make use of existing information, data and remote sensing tools to design the field sampling campaign. Using a combination of the different techniques there may be the potential to identify priority sampling and monitoring sites in advance of arriving at the field area of interest. Based on the nature of the identified field sites, specific monitoring plans can then be developed consistent with the anticipated site conditions.

The various techniques and strategies will be presented in order of data collection scale ranging from orbit-based remote sensing tools to detailed terrestrial measurement approaches. The technical aspects of each method will be briefly discussed with the emphasis being placed on the practical utility of the different methods and the information/data that could be expected to be obtained. It is clearly acknowledged that the objectives of individual projects may be highly variable and as such the methods are presented for general application in discontinuous permafrost terrain, utilizing the application within the Bogg Creek Watershed (Figure 1) as an illustrative example.

2.1.1 Remote Methods

Selection of priority monitoring sites begins with the use of desktop tools. Geographic Information Systems (GIS) programs such as ArcGIS are essential tools to display, modify and analyze geographic information that may be available at a specific site. Examples of useful information that can be informative for a desktop survey using GIS tools include surficial and bedrock geologic maps, Digital Elevation Maps (DEMs), climate data, road maps, stream and lake networks, and airborne geophysical surveys (e.g., Electromagnetic, Gravity). More detailed subsurface information can be obtained through the interpretation of terrestrial geophysics including seismic survey lines, point information from seismic shothole logs (Smith, 2015), and exploratory boreholes related to geological and geotechnical drilling. Combining the information from these different data sources can be useful in developing base maps of the area of interest and developing initial conceptual models of the geologic and hydrogeologic conditions at the site. This initial information can be used to evaluate access limitations, surface and subsurface geological materials that are likely to be encountered, and the nature of the surface water hydrology, all of which is valuable information in planning subsequent field investigations.

A specific example of the use of remote sensing data to inform hydrogeologic field investigations in this type of terrain involves the interpretation of precision optical and thermal imagery collected from satellites to map the locations of icing features on the land surface. In permafrost terrain, a common feature in the winter landscape is an “icing” or “aufeis”, which is a large sheet of ice formed by expelled groundwater or river water (Woo, 2012). Three primary types of icings have been documented: the spring icing, river icing, and ground icing. Land-fast icings in the form of spring and ground type icings are important to consider as these are typically sourced from groundwater (Glass, 2019). The spring icing is formed from a perennially flowing spring, often sourced from subpermafrost groundwater. The ground icing is formed as a result of an encroaching freezing front during winter that forces groundwater to the surface. The identification of these icing features may be of use in locating the position of groundwater discharge points, which could be of interest as priority monitoring sites for detailed field investigation with many of the techniques outlined in subsequent sections.

A remote sensing method used within the Bogg Creek Watershed to locate icings using optical and thermal satellite imagery is explained in detail in Glass (2019) following the methods developed by Morse and Wolfe (2015). The identification of icings is performed with the use of Landsat 4-5 Thematic

Mapper (TM) and Landsat-8 Operational Land Imager (OLI) optical imagery, RapidEye-3 optical imagery, and Landsat 4-5/8 120 m thermal imagery for various years with available data that would be appropriate for assessment. Following the algorithm process developed by Morse and Wolfe (2015), late spring imagery from each of these years is used to identify areal icing coverage. Although the details on the interpretation process is beyond the scope of this current document, they can be found in Morse and Wolfe (2015), Glass (2019), and Glass et al. (2020). The icing coverage from multiple years can be compared to locate areas where they consistently occur, which is indicative of a perennial spring area. These locations may be of priority interest to visit during field investigations as they may represent locations of deeper groundwater discharge. An example of icing maps generated in this fashion within the Bogg Creek Watershed is shown in Figure 2 (Glass, 2019; Rudolph, 2019).

Figure 2: Location of an icing cluster within the Bogg Creek Watershed between 2004-2017 (icings shown in pink) (from Glass, 2019) modified from Rudolph (2019).

The icings map can then be integrated with other relevant data sources to further develop maps of priority field investigation sites. For example, in combination with the icings map, analysis of terrain and geologic structures may further inform priority monitoring sites. Groundwater springs are often associated with a break in topographic slope, faulting or jointing, or between the contacts of a high hydraulic conductivity and low hydraulic conductivity formation (such as sandstone transitioning to shale) (Kresic & Stevanovic, 2010). Where these features coincide with surface water and icings there is potential for active groundwater flow, and these can be included as priority monitoring sites. High resolution satellite imagery can also be utilized to assess vegetation conditions that may limit site accessibility. Again, GIS tools can be employed to automate the construction of maps that can be continually updated as new information is obtained. Collectively this is used to update the initial conceptual geologic and hydrogeologic models. A summary of this process is presented in Figure 3 as a flow chart.

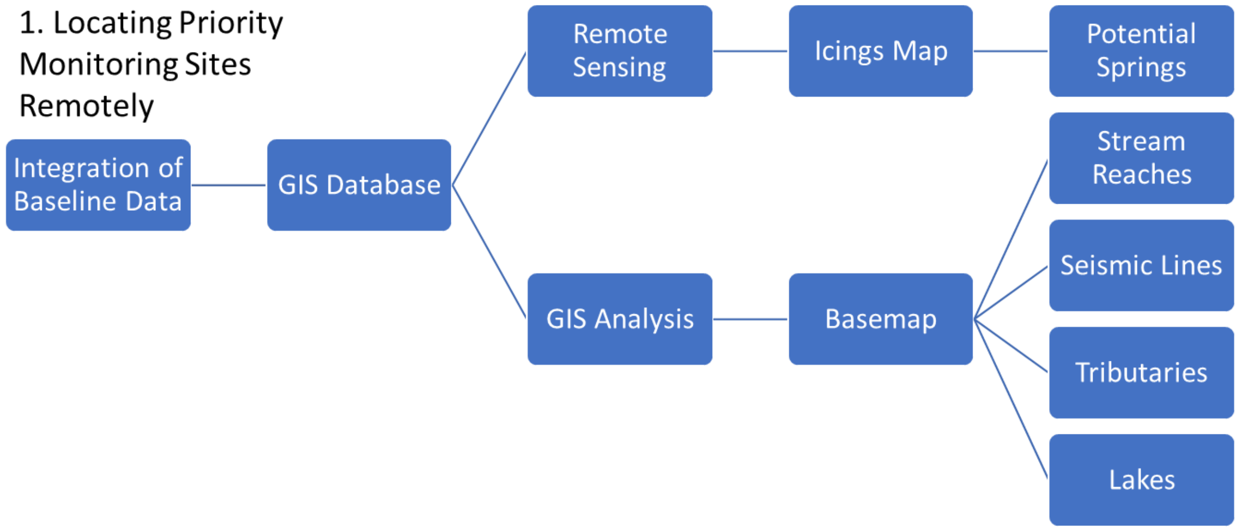

Figure 3: Process for remotely siting priority monitoring sites beginning with integration of any available site information.

2.1.2 Airborne Methods

Further screening of priority monitoring sites can be achieved through the implementation of a low-altitude thermal infrared (IR) survey, to verify if groundwater discharge is potentially occurring in priority sites. Flowing groundwater transfers heat energy by convection and conduction, and temperature variations are dampened with increased depth into the subsurface. This leads to less temperature fluctuations in groundwater compared to surface water or air temperature (Anderson, 2005). Because of this stability, temperature acts as a useful tracer for locating and characterizing groundwater and surface water interactions through temperature contrasts. In the summertime, groundwater temperatures are typically cooler than surface water and ambient temperatures, while in winter they are typically warmer (Conant Jr, 2004; Rudolph, 2019).

Groundwater emerging through seeps and springs with enough temperature difference from the surrounding surface water or nearby vegetation can be detected with IR cameras (Rudolph, 2019). The greater the temperature difference, the easier detection is. In summertime at midday when surface water temperatures are much warmer than groundwater, discharge can be highly visible by use of an IR camera. The opposite occurs in mid-winter when surface waters are colder compared to groundwater (Rudolph, 2019). This technology is most useful when paired with a helicopter flying at low elevation, allowing rapid characterization of groundwater discharge locations over a large area. A coupling of IR and visual cameras allows for imagery of ground and water temperatures to be recorded. With enough contrast, springs will appear as thermal anomalies against their surroundings. In the summer, these anomalies will appear cold and in winter they will appear relatively warm (Rudolph, 2019). Aerial traverses should be pre-planned and attempt to cover potential priority sites. Continuous footage combined with a GPS system allows for sites to be selected as ground targets for further groundwork. Other opportunistic survey targets can include creek banks, seismic cut lines, and lake shores. This footage can be used to make decisions on what targets are high priority and which will be less important to visit, depending on strength of the anomaly and its accessibility and position relative to icings or other features determined through geologic analysis. Some specific examples of cold anomalies and potential springs from the Bogg Creek watershed are illustrated in Figure 4. The summary of the screening process is presented in Figure 5.

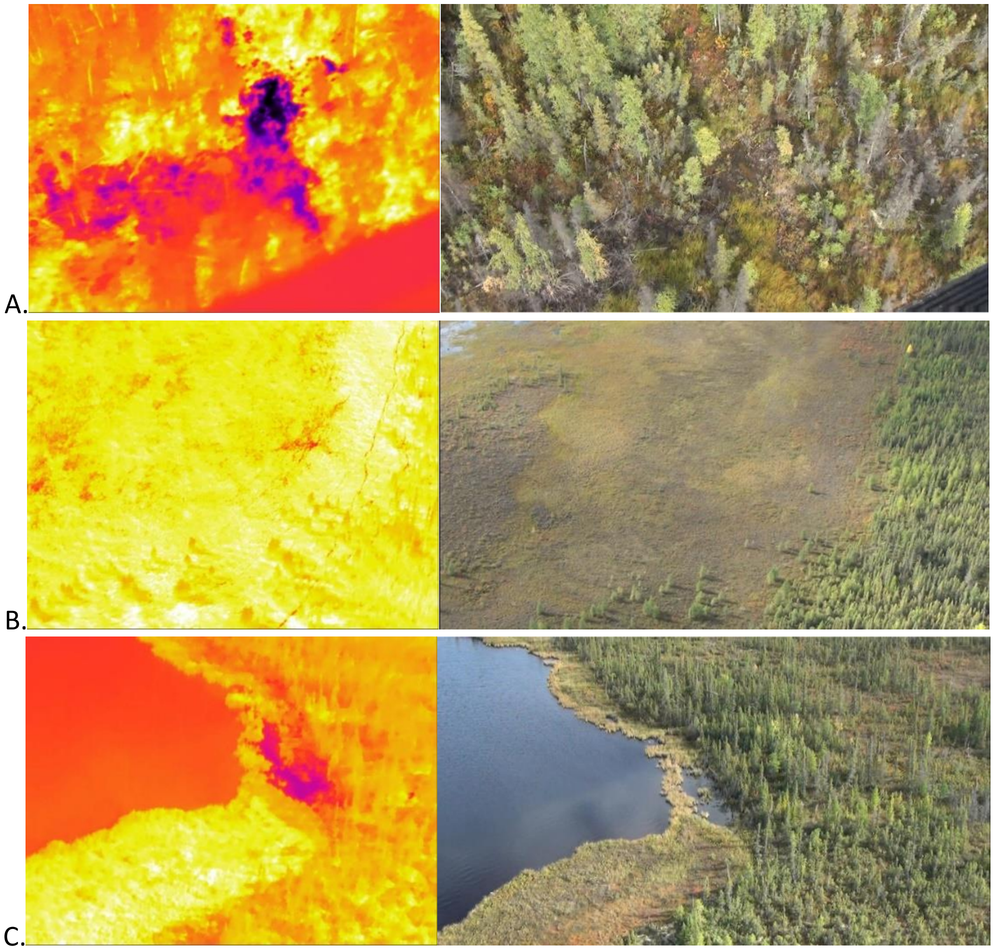

Figure 4: A): A large cold anomaly within a seismic cutline. B): Two thermal anomalies in a wetland adjacent to a lake. C): Thermal anomaly from spring-fed water pooling on the sides of a lake. Photos by B. Conant Jr.

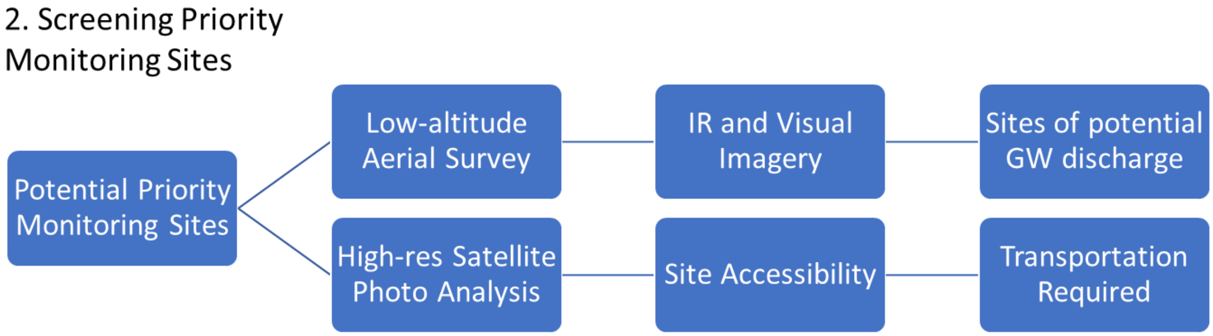

Figure 5: Screening process of priority monitoring sites using both satellite photo analysis and a thermal infrared image aerial survey. The aerial survey can be used to verify if there is potential groundwater discharge occurring at a particular site especially those identified through icing mapping. Both the aerial survey and photo analysis can be used to determine if a site will be accessible and is therefore worth visiting. This effectively removes many sites identified but that may not be accessible and prioritizes those with actual IR evidence of groundwater discharge and are more accessible.

2.2 Terrestrial Geophysical Methods

Terrestrial geophysical methods that have proven effective at mapping the presence of permafrost in the shallow environment include electromagnetic geophysics and specifically, electrical resistivity tomography (ERT). This system is relatively portable and can be managed by a small field crew although it requires the installation of electrode arrays into the ground surface. Another similar method is electromagnetic induction (EMI), which is also based on the electrical properties of the subsurface. This system does not require the installation of a terrestrial array and can be hand carried along a survey line making it a faster and less labor-intensive option (Walvoord et al., 2012).

The ERT method is designed to measure the vertical resistivity of the subsurface materials through a variety of different electrode arrays that can be selected to measure to different depth profiles. The EMI systems, on the other hand, consist of a transmitter and receiver coil, whereby the transmitter generates a primary electromagnetic field that interacts with the subsurface constituents. Conductive materials in the ground will contribute and generate a secondary electromagnetic field. Both the primary and secondary electromagnetic fields are measured by the receiver coil. The EMI instruments are manually moved from site to site and can be run along transects to collect laterally continuous information. Because there is a major contrast between the electrical conductivity and resistivity of sediments containing frozen water as compared to sediments with liquid water, these methods have proven useful in tracking the depth and continuity of the permafrost table (Walvoord et al., 2012; Rudolph, 2019).

In order to briefly demonstrate the utility of these two geophysical methods at mapping permafrost continuity in this type of terrain, data collected along the shoreline of a lake within the Bogg Creek watershed where the permafrost table was observed to plunge deeply and close to the shoreline (based on manual measurements with a permafrost probe, explained in subsequent sections) is used as an example. For the ERT mapping, a 25 m survey line was established perpendicular to the shoreline at the study site and 75 cm electrode spacing was selected in order to collect resistivity information along the survey line to an average depth of approximately 5 m. The resistivity data are presented in Figure 6. The geophysical profiles closely match the trend of the manual measurements of permafrost depth made along the survey line with the permafrost table dropping significantly towards the edge of the lake at the right side of the profile in Figure 6.

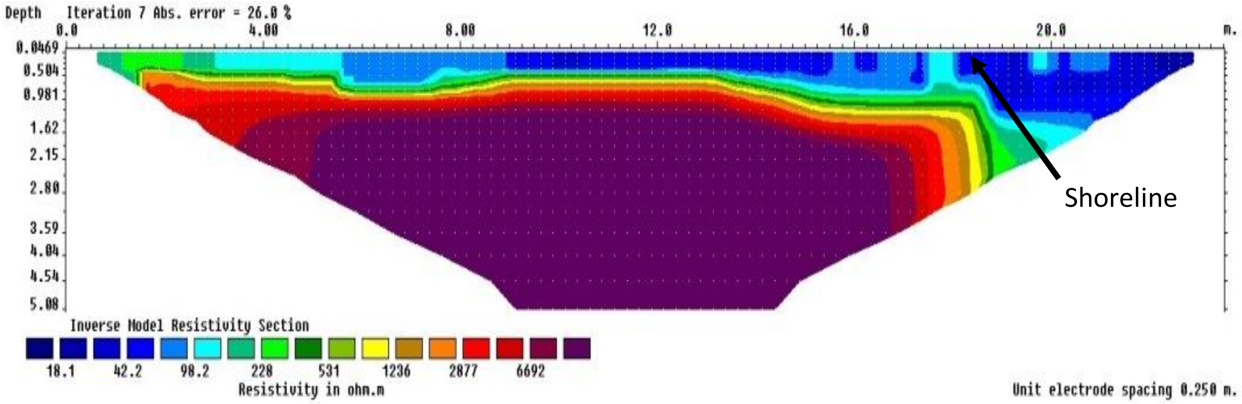

Figure 6: ERT survey data collected along a survey line oriented perpendicular to a large lake (right side of the profile) illustrating a significant increase in depth to the permafrost table near the lake (zone of lower resistivity in blue shades) (Rudolph, 2019).

The same survey line was used for the electromagnetic induction (EMI) method based on the frequency domain electromagnetic (FDEM) method (Geonics Limited EM-34-3™ and EM-31™). Coil spacings of between 10 m and 20 m were selected for the EM-34 surveys, and the fixed 3.4 m is the built in spacing for the EM-31. The coils can be arranged either perpendicular to the ground surface (horizontal dipole) or parallel to it (vertical dipole). With each measurement, one depth-averaged data point is obtained along the survey line as opposed to several data points being collected for different depths with the ERT method. Both geophysical instruments were manually carried along the survey line.

The results of the EMI surveys using both the horizontal and vertical dipole configuration are presented in Figure 7. As with the ERT method, the EMI approach also clearly detects the change in depth of the permafrost table approaching the shoreline. Considering the portable and less labor-intensive nature of the EMI systems, this geophysical method may be of value in remote terrain as a rapid mapping tool for the continuity of shallow permafrost as opposed to the more intrusive and less portable ERT methods. Both methods, however, provide useful approaches for rapidly estimating the depth and continuity of the permafrost table where the table is relatively shallow (upper 5 m). Where the table is deeper, stronger ERT systems with wider electrode spacings can be employed (Walvoord et al. 2012).

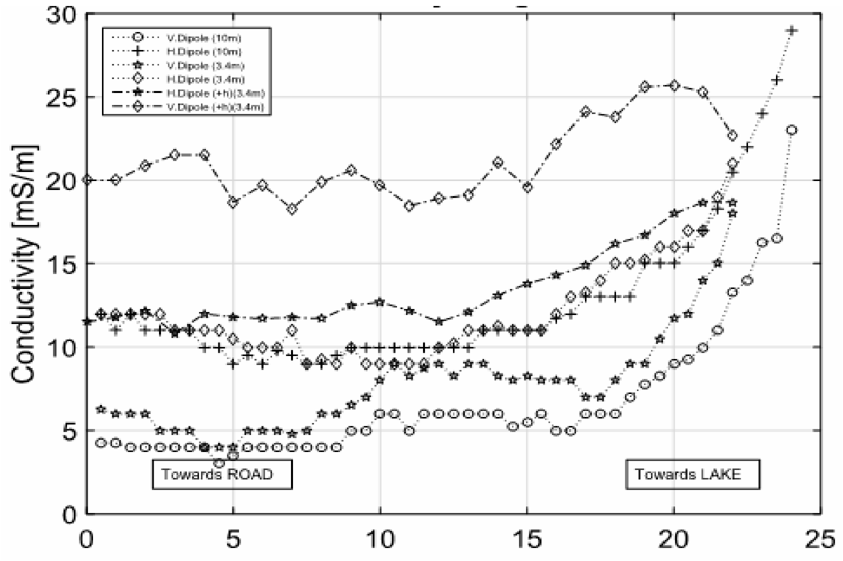

Figure 7: EMI survey data collected using several coil spacings and orientations along a survey line oriented perpendicular to a large lake (right side of the profile) illustrating a significant increase in depth to the permafrost table near the lake (zone of higher electrical conductivity) (Rudolph, 2019).

2.3 Groundwater Monitoring

2.3.1 Groundwater Samples and Physical Parameters

Taking samples of suprapermafrost groundwater, stream porewater, or spring water can be facilitated effectively through the use of lightweight, transportable sampling equipment. Portable sampling instruments such as the PushPoint "Henry" Sampler (MHE Products Ltd.) and pre-constructed mini-piezometers can be used to take groundwater head measurements and samples quickly and easily in remote areas. The PushPoint Sampler is a small drivepoint piezometer designed for taking porewater samples from the shallow subsurface or below surface water bodies. It consists of stainless-steel tubing, with a narrow drive-point tip and slotted screen at one end, and a small welded handle and sampling port on the other. An inner rod remains inside the sampler during insertion to minimize formation material from entering the screen and is removed prior to sample collection. The sampler is available in three lengths (62 cm, 124 cm and 184 cm) and is selected depending on how soft the subsurface materials are anticipated to be on site, a characteristic that controls how deep the thin probe can be manually installed. Use of the available mesh screens installed around the slotted tip is recommended with any length of sampler as smearing of clays and blockage of the slotted screen is possible.

The Henry sampler can be simply installed into soft sediment by hand without the need for a hammer and removed just as easily by pulling it out by hand. For collection of a groundwater sample, only narrow gauge plastic tubing and a syringe or vacuum pump are required. Once the inner rod is removed, groundwater level measurements can be taken easily with these samplers using a slim water level tape. This simple manual sampling tool works in water-logged wetlands, near or below surface water bodies, or on dry land areas where the water table is close to surface.

The pre-constructed mini-piezometer tips consist of small mesh screens wrapped around tubing (3/8”) that has been notched to allow for water entry. The tips average 10 cm in length and are connected to a smaller diameter tubing cut to the desired depth of installation (Lee & Cherry, 1979). The mini-piezometer is installed in sediments by manually driving a ½” steel pipe with an expendable tip to the desired depth. The pipe functions as a temporary access tube to permit the installation of the mini-piezometer and is subsequently removed from the ground, exposing the mini-piezometer tip. Installation depths are commonly between 1 m and 1.5 m and can be placed at multiple depths at the same location to monitor vertical hydraulic gradients in the shallow subsurface and collect groundwater samples from various depths. Groundwater samples can be collected from the mini-piezometer by connecting a syringe, vacuum pump, or peristaltic pump to the small diameter plastic tube and groundwater levels can be measured using a small diameter water level tape.

Both mini-piezometers and the PushPoint sampler are highly portable and easy to install and remove. Sample volumes are limited however, especially in the PushPoint sampler, so careful consideration should be given to what kind of samples will be required. Time needed to collect samples will depend heavily on the hydraulic conductivity of the subsurface materials. Physical parameters such as the hydraulic head at the sampling interval are also relatively quick to obtain with a water level tape, and several samplers can be installed at different depths to obtain a vertical (minimum 2) and horizontal gradient (minimum 3). Hydraulic conductivity can also be determined for the formation materials by performing constant, falling, or rising head single well response tests (Fetter, 2001). The measurements from these instruments can provide crucial baseline data that can be used later to determine if more long-term monitoring solutions are appropriate at a specific location. Photos of these instruments in use are shown in Figure 8.

Figure 8: The mini-piezometer and PushPoint "Henry" Sampler used to take groundwater levels and samples on dry land (left). The PushPoint sampler showing upward gradient at a spring site (right). Photo on right taken by B. Conant Jr.

Vertical hydraulic gradients can also be determined through use of simple temperature measurements below springs or in stream or lake beds. A thin steel probe with an electronic thermistor installed at the tip (temperature probe) can be manually driven into shallow sediments to obtain a profile of groundwater temperatures to compare to the temperature of surface water. Stream and lakebed temperatures are a function both of a heat transport balance between the surface water and groundwater. Under groundwater discharge conditions, the subsurface temperature is influenced by the downward conduction of heat from overlying surface water, and upwelling groundwater convection. Under recharge conditions, both convection and conduction of heat will be downwards from infiltrating surface water (Conant Jr, 2004). Simple temperature measurements of both stream water and streambed temperatures to depths of around 0.5 m below bed surface may allow for reasonable determinations of groundwater flow directions, and in some cases the rate of flux (Conant Jr, 2004). If desired, a measurement can be taken every 10 or 20 cm to obtain a full profile of subsurface temperatures. This eliminates some of the possibility of measuring natural diurnal fluctuations that may be mistaken for background temperatures. An example of this as well as a profile of groundwater recharge and discharge is shown below in Figure 9. If the flux of water upwards is high, the convective transport of heat will exceed the conduction from surface water, forming a steeper slope in the profile.

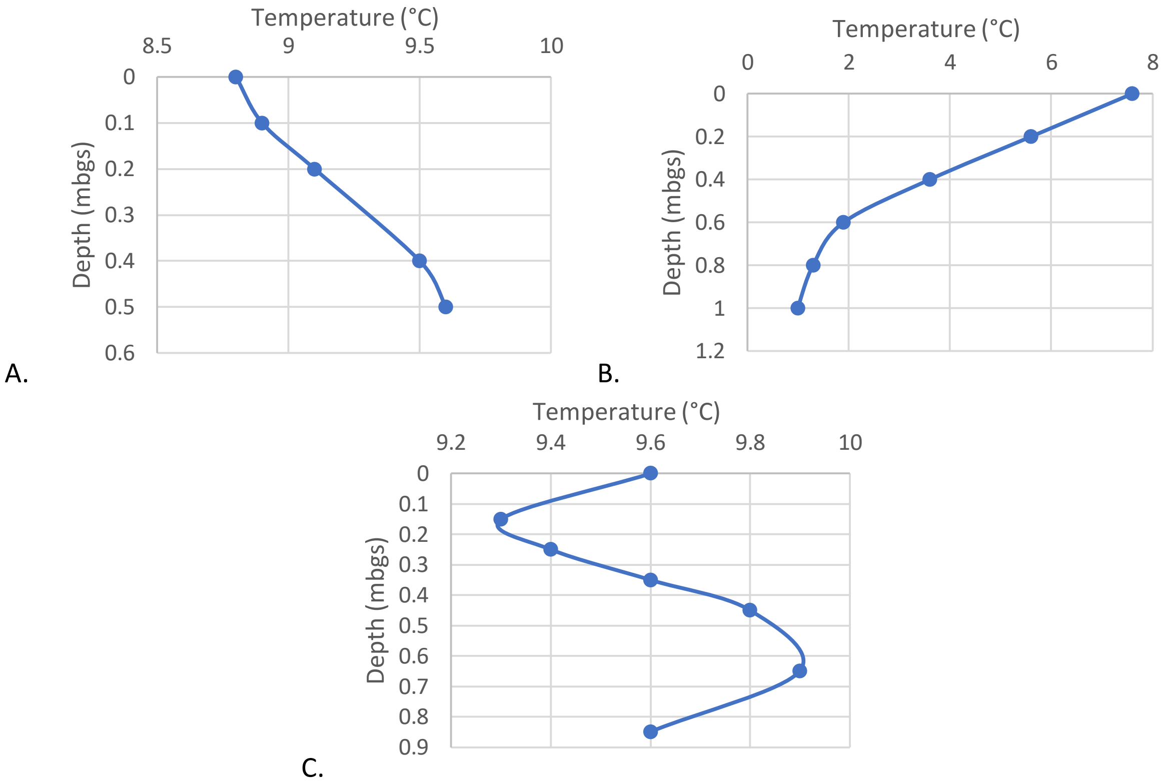

Figure 9: Temperature profiles showing A. Recharge conditions at a particular stream reach B. Dishcarge conditions measured at a groundwater spring and C. Diurnal fluctuations that penetrate below 20-30 cm. Note that these conditions are only possible in summer when groundwater temperature is less than surface water temperature. (Wicke, 2020).

2.3.2 Shallow Permafrost Conditions

The active layer or current summer thaw depth and permafrost continuity is useful information in informing the depth of the suprapermafrost zone and the presence of shallow taliks. A permafrost probe consisting of a graduated aluminum or steel rod with a handle can be used to measure the depth of the permafrost table and extent of thaw during a site visit, randomly or along a transect. Note that the true thickness of the annual active layer may not be possible to measure until just before winter freeze up, so measurements should be taken later in the year if that is required. Usage of portable sampling and measurement devices are shown below in Figure 10. Permafrost geochemistry, isotopes, ice content, and stratigraphy can also be useful parameters in determining potential for future changes and for characterizing a site. Small cores collected via specialized auger from the active layer and below the permafrost table can be logged for ice content, morphology, and sediment texture in the field and then kept frozen until further analysis can be performed in a laboratory setting. A squeezing apparatus will allow for extraction of porewaters after cores are allowed to thaw, following methods outlined in Moncur et al. (2013) and adapted in Wicke (2020). Geochemistry or isotopic composition can be analyzed in these extracted porewater samples depending on volumes produced and species of interest. The analysis of progressively deeper samples from the core can permit a determination of changes in these chemical and isotopic trends in the shallow subsurface.

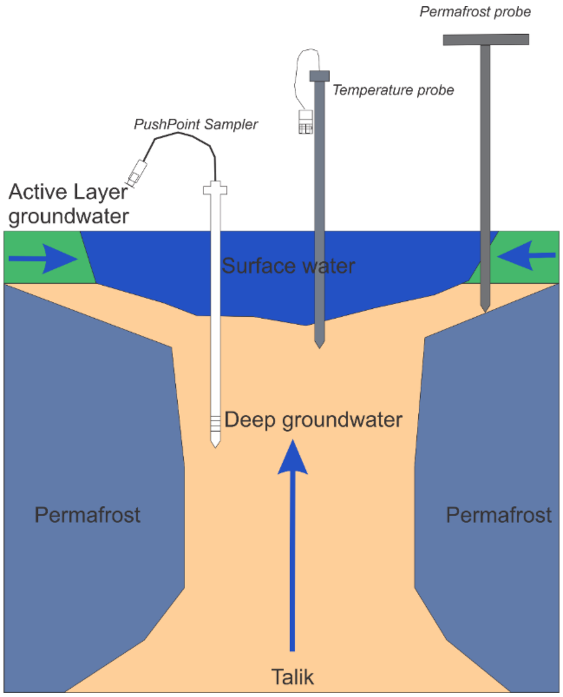

Figure 10: Conceptual diagram of equipment usage. PushPoint Sampler is used to collect samples below surface water, ideally to capture evidence of discharging subpermafrost groundwater before complete mixing. Temperature probes are used to measure temperature differences that may indicate discharge conditions, while the permafrost probe is used to map the permafrost table in the vicinity of the water body (Wicke, 2020).

2.4 Environmental Isotopes and Geochemistry

2.4.1 Geochemistry

Inorganic ions in water can often be used as groundwater tracers. Solute concentrations in groundwater evolve as water flows and encounters different rock types or lithologies (Hem, 1985). In most natural waters, the majority of the salinity is composed of 8 specie: calcium, magnesium, sodium, potassium, bicarbonate or carbonate, chloride, sulphate, and nitrate (Ca, Mg, Na, K, HCO_3 and/or CO_3 Cl, SO_4 and NO_3). Concentrations and proportions of these ions are largely controlled by lithology, water-rock interactions, flowpaths, and residence time. Water can be classified into a "type" based on the proportions of these elements (positively charged cations and negatively charged anions) relative to one another.

Initially, solute evolution within a groundwater flow system begins with rain or snowfall, which contains atmospherically derived solutes (Herczeg & Edmunds, 2000). Interacting with geologic materials, groundwater then begins to reflect the dominant rock and soil types of an area as a result of weathering reactions and mineral dissolution (Hem, 1985; Herczeg & Edmunds, 2000). Depending on the residence time and the flowpath the groundwater takes, geochemical evolution will occur, altering the water chemistry over time. Suprapermafrost groundwater flow usually takes place in shallow soils and is typically dominated by carbonate with some minor silicate dissolution. Subpermafrost groundwater flow may occur well below any unconsolidated overburden, within bedrock. Weathering reactions will then depend on the mineral make-up of the rock, with primary mineral types being carbonates (such as in limestones or dolostones) or silicates (such as in sandstones or granites) but with ion concentrations potentially being greater than in the suprapermafrost zone (Herczeg & Edmunds, 2000).

Hydraulic connections between shallow and deep aquifers allow for mixing of different groundwater flow systems to occur. Overall ion compositions are often plotted on piper diagrams, which allow basic geochemical “endmembers” to be established and provide visual indication of potential mixing (Hem, 1985). An endmember is a representative water sample from an aquifer or other water source, usually the most extreme samples that are available (such as very dilute or solute rich). In the study of regional groundwater flow systems, some subpermafrost groundwater monitoring may be required to establish important endmembers in the deep systems. Otherwise, if major rock types and minerals are known, water chemistry can be somewhat predicted. Furthermore, characterizing the suprapermafrost groundwater zone and its variability should reduce some uncertainty about a spring or surface water sample, as a significant deviation is likely indicative of another source. Mixing of different endmembers will produce a new geochemical make-up, which can often be distinguished through diagrams and calculations.

Some examples of groundwater endmembers and some surface water from Bogg Creek is shown in Figure 11. Endmembers include runoff and organic active layer porewater (Ca-SO_4 type water, top of diamond), suprapermafrost groundwater in the unconsolidated overburden (Ca-HCO_3 type water, left of diamond), and subpermafrost groundwater from two sources (Na-HCO_3 to Na-Cl type waters, right of diamond). Surface water from Bogg Creek for multiple years is also shown (Data provided directly by Husky Energy and some obtained from Husky Oil Operations, (2016)). Two tributaries overlap endmembers of the suprapermafrost and one of the subpermafrost endmembers separately, reflecting large influences (water inputs) from those sources. Water from lower reaches of Bogg Creek are shown plotting mostly in the center of the diamond, reflecting mixing of several unique water sources. Variability in the data is likely due to the different proportions of waters making up the bulk chemistry in a sample. For instance, stream water from early summer tends to plot closer to the runoff endmember, reflecting enhanced runoff as much of the ground is still frozen. As active layers thaw in late summer and rains decrease, waters then plot closer to the suprapermafrost and subpermafrost endmembers. This reflects the increased shallow groundwater flow coupled with increasing influence of all groundwater due to decreased runoff.

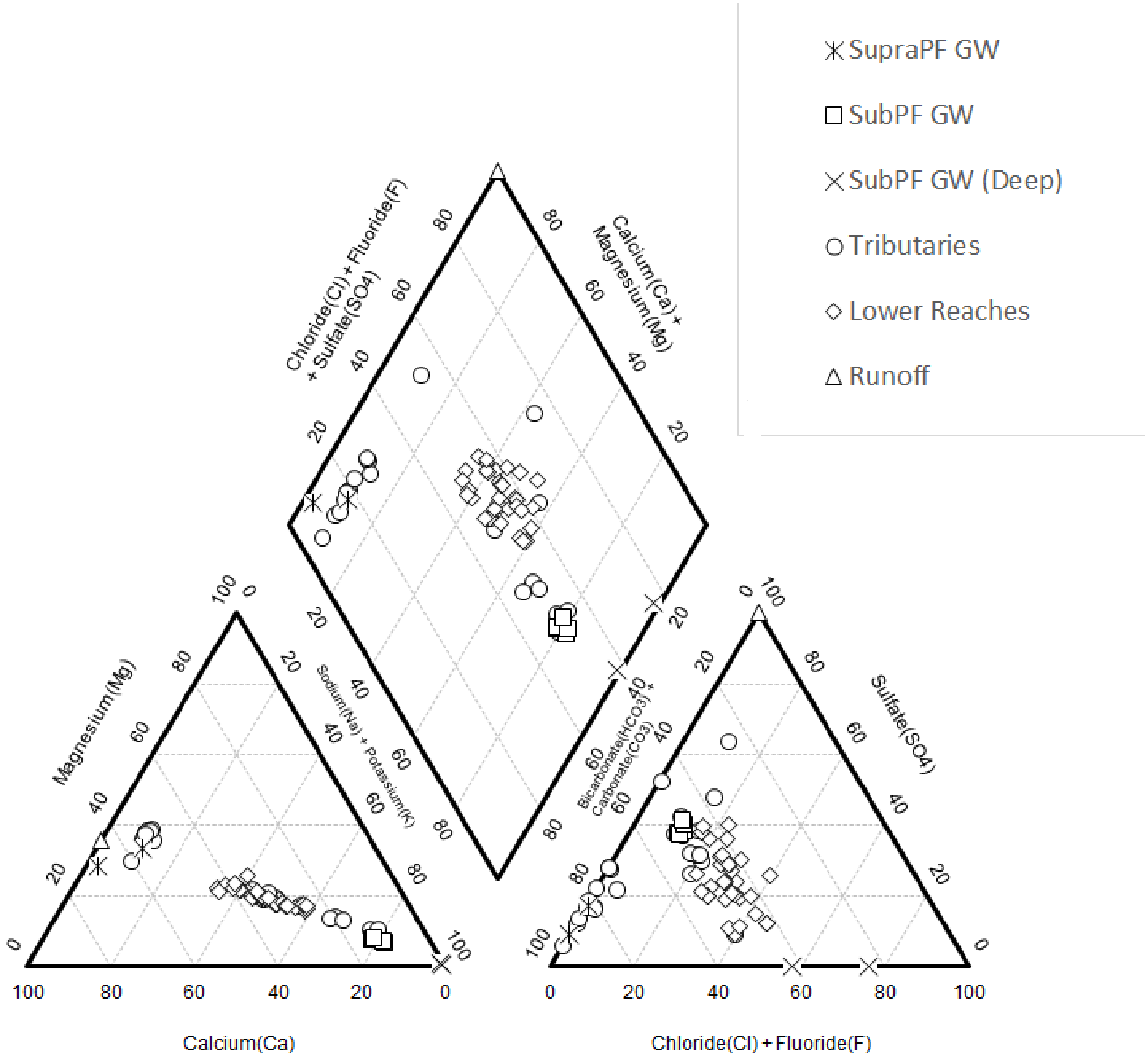

Figure 11: Piper plot of site wide groundwater and stream water. Tributaries show distinct overlap with certain endmembers and some variability due to different contributions of runoff and groundwater. Lower reaches appear to be mixtures of several endmembers and so do not overlap but vary due to different proportions of runoff and groundwater Some data provided directly from Husky Energy or obtained from Husky Oil Operations Ltd (2016) and Waterline Resources Inc., (2013a, 2013b).

Site specific chemical species may work as potential tracers as well. For example, hydrocarbon compounds are hypothesized to also act as tracers of deep groundwater flow in a bedrock environment where hydrocarbon-bearing strata are present. For example, natural seeps of petroleum exist along the Mackenzie River (Babiy, 2013) and may act as tracers for deeper subpermafrost flow (Rudolph et al., 2016). BTEX (Benzene, Toluene, Ethylbenzene and Xylenes) is hypothesized to act as a natural tracer in this environment. In the Bogg Creek example, toluene appeared in several waters but was unaccompanied by the other species. This has been reported to indicate toluene that is produced biogenically, or by microbes within a water-logged, anaerobic environment, rather than thermogenically, from temperature and pressure in oil reservoirs (Richards & Sandau, 2018).

2.4.2 Stable Isotopes of Oxygen and Hydrogen

Oxygen is known to have three stable isotopes and numerous radioactive isotopes, while hydrogen has two stable isotopes and one radioactive isotope. In isotope hydrology the oxygen isotopes ^{18}O and ^{16}O and hydrogen isotopes ^{2}H and ^{1}H are commonly used to study the sources and dynamics of groundwater or surface waters (Clark & Fritz, 1997). These isotopes are typically expressed in delta (δ) notation, in units of per mille (‰). This notation expresses the proportion of heavier (^{18}O and ^{2}H) isotopes to lighter isotopes (^{16}O and ^{1}H) that there are in a sample, in reference to a standard. Globally, $\delta^{18}O$ and $\delta^{2}H$ in precipitation is controlled by moisture sources, inland or oceanic topography, and latitude and longitude; typically, they are higher in warmer regions and lower in colder regions. Measuring $\delta^{18}O$ and $\delta^{2}H$ in precipitation throughout a given year in a particular area forms a straight line when graphed, called the Local Meteoric Water Line (LMWL) which is unique to a region (Figure 12). Precipitation $\delta^{18}O$ and $\delta^{2}H$ will vary seasonally and as such the precipitation source of groundwater within shallow groundwater flow systems may be recognizable by its $\delta^{18}O$ and $\delta^{2}H$ compared to a LMWL. Typically, snow will be more isotopically "light" (lower values) and summer rains will be more isotopically "heavy" (higher values). In many regions, LMWLs have been established through prior studies and data may be included in the Global Network of Isotopes in Precipitation (GNIP) database for a region near the study area.

A water sample that falls higher up the slope of the LMWL or is more isotopically heavy is generally composed mostly of summer precipitation that is also heavier. In contrast, water that is lower on the LMWL is more isotopically light and is comprised of lighter sources such as snow. Other sources of isotopically light water can be contributors, however, which can make interpretations difficult without other lines of evidence. Old groundwater recharged during the past in a colder climate such as during the last glaciation or water recharged at a higher elevation can both be light isotopically. Some of this old water can be flowing through deep, subpermafrost aquifers or locked up as permafrost ice. Modern groundwater in shallow aquifers is often comprised of a mixture of light and heavy isotopic waters corresponding to the amounts of snow and rainwater that recharges the aquifer. Reflecting this mixture, the $\delta^{18}O$ and $\delta^{2}H$ of modern groundwater is often around the same value as that of the weighted mean precipitation for a region (isotope values normalized to amount of precipitation) (Clark & Fritz, 1997).

In surface water, evaporation of water from an open body of water causes selective enrichment of $\delta^{18}O$ and $\delta^{2}H$ values, and a deviation off the LMWL onto a Local Evaporative Line (LEL). Groundwater with an evaporated signature suggests that the water has undergone evaporation from a shallow aquifer or was recharged by an evaporating water body (Clark & Fritz, 1997; Coplen et al., 2000).

Some example data are shown in Figure 12. $\delta^{18}O$ and $\delta^{2}H$ was used in Bogg Creek to determine the sources of surface water and groundwater. Surface water generally plots off the LMWL and along the LEL showing variability in the amount of evaporation, but some can be observed falling on or close to the LMWL. This indicates that this surface water is generally replenished with unevaporated sources such as groundwater or precipitation. Groundwater plots along the LMWL and reflects the dominant source of recharge, with most plotting around the average ($\delta^{18}O$ of -21.9‰). The lightest samples ($\delta^{18}O$ of -25.2‰) were subpermafrost groundwater taken from a series of deeper groundwater monitoring wells installed by Husky Energy within the Bogg Creek watershed as part of a baseline monitoring program (Waterline, 2012). This water was carbon dated to around 20,000 years old, placing its recharge age during the last glaciation (Waterline Resources, 2013b). Seeps and springs in the area also plotted around the average but with similar spread reflecting the complexity of water sources. Some springs plotted well below the average, indicating some component of isotopically light water may have derived from thawed permafrost, snowmelt, or subpermafrost groundwater.

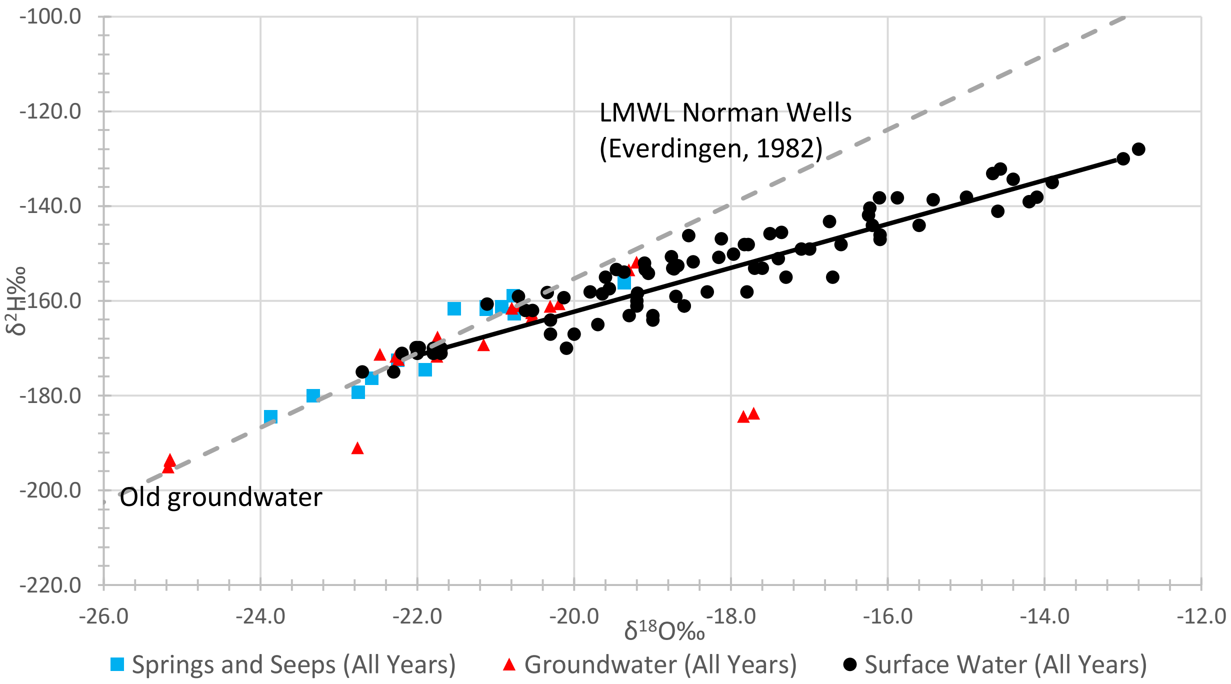

Figure 12: $\delta^{18}O$ and δ^2H data from 2012, 2018, and 2019 from around Bogg Creek and its surrounding area. Typically, groundwater (red) plot closer to the weighted average for precipitation, but some fall above or below. This case is also true for seeps and springs (blue). Surface water (black) generally shows an evaporated signal and falls on the LEL Some data retrieved from AMEC, (2013) and Husky Oil Operations Ltd., (2016)

2.4.3 Tritium

The radioactive isotope of hydrogen, ^3H, commonly referred to as tritium, is another routinely used tracer of the water molecule. With a half-life of 12.43 years, ^3H allows a relative or even absolute age constraint for young groundwater to be determined (Solomon & Cook, 2000). Tritium is often reported in Tritium Units (TU), in which 1 TU is equal to 1 tritium atom per 10^{18} Hydrogen (^1H) atoms.

Tritium is often used to determine the residence time of groundwater up to 60 years, as during the 1950-1960's, large amounts of it were produced by atomic bomb testing. Levels of tritium have since decreased steadily since the bomb peak, but due to the prevalence of nuclear power generation and natural generation levels, atmospheric TU values are usually around an average of 10 TU. Due to its short half-life, presence of a measurable amount of tritium in water provides an excellent indication of groundwater that has been recharged within the last 50 to 60 years (Clark & Fritz, 1997; Solomon & Cook, 2000).

Some example of tritium data from spring water collected within the Bogg Creek watershed are shown in Table 1. Geochemistry of these samples indicated the possibility of mixed type waters, and TU values were below that of modern water. Age calculations would place this water as being 4-13 years but this may in fact be water of different ages that have mixed to develop this tritium signature. Both lines of evidence here suggest a mix of different groundwaters. Other lines of evidence may assist in isolating the different sources and their contributions including physical hydrogeological measurements as outlined earlier.

Table 1: Samples from a large spring near a lake within the Bogg Creek watershed with TU values that suggest a component of modern water 4-13 years old.

Site	Date	^{3}H (TU)	Age
GL1	01-09-2018	7.9	4.5
GL2	01-09-2018	5.3	11.5
GL3	23-08-2019	4.9	13.0

2.4.4 Strontium

Strontium is a metal with two useful stable isotopes for groundwater tracing from a specific aquifer unit or rock type. In water samples, the ratio of ^{87}Sr/^{86}Sr is often determined in the dissolved strontium. Geologic materials will often contain a specific ^{87}Sr/^{86}Sr made up as a weighted average of the ^{87}Sr/^{86}Sr of all the minerals in that material (Clark & Fritz 1997). Groundwater that flows through an aquifer will dissolve strontium from minerals within the rock, resulting in a specific ^{87}Sr/^{86}Sr of the dissolved strontium similar to the aquifer host material. The length of time the water is in contact is important, however, as minerals have varying solubilities and ^{87}Sr/^{86}Sr values. Eventually the water will come to equilibrium and share a similar ^{87}Sr/^{86}Sr as that of the whole rock, while continued dissolution will increase the concentration of strontium. Typically, carbonates will have low ^{87}Sr/^{86}Sr but high strontium concentrations, sandstones will have intermediate ^{87}Sr/^{86}Sr and strontium concentrations and shales often high ^{87}Sr/^{86}Sr but intermediate strontium concentrations (McNutt, 2000).

In unconsolidated sediments and soil, the use of ^{87}Sr/^{86}Sr ratios is more complex due to the higher variability in water flow paths and soil mineralogy; typically it will contain higher ^{87}Sr/^{86}Sr and lower strontium concentrations compared to many rocks (McNutt, 2000; Shand et al., 2009). In surface waters, ^{87}Sr/^{86}Sr will depend on water sources as well as inputs from atmospheric and dust deposition and sediment weathering (McNutt, 2000). Runoff signatures are typically higher in ^{87}Sr/^{86}Sr but with low strontium concentrations, and groundwaters have lower ratios but higher strontium concentration in general (McNutt, 2000). For these reasons, ^{87}Sr/^{86}Sr makes a unique tracer of groundwater sourced from a particular formation, if the ratio can be determined (McNutt, 2000). This makes it difficult to interpret strontium data without appropriate endmembers. Whole rock ^{87}Sr/^{86}Sr values can be determined for different aquifers and used to constrain endmembers. There is some evidence that rock ratios do not always match ratios of their groundwater exactly, but these can be used to assess potential upper and lower bounds of dissolved ^{87}Sr/^{86}Sr endmembers when water endmembers are unavailable (Frost & Toner, 2004)

An example of this type of data used in groundwater mixing analysis is seen in data from Bogg Creek and several springs within that watershed (Figure 13). Several springs can be seen roughly plotting along a line originating from suprapermafrost groundwater. Two interpretations can be derived from this data. The first is that this demonstrates geochemical evolution of suprapermafrost groundwater taking a longer flowpath and dissolving less soluble minerals with a lower ^{87}Sr/^{86}Sr. The second interpretation is that this is the result of mixing of two endmembers, one from the shallow suprapermafrost zone, and one from a deeper groundwater source.

These data also show the relationship between three predetermined endmembers: tributary baseflow, surface runoff, and subpermafrost groundwater within several creek samples. Samples that plot closer to a certain endmember are likely to have a greater contribution of that water. Tributary 1 plots closer to the baseflow and runoff endmembers suggesting a greater influence of those waters. Tributary 2 plots quite close to the subpermafrost endmember which lends further evidence of the deeper groundwater influence on this tributary.

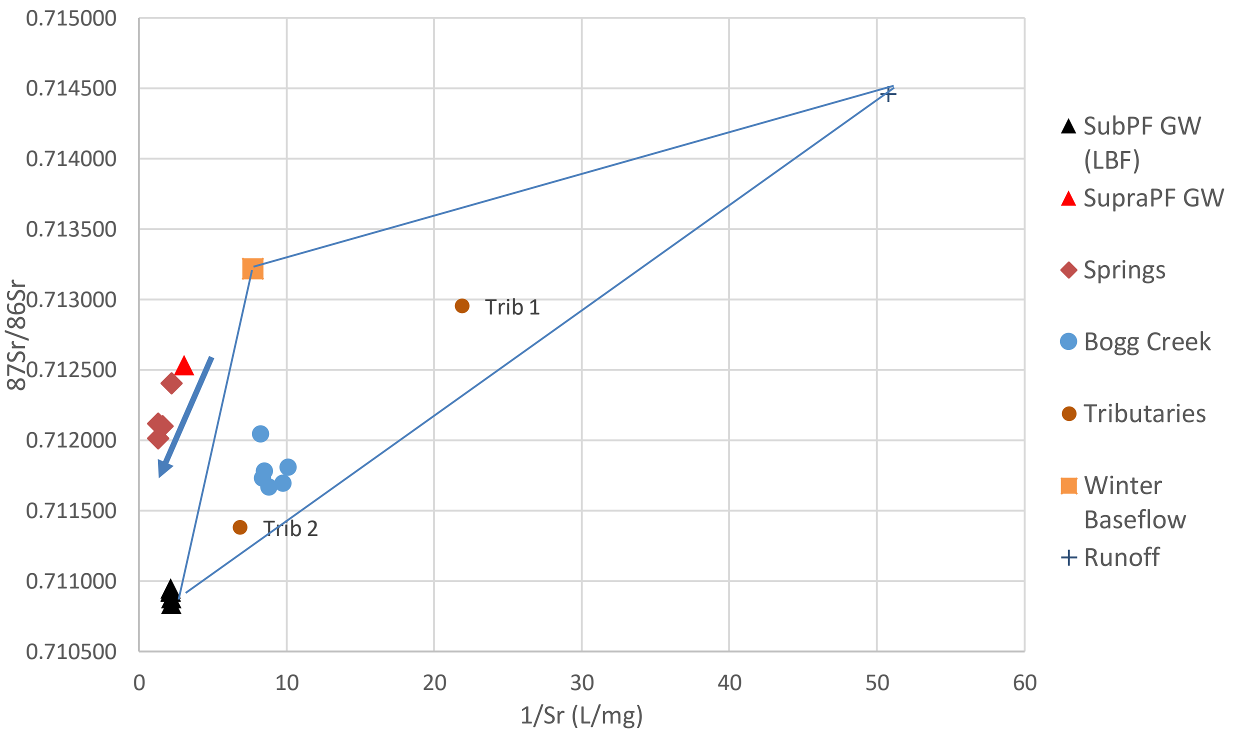

Figure 13: ^{87}*Sr/*^{86}*Sr vs 1/Sr for some spring and creek samples collected within the Bogg Creek watershed and various endmembers (Wicke 2020).*

2.4.5 Carbon

Two stable isotopes of carbon, ^{12}C and ^{13}C can be analyzed in DIC to determine certain conditions under which water was flowing. Another, more novel use, is tracing the origin of methane gas, CH_4. Carbon is expressed in similar notation as the stable isotopes of water, using the ratio of ^{13}C/^{12}C of a sample to the ^{13}C/^{12}C of a reference standard as δ^{13}C reported in ‰. Carbon in methane is fractionated according to its source. Methane can be produced in several ways naturally, but most commonly it is produced by thermal maturation of hydrocarbons (thermogenic) or through the breakdown of organic matter by microbes in the near-surface environments such as wetlands or bogs (biogenic) (Philp & Monaco, 2012). This methane may migrate upwards as a gas or be dissolved in groundwater, and has been used as a tracer of deeper groundwater flow (Philp & Monaco, 2012; Grasby et al., 2016). Biogenic δ^{13}C is often very isotopically light, between -80 to -42‰, while thermogenic methane is often higher at between -30 to -50‰ (Philp & Monaco, 2012).

Examples of thermogenic and biogenic gas from the study area are shown in Figure 14. Gas was taken from a subpermafrost aquifer, springs, a lake, and the creek (tributary and lower reach). The spring samples were taken in the summer season while all other samples were taken in winter. Spring and lake δ^{13}C fall within the biogenic range, while the subpermafrost groundwater falls within the range of thermogenic methane. The creek samples appear to fall close to the end of the biogenic range and quite close to the thermogenic range. There is a possibility that this gas is a mixture from biogenic and thermogenic sources, producing a value on the higher end of biogenic. This would imply a connection to the subpermafrost zone, allowing gaseous or dissolved methane to accumulate in the creek during winter.

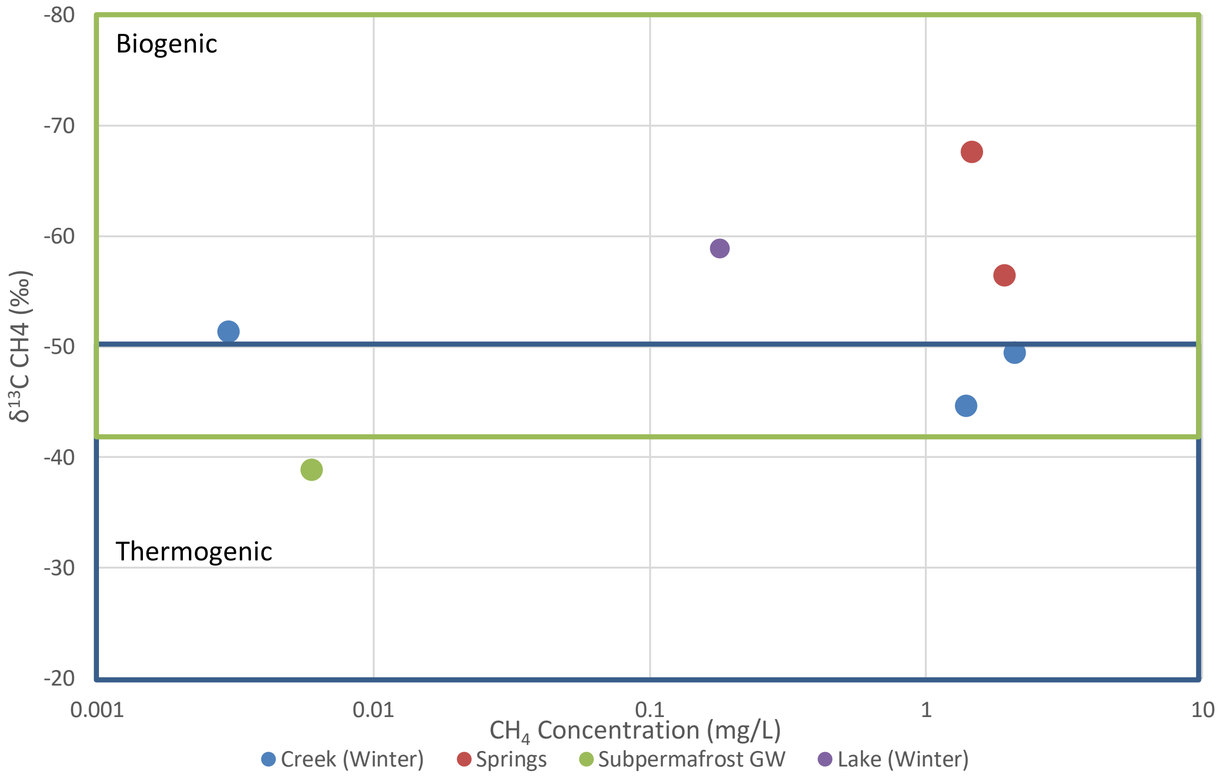

Figure 14: Methane samples given as an example in Bogg Creek. Note that concentrations are expressed on a log scale (Wicke, 2020).

3.0 Conclusions

The methods outlined above may be used to characterize baseline hydrogeological conditions in remote, discontinuous permafrost environments. These included the use of GIS and remote sensing, application of IR, geophysical and groundwater sampling technology and various geochemical and isotopic tracers in order to locate sites and characterize permafrost and groundwater flow conditions strategically. Each method complements the others, offering additional insights and perspective when fully integrated, as was demonstrated in the example of the Bogg Creek field site. Limitations do arise however, especially in regards to using these geochemical and isotopic tracers as different conclusions can be interpreted from the same data. This list is also not exhaustive and only includes methods that were tested and implemented at the Bogg Creek field site. Other techniques or tracers may be applicable in this environment. Moving forward, this document could be updated as new methods are identified and tested in the field, but those outlined provide a crucial launching point to guide future monitoring decisions at field sites underlain by discontinuous permafrost. A summary of the different data collection methods is presented as a flow chart in Figure 15 while the interpretations and utility of the various methods are presented in Figure 16

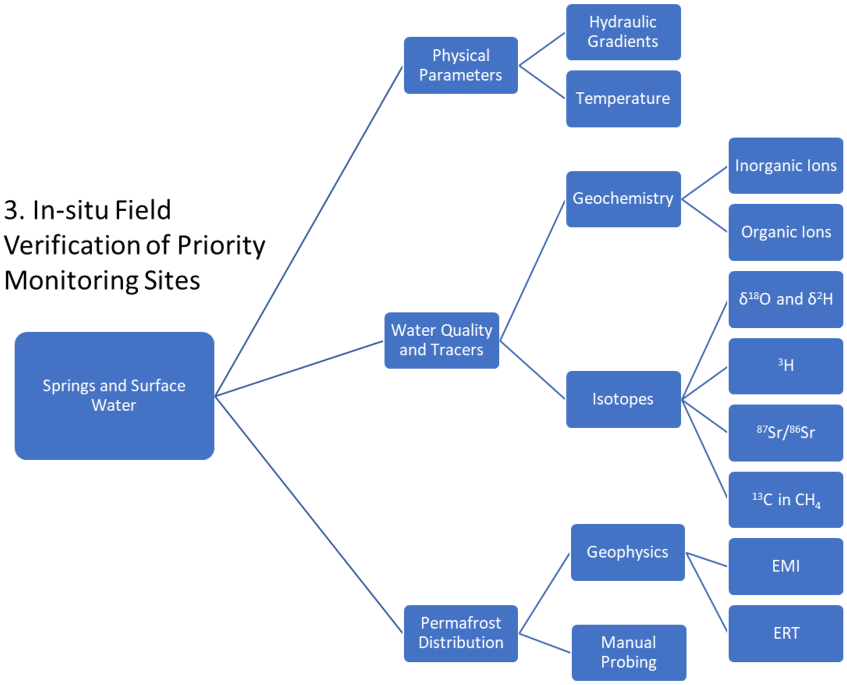

Figure 15:Summary of the in-situ field verification of the priority monitoring sites, including the various methods outlined above in previous sections.

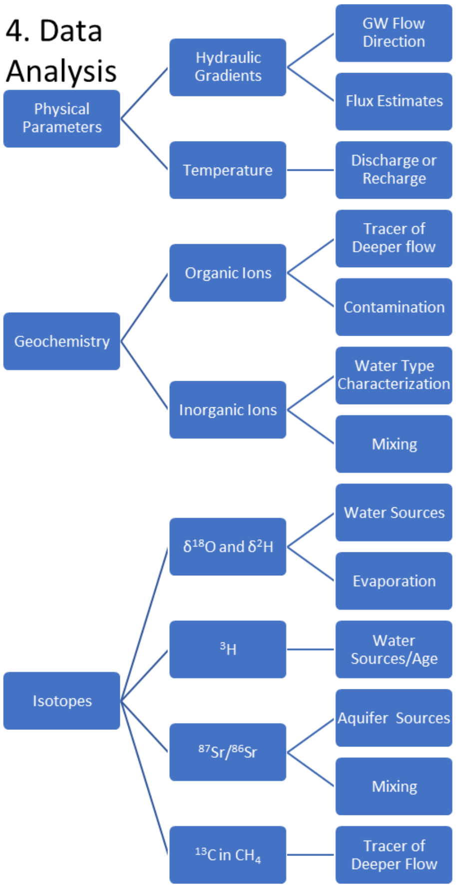

Figure 16: Summary of the various data types and their utility in understanding baseline conditions in a field site.

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