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

Sixth Annual Report to:

NWT ESRF Management Board

By:

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1.0 Introduction

Research activities completed during the past year of the project have been conducted through an extension to the initial 5-year project, graciously granted by the ESRB. Anticipated project time lines and deliverables were extended due to the limitations on field access related to the Covid-19 pandemic. The focus from the extended Year 6 has been in two main areas. The first involved the design, implementation and detailed interpretation of the airborne electromagnetic geophysical survey (AEM), which was flown in April 2021. Very preliminary, raw data were presented in the Year 5 annual report. The second major area of work has been on the further development and application of numerical modeling tools designed to simulate the influence of transient groundwater flow phenomena on surface water systems, land form change and ecology within discontinuous permafrost terrain. The modeling tools have been applied to explore various scenarios of interest related to long term permafrost thaw characteristics, land subsidence and the formation of thermokarst features, and solute fate and transport influenced by the thawing processes.

The work remains focused within the Bogg Creek watershed, near Norman Wells in the Central Mackenzie Valley (CMV), NWT. Two students, Ms. Jiaqi Weng (PhD) and Ms. Rebecca Zhao (BSc) have been working on the main components of the project and their work over the course of the past year forms a considerable part of the Year 6 annual report. Support for the research is continuing to be provided by Cenovus, who manage the Slater River hydrocarbon lease area near Norman Wells. Mr. Chris Salewich, who has been our main collaborator from Cenvovus/Husky over the entire course of the project, remains our main point of contact moving forward. Through Mr. Salewich's support, the research team met with Cenovus officials and members of the ESRB in February, 2023 to discuss results of the project to date and to review plans for the subsequent phase of the work.

The project continues to receive technical, financial and in-kind support from research colleagues at Wilfred Laurier University (WLU) and Cenovus. Leveraged 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. This report provides a summary of the research results obtained during Year 6 along with a summary of relevant presentations and publications.

2.0 Airborne Geophysical Survey

One of the main objectives of the ESRF project has been to identify and assess the utility of site characterization and monitoring approaches that can be used effectively and inexpensively to investigate groundwater processes in very remote northern terrain. Previous reports provided the results of remote sensing tools including the application of orbit-base, satellite imagery to identify potential groundwater springs and low-elevation infrared camera surveys designed to map points of groundwater discharge using heat anomalies. Over the last year, another low-level airborne remote sensing technique was employed over the Bogg Creek watershed in an attempt to map the occurrence and geometry of discontinuous permafrost to a regional scale. The mapping of permafrost depth and thickness has conventionally relied on local field measurement with permafrost depth probes, drill cores and terrestrial geophysical techniques. All of these approaches are very local in scale and in some cases expensive to complete.

In the current study, an airborne electromagnetic geophysical survey (AEM) method was utilized to determine if the data from this type of survey could provide more efficient spatial resolution of permafrost continuity and a larger scale. The method selected is based on the frequency domain approach and it utilizes several different transmission frequencies to measure geophysical responses from progressively greater depths ranging from the near surface (~2 m) to a maximum depth of about 100 m. The system is owned and operated by Xcalibur Multiphysics and is referred to as the Resolve6™ system (Slattery, S. R. and Andriashek, L.D., 2012). The AEM method utilizes six operational frequencies between 0.4 and 133 kHz and the system is illustrated in Figure 1. The feasibility and design of the survey was completed as part of a leveraged study presented by Rudolph, D. L and Smiarowski, A., 2022. The Resolve6™ system is shown in the field in figure 2.

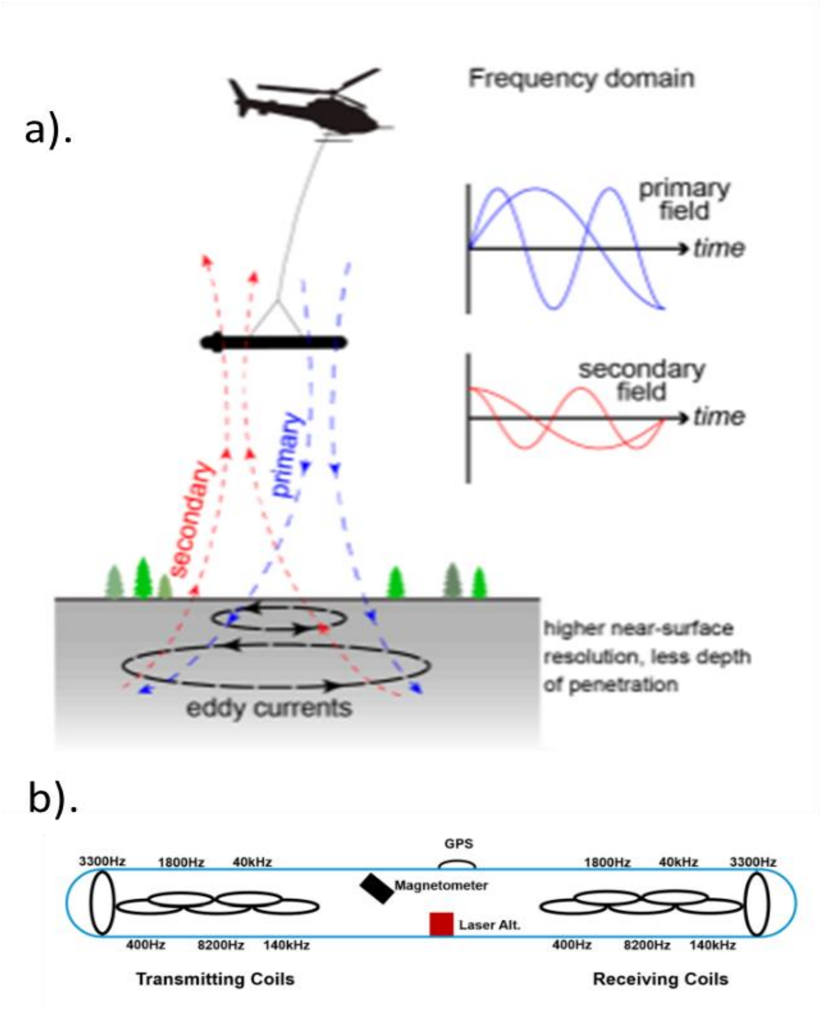

Figure 1. Illustration of the Resolve6™ airborne electromagnetic system (AEM) a). system in flight with an indication of the electromagnetic field generated at different depths in the subsurface and b). the various frequencies of transmission from the device. (from Slattery, S. R. and Andriashek, L.D., 2012).

Figure 2. Photographs of the Resolve6™ airborne electromagnetic system in field deployment. (Xcalibur, 2022).

The survey region defined for this study was selected in an attempt to cover a wide variety of surface water features, different geological terrains and landforms. The flight areas and lines are shown in Figure 3. In total, ~1100 km of flight line was surveyed from an average elevation of 35 m about the ground surface. A line separation of 70 m was selected to permit a relatively dense surface coverage. The smaller rectangular area is referred to as the West Block and the longer region along the all-season access road is labeled the Road Block (Figure 3).

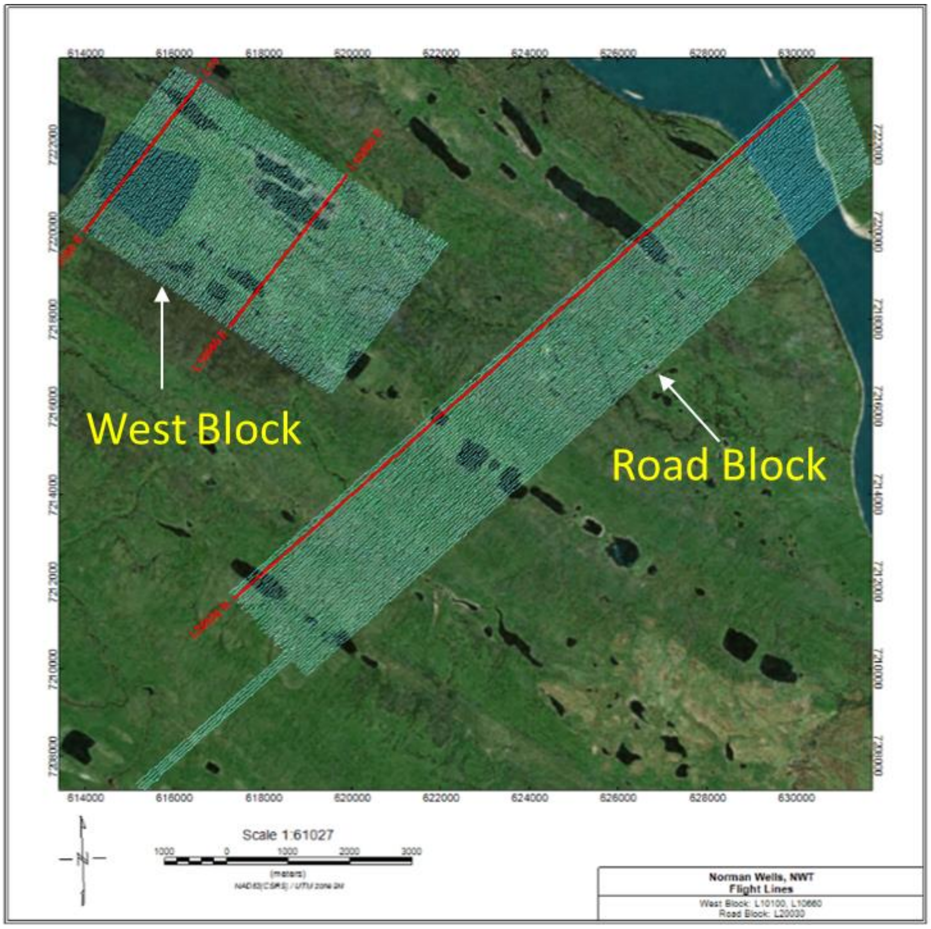

Figure 3. AEM survey region with the location of the West Block and Road Block indicted. The red survey lines are lines that were selected for data demonstration purposes. (Zhao, 2023).

Initial interpretation of the AEM survey results were focused on the variability of the EM signal with depth and the influence of surface water bodies on the subsurface EM signal. Figure 4 presents the processed (inverted) resistivity results for 6 different depths. The red colors are the most resistive and the blue colors are the most conductive. The resistive regions are interpreted to be associated with frozen subsurface materials related to annual surface frost and deeper permafrost. The overall resistivity appears to decrease with depth, potentially indicting the disappearance of permafrost. Deeper features (linear blue regions) that are visible in the Figure 4 results may be influenced by bedrock characteristics.

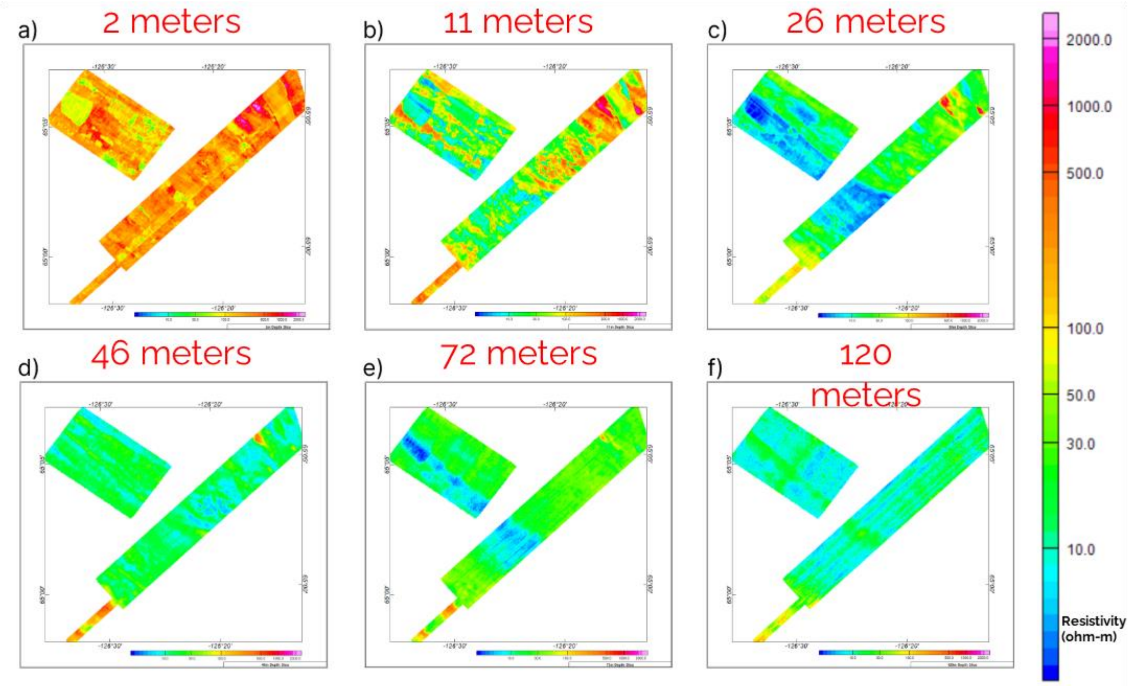

Figure 4. Inverted resistivity data at 6 different depths in both the West and Road Block areas at the regional scale. (Zhao, 2023).

In order to examine the AEM survey data in more detail, several cross sections were constructed with orientation across various surface water features. Two cross sections are presented in Figure 5 along with their location within the survey blocks. The various surface water features are also illustrated. The data indicate a disappearance of resistive permafrost beneath the surface water bodies and the disappearance of the resistive material at depths of between 20 m and 30 m, which may be the base of the discontinuous permafrost.

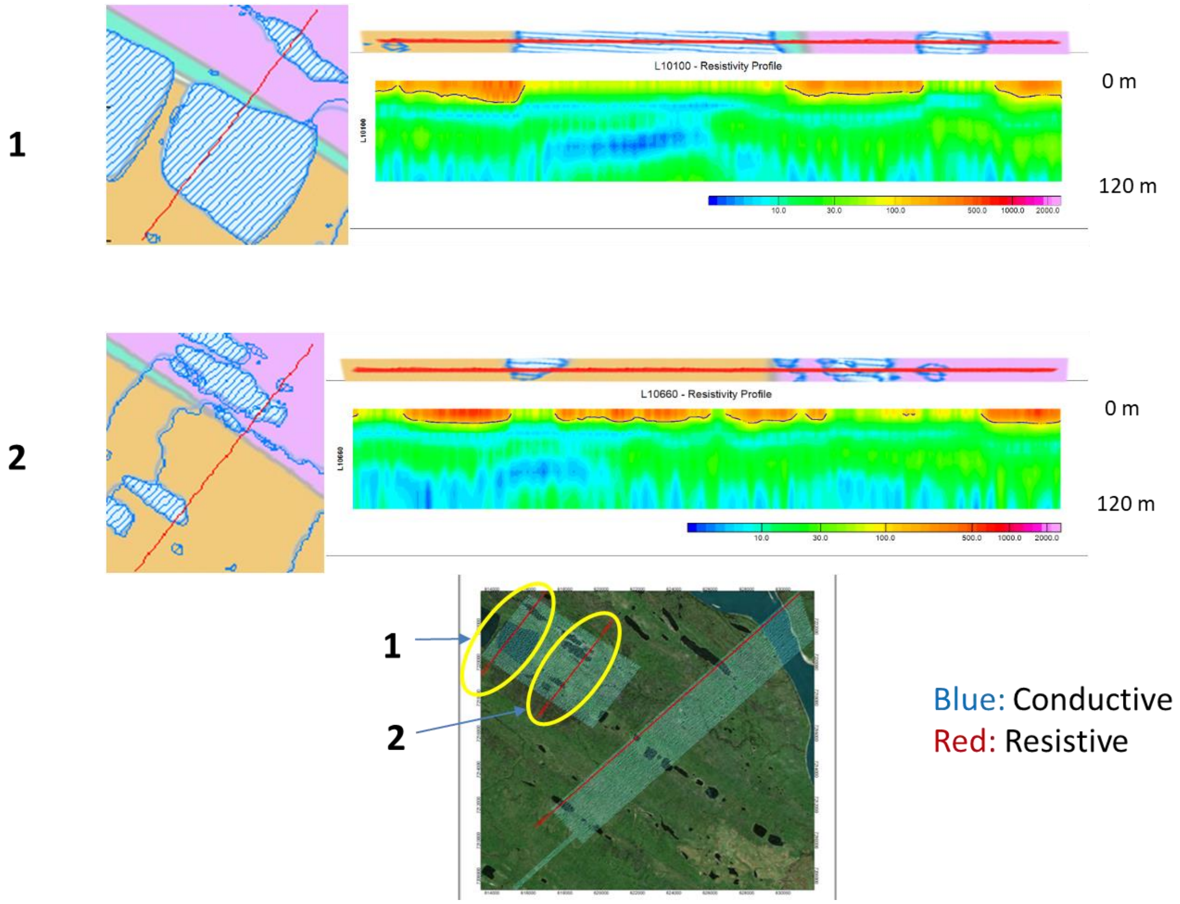

Figure 5. Vertical cross section of inverted resistive data along two of the flight lines. The red resistive regions may represent frozen subsurface conditions (permafrost) and these regions appear to be discontinuous beneath surface water bodies of various size. (Zhao, 2023).

The initial interpretation of the AEM survey data has provided encouraging results regarding the ability of the technique to detect and map permafrost structure remotely and at a fairly regional scale. More detail interpretation and modeling of the data sets is now underway and will be enhanced with terrestrial data that are planned to be collected during the 2023 field season. A more comprehensive initial coverage of the AEM survey program is contained within the BSc thesis of Ms. Rebecca Zhao, which will be submitted as a separate file.

3.0 Development and Initial Applications of Modeling Tools for Freeze-Thaw Processes

In order to numerically investigate the role of groundwater flow within a discontinuous permafrost environment, modeling tools based on a fully coupled thermal-hydraulic-mechanical-contaminant (THMC) formulation designed to simulate processes related to soil freeze-thaw dynamics and permafrost degradation have been advanced. Several papers and a series of conference presentations have been prepared to support the model development. These are summarized at the end of the report. The models have been peer-reviewed and during the course of the past year, they have been applied to the first in a series of scenarios of interest.

Numerical assessment of the main physical processes influencing the freezing and thawing of subsurface water within the unsaturated and saturated zones involves the integrated processes related to heat transfer (temperature field), hydrologic processes (hydraulic field), soil poroelastic deformation (mechanical stress-strain field) associated with water-ice phase change and solute fate and transport (chemical field) phenomena.

The main objective of the modeling work is to analyze the role of transient, seasonal groundwater flow with respect to the short- and long-term fate of the discontinuous permafrost underlying the Bogg Creek watershed area of the CMV. Specific scenarios of interest include:

- Landscape change and thermokarst formation
- Water balance and quantitative surface water impacts
- Ecosystem changes
- Dissolved contaminant release to groundwater and surface waters

The initial simulation domain and conceptual model utilize a 2D cross-sectional hypothetical gravity flow system similar to that initially proposed by Toth (1962), with hillslope areas rising from a low elevation stream feature with topographic symmetry on both sides of the stream. A conceptualization of a degrading permafrost environment is presented in (Figure 6). The 2D simulator used in this study is based on the model presented by Huang, X., Rudolph, D.L., and Glass, B., 2022, which incorporates the heat transfer, surface and groundwater flow and soil mechanics processes (THM model). This model has now been extended to include conservative mass transport processes in porous media (THMC model by Huang & Rudolph, 2023 in final revision). The plans will be to further develop the model to accommodate reactive transport processes of interest.

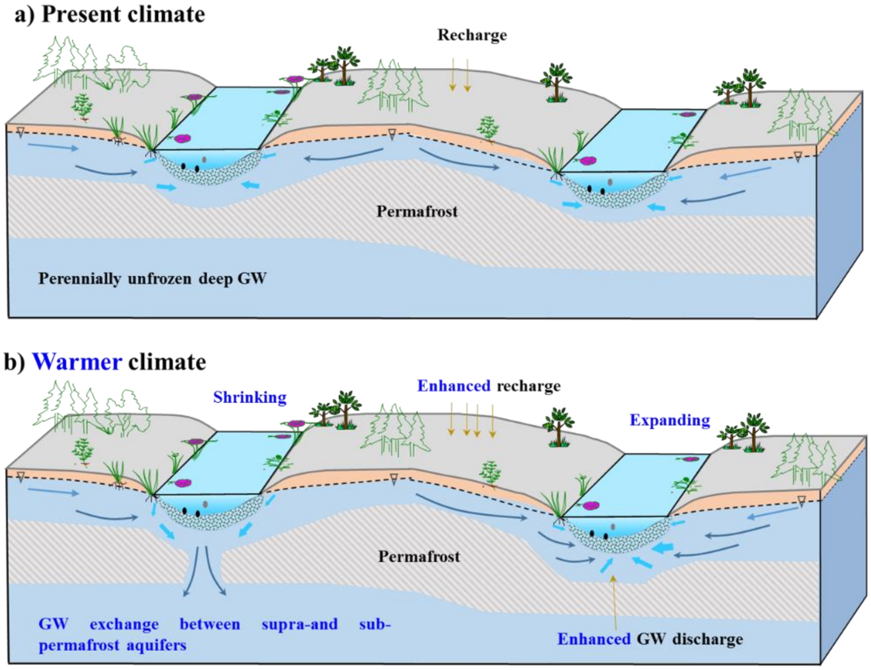

Figure 6. Conceptual sketches of permafrost evolution under (a) present and (b) warming climates (modified from Walvoord & Kurylyk, 2016).

For the initial round of numerical experiments, the finite element grid was designed to support a domain width of 1000 m and the depth is 500 m (Figure 7). The basin is symmetrical with a stream in the middle of two gently sloping hillsides. There is a 10 m elevation drop between the top of the hillslope at the lateral boundaries and the edge of the stream, which is spatially located in the center of the domain. The subsurface is initially divided into two layers, including the upper 100 m zone where the majority of the freeze and thaw processes will occur and the lower 400 m which represents the unfrozen, regional groundwater domain. The mesh discretization is finer for the upper layer to obtain higher resolution, but coarser for the lower layer to reduce computational effort. For the contaminant transport simulation scenarios, a rectangle subsurface region 100 m wide and 30 m deep is selected as the source area near ground surface. Conceptually, this could represent a small community landfill initially constructed within shallow permafrost, in frozen sediments.

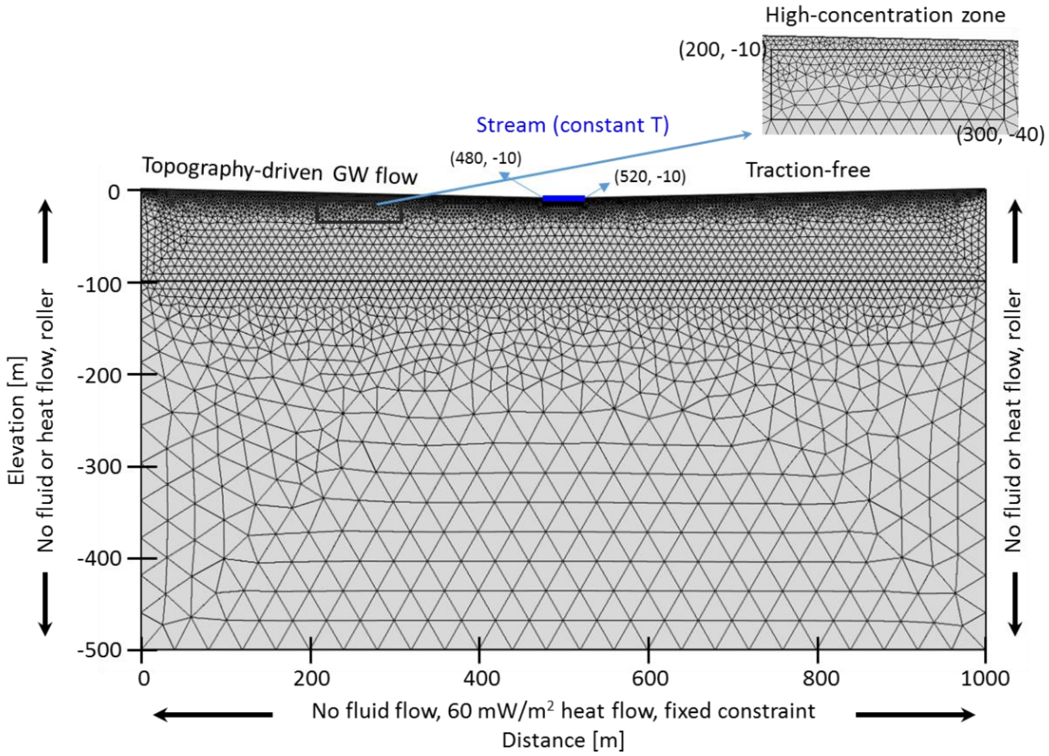

Figure 7. The geometry, mesh discretization and boundary conditions of the simulation domain. The blue line indicates the stream. The rectangle region denoted near the surface indicates the source region for the contaminant transport scenarios. Roller (vertical displacement only) and traction free (full displacement permitted) indicate boundary condition designations for the soil mechanics simulations (Huang and Rudolph, 2023).

The results from an extended freezing period (-2°C), that was used to establish a relatively thick section of permafrost within the simulation domain, followed by a 250-year thaw period are presented in Figure 8. The model calculates the formation of approximately 100 m of permafrost on both sides of the stream although the region beneath the stream remains unfrozen and represents a through talik (Figure 8a). In this initial condition, the solute contaminant remains frozen and immobile within the near-surface permafrost (Figure 8b). A warming period is then simulated with surface temperatures held steady at 1°C for 250 years. The permafrost degrades significantly (Figure 8c) and the previously trapped contaminant mass migrates towards the stream (Figure 8d). Subsequent simulations will focus on the deformation of the subsurface and land surface during the thaw period and will explore a range of parameter sensitivity analyses related to the main parameters that control the processes of interest.

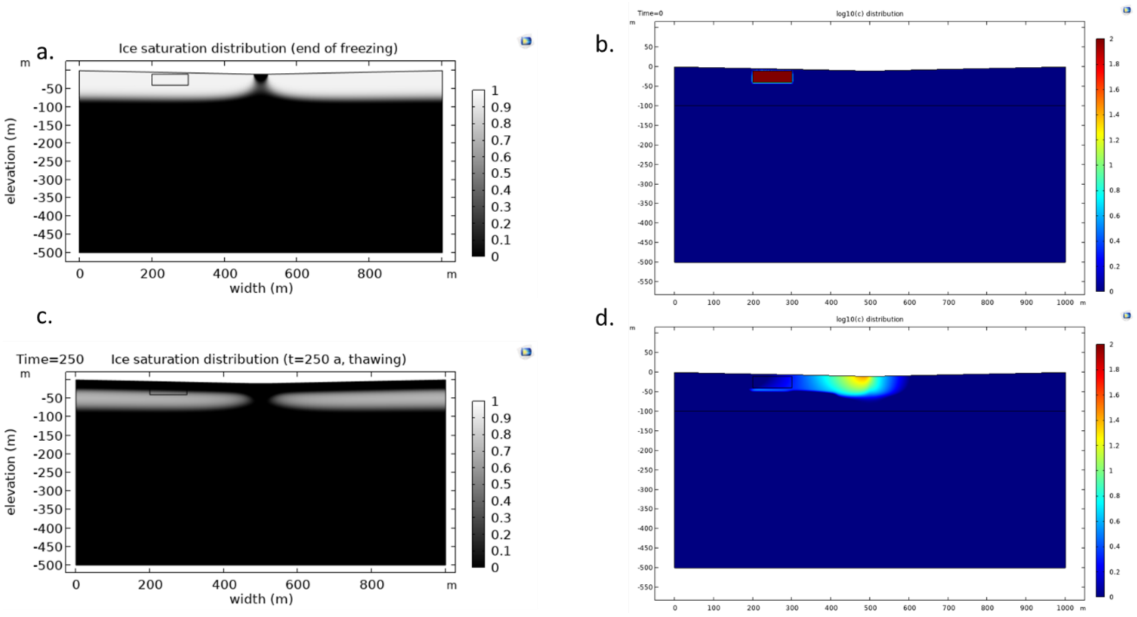

Figure 8. Numerical simulation results representing: a. subsurface ice content (permafrost) following an initial freezing period; b. solute frozen and immobile within an isolated source; c. subsurface ice content following a thaw period of 250 years and d. the migration of the solute contaminant with capture at the surface stream after 250 years of thaw and associated solute transport (Huang and Rudolph, 2023).

One of the main objectives of the modeling work will be to simulate the field conditions that have been observed within the Bogg Creek watershed. The additional site characterization and data collection planned for the 2023 field season will inform this next stage of modeling.

4.0 Proposed Year 7 Activities

The activities scheduled for Year 7, which represents an additional, no-cost extension to the original research program, will involve a series of terrestrial data collection programs and continued advancement of the modeling work. During the summer 2023 field season, field surveys using portable terrestrial geophysical methods including electrical resistivity tomography (ERT), electromagnetic induction (EMI) and ground penetrating radar (GPR) will be conducted at a series (up to 4) different field locations in order to accurately map the occurrence and depth to the permafrost table within the Bogg Creek Observatory. Main targets will be land adjacent different size water bodies and within natural and artificial clearings where permafrost degradation appears to be occurring at the most rapid rate. Data from these surveys will be used to ground truth and support further calibrate air borne electromagnetic (AEM) survey data that were collected over the field site in April 2022.

Building on the extensive geochemical data base that has been compiled by Cenovus and the University of Waterloo research team over the last decade, a targeted sampling campaign the focuses specifically on critical geochemical parameters and solute species will be undertaken during the summer 2023.The sampling will include a focus on a more detailed mapping of natural hydrocarbon releases at the ground surface and the fate and nature (including radiocarbon dating) of other carbon species that will further elucidate the nature of transient groundwater flow within the discontinuous permafrost environment.. These combined results will inform the next stage of modeling and further increase the understanding of the role of groundwater flow in this complex hydrogeological environment.

Finally, the new modeling tools will be applied to an extended group of relevant scenarios, integrating the new field data collected during the 2023 field season. The nature of the scenarios selected for investigation will be established through discussions with all collaborating parties to ensure that the highest priority issues are represented within the numerical experiments. These results have been partially shared with our colleagues from the Sahtu Renewable Resource Board, Tulita Renewable Resources Council and the Norman Wells Renewable Resources Council and will be further communicated during a virtual meeting planned prior to the summer 2023 field season.

5.0 References

Journal Papers

Huang, X. and Rudolph, D. L., 2023. Numerical study of coupled water and vapour flow, heat transfer, and solute transport in variably-saturated deformable soil during freeze-thaw cycles, in final revision with 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.

Rudolph, D. L., 2022. The nature of groundwater discharge, Groundwater Monitoring and Remediation, DOI:10.1111/gwmr.12540.

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.

Student Theses

Zhao, R., 2023. Delineating Permafrost Discontinuities Using Airborne Frequency-Domain Electromagnetics: Northwest Territories, Canada. BSc thesis, Dep. Of Earth Sciences, Univ. of Waterloo.

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.

J. Tóth, J., 1962. A theory of groundwater motion in small drainage basins in central Alberta, Canada, Jour. Of Geophysical Res., https://doi.org/10.1029/JZ067i011p04375.