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

Fifth Annual Report to:

NWT ESRF Management Board

By:

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1.0 Introduction

During the fifth year of the project, the limitations on field access related to the Covid-19 pandemic continued, which required a slight redirection of the work plans and research activities. Fortunately, with the assistance of our Government of the Northwest Territories (GNWT) collaborators and the leadership of the Sahtu Renewable Resource Board, Tulita Renewable Resources Council and the Norman Wells Renewable Resources Council, progress on the design and facilitation of a novel airborne geophysical survey was possible. The details of this survey and progress to date are included in this annual report.

In additional to the focus on the airborne geophysical survey, work was completed on the interpretation of the water chemistry and isotopic composition of surface and groundwater, which has identified different sources of water within the groundwater flow system. Extensive work was also completed on the development of new numerical modeling tools that are specifically designed to support the quantitative evaluation of key processes controlling permafrost thaw dynamics. This includes associated impacts related to land subsidence and solute mobility within the discontinuous permafrost environment of the Central Mackenzie Valley (CMV). The new modeling tools have now been published in peer reviewed journals and are being applied to the specific, data-supported conditions within the Bogg Creek watershed, which is the primary focus of the overall project. Over the course of this previous year, there have been a number of conference presentations made by the research group related to research results derived from this project. The complete list of the publications and relevant conference presentations is included in this report.

As noted in last year's annual report, Husky Energy was sold to Cenovus during the 2020-2021 fiscal year. In October, 2021, the research team met virtually with the Cenovus program management team to present an overview of the research work that has been conducted within the Slater River hydrocarbon lease area near Norman Wells. This visit was facilitated by Mr. Chris Salewich, who has been our main field contact with Husky Energy over the entire course of the project. Mr. Salewich continues to work with Cenovus and remains our main point of contact moving forward. The Cenovus officials confirmed that we would be able to maintain access to the field site, once Covid restrictions have been lifted, and they expressed interest in the current and future research activity within the Bogg Creek water shed region.

The project continues to benefit from technical, financial and in kind support from research colleagues at Wilfred Laurier University (WLU) and Cenovus. The financial and in kind support continues to be provided through our on-going participation in the Global Water Futures (GWF) program and specifically the Northern Water Futures project headed by Dr. Jenn Baltzer at WLU.

As in previous annual reports, progress on the Year 5 activities will be summarized in separate sections below. For the sake of this project report, representative examples of the data sets are provided for discussion and copies of the recent publications related to the work are available upon request.

2.0 Geochemical and Isotopic Characterization of Water Sources

Although there was no additional water sampling conducted within the 2021-2022 project year, significant advances were made in data interpretation and presentation of the results. For completeness, a diagram showing the water sampling sites, which is a combination of some of the sites originally surveyed by Husky Energy personnel and the new sites established by the University of Waterloo teams has been included for easy of referral. These sites are shown in Figure 1 relative to the Bogg Creek watershed boundary.

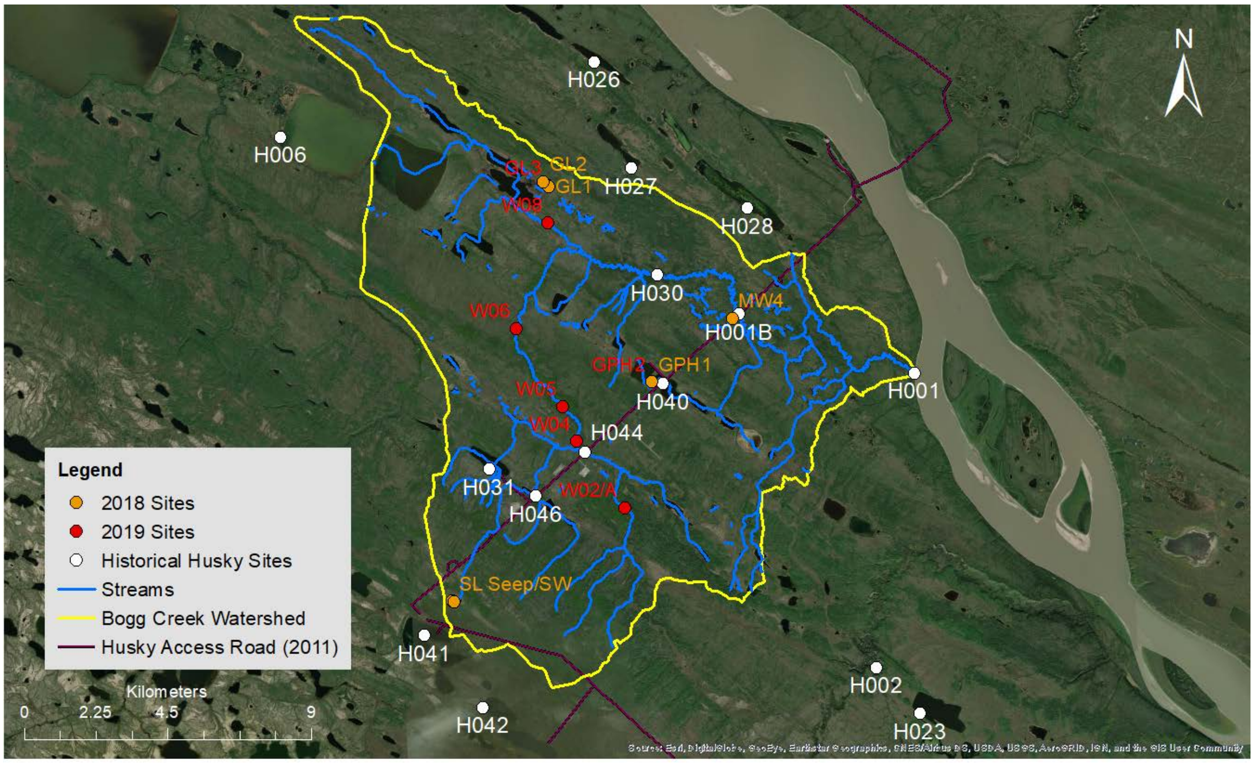

Figure 1: Regional map of sampling sites taken in the study area for each year. Satellite photos provided as part of the ArcGIS basemap feature.

A major focus of the water sampling and analysis campaigns has been to identify sources of water within the complex groundwater flow system typical of a discontinuous permafrost environment. The occurrence and continuity of the permafrost significantly influences water pathways and the interconnection of groundwater and surface water as illustrated in the conceptual diagram presented in Figure 2. Of importance in this conceptual model is distinct origins and discharge points of subsurface water and the flow pathways that groundwater will take before reaching the surface.

Insight into the nature of the water from various surface and subsurface sources can often be derived by examining the geochemical and environmental isotopic nature of the water samples collect throughout the integrated hydrologic system. Within the scope of the current project, water was collected on surface from lakes, streams, wetlands and springs and in the subsurface from shallow and deep monitoring wells. By combining the historical data originally collect by Husky personnel and the recent data collected by the UW team, some specific trends can be observed that assist in understanding the overall groundwater flow system and its interaction with the surface water bodies as shown in Figure 3.

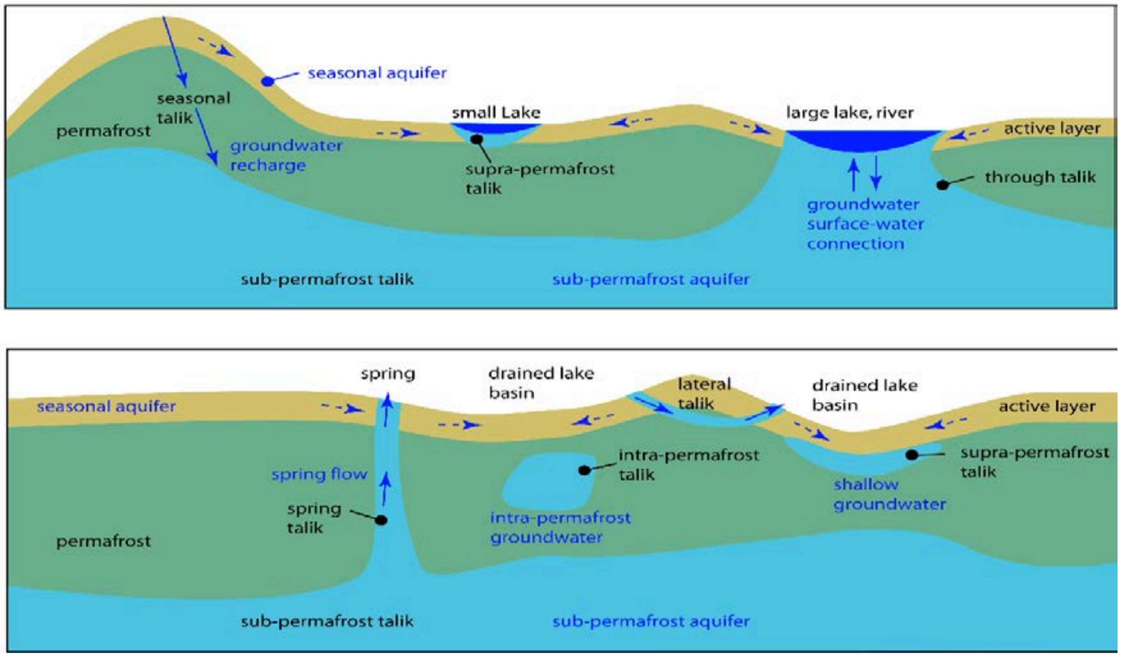

Figure 2. Complex groundwater circulation patterns within discontinuous permafrost environments. (from Scheidegger, J, 2013, after Sloan and Van Everdingen, 1988).

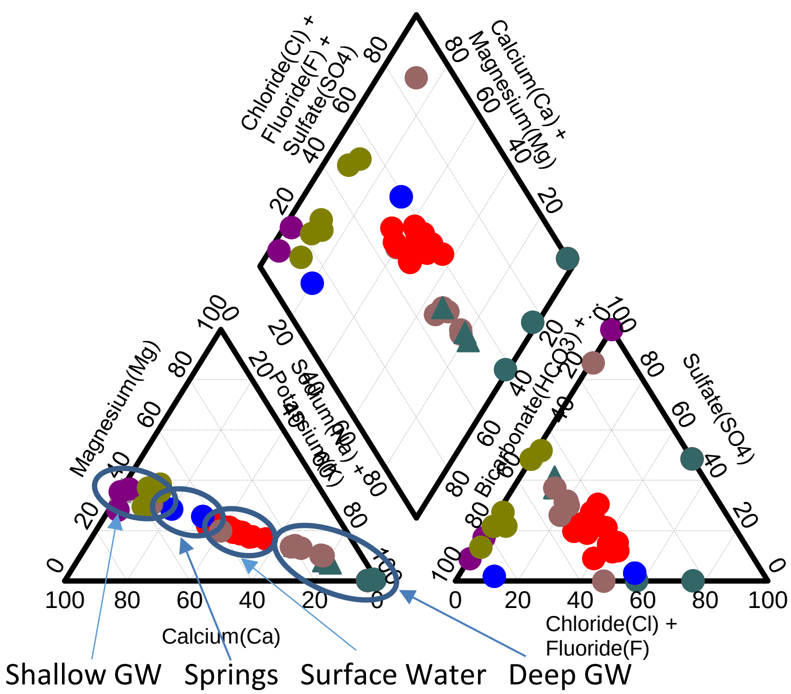

Figure 3. Geochemical signatures of surface water and groundwater sources illustrating the unique combination of dissolved solutes in the different water sources. (Wicke, 2021; Glass et al., 2020)

The samples collected from the deep groundwater flow system and the shallow groundwater environment are distinctly different and the surface water appears to be a mixture of the different groundwater sources. The springs on the other hand have a very unique geochemical signature that also suggests a combination of shallow and deep groundwater sources.

Further insight can be derived by examining the environmental isotopic signature of the combined water samples. These data are presented in Figure 4. Again, the deep groundwater source, springs and the surface water features all display very unique and identifiable isotopic compositions. The combination of the geochemical and isotopic characteristics of the water provides a method to detect the influence of the different groundwater sources on the surface water bodies and also provides one approach to identifying surface discharge of deep groundwater within the discontinuous permafrost system.

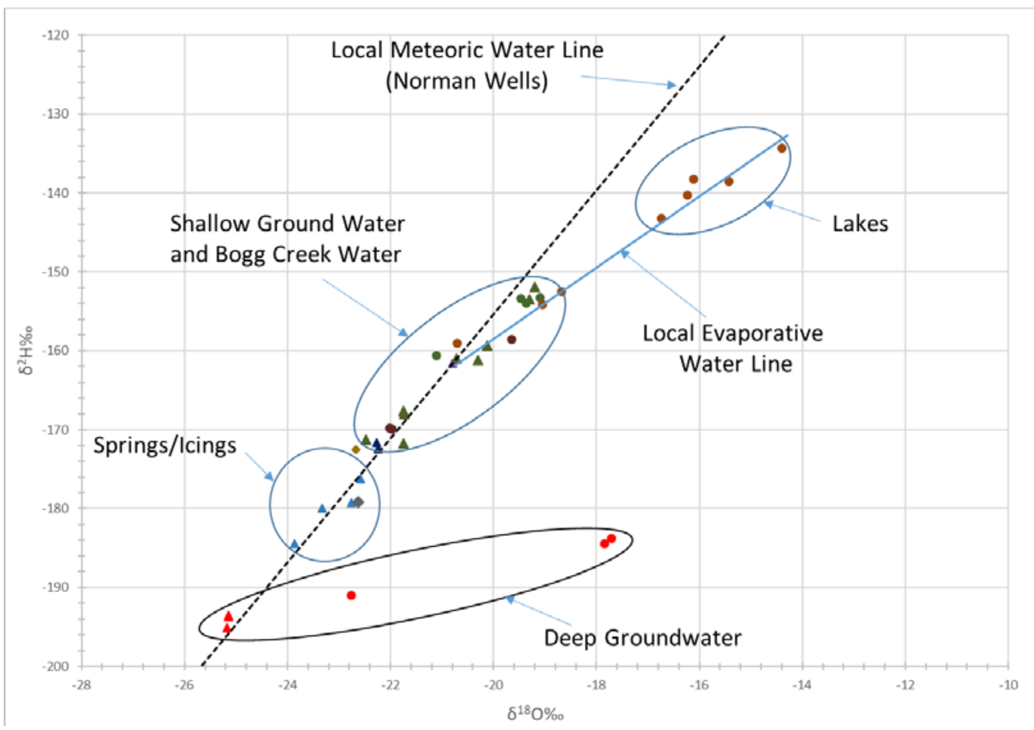

Figure 4. Environmental isotopic signatures of various water sources within the integrated hydrologic system. (Wicke, 2021; Glass et al., 2020)

One other aspect of the geochemical sampling relates to the analysis for natural hydrocarbon species. Table 1 contains some of the hydrocarbon data. There is clear evidence of dissolved natural hydrocarbons in the deep groundwater samples and evidence of toluene and methane in the surface waters and springs. Overall the concentrations were low in the near surface environment and some additional follow up monitoring would be valuable and planned for the next sampling campaign. Of specific interest, however, is the nature of the methane detected within the water samples. Through an examination of the isotopic composition of the methane, it is often possible to speculate to its origin as either being formed through near surface processes, often referred to as biogenic origin, or deeper in the subsurface often referred to as thermogenic. The isotopic composition of several of the methane samples is shown in Figure 5. There is evidence that the deep groundwater contains methane produced through natural hydrocarbon processes whereas the samples collected near the surface are predominantly derived through biologic activity in the shallow subsurface or surface water environments. This again is a useful tracer to help establish the potential for deep groundwater discharge contributing to surface waters. Additional sampling for hydrocarbons and analysis of the isotopic composition will be considered for a subsequent field sampling campaign, if that becomes a possibility.

Sample Type	Methane (mg/L)	Benzene (mg/L)	Ethyl-Benzene (mg/L)	Toluene (mg/L)	o-Xylene (mg/L)	m+p-Xylene (mg/L)	Xylenes (mg/L)
Creek	0.003	<0.00040	<0.00040	***0.00059***	<0.00040	<0.00080	<0.00089
Creek	2.100	<0.00040	<0.00040	***0.0013***	<0.00040	<0.00080	<0.00089
Creek	-	<0.00050	<0.00050	***0.00321***	<0.00050	<0.00050	<0.00071
Spring	***1.470***	<0.00050	<0.00050	***0.0142***	<0.00050	<0.00050	<0.00071
Spring	***1.930***	-	-	-	-	-	-
Spring	***0.802***	-	-	-	-	-	-
Bedrock Aquifer	<0.003	***0.00046***	<0.00040	***0.0017***	***0.00062***	***0.0014***	***0.0021***
Bedrock Aquifer	***0.006***	***0.00077***	***0.0005***	***0.0025***	***0.0012***	***0.0026***	***0.0038***
Bedrock Aquifer	<0.003	***0.00078***	***0.0005***	***0.0025***	***0.0012***	***0.0026***	***0.0038***

Table 1. Composition of selected hydrocarbon species in different water samples and sources. (Wicke, 2021).

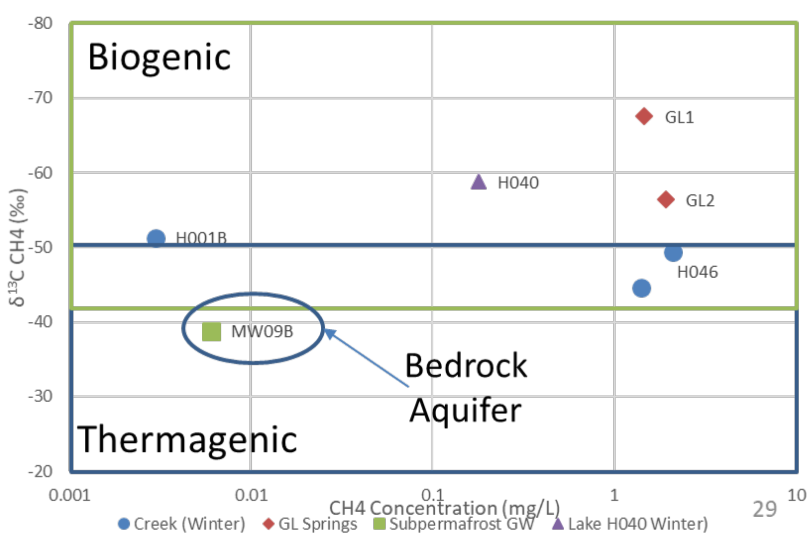

Figure 5. Isotopic composition of methane samples collected from groundwater and surface water sources. The classification of the carbon-13 composition provides an indication of the origin of the methane.

3.0 Development of modeling tools for freeze-thaw processes

Over the course of the last year of work the initial modeling tools based on a fully coupled thermal-hydraulic-mechanical (THM) model to simulate processes as related to soil freeze-thaw dynamics and permafrost degradation was advanced. Several papers were published based on this work and a series of conference presentations and posters were presented. These are summarized at the end of the report.

The main objective of the modeling work to date has been to develop sound and realistic numerical modeling tools that capture the key physical processes related to the freezing and thawing of soils. The ultimate goal is to have available a modeling platform that can quantitatively analyze the short- and long-term fate of the discontinuous permafrost underlying the Bogg Creek watershed area of the CMV. We wanted to have a complete and detailed peer review of the models and our approach before we moved to direct modeling of the study area.

Briefly, the Huang and Rudolph (2021) paper established the mathematical basis for the modeling platform with a specific emphasis on the physical processes including the simulation of ice lens growth, ground surface deformation and transient stress-strain fields in variably saturated groundwater conditions. The second manuscript demonstrated the ability of the model to simulate complex freeze-thaw dynamics as related to the seasonal formation of a frost zone and the associated changes on the stress field that could impact the integrity of buried pipe infrastructure (Huang, Rudolph and Glass, 2022). This paper provided the confidence that the model could be applied to highly transient freeze-thaw processes. A subsequent paper very recently published by Huang and Rudolph (2022), provided a model validation approach that could be used by a wide range of modeling platforms designed to capture some or all of the key freeze-thaw processes, something that had not been available in the literature.

The most recent paper that is currently under review, extends the modeling to incorporate solute transport within the THM framework. This model will now be used to begin the assessment of a series of potential future climate scenarios that will impact the integrity of the permafrost in the CMV region. The initial simulations have been completed and we are beginning to develop a more complete simulation strategy, which will be part of the next year's activities. A new PhD graduate student, Ms. Jiaqi Weng has been recruited to conduct the modeling work.

4.0 Airborne Geophysical Methods

Determining the spatial extent and continuity of permafrost at a regional scale has proven to be extremely challenging, yet of vital importance in understanding the regional water balance, groundwater flow systems and security of surface and subsurface infrastructure. One method that has shown promise in mapping permafrost at a regional scale is an airborne electromagnetic geophysical technique (AEM). A commercial system that has proven capable at delineating the limits of permafrost in northern environments is the Xcalibur Multiphysics Resolve6™ system **(**Slattery, S. R. and Andriashek, L.D.). This AEM method utilizes six operational frequencies between 0.4 and 133 kHz and has the ability to product a higher degree of vertical and horizontal resolution of apparent resistivity within the subsurface as compared to a single transmitter and receiver system. Figure 6 presents a photo of the AEM system along with an illustration of the electromagnetic fields and the resulting cross section of the subsurface electrical conductivity.

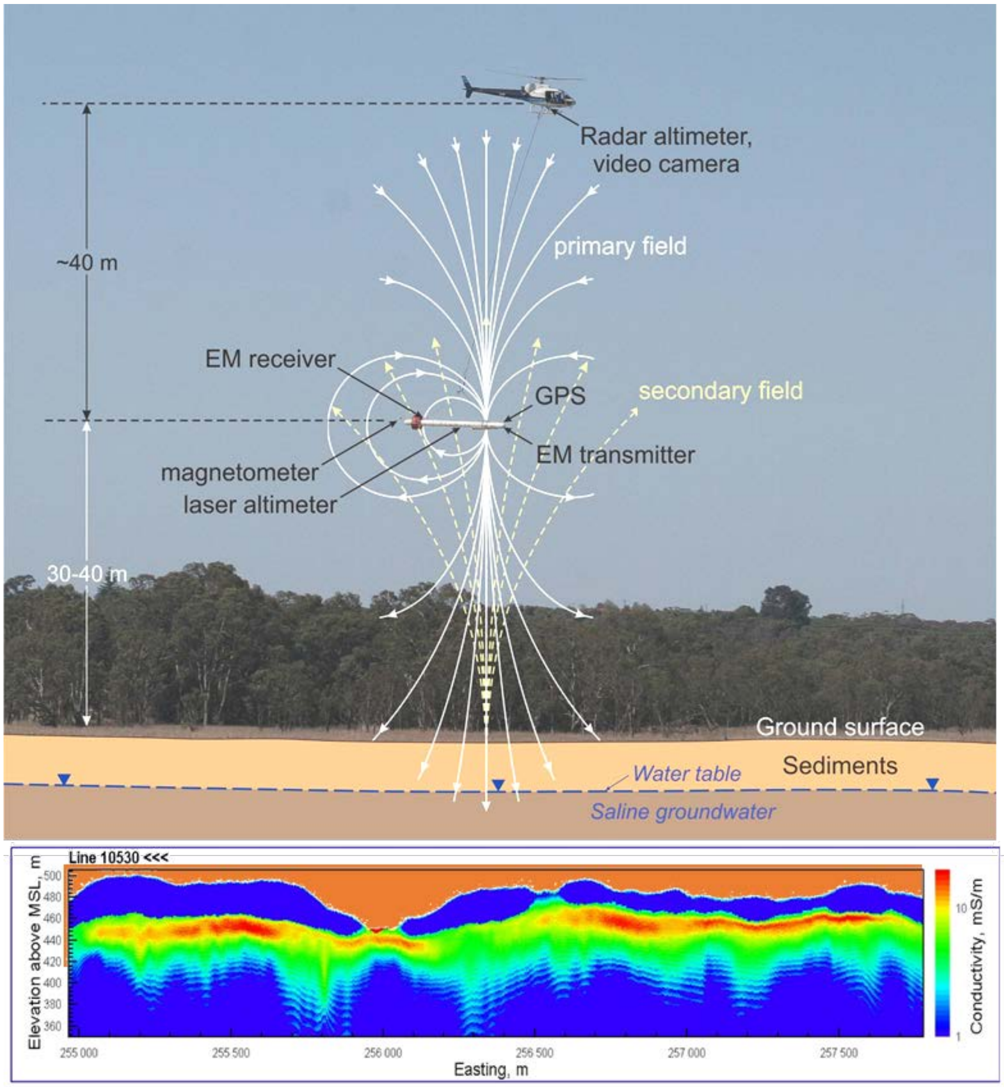

Figure 6. Resolve6 airborne electromagnetic system in operation along with an illustration of the generated and induced EM fields and a resulting cross section of subsurface conductivity. (from Xcalibur Multiphysics, 2022).

In order to assess the potential capability of the Resolve6 system to map permafrost occurrence and continuity within the Bogg Creek Watershed, numerical modeling of the subsurface resistivity response expected during the survey under a series of different conditions was conducted by geophysical specialists from Xcalibur Multiphysics. As the upper and lower boundaries of the permafrost are of specific interest for this survey, a model scenario was evaluated involving a uniform conductive layer (~ 50 ohm-m) overlying a permafrost body (~3,000 ohm-m) varying in thickness between 0 m and 50 m. This is a reasonable range of permafrost thickness that may be encountered in this discontinuous permafrost environment. The conductivity values utilized in the modeling were derived from terrestrial measurements made during the course of the current project. The results presented in Figure 7 suggest that the permafrost body can clearly be delineated at thicknesses greater than ~8 m with the specified values of layer resistivity. Under conditions where the permafrost is thicker than ~8 m both the upper and lower boundaries can be clearly identified.

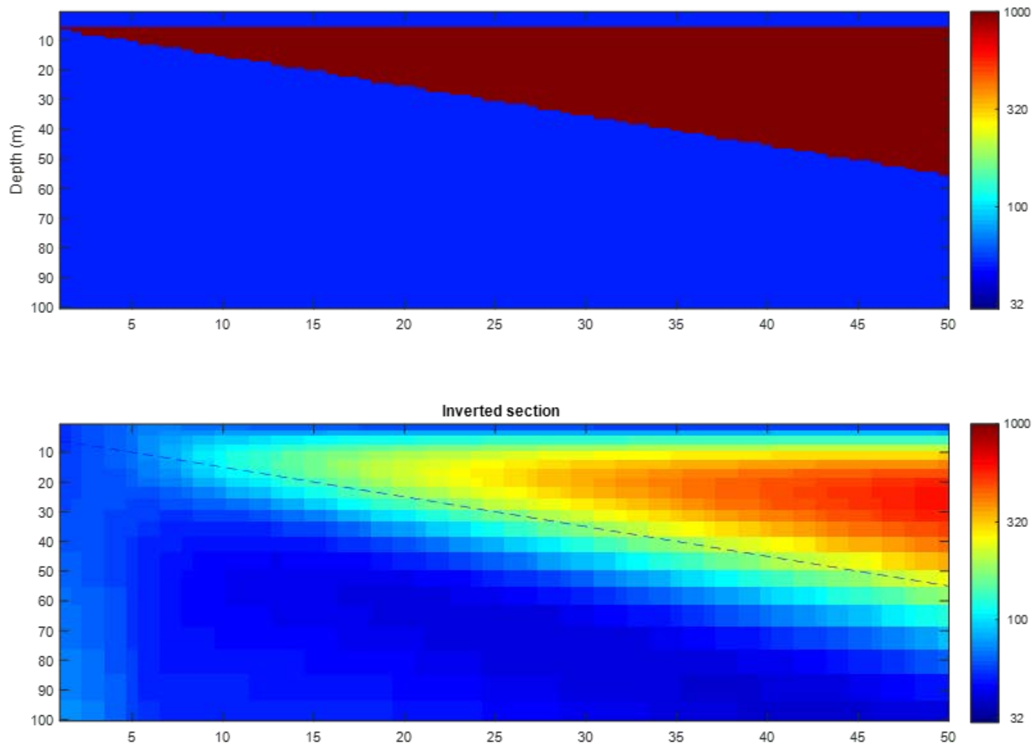

Figure 7. DC Inversion Modeling of simulated resistivity distributions in the subsurface for a two-layer model with a conductor (~ 50 ohm-m) of uniform thickness over the top of a resistor (~3,000 ohm-m) of variable thickness. The 2D image is formed by combining together a series of 1D simulation results. (Rudolph and Smiarowski, 2022).

Based on the modeling, it was concluded that under most of the conditions that are anticipate within the Bogg Creek Watershed, the Resolve6 system will have a good chance of success at mapping the upper and lower boundaries of the permafrost.

In May, 2022, Xcalibur Multiphysics was contracted to complete an ~ 1000 km combined AEM survey of two locations with the Bogg Creek watershed. Although this is beyond the current official year end for the project, we considered it to be of value enough to include the initial results in the Year 5 report. The flight plan is illustrated in Figure 8. The data are now being processes but an example of the raw data at a 10 m depth profile is shown in Figure 9. Initial results clearly indicate that the method is very sensitive to subsurface resistivity and a very high degree of variability as measured which relate with surficial features anticipated to be influencing permafrost continuity. Several features including the Mackenzie River and large lakes are clearly associated with areas of lower resistivity (blue and green shades on Figure 9) that likely relates to thawed permafrost regions. The data are now being fully processes and full interpretation relative to the land features will be underway shortly as part of the Year 6 program.

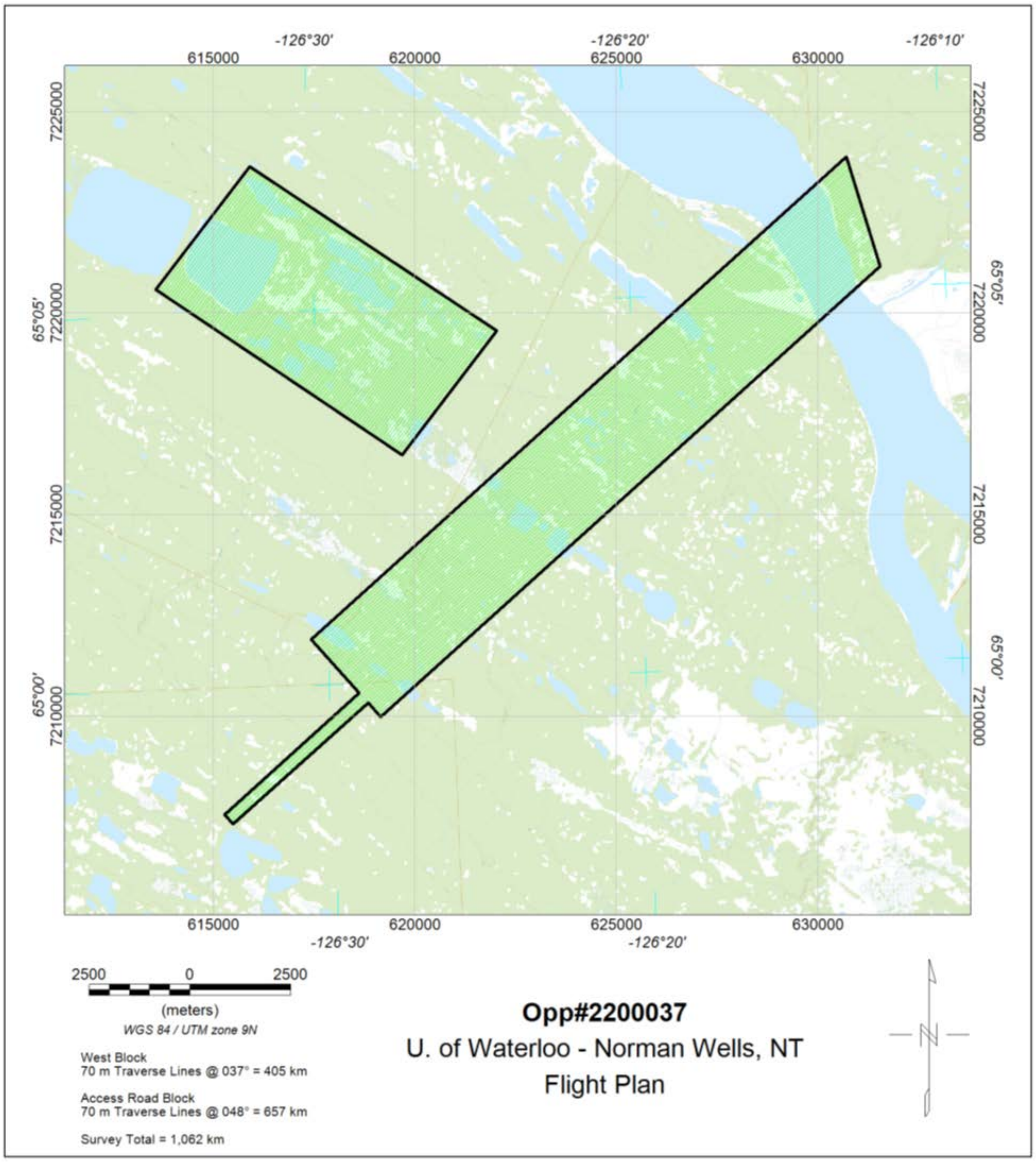

Figure 8. Proposed Resolve6 Airborne Electromagnetic Survey areas. (Rudolph and Smiarowski, 2022).

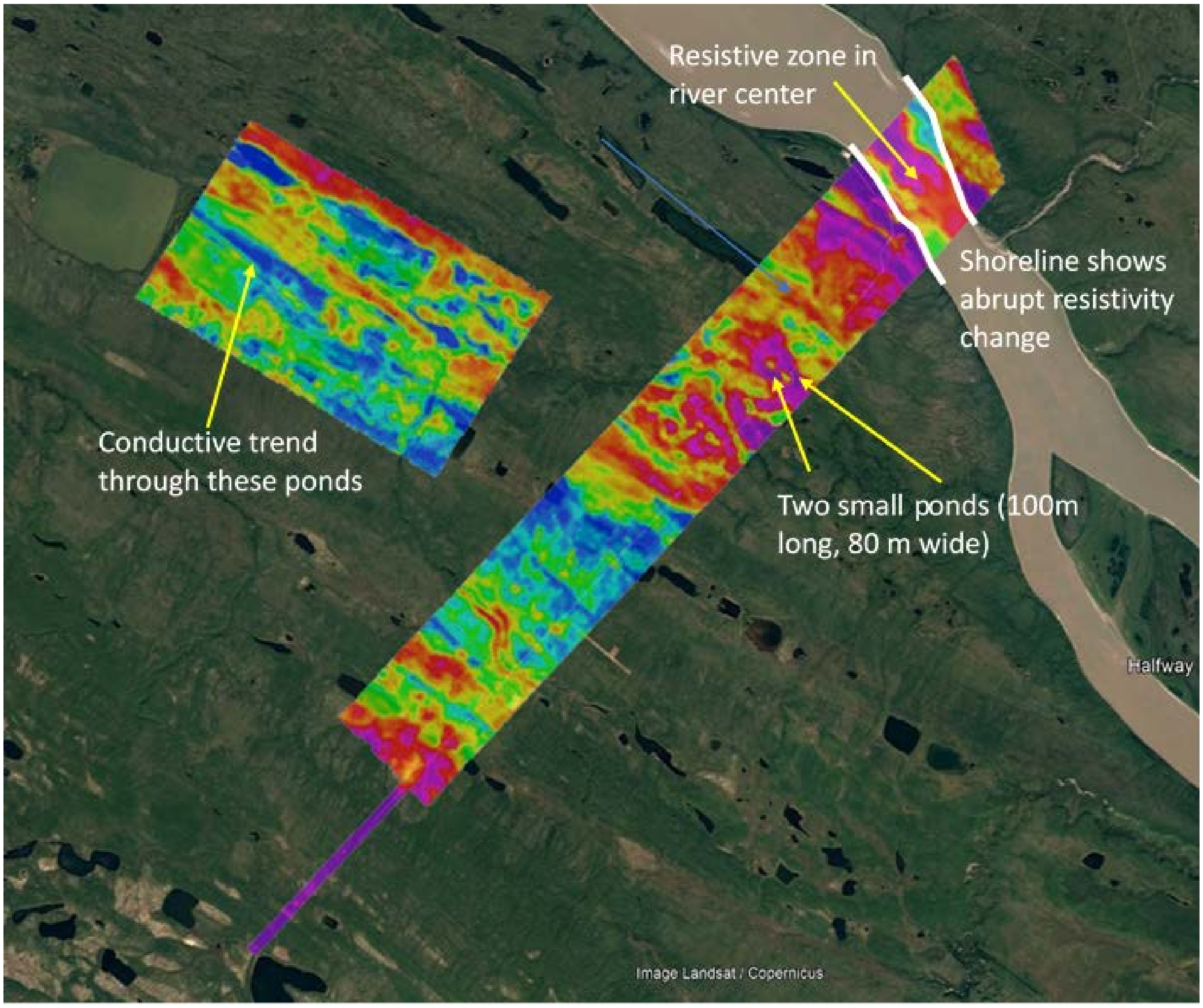

Figure 9. Initial Resolve6 AEM data from Bogg Creek survey. (Xcalibur Multiphysics, 2022).

To provide an indication of the size of the geophysical equipment, two photos are included to provide an indication of the system used in the recent survey conducted out of Norman Wells in May 2022 in Figure 10.

(a)

(b)

Figure 10. Resolve6 AEM system on site (a) and in operation (b). (Xcalibur Multiphysics, 2022).

5.0 Proposed Year 6 Activities

The activities scheduled for Year 6, the project extension year following the Covid restrictions, will involve the application of the new THM modeling platform to explore various scenarios of interest related to groundwater flow within the discontinuous permafrost environment. These results will be shared with our colleagues involved in the ecological studies within the region. The newly acquired AEM data will be fully processed and the detail interpretation of the resistivity anomalies relative to the surface features of interest will be undertaken. These results will be immediately shared with our colleagues from the Sahtu Renewable Resource Board, Tulita Renewable Resources Council and the Norman Wells Renewable Resources Council.

Depending on the restrictions related to the Covid-19 situation and the arrangements with Cenovus, a field campaign is planned within the next year to continue to develop the water data set and to focus more specifically on several target solutes including the hydrocarbons and other carbon species that may be related to permafrost thaw. We will also continue to follow collaborative opportunities with Cenovus.

6.0 References

Journal Papers

Huang, X. and Rudolph, D. L., 2022. Numerical study of coupled water and vapour flow, heat transfer, and solute transport in variably-saturated deformable soil during freeze-thaw cycles, submitted to Water Resources Research.

Huang, X. and Rudolph, D.L., 2022. A hybrid analytical-numerical technique for solving soil temperature during the freezing process, Advances in Water Resources, https://doi.org/10.1016/j.advwatres.2022.104163.

Huang, X., Rudolph, D.L., and Glass, B., 2022. A coupled thermal-hydraulic-mechanical approach to modelling roadbed frost loading on water mains, Water Resources Research, http://doi.org/10.1029/2021WR030933.

Huang, X. and Rudolph, D.L., 2021. Coupled model for water, vapour, heat, stress and strain fields in variably saturated freezing soils, Advances in Water Research, 154 (2021), https://doi.org/10.1016/j.advwatres.2021.103945.

Conference Presentations

Thorne, R., Marsh, P., Rudolph, D., Spence, C., Sonnentag, O., McKenzie, J. and Berg, A., 2022. Recommendations to enhance hydrological models for improved estimates of climate impacts on northern waters, GWF Annual Science Meeting 2022, Saskatoon, May, iposter.

Huang, X., Rudolph, D. L. and Weng, J., 2022. Thermal-hydraulic-mechanical-chemical modelling in a permafrost-affected groundwater system, GWF Annual Science Meeting 2022, Saskatoon, May, iposter.
Yin, H., Wiebe, A., Rudolph, D. and McKenzie, J., 2022. The Influence of Weather Seasonality on Well Vulnerability in Cold Regions, GWF Annual Science Meeting 2022, Saskatoon, May, iposter.

Rudolph, D. L., Wicke, A. and Glass, B., (2021). Characterizing Groundwater Flow within a Discontinuous Permafrost Environment. 49th Annual Yellowknife Geoscience Forum, November 24th – 26th.

Huang, X. and Rudolph, D.L., (2021). Thermal-hydraulic-mechanical modelling of groundwater dynamics in a permafrost basin. GeoNiagara, 2021 Annual Joint Conference of the CGS and IAH, Niagara Falls, September 26-29.

Thorne, R., Marsh., P., Rudolph, D. L., Spence, C., Sonnentag, O., McKenzie, J., M. and Berg, A., (2021). Linking hydrological and cryohydrogeological models for improved estimates of climate impacts on northern waters. Canadian Geophysical Union Annual Meeting, Banff, ALTA, June – July, 2021.

Huang, X., and Rudolph, D.L., (2021). Numerical study on water-vapor flow, heat transfer, and solute transport in variably saturated soil during freeze-thaw cycles. GWF Annual Science Meeting 2021, Waterloo, May 2021, iposter.

Graduate Student Theses

Wicke, A. (2021). Characterizing Aspects of Groundwater Flow in Discontinuous Permafrost Terrain, Within the Central Mackenzie Valley, NWT. MSc thesis, University of Waterloo, June.

Technical Reports

Rudolph, D. L and Smiarowski, A., 2022. Feasibility and Design of a Novel Airborne Geophysical Survey Method to Map Permafrost Discontinuity in Northern Environments, Government of the Northwest Territories, Yellowknife, NWT, March.

Additional References

Slattery, S. R. and Andriashek, L.D. 2012. Overview of Airborne Electromagnetic and Magnetic Geophysical Data Collection Using the RESOLVE® and GEOTEM® Surveys near Red Deer, Central Alberta, Alberta Geological Survey, Energy Resources Conservation Board Alberta Geological Survey, https://static.ags.aer.ca/files/document/OFR/OFR_2012_07.pdf.