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

Fourth Annual Report to:

NWT ESRF Management Board

By:

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1.0 INTRODUCTION

During the fourth year of the project, there were a series of minor challenges related to limitations associated with the Covid-19 pandemic that influenced the planned field activities. It has been necessary to postpone the field activities to a subsequent year as will be explained below. However, a major objective of the research work planned for Year 4 involved completing the assessment and interpretation process related to the data collected in the previous 3 years of the project. This work could be conducted in house at the University of Waterloo. A second major activity, was the continued development of a numerical modeling tool and the completion of initial scenario simulations to assess the applicability of the new model. This also was conducted at the University of Waterloo. Specifically, the Year 4 work activities associated with the project focused on: **1).** geochemical and isotopic characterization of the various identified sources of water within the hydrologic system in the study area; **2).** Summary of the utility of the portable and remote investigative strategies adopted and implemented for hydrologic field monitoring within this type of remote northern terrain; **3).** Continued development of a conceptual model of the groundwater flow system within the Bogg Creek Watershed and **4).** Complete development of the initial version of a fully coupled thermal-hydraulic-mechanical (THM) model for variably saturated freezing soil and initial simulations relevant to the study of groundwater flow in discontinuous permafrost environments.

Surface water and groundwater sampling sites that were visited during the 2018 and 2019 field campaigns with the Bogg Creek Watershed are shown on Figure 1. Information from this network of sites is an integration of data from Husky Energy and the University of Waterloo research team.

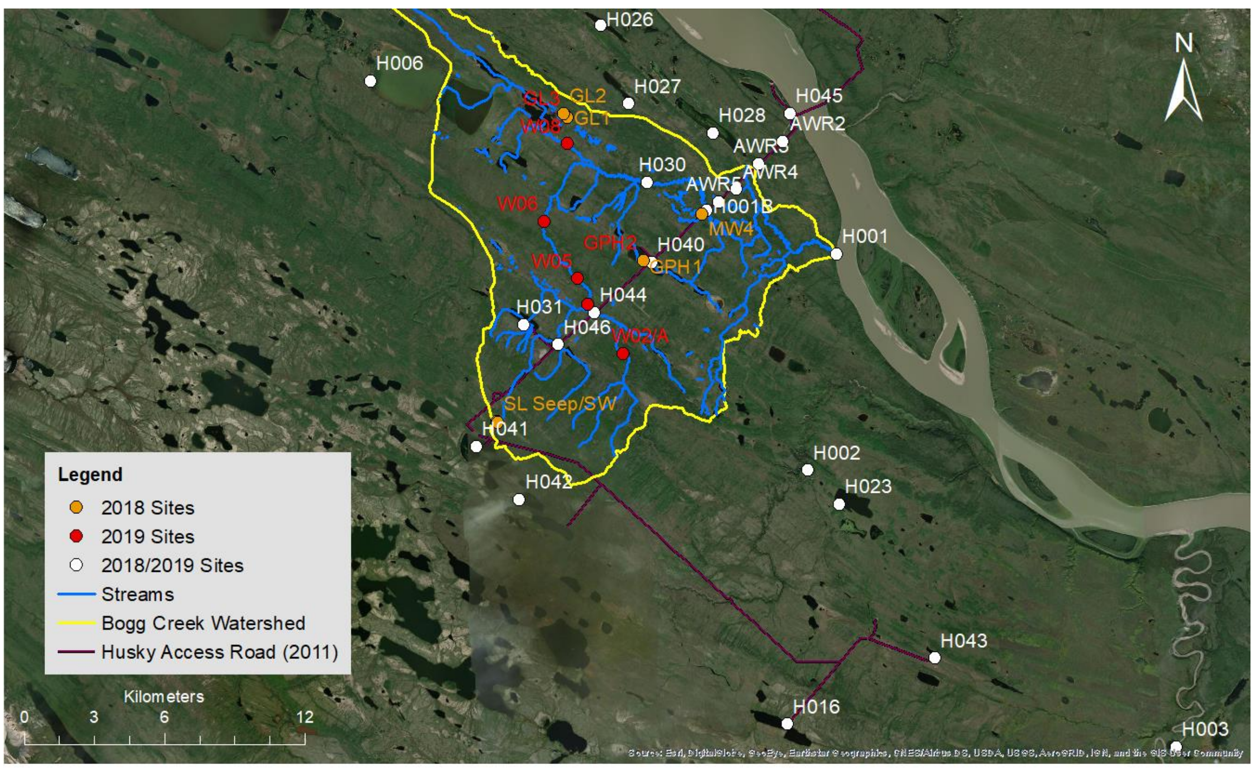

Figure 1: Regional map of sampling sites taken in the study area for each year. Satellite photos provided as part of the ArcGIS basemap feature.

The combined data sets represent sampling conducted during the late summer seasons of 2018 and 2019, when the active zone was expected to be the thickest and during the winter of 2019, under fully frozen conditions.

In Year 4, the project continued to benefit from technical, financial and in kind support from research colleagues from Wilfred Laurier University (WLU) and Husky Energy. The financial and in kind support was leveraged through our on-going research work supported through the Global Water Futures (GWF) program. The specific research program within the GWF program was the Northern Water Futures study headed by Dr. Jenn Baltzer at WLU, which was extended for a three year second phase in 2021.

During the 2020-2021 fiscal year, Husky Energy was sold to Cenovus and the future of our collaborative activities may be influenced by this change in ownership. We are maintaining communication with our past contacts at Husky Energy and will attempt to continue our productive relationship working at their Slater River lease area near Norman Wells, Northwest Territories.

As in previous annual reports, progress on each of the Year 4 topic areas listed above will be summarized in separate sections below. For the sake of this project report, representative examples of the data sets are provided for discussion. The entire analysis is contained in the MSc thesis of Mr. Andrew Wicke, which will be provided to the ESRB in June, 2021, following Mr. Wicke's thesis defense.

2.0 Geochemical and Isotopic Characterization of Water Sources

The compilation of the various geochemical and isotopic datasets led to the identification of 5 distinct subsurface water sources within the Bogg Creek watershed. These include 1). shallow seepage; 2). mineral soil and 3). organic soil groundwaters (suprapermafrost groundwater) and deeper subpermafrost groundwater from the 4). Little Bear and 5). Martin House Formations. Each of these different components contribute to the surface water flow system to varying degrees depending on the time of the season and location within the watershed. Direct runoff water such as overland flow could not be obtained at the times that the sampling was conducted, however it is only anticipated to be a major contributor to the surface water systems during the spring melt period. In some locations, the surface water in both lakes and streams appear to be recharging the subsurface, something that likely varies throughout the course of the year.

The distinct nature of the different groundwater sources is illustrated in Figure 2 relative to the annual geochemical variability of surface water within the Bogg Creek tributaries. The influence of the different groundwater sources on the geochemistry of Bogg Creek is shown in Figure 3 from the headwaters to the outlet at the Mackenzie River (all sampling point locations are shown in Figure 1). These combined data sets illustrate the complex interaction between the groundwater and surface water flow systems and how different groundwater sources are contributing to the surface water baseflow throughout the course of the year. These data provide an example of how the geochemical tracers can be used to understand the interaction between groundwater and surface water within the discontinuous permafrost environment. This information combined with the physical measurements of groundwater temperature and hydraulic head provide insight in support of a conceptual model of the subsurface flow conditions. This can also be augmented by environmental isotope data, an example of which is discussed next.

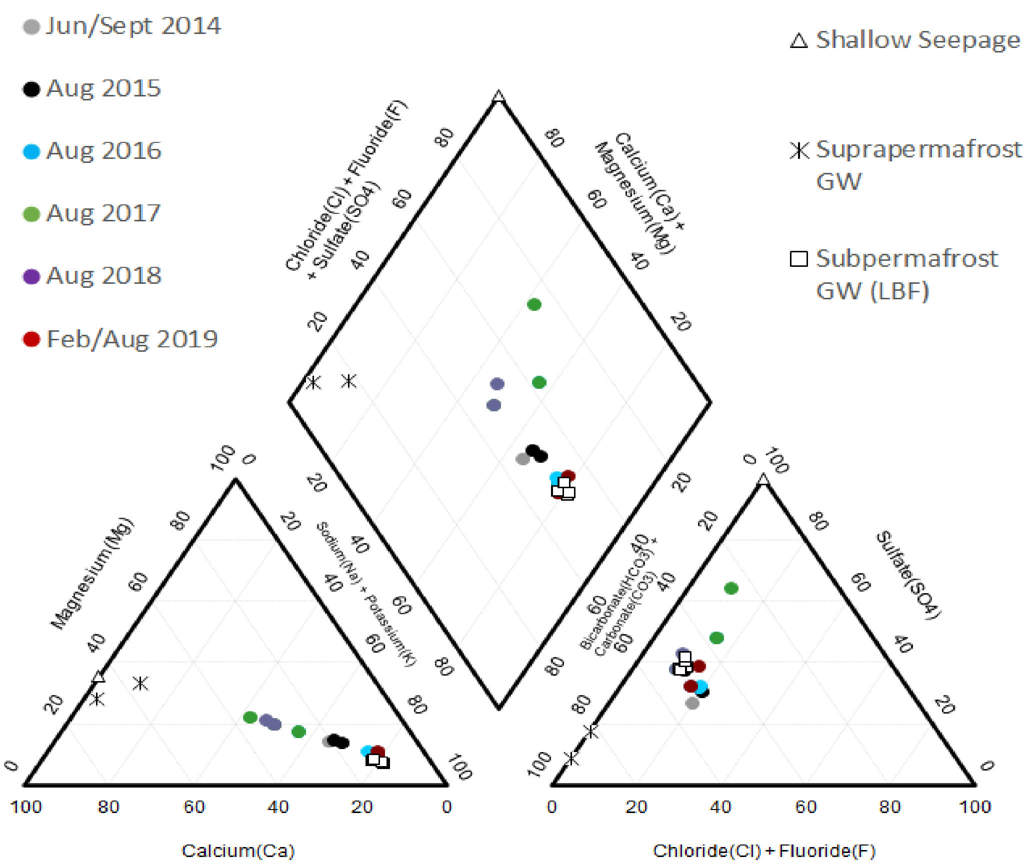

Figure2: Piper diagram of surface water samples collected from a tributary of Bogg Creek near the centre of the watershed (HO44, Figure 1, coloured dot symbols) and shallow seepage, suprapermafrost and subpermafrost groundwater for comparison.

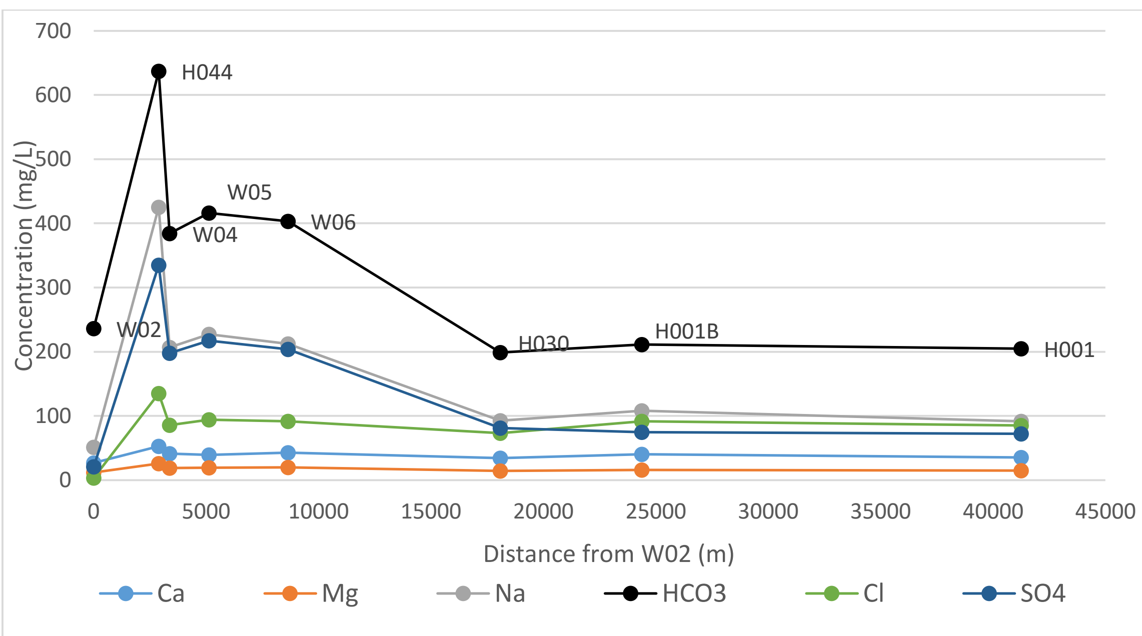

Figure 1: Concentration of major ions over distance along Bogg Creek in 2019, starting in the headwaters at W02.

The environmental isotopes of water including ^{18}O and ^{2}H have distinct values depending on the source under consideration. For example, the $\delta^{18}O$ and $\delta^{2}H$ expressions for the deep and shallow groundwater, several of the springs encountered within the Bogg Creek watershed and some surface water samples are shown in Figure 4. The influence of mixing between different sources is indicated by the location along the local meteoric waterline (LMWL) where the different samples fall. As was seen within the geochemistry data sets, the different subsurface water sources have unique isotopic compositions that assist in identifying them when they are encountered in the near surface.

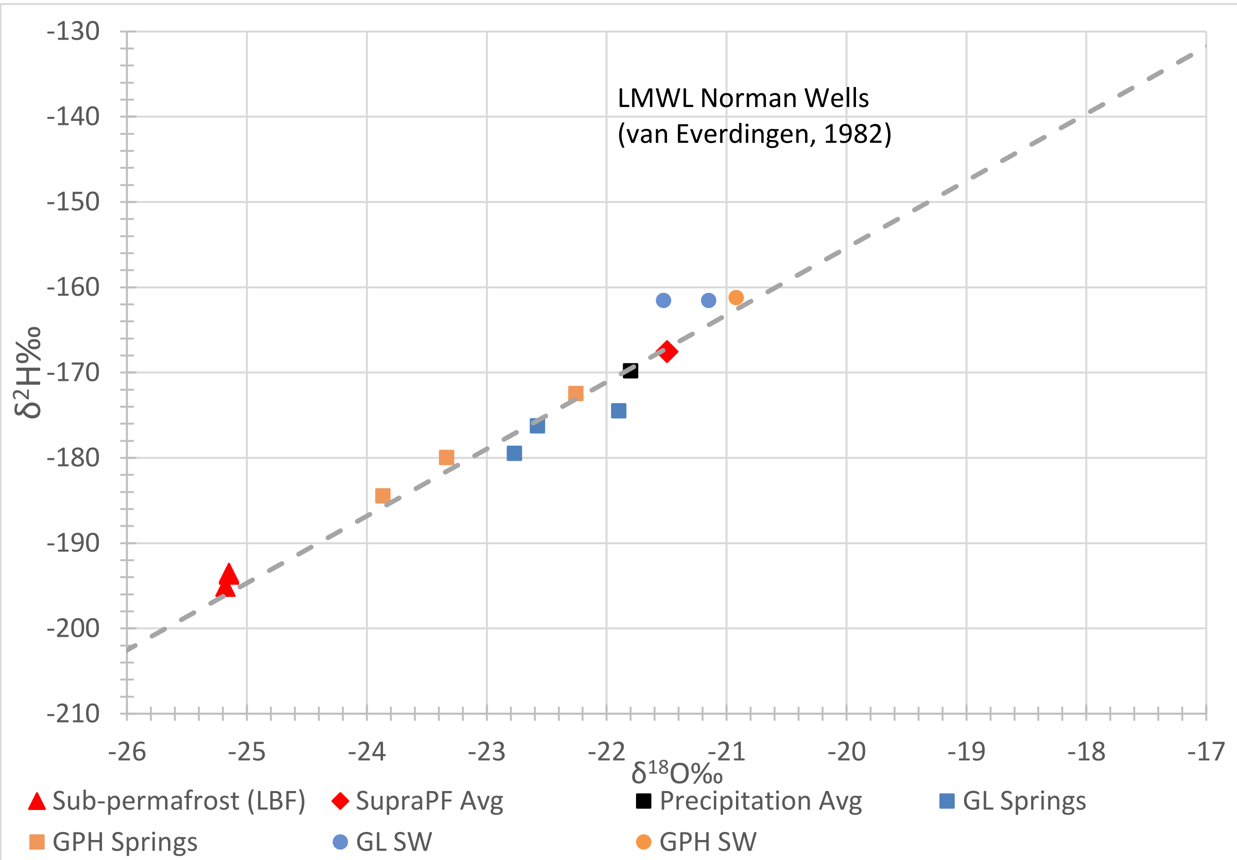

Figure 2: $\delta^{18}O$ and $\delta^{2}H$ for some examples of upwelling spring water and surface water, as well as the groundwater and precipitation averages for comparison.

The contributions of the different groundwater sources to Bogg Creek along the flow path from the headwaters to the outflow at the Mackenzie River can also be seen based on the environmental composition of the surface water as illustrated in Figure 5. These data provide additional evidence of the nature of groundwater interaction with the surface water systems and further enhance the development of the conceptual model of groundwater flow in this environment.

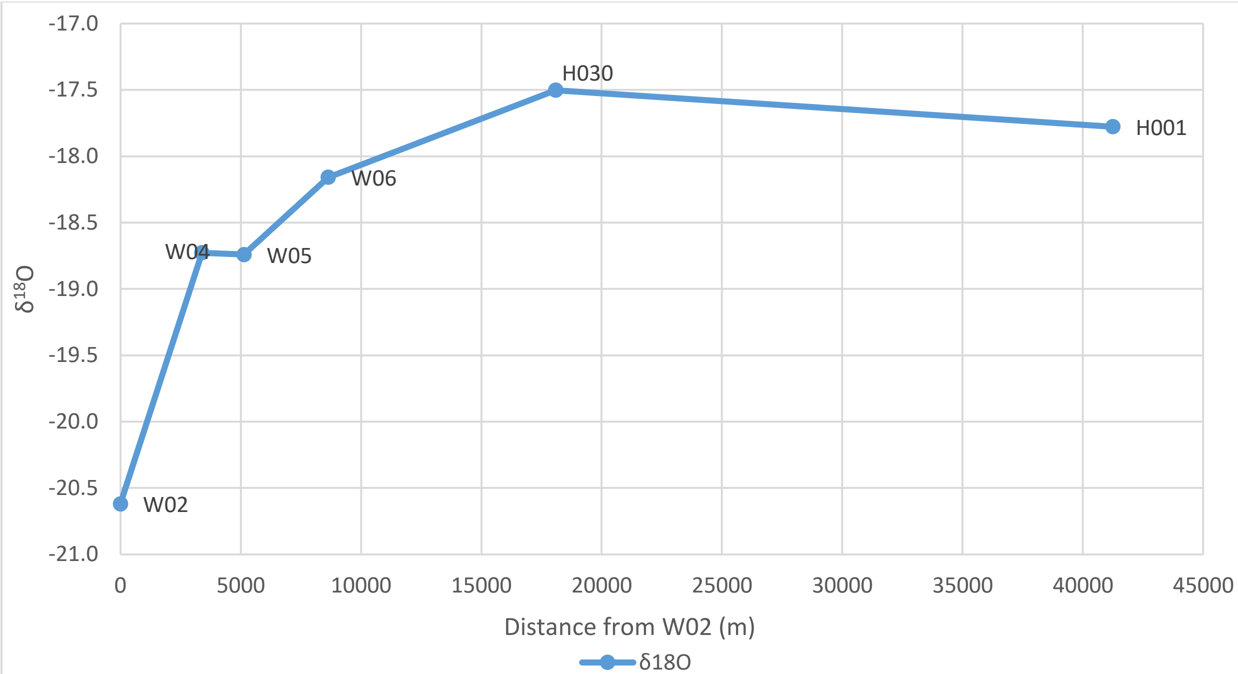

Figure 3: Evolution of $\delta^{18}O$ signature along Bogg Creek from the headwaters to the outflow at the MacKenzie River.

The combined insight gained from the geochemical and isotopic data, supported by physical hydrologic measurements made at the different field sites, inform the nature of groundwater flow and are used in the development of a proposed hydrogeological conceptual model presented below.

3.0 Portable and Remote Investigative Strategies

As part of the overall research program, a wide variety of remote and portable monitoring techniques, natural tracers and data integration strategies were proposed, employed and assessed for use within remote discontinuous permafrost terrain. The data collected with these various techniques are contained in the publication from Glass et al. 2021 and the MSc thesis of Wicke (2021), with some of the relevant data being presented in this annual report. A detailed summary of the different methods was developed by the research team during the 2020 project year and provided to the Government of the Northwest Territories (Hydrogeological Site Characterization Methods for Discontinuous Permafrost Terrain, Rudolph and Wicke, 2020).

A main conclusion of this methods assessment is that the combined insight provided by the multiple lines of evidence is much more informative than what can be derived from individual data sets considered in isolation. As conditions clearly vary from site to site, different methods may prove more or less useful in characterizing hydrologic phenomena within terrain underlain by discontinuous permafrost. A more detailed assessment of the different methods and their applications is contained in the report noted above and the MSc thesis of Mr. Andrew Wicke.

4.0 Conceptual Model of the Groundwater Flow System

Groundwater flow characteristics within discontinuous permafrost terrain are not well understood, primarily as a result of the remote nature of the environment and the challenges related to utilizing conventional hydrogeological investigation techniques including drilling. Insight into the nature of transient groundwater flow and the interaction of groundwater with the terrestrial surface can be derived through the integrated assessment of diverse data ranging from orbit-based remote sensing, to low elevation geophysical surveys and terrestrial monitoring including surface and subsurface hydrologic and geochemical measurements. During the course of the current project, a conceptual model of the groundwater flow system within the Bogg Creek watershed, a typical catchment within the Central Mackenzie Valley, was progressively developed and evolved through the addition of different types of data. Due to the highly transient nature of the seasonal climatic conditions in this landscape, groundwater flow conditions and the interaction between the surface and subsurface waters vary significantly during the seasonal cycle.

One of the most dominate factors controlling groundwater movement in this environment is the presence of permafrost and the freezing and thawing of the near surface active zone during the year. Of particular importance is the existence and location of through taliks that provide a direct hydraulic connection between the deeper hydrogeologic strata and the near surface environment. Mapping these features is challenging and an optional approach is presented for the Year 5 activities. Evidence for the existence of through taliks, however, can be derived from physical, geochemical and isotopic information collected at the terrestrial surface, as was completed within the scope of the current project.

Figure 6 presents an illustration of a conceptual understanding of the main components of the groundwater flow system within the discontinuous permafrost environment beneath the study area. A detailed explanation and justification of the different components of this hydrogeologic conceptual model is contained in the MSc thesis of Mr. Andrew Wicke and will not be include here in its entirety. The A-A' cross section is oriented from the upland region in the southwest of the study area towards the northeast and falls along Husky's all season access road from monitoring points HO41 to MW4 terminating beneath the main channel of Bogg Creek on Figure 1. Regional groundwater flow moves from the upland region towards the lower topographic position at Bogg Creek and it is hypothesized that some of the deeper groundwater may reach ground surface across through taliks where they exist beneath or near surface water features. Deeper groundwater discharges at surface contributing to lakes and streams or forming localized springs. A highly transient groundwater flow system occurs in the near surface where the active zone varies in thickness over the winter and summer seasons allowing shallow groundwater to circulate thought the organic and mineral soils of the near surface overburden materials discharging to surface water features and lowland areas. The contributions of the subpermafrost and suprapermafrost groundwaters to individual surface water bodies depend on landscape position, existence of the through taliks and the hydraulic nature of the surrounding geologic materials.

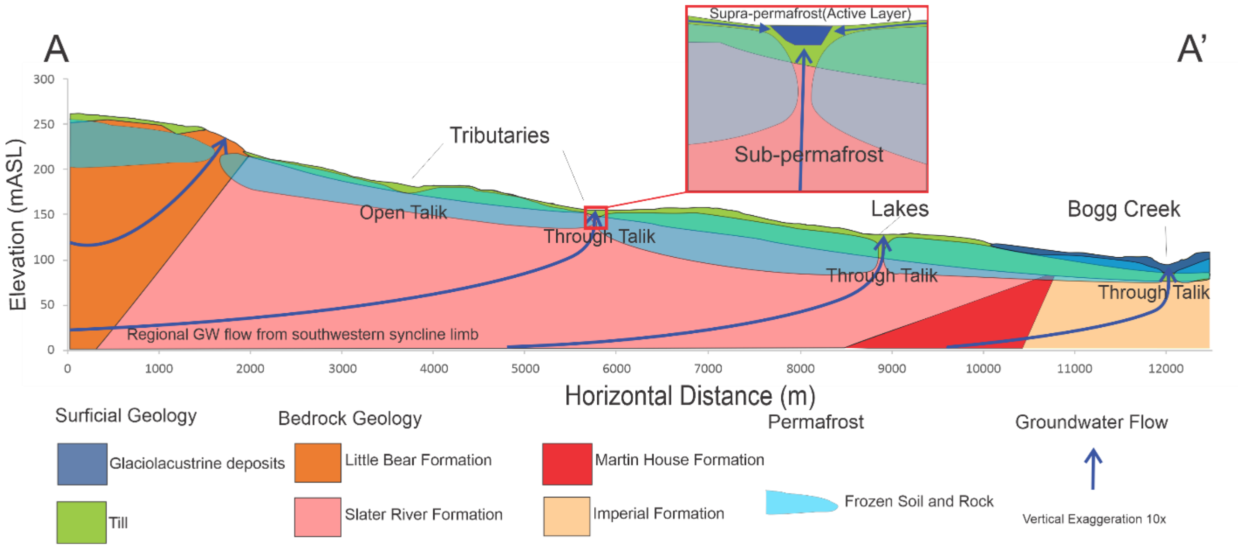

Figure 6: Conceptual model of groundwater flow in the Bogg Creek watershed. Geology, permafrost distribution, groundwater flow lines and position of through taliks are inferred based on hydrologic, geological and geochemical evidence. Permafrost is shown as semi-transparent to show stratigraphy.

5.0 Fully Coupled Thermal-hydraulic-mechanical (THM) Model

The development of the fully coupled thermal-hydraulic-mechanical (THM) model to simulate processes as related to soil freeze and thaw dynamics and permafrost degradation continued in Year 4. A series of research papers have been prepared from this work and are currently in review or under revision ((Huang et al., 2021; Huang and Rudolph (2021 a and b). Main features of this model are the capabilities to simulate ice lens growth, ground surface deformation and transient stress-strain fields in variably saturated groundwater conditions. These processes are illustrated in Figure 7.

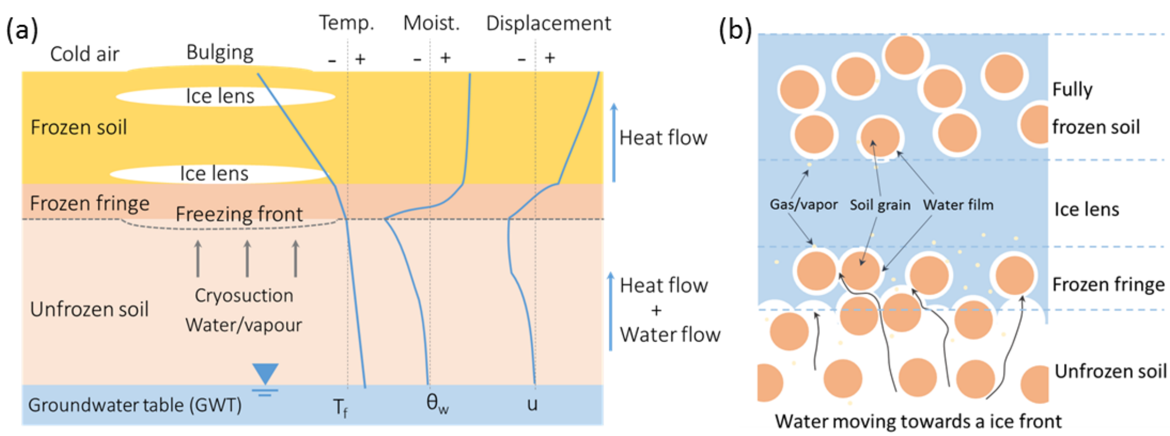

Figure 6: Schematic representation of the ice lens formation and growth in freezing soil from the (a) macro-scale to (b) pore-scale. (based on Williams & Smith (1989) and Thomas et al. (2009)).

The THM model was expanded to a two dimensional format with the objective of investigating seasonal freeze-thaw dynamics and active zone processes related to short and medium-term permafrost degradation. Initial simulation scenarios are currently underway to examine the nature of groundwater flow processes and permafrost degradation as the climate warms. The field data collected within the Bogg Creek watershed and the subsequent hydrogeological conceptual model described above are being used to inform and support the numerical experiments.

6.0 Proposed Year 5 Activities

The planned activities for Year 5 of the project will involve continued development and application of the THM modeling platform to explore various scenarios of interest related to groundwater flow within the discontinuous permafrost environment and to share these results with colleagues involved in the ecological studies within the region. We are also planning to continue to explore the opportunity to conduct low-elevation, air borne EM geophysical surveys designed to regionally map the upper and lower boundaries of the permafrost within the Bogg Creek region. Initial discussions with geophysical contractors Multi-Physics, have confirmed the feasibility and availability of their helicopter supported EM technology for this type of survey. Depending on the restrictions related to the Covid-19 situation, our plans will be to conduct surveys over the Bogg Creek area in the Fall of 2021 utilizing the Norman Wells airport and local facilities.

We will also continue to follow collaborative opportunities with the new version of Husky Energy through Cenovus.

6.0 References

Glass, B., Rudolph, D.L, Duguay, C. and Wicke, A., 2021. Identifying Groundwater Discharge Zones in Northern Canada Using Remotely Sensed Optical and Thermal Imagery. Canadian Journal of Earth Sciences. dx.doi.org/10.1139/cjes-2019-0169

Huang, X., Rudolph, D.L., and Glass, B., 2021. Potential influence of roadbed frost load on water main failure, submitted to Canadian Geotechnical Journal. (in revision).

Huang, X. and Rudolph, D.L., 2021. Coupled model for water, vapour, heat, stress and strain fields in variably saturated freezing soils, submitted to Advances in Water Research (in revision).

Huang, X. and Rudolph, D.L., 2021. An approximate analytical solution for temperature during soil freezing or thawing, Advances in Water Research (in submission).

Wicke, A. and Rudolph, D. L., (2020). Hydrogeological Site Characterization Methods for Discontinuous Permafrost Terrain, Environment and Natural Resources, Government of the Northwest Territories.

Wicke, A. (2020). Characterizing Aspects of Groundwater Flow in Discontinuous Permafrost Terrain, Within the Central Mackenzie Valley, NWT. MSc thesis, University of Waterloo, (defense pending).