

Regional hydrologic and ecologic characterization and
baseline assessment of remote northern Canadian terrain in
advance of shale oil and gas development

Second Annual Report to:

NWT ESRF Management Board



By:

David Rudolph

University of Waterloo

April, 2019

1.0 INTRODUCTION

The Year 2 work activities associated with the project have been focused on: 1). developing a field work protocol to access the Husky Slater River lease areas; 2). coordinate and expedite a regional summer and winter water sampling campaign with Husky personnel; 3). design and conduct low-elevation, helicopter-based IR and optical surveys in Bogg Creek watershed; 4). integrate remote sensing surveys with terrestrial based measurements and 5). locate and conduct terrestrial geophysical mapping of permafrost occurrence: Following the approach established during Year 1 of the project, the majority of the field activities undertaken in Year 2 were focused within the Bogg Creek Watershed shown in Figure 1.

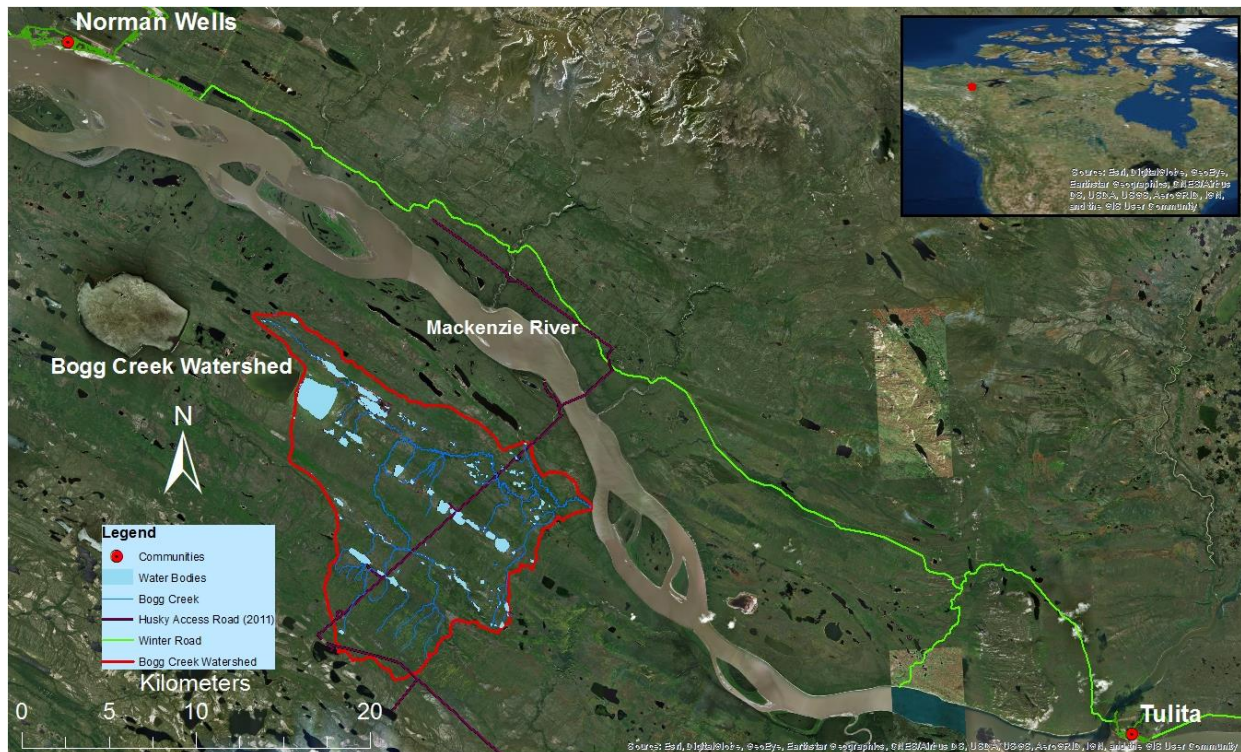


Figure 1: Satellite photo of study area and surrounding communities of Norman Wells and Tulita. Inset map showing Canada and position of study area.

This subwatershed sits within Husky’s Slater River Lease region of the Sahtu Settlement Area (SSA), which has been the focus of initial baseline monitoring by Husky personnel since 2013. Surface water and groundwater samples, isolated stream flow measurements and subsurface temperature measurements have been routinely collected by Husky from a series of monitoring locations over this time period. These data have been made available for our project. Husky has reduced the total number of monitoring sites that they visit each year but based on personal communication with Husky staff, they will continue to collect information from these locations for the next few years at least. We have focused specifically on the Bogg Creek subwatershed because it provides a logical hydrologic unit for the field investigations and because of the existence of the all-season access road that had been constructed by Husky to support initial exploratory petroleum drilling, which runs through the middle of the area (Figure 1). Based on initial discussions with Husky, the intention is for the all-season access road to remain available for use at least until 2020 and potentially longer into the future. The road is

fundamental to providing access for students and research personnel to be able to complete field investigations within the study site in all seasons.

During the course of Year 2, the research activities were coordinated with research colleagues from Wilfred Laurier University (WLU) and Husky personnel. Additional financial and in kind support for various components of the work were leveraged through our efforts within the Global Water Futures (GWF) program centered at the University of Saskatchewan and specifically through the Northern Water Futures study headed by Dr. Jenn Baltzer at WLU and the Transformative Sensors and Smart Watersheds (TSSW) project headed by Drs. Claude Duguay and Dave Rudolph and the University of Waterloo. Dr. Baltzer's students participated in the field work during the Year 2 campaign. In addition, Dr. Baltzer and colleague, Dr. Merritt Turetsky from the University of Guelph are also working in the area through an ESRF grant focused on terrestrial ecology. This work will be collaboratively associated with the current work in the Sahtu region. Finally, additional financial support was provided by the Government of the Northwest Territories (GNWT) through a grant provided to WLU.

Progress on each of the different topics listed above as activities during the Year 2 period will be summarized in separate sections below.

2). Developing a field work protocol to access the Husky Slater River lease areas

Access to the Husky Slater River Lease area was coordinated through Husky personnel, headed by Ms. Jenica von Kuster. Through Ms. von Kuster, UW and WLU personnel were instructed to complete a series of safety courses in advance of the site visit during the summer of 2018. In addition, Husky arranged for specific field clothing that would be approved to wear while on the Husky lease area and provided most of this as an in-kind contribution to the project. A detailed field work plan and time schedule was submitted to Husky for their review and approval and the visit was synchronized with their annual field sampling campaign to optimize overall field activities as much as possible.

As Husky conducts an annual sampling circuit that visits key hydrologic locations within the study area, it was decided that the UW/WLU team would travel along with the Husky personnel during their sampling campaign. This also helped to optimize helicopter time, provide the opportunity to share sampling protocol and to enhance the data collection at each of the remaining legacy monitoring sites. Husky assisted with the coordination of the helicopter rental and was able to arrange a special industrial rate that Great Slave Lake (GSL) Helicopters offered to us as well.

The majority of the field activities were centered along the all-season access road that runs through the centre of the Bogg Creek watershed (Figure 1). Access to the different field sites along the road was facilitated with both the helicopter and a set of quad vehicles that were airlifted to the site with the GSL helicopter. Field equipment for terrestrial geophysics and hydrologic monitoring was shipped from UW to Norman Wells and then airlifted to a Husky storage facility on the Slater River Lease. Arrangements for environmental monitors were made through the Sahtu Renewable Resources Board (SRRB) in Norman Wells and Tulita. The field work was conducted during the last week of August and first week of September 2018.

3). Regional hydrologic investigations and water sampling

Surface water samples were collected at 22 sites throughout the study area as part of the Husky sampling campaign in August 2018. The samples were submitted for full chemical analysis and for selected isotopic species. Groundwater samples were collected at several of these sites using a PushPoint “Henry” Sampler, which is a small portable hand-drivable sampler that acts as a temporary piezometer, or using pre-constructed mini-piezometers that were driven into the shallow subsurface manually. Groundwater levels were recorded and hydraulic gradients were determined to assess whether groundwater recharge or discharge conditions prevailed at the given site. Temperature profiles of the subsurface were taken using a long portable temperature probe at selected sites, and active layer depths were determined with a permafrost probe at most sites.

Additional surface and groundwater sampling was conducted at several locations that were identified, through the remote sensing work presented below, as icings by Glass (2018). Samples were also collected at sites that were identified as cold temperature anomalies during an airborne infrared camera survey (summarized below) that was run along several lakes, the main branch of Bogg creek and along several transects near the headwaters of Bogg Creek. The total number of sites visited, including Husky monitoring locations, was about 35. Some sites were within walking distance of one another and were revisited once, while most required a helicopter to access and were not revisited.

Sample bottles were obtained by ALS Ltd. in Yellowknife, NT. Analyses included major ions, selected metals and organics such as methane, phenols, and BTEX. Isotopes included ^{18}O , ^2H and ^3H of water, ^{13}C in dissolved methane and ^{87}Sr in dissolved strontium. ^{13}C in dissolved inorganic carbon (DIC) was proposed but not collected during this round of sampling. Water chemistry samples were analyzed at ALS Ltd. in Edmonton, AB, while isotopic analysis was conducted at the Environmental Isotope laboratory at the University of Waterloo. Metals and Strontium isotopes were filtered within 12 hours of collection by $0.45\ \mu\text{m}$ paper membranes and preserved with 1 mL 1:4 nitric acid. All samples of volatile compounds or evaporation sensitive isotopes were collected with zero-headspace. All samples were stored in coolers kept to about 4°C in the field, and refrigerated upon returning to residence. A complete summary of protocols and sample bottle details is provided in

Table 1. For a full summary of all sampling locations and samples obtained see Table 2.

Table 1: Sampling protocol summary. * denotes bottle pre-preserved by laboratory, ** is preservative not necessary if holding time not exceeded.

	Sample	Bottle Size	Bottle Type	Holding Time (days)	Filtered?	Preservative?	Zero Headspace?
Concentrations	Metals	60mL	PE	180	Yes	1 mL 1:4 Nitric Acid	No
	Major Ion	500mL	PE	3 (Variable)	No	None	No
	Phenol/DOC/NH4	100mL	Amber Glass	28	No	Sulphuric Acid*	No
	VOCS (BTEX, CH4)	2x40mL	Glass	14	No	Sodium Bisulfite*	Yes
Isotopes	18O & 2H	30mL	PE	Indefinite	No	No	Yes
	3H	250mL	PE	Indefinite	No	No	Yes
	87Sr	125mL	PE	Indefinite	Yes	1 mL 1:4 Nitric Acid	No
	13C in DIC	40mL	Amber Glass	3	No	None	Yes
	13C in Methane	60mL	Glass	14	No	Sodium Bisulfite**	Yes

Table 2: Summary of Summer 2018 sampling locations and samples obtained. See legend at bottom for explanation.

Site	Eastings	Northing	Date	Present	Major Ions	Metals	Organic Analytes	18O & 2H	3H	87Sr	13C in CH4
H003	645799	7193837	2018-08-28	H & W	SW	SW	SW	SW			
H016	629154	7194810	2018-08-28	H & W	SW	SW	SW	S+G			
H043	635452	7197627	2018-08-28	H & W	SW	SW	SW				
H023	631388	7204193	2018-08-28	H & W	SW	SW	SW	SW			
H002	630032	7205644	2018-08-28	H & W	SW	SW	SW	S+G		GW	
H042	617688	7204388	2018-08-29	H & W	SW	SW	SW	SW			
H041	615844	7206650	2018-08-29	H & W	SW	SW	SW				
H031	617878	7211864	2018-08-29	H & W	SW	SW	SW	S+G			
H006	611329	7222272	2018-08-29	H & W	SW	SW	SW				
H026	621169	7224635	2018-08-29	H & W	SW	SW	SW	S+G			
H045	629280	7220871	2018-08-29	H & W	SW	SW	SW				
H046a	619298	7210973	2018-08-29	H & W	S+G	S+G				SW	
H046b	619334	7211007	2018-08-29	H & W	SW	SW	SW			SW	
H027	622346	7221298	2018-08-29	H & W	SW	SW	SW	SW			
H030	623147	7217943	2018-08-29	H & W	SW	SW	SW	SW		SW	
H028	625969	7220048	2018-08-29	H & W	SW	SW	SW				
H001	631241	7214872	2018-08-29	H & W	S+G	S+G	SW	S+G		SW	
H044a	620862	7212376	2018-08-30	H & W	S+G	S+G		S+G			
H044b	620882	7212394	2018-08-30	H & W	SW	SW	SW	SW			
H040	623338	7214538	2018-08-30	H & W	SW	SW	SW	S+G			
AWR5	626208	7217095	2018-08-30	H & W	SW	SW	SW				
AWR4	626976	7217650	2018-08-30	H & W	SW	SW	SW				GW
AWR3	627936	7218741	2018-08-30	H & W	SW	SW	SW				
AWR2	628973	7219685	2018-08-30	H & W	SW	SW	SW				
H001B	625708	7216727	2018-08-30	H & W	S+G	S+G		S+G		SW	
GL1	619752	7220722	2018-09-01	Waterloo	S+G	S+G	S+G	S+G	GW	S+G	GW
GL2	619566	7220872	2018-09-01	Waterloo	S+G	S+G	S+G	S+G	GW	GW	GW
GPH Permafrost	623042	7214646	2018-09-01	Waterloo				X			
GPH	622986	7214593	2018-09-01	Waterloo	S+G	S+G	S+G	S+G	GW	GW	S+G
SL Seep	616730	7207723	2018-09-01	Waterloo	SW	SW	SW	SW		SW	SW
SL SW	616771	7207695	2018-09-01	Waterloo	SW	SW	SW	SW		SW	SW
H001B	625708	7216727	2018-09-01	Waterloo				GW			
MW4	625505	7216597	2018-09-02	Waterloo	GW	GW		GW	GW	GW	
MW4 Pad	625506	7216555	2018-09-02	Waterloo				SW			
MW4 Forest	625475	7216523	2018-09-02	Waterloo				SW			
MW4 Culvert	625513	7216529	2018-09-02	Waterloo				SW			
H & W	Both Husky and Waterloo present during sampling										
SW	Samples obtained from Surface water only (by Husky or Waterloo)										
GW	Samples obtained from shallow groundwater only (by Waterloo)										
SG	Samples obtained from both SW and GW (by Husky or Waterloo)										
X	Obtained from permafrost										
Blank	Not obtained										

Initial evaluation of the geochemical and isotopic data has been completed and available data are presented in Figures 2 and 3. These data are now being combined with the historical data collected by

Husky to establish trends and to assess groundwater and surface water interaction processes within the study site.

During the month of February, 2019, Husky personnel and their consultants completed the full decommissioning of the groundwater monitoring wells and the petroleum test wells that had been installed on the Slater River Lease to assess the shale oil and gas reserves. During this decommissioning process, the groundwater wells were thawed and pumped for an extended period to ensure they were functioning properly and to collect samples of groundwater from deeper in the subsurface. Samples were collected from the wells when they were first installed in 2013 and the water samples were analyzed for a full suite of compounds including some isotopes. A consulting team arranged by Husky (Waterline) also collected additional samples for analysis of the species listed in Table 1. Husky and their consultants revisited some of the summer sampling locations in order to collect samples beneath the ice for additional analysis. These included the same analyses as in summer 2019 but now also included ¹³C isotopes in DIC. As each location was iced over, an ice-auger was used to access water below and collect samples. For the summary of what was collected see Table 3.

Table 3: Summary of Winter 2019 sampling, site locations and samples collected.

Site	Easting	Northing	Date	Present	Major Ions	Metals	Organic Analytes	18O & 2H	3H	87Sr	13C in CH4	13C in DIC
MW-09A	617224	7209124	2019-02-05	Waterline+ Husky	GW	GW	GW	GW	GW	GW	GW	GW
MW-09B	617205	7209104	2019-02-08	Waterline+ Husky	GW	GW	GW	GW	GW	GW	GW	GW
H001B	625717	7216677	2019-02-10	Waterline+ Husky	SW	SW	SW	SW	SW	SW	SW	SW
H040	623438	7214579	2019-02-10	Waterline+ Husky	SW	SW	SW	SW	SW	SW	SW	SW
H046	619282	7211017	2019-02-10	Waterline+ Husky	SW	SW	SW	SW	SW	SW	SW	SW
SW	Samples obtained from surface water, under ice.											
GW	Samples obtained from groundwater, in well.											

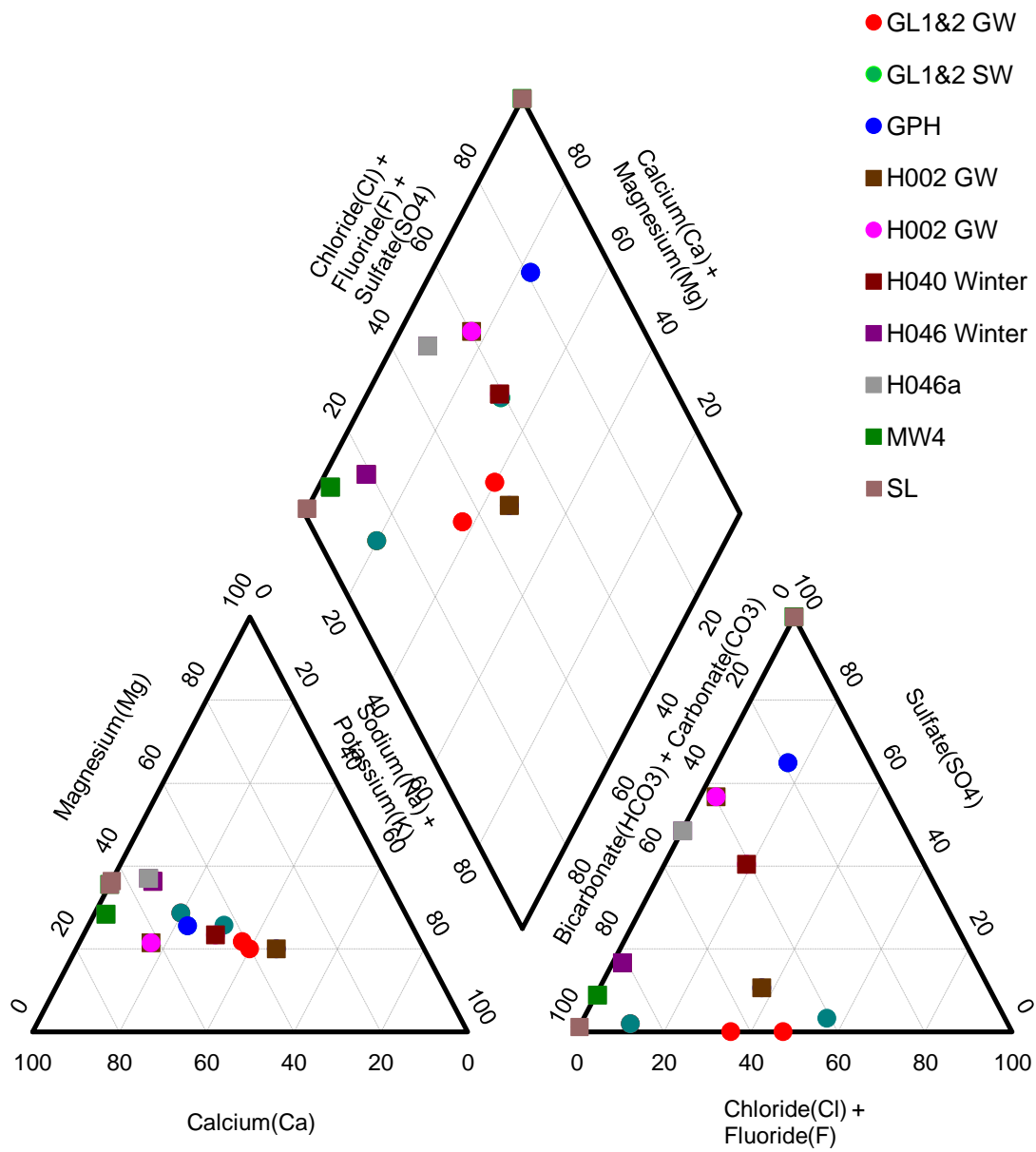


Figure 2: Preliminary geochemistry from various sampling locations sites plotted on a Piper diagram.

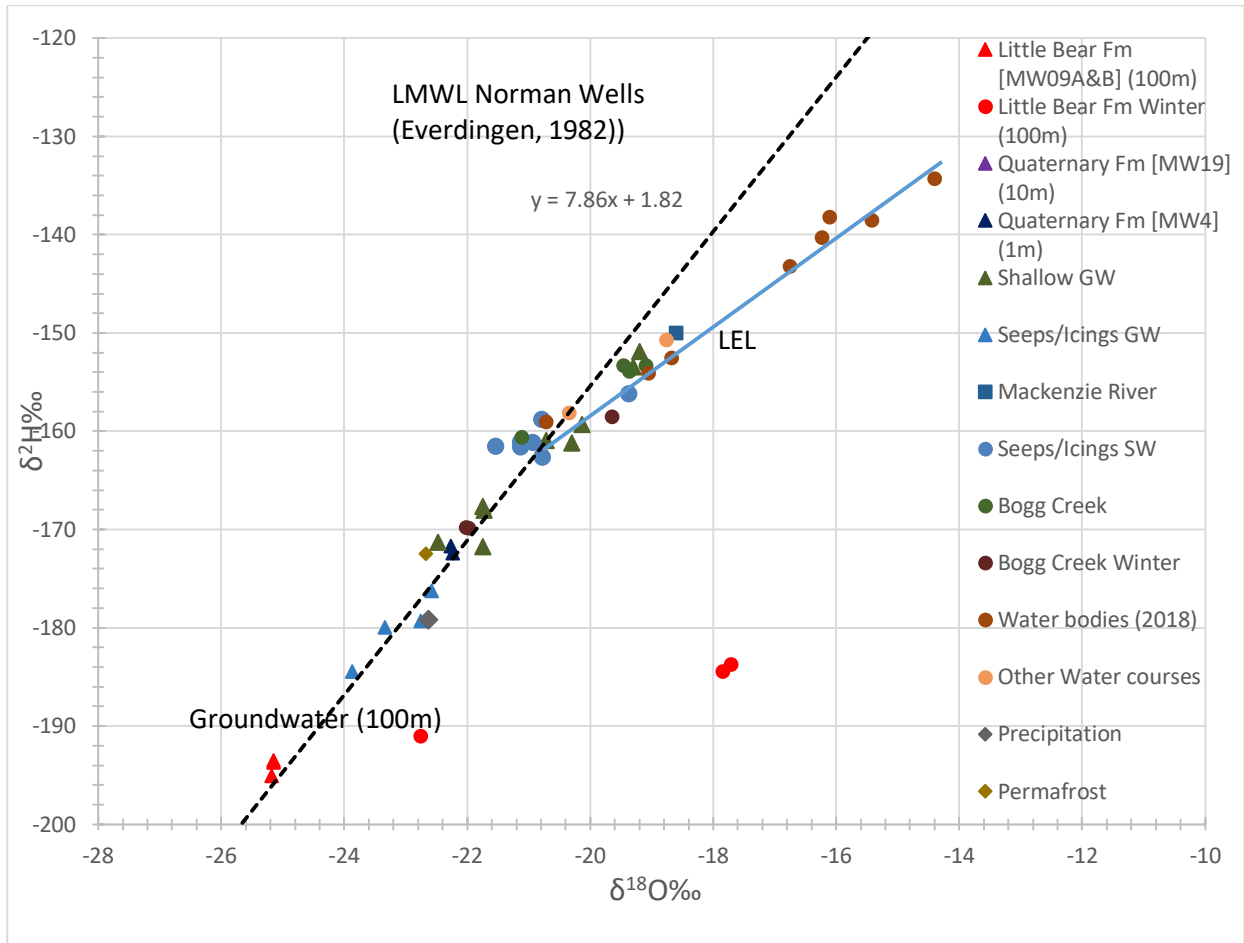


Figure 3: ^{18}O and ^2H plotted next to the Local Meteoric Water Line (LMWL) for Norman Wells.

Seep and icing shallow groundwater appear the most isotopically negative, suggesting a colder source of water (such as snowmelt or water recharged in past climate) while many open waterbodies experience evaporation, plotting along the Local Evaporative Line (LEL).

Additional insight can be obtained from the geochemical data by examining cross plots of several key species as shown in Figure 4.

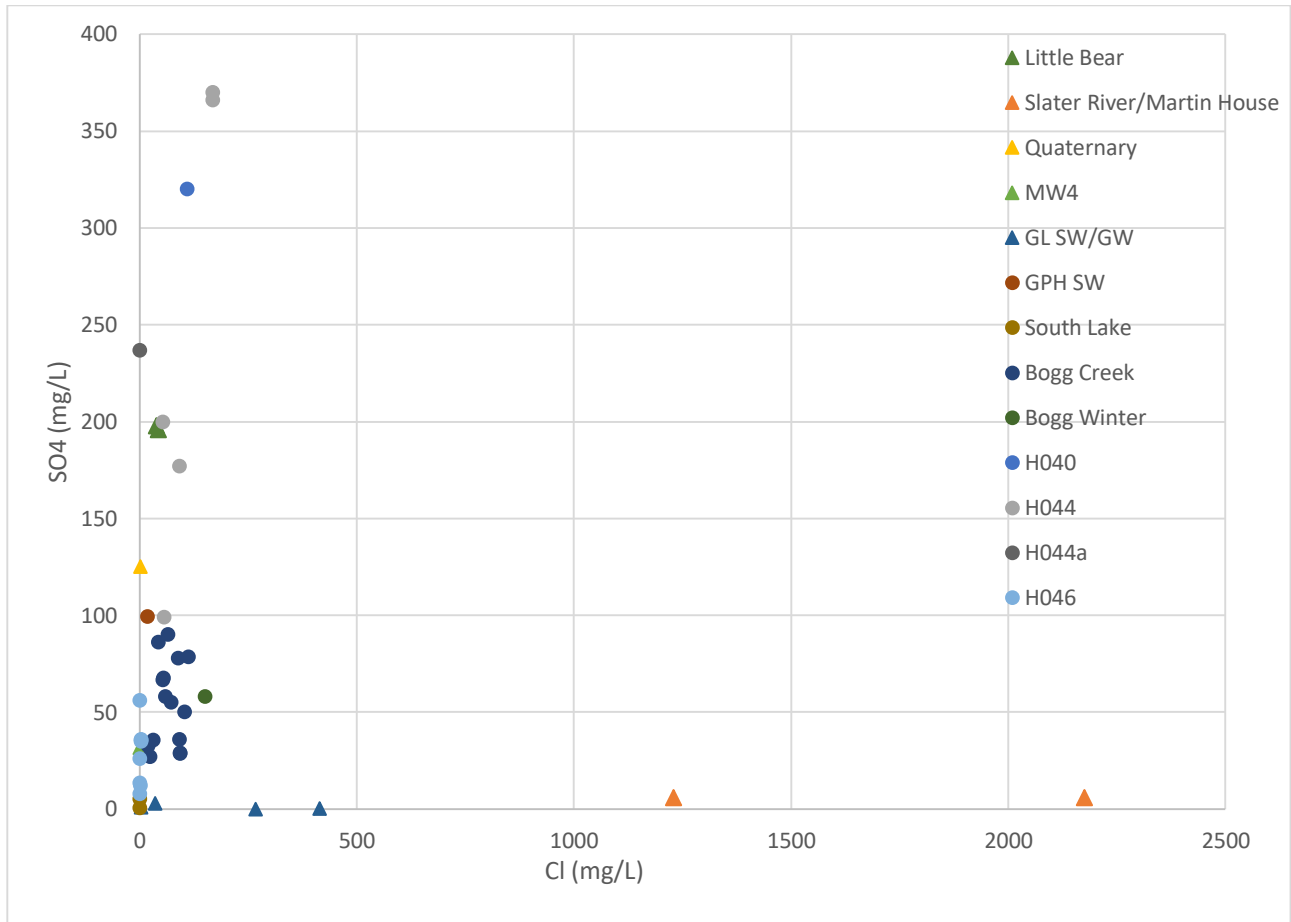


Figure 4: Chloride and Sulphate concentrations for selected sites along Bogg Creek and its tributaries, several lakes, and groundwater from Husky's monitoring wells and from summer data collection.

Data in this watershed seem to plot close to either axis (High SO_4 low Cl or vice versa). Some data (several samples of H044 and GL) plot closer to some groundwater, suggesting a possible component of deeper groundwater origin (Little Bear and Slater River/Martin House respectively).

4). Low-elevation, helicopter-based IR and optical survey

A low-altitude aerial thermal infrared (TIR) survey was undertaken to provide insight with respect to groundwater discharges and groundwater-surface water (GW-SW) interactions occurring in the Bogg Creek watershed. TIR and other temperature-as-a-tracer methods use contrasts in GW and SW temperatures to detect and delineate springs, seeps, and GW fed sections of streams in a variety of environments. This investigation was a proof-of-concept survey to evaluate the usefulness of the technique in a permafrost region. A helicopter was used to obtain images from specific reaches of stream and lake shorelines to test the ability of the method to characterize the kinds of GW discharges that occur naturally or are likely to occur as a result of climate change and changes in land use. As the climate warms, the active zone will become thicker and increase GW-SW interactions and there is the potential that taliks and gaps in the permafrost will get larger and allow larger amounts of deeper GW to more easily reach the surface and SW. Specific objectives of this work were to:

- identify areas of both shallow and deep GW discharges to SW and be able to tell one from the other,
- determine if icing areas identified in satellite images (Glass, 2019) corresponded with observable GW discharge,
- select locations to perform geochemical sampling of GW and SW
- evaluate patterns of GW discharge to determine its relation to the geology and land use disturbances.

Low altitude (< 300 m) aerial surveys were flown in a helicopter along 9 traverses (T1 to T9) within Bogg Creek on August 28, 2018. The traverses were along: the main channel of Bogg Creek (T1 and T3), tributaries of Bogg Creek (T2, T8); at the edges of lakes (T4 to T6, T7, and near T9); along the headwaters of several streams (T9); where distinct changes in surficial geology occurred (T1 and T2, and T8); in areas of potential icings identified by Glass (2019) (T3, T4 to T6, and T8); and across roads and cut lines in the trees (previously used for geophysical exploration). Aerial and ground based TIR images were also collected opportunistically later in the week when flying to specific locations to collect water samples. At this time of year, air temperatures and SW temperatures would typically be higher than GW temperatures and so in the colder areas in the thermal images would likely be GW discharge from active zone flow or deep GW.

Thermal infrared images in this study were obtained using a hand held FLIR Model T650sc camera (FLIR Systems Inc.) and flying in an Airbus AS350B3 (Astar B3) helicopter piloted by Sahtu Helicopters. The camera measures infrared radiation in the 7.5 to 14 micrometer (μm) wavelength range and has an accuracy of $\pm 1^\circ\text{C}$ (or 1% of the reading) and a sensitivity of $< 0.02^\circ\text{C}$. TIR images were collected 75 m to 300 m above the ground surface resulting in pixel resolutions of 10s of centimeters or less which is superior to satellite image resolutions that are typically meters to 10s of m in size. Infrared video from the camera was captured using a Panasonic Model CF-31 Tough Book laptop computer and FLIR Tools+ software. Visual video was collected using a Sony HDR-PJ430V camera. Tracklogs of the surveys were obtained using a Thales Navigation MobileMapper CE GPS unit with sub-meter accuracy measuring locations every second. Atmospheric conditions (air temperature and humidity) were collected using a Kestrel Model 3500 Pocket Meter and used to correct for minor atmospheric effects. TIR images were processed using FLIR Tools+ and FLIR ResearchIR Max version 4.30 software (FLIR, Inc., 2018). Visual video was processed using Adobe Premiere Elements and plotting of data and tracklogs were performed using ArcGIS™ 10.5.1 software (ESRI, 2016)

The TIR videos and individual TIR frames were examined and interpreted to determine if there were thermal anomalies that were indicative of GW fed discharges or other notable conditions. Several types of thermal anomalies were identified by the TIR survey and the interpretation and analysis of the images is still ongoing. Overall, the TIR survey was successful in locating thermal anomalies that may be GW discharge and areas of active permafrost melting. During this survey the temperature conditions/contrasts were very good and allowed for the successful detection of anomalies. The air temperature was 15°C to 16°C , stream and lake temperatures were about 6°C to 11°C , and ground water temperatures were presumed to be about 2°C to 5°C or near freezing if in contact with permafrost. However, the hydrological conditions during the survey were not ideal and may have limited the ability to find GW discharges. According to Husky Oil personnel, water levels in the lakes and

Bogg Creek were unusually high for this time of year and shoreline beaches and vegetation were inundated or flooded, which potentially means GW discharges were either obscured or reversal of hydraulic gradients may have temporarily stopped them.

The TIR survey was able to identify streams, lakes, and wet areas in a variety of settings. Not all wet areas are necessarily indicative of local GW discharge and so the images were examined to find areas that were significantly cooler where GW is discharging in larger amounts. The following types of anomalies were observed during the survey:

1. small localized areas of cool or cold water onshore near streams that are likely seeps or springs (Figure 5),
2. very small tributaries or drainage swales filled with cooler GW or active zone water discharge that flows into streams and lakes,
3. larger tributaries with poorly defined channels that flow into lakes and result in areas of cooler areas of SW adjacent to and within the lake (i.e., SW thermal plumes) (Figure 6),
4. drainage swales paralleling the winter road or cut lines in the forests collecting GW discharge,
5. springs or seeps in specific locations identified by Glass (2019) as potential icings (Figure 7),
6. cooler curvilinear features onshore that may be the boundaries between permafrost and non-permafrost terrain (e.g., at small breaks in slope where active melting may be occurring),
7. linear features that may represent water filled paths created by animals.

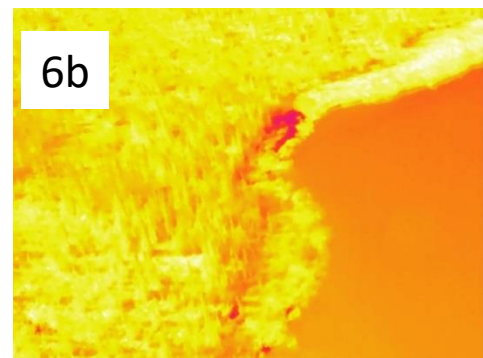
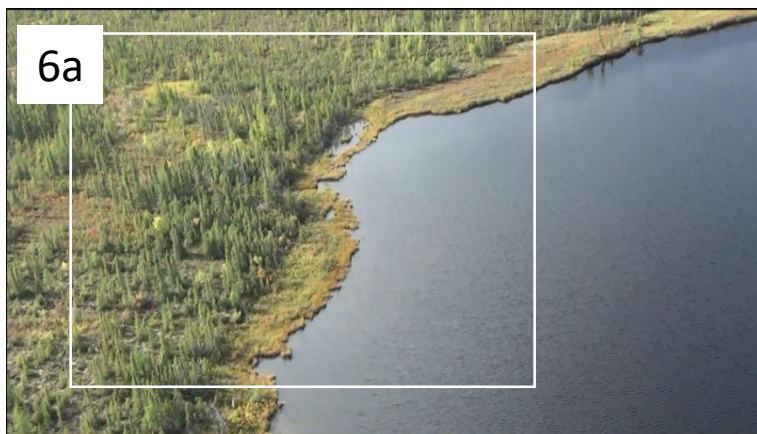
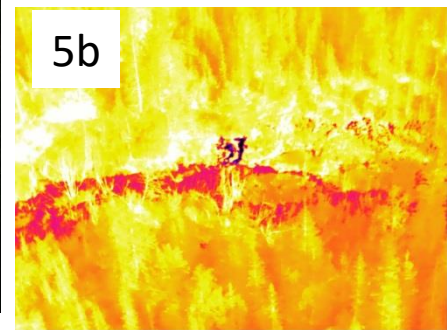
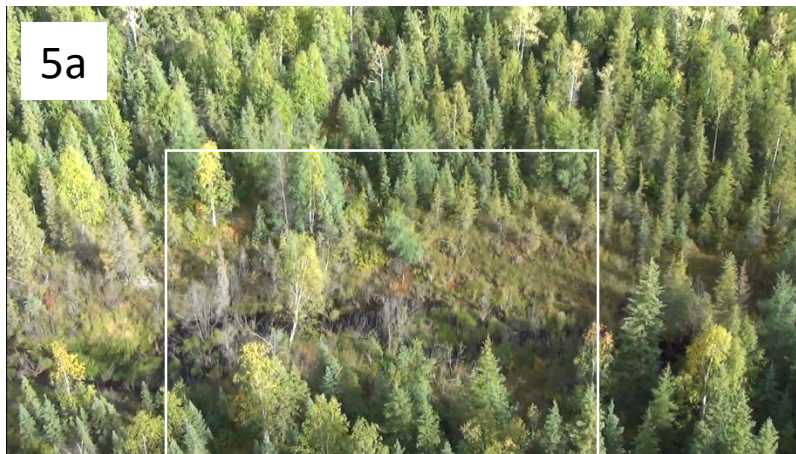
A preliminary review of the data indicates that springs and seeps were present in areas identified by Glass (2019) as icings and could be the source of those icings. Geochemical sampling of surface water and GW at thermal anomalies identified by the TIR survey confirmed the discharge of shallow and potentially deep GW. Temperature measurements alone were not able to distinguish shallow GW discharge from deeper GW discharge during this study. GW discharge appeared to be occurring in swales along some (but not all) sections of the winter road or in association with cutlines. Some of the coldest GW discharge did appear to occur at cut lines suggesting active melting of permafrost. TIR images appeared to be able to indicate active melting of permafrost around one thermoskarst depression and long a stream in other locations.

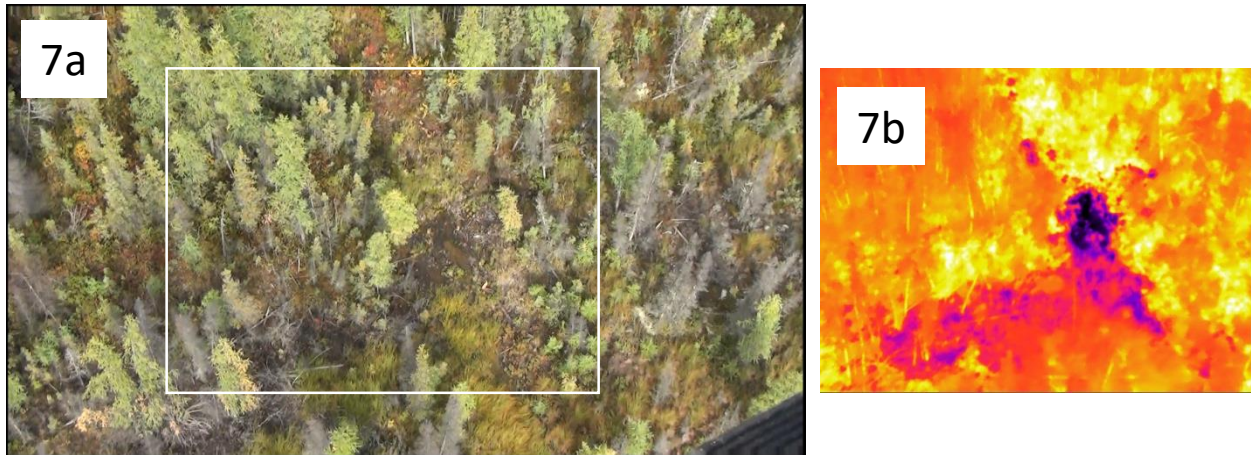
The main advantage of the TIR method is its ability to detect localized GW discharges and anomalies that cannot be identified in visual images. Many parts of the landscape appear to be relatively uniform with respect to vegetation, topography, and amount of water present, yet the TIR shows they are not uniform with respect to GW discharge. TIR can be used in real time to target specific locations for further investigations (e.g., land based visual and TIR observations, geochemical and isotopic sampling of waters). It is also a non-invasive method of investigating many kilometers of stream and lake shore in only a few hours.

There are notable limitations and disadvantages of this method. Despite using a helicopter, the amount of tree cover meant it was not possible to see or evaluate the streambanks or ground in certain areas. It should be noted that TIR can only measure temperatures at the surface of the material or water (i.e., not at the bottom of a water body) so discharges beneath SW bodies may not be detected unless they are large enough to reach the surface of the water. Timing of TIR surveys is important and must be done

at specific times to ensure success. Also the filming at oblique angles from the helicopter means the onboard GPS does not provide the exact coordinates of the thermal anomalies seen in the images so significant post processing time is needed to manually obtain locations.

The TIR survey proved to be very valuable method for identifying and inferring GW discharges in this type of terrain. The method appeared to confirm GW discharges in some locations identified in satellite images as having icings. The technique also meant strategic sampling of GW and SW could be performed to test hypotheses regarding deep or shallow sources of the water. In some instances, it was also possible to infer locations of active melting of permafrost adjacent to SW bodies.





Figures 5, 6 and 7: Pairs of visual and thermal infrared images showing colder areas as black and purple and warmest locations as white and yellow. Figure 1 shows stream with localized groundwater discharge (spring or seep) on far bank. Figure 2 shows areas along a lakeshore where small groundwater fed tributaries or groundwater seeps result in areas of cooler water. Figure 3 is a spring or seep on a cut line where an icing was identified by Glass (2019) using satellite images.

5). Integrate remote sensing surveys with terrestrial based measurements

During the initial investigation of the field site using available remote sensing data, multispectral and thermal band datasets obtained from Landsat-5/8 imagery were collected over the field site and interpreted to identify the spatial and temporal occurrence of icings within the study area. The icings may indicate groundwater seepage and this information will inform subsequent field mapping and monitoring locations. For this initial mapping exercise, three Landsat images (late spring, late winter and summer) were compiled for each of three target years (2004, 2009, and 2016). These results were previously presented to ESRB in a separate report on the Year 1 activities. As part of the follow up investigations during Year 2, Landsat 4-5 TM and RapidEye-3 datasets were used to further identify evidence of groundwater discharge zones within the Bogg Creek watershed.

Following the works of Morse and Wolfe (2015), a series of image algorithms were applied to imagery for the entire Central Mackenzie Valley, and for the Bogg Creek Watershed (a sub watershed of the CMV) for selected years between 2004 and 2017. The algorithm series extracted 'icings' from the images. Icings (also called aufeis) are surface ice lenses formed where groundwater discharges in the winter months, then freezes. Icings were statistically examined for all of the selected years to determine whether a significant difference in their occurrence and size existed (Figure 8).

It was concluded that there was a significant difference in the spatial distribution of icings from year to year, but that there were several places where icings were recurring (Figure 9). During a field visit in August of 2018, high resolution thermal imagery was captured for several of these locations and it was found that groundwater was also discharging in the summer. This provides strong evidence to suggest that the recurring icings represent springs from which groundwater discharges year-round. These springs represent ideal locations to monitor the quality of discharging groundwater. Furthermore, identifying these monitoring points remotely is expected to have drastically reduced the field efforts

that would have been required to find them in situ. This work demonstrates the value of remote geophysical methods for hydrogeological applications, particularly in areas that have limited accessibility. Following these results, several important conclusions regarding icing occurrence were made:

- i. The amount of winter groundwater discharging in this region is stable from year to year, even though the spatial distribution of icings is not.
- ii. Ground and spring icings may not function in the same way across all regions; that is to say that ground icings may still discharge water late in the winter, and spring icings may undergo periods of little or no discharge.
- iii. Due to variability in the distribution of recurring icings within thermal anomalies, and the large overall proportion of icings in weak anomalies for all years, coarse resolution thermal data should not be used to definitively distinguish ground and spring type icings. It should be used only to make suggestions as to the mechanisms governing their formation.
- iv. Priority icing/groundwater discharge monitoring locations were established for the Bogg Creek watershed in a region which is classified as a fen. The icings in this region are annually recurrent and are likely sourced from shallow springs. Several of these icing locations were verified using a high-resolution thermal camera.

This work demonstrated a completely remote method of identifying groundwater discharge zones. Moving forward, monitoring the icing distribution in this region with even higher resolution imagery would be of great value. Exploring a combination of remote and in-situ methods of resolving the source of the groundwater forming the icings depicted in this work would assist in the overall understanding of the hydrologic regime. Additionally, monitoring selected icings and their growth throughout the winter season would allow for the establishment of growth coefficients that could more precisely estimate the volume of water which reaches the ground surface during winter.

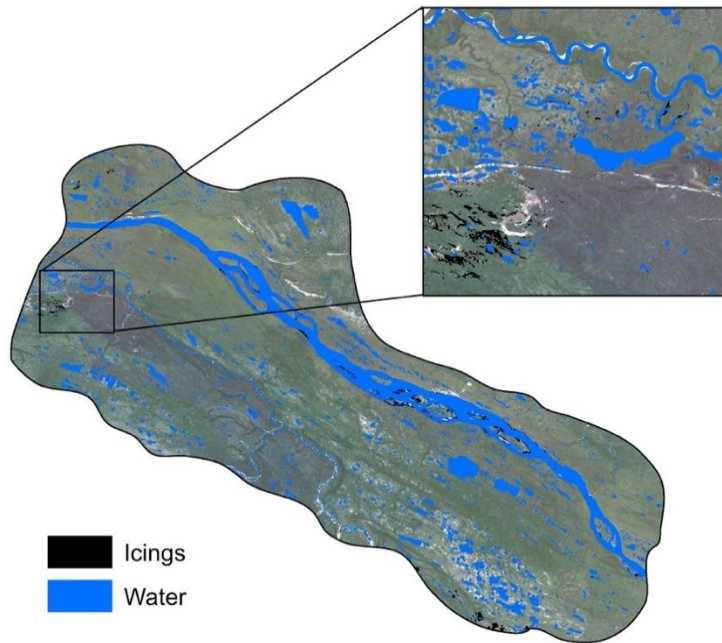


Figure 8: Example of the final icing result, shown for 2016, over a Landsat 5 Natural Color Composite. Selected subset shows a zoomed in view of the icing distribution.

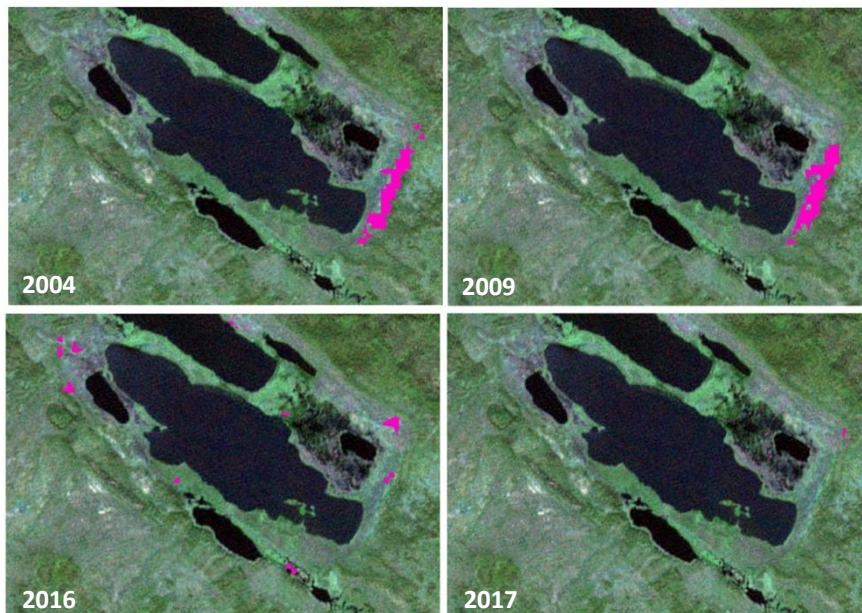


Figure 9: Progression of the Bogg Creek Icing Complex from 2004-2017 (icings shown in pink).

6). Terrestrial geophysical mapping of permafrost occurrence

The hydrologic cycle related to both surface and subsurface water flow is highly influenced by the occurrence and continuity of permafrost. In developing a baseline monitoring plan, understanding the role of permafrost in controlling groundwater-surface water interactions is critical. One method that has proven effective at mapping the presence of permafrost in the shallow environment is 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. In order to assess the utility of these two geophysical methods at mapping permafrost continuity at the field site, several different sites were selected within the Bogg Creek watershed where it was anticipated that there would be a significant variation in permafrost depth that would be a useful target to test the different methods.

The sites were chosen beneath or near landscape features that were anticipated to influence permafrost occurrence; a recently cleared forested setting (7 years) and the shoreline of a relatively large lake. It was anticipated that permafrost would be significantly deeper beneath the open clearing (Site 1, Figure 10) than in the adjacent natural woods and that it would also be much deeper near the shore of the lake than at greater distance from the shore (Site 2, Figure 10).

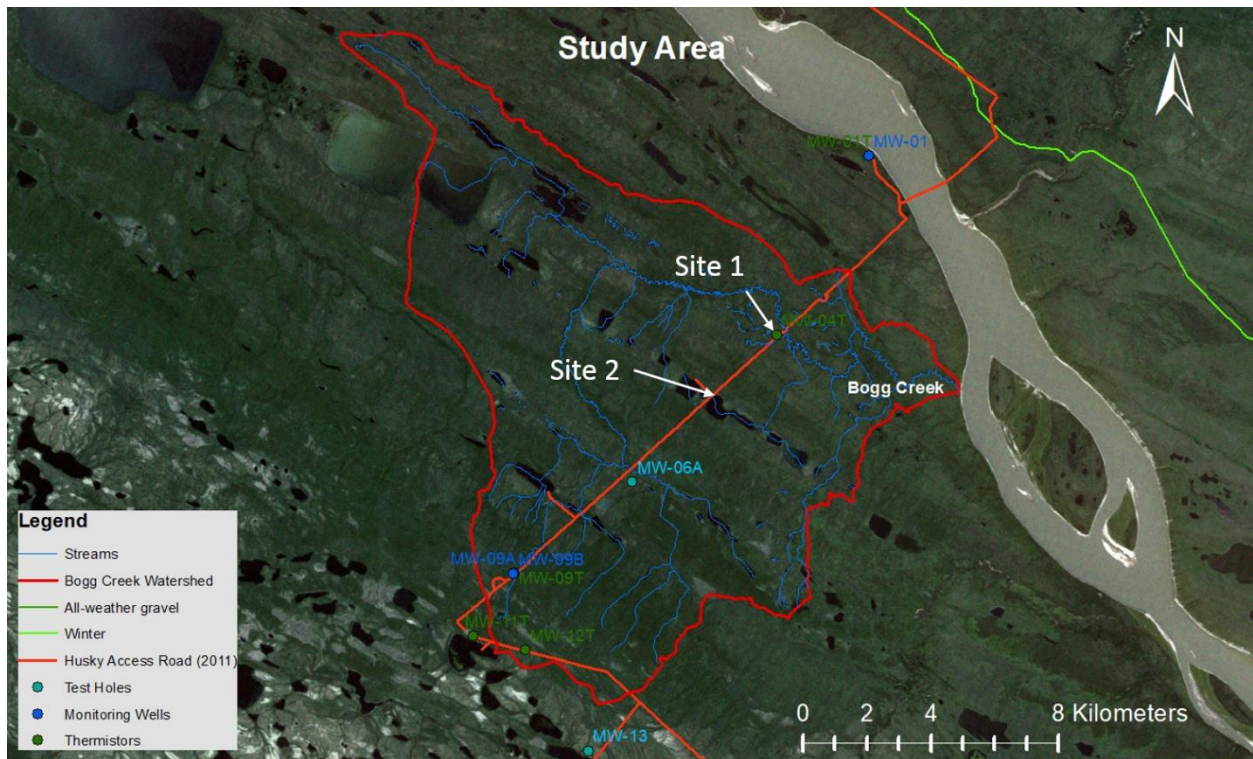


Figure 10: Field locations of ERT and EM geophysical surveys within the Bogg Creek watershed.

At both of the sites, manual measurements of permafrost depth made along the survey lines with a handheld, steel permafrost probe. The results of the soundings are shown in Figure 11 and a clear deepening of the permafrost table was detected near the edge of the clearing (Lines 1 and 2) and at the shore line of the lake (Line 4) as anticipated.

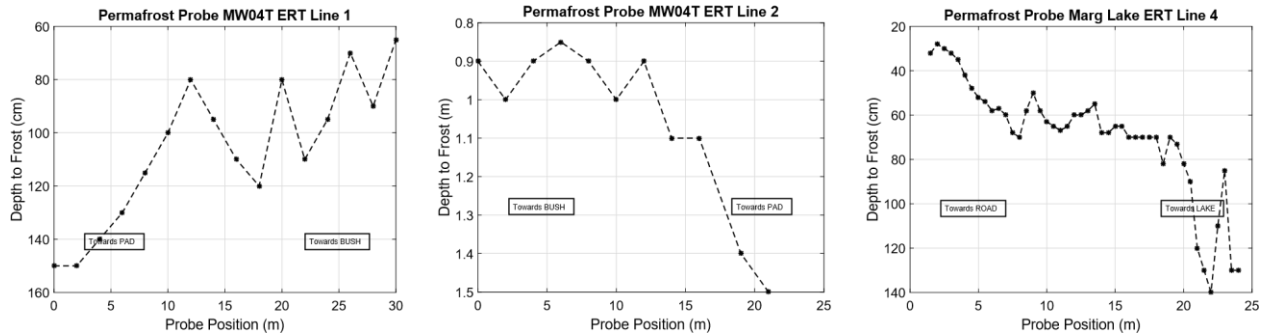


Figure 11: Permafrost probe measurements made on the survey lines at Site 1 (Lines 1 and 2) and Site 2 (Line 4).

Survey lines were established at each of the field sites and several electrode and coil spacings were tested along the same survey lines. Data from several of the ERT surveys lines (50 cm and 75 cm electrode spacings) are presented in Figure 12. The system used for this investigation is the Iris Systems Syscal™ Junior 48. As expected, the ERT method was able to clearly delineate changes in permafrost depth and continuity in the shallow subsurface. The geophysical profiles closely match the trend of the manual measurements of permafrost depth made along the survey lines.

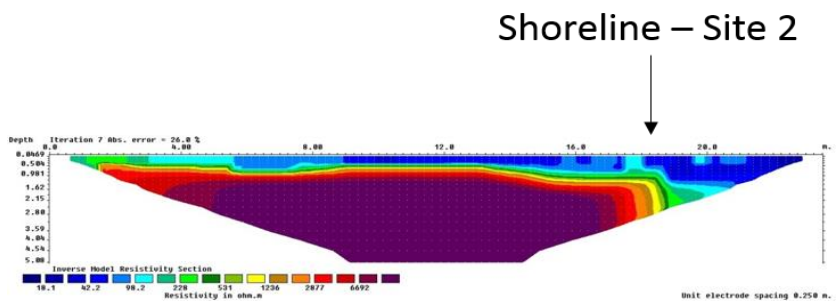
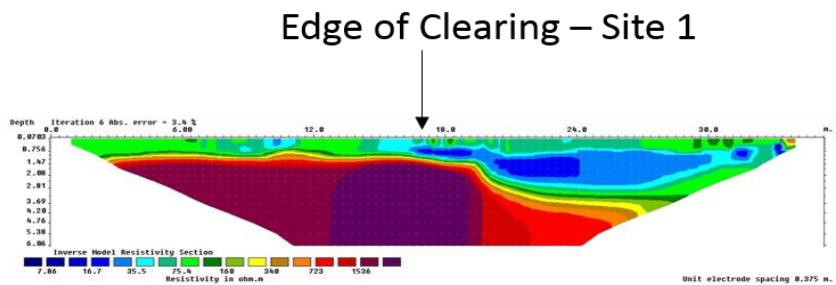
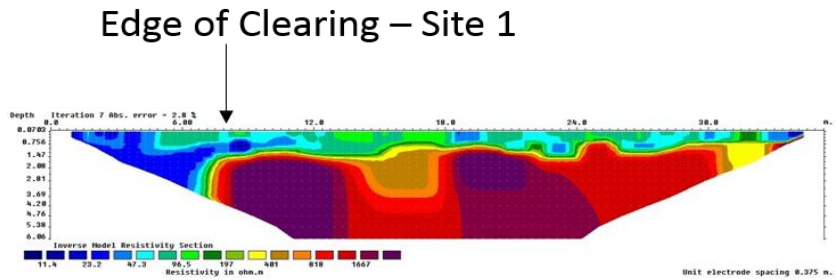


Figure 12: ERT profiles from clearing Site 1 and lake shore Site 2 indicating the position of the clearing edge and lake shore. Based on an electrode spacing of 75 cm was used for Lines 1 and 2 and 50 cm for line 4). Blue colors are associated with higher electrical conductivity likely indicative of liquid water and low ice content. The least-squares inversions were made using Res2DInv™.

The second method utilized along the same survey lines was the electromagnetic induction (EMI) method based on the frequency domain electromagnetic (FDEM) method (Geonics Limited EM-34-3™ and EM-31™). This method consists of a transmitter and receiver coil, whereby the transmitter generates a primary electromagnetic field, that interacts with the subsurface materials. 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. 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, as seen in Figure 12 above. Both methods are manually carried along the survey lines.

The results of the EMI surveys using both the horizontal and vertical dipole configuration are presented in Figure 13 again for Lines 1, 2 and 4. As with the ERT method, the EMI approach also clearly detects

the change in depth of the permafrost table at each of the sites. Although the resulting information is perhaps not as comprehensive as is available with the ERT method because of the 2-dimensional nature of the ERT results. 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. Further investigation of the applicability of this method will be undertaken in the next stage of the work.

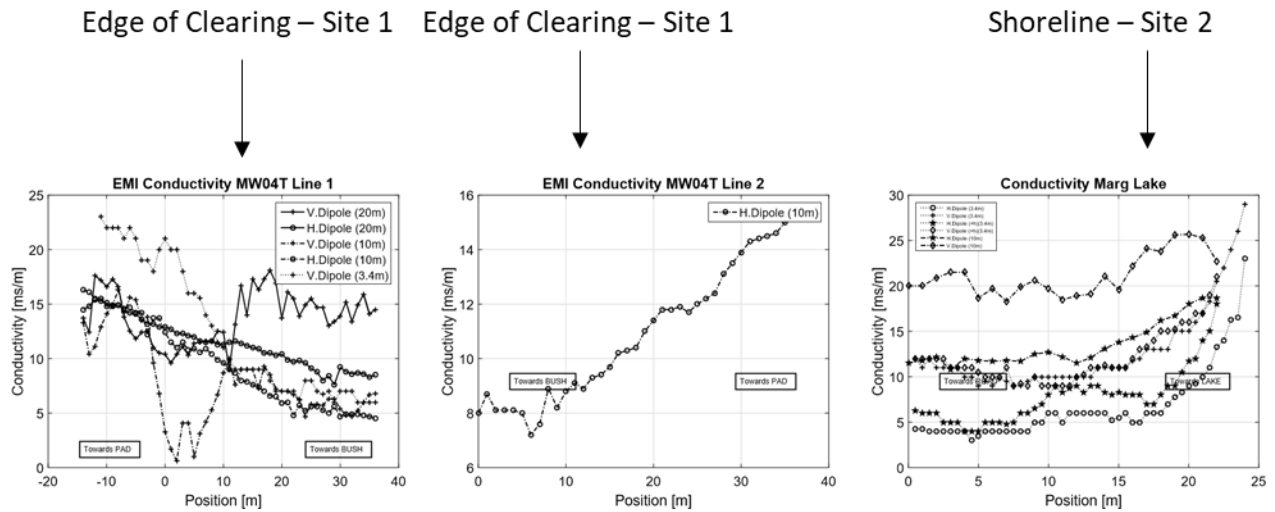


Figure 13: EMI data collected with the EM31 (10 m and 20 m coil separation) and EM 34 (3.4 m coil separation) along survey Lines 1, 2 and 4 (noted as Marg Lake).

The combined results of the terrestrial geophysical surveys illustrate that the results gathered from the permafrost probe, ERT and EMI methods are in agreement and that these portable survey methods provide multiple lines of evidence of permafrost continuity in this remote setting without the necessity for more costly, intrusive methods such as drilling for core collection or the installation and monitoring of vertical thermister strings to directly measure changes in subsurface temperature.

6). Proposed Year 3 work plan

During Year 3 of the project all of the historical and newly collected data will be collated and integrated for more in depth analysis, a follow-up field monitoring campaign will be designed for the summer of 2019 and initial numerical modeling work will be completed focused on groundwater and surface water dynamics within the Bogg Creek watershed area. Specific planned activities include:

- 1). Detailed assessment of the inorganic and organic geochemical data collected from the surface water and groundwater monitoring site within the study area in order to determine specific trends associated with origin and flow of surface and groundwater will be completed. The historical data collected by Husky since the start of their work on the Slater River Lease will be combined with the newly collected data and a field campaign to collect additional water quality data, perhaps including additional species of interest will be developed.

- 2). The potential to survey the Bogg Creek area with an airborne EMI survey method from a helicopter platform will also be explored with several different options being available. This would provide the opportunity to map permafrost continuity over a large area, which would then be calibrated with specific data collected on the ground in a form of ground-truthing.
- 3). Following the success of the IR and optical surveys on the site, it is proposed that there may be an opportunity to fly drone-based sensors over parts of the study site using hyperspectral sensors combined with IR and optical to complete more detailed and cost-effective mapping of this remote terrain with respect to groundwater and surface water phenomena.
- 4). Currently the modeling team is assessing the appropriate numerical tools that can be applied to the area to model and develop predictive simulations of water movement within the discontinuous permafrost terrain with the objective of extending our understanding of the hydrologic dynamics within this complex terrain. Initial modeling exercises will be undertaken in the Year 3 timeframe.

8). References (many of these were used during the course of the study but not specifically referenced in the text and are included here for completeness.)

AMEC Environment & Infrastructure (2014). Central Mackenzie Valley Subsurface Groundwater Baseline Study. Submitted to the Northwest Territories Geoscience Office, Government of the Northwest Territories.

Côté, M. M., Duchesne, C., Wright, J. F., & Ednie, M. (2013). Digital compilation of the surficial sediments of the Mackenzie Valley corridor, Yukon Coastal Plain, and the Tuktoyaktuk Peninsula. <https://doi.org/10.4095/292494>

Fallas, K. M., & MacNaughton, R. B. (2014). Geology, Carcajou Canyon (southeast), Northwest Territories. *Geological Survey of Canada, Canadian Geoscience Map*, (96), 127. <https://doi.org/10.4095/292288>

Fallas, K. M., MacNaughton, R. B., Maclean, B. C., & Hadlari, T. (2013). Geology, Norman Wells (southwest), Northwest Territories. *Geological Survey of Canada, Canadian Geoscience Map*, 101, 292293. <https://doi.org/10.4095/292293>

Glass, B. (2018). Examining Hydrogeological Processes in Freezing Soils using Remote Geophysical and Numerical Techniques, MSc thesis, University of Waterloo.

Morse, P. D., & Wolfe, S. A. (2015). Geological and meteorological controls on icing (aufeis) dynamics (1985 to 2014) in subarctic Canada. *Journal of Geophysical Research F: Earth Surface*, 120(9), 1670–1686. <https://doi.org/10.1002/2015JF003534>

Raska, N. (2017). 3D geologic subsurface modeling within the Mackenzie Plain , Northwest Territories , Canada, (65).

Smith, I. R. (2010). Seismic shothole drillers log records : A wealth of new permafrost-related geoscience information , Northwest Territories and northern Yukon , Canada. *63rd Canadian Geotechnical Conference & 6th Canadian Permafrost Conference*, 1450–1457.

Smith, I. R. (2015). Seismic shothole drillers' lithostratigraphic logs: Unearthing a wealth of regional geoscience information in northwestern Canada. *GeoResJ*, 6, 21–29.
<https://doi.org/10.1016/j.grj.2015.01.005>

Waterline Resources Inc. (2013a). 2013 Shallow Environmental Investigation Slater River Project Near Norman Wells, Northwest Territories.

Waterline Resources Inc. (2013b). Slater River Project Groundwater Investigation Program 2013 Winter Mud-Rotary Drilling Summary Report.

Waterline Resources Inc. (2013c). Slater River Project Groundwater Investigation Program Waters Act License Application Support Document.

APPENDIX 1

Tulí t'a for the Nę K'ə Dene Ts'ı́ ı́ (Living on the Land) Forum

Northern Water Futures (NWF) researchers, Jennifer Baltzer, Dave Rudolph, Kelly Skinner, Anna Coles, Mylene Ratelle and PhD student Carolyn Gibson travelled to the community of Tulí t'a for the Nę K'ə

Dene Ts'ı́ı̄ (Living on the Land) Forum, a workshop aimed at connecting communities within the Sahtú region with researchers to discuss research priorities in the region and for researchers to provide updates from existing projects. The Dene people of the Sahtú region have expressed deep concern about the impacts of climate change on their lands and waters. Over centuries, the Dene people of the Sahtú have developed skills and knowledge for living successfully and sustainably on the land. One of the major goals of the Nę́ K'á Dene Ts'ı́ı̄ Forum is to ensure co-development of research in the region and support the incorporation of both western and traditional knowledge into research planning, thereby ensuring that researchers and community members work side by side. The Forum was developed using a decolonizing approach where traditional knowledge and western science are combined to ensure that community members are actively engaged in the research decision-making process. This approach was exemplified throughout the workshop with the sharing of both types of knowledge and even a co-presentation on groundwater by NWF researcher Dave Rudolph and Leon Andrew, an elder from Tulı́ t'a. NWF researchers are initiating new research activities in the Sahtú region in the coming summer and Nę́ K'á Dene Ts'ı́ı̄ Forum workshop provided an ideal opportunity to develop these plans with the community.

Over the three-day workshop, researchers listened to stories about landscape change and its effects on ecosystems, livelihoods and safety. Through the Forum, the researchers gained a better understanding of the region and the effects climate-warming driven landscape change as experienced by the community. The researchers heard concerns about the impacts of wildfires on vital boreal caribou (tqdzı) habitat, the impact of warming water on fish populations, and how permafrost thaw changing how much water is on the land. There was concern about how fire impacts the frozen ground below it with stories of slumping hillslopes and riverbanks following fire. Community members have observed decreasing lake and river water levels. Changes are happening fast in the Sahtú and community members want to have a better understanding of what their lands will look like in the future; data from this region is sparse making such predictions very difficult.

The need to work together to understand changes happening on the land was emphasized. The meeting involved both elders and youth and discussions revolved around two main priorities for community involvement in NWF research: 1) Working with elders to incorporate knowledge of changes on the land into sampling design; and 2) Building research capacity in the youth through direct involvement in sampling, support for on-the-land training and bringing research into the classroom.

The Nę́ K'á Dene Ts'ı́ı̄ Forum provided an excellent opportunity for dialogue between researchers and community members to ensure that research generated in the region is of shared value. The information gathered at the forum will help researchers finalize their research plans for the coming summer and shape new research questions moving forward. NWF researchers are looking forward to continuing to collaborate with communities in Sahtú this summer.