Best Practices in Groundwater Monitoring for Northern Canada

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EXECUTIVE SUMMARY

Canada is a vast country with a very low population density and abundant freshwater resources, including groundwater. Groundwater is an important water resource for providing drinking water to communities, sustaining ecosystems and supporting industry. It is a critical component of the global Earth system that needs to be used sustainably and preserved for future generations. Given groundwater's mobility and connectivity, and despite its apparent abundance, its quality and quantity are critically vulnerable to contamination and volume changes. Therefore, knowledge of groundwater is required to ensure its proper stewardship.

A Canada-wide sustainability framework, applied at all levels of government, is needed to improve the management and understanding of Canada's groundwater. While an overarching Federal framework is still missing, the Government of the Northwest Territories (GNWT) requires a particular attention on the management of its groundwater resources. In order to progress with its groundwater stewardship plan, the GNWT collaborated with the Geocryolab research group at the Université de Montréal, in collaboration with McGill University, to review literature on best practices in groundwater monitoring, adapted to northern Canada and the Northwest Territories (NWT).

This report broadly portrays the state of groundwater knowledge within the context of the NWT. It specifically covers the following topics: 1) aquifer identification, 2) groundwater flow regime, and 3) groundwater monitoring. However, understanding the occurrence and movement of groundwater is very complex; there is no single all-encompassing method to characterize a groundwater system, particularly in permafrost conditions. Therefore, multidisciplinary and interdisciplinary assessment approaches are preferred and often required.

Due to the scarcity of permafrost-groundwater research, legislative frameworks, management, and monitoring in northern regions, we have broadly reviewed the current state of relevant knowledge for the various themes. We organized the report in four modules presenting different aspects of groundwater, and a fifth module with recommendations based on our findings.

In the NWT, groundwater is an important natural resource and we hope this report will improve its understanding and stewardship. The remainder of the executive summary introduces and summarizes each of the five modules.

MODULE 1 – FUNDAMENTAL CONCEPTS RELATED TO GROUNDWATER

Monitoring groundwater requires knowledge of hydrogeologic concepts and a broad understanding of local geologic and geomorphologic settings. For the NWT and other northern regions of Canada, knowledge regarding the distribution and properties of permafrost is also essential for monitoring. Module 1 provides a brief overview of the fundamental concepts of groundwater with a focus on permafrost hydrogeology.

MODULE 2 – KNOWLEDGE RELATED TO GROUNDWATER IN THE NWT

Groundwater and permafrost in the NWT are difficult to characterize due to the size of the territory, although some local studies provide useful information. Module 2 presents knowledge related to geology, aquifers and permafrost in the NWT. The module also refers to scientific, governmental and engineering reports that include data and interpretations about the local groundwater, permafrost conditions, and known and potential contamination sources.

MODULE 3 – FEDERAL, PROVINCIAL/TERRITORIAL LEGISLATION AND EXISTING GOVERNMENTAL MONITORING GUIDELINES

Module 3 presents the laws, regulations, guidelines, and policies that apply to groundwater resources in Canada, British Columbia, Alberta, NWT, Quebec, Yukon, and Alaska, specifically in regions affected by permafrost conditions.

MODULE 4 – MODELS, METHODS AND TOOLS FOR GROUNDWATER INVESTIGATIONS

Module 4 introduces different approaches and tools for representing, surveying, and documenting groundwater and permafrost. The investigative methods, while not exhaustive, include groundwater modeling, hydrogeologic characterization, data requirements, and water quality assessment.

MODULE 5 – RECOMMENDATIONS AND RESEARCH PRIORITIES

Module 5 provides recommendations based on the findings from this literature review. There are significant gaps between groundwater science and policy in the North, in part because there is not an effective conceptual framework for dealing with groundwater in permafrost environments, including a lack of observation data. These gaps are further exacerbated as the interactions of permafrost and hydrogeology, in the context of a warming climate, are not well understood.

Our research identified three major outstanding questions related to groundwater that must be resolved for the Northwest Territories:

1) The North is experiencing the fastest rates of climate warming in the world, leading to potentially rapid environmental change in the NWT. These changes are leading to a decrease in permafrost distribution and shifts in hydrologic regimes. How will these changes impact groundwater (e.g., supply, vulnerability, and recharge) in the NWT in the future?
2) Groundwater is an important natural resource for people, industry and the biophysical environment of the NWT. But, it is also vulnerable to contamination, over-extraction, and climate change. How best should groundwater be protected?
3) The NWT is developing and implementing transboundary agreements with neighboring territories and provinces. These agreements have an obvious and necessary focus on surface water, but also address groundwater. What is the importance of groundwater in transboundary systems, and how should it be included in implementation of these new agreements?

To address these questions, we propose several technical recommendations as described in Module 5. These recommendations include:

- Collaborate with the local communities and stakeholders to identify key values to inform groundwater monitoring and protection strategies. Further, by collaborating with the scientific community, the NWT can improve understanding of groundwater in permafrost and climate change settings.
- Create a climatic, hydrological-hydrogeological, and permafrost database, extracted from available sources (e.g. peer-reviewed publications, public datasets, government reports and industry reports) to establish the hydrogeology-related baseline conditions for the NWT. Based on this data, a preliminary groundwater aquifer map and GIS supported database of the NWT can be developed.
- Develop a groundwater management plan that incorporates key values, the state of permafrost, along with a strong understanding of the existing monitoring sites.
- Establish a preliminary groundwater observation network by utilizing existing wells, integrating their characteristics within a database, and monitoring their water levels and water quality. Monitoring operations should remain relatively simple to be sustainable in terms of time and resources. A clear monitoring plan should be developed based on regular sampling intervals (for example, monthly, quarterly or yearly sampling intervals).
- Develop intensive representative study sites that would be ideal for partnership with academic researchers, industry, and citizen-scientist outreach. These intensive sites would allow for monitoring and the development of process-based understanding of groundwater processes that could be extrapolated across the NWT.

- We recommend that data related to the drilling and completion of every new well drilled be added to the central database, including water quality data.
- Finally, develop a vulnerability criteria and risk index map for groundwater for selected regions of the NWT. This would help guide future policy development for groundwater.

CONTEXT AND INTRODUCTION

Trainer *et al.* (2010) state that Canada has less than 1 % of the world's population, but its river discharge represents over 9 % of the world's freshwater and that approximately 8.9 % of the country's surface is covered by water. Further, they also observe that the apparent abundance of water makes Canada vulnerable to the perception of unlimited supply. Groundwater represents a significant percentage of the country's freshwater supply for domestic, industrial and agricultural use (almost 10 million Canadians rely on it for drinking). Groundwater also plays a crucial role in the maintenance of ecosystem health and viability. While our dependence on groundwater is critical, our knowledge of it remains extremely fragmented, and cannot support a sustainable and integrated management initiative (Trainer *et al.*, 2010).

Following from the Federal policy prepared by Côté (2006), the Minister of Natural Resources Canada asked the Council of Canadian Academies to address the question 'what is needed to sustainably manage groundwater in Canada, from a science perspective?'. The 15-member panel, comprising members of various spheres of expertise, published a 270-page report concluding that a Canada-wide sustainability framework, applied at all levels of government, is required to improve the management and understanding of Canada's groundwater. Without such a framework, Canada's groundwater is at risk of contamination and depletion and its contribution to freshwater ecosystems remains under threat.

The Government of the Northwest Territories (GNWT) is moving in a similar direction. The unique geography of the Northwest Territories (NWT), such as the presence of permafrost, the low population density, the cold environment, and the indigenous co-management governance regime based on land claim and self-government agreements, requires particular attention in the management of its groundwater. The integrated management was already initiated by a territorial water stewardship strategy (Government of the Northwest Territories, 2010) and two action plans (2011-2015 and 2016-2020 (Government of the Northwest Territories, 2011; 2016, respectively)).

The GNWT has collaborated with the Geocryolab research group at the Université de Montréal, in collaboration with Professor Jeffrey McKenzie from McGill University, to review literature on best practices in groundwater monitoring, adapted to northern Canada. This research will benefit GNWT's understanding of hydrogeology and support the Mackenzie River Basin bilateral water management agreements with Alberta (2015a) and British Columbia (2015b). These agreements provide a framework for cooperatively managing shared waters (above and below the surface) and for establishing a common and agreed-to set of conditions regarding water quality, quantity, and aquatic life.

In 2017, a workshop on Permafrost and Hydrogeology Interactions was held in Yellowknife that brought together government, industry, and researchers with expertise and interest in cold regions groundwater. The report from this workshop (Morse, 2017) addresses groundwater quality, quantity and distribution, and provides a framework for the specific context of the NWT. It specifically targeted the following topics: 1) *aquifer identification*, 2) *groundwater flow regime*, and 3) *groundwater monitoring*. However, understanding the occurrence and movement of groundwater is very complex; there is no single all-encompassing method to characterize a groundwater system, and multidisciplinary and interdisciplinary approaches are preferred and often required. Each specific question, or need of knowledge, should require a specific and adapted methodology. The methodologies and tools to interpret groundwater-related features range as wide as the possible questions. In consequence, we have decided to organize our work in five different modules, each with a different perspective on groundwater.

Module 1 is the theoretic treatment of groundwater and permafrost. The first half of the module specifically concerns groundwater fundamentals while the second half focuses on the impact of permafrost on groundwater systems. The majority of the module is based on fundamental groundwater knowledge and the latest review publications. It also contains information from research papers where the knowledge is relatively new or specific.

Module 2 focuses on knowledge of the NWT's groundwater. The first third of the module includes an extensive literature review specific to the region. The second third of the module compiles scientific and engineering reports that include data and interpretations concerning local groundwater and permafrost conditions. The final third of the module examines known and potential contamination sources, also from scientific, institutional and engineering reports.

Module 3 provides a referenced overview of the legislation and guidelines relevant to the Canadian Government and other neighboring provinces, territories and states. The information exclusively represents public or para-public statements about water from neighboring administrations where permafrost is likely present.

Module 4 presents an overview of the tools and methods commonly used to assess groundwater. The first section details the main concepts related to the investigation of groundwater. The second section discusses modelling as a tool for groundwater characterization. The third section addresses the development of approaches and methods in hydrogeological investigation. The fourth section proposes a list of useful tools and techniques for groundwater investigation. Finally, the fifth section explores the considerations needed for selecting appropriate techniques, and presents an example of a successful survey approach and the techniques used.

Module 5 provides conclusions based on our findings for this report. In particular, we provide broad recommendations for the development of future monitoring networks, and identification of gaps in our current understanding of groundwater in the NWT.

In the NWT, groundwater is a critical natural resource and we hope this report will improve its understanding and stewardship.

MODULE

1

FUNDAMENTAL CONCEPTS RELATED TO GROUNDWATER

The occurrence, movement and storage of groundwater are largely a function of the geologic setting. Consequently, any groundwater assessment requires a broad understanding and characterization of the local geologic setting. Therefore, the starting point for understanding groundwater is to study the solid earth. Furthermore, understanding the physical properties of water itself is also necessary for assessing groundwater, especially when investigating water quality or contamination. Finally, the presence of degrading permafrost may significantly alter hydrogeological flow systems, so the properties and theory of permafrost must also be understood.

This first module summarizes the main concepts in physical hydrogeology, and includes a brief review of the key terminology and concepts that are used in other modules of this report.

FUNDAMENTALS OF GROUNDWATER FLOW

This subsection discusses porous geologic media such as rocks and sediments through which the groundwater flows and is stored, and then reviews the processes that control the movement of groundwater. The permeability values and their distribution, with reference to the NWT, are then described. This summary is not intended to be comprehensive or cover all subjects within the domain of hydrogeology.

POROUS MEDIA AND POROSITY

Geologic materials

Rocks are solid aggregates of crystalline minerals and non-crystalline mineraloid solids. The chemical nature and structure of the minerals affects the crystal's size, appearance, and stability. The rheological properties (strength) of different rocks determine how they deform and fracture, and this has a dominant control on their permeability (see next section). The mineral composition (mineralogy) of the geologic material in which groundwater flows is a primary geological control of water chemistry over time.

Rocks are classified in three main lithological categories (or rock types): sedimentary, igneous, and metamorphic (Marshak, 2013). *Igneous intrusive* (or plutonic) rocks crystallize from cooling magmatic intrusions within the earth's crust. *Igneous extrusive* rocks are lava that crystalizes at or near the Earth's surface, typically in the vicinity of volcanic vents. *Metamorphic rocks* are the complex result of long heating and compression of existing rocks, resulting in physical and mineralogical changes. There are different grades of metamorphic change and a large variety of resulting rock types.

Sedimentary rocks cover about 70 % of the rock outcrops on the Earth's surface, while most of the continental crust (75 %) is composed of igneous and metamorphic rocks (Wilkinson *et al.*, 2009). Sedimentary rocks are lithified sediments that are derived from the physical and chemical weathering of existing rocks. They are usually deposited in aquatic systems such as oceans. The main lithological categories are the coarse-grained siliciclastic rocks such as sandstone, that are generally the most permeable, and the fine-grained and less permeable mudstone or shale. Another common sedimentary rock is carbonate (e.g., limestone) that has a wide range of permeability (permeability is discussed in the following section).

Sediments are unlithified geological materials such as gravel, sand, silt, and clay, categories which are dependent on grain size. In the NWT, sediments have been extensively reworked by glacial ice flow, which deposit a wide variety of sediments and landforms (Ehlers *et al.*, 2011). In hydrogeology, "bedrock" generally refers to the crystalline rock of the continental crust that is found underlying Quaternary age sediments. Reworked sediments (e.g., tills) with clasts of various sizes and fine-grained sediments (e.g., clay) give these sediments typically low permeability. Other sedimentary features related to glacial processes, such as eskers and moraines, may contain more coarse-grained sediments that are generally more permeable (Walker & James, 1992).

Porosity

Porosity and permeability are the fundamental hydrogeological properties of porous materials that control the storage and movement of groundwater. Porosity refers to the pore space between grains in sediments or granular rocks, dissolved vugs in limestones and other rocks, open channels in macro-fractures that are visible in rock samples, and micro-fractures between and within solid mineral grains at the microscopic scale. At the largest scale, porosity includes cavernous spaces such as karst caves and flow channels in carbonate rocks, and fissures caused by faulting and other processes.

The *total porosity* is the total volume that a fluid can fill between the solid materials, and the *effective porosity* is the porosity of interconnected pores that can be filled and drained by fluid in a relatively short period of time. Over geologic time scales, all pores can be filled by water and other fluids. Rocks also contain microscopic fluid inclusions that normally do not contribute to porosity. Total porosity usually varies from much less than 1 % in dense crystalline rocks at deep depths, to less than 10 % for weathered rocks near the ground surface, to 10 to 50 % for siliciclastic rocks and sediments, depending on their composition. Clay-rich rocks such as mudstone and shale, as well as clayey sediments, have high total porosity (up to ~40 %), but the pore sizes are small and their interconnections very small or disconnected.

Representative Elementary Volume

In hydrogeology, nearly all analytical and numerical methods, and thus all reported values of hydraulic conductivity, permeability and porosity, represent an average value for a given volume of porous media. This volume is much larger than the size of individual pores or fractures. Theoretically, the minimum volume that can be studied using this approach is defined as the *representative elementary volume* (REV) (Figure 1). The REV approach allows hydrogeologists to study the movement of groundwater at field scales and larger, rather than needing to focus on microscopic or pore-sized processes.

Other useful definitions of porosity and permeability distributions at scales larger than the REV include:

- Homogeneous material – the porosity or permeability does not vary significantly in three-dimensional space of the material. Sand is typically fairly homogeneous.
- Heterogeneous material – there is large spatial variation in porosity and/or permeability of the material, complicating groundwater flow and occurrence. Most rocks and sediments are heterogeneous.

- Anisotropic material – there is a preferred or dominant orientation where the permeability is greater than in any other direction. Layered sedimentary rocks are anisotropic.
- Isotropic material – for a given material, the permeability is the same in all directions in three-dimensional space. In other words, groundwater can flow readily in all directions given a similar pressure gradient.

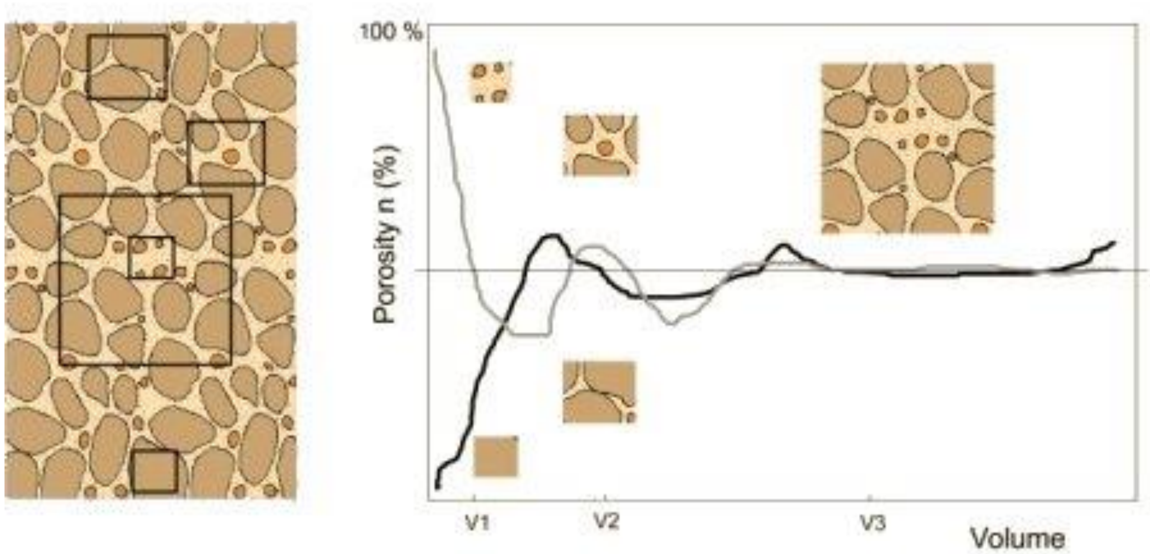


Figure 1. The illustration of the concept of Representative Elementary Volume (REV) of porous media's hydraulic properties such as porosity and permeability in hydrogeology (after Bear et al., 1993).

In fractured rocks, the overall permeability depends on the fracture size (e.g., aperture, geometry, length), the connectivity of the fractures, the distribution of the fracture network (e.g., isolated fractures, or networks that have an end, have the same permeability at larger scales as the surrounding "unfractured rock"), and the rock matrix between the fractures (Bour & Davy., 1997).

Porosity and permeability are divided into two domains: *primary* porosity and permeability refer to the matrix of cohesive rock that is not visibly fractured, and *secondary* porosity and permeability refers to the fracture networks that are open and can conduct groundwater (Figure 2).

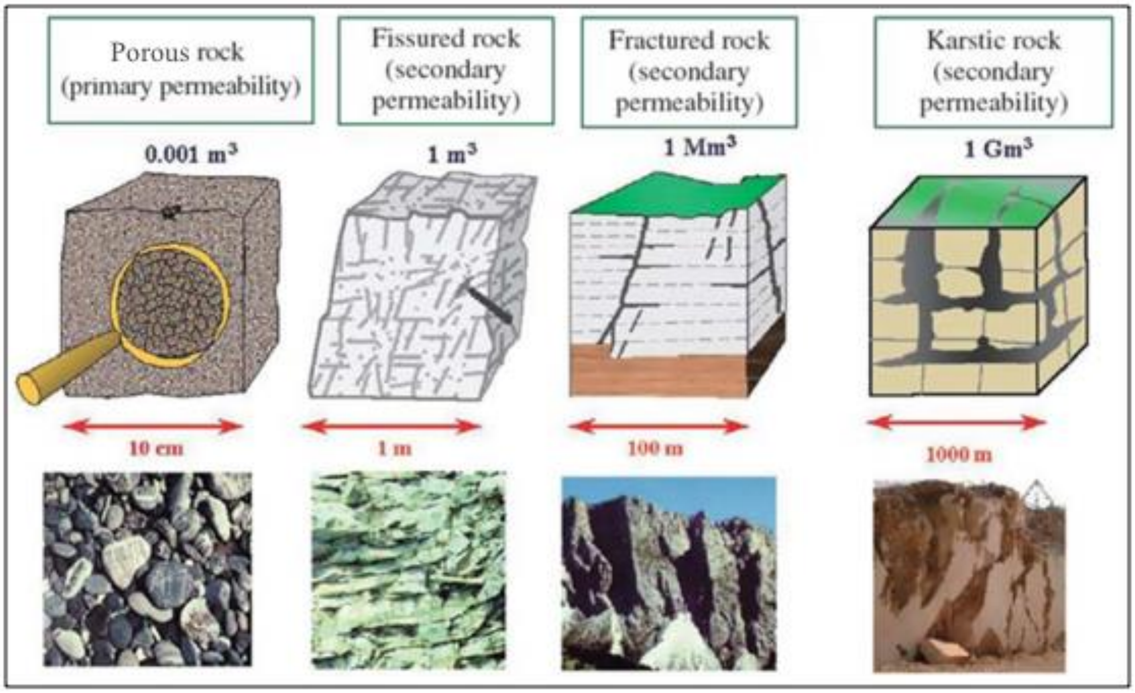


Figure 2. Graphical summary of the main types of porous materials that can be averaged in a Representative Elementary Volume to estimate hydraulic properties of rocks and sediments (Scesi & Gattinoni, 2007).

GROUNDWATER FLOW PROCESS

Darcy's Law

In porous media, where groundwater flows relatively slowly (i.e., laminar flow conditions), Darcy's Law describes the empirically-determined relationship between the flow (or discharge) rate and the driving force expressed as the hydraulic gradient (related to the physical pressure difference between two locations). The constant of proportionality is called the hydraulic conductivity:

$$Q = -K \cdot A \frac{dh}{dl}$$

Equation 1

Where: Q flow rate (m^3/s)
K saturated hydraulic conductivity in the direction of decreasing hydraulic head (m/s), i.e. in the x-direction
A cross-sectional area (m^2), at right-angle to the x-direction
dh difference between total hydraulic head of the fluid at two points separated along the x-direction (m)
dl distance between the two points in the x-direction (m)

Hydraulic conductivity and permeability

Permeability (or intrinsic permeability) refers to the ability of the solid porous media to transmit a fluid, and is independent of the fluid. This parameter is used widely in earth sciences (e.g., structural geology, geology, geophysics) as it is a property of only the porous medium. In granular media, such as sediments or clastic sedimentary rocks, it depends on the diameter of the pore sizes (and grains). While in fractured media, it generally depends on the fracture aperture and connectivity.

Hydraulic conductivity is a simplified parameter to describe permeability that assumes that the fluid is only water at near surface conditions, and that the density and viscosity of water do not vary. Hydraulic conductivity is widely reported in hydrogeologic reports, numerical models of groundwater flow, and in regional aquifer properties where the groundwater temperature and density does not vary greatly (e.g., cool fresh water). Hydraulic conductivity is a special case of permeability that assumes the water temperature and density vary very little compared to the variation of permeability (the porous media property within the hydraulic conductivity value). In geothermal flow systems, or deep groundwater flow systems where temperature and water salinity (and density) vary significantly, or in freshwater-saltwater interfaces along the ocean coasts, the fluids and solid properties must be specifically estimated.

The standard unit of permeability is m^2, but it may also be reported in other units such as the "Darcy" or mD (milli-Darcy), where 1 Darcy = 10^{-12} m^2 and 1 md = 10^{-15} m^2. In hydrogeological studies of fresh groundwater at shallow depths, the hydraulic conductivity is usually reported in m/s units.

Flow velocity

It is useful to estimate the average velocity of groundwater to be able to calculate the speed at which contaminants can be transported, or to calculate the residence times. The average linear velocity depends on the discharge rate, the cross-sectional area, and the effective porosity:

$$\vec{v} = \frac{Q}{A \cdot n_e}$$

Equation 2

Where: v average linear velocity of groundwater (m/s)
n_e effective porosity (unitless)

Hydrogeologic units (aquifers, aquitards and aquicludes) and their transmissivity

The term *hydrogeologic unit* is commonly used and refers to a geologic unit that has a permeability distinct from other surrounding units. Hydrogeologic units can be present in different geologic formations, in surficial sediments, or in parts of the same geological formation or sediment.

Much of our current conceptual understanding of hydrogeologic units originates from water resource investigations in layered sedimentary rocks, where an *aquifer* is defined as a relatively permeable geologic unit that was productive when pumped by groundwater wells. An *aquitard* is a relatively less permeable unit for groundwater flow, and an *aquiclude* is generally considered as having very low permeability and is a barrier to groundwater flow. The concept of aquifers is retained in the practice of groundwater resources management and major regional aquifers are well characterized.

Transmissivity

Transmissivity (T; m^2/s) is the product of the vertical thickness (b) of a hydrogeologic unit and its hydraulic conductivity (K):

$$T = b\ K$$

Equation 3

Transmissivity is generally applied to layered aquifers and aquitards. In geothermal engineering and petroleum engineering, where reservoirs are characterized at depths of kilometers, the hydrogeologic transmissivity is not used. Instead, the permeability-thickness is reported (in units of m^3), where c is the aquifer or reservoir vertical thickness (similar to b in Equation 3), and k is the permeability of the porous media:

$$permeability\ thickness = c\ k$$

Equation 4

The advantage of permeability-thickness is that water viscosity is excluded from the assumptions (or constant temperature and pressure are assumed), thus only the porous media "solid" properties are compared. Therefore, this parameter remains the same at all water temperatures, pressures, and depths. Note that this is not applicable for transmissivity, as this parameter assumes that density and viscosity are constants.

Specific yield and specific storage

When water is removed from a hydrogeologic unit (e.g., from pumping), the amount of water released is a function of the unit's storage. In an unconfined aquifer (i.e., an aquifer that is open to the atmosphere and not overlain by a low permeability geologic unit), the amount of water released is called the specific yield (Sy), and is similar in value to the unit's porosity (Hantush, 1964). In a confined aquifer, where the hydrogeologic unit is isolated by an overlying low permeability unit, the specific storage (Ss) is the amount of water expelled from a saturated geologic material due to a decrease in pressure (such as pumping).

Unsaturated zone

The water table is the planar surface that defines the upper boundary of the saturated zone and the lower boundary of unsaturated zone. In the saturated zone, all available pore space is filled with water, whereas in the unsaturated zone the pore space contains both water and air. Technically, the water table is defined as the boundary where the hydrostatic pressure of groundwater is equal to that of atmospheric pressure, and in some cases, there may be a small saturated fringe above this surface due to capillary forces. In soil sciences, the unsaturated zone is often referred to as the vadose zone.

The unsaturated zone can be divided into three sub-zones (Figure 3):

- the soil-water zone, which retains only water that is adsorbed to the surface of soil grains;
- the intermediate zone which holds adsorbed water plus a given amount of pendular and capillary water. This storage is a function of pore-size distribution and distance from the water table; and
- the capillary fringe, which is almost completely filled with adsorbed, pendular and capillary water that rises above the water table due to surface tension and capillary forces within the porous media.

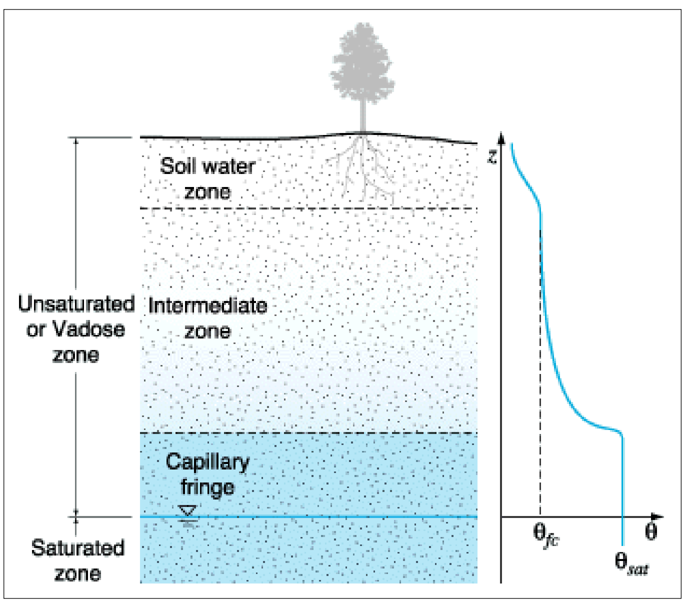


Figure 3. Schematic diagram of the capillary fringe interface between the vadose (unsaturated) zone and the saturated zone. The distribution of moisture in the vadose zone and the classification of waters is from Meinzer (1923).

LOCAL AND REGIONAL FLOW SYSTEMS

A groundwater system comprises the subsurface water, the geologic media containing the water, flow boundaries (e.g., watershed divides), sources of groundwater (e.g., infiltration of recharge), and removal of groundwater (e.g., springs, inter-aquifer flow, or wells).

Generally, groundwater flow systems are assumed to be nested. Local topographic features will drive *local flow systems* which are generally shallow and have short residence times. At the regional scale, from major topographic highs to topographic lows, there exist *regional flow systems* with comparably long residence times. In many settings, there are *intermediate flow systems* with residence times between that of the local and regional flow systems. Theoretically, there is very little interaction or mixing between the different flow systems. See Figure 4 for a graphical representation.

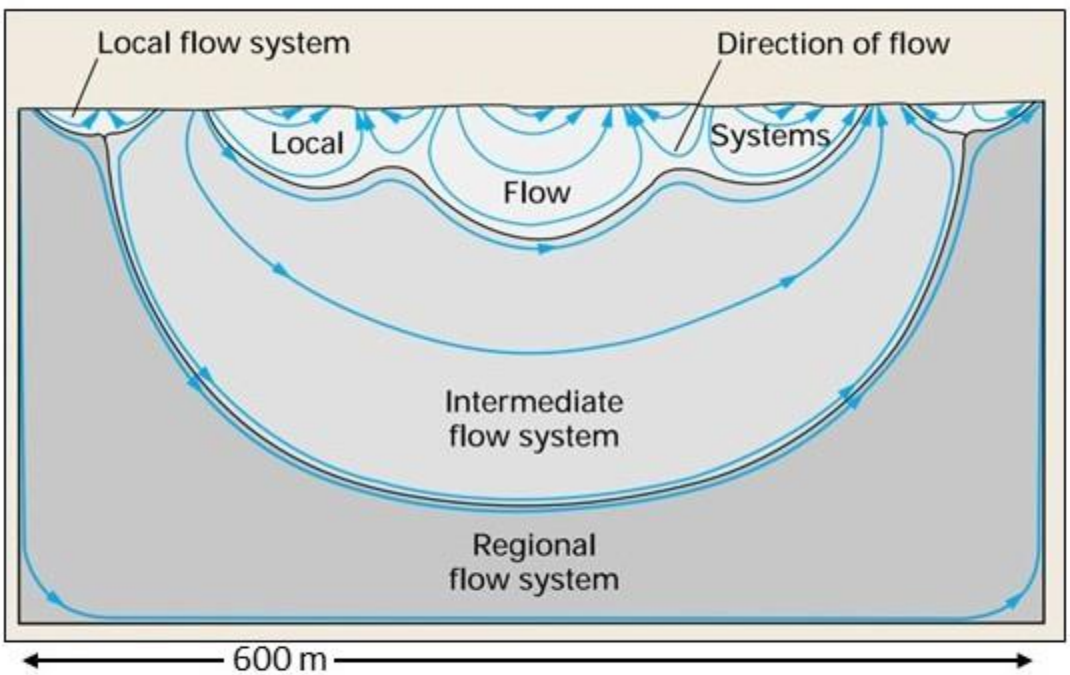


Figure 4. A groundwater flow-net in a two-dimensional vertical cross-section that describes the flow of water through the subsurface. The figure shows how a flow system develops that includes local, intermediate and regional flow systems (from Winter et al., 1998; Toth, 1963).

Over large regional scales, the depth to the water table below ground and its variation over time, combined with the length of the groundwater flow system and the hydraulic conductivity, can be used to broadly classify hydrogeological regions into (Gleeson *et al.*, 2011):

- recharge-controlled water tables (e.g., mountainous areas such as the Western Cordillera), where the groundwater flow component is an important part of the watershed water budget; and
- topography-controlled water tables (e.g., areas of the Canadian Shield and NE USA), where the groundwater table is close to the land surface and is less variable seasonally.

PERMEABILITY VALUES

Although not explicitly stated, in most consulting reports and scientific literature, permeability is reported as *bulk permeability.* This permeability is the total permeability of some tested rock volume, usually tested in-situ (at depth, inside the rock or sediment, often using a test involving one or more drill holes). Bulk permeability is comprised of two components; the *matrix permeability,* which is the permeability of the host rock only, and the *fracture permeability,* which is the permeability of an open fracture space within the host rock. In most rock types, and especially in low-porosity fractured rocks, most of the hydraulic tests that are performed report bulk permeability. The different test scales and methods used in hydrogeology and other geosciences are summarized in Bense *et al.*, (2013).

Permeability is 'scale dependent', which means that the larger the volume of rock that is tested for permeability, the larger the value of permeability will be. For heterogeneous and fractured hydrogeologic units, the scale dependency of permeability is high (Schulze-Makuch *et al.*, 1999). While for homogeneous hydrogeologic units, the scale dependency is low. The goal of hydrogeologic testing is to adequately test the rock volume at different scales and locations in order to capture the natural variability over space of the permeable flow pathways (Sanchez-Vila *et al.*, 2006), and identify the most dominant flow pathways.

Typical ranges of *bulk* permeability values for rocks and sediments are illustrated in Figure 5. These values are originally from Freeze & Cherry (1979), and are not specific to any region. Locally, permeabilities may differ by orders of magnitude in the same rock types or sediments. For rocks, the permeability of fault zones is not included in these typical ranges. For comparison, the matrix permeabilities of the "unfractured rock" are many orders of magnitude smaller for low-porosity rocks such as plutonic (igneous intrusive) and metamorphic rocks, many carbonate rocks, as well as many siliciclastic rocks that have low primary permeability.

Permeability-depth trends

Permeability is generally thought to decrease with depth. In sedimentary basins, sandstone and carbonate rocks exhibit a statistical correlation between permeability and porosity. Therefore, with depth there will be increased overburden pressure, decreasing porosity and permeability. Global petroleum reservoir data show a clear trend of decreasing average permeability with depth (1 to ~5 km) in sandstones, but not necessarily in the carbonates (Ehrenberg & Nadeau, 2005).

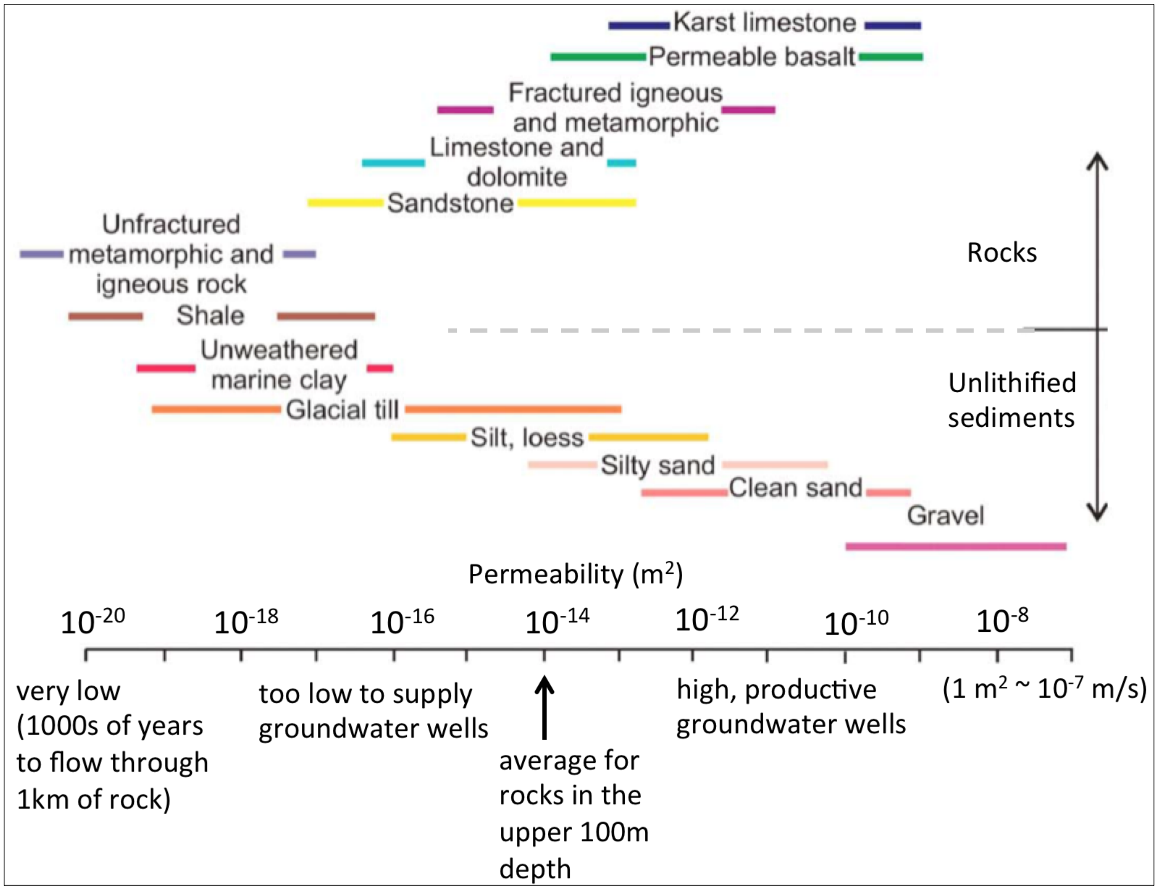


Figure 5. Typical ranges of rock and sediment permeability reported in hydrogeological textbooks, not specific to any region and not necessarily a global average or local areas with above-average enhanced permeability such as fault zones (modified after Gleeson et al., 2011, Freeze & Cherry, 1979).

In metamorphic and plutonic rocks, there are also global patterns of permeability decreases with depth. For example, 20 000 hydraulic test results were compiled at the Swiss Federal Institute of Technology in Zurich (ETH Zurich) (Achtziger-Zupančič *et al.*, 2017) from depths of 0 to 2 km, including sites from northern Canada (Figure 6). Resulting permeability distributions define a broad range of values and a clear trend with depth. Near the ground surface, mean permeability is approximately 10^{-14} m^2, but with a wide range from 10^{-18} to 10^{-8} m^2. At least half of the studied locations would be productive groundwater aquifers for small community water supply (refer to the horizontal axis in Figure 5). At 2 km depth, the test results have a mean permeability of about 10^{-17} m^2 and most results are between 10^{-20} to 10^{-14} m^2.

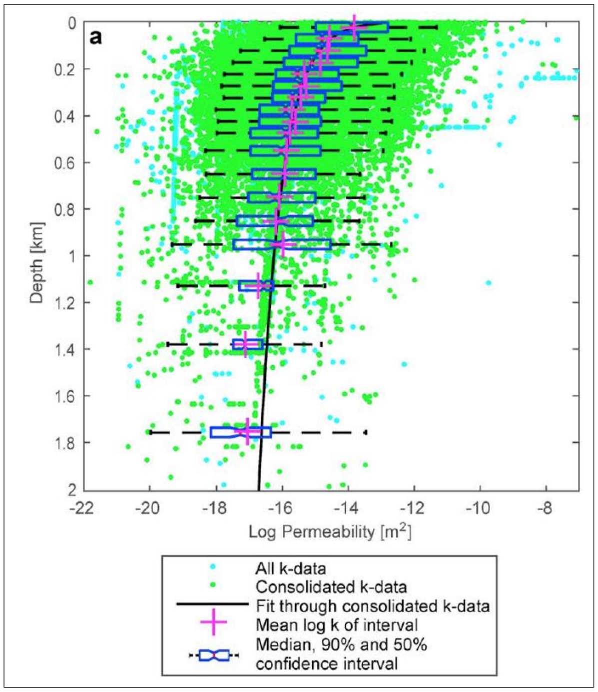


Figure 6. Decreases in permeability with depth fitted to the compiled hydraulic test data over a depth range of 0 to 2 km (Achtziger-Zupančič et al., 2017).

REGIONAL PERMEABILITY DISTRIBUTIONS IN THE NWT

There is very little information on the permeability of rocks and sediments in the NWT. As a first estimate, it is possible to survey a large number of global data sets for different rock lithologies (Gleeson *et al.,* 2011) and to assign these average bulk permeability values to the NWT. The northern portion of Gleeson's *et al.* (2011) analysis is shown in Figure 7.

While these statistical estimates are theoretical in nature and have not (yet) been validated with field testing, Gleeson's *et al.* (2011) analysis suggests that, for example:

- the carbonate (limestone) rocks on Victoria Island might have permeabilities of 10^{-12} m^2 at shallow depths because of high potential for karstification and dissolution pathways along fractures;
- the upper 100 m of the sedimentary rocks in the Western Canadian Sedimentary Basin and in the Mackenzie Mountains might have permeabilities of approximately 10^{-15} to 10^{-18} m^2, and up to 10^{-12} m^2 in karst limestones;
- the upper 100 m of fractured and weathered metamorphic rocks of the Canadian Shield might have permeabilities ranging from 10^{-14} to 10^{-15} m^2, a range that is approximately the global average for such rocks; and
- coarse-grained sediments filling valleys in parts of the Canadian Shield might have permeabilities in the range of 10^{-12} to 10^{-13} m^2.

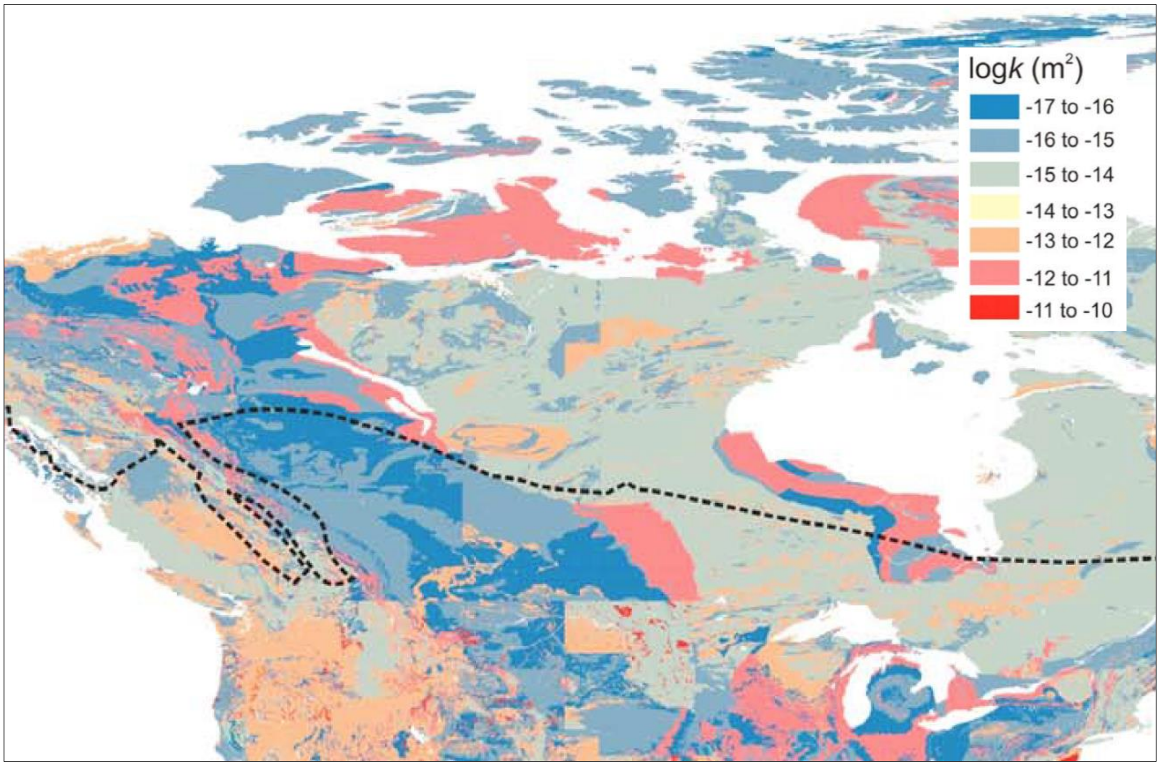


Figure 7. Estimated average rock aquifer permeability in the upper 100m based on average permeabilities from hydrogeological models, globally, by lithological category of the rocks (Gleeson et al., 2011). The permeability values are shown on a logarithmic scale (e.g., -17 means $1x10^{-17}$ m^2) and the color shades differ by one order of magnitude in their sequence. The dashed line shows the southern extent of discontinuous permafrost (Brown et al., 2001), where the permeability of frozen rock will potentially be much lower than indicated.

GROUNDWATER AS PART OF THE WATER CYCLE

Globally, water is continually transferred between different 'reservoirs', including oceans, atmosphere, surface waters, glaciers, and groundwater (e.g., NASA, 2017; USGS, 2017). In this report, we review the published information about the role of groundwater in northern Canada's water cycle, with a focus on examples from the NWT.

The large-scale NWT water cycle has been studied as part of the Mackenzie GEWEX (Global Energy and Water Cycle Experiment) Study (Kraus, 1995; Woo, 2007). An example of an inferred (conceptual) water cycle in the western part of the NWT is described in the hydrogeological report by Golder Associates (2015) (Figure 8), as part of the hydrogeological review of the Sahtu region of the Mackenzie Valley.

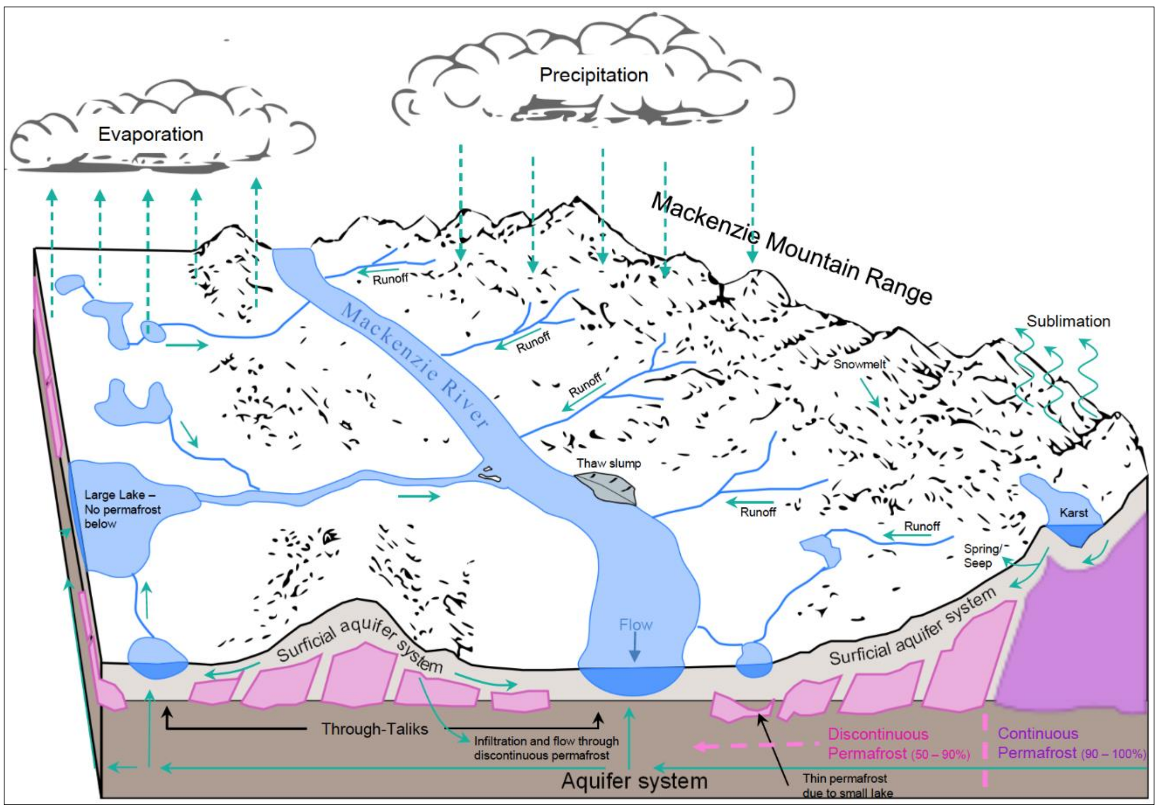


Figure 8. Conceptual model of the water cycle in central Mackenzie Valley (Golder Associates, 2015).

WATER BUDGET ESTIMATIONS

An estimation of the total quantity of groundwater in the NWT is not known to exist. Any estimate depends on the assumed porosity distribution in the surficial sediments and rocks. Since the porosity of weathered, fractured crystalline rocks, and sparsely fractured deep crystalline rocks is low, most groundwater storage is in sedimentary rocks and unconsolidated sediments that cover the NWT's western regions. Further complicating groundwater estimations, some of the groundwater is immobilized within permafrost zones. Considering the surface area of the NWT, and some hundreds of meters of sediment or sedimentary or weathered/fractured rock thickness that holds freshwater, the volume of groundwater can be qualitatively described as large, in comparison to the groundwater use in the NWT. Groundwater availability and sustainability at any location depends on the local aquifer properties and surface conditions such as recharge, thus it cannot be easily generalized to the territory until the aquifers are mapped and tested.

From the perspective of a surface water catchment area, a simple water budget can be described as:

$$P = ETS + R + GW + \Delta S$$

Equation 5

Where:

Where:	P	total precipitation
	ETS	evapotranspiration and sublimation from ice or snow
	R	surface runoff in streams and rivers, as well as artificial extractions and diversions (in northern areas, blowing snow and flowing ice can also transfer water)
	GW	groundwater flow across catchment boundaries
	ΔS	change in stored volume of surface and unsaturated zone water (ponded, in soil and vegetation, in snow and ice)

In the case of a sub-catchment that also receives surface water flow from above areas, additional inflow terms are added.

From the perspective of a groundwater aquifer, the water budget is:

$$recharge = discharge + \Delta S_{GW}$$

Equation 6

Where: ΔS_{GW} is the change in stored groundwater

The recharge to an aquifer is usually derived from infiltrating surface water, melting ice, lateral inflow from other aquifers, or flow along faults of fluids from deep hydrothermal sources. Discharge includes any form of outflow of groundwater.

GROUNDWATER-SURFACE WATER INTERACTIONS

The interaction between surface water (e.g., a stream or river) and shallow groundwater is shown graphically in Figure 9 (Alley *et al.*, 2002). A recent scientific review of the subject was done by Fleckenstein *et al.*, (2010). Generally, there are two types of these interactions: 1) hyporheic interactions, which are confined to the near stream area and include the relatively rapid exchange of stream water with the surrounding groundwater; and 2) groundwater – surface water interactions which result in a regional net gain or loss of surface water. The interaction of these two systems is complex. The section

'Watershed Hydrology and Permafrost' further presented in this module provides more detail on how permafrost controls groundwater – surface water interactions within the context of the NWT.

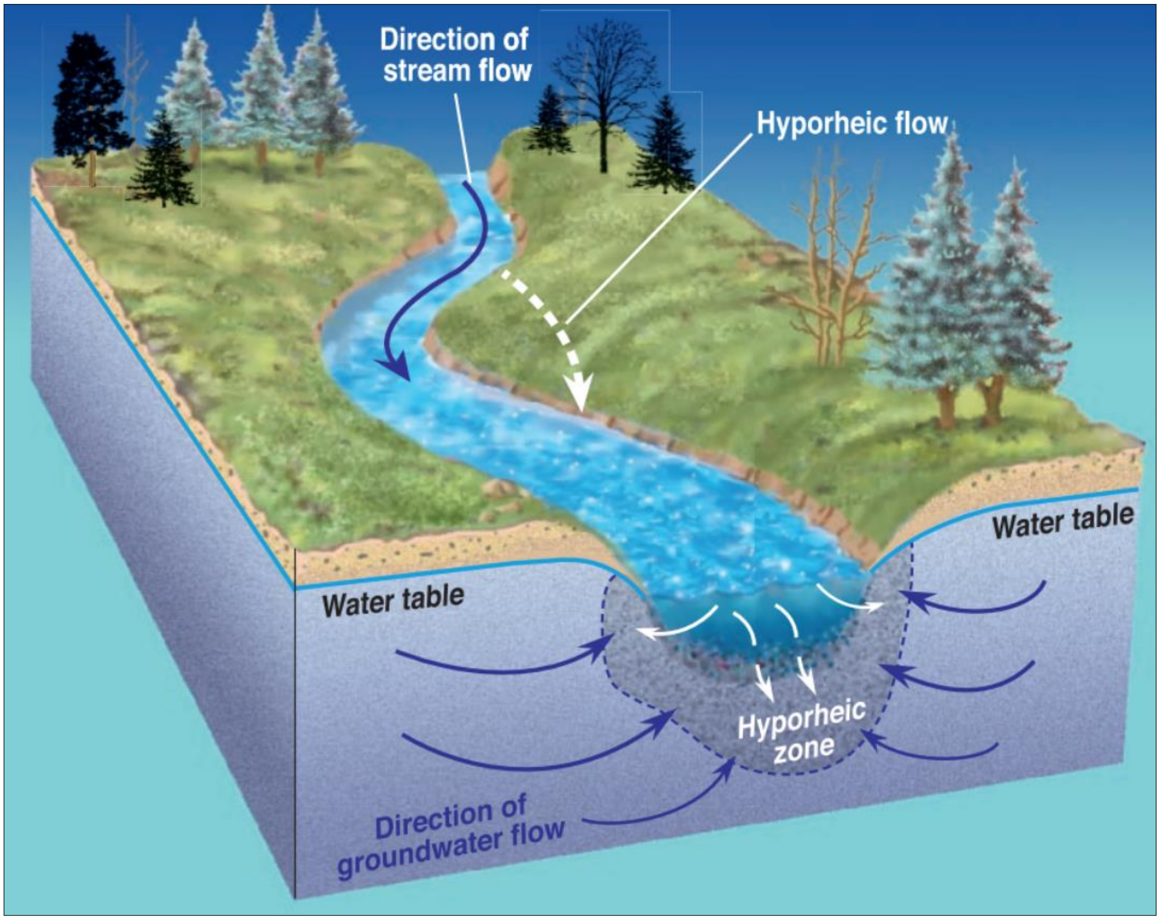


Figure 9. The near-stream environment and groundwater interactions (from Alley et al., 2002).

Groundwater residence time

The residence time of groundwater refers to the time a water molecule spends in the subsurface since infiltration. The most recent global surveys estimate that less than 6 % of the groundwater in the uppermost portion of the Earth's landmass is less than 50 years old (Figure 10), but the volume of this 'modern' groundwater is still quite large (Gleeson *et al.*, 2016). Past estimates were based on regional groundwater flow models that assumed that the water table was a subdued outline of the ground topography (Cardenas Jiang, 2010), a commonly-used assumption. Older and deeper groundwater globally has, on average, a residence time in the range of 100 to 10,000 years (UCAR, 2011). Surface water and water held in ice have a much shorter residence time.

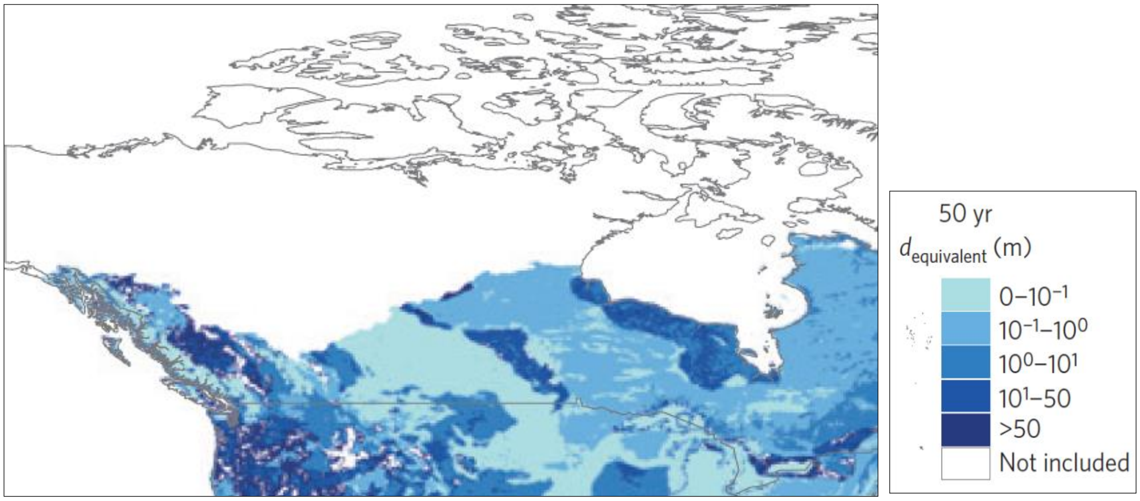


Figure 10. The global distribution of equivalent depth (as if stored above ground) of modern groundwater (<50 years old) based on groundwater recharge models, shown here for a portion of North America, including the NWT (from Gleeson et al., 2016).

GROUNDWATER GEOCHEMISTRY AND QUALITY

The following section provides a brief overview of aqueous geochemical principles as they relate to groundwater.

PHYSICAL PROPERTIES OF WATER

Water is an inorganic molecule with the chemical formula of H_2O.

Water's density has a very anomalous behavior. The density of ice at 0 °C is 917 kg/m^3, while it's liquid water density at the same temperature is close to 1000 kg/m^3, and varies with temperature (Figure 11).

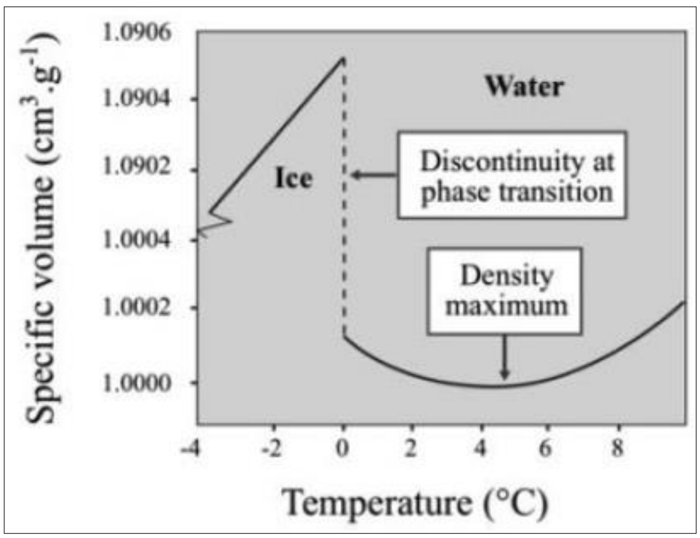


Figure 11. Temperature dependence of pure water's specific volume (inversely proportional with density) (Lécuyer, 2014).

PHASE CHANGES OF WATER

At the earth's surface and in the atmosphere, water exists in three physical states: solid, liquid, and gas. The transition between phases results from changes in environmental conditions and subsequent energy transfers. A change of state requires a gain or loss of latent heat. The addition of energy to water decreases the probability of inter-molecular bonding that in turn causes the matter to change state through melting, vaporization or sublimation. Inversely, the removal of energy causes a gain of inter-molecular bonds and a shift towards denser states through freezing, condensation or deposition.

Compared to any other material, water requires a large amount of energy to change its state (Table 1) and, compared to other materials, water also requires a large amount of energy to change its temperature (specific heat) while remaining relatively thermally conductive (Table 2). Due to the high specific heat and latent heat of water, it effectively dampens temperature oscillations in near-surface environments such as soils.

Table 1. Latent heat for pure water phase transitions across regular temperatures (Lide, 2004).

Type of transition	Lower energy phase transition	Higher energy phase transition	Related latent heat
Solid to liquid (0 °C)	Melting	Freezing	334 kJ/kg
Liquid to gaseous (100 °C)	Vaporization	Condensation	2 257 kJ/kg
Solid to gaseous (0 °C)	Sublimation	Deposition	2 591 kJ/kg

Table 2. Specific heat and thermal conductivity for pure water (Lide, 2004).

Phase	Specific heat	Thermal conductivity
Solid (0 °C)	2.05 kJ/(kg °K)	2.220 W/(m °K)
Liquid (20 °C)	4.18 kJ/(kg °K)	0.598 W/(m °K)
Gaseous (100 °C)	2.08 kJ/(kg °K)	0.024 W/(m °K)

Groundwater does not freeze exactly at 0 °C, as the theory for pure water might suggest. Solutes, positive gravity pressure and negative capillary pressure depress the groundwater's freezing temperature. Using nuclear magnetic resonance, Watanabe & Mizoguchi (2002) showed that liquid water can exist in porous media with temperatures as low as -25 °C.

AQUEOUS SOLUTIONS

The chemical composition of groundwater is important for water quality, controlling groundwater contamination, and for tracing groundwater flow systems. Natural water generally contains a complex mixture of chemical elements and molecules, including dissolved oxygen, carbon, nitrogen, sulfates, nitrates, and trace gases, in various forms, with other minerals and organic content.

A solution is a homogeneous mixture of at least two chemical compounds. More specifically, it is the dissolution of at least one solute in a solvent. Water is one of the best natural solvents due to its hydrogen-bond and resulting bipolarity. In other words, it is the substance that can dissolve the widest range of chemical compounds. In water, dissolved solutes are said to be in the aqueous phase.

Not all molecules are soluble in water, but every soluble molecule has a specific maximum solubility for a given condition (pressure-temperature). In the case of water, solubility refers to the ability of water to dissolve a solid, liquid or gas, and dissolution is the process where a solute dissolves into water. Generally, as temperature increases, the solubility of gases in water decreases and the solubility of solids increases. Pressure has a negligible effect on the solubility of solids in water, but changing pressure affects the solubility of gases, where increasing pressure increases the solubility of gas (the inverse is also true). Solutes are generally unable to be incorporated into the crystalline phase of ice, so the process of freezing normally expels them. Therefore, ice forms as a solid composed mostly of pure water and the solution's freezing temperature decreases while the remaining solution's concentration increases.

The precipitation of compounds occurs when dissolution reverses. It usually occurs when the environmental conditions change (pressure-temperature) or when a chemical reaction generates new molecules that have a low solubility for the given conditions. For example, consider a saturated solution of table salt (NaCl). Even the smallest cooling (e.g., 1 °C) would result in the precipitation of table salt because its solubility decreases as temperature decreases.

ACIDS AND BASES

Acidic and basic conditions in water result from the disequilibrium between the concentration of H^+ and OH^- ions. Water is neutral when its pH is 7; pure water is neutral. If H^+ is in excess, the water is acidic; if it is equal to the concentration of OH^-, the water is neutral; and if it is lower in concentration than OH^-, the water is basic. The pH is a measure of how acidic or basic the water is (Equation 7). As the pH falls below 7, water becomes more acidic. Conversely, as the pH of water rises above 7, it becomes more basic. For reference, rain water has a pH of 5.6, acid rain generally has a pH of 4.3, and sea water has a pH of 8.1.

$$pH = -log_{10}\left(\frac{[H^+]}{C_0}\right)$$

Equation 7

Where: $[H+]$ refers to the or molar concentration of H^+ (mol/L)
C_0 refers to the concentration of H^+ (and OH^-) in standard water (= 1 mol/L)

The carbonate-water system demonstrates the complexity of the acidic/basic chemistry of water. Atmospheric carbon dioxide gas (CO_2) dissolves in water and reacts with water to form carbonic acid (H_2CO_3), which is a weak acid. The acid dissociates to form three species: bicarbonate (HCO_3^-), carbonate (CO_3^{2-}) and H^+. This process explains why rain water in contact with the atmosphere (and CO_2 gas) is acidic (pH = 5.6).

REDOX REACTIONS AND WEATHERING OF ROCKS

Oxidation-reduction (redox) reactions are central in the process of chemical weathering. Redox reactions are the transfer of one or more electrons from one atom (or a group) to another one (or a group), to stabilize the electronic charge of the neighboring chemical compounds. Oxidation is the loss of electrons, while reduction is the gain of electrons.

For example, rust (i.e., corrosion) developing around the pillars of a bridge is a common observable oxidizing reaction.

Weathering involves the physical, chemical and/or biological processes that cause mineralogical breakdown of rock and soil materials. Weathering rates depend on many factors such as rainfall quantity and lithology of the rocks, vegetation cover, and temperature. The average rate of crystalline rock denudation in Canada is about 2 to 8 meters/million years (Peulvast *et al.*, 2009), which is much longer than the typical groundwater residence time in rocks.

Chemical evolution of groundwater

The primary control on the chemistry of groundwater is the chemical weathering of porous media. As such, the first control on water chemistry is the mineralogy of the hydrogeologic strata through and in which the water moves and is stored. Further, the residence time, pH, and redox state of the groundwater control the rate and extent to which water-rock interactions can occur, thereby further controlling water quality.

Total dissolved solids (TDS) is an easily-measured parameter used to quantify the total mass of solutes dissolved in water. It is often used to classify four types of groundwater. For reference, seawater has a TDS of 35 000 mg/L and drinking water must have a TDS less than 2500 mg/L.

- freshwater (< 1000 mg/L),
- brackish water (1 000-10 000 mg/L),
- saline water (10 000-100 000 mg/L), and
- brine water (> 100 000 mg/L).

Potential sources of groundwater contamination

Contaminants are dissolved or non-aqueous compounds that are present in groundwater that may be harmful to human, aquatic and/or ecological health (see Module 3 of this report). There are broad classes of contaminants (USGS, 2016):

- inorganic compounds: metals, alkalis, alkaline earth, rare earth, heavy metals and halogenated molecules;
- organic compounds: industrial farming products (i.e., herbicides, pesticides, insecticides, fungicides, rodenticides, and algicides), volatile organic compounds issued from industrial production (e.g., paint, petrochemicals, pharmaceutical, conservative agents, disinfectants, degreasers), plasticizers, organic solvents and sealants;
- microbiological contamination: bacteria (e.g., coliform family), viruses and parasites; and

- several physical properties of the water, including pH, temperature, turbidity, color, odor and taste.

The sources of groundwater contaminants in the NWT are discussed in the next module.

PERMAFROST BASICS

The presence of permafrost can greatly change the occurrence and movement of groundwater in the North. In the planning and management of its groundwater and surface water resources, the NWT should consider the presence of permafrost, as all of the territory is located in continuous or discontinuous zones.

This section defines what constitutes permafrost, and how it affects groundwater systems. It begins with a short definition for permafrost. It continues with a short note on how to locate and assess permafrost within a groundwater context, and ends with a discussion of general groundwater-related issues emerging from the presence of permafrost.

DEFINING PERMAFROST

Permafrost is a ground material (consolidated or not) that remains at or below 0 °C for at least two consecutive years, regardless of the presence of water or ice. Note that the definition of permafrost is a thermal condition; in other words, permafrost can exist without the presence of frozen water in the subsurface. For example, in the Canadian Shield setting, it would be possible to have permafrost in bedrock that essentially has no porewater.

The terms *permafrost body* and *permafrost zone* must be distinguished. A permafrost body is observable, while a permafrost zone has a given probability to be underlain by permafrost bodies.

DETERMINING FACTORS

Many factors affect permafrost occurrence and sustainability. Some factors are widespread (at the regional scale), such as climate and geothermal gradient, but most are site specific. They can include ground surface cover, snow cover, fire and flood history, topography, hydrological network, biota, and human infrastructure. Ground material properties such as heat capacity, thermal conductivity and hydraulic conductivity can also influence the state and dynamics of permafrost. The presence of ice or water radically modifies the ground's thermal properties.

PERMAFROST FEATURES

There are many features of permafrost that need to be identified and understood as they will directly affect groundwater systems. The following sub-section aims to describe the most important features of permafrost, including the permafrost table, the active layer, the transient layer, the zero-annual amplitude depth, the permafrost thickness and types of taliks.

Permafrost table

The permafrost table is the depth at which the maximum summer temperature does not exceed the limit of 0 °C. This boundary is perennially cryotic, which means that the temperature always remains at or below 0 °C, but is not necessarily perennially frozen, which involves the presence of frozen water.

Active layer

The active layer is often defined as shallow subsurface that thaws and freezes back every year. An alternate definition is the depth to which the temperature becomes positive during the summer, though this definition does not have the consensus (Bonnaventure & Lamoureux, 2013) (Figure 12).

Bonnaventure & Lamoureux (2013) classify five types of active layer based on their thickness. Their differences generally mirror local terrain factors (e.g., surface cover, water content, and soil development). Each type of active layer will have a potentially unique response to climatic change.

- Type 1: very thick active layer (3-8 m) and occurs in the High Arctic or high-mountain environments where the soil is very poorly developed. It is generally related to bedrock.
- Type 2: thick active layer (2-5 m) and occurs in high mountains and mid- to high-latitudes where a cover of debris characterizes the surface. It is generally related to rock glacier and debris-covered glaciers.
- Type 3: medium thickness active layer (1-4 m) and occurs where the soil on mineral substrate is relatively well developed. It is generally related to the tundra.
- Type 4: low thickness active layer (0.5-2 m) and occurs where the organic soil is well developed. It is generally related to poorly drained lowlands, mountain valleys and boggy areas.
- Type 5: variable thickness and occurs under water bodies. These are found beneath shallow streams, lakes, and pond bottoms, but do not support a talik beneath.

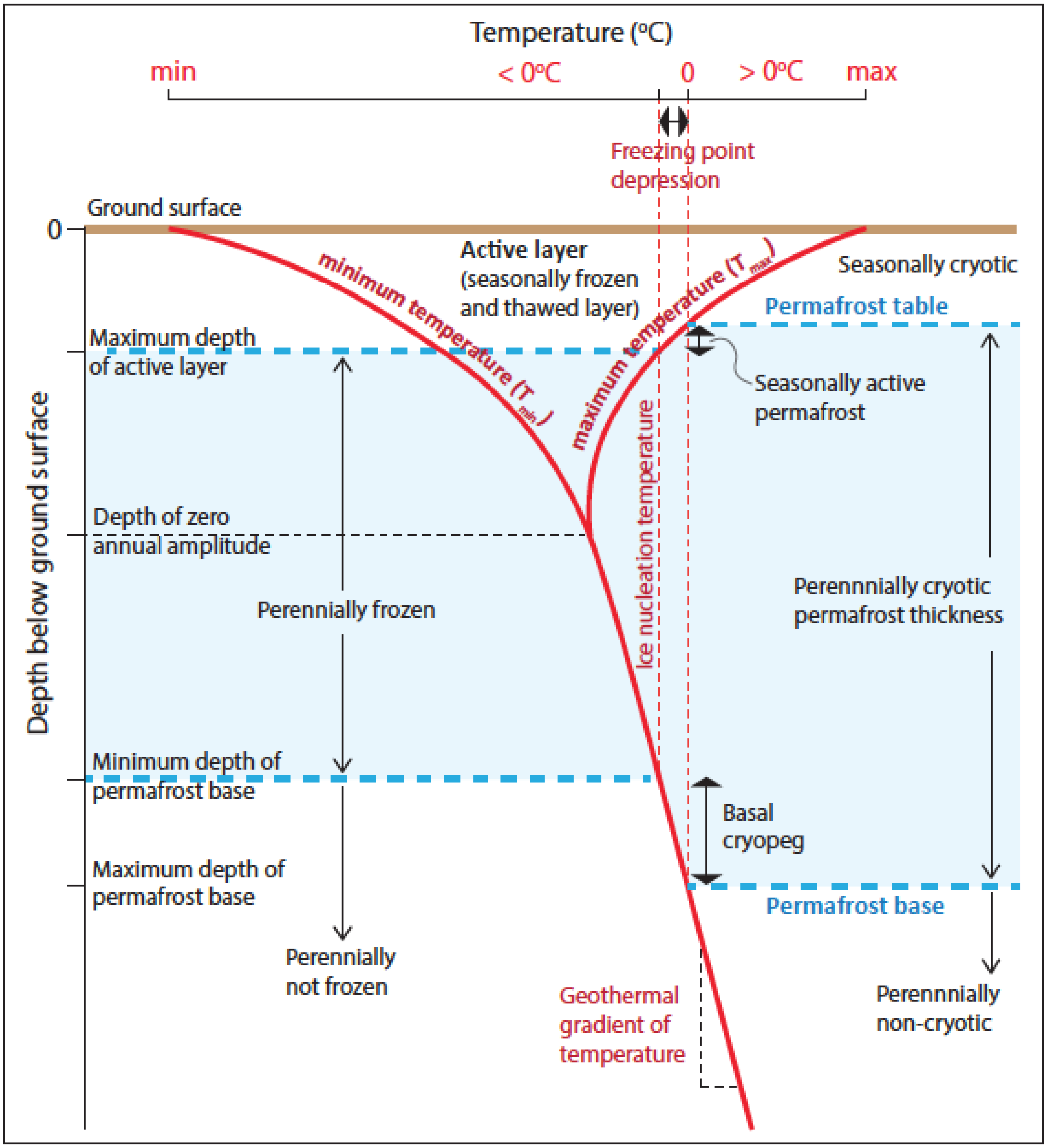


Figure 12. Typical ground-thermal regime indicating maximum and minimum temperatures, the decrease in temperature with depth, the geothermal gradient, the depth of zero-annual amplitude, and the depth of seasonal thaw (the active layer). Modified after ACGR (1988) in French (2007; p.84).

Transient layer

The transient layer is the section of permafrost that thaws only once every few decades. When added to the thickness of the active layer, it reflects the heat balance of the warmest period in the recent climatic trend. This layer rarely thaws or warms above 0 °C.

Zero-annual amplitude depth

The zero-annual amplitude depth represents the depth at which the temperature does not significantly vary (<0.1 °C) on an annual basis. The temperature at this depth is sometimes used as the permafrost body's temperature. It also represents the inter-annual heat balance resulting from the climatic trend and the ground's effective thermal diffusivity (capacity to diffuse the received heat).

Permafrost thickness

As a first order assumption, if the entire subsurface is assumed to be composed of the same material, permafrost thickness can be approximated by extrapolating the geothermal gradient as it is measured below the temperature at which the depth of zero annual amplitude occurs. Generally, permafrost is thicker with higher latitudes (Table 3).

Table 3. Some approximate permafrost thicknesses in Canada, modified from French (2007).

Location	Latitude (° N)	Mean annual air temperature (°C)	Permafrost thickness (m)
Resolute, NWT	74	-15	390-400
Inuvik, NWT	69	-9	100
Dawson City, YT	64	-5	60
Yellowknife, NWT	62	-6	60-100
Schefferville, QC	54	-4	80
Thompson, MB	55	-4	15

Taliks

No matter its size or temperature, a frozen permafrost body can contain unfrozen volumes called taliks (Figure 13).

French (2007) synthesized the variable nature of taliks:

- A closed talik is non-cryotic and occupies a depression in the permafrost table below a lake or river; its temperature remains above 0 °C because of the heat storage effect of the surface water.
- A hydrochemical talik is cryotic; freezing is prevented by groundwater with elevated TDS flowing through the unfrozen ground.
- A hydrothermal talik is non-cryotic, with a temperature that is maintained above 0 °C by the heat supplied by groundwater flowing through the unfrozen ground.
- An isolated talik is entirely surrounded by perennially-frozen ground; it is usually cryotic but may be non-cryotic (see transient talik).
- A lateral talik is overlain and underlain by perennially-frozen ground; it can be non-cryotic or cryotic.

- An open talik penetrates the permafrost completely, connecting supra-permafrost and sub-permafrost water (e.g., below large rivers and lakes). It may be non-cryotic (see hydrothermal talik) or cryotic (see hydrochemical talik).
- A thermal talik is non-cryotic and has a temperature above 0 °C due to the general thermal regime. It includes the seasonally-thawed ground in the active layer.
- A transient talik is gradually being eliminated by freezing, e.g., the initially non-cryotic closed talik below a small lake which, upon draining of the lake, is turned into a transient isolated talik by permafrost aggradation.

The cryopeg is another unfrozen permafrost feature. It is a hydrochemical talik referring to the basal portion of permafrost where the water remains unfrozen at low temperatures (< -9 °C) due to a high concentration of dissolved minerals (Pradeep Kumar, 2014).

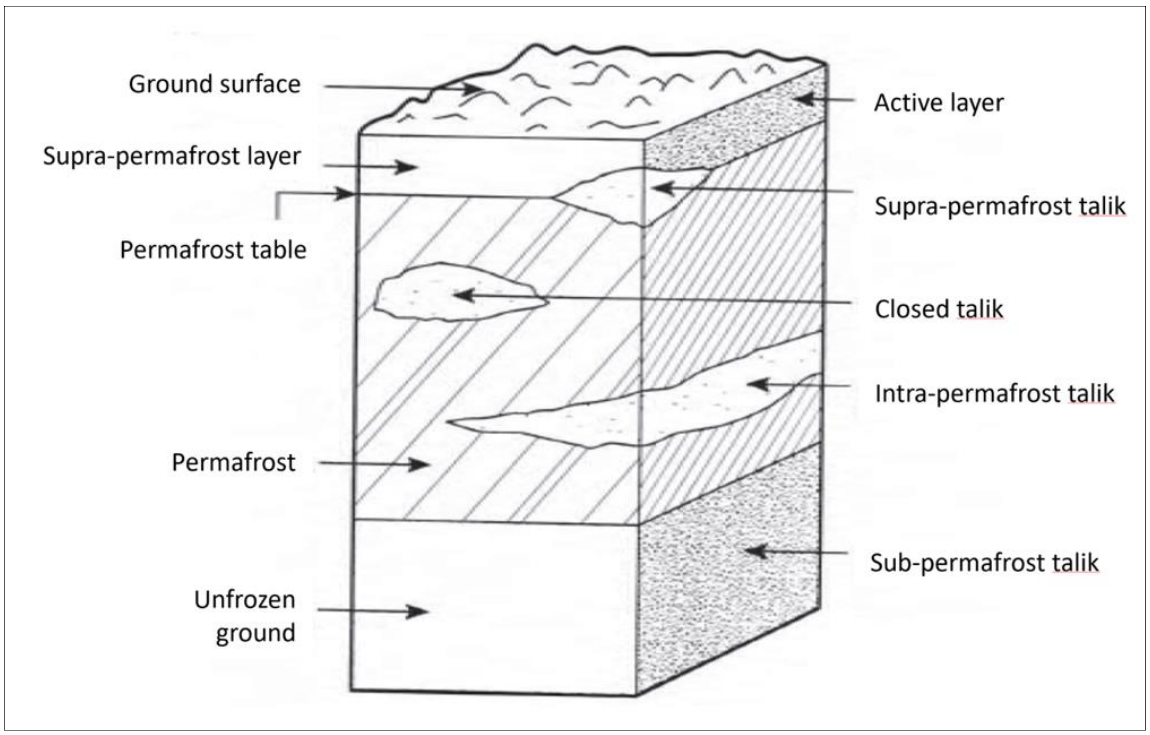


Figure 13. The relationship between permafrost, the permafrost table, the active layer, and supra-, sub-, and intra-permafrost taliks. From Ferrians et al. (1969) in French (2007). The sub-permafrost cryotic talik also refers to the cryopeg.

PERMAFROST AGGRADATION

Permafrost aggradation can be epigenetic, syngenetic, polygenetic, quasi-syngenetic or paragenetic. Epigenetic permafrost aggrades in a pre-existing ground (a cold wave progresses downward). Syngenetic permafrost aggrades synchronously with the ground's surface (new material at the surface elevates the permafrost table). Permafrost resulting from both processes in a same period is said to be polygenetic. Quasi-syngenetic permafrost results from a surficial cooling event related to a change in the vegetation cover or soil development. Finally, parasyngenetic permafrost results from an epigenetic permafrost aggradation occurring laterally in a drained lake basin. Note that the reference timescale for permafrost aggradation is not absolutely fixed; it can span from years to millennia.

Permafrost probability zonation

Permafrost occurrence coincides approximately with mean annual air temperature,, which correlates with latitude and altitude (Figure 14). The continuous permafrost zone has 90 % or more of its subsurface in the cryotic state. The southern limit of this zone coalesces with the -6 to -8 °C mean annual air temperature isotherm and corresponds to a permafrost thickness that generally exceeds 60-100 m. Permafrost thickness and continuity decrease when approaching the southern limit of the potential permafrost occurrence (Figure 15). The southern limit of discontinuous permafrost (10-90 % permafrost coverage) roughly coincides with the −1 °C mean annual air temperature isotherm. At higher air temperatures, permafrost is limited to some isolated patches and rarely exceeds 5-15 m thick.

Permafrost was originally formed under past climate conditions. Therefore, permafrost depth can be difficult to model based on present climate conditions: model results often do not agree with borehole measurements (Zhang *et al.*, 2006; Figure 16), since permafrost was originally formed under past climate conditions.

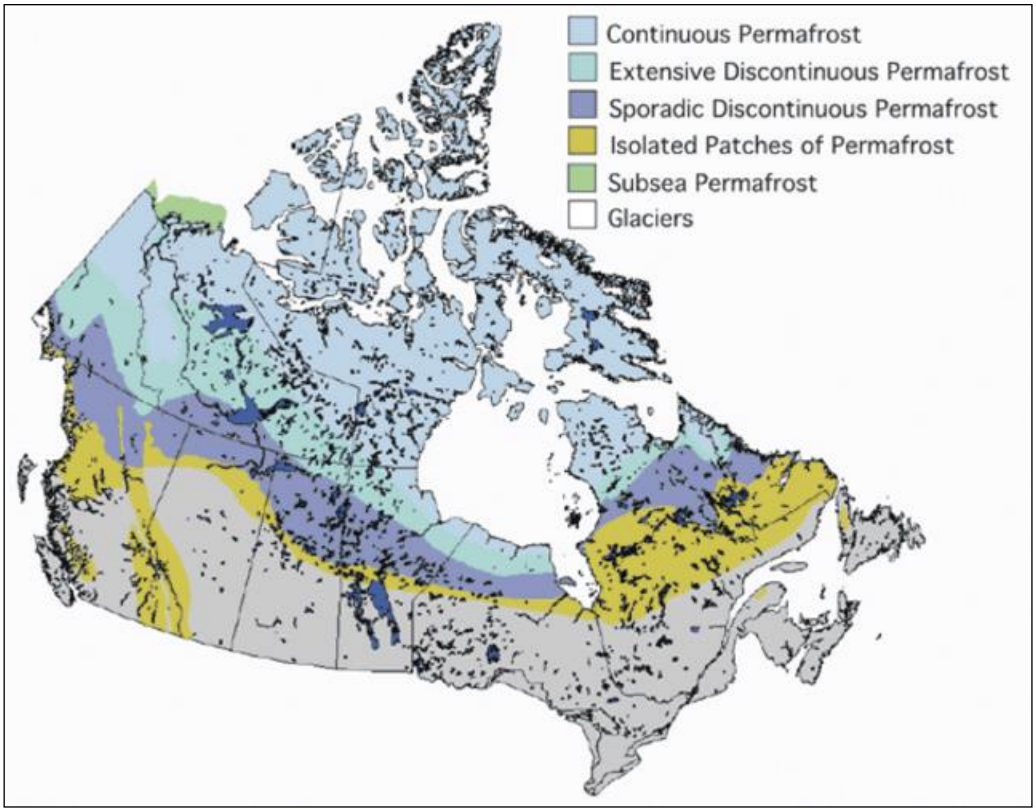


Figure 14. Permafrost distribution in Canada, from Brown et al., (2001).

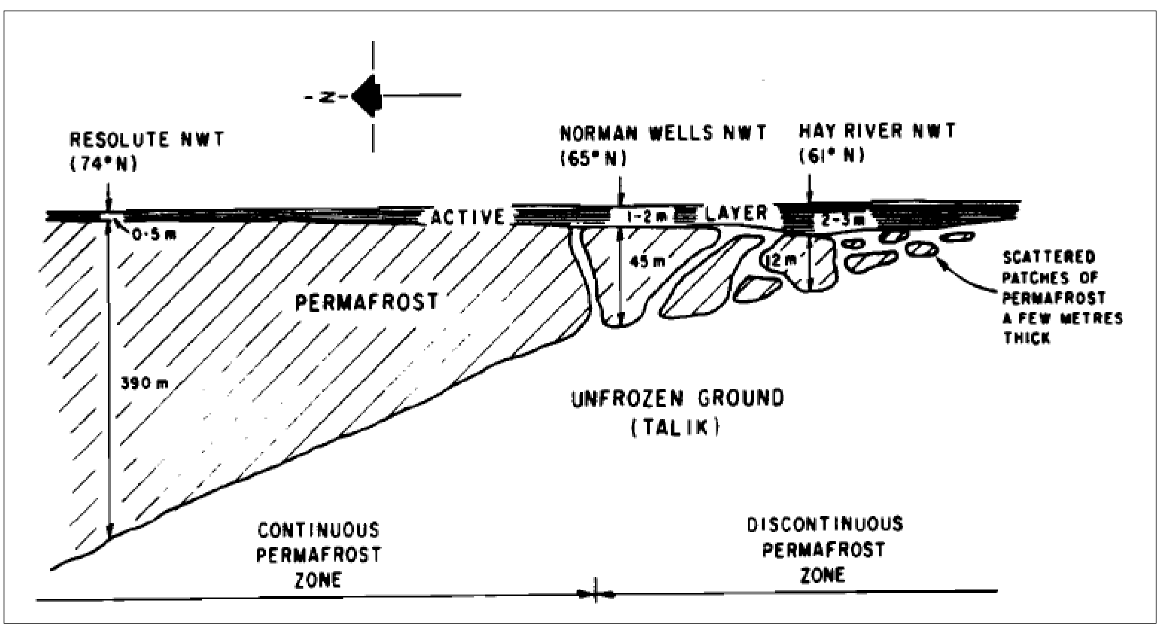


Figure 15. Vertical distribution and continuity of permafrost along the latitudinal gradient (Andersland & Ladanyi, 2004).

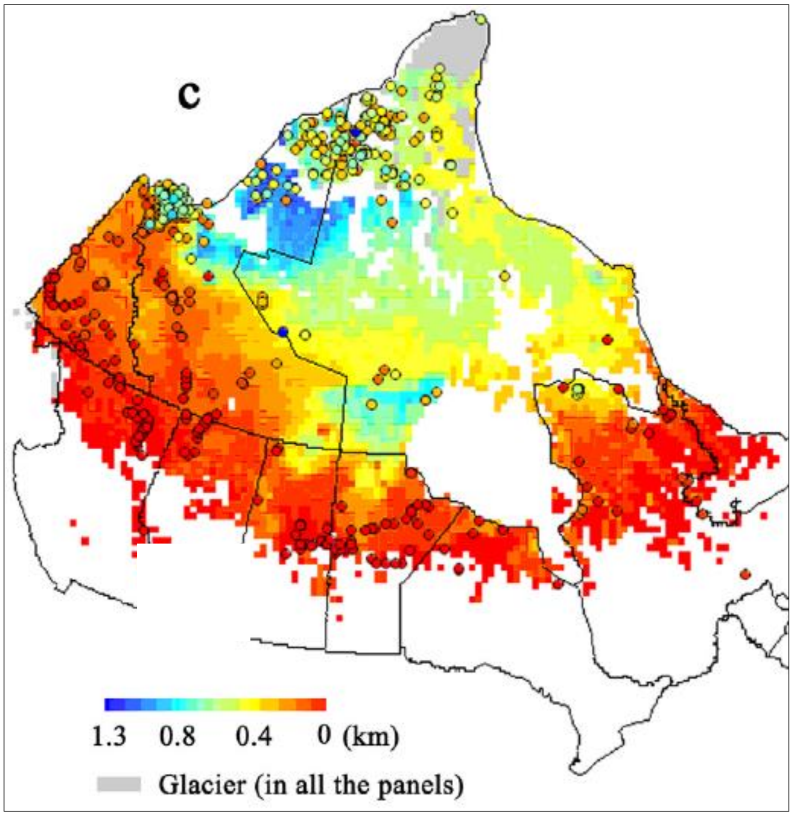


Figure 16. Measured and simulated depth to permafrost base (approximate thickness of permafrost) in Canada (Smith & Burgess, 2002; Zhang et al., 2006).

LOCATING AND ASSESSING PERMAFROST MORE ACCURATELY

As a first approximation, permafrost can be estimated based on climate, but more information, including field observations, are needed to tell exactly where it is and how deep it is. This is especially true in the discontinuous permafrost zones where the climatic factors are strongly modulated by terrain factors. The relief and aspect of the land surface indirectly control permafrost occurrence due to variations in solar radiation, weathering level, soil water content, peat and sediment accumulation, vegetation cover, snow cover, and drainage and surface water networks. These factors are linked and can co-evolve simultaneously, sometimes with a positive or negative feedback.

There has been extensive research to develop methods for the prediction of permafrost distribution. For example, Shur & Jorgenson (2007) described a permafrost classification based on climatic and/or ecosystemic drivers and Cable *et al*. (2016) developed a model to predict permafrost temperature below 1 m below ground surface (as a permafrost indicator). These approaches have similarities to the response unit approach developed by England & Stephenson (1970) to evaluate the hydrologic performance of a rangeland watershed in Idaho, USA. Exact localization of permafrost is further discussed in Module 2.

EFFECTS OF PERMAFROST ON MATERIAL PROPERTIES

Without water, the thermal regime of permafrost is entirely controlled by the thermal properties of the host rock and energy transfer is only through conduction. With the addition of water, the thermal properties and energy transfer processes are potentially more complex.

FROZEN FRINGE

When water is present, and subsurface temperature decreases below the freezing point, heat transfer leads to a state change called crystallization. While occurring, a 'zero-curtain' effect is observed in the ground's temperature profile wherein the temperature remains at 0 ˚C until the energy barrier for latent heat is overcome (see the work of Williams, 1964; Spaans & Baker, 1996; and Azmatch *et al*., 2012).

The part of the soil profile that has yet to freeze is called the frozen fringe and is isothermal as the temperature remains relatively constant. It is also partially frozen because a fraction of the pore water is not yet crystallized. Even with sub-freezing temperature a residual unfrozen water film may persist due to adsorption and capillary forces, pressure effects, and salinity. The unfrozen water in the frozen fringe may or may not be continuous and can move and transport solutes. Liquid water that is in contact with the frozen fringe often migrates towards the freezing front to form ice lenses.

In soils not directly affected by permafrost, the frozen fringe is limited to the base of the annual frozen layer. In permafrost soils, it is observed at the permafrost table during the thawing season and at the top of the basal cryopeg throughout the year. It can also be found within taliks and on their periphery. When water is present in a cooling soil, it follows the unfrozen film towards the freezing front.

UNFROZEN WATER AND CRYOSUCTION

The finer grained the soil is, the more important its specific surface area is as it results in a larger soil/ice interface that favors the persistence of a residual unfrozen water film below 0 °C. This persistence leads to a decrease in the temperature required to completely crystallize groundwater. Freezing also promotes the formation of segregated ice via cryosuction, a process by which water migrates towards the freezing front. Under these conditions, the soil is said to be frost-susceptible, a condition that is mainly determined by its grain size distribution, imbrication, and bulk density.

The most frost-susceptible soils are generally silt and clay with organic matter enrichment (Guodong, 1983). Cryosuction occurs preferentially in the frozen fringe when a continuous thin water film exists around the grains. In addition to the development of ice lenses, cryosuction leads to frost heave (where the ground surface rises proportionally with lens growth).

THERMAL PROPERTIES

The thermal properties of frozen ground (and permafrost) depend on the porosity and the proportions of ice, water and gas. Gases are effective thermal insulators and have a very small specific mass that does not add to the overall heat capacity. With increasing ice content, the soil's thermal conductivity increases because the thermal conductivity of ice is four-fold higher than that of water (Figure 17).

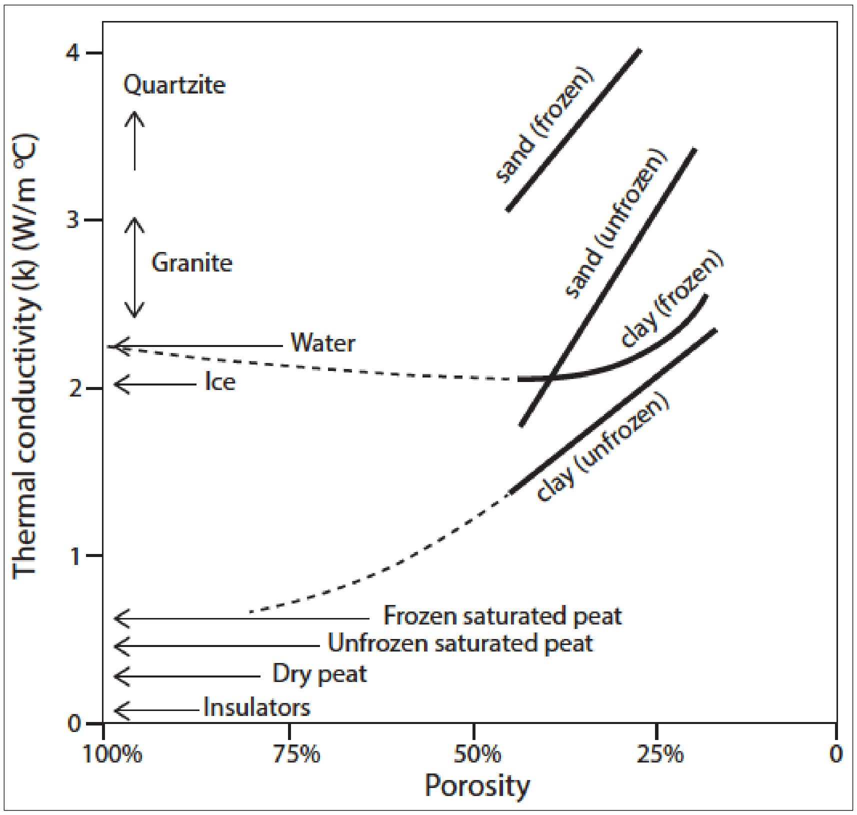


Figure 17. Relationship between thermal conductivity, porosity, and degree of saturation. From Johnston (1981) in French (2007).

Upon freezing, the liquid water in a soil changes to ice. This transition causes the soil's heat capacity to decrease because the specific heat of ice is approximately half of that of water. If the moisture content of the soil is larger, this decrease in soil heat capacity will be larger.

FREEZE-THAW CYCLES

A material that has been reworked generally has a heterogenous porosity since it has not settled and compacted. Viklander (1998) found that a succession of freeze-thaw cycles in a disturbed/reworked, fine-grained, non-plastic till had the effect of stabilizing its void ratio and hydraulic conductivity by loosening the material when over-compacted and by compacting it when loose. Bhuwani & Baolin (2010) presented similar results for the silts of the Mackenzie Valley, NWT. For more details, Qi *et al*. (2006) reviewed the influence of freeze-thaw cycles on unconsolidated material properties.

Cryostructures

When frozen and containing measurable water, permafrost can hold multiple forms of intra-sedimentary cryostructures. Some cryostructures are exclusive to a single formation process while others can result from many processes. Three main factors are involved in cryostructure development: 1) the physical properties of soil, sediment or bedrock, 2) the moisture availability, and 3) the mode and rate of permafrost formation (epigenetic, syngenetic or quasi-syngenetic). Moister sites promote the formation of ice-rich cryostructures compared to drier ones (Murton, 2013; Stephani *et al*., 2014). The identification of cryostructures can help to predict how permafrost will degrade and can ultimately help to assess how topography, and characteristics such as post-permafrost sediment/rock texture, structure, and properties, will evolve (French & Shur, 2010).

Gilbert *et al*. (2016) provided an excellent synthesis of the basics of cryostratigraphy. Individual cryostructures are identified based on the shape, distribution and proportions of ice, sediment or rock within frozen grounds (Murton, 2013 in Gilbert *et al*., 2016). Nine cryostructures are commonly described in recent literature (Figure 18) and are used to log permafrost sequences. Many cryostructures are transitional, composite or hierarchical in nature, so their description may sometimes be scale-dependent.

The process of cryosuction also affects rocks through widening joints, frost heaving, and promoting the development of cryostructures (Table 4). The resulting cryostructure is primarily determined by the rock's initial structure. Fractures developing in rocks as a result of frost development may not reclose completely, allowing for the development of a secondary macro porosity.

Permafrost - complexity

Many of the most complex facets of permafrost are directly related to groundwater, and, by extension, to ground ice. Three major phenomena result from the occurrence of permafrost:

- The freezing soil may lead to cryosuction, which results in the redistribution of soil moisture, frost heaving, and accretion of ice lenses.
- The ground may contain a volume of ice greater than its porosity, which results in ice-rich permafrost and topography that is vulnerable to thawing.
- The frozen ground is impervious and leads to hydrological regimes mostly characterized by surface and subsurface runoff events and intensified interactions between groundwater and surface-water.

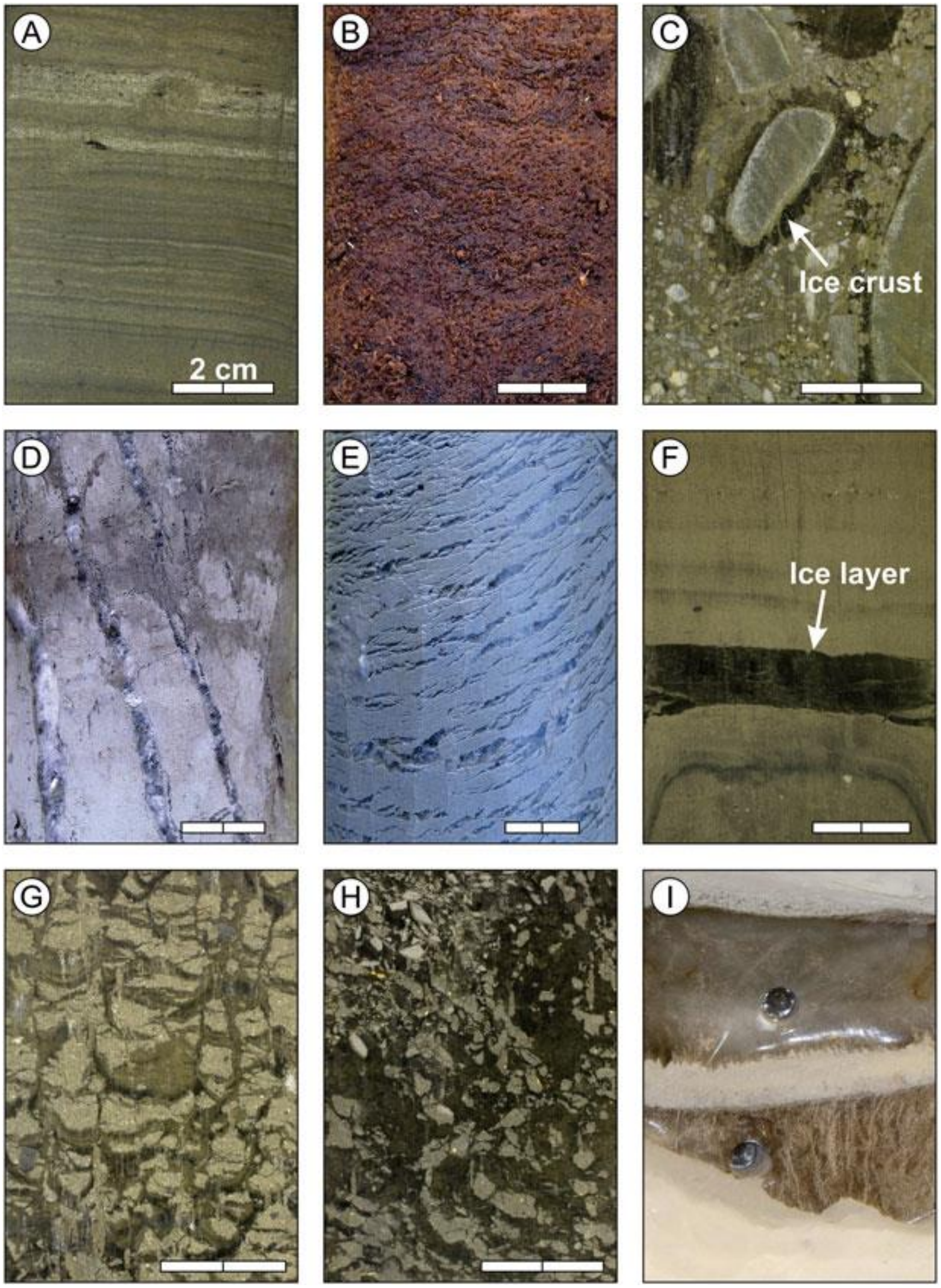
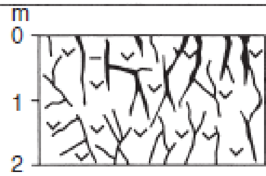
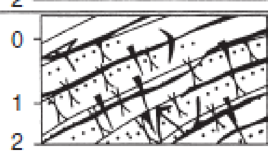
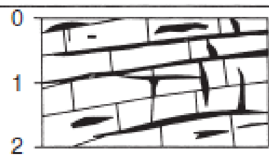
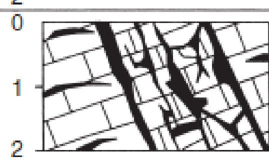


Figure 18. Simplified classification of cryostructures in unconsolidated sediments (from Gilbert et al., 2016, based on Murton (2013) and modified from previous classifications). All photographs are oriented vertically such that the long axis of the image is perpendicular to the ground surface. (A) Pore cryostructure – note the absence of visible ice, (B) Organic-matrix cryostructure – ice present in the void space but not visible, (C) Crustal cryostructure, (D) Vein cryostructure, (E) Lenticular cryostructure, (F) Layered cryostructure, (G) Reticulate cryostructure, (H) Ataxitic cryostructure, and (I) Solid cryostructure – thermokarst-cave (pool) ice overlying a vertically foliated ice wedge. Two drill holes several centimeters in diameter are visible in the ice.

Table 4. Cryogenic textures associated with solid and semi-solid rocks, modified from Kudryavtsev (1979). From Melnikov and Spesivtsev (2000). Reproduced by permission of SB RAS Publishing House in French (2007).

Cryogenic texture	Name	Rock type
	Fissured	All rocks
	Fissured-widened	All rocks
	Fissured-veiny	All rocks with joints, fissures, bedding planes and faults
	Stratal-fissured	All sedimentary rocks and metamorphic deposits
	Stratal-fissured-karst	Carbonate rocks
	Karst-fissured-vein	Carbonate rocks with joints and fissures

EFFECTS OF PERMAFROST ON WATER CIRCULATION

Permafrost is considered to be an impermeable barrier to groundwater flow. When permafrost thaws (such as in a thawed active zone), liquid groundwater flow is possible if the ground has a sufficiently high permeability. In permafrost regions, this situation can occur in taliks and at the margins of permafrost, where a pressure differential likely exists.

PERMAFROST IS AN AQUICLUDE

Within permafrost, most of the available porosity is filled with ice, preventing the infiltration and the circulation of mobile water through the frozen ground. In hydrogeology, a frozen permafrost body is said to be an aquiclude (a geologic formation that is effectively impermeable to groundwater flow). At the terrain scale, the distribution of frozen and unfrozen ground is specific to local conditions (as described above). The mosaic of aquifers/aquicludes in each permafrost area can thus be very complex, especially where the permafrost is discontinuous. The effective geometry and specific yield of an aquifer in a region affected by permafrost is determined by the same factors operating in regions without frozen ground, except that the boundaries to flow include geologic features and frost boundaries (Figure 19).

As permafrost aggrades, new ground volumes become impervious to infiltration or groundwater flow. As permafrost thaws, new subsurface drainage channels and taliks may open and promote additional drainage. With thawing, a permafrost aquiclude can quickly become an efficient aquifer.

As permafrost degrades, new groundwater connections can develop between surface water, groundwater from the active layer, and sub-permafrost water (Figure 19). The related hydrological changes can lead to an increase or a decrease of units of stored water. For example, a deeper active layer could enhance the recharge of surface waters, but development of a talik could trigger the complete drainage of a perched aquifer (Figure 20). Increased subsurface connections may also allow the seepage of an artesian spring (groundwater outflow at the surface) if the sub-permafrost aquifer pressure is higher than the pressure of the supra-permafrost aquifer.

Sub-permafrost and intra-permafrost groundwater, especially when old and deep, tend to have high solute concentrations, making them undrinkable and potentially toxic for the ecosystems if they are discharged. The cryopeg effectively acts as a hydrogeologic interface, creating a confined aquifer. In the context of permafrost degradation, an over-pressured sub-permafrost aquifer could release water with a high salt content to the surface hydrologic network. This could have potentially detrimental environmental impacts.

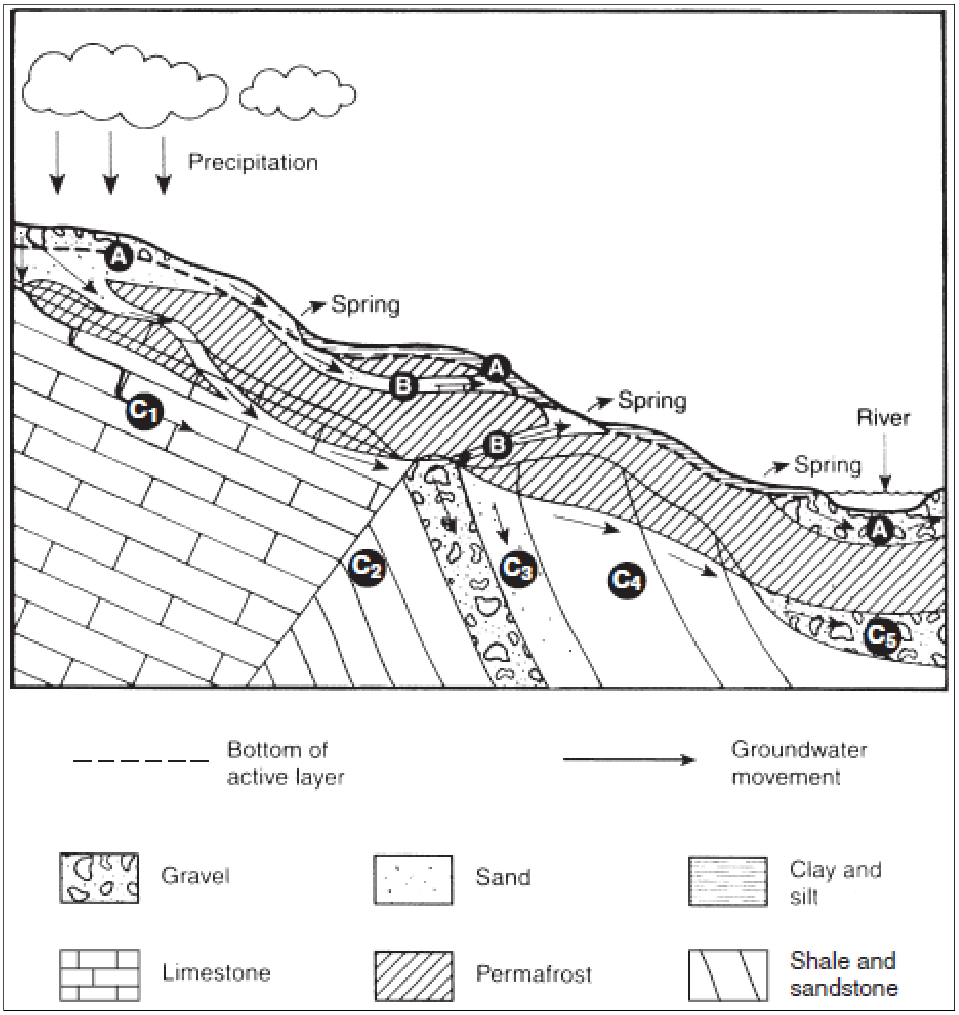


Figure 19. Occurrence of different types of groundwater in permafrost areas. Legend: A, supra-permafrost water; B, intra-permafrost water; C, sub-permafrost water; C1, karst water in solution channels; C2, fissure water in fault; C3, aquifer in porous rock; C4, fissure water in bedrock joint; C5, alluvial water in alluvial deposits. From Cederstrom et al. (1953) in French (2007).

WATER MIGRATION IN FROZEN GROUND

While groundwater flow decreases with subsurface freezing, some water remains liquid at temperatures below freezing. It may represent an important flux of water and may enhance solute transport. A portion of the pendular and capillary water remains liquid below 0 °C and can migrate at the mineral-ice interface. This thin continuous film of capillary water constitutes the pathway for water to move during cryosuction. The difference between pendular and capillary water is that the first is trapped in dead-end pores (i.e., it is hydrologically disconnected), while the latter constitutes a continuous film.

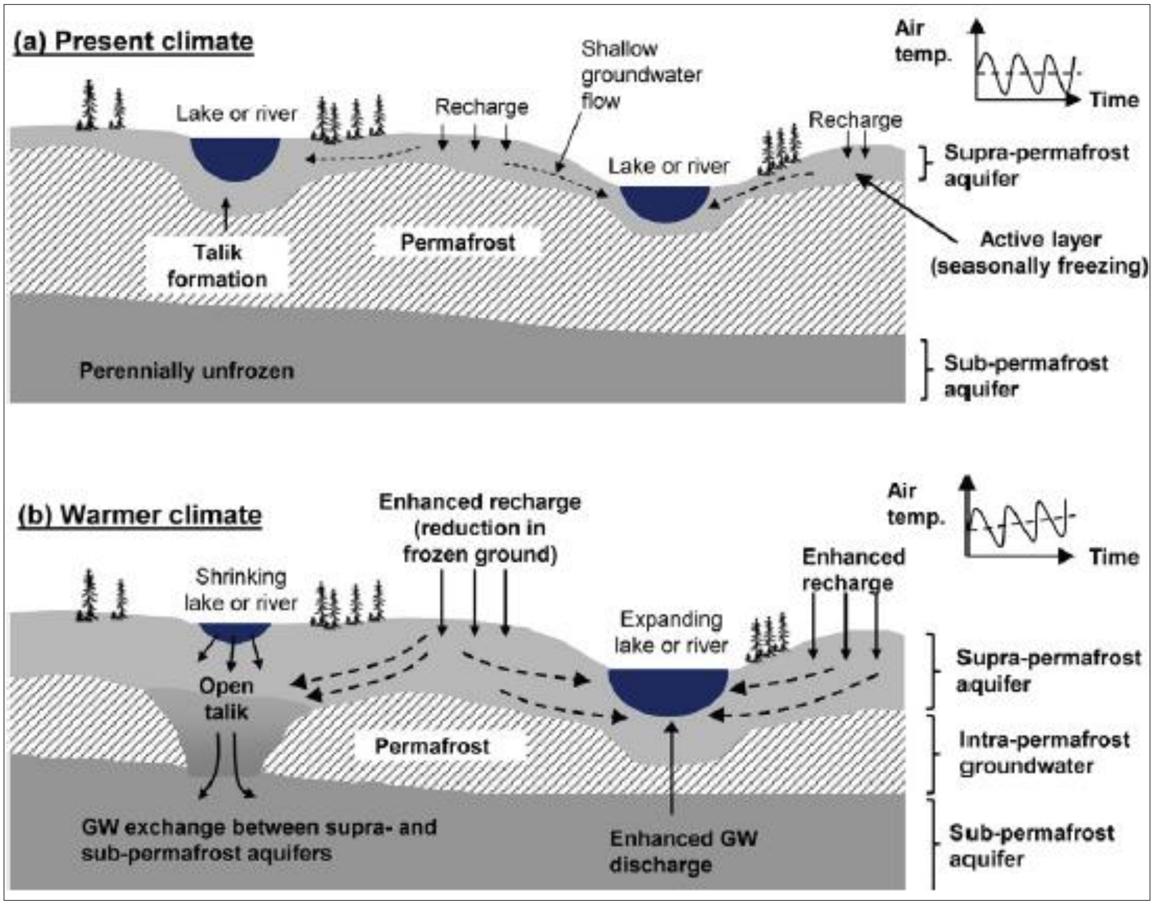


Figure 20. Evolving hydrogeologic conditions due to the thawing of discontinuous permafrost for (a) present climate and (b) warmer climate. For the warmer climate (b), newly formed open taliks can facilitate groundwater (GW) movement to sub permafrost aquifers, and thereby affect surface water (left). Conversely, increased recharge and enhanced groundwater discharge through activated aquifers can lead to expanding lakes (right) (modified from Kurylyk et al. (2014a) in Walvoord & Kurylyk, 2016).

Azmatch *et al*. (2012) measured frozen hydraulic conductivity based on the soil freezing characteristic curve (water retention curve upon freezing). Water flux is primarily driven by electrostatic and electromagnetic forces that result from the intersticial geometry, the intrapore frost geometry (during freezing), the particle mineralogy, and the water chemical composition. However, gravity can also be a strong driver for water movement. During freezing, water adsorbed onto the surface of mineral particles is the most difficult to freeze as it is strongly bonded to grain surfaces. Although this liquid water is generally not mobile, it is important for some chemical reactions or ion migration processes.

A partially frozen permafrost body (i.e., containing unfrozen water) undergoing significant amounts of mechanical stress is expected to develop creeping (slow strain). The creeping movement results from the drainage of pendular and capillary water, and the conversion of ice into capillary and pendular water. Frozen saturated soils can also be permeable to other fluids, such as fossil fuels. In Alaska, McCauley *et al*. (2002) found that a frozen, organic-rich silty sand had a hydraulic conductivity of 10^{-8} cm/s when contaminated with a mixture of diesel and jet fuel. This hydraulic conductivity is similar to that of loose clay, and is significantly higher than that expected for permafrost.

WATERSHED HYDROLOGY AND PERMAFROST

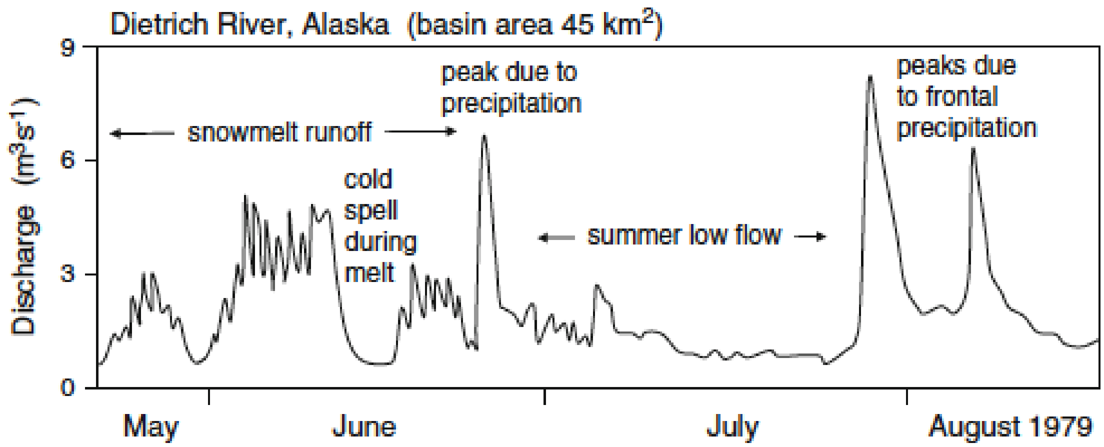
The impervious nature of permafrost has a strong influence on groundwater recharge, by affecting aquifer recharge and river base flow. In a given region or watershed within the discontinuous permafrost zone, the proportion of permafrost and non-permafrost areas directly impacts the overall water budget, including the separation of precipitation between groundwater recharge and runoff.

Figure 21 shows a typical hydrograph (stream discharge time series) for three different watersheds in different terrains with different areas. The subarctic nival regime (Figure 21a) is affected by discontinuous permafrost where taliks control baseflow. Snowmelt is the primary source of runoff and large rain events generate considerable runoff, which extends over a relatively long period.

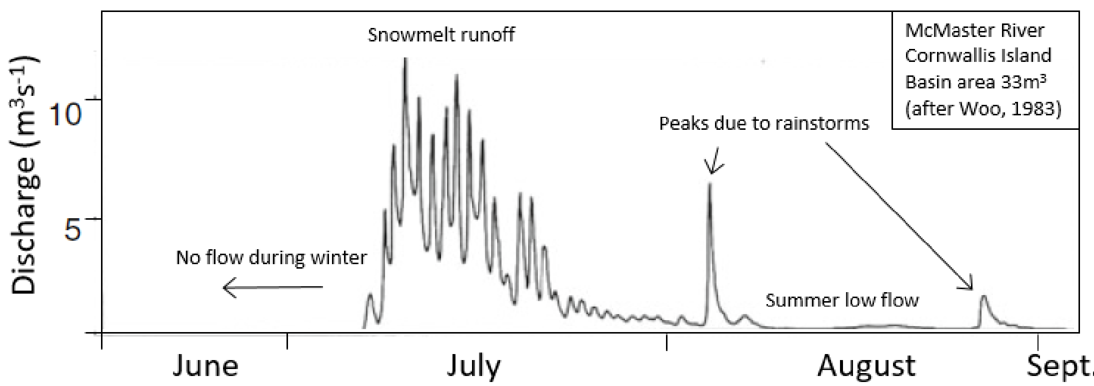
Alternatively, the arctic nival regime (Figure 21b) is characterized by continuous permafrost, which limits the generation of significant river baseflow. Snowmelt is the strongest driver of runoff. Despite being less frequent than in the subarctic, rain events generate large and short-lived runoff events. These runoff events are shorter than in the subarctic nival regime but tend to increase in length and decrease in magnitude towards the end of the summer. This seasonal transition is due to the annual development of the active layer throughout the summer, leading to increased storage of shallow groundwater.

The proglacial regime (Figure 21c) is characterized by a late snowmelt peak (delay due to the relatively high altitude of the glaciated watershed). Snowmelt generates the first melt event (strongest runoff), and the subsequent events mirror the incremental progression of the glacier melting at progressively higher altitudes.

(a)


Dietrich River, Alaska (basin area 45 km2)
Discharge (m3s-1)
9
6
3
0
snowmelt runoff
peak due to precipitation
cold spell during melt
summer low flow
peaks due to frontal precipitation
May
June
July
August 1979

(b)


Discharge (m3s-1)
10
5
Snowmelt runoff
McMaster River
Cornwallis Island
Basin area 33m3
(after Woo, 1983)
Peaks due to rainstorms
No flow during winter
Summer low flow
June
July
August
Sept.

(c)

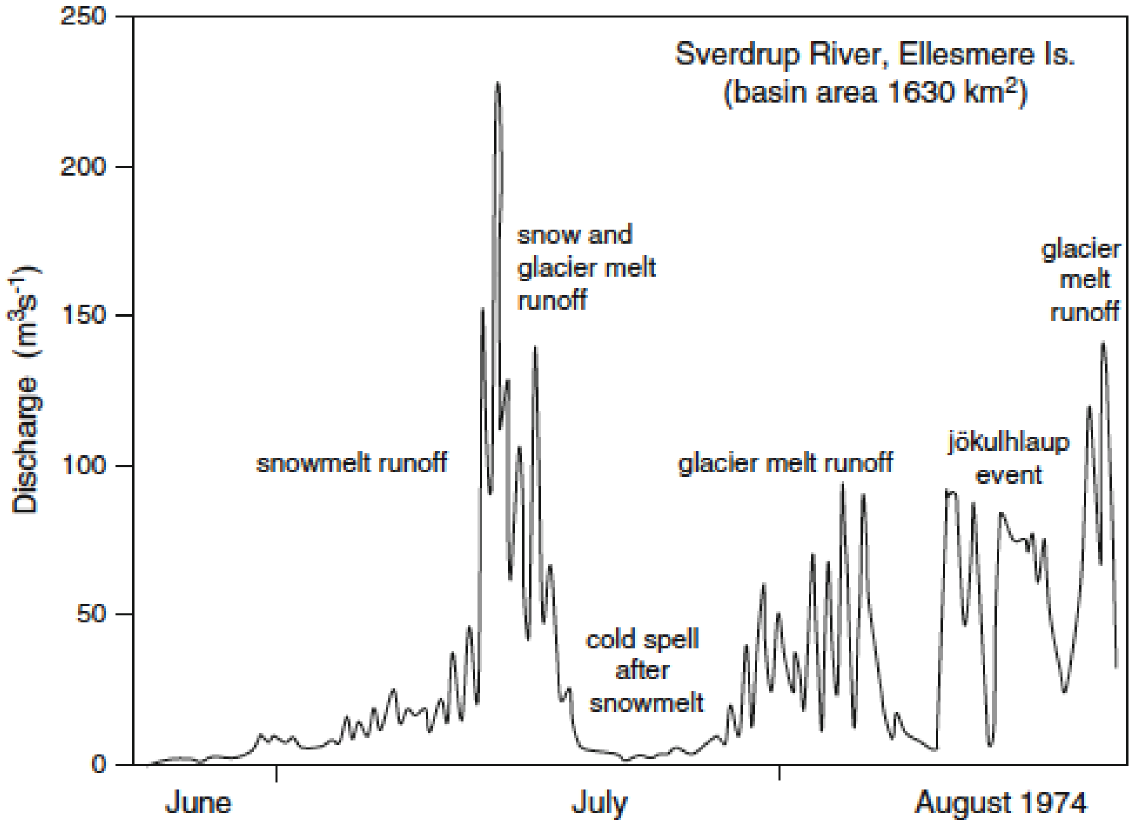


Figure 21. The typical stream flow regimes in periglacial environments. (a) Subarctic-nival regime; (b) Arctic nival regime river showing prominent diurnal cycles during snowmelt high flows followed by summer low flows spiked by rain events, and (c) proglacial regime; also shown is the episodic drainage of a proglacial lake (Woo, 2012).

Permafrost landforms and impact on hydrological processes

The local presence of permafrost can be manifested in particular landforms which are created, in part, by the presence of groundwater.

Patterned ground

Patterned ground is characterized by the repetition of a specific geometry of a terrain's surface expression. Many types of patterned ground exist, and their geometry varies depending on the geologic substrate, slope, climate, hydrology, and level of soil development. Their development is preferentially enhanced by the presence of permafrost.

Patterned ground increases the surface rugosity (e.g., in sorted circles, steps, polygon networks), limits the surface runoff, favors subsurface flow and reduces the velocity of meteoric water. However, groundwater recharge likely is not enhanced by patterned ground, since it often occurs in regions underlain by permafrost. Patterned ground can also channelize surface water discharge (e.g., water tracks, sorted stripes, and sand-wedges) and inhibit recharge towards potential aquifers.

Ground-ice

The presence of ice lenses can trap and/or block the infiltration of meteoric water before it reaches a potential aquifer. The resulting frost heave may also divert surface flow. Frost cracks and ice wedges have the effect of trapping meteoric waters; they generally result in a patterned ground (i.e., ice-wedge polygon networks) that inhibits the drainage in regions with low topographic relief.

Cryoturbation

Cryoturbation results from multiple freeze-thaw cycles, which has the net effect of mixing the soil. The result of cryoturbation is a complex soil strata with a variable distribution of porosity and hydraulic conductivity (potentially developed by successive freeze-thaw cycles). Cryoturbation can reverse the normally occurring sedimentologic patterns, concentrate recent surface weathering products, or bury organic residues at the bottom of the active layer.

Cryoturbation may add vertically-oriented macro porosity in horizontally-layered sediments. This secondary porosity would favor vertical infiltration and retention of water in the subsurface. The secondary porosity would also persist after permafrost thaws, enhancing the groundwater recharge process.

Landform-related indications of groundwater

Some permafrost landforms are the result of the interaction between groundwater and permafrost. For example, the development of a frost blister or a pingo normally occurs in continuous permafrost. They indicate the presence of super-cooled and/or artesian groundwater system below a relatively thick and continuous aquiclude (here the permafrost body).

The development of an organic terrain indicates a positive surface-water budget (i.e., the total amount of precipitation and groundwater discharge is greater than amount of evapotranspiration). Palsas, lithalsas, and peat plateaus occur in the sporadic discontinuous permafrost zone (i.e., 10-50 % permafrost coverage, 10-60 m thick). These landforms indicate that the climate is not cold enough to aggregate permafrost, but that the ecosystem equilibrium favors (or has favored) its propagation. Further, these landforms may form discontinuous and relatively thin (5-15 m) aquicludes with a positive water budget.

Rock glaciers also indicate that the local climate is barely sufficient to sustain permafrost, but the rock mound’s structure (its macro porosity) favors permafrost aggradation. Since it may have a core of ice, a rock glacier constitutes a discontinuous and localized aquiclude. However, water still transits on its surface or subsurface during the summer and only a small portion of the water may stay trapped to aggregate the ice-core.

The preservation of ice-cored moraines or buried glacier ice are directly controlled by the local climate and indirectly by ecosystemic relationships. Ice within moraines, being thermally vulnerable, can melt and trigger a collapse of the terrain. Hence, the presence of massive ice has a strong potential influence on the hydrologic and hydrogeologic fate of a terrain. For example, ice-rich terrains can be affected by landslides that may contribute to a rise in river or lake water levels. Elevating the water table may connect two distinct water systems, bring groundwater to the land surface or even flood the land surface. Alternatively, mass movements triggered by the thawing of massive ice can favor the drainage of a terrain and divert streams, including recharge areas.

Thermokarst

Networks of ice-wedge polygons have been found to strongly accelerate the drainage of wetlands due to permafrost degradation and thermo-erosion (Fortier *et al.*, 2007). When permafrost thaws, it results in ground surface subsidence that potentially triggers surface water accumulation and enhances the formation of thermokarst. The development of thermokarst is the first step in the development of hydrologically-connected taliks, including the formation of pathways for groundwater to migrate between deep and shallow flow systems (Rowland *et al*., 2010; Kokelj & Jorgenson, 2013). Mass wasting events, triggered by thermokarst, can also be related to groundwater. Mass movement events that occur on sloped terrain can affect the hydrologic drainage network. For example, a mass wasting event can dam a stream, leading to elevated base level, perched aquifers, and the subsequent formation of new thermokarst.

EFFECTS OF PERMAFROST ON GROUNDWATER CHEMISTRY

The formation of permafrost can directly affect the solute concentrations because ions contained in groundwater are not readily incorporated into the structure of the frozen pore water. This expulsion process is more efficient with slow freezing rates, and has the potential to increase solute concentrations in the active layer, closed taliks, and cryopegs. Simultaneously, the solute expulsion decreases the freezing point of the remaining pore water. The resulting increase in solute concentrations below permafrost bodies may render groundwater non-potable in regions where only fresh water is expected.

CONCEPTS SUMMARY

Hydrogeology is the study of the occurrence, storage, and flow of water through the ground. The flow of groundwater is a function of the hydraulic gradient and the permeability of the geologic material. Permeability is a difficult parameter to measure, and its value spans many orders of magnitude depending on the geologic setting. Darcy's Law allows for the calculation of the flux of groundwater based on these two parameters, combined with the cross sectional area of an aquifer. The storage of groundwater is a function of the porosity of the geologic material. The flow of groundwater is commonly categorized based on the size of the flow system, where flow from local topographic highs and lows is called a 'local flow system' and large systems are called 'regional flow systems.' These systems have different residence time scales, which could vary from decades to thousands of years.

Groundwater is capable of dissolving both natural solutes and contaminants. The concentration is a function of the source material’s solubility, and the combination of the pH and the redox state of the water. As groundwater flows through hydrogeologic systems, its chemistry will evolve as a function of the aquifer’s geologic conditions. Further, there are many potential sources of contaminants.

In cold regions, permafrost exerts a primary control on the presence and movement of groundwater. Because permafrost is essentially an impermeable barrier to groundwater flow, when it is present it decreases the flow of water. Taliks and the seasonally-thawed active zone provide pathways through which groundwater can potentially flow. The formation and presence of permafrost can also alter groundwater chemistry and the structure, permeability and porosity of the subsurface, which also changes groundwater systems.

MODULE

2

KNOWLEDGE RELATED TO GROUNDWATER IN THE NORTHWEST TERRITORIES

In the NWT and its neighboring regions, some limited knowledge exists regarding the occurrence of groundwater resources (e.g., geoscientific studies, maps, assessments). This information comes from documents regarding the local and regional scale permafrost, related geotechnics, and hydrology. The Source Water Assessment and Protection document (Government of the Northwest Territories, 2012) identifies the main contaminant sources in reference to protecting water resources for communities and regions, including landfill leachate, sewage lagoons, household septic tanks, fuels, road networks, household storage and vehicles, forest fires, industrial activities such as mining and exploration, and erosion by streams and snowmelt thaw. ARKTIS Solutions Inc. (2016) further detail the main potential sources of contamination for groundwater in NWT aquifers, including landfills, petroleum exploration and production, and mining activities.

This module first provides an overview of the hydrogeological regions and the main types of aquifers found in the NWT. The second section discusses the studies that were found to provide information on permafrost and groundwater in the NWT and its northern neighboring regions. In the two last sections, we discuss the reported and potential groundwater contamination sources in the NWT and northern Canada. This includes a review of the hydrogeological aspects of contaminated sites from scientific and engineering publications, highlights from examples of permafrost hydrogeology, and investigation methods and results, mainly from northern Canada, but also from Alaska and northern Europe.

OVERVIEW OF THE HYDROGEOLOGICAL REGIONS OF NWT

Canada is divided into nine major hydrogeological regions (Sharpe *et al.*, 2008), of which four are found in the NWT (Figure 22): *Permafrost*, *Cordillera*, *Western Plains* and *Canadian Shield*. Following is a description of each region, adapted by the Groundwater Information Network (GIN, 2017).

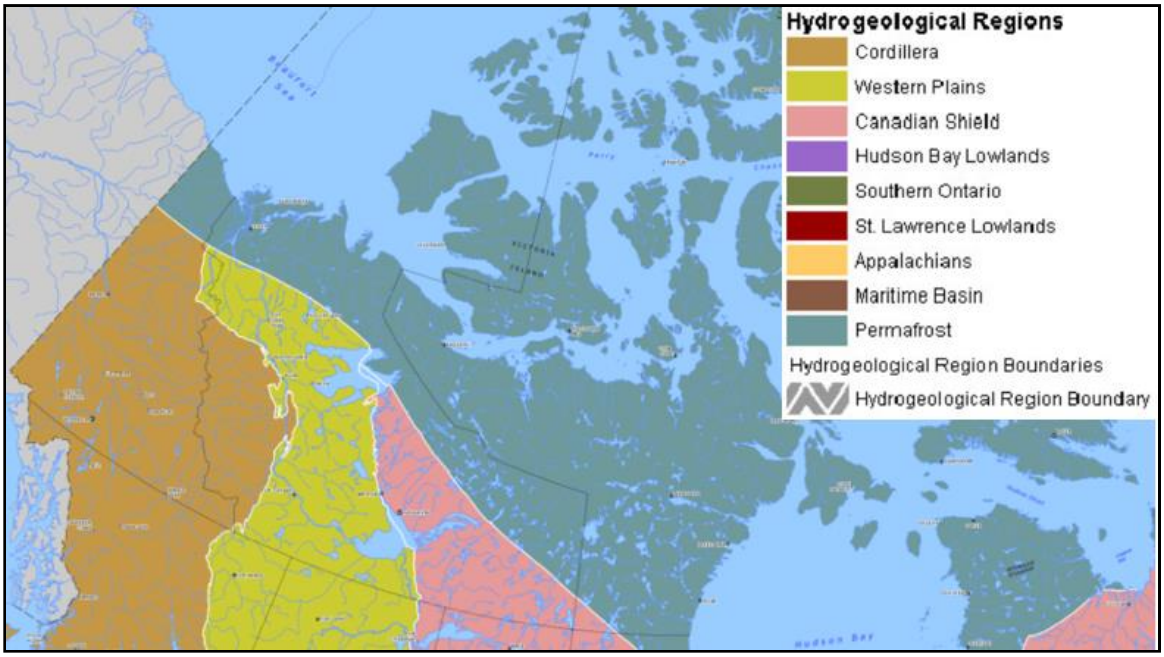


Figure 22. Hydrogeological regions of Canada (modified from GIN, 2017). Not all the regions in the legend are represented in the Figure.

PERMAFROST REGION

The region underlain by continuous permafrost ("Permafrost Region", Figure 22) covers the northern part of the rugged terrain of the Canadian Shield and the gently undulating regions of the Mackenzie Valley, Arctic Archipelago and mountainous areas. Mountainous terrain in the northern Cordillera is important because of the possible restriction of permafrost to lower elevations where atmospheric inversions in winter can lower the mean annual air temperature.

The region of continuous permafrost contains a diverse array of geology including igneous and metamorphic rocks of the Canadian Shield, sub horizontal sedimentary rocks of the central Arctic, and folded and faulted sedimentary rocks of the northwest Arctic Islands. Evaporites are found both in the Mackenzie Valley and in the central to northern Arctic Islands. Surficial sediments consist of regional till sheets, localized glaciolacustrine and glaciomarine deposits, and glaciofluvial deposits.

Hydrogeologically, permafrost primarily functions as a barrier to groundwater flow, especially if the permafrost is ice-bonded (i.e., all of the pores or fractures within the geologic medium are filled with ice). Thus, permafrost can act as the cover for a confined aquifer or it can form the base of an unconfined aquifer. With distance north, permafrost becomes thicker, extending to depths of over 500 m and precluding sub-permafrost potable aquifers. The active layer, when it is thawed, functions as an unconfined aquifer. Discharge of groundwater from taliks can result in icings, accumulations of ice on the ground surface that often occur near rivers. Relatively little is known about the permafrost control of groundwater flow (McKenzie & Voss, 2013).

Within the permafrost zone, groundwater is utilized extensively for water supply in southern Yukon. Many communities draw their municipal supply from coarse valley fill aquifers, which are likely confined below the permafrost; however, this is poorly documented.

CORDILLERA REGION

The Cordillera region (Figure 22) is a mountainous region consisting of a series of north-south trending mountain ranges and intervening interior plains and intermontane valleys. The plains are most extensive in the north, whereas the larger intermontane valleys are more prominent in the south. Mountain relief is commonly 1000-3000 m above sea level (m.a.s.l.). The physiography reflects the underlying geology. The eastern mountains are dominated by deformed, folded and faulted sedimentary rocks whereas the coastal mountains have more volcanic and massive plutonic rocks. Some of the north central plateaus are predominantly underlain by large shield volcanoes and lava flows. Surficial deposits are thick (100 m) in the intermontane valleys and along major river valleys. Deposits include extensive glacifluvial, glaciolacustrine deposits, and below the marine limit, glaciomarine sediment. In the mountains, alluvial fans and valley aprons are also present.

Groundwater is extracted from both bedrock and surficial sediment aquifers. Flow in bedrock is typically through secondary fractures, such as bedding planes, joints or faults. Flow in karstic and volcanic lava flow rocks may also occur in dissolution channels and in interbed zones. Both deeper confined and shallow unconfined surficial aquifers are important. Extreme artesian conditions can exist in confined aquifers in intermontane valleys where connection to adjacent elevated bedrock systems provide substantial hydraulic head. Where shallow unconfined glacifluvial or fluvial aquifers are located adjacent to rivers and streams, they may have direct connection with surface water.

Groundwater recharge is seasonally dependent. In coastal areas, recharge occurs in winter and early spring when precipitation is greatest. Recharge in interior regions occurs in late spring to early summer due to snowmelt. Warm temperatures and vegetation promote high evapotranspiration losses throughout summer.

Groundwater quality is generally very good across the region, with local occurrences of elevated nitrate, arsenic, fluoride, and boron. High salinity due to seawater intrusion may affect coastal aquifers, and high salinity at deep depths may occur inland.

WESTERN PLAINS REGION

The topography of the Western Plains (Figure 22) region is from 1200 m.a.s.l. in the southwest to 200 m.a.s.l. along the northeast edge of the basin and averages 280 m in the Manitoba Lowlands. Two prominent 'prairie steps' disrupt a landscape characterized by flat to gently rolling and hummocky terrain. There are two prominent drainage systems: the Saskatchewan-Nelson River drains to Hudson Bay, and the Mackenzie River drains to the Arctic Sea. The geology of this region is represented by the Western Canada Sedimentary Basin (WCSB) which consists of a sedimentary wedge that thickens from the Shield edge to ~6 km in the southwest. Basal carbonates and evaporites, with intervening shale, outcrop only in the east. The overlying marine sandstone and thick shale are cut by incised valleys and overlain by younger fluvial sandstone units (e.g., Paskapoo). Surficial sediment thickness is variable, being thickest along buried valleys. The surficial succession commonly consists of till-sand and gravel, and till-glaciolacustrine sediment.

The region is divided into bedrock and sediment-dominated terrains. The bedrock hydrostratigraphy is commonly assigned to three divisions, i) a lower clastic unit, ii) a middle unit of carbonates and evaporates, and iii) an upper clastic unit. The distribution of potable water in the region is commonly controlled by depth and the nature of shallower, overlying units. Basin edge topography influences regional flow systems by introducing fresh meteoric water as recharge from isolated uplands. Across the region, surficial aquifers, and particularly buried valley aquifers, are important. Near surface bedrock aquifers dominated by marine and fluvial sandstone are important. Shallow fluvial sandstone aquifers are important but, due to inter-bedded mudstones and isolated channel sands, have variable yield and quality. Given low topography, flat-lying stratigraphy, and high bedrock heterogeneity, local scale flow systems driven by minor topographic variations are prominent across the region.

CANADIAN SHIELD REGION

The regional landscape of the Canadian Shield (Figure 22) consists of a series of peneplain uplands between ~200-1000 m.a.s.l., having a topographic relief of 50-100 m. Greater relief of 150-300 m occurs along river valleys incised into uplands and plateaus. A series of large lakes occur along the southern border of the Shield with sedimentary basins (e.g., Great Bear Lake, Great Slave Lake).

The Shield is composed of Precambrian igneous, metamorphic and meta-sedimentary crystalline rocks formed during several phases of mountain building and other tectonic events. Subdivided into geological provinces according to deformation style and age, each geological province comprises banded or foliated rock that have been metamorphosed and deformed to various degrees as greenstone-sediment terrains and adjacent gneissic belts. These have been intruded by granitic rocks and regional dyke systems. Much of the area has a discontinuous cover of thin glacial sediment. Thicker surficial deposits occur in areas of glacial landforms such as drumlins, eskers and moraines.

Ubiquitous crystalline rocks are characterized by consistently low primary porosity, permeability and variable fracture patterns, and generally have low water yields. Fracture zones are found to yield potable water to depths of ~100 m, and at greater depths the groundwater becomes progressively saline. High total dissolved solids of 50-100 g/L occur in the sparsely fractured deeper rocks. Elevated heads in Shield rocks remain due to surface loading from the Laurentide Ice Sheet. Surficial sediment aquifers are important, particularly high-yield glacifluvial aquifers that provide most of the potential municipal drinking water supply from groundwater. Recharge and discharge patterns are likely localized by fracture patterns. The modest undulating relief on the Shield provides low driving force for groundwater, leading to low flow rates and reduced mixing at depth. Water quality can be compromised in bedrock fracture systems due to bedrock mineralization, particularly due to uranium and radon gas.

TYPES OF AQUIFERS IN THE NWT

Within the NWT, there are many different types of aquifers. They can be grouped by the nature of their porosity and lithology, including:

- Quaternary sediments, such as glacially reworked tills, eskers, and fluvial sediments;
- Canadian Shield, including shallow fractured-rock aquifers from tens of meters to less than 100 m depth, and deep fractured aquifers along major geologic structures, deeper than 100m depth;
- Carbonate sedimentary rock aquifers in the Interior Plain and the Mackenzie Mountains; and
- Clastic sedimentary rock aquifers in the Liard Basin, and in the northern portion of the Western Canadian Sedimentary Basin.

The distribution of freshwater in the aquifers in the NWT is not a simple function of the present-day water budget and flow system, but is also a result of sub-glacial melt water and forced recharge from below the Laurentide Ice Sheet (Grasby & Chen, 2005; Greene *et al.*, 2008). This has been shown through isotopic studies, pressure data, and hydrogeological mapping and conceptual reconstruction of groundwater conditions in the past with the help of numerical flow simulations (e.g., Bense & Person, 2008).

The geology and hydrogeology of the sedimentary basins and the Mackenzie Mountains in the NWT has been reviewed elsewhere (Martel et al., 2011; AMEC, 2014; Golder Associates, 2015a; Pierce & Falck, 2015; Golder Associates, 2017). In this report, we review in details the less-studied aquifers in the fractured rocks of the Canadian Shield (shallow and deep), and the sediments covering the shield rocks.

Figure 23 presents an example of an aquifer located in the Canadian Shield region (Coppermine River Valley) that has been characterized by St-Onge (2012).

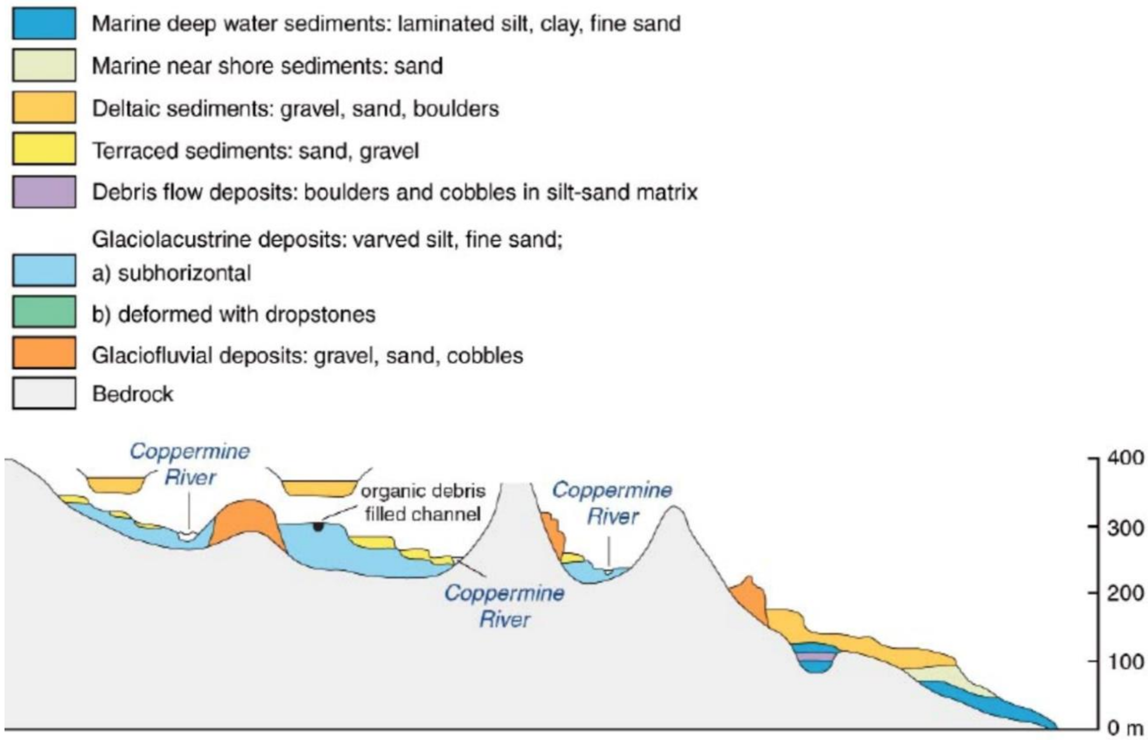


Figure 23. Sedimentary sequences covering depressions in bedrock topography at the Lower Coppermine River Valley, Nunavut and the NWT (St-Onge, 2012).

ESKER AQUIFERS

Eskers are highly permeable sandy deposits that can form productive aquifers, although they have limited spatial extent. The distribution of eskers is presented in Grasby & Chen (2005) (see Figure 24). Hydrogeological studies of esker aquifers in Quebec, located on Canadian Shield rocks, demonstrated that the groundwater age in deeper portions of an esker can be up to a thousand years old, while the surficial groundwater at the top of an esker is typically much younger, on the order of years.

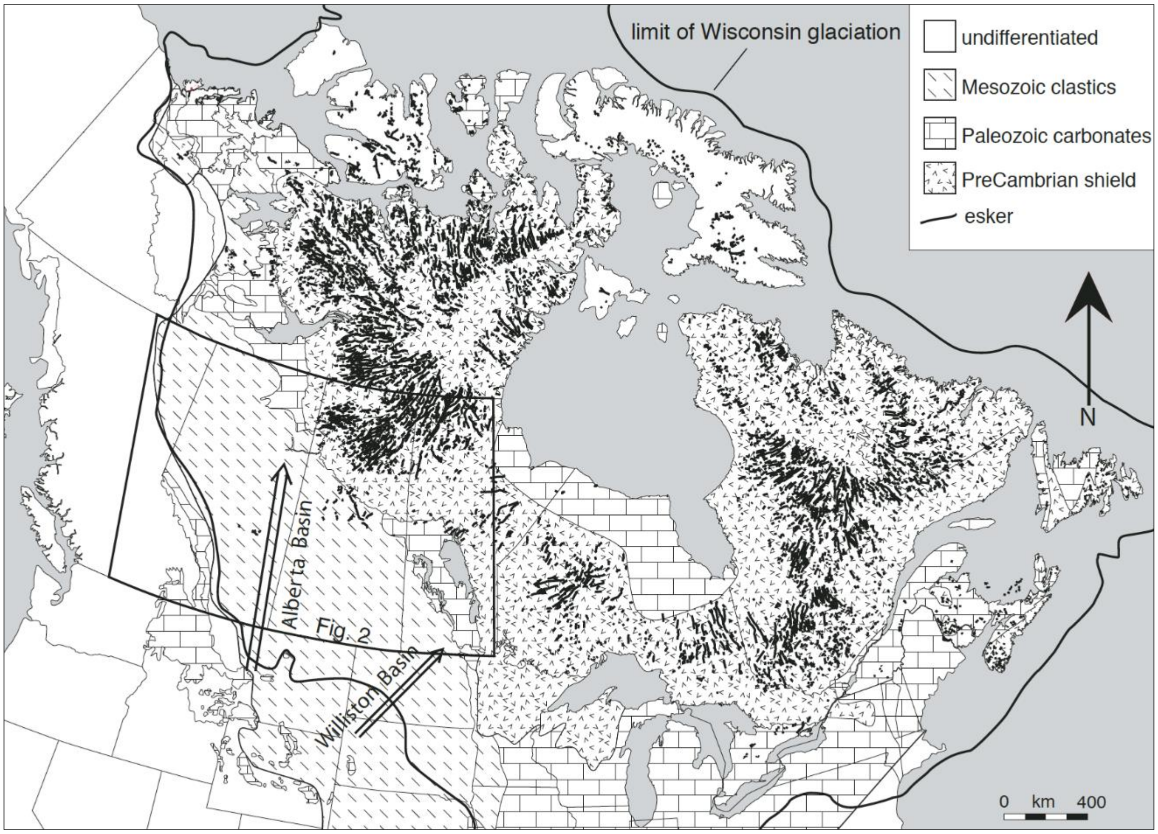


Figure 24. Distribution of major eskers in Canada, map from Grasby & Chen (2005), after Fulton (1995), and glacial maximum boundary from Dyke & Prest (1986)

MORAINES

Moraine deposits are rocks and sediment deposited by glaciers. While there are limited hydrogeologic data on moraine aquifers in northern Canada, there are examples from other regions of the sedimentary layering and the hydraulic conductivity distributions of those sediments (e.g., from the Oak Ridges Moraine in southern Ontario, which was deposited during the retreat of the Laurentide ice sheet (Gerber & Howard, 2002)).

SHALLOW FRACTURED ROCK AQUIFERS

Fractured rocks are important for water supply in many regions of the world (Singhal & Gupta, 1999). The Canadian Shield covers approximately half of the NWT and is expected to locally form a productive aquifer for groundwater wells. Since the crystalline rock, such as gneiss or granite, has low matrix or primary permeability, the groundwater flow occurs predominantly through the network of open and connected fractures. The causes of fracturing or jointing, and their present fill or open aperture, are complex. There are numerous sources of these important fractures, including old geologic features (e.g., cooling joints after magma intrusion and crystallization to granitic rock), intrusions of magma dykes causing fracturing, rheological contrasts between different rock units and tectonic stresses, fault zone reactivation, horizontal joints caused by unloading of the land after glaciation, and dissolution channels in carbonate rocks.

The barrier nature of fault zones is also apparent in many areas, and a block model of fractured rock with conductor domains can be visualized that is bounded by faults containing low-permeability clay-rich gouges and breccias. The Canadian Shield contains a great number of ancient fault zones and exhumed shear zones (formed in ductile conditions at depth) in different orientations and ages. Most of these fault zones and shear zones are now sealed with minerals ("cemented") that fill the fractured networks that used to be open. Field studies in such environments at an Ontario site in the Canadian Shield concluded that a fault zone appeared to form a hydraulic barrier to the shallow groundwater flow system (Gleeson & Novakowski, 2009; Figure 25).

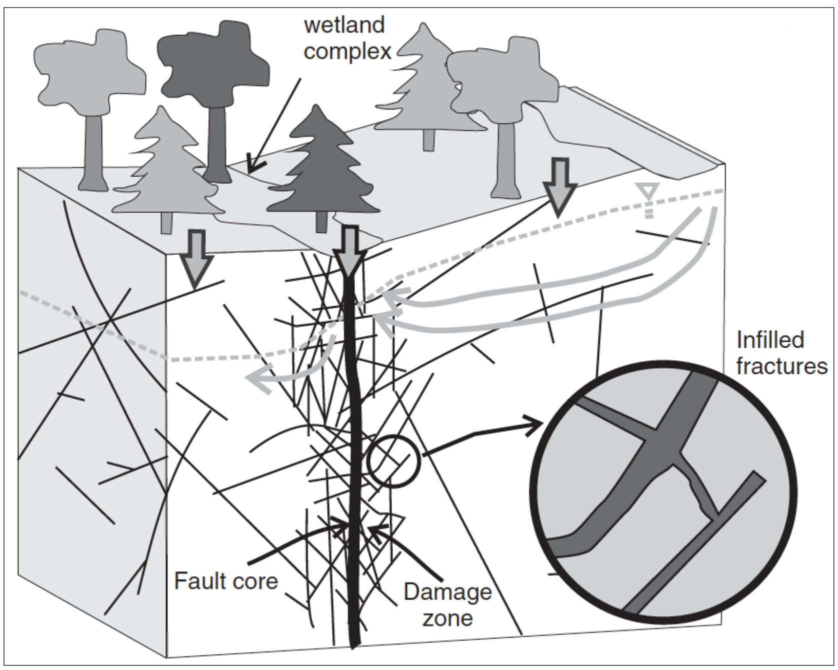


Figure 25. An idealized cross-sectional domain through a fault zone (lineament on the landscape). The fracture space is sealed by minerals such as clays. Approximate flow lines are shown (portion of figure from Gleeson & Novakowski, 2009).

CANADIAN SHIELD DEEP AQUIFERS

<u>*Block-scale units with Hydraulic Conductor Domains*</u>

At a regional "block scale" of 1 km or more, fractured metamorphic rocks generally have zones of structurally enhanced permeability in the otherwise low-permeability metamorphic and plutonic rock. This concept has been developed from deep drilling and testing, as well as modelling, in metamorphic rocks on the Fennoscandian Shield in southern Sweden (Rhen *et al.*, 2003), Finland (POSIVA, 2003), Switzerland (Thury *et al.*, 1994), and Canada (Stevenson *et al.*, 1996), among other locations around the world.

Figure 26 illustrates this standard conceptual model for fractured shield rock. In Canada, the Atomic Energy of Canada Limited has done hydrogeological test work at the Whiteshell Research Area in Manitoba, and other sites in Ontario, to map these permeable fault zone domains (Everitt *et al.*, 1998). A series of fault zones were shown to have heterogeneous permeability distributions and contain narrow zones of high permeability. Hydrogeological observations at mineral exploration and mining projects in the NWT, where permeable fault zones were drilled and tested (see Module 3), confirm the conceptual validity of this model for the NWT.

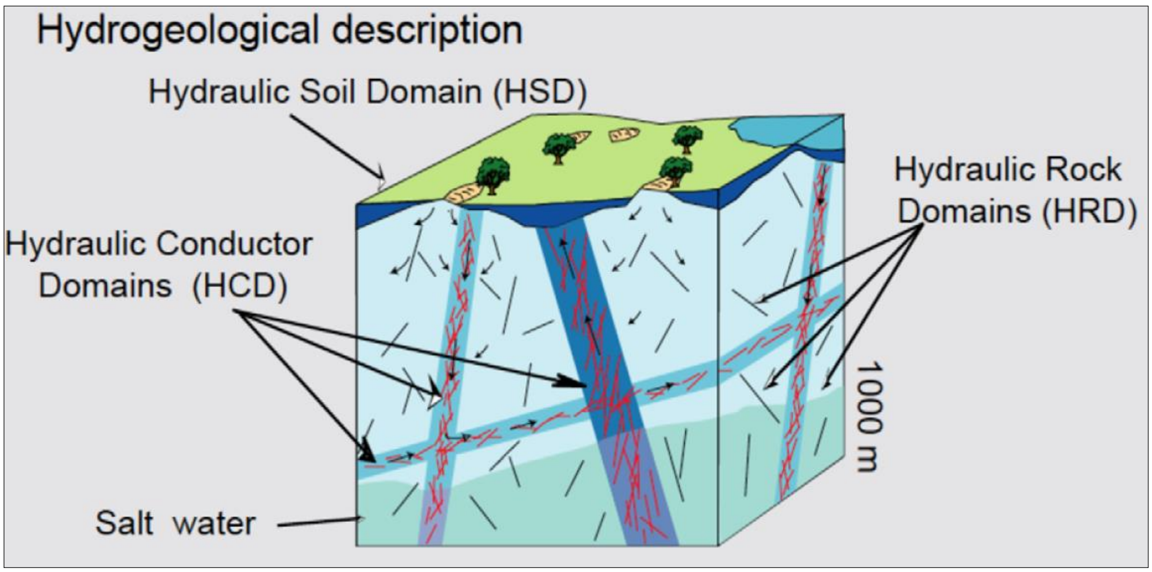


Figure 26. Hydrogeological conceptual model of crystalline bedrock with Hydraulic Conductor Domains along fracture (fault) zones (from Tsang et al., 2015, after Rhen et al., 2003).

PERMAFROST AND GROUNDWATER IN THE NWT

This sub-section details site-specific or regional permafrost and/or groundwater settings. They are presented with a regional classification: The Interior Plains, The Canadian Shield, The Mackenzie Mountains, the Mackenzie River Delta, and the Arctic Islands.

THE INTERIOR PLAINS

Interior Plains near Norman Wells

AMEC (2014) studied aquifer extent based on wells that were drilled and hydraulically tested in 2013 by the petroleum industry. Well depths were on the order of 100 to 300 m and the aquifer and aquitard units were partially mapped. This baseline study provides some estimates for depths to groundwater and recharge rates, but the permafrost conditions and related aquifers were not identified. Golder Associates (2015a and 2015b) wrote detailed hydrogeological reports and provided estimates of hydrogeological parameters and conditions for various geological formations and quantities of water. The reports also discussed local traditional knowledge and related vegetation type to permafrost distribution. Aquifer vulnerability was not mentioned, but perceived changes in water quality by the residents due to natural resource exploitation and exploration activities were discussed. Rudolph *et al.* (2016) reviewed the previous reports and discussed the gaps in information and needs for future data collection.

In deeper saline aquifers (that are not useable as drinking water sources but are of interest to the hydrocarbon industry) there are published summary reports pertaining to hydraulic properties, despite a relatively small amount of data. Sedimentary rock formations have been mapped from petroleum industry wells and geophysical surveys (e.g., Hayes & Dunn, 2012).

Liard River Basin (transboundary aquifers)

In the Liard River Basin, Golder Associates (2017) provided a summary of the regional aquifers that both are within NWT borders and extend across the boundaries with British Columbia and Alberta. Their analysis includes groundwater quality data. The report suggested that the degradation of discontinuous permafrost will lead to an increase in surface-groundwater interaction and contaminant transport from surface water (e.g., from agricultural sources or hydrocarbon industry sources in some areas). The report states that knowledge of groundwater aquifers is "limited" due to a general lack of data. The database could be expanded through locally focused aquifer hydrogeological characterization and aquifer vulnerability assessments (e.g., at population centers or centers of industrial activity).

Research at the Scotty Creek Research Station in the Liard River Basin has shown how permafrost degradation over a period of many years changes shallow hydrogeological conditions (Connon *et al.*, 2014; Kurylyk *et al.*, 2016).

Hay River Basin (transboundary aquifers)

The Hay River Basin lies mostly in Alberta and British Columbia, and extends partially into the NWT. A baseline study by Stantec (2016) focused on surface water hydrology and water quality. Groundwater observation wells in Alberta and British Columbia are included. The report recommended a review of the groundwater quality data in groundwater wells and the development of a database and reporting system for groundwater in the NWT. For example, the risk factors and potential sources of groundwater contamination from hydrocarbon extraction could be included in aquifer vulnerability assessments.

THE CANADIAN SHIELD

A large portion of the NWT is characterized by the fractured rock geology of the Canadian Shield. These rocks are not used for community drinking water. At many locations across the NWT's Shield, the mining industry has collected detailed hydrogeological data as part of their engineering testing programs (geotechnical and hydrogeological), environmental assessments, and monitoring. These include at the Diavik Diamond Mine (Golder Associates, 2012; Bieber *et al.*, 2006), Snap Lake Mine, Gahcho Kué Mine (Emerson *et al.*, 2006; DeBeers Canada Inc, 2010), and Giant Mine (SRK Consulting, 2002a). Con Mine near Yellowknife (Douglas *et al.*, 2000) is an example of a mine site at which groundwater conditions at hundreds of meters' depth have been studied.

Mine sites in Nunavut also have hydrogeologic information that could be compiled and used to determine properties of different rock types at varying depths and permafrost conditions (e.g., Lupin Mine and research site (Stotler *et al.*, 2009; 2011) and the Hope Bay mining project near the Arctic Coast (Mayer *et al.*, 2014)).

THE MACKENZIE RIVER DELTA

At the regional scale, past studies of the Mackenzie River Basin were almost exclusively focused on surface water hydrology and interactions with the atmosphere (e.g., the GEWEX study – Krauss, 1995) and do not provide information about groundwater conditions. In the continuous permafrost region of the northern Yukon, a study by Utting *et al.* (2012) used isotopes to identify the dynamics of groundwater flow. There are numerous publications on the hydrology of the Mackenzie River Delta but they have little relationship to community water supply, and we do not review this specific literature.

THE MACKENZIE MOUNTAINS

The studies in the Mackenzie Mountains are also mainly focused on surface water hydrology. There have been extensive stream sediment sampling, while watershed hydrological mapping is in progress (e.g., Pierce & Falck, 2015). Information on groundwater quality of natural springs have been used for geochemical exploration by the mineral resource industry (Caron *et al.*, 2008) and such baseline data are useful for regional groundwater quality assessment in the mountainous regions.

The Arctic Islands

In the Arctic Islands, the seasonal thaw of the active layer above the thick permafrost completely controls the local groundwater flow system, including the aquifer hydraulic properties, thickness, and, indirectly, the recharge rate. The seasonal and long-term variation of permafrost extent, as a hydraulic property, needs to be considered in aquifer vulnerability mapping. There has been some research on the islands' shallow groundwater flow system that attempted to quantify the groundwater discharge rates to small lakes and streams (Dugan *et al.*, 2012). The geology of the islands is still being studied by the Geological Survey of Canada (e.g., Mathieu *et al.*, 2013).

KNOWN SOURCES OF GROUNDWATER CONTAMINATION IN THE NWT

The information in this module is organized into separate sections related to industrial, commercial, and other activities that represent common sources of contaminant in northern Canada, particularly in the NWT. Case studies are presented for northern Canada and Alaska. We first discuss the contaminant sources related to the mining industry as this has been historically the most important for the NWT. The second sub-section discusses the hydrocarbon extraction industry and contamination of groundwater and soils by hydrocarbons such as fuels and oils. We briefly discuss the groundwater contamination at military radar sites in northern Canada, municipal and residential wastes, and other commercial contaminant sources. The final sub-section reviews the widely distributed contaminants that affect groundwater quality, such as the atmospherically-deposited industrial contaminants and naturally-occurring groundwater contaminants from geological sources.

MINE-RELATED CONTAMINATION

Historic mining and mineral exploration in the NWT left a legacy of many contaminated sites (Auditor General of Canada, 2002). The descriptions of these sites can be found in many publications:

- Indigenous and Northern Affairs Canada (INAC) website lists about 35 closed mines in three different aboriginal settlement areas in the NWT;
- Project remediation update brochures called "The Big Picture" by INAC (2008a, 2010);
- AANDC (2015) Northern Contaminated Sites Program performance reports;
- Federal Contaminated Sites Portal;
- Silke (2009) reviewed the history of mining operations in the Northwest Territories;
- ReSDA (2016) has a detailed summary of mines in the Northwest Territories.

Ongoing research on permafrost hydrogeology and contaminants in the NWT was discussed during a conference in 2016 (Morse, 2017). The latest ongoing hydrogeological and other natural science research in the NWT is summarized in abstracts of the annual Compendia of Research in the NWT for the years 2013 to 2015 (Mercer *et al.*, 2014; Mercer, 2015; Michel *et al.*, 2015).

We only briefly discuss some remediation activities as part of the hydrogeological review and we direct the readers to more technical or scientific literature for additional information.

Mine tailings

The mine tailings usually contain by-products of the mineral ore milling and extraction such as mercury, ammonia, cyanide, arsenic, heavy metals, and radionuclides, depending on the mineralogy of the extracted ore. Seepage from tailings is a source of contamination of ground and surface water, down-gradient from the properties. Historically, tailings were dumped as slurry and filled terrain depressions or were dumped directly into ponds, lakes, and stream valleys. Modern mines build specially-designed tailings storage facilities that offer some containment and protection from contaminated groundwater seepage from the tailings. The soil hydrology aspects of mine tailings in permafrost conditions are reviewed by Elberling (2004).

At historic mines, tailings were not controlled due to a lack of hydrogeological knowledge and governmental regulation. Some examples of mines in the NWT undergoing assessment and remediation are:

- The **Giant Mine** site has large areas of tailings contaminated with arsenic (SRK Consulting, 2013);
- **Discovery Mine** has tailings piles containing mercury, widely spread, that have contaminated sediment in proximal lakes. The remediation is ongoing and involves dealing with past mining infrastructure, tailings, contaminated soils, monitoring piezometer sampling, and more (INAC, 2005);
- **Tundra Gold Mine** has tailings piles contaminated with heavy metals. The underground mine reached depths of about 400 m and the depth to bottom of permafrost was about 330 m (Dubnie, 1972; INAC, 2010);
- At the **Silver Bear Properties** (Terra, Northrim, Smallwood, Norex mines) heavy metals have leached from tailings ponds. Tailings also cover a lake bed. The remediation plans include covering of tailings with waste rock, using wetland natural attenuation to reduce arsenic levels in the lake water, and monitoring of water quality (Bright, 2015).

Waste rock piles

Waste rock from mining operations is a common source of acidic rock drainage (ARD) that contains dissolved heavy metals with potential to contaminate groundwater and surface water. The hydrological and gas flow processes in waste rock piles are described in many studies (e.g., Dawson & Morin, 1996; Lefebvre *et al.*, 2001). The seasonal freeze-thaw cycle (moderated by a warming climate) and the geochemistry of the rock pile determine how much the waste piles freeze, thus controlling their hydrology. For example, at Ekati Diamond Mine in the NWT, the waste rock does not freeze as much as expected (Morin, 2003). A recent review by SRK Consulting (2010) was done on the hydrology of waste rock covers in northern climates. At the Diavik Diamond Mine, an ongoing study by researchers at the University of British Columbia includes constructing, instrumenting, and testing experimental waste rock test piles (Neuner *et al.*, 2013). The hydraulic properties of unsaturated and saturated rock matrix were tested, water infiltration rates and heat flow were measured, and water quality and rock geochemistry sampled (Pham *et al.*, 2015).

Hazardous waste storage

At industrial sites such as mine properties, hazardous waste can be spilled on soils. Contaminants include PCBs from electrical equipment coolants, lead from paints and batteries, DDT insecticide sprayed around the mine facilities, and petroleum products (hydrocarbons). Furthermore, in the NWT, arsenic trioxide was a by-product of the gold extraction process from the mined rock.

Giant Mine (NWT) – Case study of hazardous waste storage

At Giant Mine, a now-closed gold mine 5 km north of Yellowknife, large quantities of arsenic trioxide dust remain stored in underground stopes (chambers) (Smecht *et al.*, 1975; Sandlos and Keeling, 2012; INAC, 2017). The property was a source of contamination into the adjacent bays of Great Slave Lake and nearby lakes due to the dispersal of wind-blown arsenic dust from roasting emissions and tailings (Falk *et al.*, 1973; Palmer *et al.*, 2015). The groundwater is contaminated with arsenic from the arsenic-rich mine tailings that cover large areas, as well as other sources (Clark & Raven, 2004).

The Giant Mine site has been studied by hydrogeological and environmental consultants since the 1990s. Following is a summary of the relevant observations related to permafrost hydrogeology.

- A network of multi-level monitoring wells outside the mine, and one multi-level well inside the mine shaft, were installed (SRK Consulting, 2002a) and have been subsequently used to monitor the groundwater pressures and water quality (SRK Consulting, 2004; Royle, 2007).
- The geological structures were mapped (SRK Consulting, 2007a) and the pressure data indicated that the major fault zone in the area, the West Bay Fault, acted as a barrier to groundwater flow across it, while some other faults were likely conduits for groundwater flow (Mackie, 2002). The mine-dewatering operations drained groundwater at a rate of 1940 m^3/day.
- A detailed review mapped the temperatures and permafrost conditions observed over the years during which the mine operated (SRK Consulting, 2002c).
- An expert group, involving the Canadian Government and multiple consultants, agreed on a remediation plan to freeze the rock around the underground stopes that store the arsenic trioxide dust in an effort to re-create the previously existing permafrost (SRK Consulting & SENES Consultants, 2007, SRK Consulting, 2013).

Permafrost is discontinuous in the Yellowknife area. It is relatively easy to identify permafrost below tree-covered muskeg, but difficult to do so under the rock outcrops. In this region there is no permafrost below surface water (Brown, 1973). Some patches of permafrost can also be the remnants of an earlier cooler climate. Observations at Giant Mine suggest that permafrost was present below peat-covered sediments. Permafrost existed within the underground mine between depths of 35 m and 85 m, although the temperature of the tunnel walls was close to the freezing point (-1.3 to +0.4 °C). Permafrost existed below the sediment-filled Baker Creek valley, and the bottom of permafrost was about 76 to 82 m deep (McDonald, 1953). Drill holes in the sediment below the valley found permafrost at shallow depths, but in other parts of the mine under rock outcrops there was no permafrost (Espley, 1969). At the present time, permafrost occurs sporadically around the tailings piles (Figure 27).

In the 1950s, mine engineering investigations tried to identify a secure location for the long-term storage of the toxic and highly-soluble arsenic trioxide dust. According to Muir (1951), the general manager of the mine at that time, the underground chambers for storage of arsenic trioxide dust were chosen in areas of relatively less-fractured and faulted rock and where permafrost existed. It was hoped that this location would prevent groundwater inflow and arsenic dissolution and mobilization. A 200 m long mine drift was excavated and horizontal drill holes were used to probe the rock.

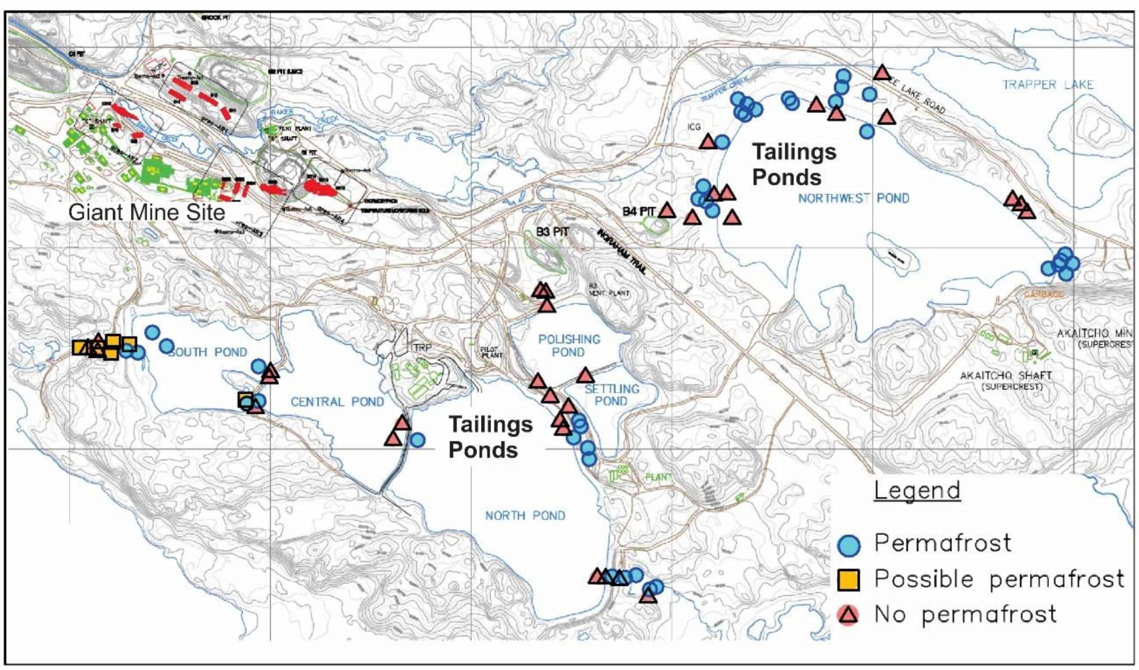


Figure 27. Occurrence of permafrost in tailings areas at Giant Mine, NWT (modified for clarity after SRK Consulting, 2002b).

At the closest mine stope (#208) to the proposed location, the mining engineers reported that all faults and fractures were filled with ice. The chambers (stopes) were excavated, causing only temporary thawing of the ice on the excavation walls. Normally at the mine, the tunneling caused the permafrost to thaw for a "few inches", but it then froze again within hours. Underground rock temperatures in the upper levels were between -2.2 and 0 °C, and much warmer (10 °C) at the bottom of the mine at about 600 m depth (Espley, 1969). The geothermal gradient was also confirmed at the nearby Con Mine in Yellowknife (Boyle, 1961). The mine was considered at one time as a low-temperature geothermal project (35 °C at 2.5 km depth) for community heating system (Ghomshei, 2007).

The mine ventilation in the tunnels, in addition to geothermal heat, has resulted in a general warming of the entire mine-works, enough to begin thawing the permafrost. Engineers attempted to cool the separated arsenic chambers by blowing cold winter air into them, but by the 1970s the permafrost at shallow depths was not returning to the mine tunnel walls (de Smecht *et al.*, 1975). The federal agency DIAND, responsible for regulating mining activities in the NWT, recommended a monitoring program of underground temperatures and a delay of planned mine re-flood until the permafrost existence was confirmed, as it was known at the time that shallow permafrost thawed at other underground mines in that region (SRK Consulting, 2002c, review and references within). The analytical and numerical models by SRK Consulting (2002c) suggested that the permafrost was already warm and close to thawing and that the mining activity accelerated the thawing process.

In conclusion, the Giant Mine case study provides important information and lessons-learned about managing mine waste in a permafrost terrain. The permafrost conditions were well described; it is naturally occurring under thick cover of sediments and appears uncertain under the bedrock outcrops. It is discontinuous and part of it consists of remnants of a previously colder environment. This permafrost is sensitive to temperature changes caused by the mining activities on decadal time scale.

Importantly, this site demonstrates how hydrogeological data and permafrost mapping improve the understanding of groundwater in the site and region. Finally, the study of Giant Mine demonstrated that artificial ground freezing is an effective methodology for groundwater contamination control at a local-scale in relatively low-permeable fractured rocks, although the costs are considerable.

Radionuclides

In the NWT, uranium ore was mined at several sites, leading to soil and water contamination (Barrie *et al.,* 1992). At the Rayrock Mine there are radioactive tailings that were dumped in lakes nearby (Veska & Eaton, 1991). The transportation route from Port Radium to Fort McMurray was tested in high detail for soil contamination of radionuclides as well as groundwater sampling (AMEC, 2005; Canadian Nuclear Safety

Commission, 2017). The most contaminated soil was removed. There was also some radionuclide contamination at Contact Lake Mine, where silver and uranium were mined, and the waste rock had been dumped near a lake. The remediation efforts include monitoring of water quality and removal of the contaminated soil.

More information about the recommended sampling and testing procedures of radionuclides in groundwater are provided in Government of Canada (2016) Radionuclides in Groundwater Bulletin.

Saline water discharge

Saline water discharges from naturally-occurring groundwater seeps or from mining and exploration drilling activities. The source of this water is generally from deep groundwater along structures such as faults or thawed zones such as taliks. The sources from mining activities are usually from naturally-occurring deep saline groundwater that has been pumped out to dewater mine structures. The sources can be intentional (e.g., brines created to prevent freezing of drill rods in permafrost zones) or unintentional (upwelling of deep saline water through abandoned open drill holes or open pits).

Brackish or saline groundwater that is pumped from mines in the NWT can be a contaminant because of the elevated total dissolved solids (TDS). Mines routinely discharge such water to surface waters or tailings under permits, but excessive discharge to freshwaters can negatively affect water quality. At the Snap Lake Mine in the NWT, deep groundwater inflow occurred from below permafrost and within taliks. A rather small number of boreholes were tested prior to mine construction, and the hydraulic conductivity of the bedrock was deemed low, but only a small part of the rock volume and its structures were tested prior to the mine construction. The modeled maximum inflow rate to the mine was expected to be 26000 m^3/day in 2018 (DeBeers Canada Mining Inc., 2002), while the actual inflow rate in 2012 was 32516 m^3/day (DeBeers Canada Mining Inc., 2013).

Drilling brines in sumps

Saline drilling fluids – used to prevent freezing of the drill hole in permafrost areas – are typically disposed in sumps that are excavated during the winter in frozen soils and covered. The problems of sump leakage have been studied since the 1980s (French, 1980), and more recently a hydrogeological study was done on five drilling mud sumps in the Mackenzie Delta and in Tuktoyaktuk (Dyke, 2001), as shown on Figure 28. The migration of dissolved salts from the sumps has been used as a tracer to show the extent of the transport in the active layer. The thawing ice-lens material was suspected of increasing the hydraulic conductivity of the soils. The difference in density between the brines and the surrounding fresh groundwater also contributed to its migration on flat terrain. To improve the sump design and construction practices, guidelines were developed by Hardy BBT Ltd. and Stanley Associates Engineering Ltd. (1988), Piteau Engineering Ltd (1989), and Ellis & Associates Inc. (2004).

A review of former drilling sumps by Kokelj and GeoNorth Ltd. (2002) found that 82 % of the sumps surveyed have collapsed, and that the active layer has deepened around the sumps. Typically, the drilling fluids were stored 1.2 to 2.0 m below ground surface, below the presumed maximum seasonal thaw. Some leakages were caused by sump subsidence induced by partial melting of the ground ice, new vegetation growth around the sump, more snow accumulation, and inadequate cover of the sumps. Kokelj *et al.* (2010) measured temperature profiles at a few former drill waste sumps and used a two-dimensional numerical model to simulate land cover conditions and changing climatic conditions. Thienpont *et al.* (2010) sampled sediments in 100 small lakes in the Mackenzie Delta. The statistics suggested that elevated conductivity in lake waters originated from the salt water drill sumps.

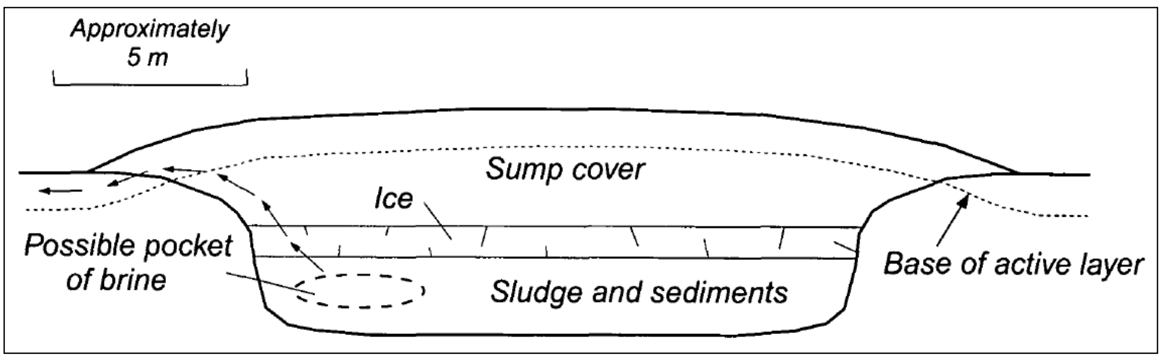


Figure 28 Generalized cross-section of a sump holding drilling mud and brines in Mackenzie Delta, NWT (from Dyke, 2001).

<u>*Leakage and spills of chemicals used for oil and gas exploration and development*</u>

A large amount of research has recently focused on the risks of groundwater contamination from shale gas exploration and extraction:

- US EPA (2012) - large scientific review with many case studies from continental USA;
- Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction (2014) - review for Canada;
- Government of Quebec (2014) - review of risks of contamination and exploration activities in southern Quebec;
- Nova Scotia Independent Review Panel on Hydraulic Fracturing (2014) - includes examples of maps of natural methane emissions;
- Becklumb *et al.* (2015) - review of environmental risks of shale gas exploitation in Canada.

The most direct source of shallow groundwater contamination during fracking activities are spills from wastewater ponds beside the drill rigs. The chemicals added to water used in hydraulic fracturing processes and chemical stimulation are hazardous if spilled. Another common source of contamination is from leaking faulty casings or abandoned oil wells. The US EPA (2012) report has case studies from hydrogeological and environmental investigations in the continental USA.

The question of vertical movement of injected fluid via fractures and cracks in less permeable sedimentary rocks was studied through simulations by many researchers (e.g., Gassiat *et al.*, 2013). Seismic evidences from a large dataset of monitoring stations in areas where hydraulic fracturing activities take place show that the microseismicity did not extend beyond 600 m above the injection zone (Flewelling *et al.,* 2013), and the geomechanical considerations suggest that the shear displacements along fractures or faults extended only 10 m or less. Overall, a low risk of contamination was expected because induced fractures in shale layers extend to a few hundred meters at most, while the injection depths are typically 1.5 to 4 km (Becklumb *et al.,* 2015 and references within). However, there is a relative lack of data on the topic, and more monitoring is needed to adequately assess the problem (Government of Quebec, 2014).

DEEP MINE-GROUNDWATER MONITORING IN CONTINUOUS PERMAFROST AREAS

Mining activities impact the subsurface to depths of hundreds of meters in most cases, deeper than the bottom of permafrost in continuous permafrost zones. As part of proposed mine environmental assessment and monitoring during the periods of active mining and post-closure, groundwater should be sampled at key depths. Special sampling methods have been developed for permafrost conditions. In the following summary, we present a few cases of deep hydraulic testing and groundwater sampling at mining projects in the Arctic region in continuous permafrost conditions (in Nunavut and the NWT).

Lupin Mine (NU) – Case study

The Lupin Mine has been used as a research site for deep groundwater flow in a continuous permafrost zone. Mine-dewatering causes changes in hydraulic gradients and has even created unsaturated zones below the permafrost (Ruskeeniemi *et al.*, 2004). This causes a wide range of salinities in the samples because of mixing of water from different depths drawn toward the depressurized zone around the mine, and possibly methane hydrate dissociation reactions, thus complicating the interpretation of results in relation to the hydrogeological conceptual model (Stotler *et al.*, 2009). Other contaminants that are present in groundwater at the Lupin Mine were nitrates from blasting, and sulfide oxidation from exposed rocks. The report by Gartner Lee Ltd. (2006) described the local hydrogeology determined through investigations by consulting firms for the mining company. There were saline fluid inclusions (pockets of saline water) within the permafrost. The mining company tested two drill holes with packer equipment at 100 m intervals through the permafrost and thermistor strings were installed.

Although taliks exist under deep lakes in the area, the hydraulic properties are largely unknown. A talik that is present in low-permeability rocks, without major fracture zones, may be hydrogeologically insignificant, but a talik intersecting or related to a fault or other more permeable structure may be a permeable zone (Ruskeeniemi *et al.*, 2004).

A 480 m deep drill hole was equipped with testing and sampling equipment (thermal, hydraulic, geochemical) below the base of permafrost at 458 m (Freifeld *et al.*, 2008). The groundwater samples were taken using specially-developed equipment for cold regions. The problems with sampling in drill holes in permafrost are (Stotler *et al.*, 2011):

- short time of sampling before the drill hole freezes in cold permafrost zone,
- low permeability of the permafrost zone precludes pumping of the zone to flush drilling fluids (samples extracted can be contaminated with drilling brine).

Technological solutions exist to prevent the borehole from freezing after installation, such as the multi-port Westbay Well (Westbay Instruments, 2017). With this system a long piezometer tube is connected to sampling zones between permanently inflated packers that allows a small probe to travel in an antifreeze-gel-filled tube and connect to the sampling ports to withdraw groundwater samples. In cold regions, the pumping water risks freezing in certain situations, and, in rocks of very low permeability, sample collection is difficult.

Doris North Project (NU) – Case study

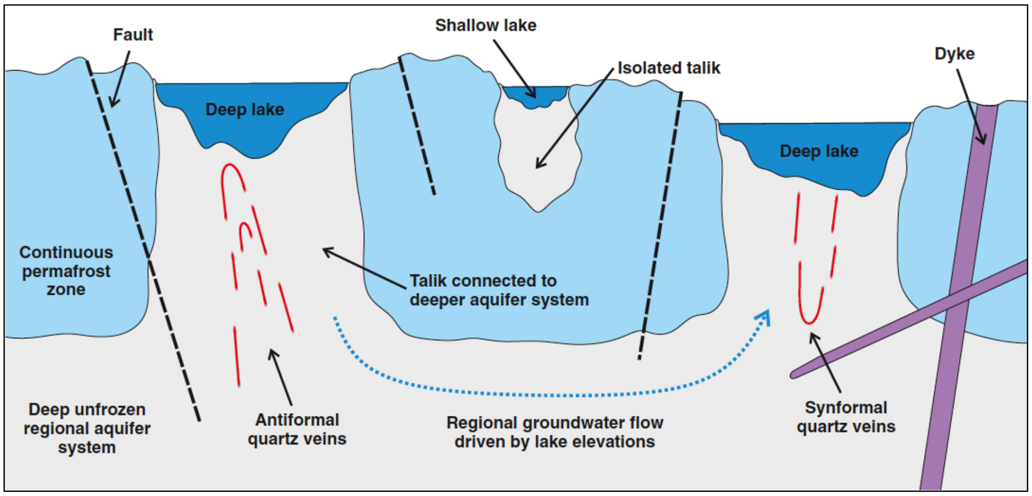
Recently the Doris North Gold Mine opened in Nunavut Territory, in the Hope Bay project area on the mainland of the Arctic Ocean coast, south of Victoria Island. Doris Lake is an elongated water body filling the exposed bedrock topography of the area. Ground temperatures, measured in 25 boreholes, show spatial variation from -3.6 to -9.5 °C (Smith *et al.*, 2013), depending on proximity to lakes, topography, and snow cover (Smith *et al.* 2010). Hydraulic tests were carried out using water-inflated packers and in multi-port wells in talik zones under the lakes and under the permafrost (SRK Consulting, 2005). A schematic representation of the groundwater flow system and permafrost extent is shown in Figure 29 (Mayer *et al.*, 2014). The permafrost is up to 500 m in depth. Similarly, thick permafrost and open taliks under deep lakes were detected at other deposits in this area (Figure 29b).

The data collected led to a hydrogeological conceptual model (SRK Consulting, 2011) that assumed groundwater flow in the talik zones, particularly along fractured rock near faults, quartz veins and diabase dykes (Mayer *et al.*, 2014). Complicating the natural hydrogeology were the hundreds of exploration drill holes that may be partially or fully open because the post-drilling cementing could not be verified in many cases. The studies also identified the potential contaminant sources that may contribute to solute release from the site (SRK Consulting, 2007b):

- waste rock, underground contamination with explosive residue, drilling brines,

- the mill site, treated tailings, sewage effluent,
- solutes from sediment erosion and thawing permafrost.

(a)



(b)

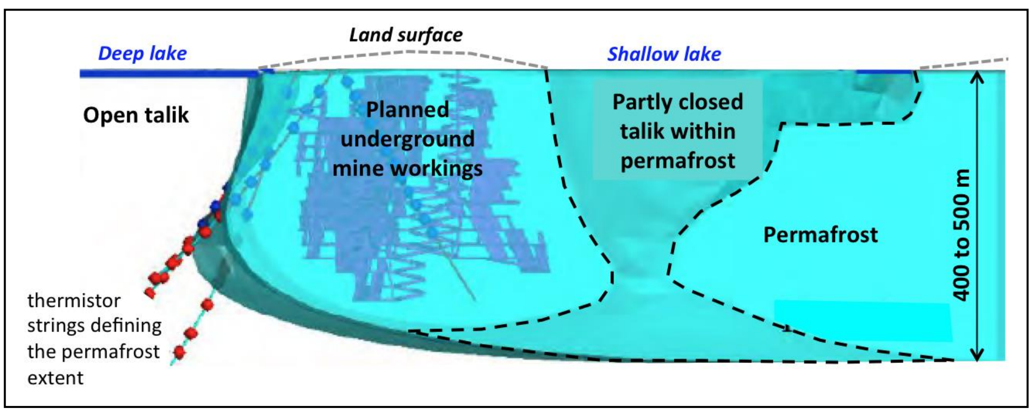


Figure 29. (a) Generic hydrogeological conceptual model at northern Canadian mine sites, based on hydrogeological investigations at Hope Bay project and Doris North Mine, Nunavut (from Mayer et al. 2014). (b) Part of a conceptual model of a mine site to the south of Doris Lake, in Hope Bay Project area. Modified after SRK Consulting (2016).

Diavik Mine (NWT) – Case study

The Diavik Diamond Mine is located on East Island in Lake Lac de Gras in north-central NWT. Golder Associates has undertaken a large number of hydrogeological and geotechnical investigations in this area (Kuchling *et al.* 2000; Golder Associates, 2012a; 2012b). Only some of the drill holes found permafrost and the likely extent of the permafrost under the islands was modeled numerically (Nixon, 1998). The results from these studies agree with research of permafrost under northern lakes in the Mackenzie Delta (Bieber *et al.*, 2006).

Other mining projects in Nunavut

South of the Bathurst Inlet in Nunavut, hydrogeological data were collected as part of exploration at the Back River Project. Thermistor strings and a Westbay multi-level well were installed, rocks hydraulically tested, and permafrost observations made (SRK Consulting, 2012). Permafrost thickness reaches up to 490 to 570 m in this area, some of the thickest permafrost observed in Canada. A talik zone at least 155 m deep was found beneath the Llama Lake, but no talik was found under a shallow lake (1.5 m deep) (Rescan, 2014).

The Kiggavik exploration project is located east of Baker Lake, Nunavut. Thermistors were installed through 220 to 280 m thick permafrost (AREVA Resources Inc., 2014). Numerical simulations predict the effects of the proposed open pit mine and tailings storage on groundwater quality. A model by Su *et al.* (2013) showed that during the mining operations, the induced thawed layer would be on the order of 5 m on pit sides and 10 m at the bottom, below the "warm" tailings fill. Models using coupled groundwater flow, heat flow, and geomechanics produced results that ranged from a small thaw to a complete permafrost thaw, depending on the assumptions used in the model (Wan and Booshehrian, 2015).

HYDROCARBON SPILLS

Diesel fuels and oils are the most common soil contaminants occurring at industrial sites. Statistics compiled in the Hazardous Materials Spill Database of the NWT (Government of the NWT, 2017a) show the quantities of spilled substances. In one year, 2016-2017, thousands of liters of diesel fuel or oil, and smaller quantities of hydraulic fluid, coolants, as well as sewage and other waste water were spilled, usually at mines, camps, and along roads and pipelines.

The research on mobility of hydrocarbon contaminants in groundwater in cold regions is extensive (e.g., Grant & Iskandar, 2000). In 1976, experimental spills on soils were studied at a research watershed 25 km north of Fairbanks, Alaska, in soil with an active layer depth of 15 to 50 cm (Johnson *et al.*, 1980). Collins *et al.* (1993) reported the effects 15 years after the spills, although the focus of the studies was on vegetation and the distribution of the contaminants in soils and not on groundwater. Barnes (2014) suggested that the flow paths are preferential and there is remobilization during freeze-thaw cycles in the active layer. Small experimental oil spill studies in the NWT by Seburn & Kershaw (1997) demonstrated a local deepening of the active layer by 130 % (e.g., from 0.6 to 1.6 m) because of changes in surface thermal properties over the long term (e.g., albedo). A report by Lee *et al.* (2015) recently reviewed the contaminant mobility in aquatic environments and groundwater interactions at the lake and ocean shores.

A crude oil spill occurred adjacent to Imikpuk Lake near Barrow, Alaska. McCarthy *et al.* (2004) describe the hydrogeological investigations and the distribution of free hydrocarbons in the thawed and frozen materials. The shallow aquifer was composed of gravels and coarse sands, with lenses of finer grained material. Continuous permafrost, up to 300 m thick, underlined the site and the active layer depth was 0.5 m to 2 m, of which only about 1 m was saturated seasonally. One of the remedial actions was the installation of 3.5 m deep and 500 m long "permafrost-enhanced subsurface barrier" to prevent lateral movement of contaminated ground water to the lake, including a trench to collect the hydrocarbons. Eleven boreholes were drilled. The investigation results showed that the permafrost was a barrier to groundwater flow, but it was not as effective at stopping the flow of petroleum hydrocarbons. The distribution of frozen liquid water in the permafrost zone was highly complex, and small discrete zones were filled with hydrocarbons. The authors suggested that brine water ponded below the active layer can stop the downward migration of hydrocarbons.

In the NWT, ARCADIS (Livingstone, 2016) studied soil and groundwater conditions along the WW-II era former pipeline along the Canol Trail, or CANOL (Canadian Oil) Project in the NWT (INAC, 2010). At 11 sampling and testing sites, using 53 drillholes and test pits, the former oil spills were mapped, which were usually long and thin and followed the topography. There was no indication of a free oil table in the active layer, and the groundwater quality was generally below the guidelines, likely because of the natural decomposition of oil over 70 years.

In the NWT, there are cases of remediation and hydrogeological testing of organic compound contaminants. OxyTek (2013) described the hydrogeological conditions at the site of an organic spill site at James Creek Maintenance Camp, along Highway 8 in the NWT. Two plumes of organic contaminants were delineated with more than 53 shallow boreholes in the 2.7 m thick active layer of low-permeability sediments above the bedrock. Results delineated a plume that appeared to pool on top of the permafrost surface, at the top of shale bedrock. The drill holes could not penetrate deeper into the rock with the drilling methods used on site. In another case, a spill of fuel tanker truck occurred along the Winter Road in the NWT, about 100 m from a lake (Shaikh, 2015). The remediation involved excavation of contaminated snow and soil down to the top of permafrost. About 37 monitoring piezometers were installed to delineate the hydrocarbons in the shallow aquifer (Mailath, 2015).

North Pole Refinery (AK) – Case study of a hydrocarbon plume

A spill of benzene (sulfolane) occurred at a refinery on the Tanana River floodplain, east of Fairbanks, Alaska (Alaska Department of Environmental Conservation, 2017). A hydrogeological investigation was completed in a talik zone below the river floodplain

(Barr Engineering, 2012), and site investigation reports were written by ARCADIS (2013). The alluvial aquifer consists of alternating lenses of sand, gravel and silt, and the sediment is up to 180 m thick above the bedrock. More than 500 monitoring wells were used at the site and tens of thousands of groundwater samples were taken at and in adjacent areas.

Permafrost underlying the floodplain has an irregular upper limit or it consists of disconnected zones. During the drilling of monitoring wells, permafrost was observed in 33 drill holes. The depth to top of permafrost varied at the refinery site at depths of 8 m to 43 m, but the drill records from the surrounding residential area show depths to the top of permafrost from 0.3 to 20 m, and the bottom of permafrost between 4 and 74 m. The thickness of the permafrost "layer" was about 73 m, on average. The depth is, on average, greater under the Tanana River and other water channels. Airborne and ground-based geophysical surveys were carried out to help map the top and bottom of permafrost (ARCADIS, 2013). A three-dimensional model (Figure 30) was created of the permafrost zone and a linear trend was apparent of deepened active layer along the highway and the railroad in the area, suggesting some effect of surface disturbance and cover on the depth of permafrost at a time scale of one century (Barr Engineering, 2012).

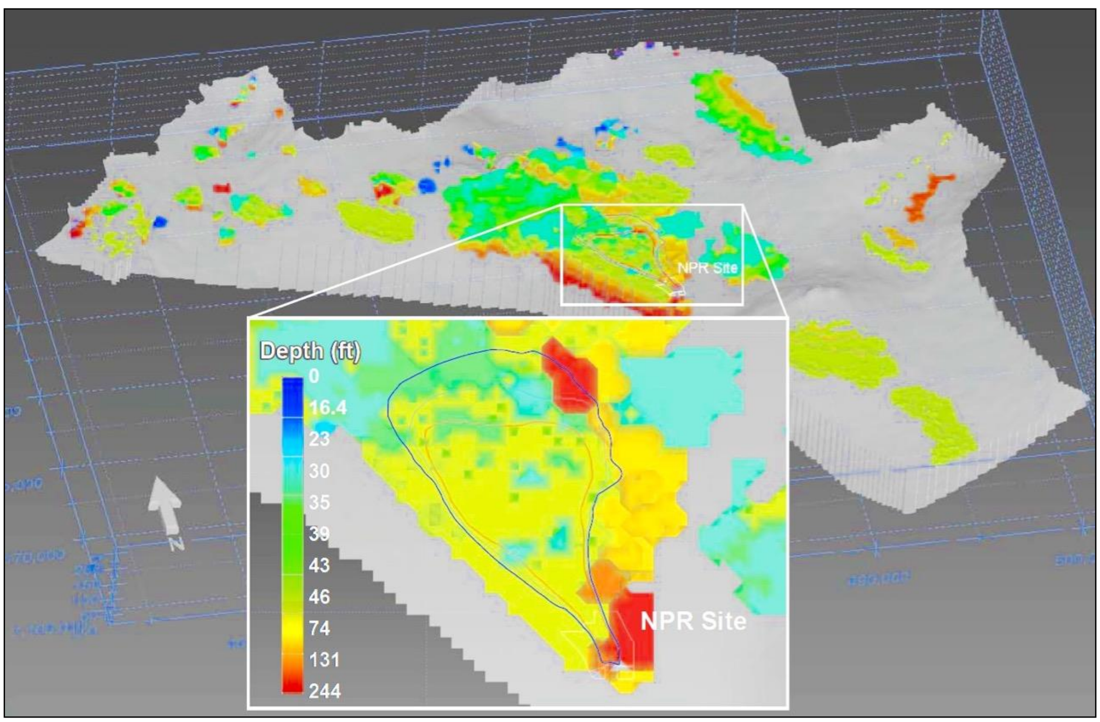


Figure 30. Perspective-view of a model of permafrost distribution and depth at North Pole Refinery, Alaska (from Fig 44 in Barr Engineering 2012). The coloured areas show permafrost patches, in sediments above the bedrock surface (grey solid shape).

The benzene plume is thought to have migrated downward until reaching an area of shallow permafrost; observations showed that it may have migrated around and over the permafrost (Barr Engineering, 2012). Pump tests at the site suggest a very high average hydraulic conductivity in the upper 50 m of sediment above the permafrost. Permafrost modifies the groundwater flow and contaminant transport in the aquifer (Carlson & Barnes, 2011). In the vicinity of the sulfolane plume, undulations in the permafrost surface and the reduction in the aquifer thickness would also result in increased flow velocities from south to north. In the offsite study area, groundwater, and therefore sulfolane, may be migrating up and over the shallow permafrost areas. The broadening of the plume appears to correspond with the area of shallow permafrost. In their conceptual model report, ARCADIS (2013) concluded that the groundwater flow and transport is dynamic and extremely complex (Figure 31). The complicating factors were attributed to heterogeneity of sediments, discontinuous permafrost, seasonal changes in groundwater levels near the rivers, and the freeze-thaw cycles in the soils.

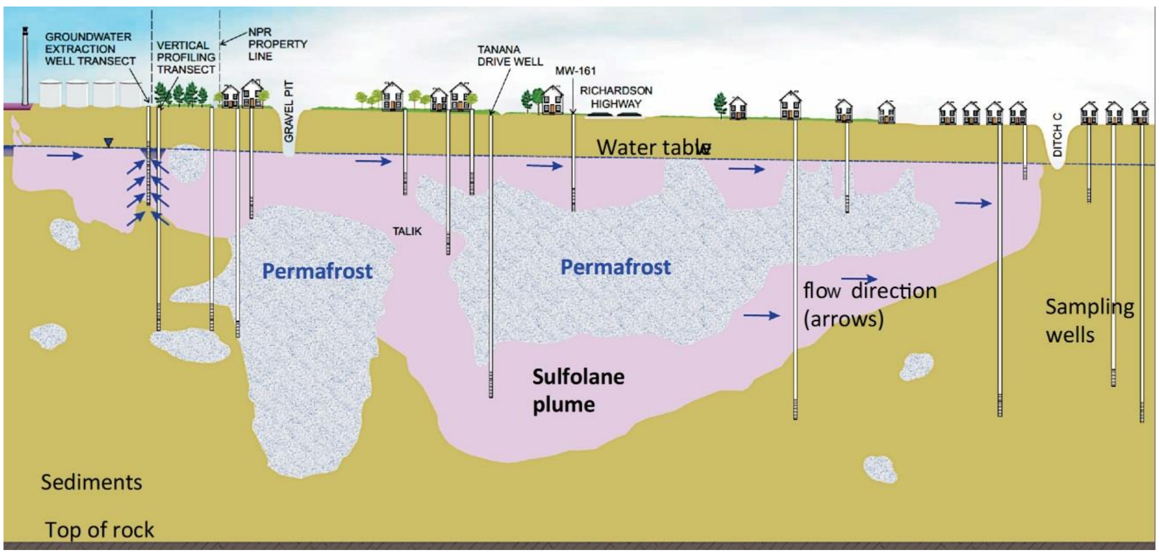
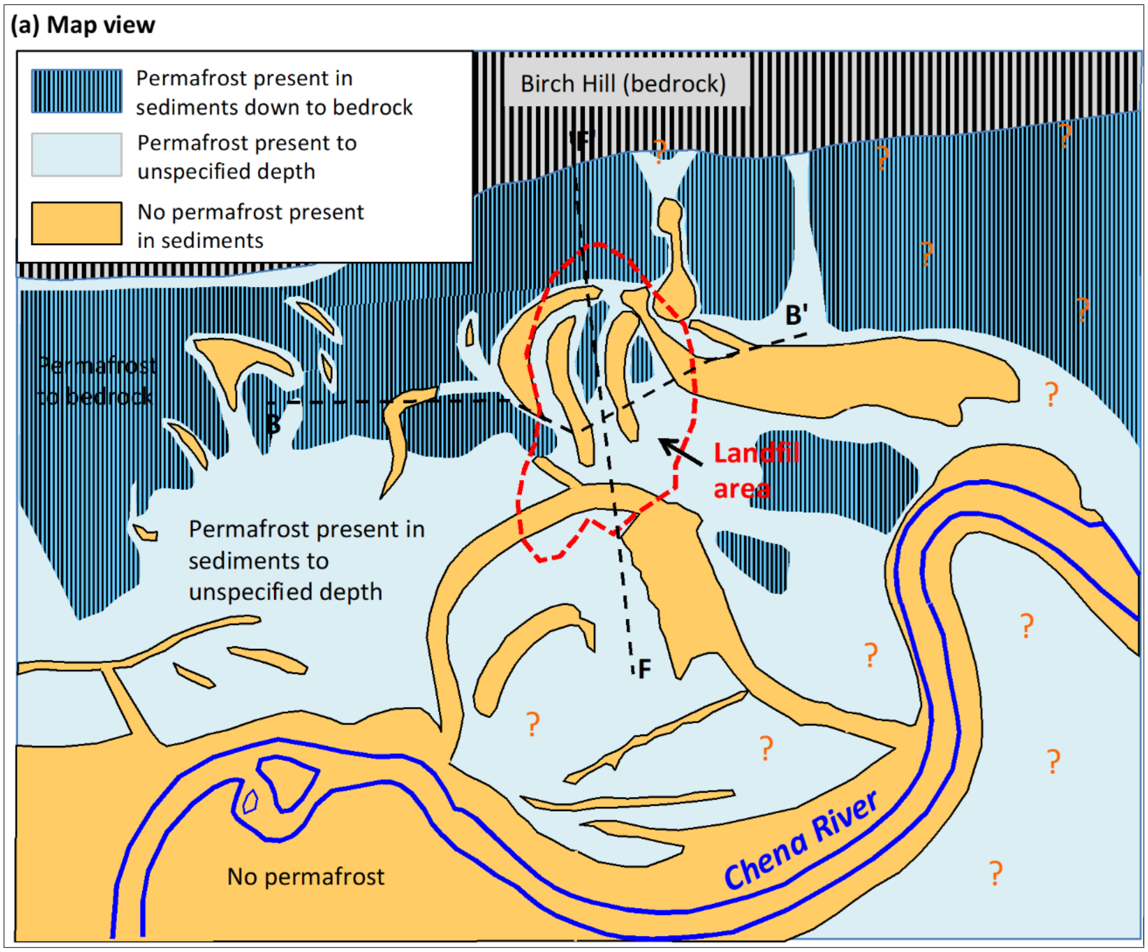


Figure 31. Conceptual sulfolane plume cross-section (modified after ARCADIS, 2013).

<u>*Fort Wainwright landfill (AK) – Case study of a hydrocarbon plume*</u>

Fort Wainwright, near Fairbanks, Alaska, is a contaminated military base where a large plume of petroleum was found in the subsurface in areas of discontinuous permafrost. The shallow aquifer consists of alluvium over fractured phyllitic schist rock with a weathered-rock depth of about 30 m (Peapples *et al.*, 2000). Extensive investigations were done to map the permafrost and to delineate the contaminant plume (Lawson *et al.*, 1998, Kopczynski *et al.*, 2003), including geophysical surveys, drilling of test holes, and installation of monitoring wells. The results were used to map the extent of permafrost in three dimensions in the sediments above the bedrock. In plan view (Figure 32a), the permafrost is extensive near the valley walls and is present over most of the thickness of the overlying sediments. Toward the Chena River, former river channels and present-day sloughs, the permafrost is thinner. Not all of the permafrost was mapped in detail but there exist irregularly-shaped zones of completely thawed sediments that are small-scale taliks. These frozen and thawed zones are clearly seen in the cross-section diagrams in Figure 32b.



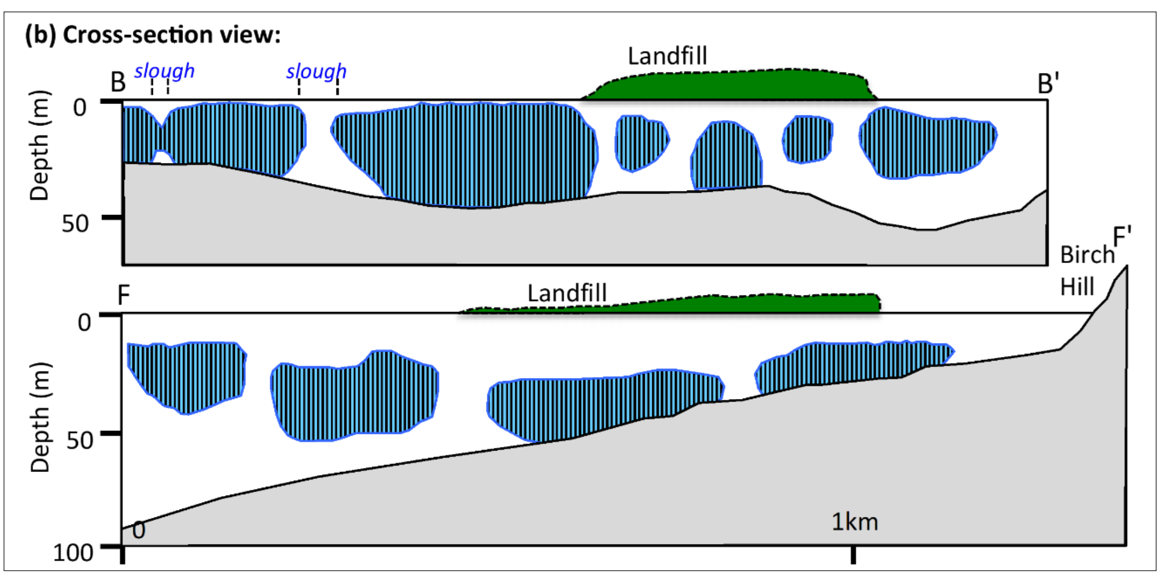


Figure 32. Hydrogeological conceptual model of the river floodplain sub-permafrost aquifer, (a) in plan view, indicating the permafrost and thawed areas and inferred flow paths, and (b) two cross-sections through landfill area at Fort Wainwright, Alaska (modified from Lawson et al., 1998). The green is landfill, the blue regions are permafrost, and the gray is impermeable bedrock.

The groundwater flow and contaminant transport appear to be channelized and strongly affected by the permafrost. Tracer tests suggested that the flow was largely one-dimensional, channel-like, due to the confining of the unfrozen channel (Hinzman *et al.*, 2000). Different geophysical methods were used at this site. Useful references about those methods and results from this site and central Alaska can be found in Minsley *et al.* (2012) and Walvoord *et al.* (2015).

<u>Colomac Mine (NWT) – Case study of a hydrocarbon spill remediation</u>

At the Colomac Mine, NWT, a diesel fuel and gasoline spill caused the contamination of sand and gravel (0 to 4.6 m thick) and the underlying fractured rock near the shore of a small lake (INAC, 2010). This type of hydrocarbon is a light non-aqueous phase liquid (LNAPL). The remediation of the diesel spill in the soil and groundwater aquifer was done by soil treatment, collection of free product in a deep trench excavated in rock, and monitoring of water quality. A PhD dissertation was written on this remediation effort as described in published articles by Iwakun *et al.* (2008, 2010, 2012). Roy and Bickerton (2011) stated that estimating the thickness of LNAPL in fractured rocks at this site is uncertain and difficult, especially in the presence of seasonally frozen soil and rock, and that the previous studies were somewhat optimistic as to their contaminant delineation results.

<u>DEW-line radar sites – Case study of the remediation</u>

The Canadian Distant Early Warning Line (DEW Line) long-range radar sites were located along the arctic coastline. As part of this review we briefly present the hydrogeological aspects of some examples from the DEW Line remediation projects that were found in the published literature.

The remediation and post-closure monitoring activities have been managed by the Environmental Sciences Group of the Royal Military College (RMC) following an updated protocol as described in INAC (2008b). A report (Environmental Sciences Group, 1993) summarizes the impact of the DEW Line. Hazardous contaminants were found leaching from containers, and had previously spilled on soils, which contained PCBs, fuels and heavy metals. The sites also had landfills where some hazardous materials were buried. Unexploded or buried ordnances were also present at some locations. In addition to the general cleanup and demolition of surplus infrastructure, the hydrogeological aspects of the remediation involved improvements to existing landfills, construction of new engineered landfills, soil remediation onsite and offsite, and monitoring (Eagles, 2012). In many cases, the contaminated landfill materials and soils were excavated and removed.

Iqualuit, Nunavut, was the location of a military base (Upper Base) and radar installations. The buildings, landfills, and soils were contaminated with PCBs. From a hydrogeological perspective, the contamination was on the side of a hill, in a catchment draining to a lake that led to the water supply of Iqaluit (Poland *et al.*, 2001). At one location, the PCB-containing liquid infiltrated through the active layer of soil (2 to 3 m thick), and flowed on top of the bedrock surface. The contaminated soil was found at a depth of 1 to 2 m below the uncontaminated soil layer. At another site, the PCB-containing water seeped through a concrete floor of a building to a depth of 75 cm, into the underlying soil, down to the top of bedrock, and along the bedrock surface.

At the Canadian Forces Station Alert, Ellesmere Island, the soil and groundwater contained high concentrations of TPH compounds (Biggar *et al.*, 1998; Biggar, 2004). The spilled fuel was found pooled on top of the permafrost below the thawed soil layer. More detailed investigations also showed that the fine-grained permafrost was not impermeable to the fuels because of presence of thermally-induced cracks and fissures from seasonal temperature changes, and capillary suction in the pores.

A landfill was remediated at Sarcpa Lake (CAM-F radar site), Melville Peninsula, Nunavut. The soils and debris at this location had the highest PCB contamination levels among all the DEW Line installations. Over a 35-year time period, the PCBs migrated a distance of approximately 20 m. The frozen soil containing PCBs was excavated and a new landfill was constructed and monitored (INAC, 2007). The report gives a good example of monitoring of a small landfill in the arctic environment using two shallow wells, soil thermistors, and sampling.

A large installation that contained stored containers of pure PCBs was located on Cape Warwick (BAF-5 radar site), Resolution Island, Nunavut (Poland *et al.*, 2001). In the 1990s, the PCBs were found draining to the sea from the radar site which was on top of a cliff and leachate barriers were installed (ditches with absorbing materials for the contaminants). Kalinovich *et al.* (2008) described that by 2003, 96 % of the contaminated soil was removed and there was no observed flowing groundwater. However, PCBs were also detected in fractured bedrock below the thin soils and special barriers were constructed to intercept the PCB leachate.

At Brevoort Island (BAF-3 radar site), east of Iqaluit, fuel that spilled or leaked from storage tanks migrated downslope towards the ocean shore (Bathurst *et al.*, 2006). The initial remediation step was the construction of a hydraulic barrier with a geomembrane and geosynthetic clay liner placed along seepage collection trenches. The active layer thawed to about 2.6 m and was monitored with thermocouples in piezometers to a depth of 3 m. In addition, the permeability of the membranes and the clay liner were tested in laboratory and estimated for different conditions (e.g., saturated, unsaturated, frozen, unfrozen).

Stokes Point (BAR-B radar site), Yukon Territory, is located in the Ivvavik National Park. Groundwater was tested in shallow pits excavated manually and showed hydrocarbon contaminants, but most of the cleanup effort focused on the ground surface (Environmental Sciences Group, 2009).

The following reports and resources are available for further information:

- Environmental Sciences Group (1994);
- Environmental Sciences Group (2012) describes the DEW Line project's hydrocarbon remediation "landfarms", 0.3 to 0.4 m deep layer of contaminated soil, designed to increase the biodegradation and volatilization of the hydrocarbons in soil;
- Queen's University Analytical Services Unit list of projects on Resolution Island, Winisk (Site 500), Ekalugad Fjord, Sarcpa Lake, and Iqaluit (Queen’s University, n.d.);
- INAC (2010) and AANDC (2015) reports list some other former military sites in the NWT and remediation efforts.

MUNICIPAL AND RESIDENTIAL WASTE

Residential contaminant sources

From the perspective of groundwater contamination, risks from residential sources were identified in the 2012 SWAP guidance document (Government of the NWT, 2012). The sources may include:

- household septic systems or other liquid waste storage tanks,
- household fuel storage,
- boats, recreational vehicles, and others.

According to a recent presentation by GNWT (Workman, 2016), 95 % of households in the NWT have in-home water and sewer service, and many households rely on above-ground septic tanks and sewage trucking for community sewage systems such as sewage lagoons.

Sewage lagoons

Facultative sewage lagoons are commonly used in northern Canada (Tilsworth *et al.*, 1984). Most of the engineering literature on sewage lagoons discuss and analyze the performance and water quality of effluent, as well as the management of the treatment systems (Johnson & Wilson, 1999; Kadlec, 2009; Chouinard *et al.*, 2014). In the 1990s, the sampling of coastal waters near Iqaluit, Nunavut, indicated that contaminated water with bacteria was seeping out of the sewage lagoon and discharging to the tidal flat at a rate of about 20 L/s (e.g., Samuelson 1998). In addition to the sewage lagoon, solid waste disposal sites also contributed to contamination of local waters and the coastline. There were many instances of sewage spills from the lagoon because of erosion of the confining earth structure. The report does not specifically mention groundwater. In the NWT, several wetland treatment areas beside facultative (sewage) lagoons were studied by Yates (2012). In Ulukhaktuk, the treatment wetland is down-gradient of the facultative lagoon that handles the sewage treatment for the hamlet of 400 people on Victoria Island (NWT). Groundwater samples were taken along transects to evaluate the performance of the wetland in removing contaminants.

Dumps and landfills

Landfills can be a source of groundwater and surface water. In the NWT, the solid waste facility at Hay River provides an example of a completed landfill management plan that includes a plan for groundwater monitoring (EBA Engineering Consultants, 2010). The landfill site is located on top of 2 to 15 m sediments consisting of clay, silt and sand layers in an area of discontinuous permafrost. No ice was found in the monitoring boreholes supervised by EBA in previous years, but the report noted that there were reports of ice in drillings. In all monitoring wells, landfill leachate was detected and it was estimated that it was likely discharging down gradient to the Hay River. Groundwater sampling and analysis indicated that elevated concentrations of salts, nitrates, ammonia, arsenic and other contaminants were present. More monitoring was recommended, although no other remediation was suggested.

Another example of hydrogeological assessment of a landfill is in Fairbanks, Alaska, at the Fairbanks-North Star Borough landfill, to the south of Fort Wainwright contaminated site. A study by the US Geological Survey (Downey & Sinton, 1990) assessed the hydrogeological conditions and water quality, and a leachate plume was discovered. The plume was found near the water table and above the permafrost. The groundwater discharged to a ditch, but the concentrations of contaminants were low and not of concern.

In Nunavut, solid waste management is an important problem for communities and was reviewed by ARKTIS Solutions (2011). The communities did not use groundwater as a water supply. In cases of groundwater use, the report recommended a minimum distance of 30 m between the dump and the drinking water wells, which is much shorter than regulations in other provinces.

OTHER POTENTIAL COMMERCIAL, INDUSTRIAL, AND AGRICULTURAL CONTAMINANTS

In the NWT, there are other potential sources of contaminants groundwater. These include any commercial, industrial, and agricultural activities where accidental spills of contaminants may occur, or where commonly used chemicals are applied to the ground surface where it may accumulate and contaminate the groundwater. Some of these activities include, but are not limited to, the following:

- garages and shops, small industries (e.g., fuel and chemical storage, spills),
- transportation network of roads and airstrips (including road salt water runoff and infiltration),
- railways and rail yards, ports and airports,
- agricultural activities (e.g., animal waste, pesticides, fuels).

WIDELY DISTRIBUTED AND/OR NATURAL CONTAMINANTS

ATMOSPHERIC TRANSPORT AND DEPOSITION OF GLOBAL POLLUTANTS

A large part of the "background" contaminant concentrations in the entire arctic region in shallow groundwater, surface water, and soils originate from widely dispersed trace amounts of contaminants derived from atmospheric deposition (AMAP, 2003; NCP, 2003). These contaminants include persistent organic pollutants (NCP, 2013), mercury (NCP, 2012), PCBs, radionuclides, and other chemicals emitted from global industrial sources and transported by winds (and ocean currents, for coastal areas). A large number of studies have been done on freshwaters, soils, and air (e.g., Barrie *et al.*, 1992; Macdonald *et al*., 2000; AMAP, 2003). These past studies were exclusively focused on surface waters and not on groundwater.

A recent study from northern Sweden's wetlands and bogs shows that in the past warming episode (e.g., years 1400-1500) and at present time, there is increased release and transport of mercury that was stored in previously-frozen organic matter (Rydberg *et al.*, 2010). In catchments affected by past mining activities within a permafrost zone, lake sediments may show delayed impacts long after the mining activity. This delay is partly due to recent thawing permafrost and increased mobility of contaminants deposited on soils and lake sediments from past fall-out from the atmosphere or water deposition (Klaminder *et al.*, 2010; Bedmar *et al.*, 2011). This is scientifically interesting because the apparent lack of impacts at a given time may be a temporary situation, and highlights the importance of long-term monitoring and sampling of waters and sediments downstream of mineral mine sites. In the NWT, an ongoing study in the Jean Marie River and McGill Lake areas by Laurent (2015) aims to measure the mercury content in permafrost and in lake sediments.

Hydrological studies suggest that river and wave erosion of areas that contain contaminants contribute to contaminant transport in surface waters, or may increase in contribution due to climate change (Macdonald *et al.*, 2005; Johnson & Matz, 2011). Surface-groundwater interactions of such contaminant mobilization are potentially important in some cases, especially at contaminated sites. The only references to groundwater were that the contaminants stored in permafrost, presumably from atmospheric deposition or other sources, may be released to the hydrological system (AMAP, 2003), and, by connection, to the groundwater flow system. A particular case is frozen tailings facilities and other mine wastes that may thaw in the future. In the NWT, a study of permafrost thaw and slumps in the Peel Plateau is quantifying the effects of large amounts of sediments fluxes into surface water (Kokelj, 2014).

SALINE GROUNDWATER

Groundwater of drinking-water quality, or "freshwater", is only present in the upper 300 to 400 m in the fractured rock aquifers of the Canadian Shield because there is a trend of increasing salinity with depth (Gascoyne *et al.*, 1987). At depths of 500 m and below, high salinity makes the water undrinkable without treatment. At many locations, at depths below 1 km, there are sodium-chloride brines. Similar trends are seen globally in shield rocks (Bucher & Stober, 2010). More references and numerical simulations can be found in the study by Lemieux *et al.* (2008) at the continental-scale (all of Canada).

Although shallow groundwater is usually fresh, there are locations in the NWT where saline groundwater is present near the surface because of natural processes in soils and rocks. This occurs along the Arctic Ocean coast, the Mackenzie Delta, and at some locations along the upper Mackenzie Valley. A database of northern salinity measurements was presented by Hivon and Sego (1993). The salinities had large variability from 0 to 45 g/l at depths of 0 to 40 m. Hypersaline meromictic lakes exist in the Canadian Arctic in which there is strong stratification of salinity with depth (e.g., Garrow Lake, on Little Cornwallis Island), and in other regions such as northern Russia, according to Gascoyne (2000). Some natural springs in the NWT are also point sources of groundwater with elevated salinity (Woo, 2012), such as springs to the south-west of Norman Wells, NWT. Those springs discharge from below the permafrost layer along karstic taliks and are often saline (Hamilton & Ford, 2002).

ARSENIC IN GROUNDWATER FROM NATURAL SOURCES

In the NWT, arsenic is present in natural soils and groundwater (Government of the NWT, 2017b). Mcguigan *et al.* (2010) provides a review of the availability of information on arsenic in Canada. Groundwater and soil arsenic in the USA (Welch *et al.* 2000) suggest that the naturally-elevated arsenic level originates from weathering of rock outcrops. Klassen *et al.* (2009) presented a geospatial assessment method of the observed natural arsenic hazard in New Brunswick, Canada. In Alaska, there are elevated arsenic levels in areas near Fairbanks (USGS, 2001). The thawing of permafrost may mobilize the arsenic (Jones, 2016). At and around known contaminated sites, detailed chemical analysis can distinguish the natural from mine-related sources of arsenic, as seen with a case study at the Giant Mine in the NWT (Wrye, 2008).

HEAVY METALS AND RADIONUCLIDES IN SPRINGS

Acidic groundwater with elevated metal concentrations can occur naturally and is often referred to as 'acid rock drainage'. Waste rock exposed in piles at mine sites can result in similar drainage conditions. Some springs have low pH and high heavy-metal concentrations originating from dissolution of metal sulfides (van Everdingen, 1991). Numerous springs in the Mackenzie Mountains have elevated dissolved metal content and are useful for geochemical-mineral exploration (Caron *et al.*, 2008). Natural sources of radionuclide contamination in groundwater are from atmospheric transport and deposition of trace amounts, groundwater interaction with soils rich in uranium or rock outcrops, and some thermal springs. For example, waters containing radium discharge at Flybye springs in the northern Mackenzie Mountains (Cecile *et al.*, 1984).

HYDROCARBON SEEPS AND METHANE GAS

Natural hydrocarbon seeps occur in areas of the NWT. A review by the Norway-based Arctic Monitoring and Assessment Program (AMAP) in 2010 listed known areas of natural hydrocarbon seeps in Canada:

- area near Norman Wells in the Mackenzie River Valley (Janicki, 2001),
- lower Mackenzie River valley and delta (Yunker *et al.*, 2002),
- Rond Lake near Fort Good Hope (Janicki, 2001),
- the Smoking Hills on Cape Bathurst - vents from burning bituminous shales,
- submarine vents near the coast of Beaufort Sea, and in on the coast of Baffin Island at Scott Inlet (Nunavut).

In the baseline study of hydrogeological conditions of the Central Mackenzie Valley, Rudolph *et al.* (2016) recommended mapping, testing, and monitoring of the concentrations of naturally-occurring hydrocarbon contaminants.

Methane gas occurs naturally in groundwater in the NWT, particularly in wetland areas (Liblik *et al.*, 1997). Airborne surveys recently mapped methane emissions in parts of the Mackenzie River Delta (Kohnert *et al.*, 2014). Methane is also emitted in sedimentary basins in northern Alberta (Ing, 2015) and likely in southern NWT.

MODULE

3

FEDERAL, PROVINCIAL/TERRITORIAL LEGISLATIONS AND EXISTING GOVERNMENTAL MONITORING GUIDELINES

In this chapter, we review groundwater-related guidelines and relevant documents related to the laws, regulations, and policies that apply to groundwater resources. This review covers jurisdictions that are partially affected by permafrost conditions, including Canada (Federal), Northwest Territories, Yukon Territory, Nunavut Territory, provinces of Quebec, Alberta, British Columbia, and the State of Alaska (USA).

Table 5 provides a summary of the guidelines by topic, and Table 6 summarizes the laws and regulations by jurisdiction.

In addition to the summary provided here, Nelson and Quevauviller (2016) can be consulted for additional relevant discussion on fundamental legal principles related to groundwater quantity, quality, use and protection for the United States, Australia and the European Union.

CANADA

GUIDELINES FOR WATER QUALITY

The Government of Canada sets guidelines for maximum levels of a wide range of chemical constituents found in water, including contaminants in drinking water, surface water, and groundwater. The current Canadian Environmental Quality Guidelines are listed on the Canadian Council of Ministers of the Environment website (CCME, 2017):

- Guidelines for Canadian Drinking Water Quality (Community Water Supplies);
- Guidelines for Canadian Recreational Water Quality;
- Canadian Water Quality Guidelines for the Protection of Aquatic Life (e.g., factsheets, indices, protocols, guidelines for use);
- Canadian Water Quality Guidelines for the Protection of Agricultural Water Uses (factsheets, protocols, summaries).

For drinking water, water quality limits are designed to prevent human health effects from water at the point of source exposure (e.g., water discharging from the tap) as described in the Guidelines for Canadian Drinking Water Quality (Government of Canada, 2017a). The guidelines only provide brief comments on the likelihood of a particular contaminant of concern being found in groundwater.

The Guidelines for Canadian Recreational Water quality provides guidance on the factors that can interfere with the safety of recreational waters from a human health perspective (Health Canada, 2012). However, these guidelines focus mainly on surface water.

The environmental effects of contaminants in groundwater are usually understood to refer to the impact on aquatic life. These concentrations are described in the Canadian Water Quality Guidelines for the Protection of Aquatic Life (CCME, 1999; 2007a).

Additionally, soil quality guidelines have been established for different land use areas (i.e. residential, parkland, agricultural, commercial and industrial) that provide the limits on contaminant concentrations (Government of Canada, 2012). These guidelines focus on limiting the exposure of contaminants to soil organisms, wildlife, livestock, and human exposure to vapours originating from groundwater sources.

Permafrost is also not considered in the Soil Quality Guidelines (CCME, 2007b). Based on our review, the contamination of permafrost - or of water pockets within the permafrost - is not currently regulated. The local hydrogeological conditions and the groundwater-surface water interactions will dictate how the contaminants are transported. In the case of permafrost-groundwater flow systems, the water quality (potability) and the hydrogeological conditions in the active layer, as a "groundwater exposure pathway", should be evaluated on a site-specific basis (CCME, 2008).

Guidelines for federal contaminated sites

There are several guidelines for Federal Contaminated Sites. This report focuses on those that are relevant to the NWT, including:

- Guidance Manual for Environmental Site Characterization in Support of Environmental and Human Health Risk Assessment (Canadian Council of Ministers of the Environment, 2016);
- Guidance Document on Federal Interim Groundwater Quality Guidelines for Federal Contaminated Sites (Government of Canada, 2016a);
- Decision Making Framework of the Federal Contaminated Sites Action Plan (Government of Canada, 2016b)
- Guidelines for the Closure and Reclamation of Advanced Mineral Exploration and Mine Sites in the Northwest Territories (MVLWB/AAND, 2013);
- Guidelines for Designing and Implementing Aquatic Effects Monitoring Programs for Development Projects in the Northwest Territories: Recommended Procedures for Developing Detailed Designs for Aquatic Effects Monitoring Programs (Government of Canada, 2009a and 2009b).

The latest guidance manual from the Canadian Council of Ministers of the Environment (2016) concluded that the characterization of groundwater flow and contaminant transport in permafrost can be highly complex. The guidance recommends consultation with specialists in the field of permafrost hydrogeology.

There are currently no Canadian environmental quality guidelines for groundwater, but there are Interim Groundwater Quality Guidelines (Government of Canada, 2016a) and the Federal Contaminated Sites Action Plan Decision-Making Framework (Government of Canada, 2016b). The numerical guidelines have three tiers (levels), depending on the intensity of contaminated site assessment:

- Tier 1: application of the generic numerical guidelines (the lowest numerical guideline value);
- Tier 2: development of site-specific remediation objectives by modifying, to some degree, the numerical guidelines based on site-specific conditions such as exposure pathways and receptors;
- Tier 3: site-specific risk assessment for site-specific remediation objectives.

For Tier 1, the point-source acceptable concentrations can be adjusted depending on the distance of the groundwater point source to the nearest surface water. For Tier 2 and 3, models can be developed to simulate groundwater flow and its interactions with surface water, and to estimate the acceptable concentrations at point sources. In practice, most contaminated sites are assessed for local conditions through sampling and monitoring and/or modelling of groundwater flow, whereas the generic numerical guidelines are usually used without modification. The tiered framework shows that the contaminant concentration guidelines have some flexibility in their application.

The Guidelines for the Closure and Reclamation of Advanced Mineral Exploration and Mine Sites in the Northwest Territories (MVLWB/AAND, 2013) considers groundwater with contaminated soils. The document explicitly focuses on challenges of Northern environments, including the role of frozen ground as a barrier to contaminant transport, the difficulty of applying common hydrogeology techniques to cold regions, and the implication of facilities, such as buildings, altering the subsurface thermal regime and permafrost distribution.

The Guidelines for Designing and Implementing Aquatic Effects Monitoring Programs for Development Projects in the Northwest Territories (Government of Canada, 2009a) concerns watershed and surface water monitoring and states that: "guidance on the selection of groundwater sampling locations is beyond the current scope of this document".

Municipal waste storage in northern areas

For the management of municipal waste (solid and liquid), the Environment Solid Waste Management for Northern and Remote Communities report (Environment and Climate Change Canada, 2017) summarizes the best practices for the solid waste facilities such as landfills in northern and remote areas. Groundwater is only briefly mentioned. The website also lists more online resources (Environment and Climate Change Canada, 2013).

NORTHWEST TERRITORIES

LAWS

Since the *NWT Lands and Resources Devolution Agreement* came into effect on April 1, 2014, the Government of NWT (GWNT) is responsible for managing the land and water in non-federal areas (Government of the Northwest Territories, 2014a). Under the Devolution Agreement, the federal *Northwest Territories Waters Act* was mirrored and enacted as territorial legislation on April 1, 2014. Under the *Waters Act*, the GNWT has the authority to regulate the water use and the disposal of wastes into water (Government of the Northwest Territories, 2014b; 2016a).

The Federal Government retains the responsibility to manage and remediate the contaminated lands under federal management. These legacy sites include former military installations, abandoned and closed mines, and other industrial legacy sites (INAC, 2010). The *Mackenzie Valley Resource Management Act* and the Mackenzie Valley Federal Areas Waters Regulations outline the requirements associated with use of water and deposit of waste in federal areas of the NWT (Government of Canada, 2016b and 2016c).

The laws governing water in the NWT are:

- *Mackenzie Valley Resource Management Act*;
- *Waters Act;*

There are five regulatory boards in the NWT (Government of the Northwest Territories, 2017). These regulatory boards have responsibility for water licensing. Their website provides information regarding water management and decision making in the NWT. The regulatory boards within the Mackenzie Valley have authorities within the boundaries of the management that are the result of four settled comprehensive land claims (INAC, 2013). A fifth land and water board, known as the Mackenzie Valley Land and Water Board, represents the unsettled claim areas in southern NWT. The regulatory boards and their associated land claim areas are:

- Mackenzie Valley Land and Water Board (Unsettled Claim Areas in the NWT and Transboundary Projects);
- Gwich'in Land and Water Board (Gwich'in Settlement Area);
- Wek'èezhìi Land and Water Board (Wek'èezhìi Management Area);
- Sahtu Land and Water Board (Sahtu Settlement Area);
- Inuvialuit Water Board (Inuvialuit Settlement Region).

REGULATIONS

- Mackenzie Valley Land Use Regulations;
- Waters Regulations;
- Mackenzie Valley Federal Areas Waters Regulations;
- Exemption List Regulations;
- Water Supply Systems Regulations (R-108-2009, Public Health Act) (Government of the Northwest Territories, 2011a);
- Spill Contingency Planning and Reporting Regulations.

POLICIES

In 2010, the GNWT and Indigenous and Northern Affairs Canada released *Northern Voices, Northern Waters: NWT Water Stewardship Strategy*, a partnership document describing the long-term strategy for the stewardship of water resources in the NWT. It focuses on integrated resource management and expansion of monitoring networks for both surface and groundwater. Two Action Plans were released subsequently to lay out a detailed path for how water partners would achieve the visions and goals of the Water Strategy. Most recently, the *NWT Water Stewardship Strategy Action Plan 2016-2020* was released to define the second implementation phase of the Water Strategy (Government of the Northwest Territories, 2016b). On "Key to Success" in the Action Plan is to implement a groundwater monitoring network for the NWT.

GUIDELINES

There are numerous water-related guidelines for the NWT. The federal guidelines for contaminated sites remediation prepared by Government of Canada were listed in the preceding sections. The following NWT specific guidelines are most relevant to this study:

- Environmental Guideline for Contaminated Site Remediation (Government of the Northwest Territories, 2003);
- Guideline for Industrial Waste Discharges in the NWT (Government of the Northwest Territories, 2004) - This document concerns effluent discharges to municipal sewage systems, non-point source discharge, and landfill leachate; groundwater is not mentioned;
- Northwest Territories Source Water Assessment and Protection (SWAP) Guidance Document (Government of the Northwest Territories, 2012);
- A Guideline to the Spill Contingency Planning and Reporting Regulations (Government of the Northwest Territories, 2011b);
- Guidelines for Developing a Waste Management Plan (Mackenzie Valley Water Board, 2011) - a good overview of guidelines and management practices of various hazardous wastes in the NWT;

- Guidelines for the Planning, Design, Operations and Maintenance of Modified Solid Waste Sites in the Northwest Territories (Kent *et al.*, 2003).

The Solid Waste Sites Guidelines (Kent *et al.*, 2003) recommend that, in permafrost areas, landfills can be closed by covering with previously-excavated permafrost-containing soils, to provide "encapsulation" of the solid waste, as long as the new cover is thicker than the active layer. We note that the success of such practice depends completely on the stability of climatic conditions and no change in local water table or surface water conditions.

YUKON TERRITORY

LAWS

In Yukon, groundwater management is a shared responsibility between four Yukon government departments and the associated legislative guidance documents:

- Environment Yukon, Water Resources and Environmental Programs Branch (*Environment Act, Contaminated Sites Regulation*)
- Health & Social Services, Environmental Health Services (*Public Health and Safety Act*)
- Energy, Mines and Resources (*Lands Act, Oil and Gas Act, Agriculture Development Act, Quartz Mining Act, Placer Mining Act*)
- Community Services (*Municipal Act*).

The *Waters Act* (Government of Yukon, 2003) provides the standards for the design, construction, operation and maintenance of work related to water use or waste deposition. Even though the *Waters Act* does not provide a definition of groundwater, it is implied in the definition of 'waters' meaning "any inland water, whether in a liquid or frozen state, on or below the surface of the land". The *Waters Act Regulation* defines groundwater as "all water in a zone of saturation beneath the land surface, regardless of its origin". The Regulation also provides a definition of 'watercourse' meaning "a natural watercourse, body of water or water supply, whether usually containing water or not, and includes groundwater, springs, swamps and gulches".

The management of groundwater in Yukon is further firmly tied to the Yukon First Nation Final Agreements which provide guidance on the rights of First Nations to water in relation to their settlement land. Section 14.8.1 sets out that "…a Yukon First Nation has the right to have Water which is on or flowing through or adjacent to its Settlement Land remain substantially unaltered as to quantity, quality and rate of flow, including seasonal rate of flow". Settlement Land may include subsurface rights.

The *Environment Act* (Government of Yukon, 2017) provides the legislative framework for the protection of the territory's land, water and air. It includes fuel storage and handling, solid waste management, hazardous waste management, air emissions, and spill clean-up or assessment. The *Environment Act* only mentions groundwater where an applicant will change the use of soil or groundwater. The regulations that are related to groundwater are:

- Contaminated Sites Regulation (O.I.C. 2002/171 Environment Act) (Government of Yukon, 2002a) - provides numerical values for contaminant concentrations in soil, surface and groundwater (the surface water standard is the groundwater number x 10);

- Solid Waste Regulations (O.I.C. 2000/11 Environment Act - states that the active working area of a dump must be >1.5 m from the groundwater table, and that the groundwater should be monitored;
- Special Waste Regulations, Spill Regulations, and Storage Tank Regulations do not mention groundwater.

The *Public Health and Safety Act* (Government of Yukon, 2002a) refers to groundwater drinking water protection:

- Drinking Water Regulation (O.I.C. 2007/139 *Public Health and Safety Act*) (Government of Yukon, 2002b) - Provides requirements and rules for locating groundwater sources for drinking water from drilled wells, provides the minimum distances from sewage and waste disposal sites, requires a hydrogeological study, and prescribes that the well must be constructed in accordance with the "Guidelines for Well Water Construction". For large public drinking water systems each groundwater source well must be tested for water quality.
- Sewage Disposal Systems Regulation (O.I.C. 1999/82 *Public Health and Safety Act*) (Government of Yukon, 1999) only mentions that a soil absorption system or pit privy shall be located no less than 1.2 m from the seasonal high groundwater table or impermeable barrier such as bedrock, clay or permafrost.

Guidelines

The Government of Yukon has a short list of guidelines on their website related to domestic groundwater wells, and basic information about aquifers:

- Groundwater and Aquifers (Government of Yukon, 2014a);
- Water Wells (Government of Yukon, 2014b);
- Domestic Water Well Program Guidelines (Government of Yukon, 2015);
- Assessment Guideline for Well Water or Groundwater Under the Direct Influence of Surface Water (GUDI) (Government of Yukon, 2006);
- Planning and Managing a Rural Drinking Water System;
- Guidelines for disinfecting your drinking water well.

Under the *Contaminated Sites Regulation* of the *Environment Act*, the following protocols provide guidance on the protection of groundwater:

- Application of Water Quality Standards
- Groundwater Monitoring Well Installation, Sampling & Decommissioning
- Determining Background Groundwater Quality

For the mining industry, there is one guideline for estimating water mass balances for planned development sites, depending on location (e.g., climate, recharge) called the Guidance Document on Water and Mass Balance Models for the Mining Industry (Golder Associates, 2011).

NEXT STEPS:

One of the key goals identified in the Yukon Water Strategy is to increase the understanding and management of Yukon's groundwater. Departments are working towards developing a regulatory framework to manage and protect this resource.

NUNAVUT TERRITORY

The Government of Canada, through Indigenous and Northern Affairs Canada (INAC), manages and regulates the water resources of Nunavut. The Nunavut General Monitoring Plan (NGMP) (Government of Canada, 2016d) has a goal of long-term data collection in Nunavut Territory, including its environment, through scientific observation methods and through traditional knowledge gathering. See *Nunavut Waters and Nunavut Surface Rights Tribunal Act* (S.C. 2002, c. 10) for more information (Government of Canada, 2016e). The Nunavut Waters Regulations (SOR/2013-69) (Government of Canada, 2017b) defined 65 Water Management Areas. The Nunavut Water Board (NWB) (2017) is involved in the promotion of good management and protection of freshwaters in Nunavut by incorporating Inuit Qaujimajatuqangit and scientific knowledge in decision-making. One of the stated goals of the NWB is learning about the regional distribution of groundwater resources. There are very brief guidelines on the topic of Contaminated Site Remediation (Government of Nunavut, 2002), but nothing specific to permafrost areas.

PROVINCE OF QUEBEC (INCLUDING THE NUNAVIK REGION)

LAWS

In Nunavik, northern Quebec, there are several laws regulating environmental protection and water resources. The Bureau d'audiences publiques sur l'environnement (BAPE) is Quebec's environmental assessment commission that reports the potential impact of development and land use change on water resources. The main laws related to water resources are published online:

- *Environment Act* of 1978 (Loi sur la qualité de l'environnement) regulates the environmental protection and sustainable development, including water supply. Parts of the legislation provide requirements for water well installation. (Gouvernement du Québec, 2017a)
- *Collective Character of Water Act (Loi affirmant le caractère collectif des ressources en eau et visant à renforcer leur protection*) prescribes that the water resources in Quebec be managed as an integrated resource (watershed and groundwater management). (Gouvernement du Québec, 2017b)
- *Act for Compensatory Measures for Projects Affecting Wetlands or Hydrological Network (Loi concernant des mesures de compensation pour la réalisation de projet affectant un milieu humide ou hydrique*)
- Regulation on water extraction and protection, or RPEP *(Règlement sur le prélèvement des eaux et leur protection*), regulates water well installations and groundwater extractions, including geothermal systems. (Gouvernement du Québec, 2017c)

POLICIES

There are several relevant policy documents of the provincial government on water resources and groundwater:

- National Water Policy (*Politique nationale de l'eau*) (Gouvernement du Québec, 2011);
- Regarding the groundwater and soils in contaminated lands (e.g., brownfields), the Quebec government has a policy on soil protection and contaminated land reclamation (*Politique de protection des sols et de réhabilitation des terrains contaminés*) that dates to 1998. The latest summary document has the Action plan for 2017-2021. The strategy is to reinforce water management with an adaptive and flexible management, including adaptation to climate change. (Gouvernement du Québec, 2017d);
- Quebec Strategy for Water 2017-2032 (Stratégie Québécoise de l'eau 2017-2032): Reinforce water management with an adaptive and flexible management, and adaptation to climate change to protect potable water

resource and sustainable development; this included a public consultation in October 2016.

GUIDELINES

The technical and managerial guidelines include the following:

- Guide to Pump Testing and Interpretation (Chapuis, 2007);
- Criteria Applicable in Case of Groundwater Contamination (Gouvernement du Québec, 2017e) contain the numerical values of contaminant concentrations in soil and water;
- A Guide to Implementing Vulnerability Analysis for Drinking Water Supply in Quebec (Gouvernement du Québec, 2016a) has information on groundwater monitoring and well capture zone determination;
- A Guide to Principles of Mitigation and Compensation of Agricultural Activities Relating to Water Extraction Facilities (Gouvernement du Québec, 2016b).

In the Nunavik region (i.e., northern Quebec), the Kativik Environmental Advisory Committee is the local organization interested in improving water quality.

PROVINCE OF ALBERTA

LAWS

Alberta has three laws regulating environmental protection and water and land resources:

- The *Environmental Protection and Enhancement Act* (EPEA) (Government of Alberta, 2017a) and regulations focus on the activities that require government's approval and the requirements;
- The *Alberta Water Act* (revised statutes as of 2014 - Government of Alberta, 2014) is intended to manage and protect water resources in a sustainable manner;
- Related to the *Alberta Water Act* is a compilation of laws and rules described in The Water (Ministerial) Regulation (Government of Alberta, 2015) that apply to the use or diversion of surface or groundwater. A license is required for groundwater extraction.

POLICIES

The Province's strategic plan for water management is described in the document titled *Water for Life* (Government of Alberta, 2003). Other policies focus on the oil and gas industry's use of groundwater. The Water Allocation and Conservation Guideline/ Policy for Oilfield Injection (Government of Alberta, 2006) presents objectives to reduce or eliminate allocation of non-saline (fresh) water for oilfield injection, while respecting the rights of current license holders.

GUIDELINES

In Alberta, the guidelines for the Groundwater Protection of Domestic Use Aquifers apply only to freshwater (non-saline) aquifers. The threshold to be considered a freshwater aquifer is total dissolved solids of less than or equal to 4000 mg/l at the base of the aquifer. Shallow groundwater that is naturally saline, with a TDS greater than 4000 mg/l, is not considered a Domestic Use Aquifer source, although the presence of shallow saline groundwater does not preclude the presence of deeper fresh water at a given site (Government of Alberta, 2010a; 2010b).

The guidelines for groundwater use are:

- Guide to Groundwater Authorization (Government of Alberta, 2011) explains the regulations for submitting an application for groundwater use;
- Guidelines for Licensing Water Diversion Projects (Government of Alberta, 2010c);

- Water. Education and Guidelines. Working Well. Resources and Related Links (Government of Alberta, 2017b) - online resources, fact sheets, videos, brochures.

There are also specific guidelines for groundwater quality:

- Environmental Quality Guidelines for Alberta Surface Waters (Alberta Environment & Sustainable Resource Development (ESRD), 2014) are the main scientific recommendations that list criteria for water quality in various water uses, and protection of the aquatic ecosystems;
- Alberta Tier 1 and Tier 2 Guidelines (Government of Alberta, 2010a; 2010b; Alberta Environment and Parks (AEP), 2016).

The Tier 1 and 2 Guidelines describe the assessment and monitoring tools for restoring the quality of soil and groundwater and give the numerical guidelines, or the maximum contaminant concentration values in soil and groundwater, to be used for remediation targets. Tier 1 guidelines are generic guidelines for application at a range of sites within a given area, while Tier 2 guidelines are for site-specific work. The Tier 1 remediation guidelines were developed for unconsolidated soil material (unlithified overburden materials); therefore the presence of (fractured) bedrock may require a Tier 2 re-evaluation. The guidelines do not mention permafrost zones. In the reference list there are more detailed documents and guidelines about particular contaminant types in soils.

PROVINCE OF BRITISH COLUMBIA

LAWS AND REGULATIONS

In British Columbia, the main law governing surface and groundwater resources is the *Water Sustainability Act* (WSA) of 2016 (Government of British Columbia, 2017a). The law applies to licensing, diversion and use of water, and to protection of water resources, including ensuring environmental flow needs. The licensing of groundwater helps the BC Government to quantify the resource use. Under the *Water Sustainability Act* (WSA), the *Groundwater Protection Regulation* (GWPR) regulates minimum standards for well construction, maintenance, deactivation and decommissioning, and recognizes the types of qualified people certified to drill wells, install well pumps, and perform related services (Government of British Columbia, 2017b; 2017c). The GWPR ensures that activities related to wells and groundwater are performed in an environmentally safe manner. Surface water and groundwater are managed and regulated as an interconnected resource. Groundwater use for non-domestic purposes is licensed. The WSA does not apply to "geothermal resources", which are governed by the *Geothermal Resources Act* (Government of British Columbia, 1996a).

The *Water Protection Act* confirms the Province's ownership of surface and groundwater, defines limits for bulk water removal, and prohibits "large-scale diversion" of water between major provincial watersheds and/or to locations outside of the province.

The *Environmental Management Act* regulates industrial and municipal waste discharge, pollution, hazardous waste and contaminated site remediation, and provides the authority for introducing wastes into the environment, while protecting public health and the environment (Government of British Columbia, 2003). The Contaminated Sites Regulation governs all matters in BC related to contaminated sites and site remediation (Government of British Columbia, 2016a).

"Geothermal resources" are regulated by the *Geothermal Resources Act* (Government of British Columbia, 1996b). A "geothermal resource" is defined as the Earth's natural heat and all substances that derive an added value from it, including steam, water and water vapour heated by the natural heat of the earth and all substances dissolved in the steam, water or water vapour obtained from a well. It does not include water that has a temperature less than 80^{o}C at the point where it reaches the surface, or hydrocarbons.

In BC, groundwater is separated for legal purposes into generally shallow and cool groundwater, which is governed by the WSA, and the generally deep (with exceptions of natural geothermal discharges near hot springs) and hotter groundwater, which is governed by the *Geothermal Resources Act*. However, there seems to be some ambiguity between these regulations for deep groundwater that does not affect the vast majority of groundwater users but may affect some industrial deep groundwater users.

GUIDELINES

British Columbia has a comprehensive set of guidelines on groundwater resources. The water quality guidelines provide numerical values of contaminant concentrations in water and were intended for protection of drinking water, aquatic life, wildlife, agriculture, and recreation. These are:

- Summary of Water Quality Guidelines: Drinking Water Sources (Government of British Columbia, 2017d);
- British Columbia Approved Water Quality Guidelines: Aquatic Life, Wildlife & Agriculture (Government of British Columbia, 2017e);
- Guidance Document for Determining Ground Water at Risk of Containing Pathogens, Including Ground Water Under Direct Influence of Surface Water (Government of British Columbia, 2015);
- Guidance for Technical Assessment Requirements in Support of an Application for Groundwater Use in British Columbia (Todd *et al.*, 2016);
- Well Protection Toolkit (Government of British Columbia, 2000) has guidelines that explain the process and steps for the development of a community well protection plan to prevent contamination of the aquifer supplying the water supply wells. The document has a useful table (Table 5) containing a long list of websites for Acts and Regulations, various groundwater related reports and guidelines from the federal government, BC, and the USA;
- Groundwater Wells: Information for Property Owners - online brochures, forms. (Government of British Columbia, 2017f).

The guidelines for groundwater at industrial and contaminated sites are:

- Water and Air Baseline Monitoring Guidance document for mine proponents and operators (Government of British Columbia, 2016b);
- Guidelines for Groundwater Modelling to Assess Impacts of Proposed Natural Resource Development Activities (Wels *et al.*, 2012).

Mapping of surficial aquifers based on surficial geology maps and the distribution of groundwater wells has been actively done in BC since at least 1994, with over 1,100 surficial aquifer map polygons defined up to 2016 using an aquifer classification system (British Columbia Ministry of Environment, 2017; Wei *et al.*, 2009). Detailed mapping within aquifer areas can produce "aquifer vulnerability" maps (see Module 4 of this report). There are guidelines for aquifer mapping and classification:

- Guide to Using the BC Aquifer Classification Maps for the Protection and Management of Groundwater (Berardinucci & Ronneseth, 2002);
- A Guide to the use of intrinsic aquifer vulnerability mapping (Liggett *et al.*, 2011).

STATE OF ALASKA (USA)

LAWS AND REGULATIONS

In Alaska, water is a public resource and the water use rights are governed by the *Alaska Water Use Act* (Alaska State Legislature, 2011). Alaska laws and regulations are included in this review as much of the state has similar geography in terms of climate and permafrost to the NWT. It allows a specific amount of water from a specific water source to be diverted, impounded, or withdrawn for a specific use (Alaska Department of Natural Resources, 2006). Most regulations are listed at the State of Alaska webpages on the 30th Legislature (2017-2018), under the Alaska Admin Code.

Groundwater use

Any groundwater at a site is considered to be a drinking water source unless a responsible person or the department determines that it is not a drinking water source. For example, a hydrogeological assessment may consider the following criteria to determine the state of a drinking water source: the depth to groundwater, aquifer hydraulic properties, the presence of permafrost, groundwater quality, the existence and enforceability of institutional controls, land use of the site and neighbouring property, the need for a drinking water source and the availability of an alternative source, and transport pathways of potentially contaminated groundwater from a site to another site that is a drinking water source.

There are also requirements for establishing groundwater monitoring systems at solid waste disposal facilities; guidelines for parameters of water quality in groundwater detection monitoring; guidelines for groundwater sampling and analysis; and guidelines for the clean-up of groundwater and surface water, including contaminant concentration limits. There is an exception for freeze-back landfills: if the owner or operator demonstrates that the landfill will freeze at a site in a permafrost region, the department will not require the installation of a liner, groundwater monitoring, or methane gas monitoring. (Note that within the context of climate change and increased permafrost thaw, there are major concerns about this type of containment system.)

GUIDELINES

The following guidance documents were prepared by the Alaska Department of Environmental Conservation (dates for references in brackets):

- Water Quality Standards (2017a);
- Guidance for the Implementation of Natural Condition-Based Water Quality Standards (2006a; 2006b) has procedures used by the Alaska Department of Environmental Conservation to implement natural condition-based water quality standards;

- Implementation Guidance: 2006 Mixing Zone Regulation Revisions (2009) defines a mixing zone (2017b) as a portion of a water body where a permitted wastewater discharge undergoes initial dilution. Specific water quality criteria within this defined area are permitted to exceed the numeric limits;
- Clean-up Levels Guidance (2008) uses the Standardized default exposure parameters developed by the United States Environmental Protection Agency (EPA) for values of contaminant concentrations in water, except for exposure frequency;
- Guidance for Clean-up of Petroleum Contaminated Sites (2000);
- On-site Disposal Systems (2017c) is an information website that has forms and guidelines about system installation, maintenance, sewage clean-up procedures, and more;
- User's Guide to the Alaska Department of Natural Resources, Division of Mining, Land & Water Alaska Hydrologic Survey Water Well Log Tracking System (2017d).

There are also useful guidelines published by the United States' Federal agencies, for example:

- Guidelines for Evaluating Ground-Water Flow Models (Reilly & Harbaugh, 2004);
- Protecting Underground Sources of Drinking Water from Underground Injection (UIC) (US EPA, 2017);
- Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells (US EPA, 1991).

Table 5. Summary of guidelines by topic.

Juris-diction	Guideline Name	URL
Water quality guidelines (contaminant concentration limits by type of water use)		
Canada	Guidelines for Canadian Drinking Water Quality (Community Water Supplies)	http://ceqg-rcqe.ccme.ca/en/index.html
Canada	Guidelines for Canadian Recreational Water Quality	
Canada	Canadian Water Quality Guidelines for the Protection of Aquatic Life	
Canada	Canadian Water Quality Guidelines for the Protection of Agricultural Water Uses	
Canada	Summary of A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines (CCME 2006). Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health	http://ceqg-rcqe.ccme.ca/download/en/342/
Canada	Guidelines for Canadian Drinking Water Quality - Summary Table.	https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/water-quality/guidelines-canadian-drinking-water-quality-summary-table.html
Alberta	Environmental Quality Guidelines for Alberta Surface Waters	https://open.alberta.ca/publications/9781460138731#summary
BC	Summary of water quality guidelines: Drinking water sources	https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/waterquality/wqgs-wqos/approved-wqgs/source_drinking_water_quality_guidelines_bcenv.pdf
BC	British Columbia Approved Water Quality Guidelines: Aquatic Life, Wildlife & Agriculture	https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/waterquality/wqgs-wqos/approved-wqgs/wqg_summary_aquaticlife_wildlife_agri.pdf
Alaska	Water Quality Standards	http://dec.alaska.gov/media/1046/18-aac-70.pdf
Community water supply systems		
Yukon	Assessment Guideline for Well Water or Groundwater Under the Direct Influence of Surface Water (GUDI)	http://www.hss.gov.yk.ca/pdf/well_ground_guidelines.pdf
Quebec	Guide to pump testing and interpretation	http://www.mddelcc.gouv.qc.ca/eau/souterraines/guide_pompage/index.htm

Juris-diction	Guideline Name	URL
Quebec	A guide to implementing vulnerability analyzes for drinking water supply in Quebec	http://www.mddelcc.gouv.qc.ca/Eau/prelevements/guide-analyse-vulnerabilite-des-sources.pdf
Quebec	A guide to principles of mitigation and compensation of agricultural activities relating to water extraction facilities	http://www.mddelcc.gouv.qc.ca/Eau/souterraines/Guide_compensation.pdf
BC	Guidance document for determining ground water at risk of containing pathogens, including Ground Water Under Direct Influence of Surface Water	http://a100.gov.bc.ca/appsdata/acat/documents/r20531/garp_v2_dec2015_final_1449696195712_9696014840.pdf
BC	Well Protection Toolkit	http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/wells/well_protection/wellprotect.html
USA	Guidelines for Evaluating Ground-Water Flow Models	https://pubs.usgs.gov/sir/2004/5038/PDF/SIR20045038_ver1.01.pdf
USA	Protecting Underground Sources of Drinking Water from Underground Injection (UIC)	https://www.epa.gov/uic
Domestic groundwater wells		
Canada	Groundwater (online resources)	https://www.ec.gc.ca/eau-water/default.asp?lang=En&n=300688DC-1
Yukon	Domestic Water Well Program Guidelines	http://yukonwater.ca/understanding-yukon-water/drinking-water/water-wells
Yukon	Planning and Managing a Rural Drinking Water System	http://yukonwater.ca/understanding-yukon-water/water-facts-and-information/groundwater-and-aquifers
Yukon	Guidelines for Disinfecting Your Drinking Water Well	http://www.community.gov.yk.ca/pdf/Domestic_Water_Well_Program_Guidelines_2015.pdf
Alberta	Water. Education and Guidelines. Working Well. Resources and Related Links (15 fact sheets for well owners, e-books, videos)	http://aep.alberta.ca/water/education-guidelines/working-well/resources-and-related-links.aspx
BC	Groundwater Wells: Information for Property Owners	http://www2.gov.bc.ca/gov/content/environment/air-land-water/water/groundwater-wells/information-for-property-owners
Commercial groundwater use or water diversion		
Yukon	Guidance Document on Water and Mass Balance Models for the Mining Industry	http://www.env.gov.yk.ca/publications-maps/documents/mine_water_balance.pdf
Alberta	Guide to Groundwater Authorization	https://open.alberta.ca/publications/5612701
Alberta	Guidelines for Licensing Water Diversion Projects	https://open.alberta.ca/publications/9780778588061

Juris-diction	Guideline Name	URL
BC	Guidance for technical assessment requirements in support of an application for groundwater use in British Columbia	http://a100.gov.bc.ca/appsdata/acat/documents/r50847/TechAssess_1473197338159_3194880156.pdf
Groundwater contamination monitoring		
Canada	Guidance Manual for Environmental Site Characterization In Support of Environmental and Human Health Risk Assessment	http://www.ccme.ca/en/files/Resources/csm/Volume 1-Guidance Manual-Environmental Site Characterization_e PN 1551.pdf
Canada	Guidance Document on Federal Interim Groundwater Quality Guidelines for Federal Contaminated Sites	http://esdat.net/Environmental%20Standards/Canada/Fed/Fed%20Interim%20GW%20En14-91-2013-eng.pdf
Canada	Decision Making Framework of the Federal Contaminated Sites Action Plan	https://mvlwb.com/sites/default/files/documents/wg/WLWB_5363_Guidelines_Closure_Reclamation_WR.pdf
NWT (federal)	Guidelines for the Closure and Reclamation of Advanced Mineral Exploration and Mine Sites in the Northwest Territories	https://mvlwb.com/sites/default/files/documents/wg/WLWB_5363_Guidelines_Closure_Reclamation_WR.fhttps://mvlwb.com/sites/default/files/documents/wg/WLWB_5363_Guidelines_Closure_Reclamation_WR.pdf
NWT (federal)	Recommended Procedures for Developing Detailed Designs for Aquatic Effects Monitoring Programs)	http://www.enr.gov.nt.ca/sites/enr/files/aemp_technical_guidance_document_volume_4.pdf
NWT (federal)	Best Practices for The Solid Waste Facilities Such As Landfills In Northern And Remote Areas	http://publications.gc.ca/site/eng/9.826705/publication.html
NWT	Environmental Guideline for Contaminated Site Remediation	http://www.enr.gov.nt.ca/sites/enr/files/guidelines/siteremediation.pdf
NWT	Guideline for Industrial Waste Discharges in the NWT	http://www.enr.gov.nt.ca/sites/enr/files/guidelines/industrial_waste_guidelines.pdf
NWT	Northwest Territories Source Water Assessment and Protection (SWAP) Guidance Document	https://www.enr.gov.nt.ca/sites/enr/files/source_water_assesment_and_protection_swap_guidance.pdf
NWT	A Guideline to the Spill Contingency Planning and Reporting Regulations	https://www.enr.gov.nt.ca/sites/enr/files/reports/guide_to_spill_contingency_planning_and_reporting.pdf
Nunavut	Contaminated Site Remediation (brief outline)	ftp://ftp.nwb-oen.ca/other%20documents/Guidelines/090728%202002%20Guideline%20for%20Contaminated%20Site%20Remediation-IMLE.pdf

Juris-diction	Guideline Name	URL
Alberta	Alberta Tier 1 / 2 Guidelines	http://aep.alberta.ca/land/programs-and-services/reclamation-and-remediation/contaminant-management/remediation/part-one-soil-and-groundwater-remediation-guidelines/default.aspx
BC	Water and air baseline monitoring guidance document for mine proponents and operators	https://www2.gov.bc.ca/assets/gov/environment/waste-management/industrial-waste/industrial-waste/water_air_baseline_monitoring.pdf
BC	Guidelines for groundwater modelling to assess impacts of proposed natural resource development activities	http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/groundwater_modelling_guidelines_final-2012.pdf
USA	Cleanup Levels Guidance	https://dec.alaska.gov/spar/csp/guidance/cleanuplevels.pdf
USA	Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells	https://www.epa.gov/sites/production/files/2015-06/documents/fieldsamp-wellshandbook.pdf
Alaska	Guidance for the Implementation of Natural Condition-Based Water Quality Standards	http://dec.alaska.gov/Water/wqsar/pdfs/NaturalConditionsGuidance.pdf
Alaska	Implementation Guidance: 2006 Mixing Zone Regulation Revisions	http://dec.alaska.gov/Water/wqsar/wqs/pdfs/MixingZoneGuidance2-3-09.pdf
Alaska	Guidance for Cleanup of Petroleum Contaminated Sites	http://dec.alaska.gov/spar/csp/guidance/petr2000.pdf
Aquifer mapping and ranking		
BC	Guide to Using the BC Aquifer Classification Maps for the Protection and Management of Groundwater	http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/reports/aquifer_maps.pdf http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/Aq_Classification/Aq_Class.html
BC	A Guide to the use of intrinsic aquifer vulnerability mapping	http://cvrd.bc.ca/DocumentCenter/Home/View/7838
Municipal waste storage in northern areas		
Canada	Best Practices for the Solid Waste Facilities Such as Landfills in Northern and Remote Areas	http://publications.gc.ca/site/eng/9.826705/publication.html
NWT	Guidelines for Developing a Waste Management Plan	https://mvlwb.com/sites/default/files/documents/MVLWB-Guidelines-for-Developing-a-Waste-Management-Plan-Mar-31_11-JCWG.pdf

Juris-diction	Guideline Name	URL
NWT	Guidelines for the Planning, Design, Operations and Maintenance of Modified Solid Waste Sites in the Northwest Territories	http://www.enr.gov.nt.ca/sites/enr/files/guidelines/solidwaste_guidelines.pdf
Alaska	On-site Disposal Systems	http://dec.alaska.gov/water/wwdp/onsite/

Table 6. Summary of water laws and regulations listed in this report, by jurisdiction

Law or Regulation	URL
Federal (Canada)	
Mackenzie Valley Federal Areas Waters Regulations (SOR/93-303)	http://laws-lois.justice.gc.ca/eng/regulations/SOR-93-303/index.html
Mackenzie Valley Resource Management Act. S.C. 1998, c. 25	http://laws-lois.justice.gc.ca/eng/acts/M-0.2/
Metal Mining Effluent Regulations. SOR/2002-222	http://laws-lois.justice.gc.ca/eng/regulations/SOR-2002-222/
Northwest Territories	
Waters Act, S.N.W.T. 2014, c.18	https://www.justice.gov.nt.ca/en/files/legislation/waters/waters.a.pdf
Environmental Protection Act, R.S.N.W.T. 1988, c.E-7.	https://www.justice.gov.nt.ca/en/files/legislation/environmental-protection/environmental-protection.a.pdf
Mackenzie Valley Federal Areas Waters Regulations (SOR/93-303)	http://laws-lois.justice.gc.ca/eng/regulations/SOR-93-303/index.html
Water Supply Systems Regulations (R-108-2009, Public Health Act)	https://www.justice.gov.nt.ca/en/files/legislation/public-health/public-health.r7.pdf
Yukon Territory	
Environment Act.	http://www.gov.yk.ca/legislation/acts/environment_c.pdf
Waters Act, Chapter 19	http://www.gov.yk.ca/legislation/acts/waters.pdf
Public Health and Safety Act	http://www.gov.yk.ca/legislation/acts/puhesa.pdf
Contaminated Sites Regulation. O.I.C. 2002/171 Environment Act. Sept. 30/02	http://www.gov.yk.ca/legislation/regs/oic2002_171.pdf
Sewage Disposal Systems Regulation (O.I.C. 1999/82 Public Health and Safety Act). Jun 30, 1999	http://www.gov.yk.ca/legislation/regs/oic1999_082.pdf
Legislation. List of all Acts and Regulations in Yukon	http://yukonwater.ca/managing-yukon-water/legislation
Nunavut Territory	
Nunavut Waters and Nunavut Surface Rights Tribunal Act (S.C. 2002, c. 10)	http://laws-lois.justice.gc.ca/eng/acts/N-28.8/
Nunavut Waters Regulations (SOR/2013-69)	http://laws-lois.justice.gc.ca/eng/regulations/SOR-2013-69/index.html

Law or Regulation	URL
Province of Quebec	
Loi sur la qualité de l'environnement (Environment Act) (1978), c. 94, a. 1. Chapitre Q-2	http://legisquebec.gouv.qc.ca/fr/ShowDoc/cs/Q-2/
Loi affirmant le caractère collectif des ressources en eau et visant à renforcer leur protection (Collective character of water Act). Chapitre C-6.2.	http://legisquebec.gouv.qc.ca/fr/ShowDoc/cs/C-6.2
Règlement sur le prélèvement des eaux et leur protection (RPEP) (Regulation on water extraction and protection). Chapitre Q-2, r. 35.2	www.mddelcc.gouv.qc.ca/Eau/prelevements/reglement-prelevement-protection/index.htm
Province of Alberta	
Environmental Protection and Enhancement Act. Revised Statutes of Alberta 2000 Chapter E-12	www.qp.alberta.ca/documents/Acts/E12.pdf
Water Act. Revised Statutes of Alberta 2000 Chapter W-3	www.qp.alberta.ca/documents/Acts/w03.pdf
The Water (Ministerial) Regulation. Alberta Regulation 205/1998 with amendments up to and including Alberta Regulation 185/2015	www.qp.alberta.ca/documents/Regs/1998_205.pdf
Alberta Land Stewardship Act. Statutes of Alberta, 2009 Chapter A-26.8	www.qp.alberta.ca/documents/Acts/A26P8.pdf
Province of British Columbia	
Water Sustainability Act [SBC 2014] CHAPTER 15	www.bclaws.ca/civix/document/id/complete/statreg/14015
Groundwater Protection Regulation. BC Reg. 39/2016 O.C. 113/2016	www.bclaws.ca/civix/document/id/complete/statreg/39_2016
Groundwater Protection Regulation	www2.gov.bc.ca/gov/content/environment/air-land-water/water/laws-rules/groundwater-protection-regulation
Water Protection Act (WPA). [RSBC 1996] CHAPTER 484	www.bclaws.ca/EPLibraries/bclaws_new/document/ID/freeside/00_96484_01
Environmental Management Act (EMA). [SBC 2003] CHAPTER 53	www.bclaws.ca/Recon/document/ID/freeside/03053_00
Contaminated Sites Regulation. BC Reg. 375/96, O.C. 1480/96.	www.bclaws.ca/EPLibraries/bclaws_new/document/ID/freeside/375_96_00
Geothermal Resources Act [RSBC 1996] Chapter 171	www.bclaws.ca/civix/document/id/complete/statreg/96171_01
State of Alaska	
Water Use Act. 2011 Alaska Statutes, Title 46. Water, Air, Energy, And Environmental Conservation, Chapter 46.15	http://www.legis.state.ak.us/basis/folio.asp

MODULE

4

MODELS, METHODS AND TOOLS FOR GROUNDWATER INVESTIGATIONS

There are many reasons to conduct a groundwater investigation. The resulting output of the investigation can be extremely diverse. For this reason, comprehensive groundwater surveys are required to better understand critical information such as biogeochemical cycling, the sustainable yield of an aquifer, the distribution of point source or diffuse contamination, heat transfers, and the vulnerability of the resource.

The identification of aquifers is based on the collection of a wide range of spatial data and ground properties. The deduction of flow direction and rate requires topographical data, spatial information on hydraulic head, sediment characteristics data, and knowledge of reservoir volume. The assessment of water quality is based on techniques of aqueous chemistry and requires an understanding of the fundamental theory behind living systems. The resulting data should be easily accessible to inform decision-makers and the general population alike (private and public sectors).

This module presents an integrative overview of the tools and methods commonly used to assess groundwater. The first section of this module addresses the main concepts related to groundwater survey. The second section discusses modelling as a tool in groundwater survey. The third section addresses the development of approaches and methods. The fourth section proposes a list of useful tools and techniques. Finally, the fifth section explores the considerations for selecting techniques and presents a successful survey approach and techniques used.

GROUNDWATER INVESTIGATIONS

Survey, investigation or assessment are some terms that mean the process of monitoring, researching, describing or assessing the groundwater and its related phenomena. The objective of the groundwater survey is to improve the conceptual model of the groundwater system. A model is a representation of ideas, concepts, and processes of some phenomena. The model's domain can be spatial, temporal, conceptual, or a combination of all three. In hydrogeology and hydrology, models refer to the distribution, flow processes, and properties of water, subsurface of the Earth and its surface, and interactions with the atmosphere and the ecosystem, for example. This section presents the main steps contributing to a groundwater investigation.

HYDROGEOLOGICAL INVESTIGATION PROCESS

There should be an initial motivation or purpose for conducting a groundwater assessment in a particular place. It leads to a definition of specific research or water management questions. A certain level of experience and theory is needed to ensure the question is specific enough to orient the groundwater survey. The notion of scale is central to the definition of the study (e.g., Bloschl & Sivapalan, 1995).

In practical groundwater management, the data collection is planned with specific goals and data deliverables.

Some useful concepts are as follows.

- An approach is selected to achieve the objective. It encompasses a set of logical assumptions. Determining the assumptions requires a sufficient theoretical knowledge. Care must be taken to limit the domain and define the studied object and spatiotemporal resolution.
- A method is a plan or set of orderly procedures, well established, that are based on a credible approach. It reveals what needs to be done in a systematic way and how to focus on achieving the goals. The method selection considers financial limits, whether a measurement must be made directly or indirectly , the time frame, and the precision needs.
- A technique refers to a precise strategy designed to generate something specific (i.e., groundwater-related information). It is normally well described, has few ambiguities, and is readily available.
- A tool refers to the final realization of a technique, it is readily useable to fulfil specific needs of a groundwater survey.

Data collection leads to a refined or improved conceptual model. The results of each round of data collection or monitoring are reviewed, the conceptual models are updated, and new plans are made to fill the information gaps. The data collection continues until the model is satisfactory or the objectives are achieved. A specific care needs to be observed for managing the data and controlling their quality.

Data management

Successful groundwater study and management requires an integrated view of multiple disciplines, which results in major implications for data management. As the importance of the value of groundwater systems increases, there is a growing number of larger data sets originating from a variety of sources to manage. The capacity for generating data also increases quickly. Implementing and developing a data management plan is therefore critical. The following discussion is based on review work by WMO (2008) and Fitch *et al.* (2016), unless otherwise noted.

Hydrogeological studies require the gathering of information from different geoscience disciplines (e.g., hydrology, hydrogeology, geology, climatology, engineering) in the form of existing data, or new measurements (Gogu *et al.*, 2001). Combining all of this information is crucial as the resulting models highly depend on the quality of the data.

Data management can be defined as a sequence of procedures that, along with specific tools and tasks, allow storage and access to data while maintaining their integrity and quality. It ensures that data is accurately and efficiently stored in a database, is accompanied by exhaustive metadata and links to technical notes about the data, and is presented in a consistent form to be easily accessible and distributable. Special care as to the quality of data storage is also important because of the growing need to share information across different jurisdictional and groundwater management organizations.

There are different general data management models that can be applied to various projects. Their purpose is to define the different processes and the sequence in which they should be executed to enable good data management. Thomas *et al.* (2009) give examples of model structures that could be suited to groundwater management purposes. The workflows can include, but are not limited to: the definition of the study, data collection, data validation, data analyses and data dissemination. They are meant to help the user through the most important steps of the process.

HYDROGEOLOGICAL MODELLING

The next sections aim to present some relevant techniques for modelling groundwater in a context where permafrost influences the geosystems. The first sub-section introduces what a model is and why to use it. The next sub-section presents one of the most basic quantification in hydrology: the water budget. The third sub-section presents groundwater flow modelling. The following two sub-sections present methods for modelling permafrost and, the final sub-section aims to present briefly the state of knowledge on combined modelling groundwater and permafrost.

PURPOSE

The practice of modelling the hydrogeological system supports the investigation and/or the monitoring process from the beginning (i.e., starting hypothesis) to the end (i.e., representing outcomes). For instance, a preliminary model that faithfully represents field conditions, and is adapted to the objectives of the investigation, needs to be well understood in order to specify which, when, where, and how data will need to be gathered.

Groundwater models have different purposes (Zhou & Li, 2011). They can be used to:

- interpret groundwater system dynamics and understand flow patterns;
- simulate the responses of a groundwater system to stresses;
- assess recharge, discharge and aquifer storage processes, and quantify sustainable yield;
- predict future conditions or impacts of human activities;
- support the planning of field data collection and design practical solutions;
- evaluate groundwater development scenarios;
- design and assess alternative polices;
- visualize data and communicate key messages to decision-makers and the public.

Groundwater modelling can also be used to support the modelling of matter that is coupled with the water cycle. This is the case for the biogeochemical cycles (e.g., carbon, nitrogen, phosphorous or sulfur cycles) and for suspended sediments, nutrients, contaminants and pollutants.

A model can take multiple forms depending on its nature, its purpose and objectives, and the availability of data it includes. For example, a model representing nitrogen cycling at the watershed scale will not be the same as one representing the groundwater recharge of that aquifer.

A complete work on the topic of groundwater modelling is provided by Anderson *et al.* (2015). The webpage of the USGS (https://water.usgs.gov/software/lists/groundwater/) lists a wide variety of modelling freeware.

Groundwater flow models

A groundwater flow model consists of a representation of the ground storage (water budget), modulated by the solution of the Darcy's equation, to iteratively minimize the hydraulic gradient.

The groundwater flow models are necessarily referenced on the time dimension, and at least one spatial dimension, normally the vertical one. In consequence, the simplest flow model is 1D. However, 2D and 3D modelling are more relevant to the representation of flow.

The simulation of communicating cells in 1D, 2D and 3D models require the use of a finite difference grid or a finite-element mesh. Their complexity increases exponentially with the addition of dimensions, hence the components' properties and boundaries to input in simulations need to be as simple and accurate as possible.

Software already exists for modelling groundwater. MODFLOW 6 is a modelling software used worldwide due to its flexible modular structure, its complete coverage of hydrogeological processes, and the fact that it is readily and freely available to the public. Extension modules can be added to include heat and solute transport, and variable saturation.

SUTRA is another powerful and public software that provides the possibility to directly deal with heat and solute transport, a variable water density, and a variable saturated zone.

These software packages can be used to model in 3D. One of the biggest differences is that MODFLOW is based on a finite-difference grid while SUTRA works on a finite-element mesh. As a result, MODFLOW requires less computational power, but it is limited to the representation of the water volume and the integration of secondary components of groundwater (heat and solutes) requires add-ons. SUTRA is heavier to run but can deal directly with these. The use of a finite-element mesh also eases the refinement of the spatial grid around areas of interest. The operation of this software is facilitated by the use of the graphic interface Model Muse.

Other popular software for groundwater modelling include, but are not limited to:

- FEFLOW (www.feflow.com),
- Soil Vision (http://www.soilvision.com),

- GeoStudio (www.geo-slope.com) and,
- COMSOL Multiphysics (www.comsol.com/comsol-multiphysics).

The section on groundwater modelling tools from TechnoMine references most of the commercial and public software, and the section on groundwater resources software details the list of potentially useful tools the USGS can provide:

- http://technology.infomine.com/articles/1/1750/groundwater.hydrology.model/groundwater.modeling.tools.aspx
- https://water.usgs.gov/software/lists/groundwater/

Modelling of permafrost with the Stefan equation

Permafrost models require different techniques than simple groundwater flow models. One of the most relevant phenomena to model in permafrost science is the freezing front, despite the fact that it does not exactly represent the permafrost table. The Stefan equation allows for the estimation of the thaw depth in ice-water bearing environments, where the ice content is limited to the ground's void volume:

$$Z = \sqrt{\frac{2TKt}{Q_i}}$$

Equation 8

Where:

	Z	refers to the depth (m)
	T	refers to the ground surface temperature (°C)
	K	refers to the thermal conductivity of the unfrozen soil (w/m-°C)
	t	refers to the duration of the thawing season (s)
	Q_i	constitutes the volumetric latent heat of fusion and is expressed as:

$$Q_i = L\rho_d(W - W_u)$$

Equation 9

Where:

	L	refers to the latent heat of ice (334.4 j/g)
	ρ_d	refers to the dry density of the soil (kg/m^3)
	W	refers to the total moisture content (% vol)
	W_u	refers to the unfrozen water content (% vol)

This equation and other models for the computation of the active layer thickness have been discussed by Bonnaventure and Lamoureux (2013).

The temperature of permafrost at any depth below the zero-annual amplitude depth can be computed by the simple conduction theory:

$$T_z = T_s + G_g Z$$

Equation 10

Where:	T_z	refers to the temperature at a given depth (°C)
	T_s	refers to the surface temperature (°C)
	G_g	refers to the geothermal gradient (°C/m)
	Z	refers to the depth (m)

The surface temperature at a given time ($T_{S,t}$) can be simulated by a sinusoidal function:

$$T_{S,t} = T_m + A_S \sin\frac{2\pi t}{p}$$

Equation 11

Where:	T_m	refers to the mean air temperature (annual or daily; °C)
	A_s	refers to the amplitude (°C)
	t	refers to the time (hours or years)
	p	refers to the period (same than t)

As depth increases, the diurnal and seasonal temperature variation that is seen at ground surface is attenuated and time-lagged (delayed). The function of temperature in the subsurface with depth and tie can be related to the ground surface temperature:

$$T_{Z,t} = T_m + A_S \exp\left(-Z\sqrt{\frac{\pi}{\alpha_u p}}\right)\sin\left(\frac{2\pi t}{p} - Z\sqrt{\frac{\pi}{\alpha_u p}}\right)$$

Equation 12

Where:	α_u	refers to the thermal diffusivity of the soil (s/m^2)

As a water budget is done to model hydrology, a heat budget can be done to model permafrost. This is a complex process, especially if the model is referenced on more than one dimension, because it needs to include the water budget as an input. In effect, the storage of water means the storage of specific and latent heat in a thermal balance equation.

Climate-dependent permafrost models

The thermal state of the ground can be modelled with a high level of precision by using software based on a finite-difference grid or finite-element mesh, like COMSOL and GeoStudio, where the heat storage is communicated according to the pure conduction theory. This process-based approach is useful especially in simple environments that are relatively small and well-documented. As an input, it normally uses the observed past climate, or the projected future climate. The output of climatic simulations is generated by a global atmospheric circulation model.

This first approach considers that permafrost is dependent, among others, on climate, and it avoids the consideration of potential feedback. Hence, it is most relevant for small areas (regional scale or smaller), and it requires a very comprehensive description (and measurement) of the environment.

Simplified coupled models

Accurately computing the precise heat budget at the interface between the ground and the atmosphere is a very difficult task because of its complexity. Another approach for modelling permafrost aims to integrate its retroaction with the global climate in global circulation models. To do so, the high complexity of surface processes and properties need to be synthesized and broadly averaged.

The coupling between the atmosphere and the ground temperature, being influenced by snow, wetness, vegetation and albedo, can be empirically-modelled using the N factor. One is computed for the thawing period (N_t) and another one for the freezing period (N_f):

$$N_t = \frac{I_{ts}}{I_{ta}} \quad ; \quad N_f = \frac{I_{fs}}{I_{fa}}$$

Equation 13

Where:
- I_{ts} refers to the soil's thawing index (°C-days/year)
- I_{ta} refers to the atmosphere's thawing index (°C-days/year)
- I_{fs} refers to the soil's freezing index (°C-days/year)
- I_{fa} refers to the atmosphere's freezing index (°C-days/year)

The N factors are used to convert atmospheric temperatures into ground surface temperatures where they are relevant. The computed surface temperature serves as an input in the heat balance of the ground.

For modelling the mean annual temperature at the permafrost table, the N factor can be integrated into the TTOP model (Riseborough *et al.*, 2008), a 1D model that can be efficiently integrated in a global circulation model such as the 4th generation coupled global climate model
(https://www.canada.ca/en/environment-climate-change/services/climate-change/centre-modelling-analysis/models/fourth-generation-coupled-global.html).

Modelling of groundwater flow in permafrost conditions

In the past decade, there has been an emergence of research on the interaction of groundwater and permafrost. The study of heat and water transport in permafrost regions uses increasingly complex models. This emerging field is very relevant to groundwater questions in the Northwest Territories.

This sub-section aims to provide a brief overview of the current state of permafrost-groundwater modelling. It first discusses an approach for modelling where the groundwater system is dependent on permafrost, but the permafrost distribution is not dynamic. Then, it discusses the approach of coupling thermal and hydrogeological models to study the dynamic interaction between groundwater and permafrost. It finishes by discussing the state of physical modelling and benchmarking the fully coupled numerical models.

Permafrost-dependent groundwater models

A first question about permafrost-groundwater relations is how groundwater fluxes change when the distribution of permafrost changes. To simulate the effect of permafrost on groundwater, one efficient approach is to simply reiterate the computation of a same hydrogeological model where the extent (and thickness) of permafrost varies. For example, Walvoord *et al.* (2012) have used MODFLOW to apply this approach. In their model, the permafrost bodies were simply defined as aquicludes with low hydraulic conductivity, and no formal computation of the thermal processes were needed in the work. The permafrost extent is changed in steps and a separate model solution is computed for each step, at which point the permafrost distribution is modified to continue to the next simulation step.

This approach is relevant and was successful to estimate how the overall water budget and its timing will shift in a watershed where the permafrost extent is expected to change. However, the results remain limited to the broad scale, and can't take into account potential feedbacks with the vegetation or the permafrost itself. Overall, the discussed approach assumes that permafrost is a variable that is independent of groundwater.

Fully coupled thermo-hydrogeologic process-based models

How does groundwater flow impact permafrost? Rowland *et al.* (2011) have used the model ARCHY, a finite-difference grid integrating the coupled dynamics of heat, water and solute, to show how the presence of sub-permafrost groundwater flow reduces the thickness of permafrost, and increases the rate of localized permafrost degradation in response to disturbances such as talik formation. Using a 2D simulation at the local scale (about 10-1000 m), their approach was based on the comparison of three permafrost scenarios: without groundwater flow, where the groundwater is limited to vertical flow (from a lake, downwards to the subpermafrost aquifer by the sublake talik), and with a lateral flow of groundwater.

This approach, employing process-based coupled heat and mass models, is especially relevant for relatively small and adequately documented terrains. It was successfully used for the assessment of permafrost sustainability where the hydrogeologic pattern is expected to change. Walvoord and Kurylyk (2016) reviewed several of them. In general, the models have been used to demonstrate that increased active layer thickness may enhance groundwater storage during the recharge season and thus increase baseflow (Walvoord and Kurylyk, 2016).

Most of the permafrost hydrogeological models were limited to a 2D representation, of a terrain less than 10 km long, sometimes real and sometimes hypothetical. Kurylyk *et al.* (2016) successfully modelled in 3D an intensively documented terrain (Scotty Creek, NWT) to simulate the vertical and lateral heat transfer, coupled with the groundwater flow. The work demonstrated that 1) again, lateral heat transfer can influence permafrost thaw rates, 2) landscape evolution arising from permafrost thaw acts as a positive feedback mechanism that increases the energy absorbed at the land surface and produces additional permafrost thaw and, 3) flow rates in local groundwater flow systems may be enhanced by the degradation of isolated permafrost bodies.

Most of the studies reviewed by Walvoord and Kurylyk (2016) have particularly focused on the role of groundwater flow in taliks and have demonstrated that open through-permafrost talik can substantially enhance groundwater exchange between supra- and subpermafrost aquifers. These models are driven by a three-dimensional Richards-type equation for water flow with a three-dimensional heat transfer equation (McKenzie *et al.*,2007).

Walvoord and Kurylyk (2016) highlight some challenges in using the fully coupled process-based modelling approach:

- The accuracy for representing thermal and hydraulic conductivities in partially frozen soils is low.
- Most studies have been restricted to idealized environments, and few have been reproduced field conditions (e.g., multidecadal permafrost thaw or groundwater flow rates). This is mainly due to the scarcity of field data.
- Most of the models do not include a land surface scheme and can't deal with the hydro-thermal processes occurring at the ground surface.
- Simulations are typically restricted to two dimensions, simple structure and geometry, and relatively small spatial scales due to the computational resources required to obtain the numerical solution. The equations are highly nonlinear and generally demand small time steps and a fine mesh or grid.

- Many permafrost heat transfer modelling tools are “too complex to be used by anyone other than modelling experts” (Fritz *et al.*, 2015).

The difficulty of instrumenting field sites, representing the unfrozen water content (< 0 °C), and integrating both the land surface and subsurface processes remains a challenge for modelers (Ireson *et al.*, 2013).

Physical modelling and benchmarking

The codes that served for modelling permafrost hydrogeology are of a similar nature (e.g., fully coupled thermo-hydrogeological processes); they all consider heat conduction, heat advection, thermal dispersion, pore water phase change, and hydraulic conductivity change. The modelling community recognizes that models lack calibration and initiated benchmarking of the codes via the international cold regions groundwater modelling network, known as InterFrost (Grenier *et al.*, 2015; Rühaak *et al.*, 2015).

The difficulty of benchmarking the models is being addressed by the use of the cold chamber facility of GEOPS laboratory (Consortium between Paris-Sud University and the French National Center for Scientific Research – Grenier *et al.*, 2015). Roux *et al.* (2017) just published the first results of a set of experiments to compare the results of numerical and physical simulations of the evolution of a river’s talik physically modelled in the laboratory. Their conclusions are encouraging; the numerical model simulations fit the laboratory results, but the convective heat transfer coefficient for each experiment was calibrated against experimental data. This means that the heat transfer coefficient is expected to be specific for every different hydrogeological system, and to change with time as the permafrost thaw front propagates. Despite this limitation, the trend was clear, and the sensitivity of the thawing front propagation to water temperature variations was much higher than to water velocity (Roux *et al.*, 2017).

A prior attempt to compare physical and numerical simulations has been made at the Geocryolab (University of Montreal – Veuille *et al.*, 2015; Fortier *et al.*, 2016) and the conclusions were similar. The development of a newer and more sophisticated physical model is ongoing and will include a monitoring setup that aims to overcome the recurrent lack of control and measurement encountered in former studies (Fortier et al, 2016; Roux *et al.*, 2017).

APPROACHES AND METHODS

The approach and methods are specific to each project and need to be adapted. This section presents some of the most popular approaches related to specific needs of knowledge about groundwater.

SINGLE-WELL CHARACTERIZATION

Drilling a borehole suits various specific objectives. Among them, it allows the measurement of the water level, its sampling, the installation of a well to monitor groundwater regularly, the description of the soil, stratigraphy and bedrock, and the sampling and direct measurement of the subsurface for determining geotechnical properties.

The drilling operation represents a good opportunity to log the material extracted and characterize the geologic formation. Logging should include, where possible, the earth material visual description, lithologic and sedimentologic identification, stratigraphic trends, voids, and faults and bedding planes. All of this will inform the geometry, homogeneity and isotropy of an aquifer.

Boring a hole can be achieved using different tools, from a shovel and sampling hand-auger at the surface to the rock-cutting corer at depth. Many techniques and apparatus can be used to allow repeat observations in the hole. A well is permeable throughout its depth, while a piezometer's is restricted to a certain depth in order so that it can monitor a particular aquifer or the hydraulic head of a certain depth. A well inside permafrost that is designed to house a thermistor string is usually filled with an anti-freeze liquid to allow servicing.

Water level monitoring usually uses a pressure transducer or a water level dipper (beeping measuring tape). Both techniques can be read and logged manually, but pressure transducers can also be automatically logged using a datalogger. There are many different commercial versions of dataloggers and transducers. Transducers can also monitor the concentrations of various elements, pH, electrical conductivity, and temperature. Well testing is necessary to obtain the effective *in-situ* aquifer properties.

The piezometer test allows for characterization of an aquifer's hydraulic conductivity. Sometimes named a slug or bail test, it produces results by changing suddenly the water level (using a slug or a bail) and logging its recovery. The test is economical, has a short range of influence, and assumes isotropy and homogeneity. The conception of the test and computation of the result vary according to whether or not the aquifer is confined, and whether or not the well is screened throughout its entire length (Hiscock & Bense, 2014).

The step drawdown test measures the well efficiency and performance by pumping the water by steps of increasing rate. The operator of the test needs apparatus to pump the well, control and measure the outflow, and divert it away from the zone of influence of the test. The water level needs to stabilize before each rate increase. The result is limited to the maximum discharge rate (or the well production capacity). Karami and Younger (2002) provided further details of the method.

Any pumping test assumes the aquifer is infinite, homogeneous and isotropic, so no boundary or unconformity can disturb the expected radial growth of the cone of depression while pumping. Since the drawdown may reverse the normal water flux, care should be taken to avoid contamination of the aquifer by seawater or other contaminant during the operation. An informative technical guide is provided by the Ministry of Environment of British Columbia (2017).

Like water level and temperature, the chemical composition of groundwater can vary over time, especially with seasons or during recharge or after withdrawal events. Therefore, analyses should be repeated to detect the aquifer dynamics. A point to consider is that shallow waters cycle quicker than deeper waters.

Geotechnical measurements provide information for groundwater surveys. Geotechnical characterization of samples includes determining the specific gravity, bulk density, porosity, water content, specific yield, particle-size distribution, pore-size distribution, residual water curve, hydraulic conductivity, strain-stress behavior, and liquid and plastic limits. X-ray computed tomography can be used to provide a 3D model of a core's density and offers a very good opportunity to visualize the detailed geological structure. See Sarsby (2000) for details about physical and geotechnical tests.

The chemical analysis of samples provides information on the baseline and undisturbed chemistry of the earth, and on the presence of contaminants. Sampling and analyzing the borehole water is undertaken to determine the baseline hydrochemical conditions and allows for further comparison after a potential disturbance (such as a a land use or climatic change). Flowing, mixing and diffusing conditions can be determined using coloring, chemical or isotopic tracers.

The relevance of characterizing an aquifer by measuring samples remains limited. Important information comes from *in-situ* testing operations. Imaging the walls of the borehole by an optical or acoustic televiewer could help the investigators ''see'' and interpret the size, dip and strike of a fissure or the particular geometry of a joint network or other factors driving secondary porosity that cannot appear in the samples. The slope and orientation of the void network or a lithologic contact is also very valuable to consider the heterogeneous nature of hydraulic conductivity and storage.

Multi-well characterization

A multiple-wells study offers the same opportunities as a single well, but adds some information on spatial variability. It allows determination of the geometry of a hydrogeological unit by integrating the stratigraphy, sedimentology, fractures and bedding planes recorded in the wells. Testing the geotechnical properties of some representative samples allows inference of a typical value for a whole hydrogeological unit.

A multiple-well approach allows spatial interpretation of aquifer behavior. More precisely, the constant discharge tests can serve to compute the transmittivity and storage of the aquifer. They use the same equipment as the step-drawdown test but require the water level to be monitored in surrounding wells. Another technique is the constant discharge test. It operates in three phases: the normal condition monitoring, the pumping phase, and the recovery period. Batu (1998) can be consulted for the different aquifer test specifications and solutions for result analysis.

The use of tracers can be very useful in the multiple-well testing approach, to estimate the connectivity and diffusion behavior of the aquifer between various points. Finally, cross-hole sonic logging (CSL) and seismic travel-time tomography (CT) offers a very efficient way to visualize, in detail, the geological structure and enhance confidence in the interpretations.

Some special techniques have been explored in the multiple-well test paradigm in order to spatially infer the measurement of an aquifer's dynamic properties. Legchenko *et al.*, (2004) used proton magnetic resonance sounding (MRS) to interpolate the measurements of specific yield and hydraulic conductivity between measured wells, while Tsoflias *et al.* (2001) conducted a similar study using georadar.

Measuring and assessing water quality

Water quality is not an intrinsic property; it is rather the expression of its chemical (and bacteriological) suitability for a planned use or healthy contribution to ecosystem functions. Generally, monitoring programs are designed to determine whether water quality is acceptable for drinking, swimming, irrigation, or aquatic life. They might also be designed to determine whether the water quality of a river, stream, lake or groundwater body is improving or deteriorating over time, and to identify the factors contributing to that change (CCME, 2011). The information required by a monitoring plan is expected to be specified to address the specific objectives (CCME, 2006).

There are two common approaches for assessing groundwater quality. The first focuses on the characteristics of the groundwater where it is pumped, for direct use. The second focuses on the characteristics of water near the place where it is potentially used. This consideration is especially relevant where a potential source of contamination could deteriorate a distant location of groundwater importance, where perhaps it is used directly or affects the ecosystem in some way.

The first approach requires consistent follow-up, sampling and measuring at points of water extraction (or in springs where groundwater seeps out of the ground). The second approach requires that the fate of the problematic matter is simulated using process-based models of water and solute transport. Ground truthing by relevant measurements are necessary in the process.

No matter the approach, there are some standard measurements that can be made *in-situ* (e.g., temperature, pH, electric conductivity, dissolved oxygen, turbidity and other visible anomalies). Other measurements are made in the laboratory. This includes total solids (total, suspended, dissolved, inorganic, and organic), nutrients (such as different forms of nitrogen, phosphorus, and carbon), metals (measured as total, dissolved, or extractable), pesticides, and more complex organic compounds such as polychlorinated biphenyls, polycyclic aromatic hydrocarbons, dioxins and furans, and many others (CCME, 2011). The bacteriological community of water is also of concern.

A first step in targeting elements and compounds to measure would be to consider the list of federal requirements regarding water quality, for different purposes. For reference, Condesso de Melo (2008) provided a good overview of the elements and compounds found in natural groundwater, and chemical processes that affect them. Rice *et al.* (2012) is a good reference for the state-of-the-art approaches for measuring the water chemistry. To ensure that the sampling and shipping operations have been safe for workers and the samples, and that they remain representative, the protocols manual for water quality sampling in Canada (CCME, 2011) can be consulted.

Just like the water level or content, the chemical compounds found in groundwater or in the soil solution vary in space and time. The guidance manual for optimizing a water quality monitoring program design (CCME, 2015) can be consulted. Finally, a general guidance paper has been published to harmonize how water quality monitoring is conducted in Canada (CCME, 2006). More specifically, it aims to 1) promote the linkage of distributed monitoring networks where desirable, 2) increase sharing of data and information, and 3) support a collective effort to achieve water quality objectives.

MEASURING AND ESTIMATING WATER QUANTITY

As seen in Module 1, the water budget is a powerful approach for modelling across different domains, from the management of the areal recharge of an aquifer below a specific watershed to the 3D process-based assessment of a contaminant plume in certain conditions. Another use of the water budget is in the sustainable management of groundwater extraction. The level of expertise required to complete a water budget is high, but this can be minimized by integrating viable assumptions. The most common data that are needed to feed such a budget include:

Precipitation (P)

- Snow
- Rain
- Dew

Incoming fluxes (Q_{in})

- Diversion from another watershed (by the subsurface)
- Artificial injection

Evapotranspiration (ET)

- Evaporation from the surface or the bare soil
- Sublimation from snow and ice covers
- Evapotranspiration from the vegetation

Outgoing fluxes (Q_{out})

- Diversion toward another watershed
- Baseflow of rivers
- Surface runoff
- Artificial withdrawal

Storage (S)

- Storage in the vegetation
- Storage in the snowpack
- Storage in the vadose zone
- Storage in the saturated zone

Various techniques can be used to acquire the needed measurements. Precipitation can be measured directly using rain and snow gauges. Time series of precipitation can be found for locations where Environment and Climate Change Canada operate a meteorological station (www.meteo.gc.ca).Interpolation can be achieved between the points to estimate the value for a precise location.

The evapotranspiration term is difficult to measure. An estimation of evapotranspiration and other weather-related time series can be obtained from Environment and Climate Change Canada. Resolving the water balance equation is the easiest common approach to estimate the evapotranspiration, but this one does not help when solving the water budget for groundwater storage.

Many techniques are available to measure or estimate the discharge of a stream. Dobriyal *et al.* (2016) have reviewed existing gauging techniques and discussed their potential and limitations in relation to stream discharge, the accuracy of results, the accessibility of terrain, and financial and physical resource requirements. Time series of streamflow can be obtained from the Water Survey of Canada, which operates gauging stations on many of Canada's rivers and streams.

The hydrograph separation method can be used to interpret the contributions of different sources (e.g. surface, unsaturated and saturated subsurface) to river discharge. Measuring the chemical and/or isotopic signature of the stream during a hydrological event and comparing it with the subsurface and groundwater signature is a common hydrograph separation tool (Pinder and Celia, 2006). A river's base flow can be estimated from stream gauging data using the hydrograph separation method. It consists of graphically subtracting the streamflow peaks related to storm runoff from the time series of river discharge (Hiscock and Bense, 2014).

Groundwater abstraction is the easiest parameter to monitor: the use of calibrated flow meters on the piping network record exactly how much water is pumped. The manager of a pumping station should be able to provide a time series of data.

The heat budget works the same way and offers similar possibilities to the water budget (i.e., 1D, 2D and 3D process-based thermal numerical modelling, reverse modelling for the estimation of evapotranspiration or groundwater flux). It inherently includes the water budget due to the thermal mass it represents. The water budget can also contribute to a chemical budget. For example, such an approach would contribute to understanding the speciation of a contaminant where a contaminated groundwater plume interacts with the soil or surface water and the toxic molecules threaten to integrate the food chain.

The possible techniques to compile a budget range from a simple numerical table such as a MS Excel spreadsheet, to a complex code for process-based simulation, such as SUTRA.

ASSESSING GROUNDWATER VULNERABILITY TO CONTAMINATION

In this sub-section, we review the best practices for assessing the vulnerability of groundwater aquifer contamination. We also discuss how the identification and characterization of aquifers is used to determine vulnerability of groundwater resources in terms of their quality and quantity, in addition to identifying the factors which may affect groundwater.

Aquifer vulnerability is a general concept that combines physical properties of an aquifer with other information related to the risk of contamination. It may be thought of as two concepts: 1) *intrinsic vulnerability*, which depends on the natural hydrogeological conditions and properties, regardless of contaminant type; and 2) *specific vulnerability*, which applies to the transport of a particular contaminant and its physical properties

(Gogu & Dassargues, 2000; Focazio *et al.*, 2002). Some mapping methods and assessments, carried out over the past 50 years, also consider more general environmental and social aspects such as population density and land use (Plummer *et al.*, 2012).

The purpose of aquifer vulnerability assessments is usually to produce maps for government planners and managers of groundwater resources to identify the most sensitive areas of groundwater contamination from sources at the ground surface, and to provide information for more detailed studies, including monitoring and local aquifer characterization (Aller *et al.*, 1987; Gogu & Dassargues, 2000; Liggett *et al.*, 2011). In most areas, mapping refers to surficial aquifers, but it can also be carried out for deeper aquifers. The aquifer characterization must to be carried out to some level of detail to accurately assess the aquifer vulnerability, usually following other baseline studies of groundwater conditions.

Aquifer vulnerability mapping can be applied at many scales: regionally, for a single aquifer or part of an aquifer, and locally (e.g., drinking water well protection zones where contamination is to be avoided in a specified capture zone of the wells). For regional mapping, there are generally two main approaches:

- Index (or overlay) methods that use categorical variables that describe the aquifer and flow system properties.
- Process-based methods or numerical modelling of the flow system and potential contaminant transport.

Index methods

Index methods involve the weighted overlay of influencing factors to represent the vulnerability of shallow aquifers regarding contamination in general. They are analogous to using layers of maps in GIS software, with each layer describing one physical property (influencing factor) of an aquifer's state. The vulnerability assessment is calculated using assigned scores (e.g., 1 to 5). The scores simplify the actual numerical values of the aquifer properties, such as water table depth, or subsurface hydraulic conductivity. The result of the index calculation at a map location (e.g., a municipal well) gives the total rating of groundwater vulnerability or susceptibility (Focazio *et al.*, 2002).

In the 1990s, the development of GIS mapping systems and aquifer vulnerability methodologies resulted in many different index methods (Corniello *et al.*, 1997, and review by Gogu and Dassargues (2000). Index methods used in Canada include the AVI method in agricultural areas in Saskatchewan (van Stempvoort *et al.*, 1993). The DRASTIC method developed by the United States Environmental Protection Agency (US EPA; Aller *et al.*, 1987) has become the most widely used index method.

Neukum *et al.* (2008) compared several aquifer vulnerability index methods with on-site measurements and models. They showed that the methods could produce quite different results.

The DRASTIC index

The name of the DRASTIC index is an acronym for the main variables used in the vulnerability calculation: depth to water (D), net recharge (R), "aquifer media" type (A), "soil media" type (S), topographic variation (T), "impact of vadose zone media" (I), and the hydraulic conductivity of the aquifer (C). Table 7 explains these variables. In Canada, DRASTIC has been used extensively in British Columbia (Liggett & Allen, 2011; Holding & Allen, 2015) and in a few cases in other provinces. The guideline documents from British Columbia by Liggett *et al.* (2011) and Liggett and Gilchrist (2010) have the most details about the practical implementation of mapping of surficial aquifer "intrinsic vulnerability". This term is defined as the relative degree of natural protection of groundwater from potential contamination. This type of approach could serve as a guideline for shallow aquifers in the NWT, such as those present in river valleys. An example of DRASTIC parameter distribution is shown in Figure 33 from mapping of shallow aquifer vulnerability in North-Eastern British Columbia undertaken by Holding & Allen (2015).

There are limitations to the DRASTIC method. A Swedish study by Rosen (1994) concluded that the qualitative aspects of the DRASTIC method give simplistic results that may not be clear in meaning, and that the resulting index overestimates the vulnerability of aquifers composed of porous materials versus aquifers in fractured rocks. Denny *et al.* (2007) proposed a modified index for areas where fracture and structural data is available. However, that method has not been widely used since. In mountainous areas in Switzerland, a special indexing method is applied for assessing the vulnerability of spring water sources to contamination in fractured rocks (Pochon *et al.*, 2008) and some of those concepts might be applicable to similar areas in the NWT such as the Mackenzie Mountains. Nevertheless, an index method is meant to be a simple assessment, and complex aquifers are best modelled numerically after proper characterization of hydraulic properties and other field conditions.

To date, the DRASTIC method has not been applied to permafrost regions. However, a similar method has been developed and used by Grandmont *et al.* (2011) to assess the vulnerability of permafrost regarding thaw settlement in Tasiujaq (QC). Other related assessments have also been carried out for various communities in Yukon Territory (e.g., Benkert *et al.*, 2013). The dynamic variability of permafrost distribution in time and space makes an index approach more challenging. Situations such as the confinement of deep aquifers under continuous permafrost are not incorporated. An index method could be modified to have some temporal component (e.g., different aquifer vulnerability scenarios in different years as a function of climate change). Another limitation is that seasonal shallow aquifers in the active layer and the deep aquifer confined under the permafrost would require two different vulnerability assessments because the overlay method of an index is only for one aquifer over a map space.

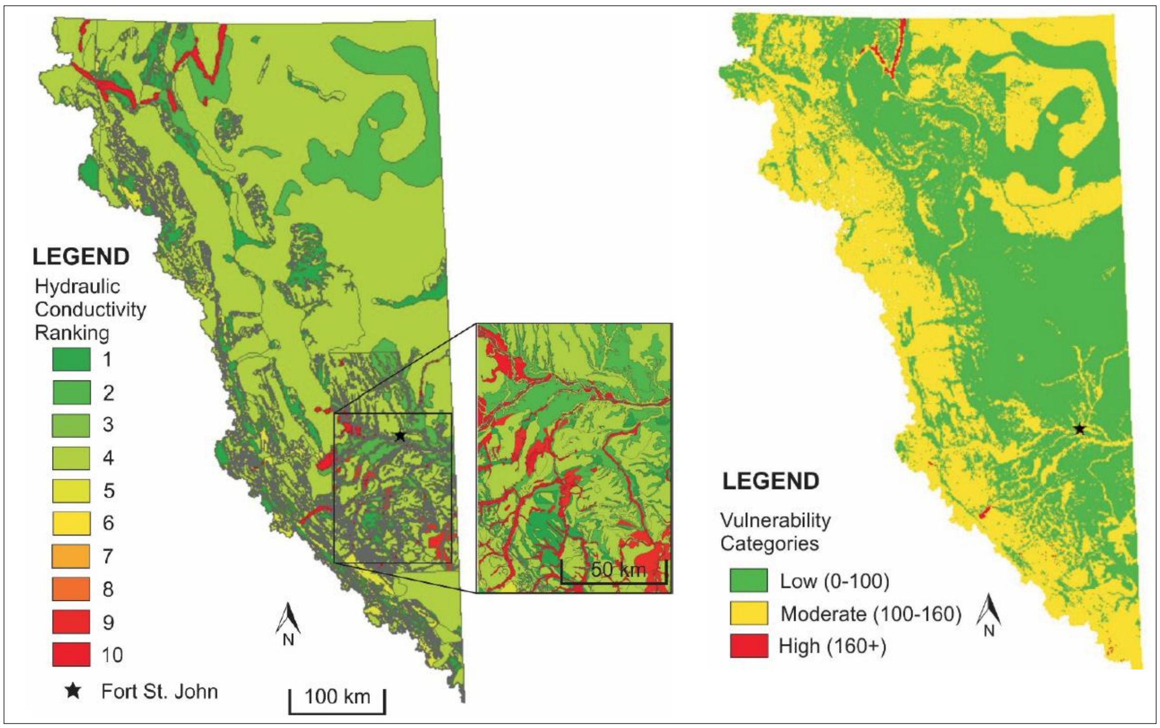
Table 7. DRASTIC parameter descriptions and combination to form the final intrinsic vulnerability map. Modified after LIggett et al 2011, from BC Guideline to Use of Intrinsic Aquifer Vulnerability Mapping.

D	Depth to water table: In an unconfined aquifer, the depth to water table is used. In a confined aquifer, the depth to top of aquifer is used. Smaller depth value means that the contaminants travel over a shorter distance vertically and typically reach the aquifer faster, thus resulting in more vulnerability. Certain contaminants can be naturally attenuated over enough time in the soil or vadose zone of the aquifer.
R	Recharge that infiltrates to water table: The recharge rate controls how much water can transport the contaminants towards the water table. Net recharge depends on precipitation amounts, local climate and land cover that control the evapotranspiration, and the aquifer/soil media that controls infiltration. In places where more water infiltrates to recharge the aquifer, more contaminants can be flushed into the aquifer from the ground surface.
A	Aquifer media: The grain size of the aquifer media is correlated with permeability, as is the amount of fracturing in rocks. The type of aquifer media directly controls the vulnerability to contamination.
S	Soil media: Coarse textured soils have a higher vulnerability than fine textured soils because contaminants are transported more rapidly and are less attenuated. Cracking soils (e.g., dry clay) are also more vulnerable to contamination infiltration.
T	Topography: Vulnerability is decreased in steeper terrain because the contaminants are more likely to flow downslope (runoff) rather than infiltrate to an aquifer.
I	Vadose zone media: The vadose (unsaturated) zone lies between the top of the soil surface and the water table surface. The grain size and level of fracturing affect the vulnerability.

C	Conductivity: The aquifer hydraulic conductivity is one of the main parameters that affect the groundwater flow through the aquifer media.

DRASTIC	Intrinsic vulnerability index value at one location: = 5D + 4R + 3A + 2S +1T + 5I +3C

Further research is needed to develop an appropriate aquifer vulnerability assessment method in the permafrost-dominated regions of the NWT.



(a) (b)

Figure 33. Examples of shallow groundwater intrinsic vulnerability assessment in northeastern British Columbia: (a) Hydraulic Conductivity Parameter Map. (b) Ministry of Environment categorization of DRASTIC Intrinsic Vulnerability. From Fig. 10 and 12 in Holding & Allen (2015), Simon Fraser University.

Process-based methods (numerical modelling)

Numerical models of groundwater flow systems are now the most commonly used tool to simulate potential or existing contaminant flow paths (Snyder *et al.*, 1998, Focazio *et al.*, 2002). A wide variety of modelling tools are available (U.S. Geological Survey, 2016).

In the past, for single wells and well fields, analytical and numerical methods were developed to define the well capture zones and to assess aquifer vulnerability in terms of travel times and distances of groundwater from potential contamination sources (Frind *et* *al.*, 2006). Whereas the index method gives an arbitrary score for each mapped area, the results of numerical flow simulation can give a more realistic assessment. These models have their own challenges such as the need for field data and proper calibration.

Numerical modelling approaches can also help predict future change in groundwater systems. For example, models can be used to simulate future climatic changes and induced changes in the groundwater recharge and discharge in river valleys and elsewhere (e.g., Scibek *et al.*, 2007). Models can be constructed to study regional groundwater flow (e.g., regional flow model in the southern Canadian Shield - Sykes *et al.*, 2009), although for aquifer management and vulnerability mapping the usefulness of these regional models will depend on the amount of data available for model calibration and model resolution. In permafrost regions of Alaska, regional numerical models have been used to study the changes in groundwater flow caused by changes in permafrost distribution due to climate-induced thaw (Walvoord *et al.*, 2012). As a rule, accurately anticipating the change helps in assessing the vulnerability.

A more advanced method that was recently developed in Europe combines the three-dimensional numerical flow models and assigns sensitivity coefficients that quantify how the detrimental effects of a contamination is transmitted through the flow system and what are the potential impacts on groundwater (Beaujean *et al.*, 2014). The vulnerability can be mapped in three dimensions with a vulnerability value, analogous to mapping of hydraulic properties in three dimensions, but expressing the aquifer vulnerability. This type of assessment may be applicable for relatively simple hydrogeological flow systems with large amounts of hydrogeological data, and where different vulnerabilities could be studied.

Statistical methods

Statistical analysis of spatially distributed variables such as aquifer properties and sources of contamination may also be used to provide insights about aquifer vulnerability and risk. The statistical analysis is usually carried out through multiple regression methods and then applied to a spatial distribution of the variables to produce probability maps of aquifer vulnerability. This may take the form of a map showing the probability to encounter water that exceeds the quality threshold (e.g., Focazio *et al.*, 2002 – Figure 34).

In some aquifer studies, index methods are combined with statistical analysis to modify and quantify the scoring system. Rupert (2001) gave an example of calibration of the DRASTIC index using statistical analysis. At regional scales, changes in land use over time can be tracked and correlated to aquifer vulnerability and groundwater contamination levels (e.g., Stevenazzi *et al.*, 2015).

Statistical methods are complementary to index methods and are useful in areas where large amounts of data exist, for data exploration using descriptive statistics, and to determine correlations between variables. While the index maps offer subjective spatial patterns, the statistical tests are more definitive and rigorous. Spatial statistics can also be easily calculated using GIS systems and supplement the overlay-based analysis of DRASTIC method.

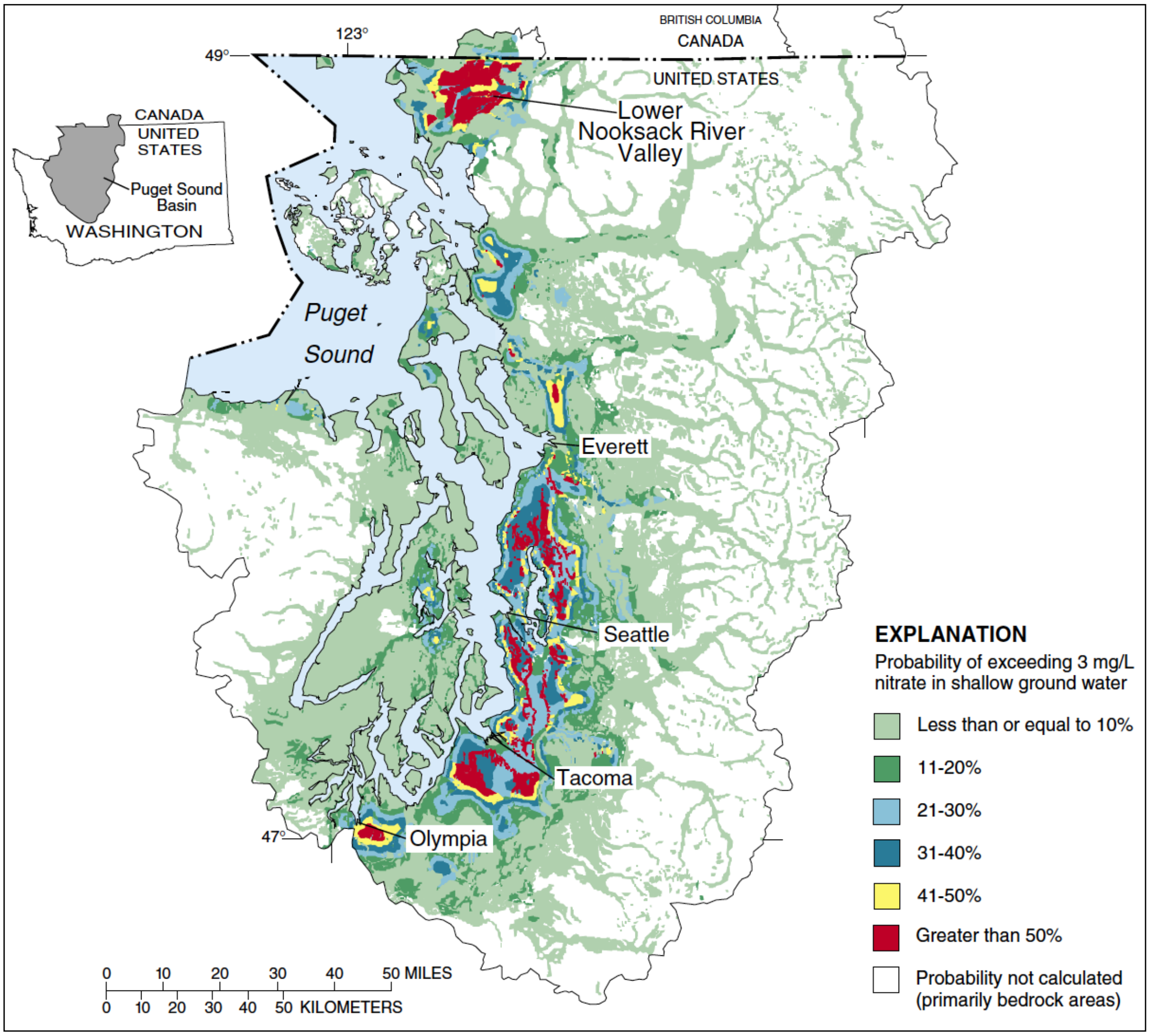


Figure 34. Example of logistic regression statistical assessment of aquifer vulnerability to nitrate contamination from agricultural sources in Puget Sound region of Washington State, USA (from Focazio et al., 2002, Fig 8., originally modified from Erwin & Tesoriero, 1997).

Developing a subsurface vulnerability assessment in the NWT

By using an index such as DRASTIC, the NWT could develop a map of subsurface water vulnerability. A spatial vulnerability index would require:

- The aquifer media and surficial geology
- The permafrost distribution

- The depth to groundwater table
- The recharge rate to aquifer

The surficial geology is the most important data required for regional aquifer vulnerability mapping. Detailed regional mapping of surficial geology is required to initially classify the surficial aquifers by the material type. Material may consist of Quaternary sediments, fractured crystalline rocks, and sedimentary rocks. Mapping of surficial geology in the vicinity of Yellowknife is detailed and readily available.

The permafrost thickness and occurrence determine the extent of the aquiclude it represents. Its properties are known at many locations from drill hole measurements (Taylor *et al.*, 1998; Smith and Burgess, 2002). Satellite-based remote sensing is useful at a regional scale, but must be calibrated to local conditions. For example, some types of vegetation cover are sensitive to permafrost presence and the mapping of changes in vegetation by remote sensing can detect the changes in permafrost conditions in the shallow subsurface (National Research Council, 2014). However, for detailed aquifer characterization, drilling, temperature profiling, and geophysical surveys must be undertaken to characterize the extent of permafrost in three dimensions. Many research data have already been published, especially around Yellowknife. Work at Giant Mine, near Yellowknife, provided much information about the deep permafrost and groundwater, as was discussed in Module 2.

The main purpose of determining the depth to water table in the vulnerability index methods is to qualitatively represent the travel time of potential contaminants from the ground surface to the groundwater table through the unsaturated zone. The depth to water table or the thickness of the unsaturated zone is easily measured at any location using groundwater wells and piezometers, but extrapolating these depths beyond the vicinity of clusters of wells is highly uncertain. It is possible to map the depth to groundwater at a regional scale by interpolating well data, although significant errors can arise (on the order of meters to tens of meters). Alternatively, a statistical approach can be adopted. In this approach, statistical relationships are established between depth to the water table and factors such as topography, aquifer media type, and depth to bedrock.

The recharge rate of aquifers is difficult to measure at any scale. The baseline reports of the Mackenzie Valley, listed in Module 2, give some useful estimates. Stream base flow in monitored catchments also provides an upper limit to the recharge rate in those catchments. Hydrological studies at small and densely instrumented watersheds can be used as examples of aquifer-surface water interactions in the presence of permafrost and to help estimate recharge and discharge rates of groundwater.

The data compilation and acquisition required is usually included in a wider program of knowledge acquisition. For example, the Groundwater Knowledge Acquisition Program is a unique and systematic program of regional hydrogeological mapping implemented in 2008 by the Quebec Ministry of the Environment (Cloutier *et al.*, 2015). It precisely defines the conceptual model of regional groundwater (Figure 35) and includes the analysis of aquifer vulnerability using the DRASTIC index method as one of its output (Figure 36).

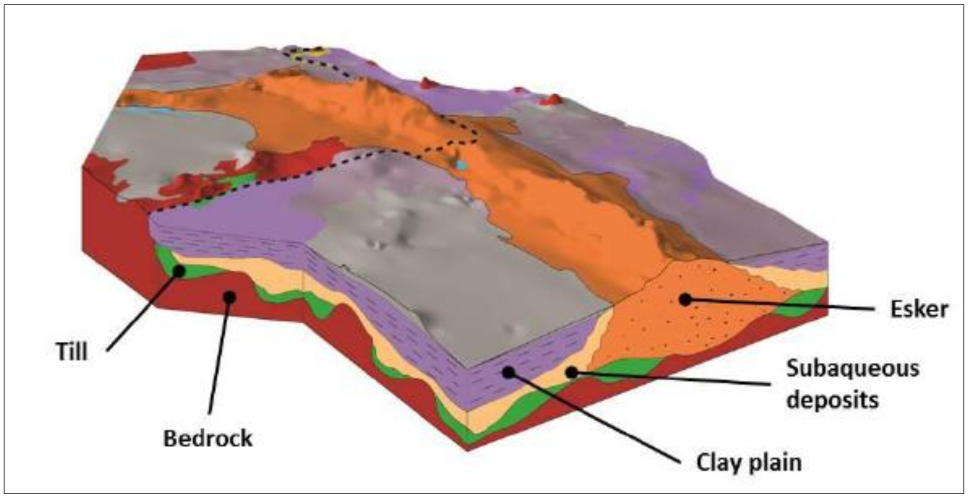


Figure 35. Conceptual diagram illustrating an esker segment and its relation with the fine-grained deposits of the clay plain (regional aquitard) within the hydrogeological framework of the study area (Cloutier et al., 2015).

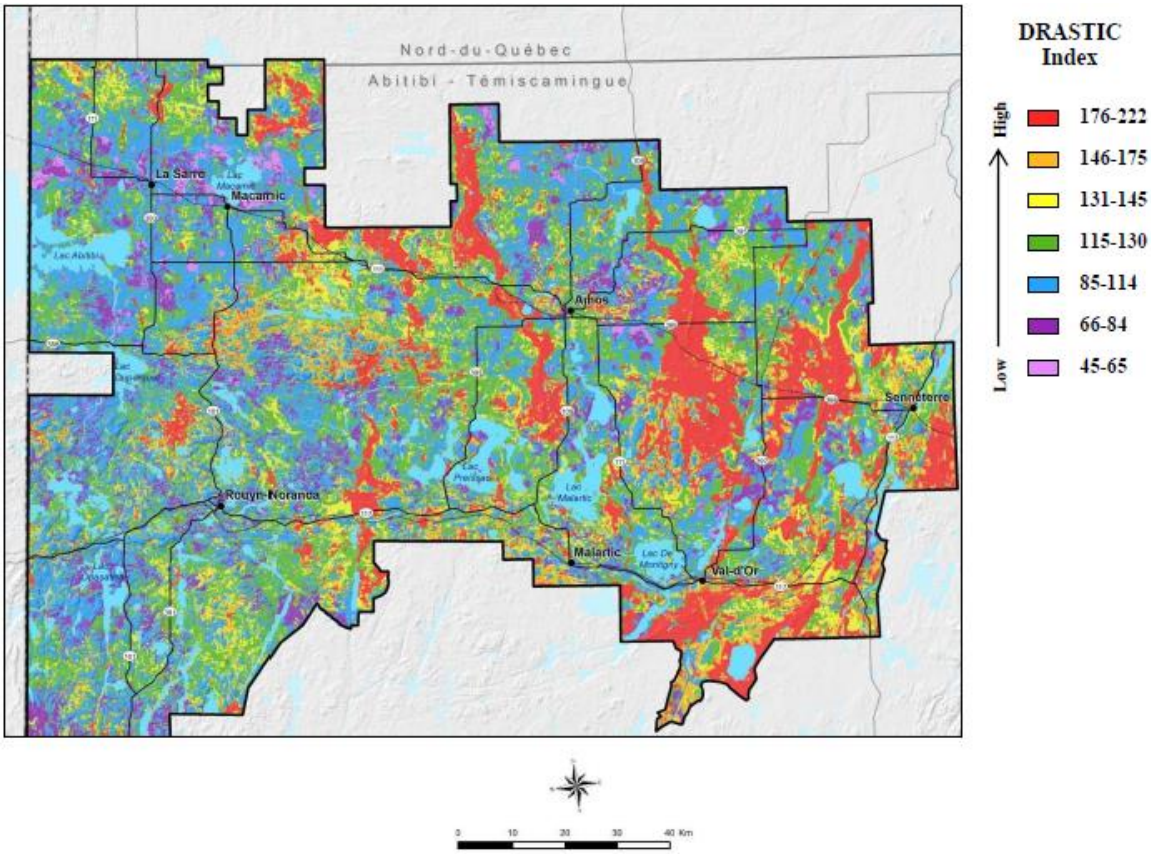


Figure 36. Map of the aquifer vulnerability evaluated using the DRASTIC method (Cloutier et al., 2015).

Along with the contributing factors, the synthesis also provides maps for other themes relevant to groundwater such as the regional potentiometric surface, the spatially distributed recharge, the preferential recharge and discharge zones, and the activities that are potential sources of pollutants. As an example, Cloutier *et al.* (2015) used a three phase approach for the region of Abitibi-Temiscamingue (Figure 37):

1. Exhaustive inventory and compilation of existing data;
2. Complementary field work and laboratory analyses;
3. Data analysis, interpretation, production of thematic maps and research reports, and transfer to regional stakeholders.

Their work led to a comprehensive understanding of the hydrogeology of the study area that is able to support prevention over remediation measures if shared with responsible governments. However, they recognize that the transfer to regional stakeholders and the adequate integration and use of the hydrogeological information in land management strategies remains a major challenge.

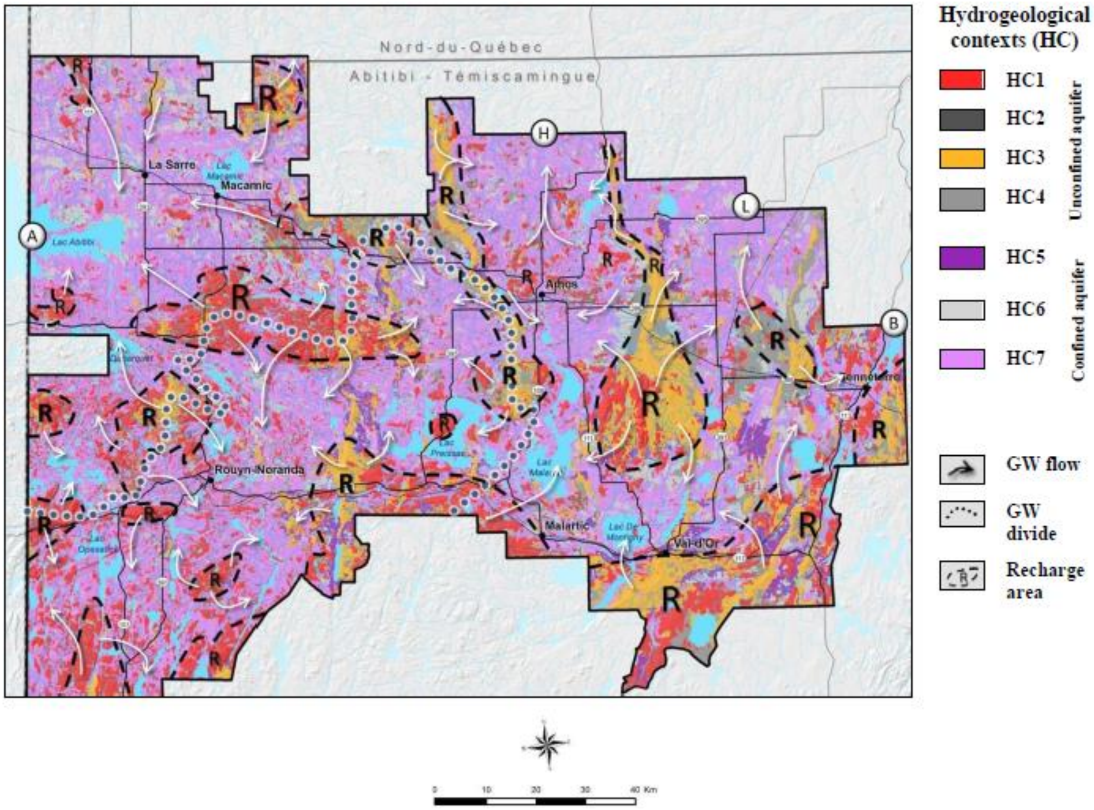


Figure 37. Regional hydrogeological synthesis of the North part of the region. Each HC were defined on the basis of their hydrogeological characteristics, including recharge, vulnerability and water quality (Cloutier et al., 2015).

TECHNIQUES AND TOOLS

This section presents a selection of techniques and tools recommended for hydrogeological surveys.

GENERAL MAPS, MODELS AND PICTURES

The geospatial data collections readily available from public platforms, such as Google Earth and ArcGIS base maps, are of particular interest because they can provide large scale terrain models and land cover interpretation. As a first approximation, the information they provide can be used for delineating watersheds, predicting the direction of runoff, and roughly determining the boundaries of landforms and terrain units presenting a specific surficial or bedrock geology. The data from these types of public web-based platforms are generally acquired by satellite imagery and they are ideally suited for relatively large regions as their interpretation is underlain by a low level of accuracy/precision. Despite these limitations, publicly available imagery can be very valuable.

Aerial photography represents another source of data often available from public collections. Interpretation of these images by stereoscopy can be used in a way similar to the online base maps, but with a higher potential for precision and accuracy.

Another opportunity for finding relevant broad-scale information is the ArcticDEM. It consists of a public-private initiative to automatically produce a high-resolution (2-8 m), high quality, digital surface elevation model of the Arctic using optical stereo imagery, high-performance computing, and open source photogrammetry software.

The Ecological Framework of Canada

The Ecological Framework of Canada is a powerful classification of the landscape in regards to environmental characteristics such as the climate, soil, topography, bedrock geology, landform occurrences, biota, and presence of anthropogenic activities. Each land unit represents an area where the ecological characteristics are relatively homogeneous. The system is hierarchized in four different levels of generalization (ecozones, ecoprovinces, ecoregions and ecodistricts), where the smallest units (ecodistricts) are nested within the larger.

This framework is public, already completed, and available online for free. Along with Google Earth or the ArcticDEM, the information contained in the framework can provide hydrogeologists with a relatively complete overview of the terrain to investigate.

Quantitative data such as annual mean temperature and precipitation are also contained in the Ecological Framework of Canada at the scale of ecozones and ecoregions. For example, data on local precipitation in the framework can be inferred to a locality contained in an ecological unit. For instance, in the NWT, rain and snow are generally low, and their spatial distribution is specific for each ecozone. Table 8 shows the normal maximum annual means of precipitations for all ecozones of the NWT.

Table 8. Normal maximum annual precipitation in the ecozones of NWT. Source: Ecozones.ca

Ecozones	Normal maximum annual precipitation
Boreal Cordillera (limited to the Selwyn Mountains)	700-3000 mm/year
Boreal Plains (limited around Fort Smith)	450 mm/year
Northern Arctic (from Victoria Island to higher latitudes)	200 mm/year
Southern Arctic (limited to the border with Nunavut)	250-500 mm/year
Taiga Cordillera (limited to the Mackenzie Mountains)	250-300 mm/year

Taiga Plains (from around Great Slave Lake to Inuvik)	250-500 mm/year
Taiga Shield (Southeastern NWT)	250-500 mm/year

For comparison, the precipitation southward, for the Mixedwood Plains (near Toronto) and Boreal Shield (between James Bay and Montreal) ecozones, is between 600-1000 mm annually. On an annual timescale, the precipitation of each ecozone of the NWT exceeds evapotranspiration, resulting in an overall positive water budget. Further, some important differences in the timing of precipitation can be observed for each ecoregion within a given ecozone.

The description of the ecozones is at the broad-scale; the ecoregions provide broad information about the environmental setting, while the ecodistricts provide the maximum level of detail and precision. Note that the ecodistrict details are only available in the form of a downloadable data file (i.e., shapefile) for use in a geographic information system (GIS) program, and the descriptive terms are constrained in the attribute table (ArcGIS, 2015). The methodology used to create the ecodistricts map is found within the Ecological Framework of Canada's website (Government of Canada, 2017a).

The data referenced in the Ecological Framework of Canada represent what is actually known, but may lack precision or accuracy for a local site investigation. This tool is especially relevant in the first steps of an investigation (creation of a working hypothesis or conceptual model) in broad scale studies, and favors continuity over exactitude.

Canadian map series

A large selection of base maps and specific maps can be found on the Canadian Government geographical platform, Geogratis. The available cartographic products are generally in 1 : 50 000, 1 : 250 000 or 1 : 1 000 000 scales.

Many products are available, including up to date interpretation of the country's bedrock geology, surficial geology, elevation, topography (e.g., roads, buildings, transmission lines), surface water, land cover classification (e.g., bare ground, type of vegetation, wetland class). Their resolution and accuracy are relatively low to maximize their spatial coverage.

Geogratis is the primary hub for most Canadian governmental geoscientific data. For groundwater in the NWT, Geogratis has the bedrock geology of the Slave Craton and environs (Hoffman, 1993), the hydrogeological regions in the Atlas of Canada (Government of Canada, 2017b), and other water-climate related works (Natural Resources Canada, 2017). This last webpage includes data on potential evapotranspiration, rain, snow, groundwater levels in some boreholes, and more. Most of the data can be downloaded in widely used data formats such as PDF, shapefile, JPEG and/or TIFF to facilitate integration in a GIS project.

Geology and surficial geology information

Geology is the fundamental control on the occurrence, movement and chemistry of groundwater. In the NWT, the Northwest Territories Geological Survey (NTGS) is the primary source of geological information (NTGS, n.d.a). Their maps and shapefiles are generally published on the Canadian Government web platform. The major features of Arctic Canada's tectonic history are found in St-Onge *et al*. (2015).

Surficial geology and Quaternary geomorphology

The Quaternary is the most recent, and the existing, of the three periods of the Cenozoic Era, and spans from 2.58 million years before present. During this period, glacial-interglacial oscillation started to become extensive, leading to major patterns of erosion, transport and deposition of sediments. The result of the last passage of extensive glaciers on North America is still well-preserved in the NWT, despite most of Canada being free of ice sheets for at least 5 000 years. The influence of the last glaciation on Canadian geomorphology is widespread and generally limited to the upper hundred meters.

The erosion, sedimentation, and glaciotectonics related to the Quaternary have a direct influence on groundwater quantity, fluxes and quality through surficial geology. Further, there is strong evidence that large ice sheets can drive deeper groundwater recharge that still exists today (Grasby *et al.*, 2000). As such, the Quaternary history of a region can provide important information about the shallow ground structure and how it controls hydrology. The NTGS has active projects mapping the surficial geology of the NWT (NTGS, n.d.b). The maps and shapefiles from the mapping efforts are generally published on the Canadian Government web platform.

The major features of Arctic Canada's surficial geology are found in the Canadian compilation by the Geological Survey of Canada (Geological Survey of Canada, 2014a). The extent of map tiles of most of the surficial maps, available as of 2012, can be viewed with web applications (Normandeau, 2017, personal communication) and are shown in Figure 38.

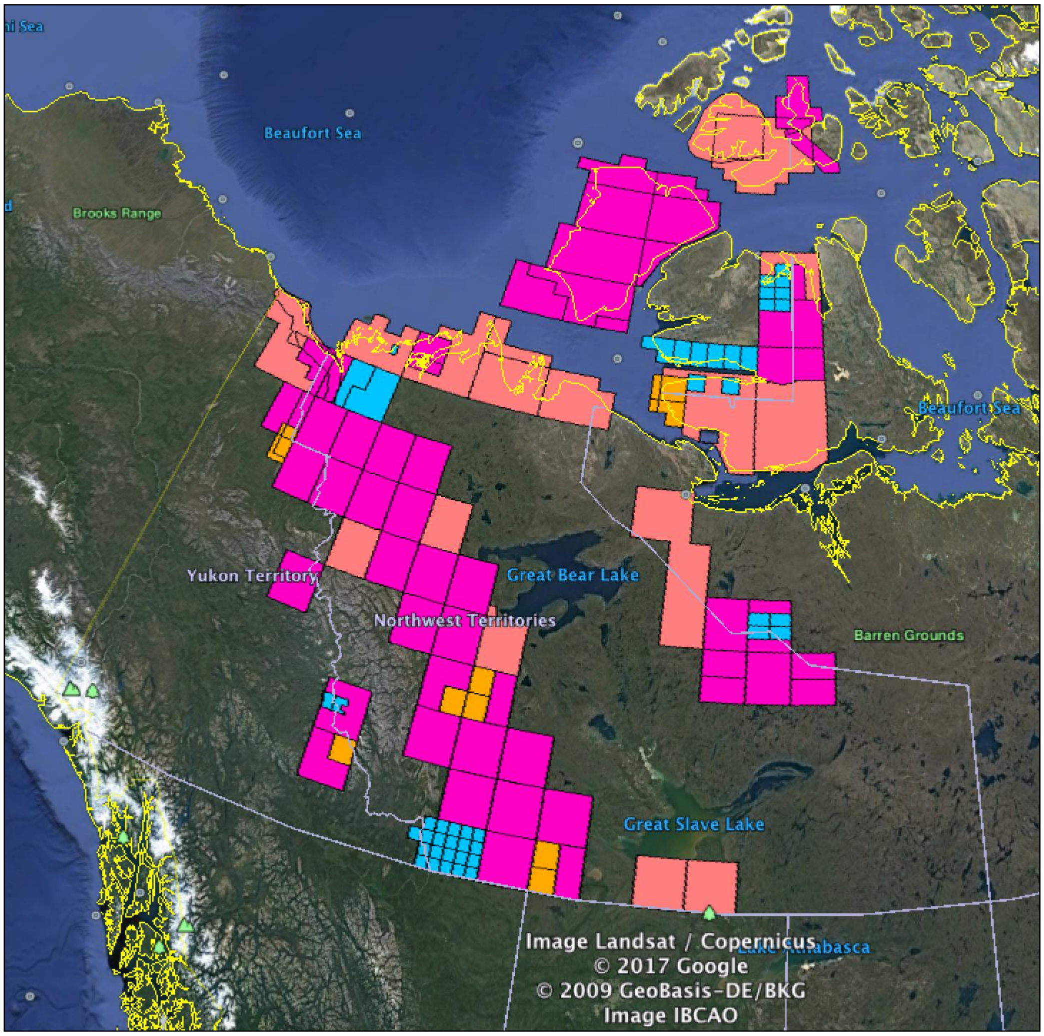


Figure 38. Location of available surficial geology maps for the NWT at scales of 1:250000 (orange), 1:125000 (pink), 1:100000 (yellow), 1:25000 (blue), from Google Earth map provided by NWT Geoscience (http://www.nwtgeoscience.ca/project/summary/surficial-geology). Other areas of the NWT are mapped at scales 1:500000 and 1:1000000.

The mapping of surficial geology from remote observations is in progress (Stevens *et al.*, 2017) using the GSC's "surficial data model" that has more standardized cartographic symbols and map features that are suitable for digital map production and dissemination (Cocking *et al.*, 2016). Some preliminary maps are available after the conversion to the new model (Geological Survey of Canada, 2014b). For example, the Interior Plain has been mapped at various map scales (125:000, 100:000, 25:000). Although many of the map sheets were originally published on paper, many are now scanned as images (e.g., 125:000 scale Map 12-1979 of Root River area (Boydell & Rutter, 1980); 100:000 scale map of Dahaddini River area (Duk-Rodkin, 2009)). The most detailed mapping in the NWT is usually at the 25:000 scale. Only a relatively small portion of the NWT has been mapped at this scale; notably in the south-east corner of the NWT (e.g., Etanda Lakes area – Smith, 2003), part of Mackenzie River delta, and on parts of Victoria Island.

VISUAL CHARACTERIZATION

Much information can be derived from visual observation in the field or visual interpretation of aerial pictures and satellite images. The following features are used to infer or confirm the presence of groundwater:

- Topography: slopes and topographic lows
- Presence of freshwater
- Bedrock outcrops
- Fractures, bedding planes, alteration
- Surficial deposits (and their thickness)
- Wetness index
- Soil types (Soil Classification Working Group, 1998).
- Vegetation types
- Wetland types (Canadian Wetland Classification System (Warner & Rubec, 1997) are used to infer hydraulic properties
- Cryostratigraphy (French & Shur, 2010)

Many physico-chemical properties can be inferred from the identified rocks and sediment by using empirical charts. The alteration level at the periphery of fissures and fractures should also be described.

GIS

Geographical information systems (GIS) consist of a tool designed to store and represent data with their associated spatial location. It is used to store and manage data, draw maps, and produce models. By allowing the combination of multiple factors from various sectors (e.g., social, economic, environmental) it can render a global and integrated view of a system. Two common software for storing geographical information are: ArcGIS, a commercial and powerful software; and QGIS, which may be less powerful than its competitor, but has the advantage of being an open-source application, accessible to a wider range of users. Both can be extended with numerous add-ons to integrate other tools. For example, Arc Hydro Groundwater data model is a GIS-based model that can be used to manage groundwater data, create maps of water levels and water quality, build 2D cross sections and 3D hydrogeologic models, and create workflows with MODFLOW models in ArcGIS. Another example is Groundwater Vistas, a software especially adapted for hydrogeological data, which allows the user to directly input 3D-referenced data with the 3D reference.

WATER LEVEL

The detection of water level or head is necessary to compute the velocity and direction of groundwater. Along with the hydraulic conductivity and aquifer geometry, this is one of the fundamental parameter of groundwater flow modelling (equations are generally based on Darcy's law).

Level measurements can easily be performed directly using an electronic water probe, a pressure sensor or a capacitance string. Both need to be inserted in a water observation well, a stilling well or a piezometer. Observation wells or stilling wells are screened and let water in along their entire length, while piezometers have hermetic walls and are screened just at the elevation where the water needs to be sensed. Measuring water level from wells or piezometers is time-consuming but it is simple, efficient and cheap.

POROSITY AND WATER CONTENT

The water content and saturation level of the vadose zone are necessary information for resolving the water budget and predicting the proportion between surface runoff and groundwater recharge.

The most common techniques used to remotely detect groundwater are gravimetry, thermal anomaly, electromagnetic response (e.g., georadar, electrical resistivity, TDR), acoustic resonance and nuclear sensing (e.g., neutron scattering, Gamma-ray attenuation, and nuclear magnetic resonance). The best results are obtained from a combination of these techniques. For a detailed appreciation of water sensing techniques, see McKim *et al*. (1980), Topp (2003), Annan (2005), Robinson *et al*. (2008), and Bavusi *et al*. (2013).

Lab testing

One of the easiest ways to measure the porosity and water content is by physical and geotechnical testing. Most of these are detailed in Sarsby (2000) and other manuals of geotechnics, hydrogeology, or soil science. The water content can be estimated by measuring the porosity in the laboratory, a value very similar to the sum of the specific yield and retention of a material. The specific yield refers to the mass of water that freely drains from a sample, and the specific retention refers to the mass of water that remains and can be evaporated by heating at 105 °C for a specific time. These mass measurements are easy to perform; only basic materials and skills are required. The best results are obtained on undisturbed samples which are more representative of field conditions.

Empirical relationships

The porosity, specific yield and retention can also be estimated by empirical relationships between a sample's lithology and/or grain-size distribution with previously measured porosity (Module 1). For example, there is a good correlation between the particle size distribution and the porosity of a soil (Nelson, 1994). Variations arise because the porosity is highly sensitive to compaction and consolidation (Nawaz *et al*., 2013).

Well testing

Regarding the porosity, *in-situ* measurements by well testing can measure only an effective value, the mobile water content, for the entire affected environment. For example, the specific yield of an aquifer may be inferred from a pumping test in a well (Ramsahoye & Lang, 1961). The slug test and various versions of pumping test are designed to give many of the hydraulic properties of an aquifer. They will be discussed later in the section on flux measurement because they primarily inform on an aquifer's dynamic properties. The resources needed for a well test are significant and increase with the size of the drill hole. The data is site specific and fully representative of local conditions.

Tensiometry

The tensiometry is the measure of the matric suction potential of a material. Every porous material has a specific water retention curve related to its pore-size distribution (Barbour, 1998). This curve can be exploited to infer the water content from the material's tension (matric suction) measured by a tensiometer. A tensiometer can be installed in the ground, being relevant only in the vadose zone, but the need for complex calibration and the elevated sensitivity makes that other techniques are better for measuring the unsaturated water content for hydrogeologic purpose. This technique is mainly adapted for the need of agronomists.

Gravimetry

The measurement of a micro-change in the local gravitational field can help to interpret a change in the water content of a big aquifer. It has an advantage over well monitoring because measurements are made without the need for invasive and time-consuming operations (drilling and instrumenting). Muskett & Romanovsky (2011) used gravity measurements from the Gravity Recovery and Clime Experiment (a satellite mission) to detect changes in the water content of frozen porous media.

However, the use of gravimetry is limited because it can only estimate changes in regional-scale storage, and cannot provide a finite water level or volume (Pfeffer *et al*., 2011; Koch & Long, 2012). Also, the installation for measuring needs to be permanent to ensure the constancy of the calibration, making it an expansive technique to use.

Thermometry

The water contains specific heat and latent heat. By compiling a heat budget and knowing the heat content change of a sample, the water content can be derived (Robinson *et al*., 2008).

Remotely sensing the thermal behavior of the ground from radiometry in the infrared band appears to be useful especially for mapping purpose. The mapping of emissivity (Luscombe *et al*., 2015) and temperature anomalies have been used to infer the soil moisture content (Matsushima *et al*., 2012).

Zhang and Zhou (2016) reviewed the methods for soil moisture estimation from remotely sensed temperature. They conclude that several limitations exist in the actual methods. Thermal infra-red spectroscopy is limited to the first micrometer of material (Robinson, 2008) and can be useful to inform about surface water-groundwater interaction (e.g., Portnoy *et al*., 1998; Eschbach *et al*., 2017).

Time-domain reflectometry (TDR)

Sensing the relative permittivity (or dielectric constant) of a material can indicate its volumetric water content. The more a soil is permittive to a magnetic field, the more water it contains. As Topp (2003) puts it, the time-domain reflectometers (TDR) operate by launching a fast voltage step-rise along the transmission line (probe) in the soil. The velocity of propagation of the pulse is related to the dielectric permittivity, and thus to the water content.

This technique is very efficient and cheap for *in-situ* sensing of water content in granular material. The measure is very precise and representative of the soil water content between the two electrodes, which have to be inserted with minimal disturbance.

Frequency-domain reflectometry (FDR or capacitance)

The frequency-domain reflectometry can sense the water because of its polar nature; it makes it susceptible to absorb energy when it is submitted to an electromagnetic field by forming a temporary molecule polarization. Hence, the relative permittivity of the soil can be sensed by analyzing the resonance frequency of an electromagnetic wave applied to the ground within a given relatively high frequency (around 10-250 MHz) (Gardner *et al*., 1998). This method is easier to adapt to terrain conditions than TDR but is more sensitive to local calibration (Robinson *et al*., 2008). Measuring with this technique is not commonly used due to the higher success of TDR.

Neutron scattering

The neutron scattering technique uses the emission of high energy neutrons, generally issued from the atomic decay of an americium-beryllium compound (Chanasyk & Naeth, 1996). When these neutrons hit particles of a low atomic mass, their energy is considerably absorbed and they transform in slow neutron. In the ground, only the hydrogen-bond of water can significantly absorb the neutron's energy, hence the measurement of the cloud of slow neutrons reported on the high energy leads one to deduct the amount of water contained in the volume measured, in any state. The radiation emitted and the need to dispose of radioactive elements overwhelmingly limit the use of this technology.

Nuclear magnetic resonance (NMR)

Nuclear magnetic resonance (NMR) involves the disturbance of the normal spin of a nucleus (i.e., a proton or a neutron). The proton contained in free water has a spin characterized by a specific frequency when submitted to a constant magnetic field. When disturbing this magnetic field with a pulsating one of higher energy at the ''water specific'' frequency, the alignment of the water molecules drifts temporarily. After the pulsating disturbance stops, a relaxation time occurs. During this time, the water molecules reemit an amount of energy proportional to their absolute quantity. The energy release measured during the relaxation time is used to infer the total water content in the influence area of the magnetic field. In other words, the resonating magnetic field following the magnetization of a bundle of protons directly gives their count in a given known volume.

This technique is normally used in a laboratory with very small samples, but it has been adapted to measure the depth-dependent mobile groundwater content from the surface by Legchenko *et al*. (2002). The interpretation of the sounding can profile the water content down to 170 m deep. As with many other geophysical methods, NMR is site-dependent but its potential for giving an absolute measurement without the need of a drill hole appears to be promising.

MEASURING THE WATER FLUX

To report flowing water, the time variable must be included. Any temporal change in the water content or level of a system could be interpreted as a gain or loss, related to a flux. Hence, it is useful to record time-series, especially of the water level.

Tracers

Tracers can be used to deduct the velocity and direction of water. These can be chemical, coloring, isotopic or thermal. Important methodological work has already been developed for this technique, which makes it very useful and cheap to use. However, dispersion and diffusion can occur and mislead the interpretation of the results.

Hydraulic conductivity

The hydraulic conductivity is used to compare the ability of different materials and hydrogeological structure to conduct water in similar conditions. Along with the water level and aquifer geometry, this is one of the fundamental parameters of groundwater flow modelling (based on Darcy's law). It can be tested in the laboratory using a permeameter, or derived from well testing (slug test and bail test). Packers can be used to isolate certain portions of the aquifer and direct the observations of hydraulic conductivity at specific depths. Some relationships can be observed between the porosity of materials and their permeability (Ma, 2015).

The slug and bail tests are cheap and easy to conduct, so they are very useful where resources are limited. However, they have a relatively small volume of influence regarding a whole aquifer. Testing of some more dynamic techniques may be advised where the knowledge is critical.

Much information can be retrieved from the wide range of possible pumping tests. An overview has already been given in a preceding section (Well testing).

Infiltration rate

The infiltration rate is important to resolve the water balance equation used to predict the threshold precipitation rate before a runoff event is triggered. The infiltration rate is specific to every ground surface and varies with its density and moisture content.

It can be measured directly using a single ring infiltrometer (Xu *et al.*, 2012), a double ring infiltrometer (ASTM D3385, 2003) or a tension disk infiltrometer (Latorre *et al.*, 2013). The infiltration rate can also be estimated from pedotransfer functions when other soil properties are known (Shoja *et al.*, 2015).

TOMOGRAPHY

Tomography refers to using geophysical methods to create two and three dimensional maps of the structure of the subsurface. These methods, as described below, are critical for developing an understanding of how the geology of a given region may control hydrogeology.

Acoustic and seismic soundings

Profiling the reflection and refraction of mechanical waves may help to characterize groundwater because its presence modifies the ground's capacity to transfer an acoustic or seismic wave. However, the results of seismic soundings remain qualitative and should be limited for supplementing other geophysical and geological techniques (Pride, 2005).

This technique would be useful for example to interpolate the water level between two measurement points (e.g. between two observation wells), where the earth material allows a good interpretation of the signal. A very good understanding of the technique, and the physical geography, is required to have a robust interpretation. The operation of the acoustic and seismic soundings requires expansive instruments, time and a good access to deploy the equipment.

Ground-penetrating radar (GPR)

The ground penetrating radar (GPR) uses the transmission and reflection of high-frequency (1-1 000 MHz) electromagnetic waves into the subsurface with antennas. The right technique to interpret a wave's travel-time or reflected amplitude provides information about the permittivity of subsurface materials that is translated to water content (Huisman *et al*., 2003; Annan, 2005).

GPR is a powerful technique but it remains limited because many assumptions must be made and the radar's signal is influenced by many factors other than the water content. For acoustic soundings, the operation of a GPR requires expansive instruments, time and a good access for dragging the equipment.

Electrical resistivity

The determination of the electrical conductivity (EC) of the ground relates to the presence of groundwater but also to the chemical nature of the solution. Organic molecules do not contribute to EC, while the ionic charge does. The measurement of the ground's electrical conductivity (or resistivity) indicates the presence of connected ion-bearing free groundwater, metallic minerals, and adsorbed groundwater on clay and organic particle.

Measurement of electrical conductivity has become common to assess soil salinity, infer the electrical conductivity of the soil solution for predicting soil nutrient content, or to parameterize models describing solute transport in soil (e.g., conductive tracers) (Robinson *et al*., 2008). It can be performed directly using various electrode arrays or by electromagnetic induction (EMI).

The grounds anisotropy can greatly affect the measured conductivity since a conductive layer can be used by the measurement in one direction but not in the perpendicular direction. Soil temperature is also important to consider; the conductivity may change by c. 2 %/°C and is specific to each groundwater setting. This is the main reason why dielectric sensors (i.e., TDR technique), although more expensive, replaced resistivity to determine point measurements of water content. Electrical resistivity is better used for tomographic analyses (i.e., 2D-3D profiling the contrasted signal). A very good knowledge of the theory behind electricity, the tool used and the physical geography is required to ensure a robust interpretation of a tomography.

Remote-sensing

Most of the sensors used for remote-sensing measure the radiation emitted by the Earth. They are sometimes a function of the surface temperature and emissivity, sometimes the result of reflection of the sun's light, sometimes the return of the antennas' radar signal. This sub-section observes the different means of transportation and their remote-sensors.

To cover larger areas, a wide range of sensors can be hauled at high altitude, over a very large distance, within a regular and systematic flight plan. Satellites, planes, helicopters, drones or balloons are included in the list of vehicles offering good potential for remote sensing. Their price, hauling capacity, ease of use, stability and working altitude, all influence the final products.

Satellite

The use of satellites offers observations with the widest scale. Their spatial and spectral resolution continue to increase, but they remains coarse in comparison with the tools used closer to the surface.

Historically, the primary use of satellites has been to map structural geology or bedrock fractures for groundwater resource evaluation (Waters *et al.*, 1990) More recently, interpretation techniques for satellite observation allow measurement of vegetation characteristics, topography, temperature, soil moisture, and gravity. These are used to gather information about the presence of groundwater (Becker, 2006).

Becker (2006) reviewed a selection of active satellite-based sensors potentially relevant to groundwater investigation (Table 9). The work concludes that:

- Satellite-based remote sensing for ground water is clearly in its infancy. At present, the best that can be achieved with satellite sensors is to determine:
    - spatial distribution of geological features,
    - spatial distribution of groundwater discharge and recharge areas,
    - moisture and storage changes over vast areas, or measurement of surface water heads in large water bodies.
- Surface water level may be measured through orthoimages (e.g., ASTER), radar altimetry (e.g., TOPEX/Poseidon), interferometry (e.g., SRTM), or lidar ranging (e.g., ICESAT). None of these current data sources are ideal for accurately measuring surface water elevations but may be important sources of information where no other water elevations are available.

- Satellite sensors are collecting data at a spatial scale that is 1 or 2 orders of magnitude larger than necessary to resolve important shallow water features.

Since this review has been published, new commercial imaging satellites have emerged on the market, like the Worldview constellation, that offer images with a resolution of 0.4-2 m in the visible light and infrared range. This is close to the resolution potentially supported by air-borne tools. In accordance with their level of technology, their prices are relatively elevated.

Table 9. A select list of active space-based sensors that report data of potential use for investigations of groundwater (Becker, 2006).

Sensor	Launch Year	Ground Resolution (m)	Precipitation	Surface Temperature	Soil Moisture	Water Storage	Snow Water	Land Cover	Topography
AMSR-E	2002	5400–56,000	×	×	×		×		
ASTER	1999	15, 30, 90		×				×	×
AVHRR	1991–2003	1100	×	×	×		×		
GRACE	2002	300,000				×			
ENVISAT-RA2	2002	~1000		×					×
Landsat-7	1999	30, 60		×				×	
MODIS	1999	250, 500, 1000		×				×	
OrbView-2	1997	1100		×				×	
OrbView-3	2003	1, 4		×				×	×
RADARSAT-1	1995	8–100			×				
SRTM	2000	30, 90							×

It is interesting to note that the Canadian Government continuously works to develop its Long-Term Satellite Data Records (LTSDR) acquired from various satellites, in the infrared and visible spectral range, with a resolution of 250-1000 m. The resulting mosaics can be useful to retrieve continuous wide-scale earth-surface physical modelling input parameters such as the Leaf Area Index (LAI), radiation, snow cover, albedo, forest cover, land cover (and change), evapotranspiration, or Net Primary Productivity (NPP). The time series are useful to track the land surface variation in response to climate changes, and are currently used for the development of remote sensing in support of wide scale groundwater studies (Wang *et al.*, 2012).

RADARSAT provides images of single aperture radar of the earth surface with a resolution of 8 x 8 m (RADARSAT-1) or 1 x 3 m (RADARSAT-2 and constellation to come). They can be used in combination with polarimetric interpretation method to interpret snow, ice, soil moisture and surface water. They can also help in geological mapping. The image series can be complemented by similar products from the ENVISAT program of the European Space Agency (ESA).

Land subsidence is sometime related to hydrogeological processes. The Interferometric synthetic aperture radar (InSAR) technique can be used to provide interferometric data to deduct, with a relatively high precision, variation in the elevation of the ground surface. The Shuttle Radar Topography Mission and most remote sensing satellites have gathered such data (see RADARSAT, ALOS PALSAR, TerraSAR-X, COSMO-SkyMed, Sentinel-1A and 1B). Interferometry can also be operated from the ground level.

The LANDSAT program offers multi-spectral images (0.433 – 2.3 μm and 10.3 – 12.5 μm) of the earth with a spatial resolution of between 15 and 60 m. These can help in mapping the hydrologic network and classifying the land surface.

Macro and mesoscopic scales using air-borne instruments

The use of air-borne sensors favors accuracy and precision for catchment-scale investigations. Planes and helicopters, with pilots, have been extensively used for surveying the land, using many sensors relevant to hydrogeology. The potentially contributing technology that can be carried by planes and helicopters include passive and active sensing techniques. The passive techniques are limited to optical sensors (visible light, near infrared, thermal infrared and C-L-band microwaves). Alternatively, active sensing techniques include light detection and ranging (LiDAR), radio detection and ranging (RaDAR), electromagnetic surveying (EM), and electrical resistivity by EM induction.

The use of unmanned aerial vehicles (UAVs, or drones) is becoming more popular as their low price reduces costs. The types of vehicles potentially used include fixed-wing vehicles, multi-rotor vehicles, tethered balloons or kites, and blimps (DeBell *et al.*, 2016). Despite their apparent ease of use the need for licensing remains limiting, especially in inhabited places. Their sensing payload is smaller than planes and helicopters since they have a small hauling capacity. In consequence, generally, only passive sensing can be achieved (some UAV can have LiDAR, which is active sensing).

The potentially contributing technologies that can be carried by drones include:

- Optical sensors, visible light photography
- Light detection and ranging (LiDAR)
- Thermal imaging
- Multi and hyperspectral measurements

The National Air Photo Library can be used to order aerial pictures in Canada. The image scale normally varies between 1:12000 and 1:40000 with very good definition. They are in real color, panchromatic or false color including the near infrared band.

Stereo-pairs of air-borne or satellite photography can be used to directly visualize the topography using a stereoscope. They can also be used to derive a digital elevation model using GPS benchmarks with the structure-from-motion technique (Remondino *et al.*, 2011, Schönberger *et al.*, 2016). This method enabled creation of the ArcticDEM presented in Module 2 and is also promising for smaller surveys.

Combining satellite measurements with physically-based models may be the only practical approach for understanding the role of groundwater in the global water cycle (Becker, 2006).

Web-based data sources mentioned in this section are:

- Worldview constellation: https://www.digitalglobe.com/about/our-constellation
- Long-Term Satellite Data Records: http://www.nrcan.gc.ca/earth-sciences/geomatics/satellite-imagery-air-photos/long-term-satellite-data-records/10935
- RADARSAT geological mapping: http://www.asc-csa.gc.ca/eng/satellites/radarsat2/applications.asp
- LANDSAT: https://landsat.gsfc.nasa.gov/landsat-data-continuity-mission/
- The National Air Photo Library: http://www.nrcan.gc.ca/earth-sciences/geomatics/satellite-imagery-air-photos/9265

ON THE SELECTION OF PREFERRED TOOLS

The set of tools and techniques to include in a given groundwater survey must be selected to optimize their contribution. Kalbus *et al.* (2006) presented an overview of state-of-the-art methods for measuring interactions between groundwater and surface water. Despite being adapted to their specific domain of application, their considerations for choosing appropriate methods are worth a long citation. Figure 39 shows the spatial scales of the techniques discussed in the citation.

> *"The study goal plays a decisive role for the choice of appropriate methods to characterize groundwater – surface water interactions. The objective of the research project defines the required measurement scale which in turn constrains the possible methods. A regional assessment of water resources or the fate and transport of pollutants requires information on a large scale, requiring methods that represent a large sample volume, such as pumping tests or surface water methods. Equally, if the impact of groundwater discharge on surface water quality or vice versa is of concern, measurements on a large scale may be more appropriate. In contrast, investigations of the spatial variation of exchange processes and flow paths between groundwater and surface water require measurements that allow for high spatial resolutions, such as temperature profiles or piezometer methods. If temporal variations or trends are of concern, long-term monitoring of certain parameters may be required. Automated sampling methods and probes coupled with data loggers are most suitable for that purpose. The choice between methods on a similar scale may be more of an operational character, considering factors such as accessibility of the study site, portability of the equipment, and financial and human resources, among others. […] Uncertainties inherent in the different techniques may be taken into account when selecting methods to study groundwater – surface water interactions. Measurements of hydraulic conductivity are generally characterized by high uncertainties, because hydraulic conductivity can vary over several orders of magnitude. Hence, flux estimates based on the Darcy equation are inherently inaccurate, which relates to the majority of methods applied in the aquifer and the transition zone."* (Kalbus *et al.*, 2006, p.882-883)

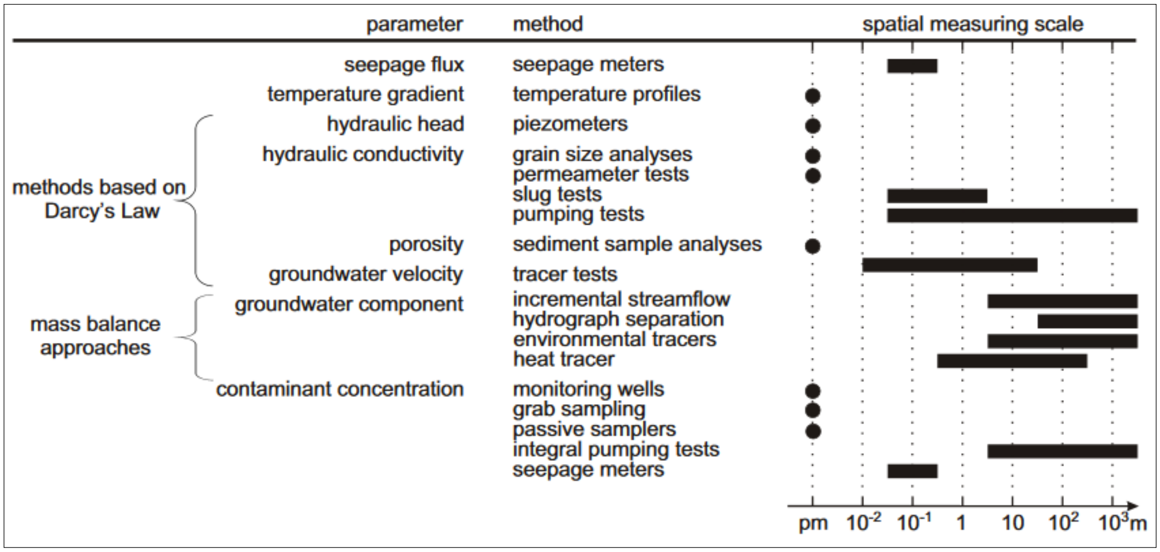


Figure 39. Spatial measuring scales of the different methods to measure interactions between groundwater and surface water. The spatial scale is given as radius or distance of influence. Dots represent point measurements (pm). From Kalbus et al. (2006).

The iterative and integrated approach developed by Golder Associates Ltd. (2010) is also worth a long citation. Its objective was to assess the contamination of a site in the context of fractured bedrock in British Columbia. It states that, although it uses scientific approaches, its objectives differ from a scientific investigation, where the goal may be knowledge for its own sake, because a site assessment needs to test its conceptual models with a view to their consequences (Golder Associates Ltd., 2010).

> *"For fractured bedrock assessment, an iterative and integrative approach is vital. Iterative means creating a conceptual model, testing the model with data, and revising the model as information is gathered. Integrative means using all the geologic, hydrologic, geophysical, and geochemical data to mutually constrain site interpretations. This report divides the site assessment into four stages:*
>
> *1) desk studies,*
>
> *2) the surface-based characterization,*
>
> *3) the single-well characterization and,*
>
> *4) the multi-well characterization.*
>
> *Desk studies identify a range of possible site conditions using published information on regional geology, existing data from nearby sites, and data from analog sites in similar hydrogeologic settings. This stage should produce a preliminary conceptual model of flow. It also should produce*

characterization plans that define a detailed surface characterization program and a general subsurface characterization program.

Surface-based studies should investigate rock exposures for characteristics that influence or indicate groundwater flow such as open fractures, preferred orientations of fractures, water seepage, and weathering along fracture surfaces. Surface-based geophysics does not have the resolution to locate individual flowing fractures, but it may discover thicker features such as faults or fracture zones that concentrate groundwater flow. The most useful methods are electrical including, ground penetrating radar, electrical sounding, and VLF (very low frequency) electromagnetic surveys.

Single-well characterization starts with a subsurface investigation plan. Well drilling should be done iteratively using the information from each hole to plan the location and activities of the next. The most important activity in a well is the identification of conducting fractures, which should be done using a hydraulic method such as flow logging or detailed packer testing. It is not possible to identify conducting features based on geologic or geophysical interpretation alone without some hydraulic confirmation. Fortunately, flow logging has become practical for this purpose. Image logs using optical televiewers provide the geometric and geologic characteristics of the flowing fractures.

Image logs reduce the need for core; however, core complements the image log for direct observations of contaminants and for assessing matrix diffusion by providing rock samples for porosity testing or by direct observations of contaminants in the rock matrix. Flow logs should be run in both ambient (non-pumping) and pumping modes. The ambient flow log gives valuable information on vertical hydraulic gradients. Flow logs with pumping identify the conducting fractures and their depths. The final stage of characterization in a well consists of pumping, packer, or slug tests for hydraulic properties and groundwater sampling of specific conducting features.

A multipoint monitoring system must be installed with separate zones for each significant conducting feature. The multipoint system should eliminate the well as a pathway for contaminant transport. Sampling and hydraulic characterization may be run after the installation of the monitoring systems, if it has the capacity for pumping from its zones.

Multi-well characterization begins with monitoring the responses in the first well to drilling and testing in subsequent wells. These interference data provide valuable information on fracture-network connectivity. Each *new well should be characterized by the approach outlined for single-well characterization. The multi-well data set should be sufficient to define the groundwater flow field, identify the controlling fractures, map the important aspects of the fracture network, and define the spread of contaminated groundwater from the site. This data set supports assessments of future contaminant movement and the design of remediation programs."* (Golder Associates Ltd., 2010, p.ii-iii)

MODULE

5

RECOMMENDATIONS AND RESEARCH PRIORITIES

For the Northwest Territories (NWT), groundwater is a vital resource for communities, industry, and ecosystems. The monitoring, protection, and governance of groundwater in the NWT presents specific challenges. The area of the NWT is very large (1.346 million km^2) with an extremely low population density, and much of the territory is difficult to access. Further compounding the difficulty of monitoring groundwater in the NWT is the presence of permafrost, which acts as a barrier to groundwater flow. To develop a groundwater management plan and detect changes in groundwater resources over time, baseline groundwater data are required. These data allow for the characterization of aquifers, potable/useable groundwater sources, and the delineation of groundwater interactions with surface water and ecosystems.

This report covers four different themes central to the management of groundwater in the NWT. We present a wide range of information on groundwater, from fundamental theory through to legislation related to groundwater, and understanding groundwater vulnerability, with a specific focus on the NWT and permafrost.

Based on our findings and observations, we identified three major outstanding questions related to groundwater that must be resolved in the NWT:

1) The North is experiencing the earth's fastest rates of climate warming, leading to environmental change in the NWT. These changes are leading to a decrease in permafrost distribution and shifts in the hydrologic regimes. How will these changes impact groundwater (e.g., supply, vulnerability, and recharge) in the NWT in the future?
2) Groundwater is an important natural resource for people, industry and the biophysical environment of the NWT. But, it is *vulnerable* to contamination, over-extraction, and climate change. How best should groundwater be managed and protected?
3) The NWT is developing and implementing transboundary agreements with neighboring territories and provinces. These agreements have an obvious and necessary focus on surface water, but also address groundwater. What is the

importance of groundwater in transboundary systems, and how should it be included in implementation of these new agreements?

In this report we present general recommendations to support groundwater governance in the NWT. Morse (2017) made six general observations regarding the management of groundwater in northern environments:

- There is a significant gap between groundwater science and policy.
- There is no conceptual framework for dealing with groundwater in northern environments affected by permafrost.
- The interactions of permafrost and hydrogeology, in the context of a warming climate, are not well understood.
- The adaptation of hydrological models to northern environments must be improved.
- Baseline permafrost and hydrogeology data for modelling and decision making are poorly defined.
- The Canadian community of earth-science practitioners has not yet identified effective instrumentation systems to quantitatively characterize interactions of groundwater with its environment and to quantify the related impacts on ecosystems.

RECOMMENDATIONS TO THE SCIENTIFIC COMMUNITY

THEORETICAL FRAMEWORK

In northern Canada, there is limited technical and scientific experience in dealing with groundwater-permafrost systems and this new field of research does not yet have an integrative theory.

We recommend that a conceptual theoretical framework of multi-scalar permafrost-groundwater relations be developed in collaboration with the scientific community. This framework could assist in developing policy and regulation regarding groundwater in the NWT.

PROCESS-BASED MODELLING

Process-based models provide a theoretical understanding of relevant hydrological processes and provide a framework for incorporating specific system responses to altered or changing environmental conditions. A process-based model for groundwater-permafrost systems will contribute to a better understanding of how external factors (e.g., development, climate change, contamination) will affect groundwater. These models are helpful to evaluate and anticipate groundwater interactions within surface and subsurface environments at specific locations, such as the assessment of point-source contamination. However, they require large amounts of scientific data and they can be adjusted based on data availability (such as large-scale monitoring surveys).

We recommend that research continue to calibrate and refine a process-based groundwater-permafrost model.

CLIMATE CHANGE

Climate change (and related permafrost distribution changes) represents one of the major knowledge gaps in evaluating how the hydrogeology of the NWT will change in the future. There is already extensive evidence of changes in the hydrologic systems of northern Canada as a result of active layer deepening, increases in permafrost temperature, and permafrost thawing. The net result of all of these changes is an increase in the mobility and connectivity of groundwater.

Developing capacity to anticipate and plan for the impacts of climate change requires baseline climate, environmental, and hydrogeological data in addition to a monitoring program to detect changes.

We recommend producing climatic, hydrological-hydrogeological, and permafrost databases for data extracted from the literature (peer-reviewed and government/industry reports) and from public datasets to establish the hydrogeology-related baseline conditions in the NWT. Eventually, modelling of permafrost distribution and change is required to simulate changing hydrogeological conditions and assess groundwater vulnerability.

GENERAL HIGH-LEVEL RECOMMENDATIONS

DEFINE NWT'S VALUES AND SET ACCEPTABLE THRESHOLDS IN GROUNDWATER LEGISLATION

Prior to developing a groundwater management plan, ***we recommend identifying key values related to groundwater in the NWT***. Preservation of the importance of groundwater for traditional activities such as fishing, hunting, gathering, and agriculture is important for sustainability and ensuring impacts from development of groundwater resources is better understood. Therefore, legislation or policy governing groundwater should identify thresholds to preserve groundwater quality and quantity.

ASSESS AND ADJUST REGULATIONS AND GUIDELINES FOR MANAGEMENT

In this report, we provide a high-level overview of the relevant federal, territorial, provincial, and Alaskan guidelines that are currently used to govern groundwater (Module 3). In many cases, these guidelines have limited applicability for the NWT as they do not directly relate to permafrost environments. The guidelines from other jurisdictions are relatively well-developed regarding water in general, but generally overlook the need to protect the groundwater.

We recommend evaluating and adapting guidelines and regulations related to surface and groundwater to reflect the climate and geography of the NWT (i.e., the presence of permafrost).

CONSIDER PERMAFROST AND CLIMATE CHANGE IN LEGISLATION

We recommend that when developing or amending regulations and guidelines in the NWT that the presence, sustainability and vulnerability of permafrost be considered. This would help to ensure that surface-groundwater interactions are minimized. These interactions are very sensitive to climate change and surface disturbance, especially in the discontinuous, isolated, and relict permafrost zones.

CONTINUE GROUNDWATER-RELATED WORK AT A TRANSBOUNDARY LEVEL

The transboundary water agreements offer an opportunity to develop a management and characterization plan based on the hydrological units instead of political frontiers. ***The perpetuity and reinforcement of the cooperation of neighboring jurisdictions that share common hydrological units is recommended.***

DIFFERENTIATE, MAP AND CHARACTERIZE AQUIFERS FOR BASELINE DATA

We recommend producing a preliminary aquifer map for the NWT based on compilation of existing products such as the ArcticDEM, the geologic map, the surficial deposits map, and the map of wetlands presented in Module 2.

DEVELOP A PLAN TO MONITOR GROUNDWATER

There is a clear need to develop a groundwater management plan for the NWT. Such a plan requires monitoring and a preliminary model / coarse aquifer map.

As a first step, **we recommend that groundwater monitoring guidelines be developed.** At a high level, the first step in developing monitoring guidelines is deciding the purpose of monitoring. At a more local/site scales, there is an obvious need for monitoring in terms of environmental impacts. For water supply, there is a need for monitoring to ensure the quality and quantity of water resources. At a larger, territory scale, monitoring is obviously difficult due to access difficulties and the remote nature so focusing on areas of interest or risk is important.

DEVELOP REPRESENTATIVE STUDY SITES FOR FOCUSED INTENSIVE MONITORING

New observation sites are likely required to cover the most important and/or extensive aquifers. ***We recommend having a preliminary model*** (local to regional aquifer system scale) ***available to orient the placement of every new site*** to ensure that measurements are and will remain representative of the cryo-hydrogeological unit that is being observed. In addition to a broad observation network, ***we recommend developing intensive representative study sites***. These sites would have a high density of monitoring equipment and would focus on understanding processes at different types of aquifer systems that occur in the NWT (i.e. at minimum in areas of permafrost in the Interior Planes).

COLLECT PHYSICAL MEASUREMENTS AND DATA WITH REGULAR SAMPLING

A detailed list of all required field observations is impossible to draft in the absence of clear objectives based on guidelines and regulations. However, there is a minimal set of data that should be collected.

We recommend that a clear monitoring plan be developed based on regular sampling intervals (for example, monthly, seasonal and yearly sampling intervals). The observation of each site (permafrost and groundwater) should be made at regular dates (i.e., seasonal transitions, maximum development of active layer at least). The inclusion and collaboration of local communities has been shown to be extremely beneficial in other regions (i.e., a citizen-scientist approach).

SPECIFY CHEMICAL OBSERVATIONS

There are many potential sources of contamination in the NWT, including mining and oil/gas industries and municipal waste disposal. As such, it is important that groundwater quality is monitored in addition to groundwater level.

We recommend that every new drilled well has its water's quality tested. After an initial baseline hydrochemical analysis***, we recommend regular sampling of monitoring wells for water quality*** (e.g., yearly sampling) to monitor the change at a given time. ***We recommend that the inventory of chemicals used by a land-user be considered*** to target specific water analyses.

DEVELOP A GROUNDWATER VULNERABILITY MAP

Requirements for groundwater vulnerability and risk mapping should be introduced and/or expanded in a management plan. The vulnerability of groundwater due to its potential degradation should be included in such a plan.

We recommend developing and compiling a vulnerability criteria index and map, in addition to a risk map, for selected areas. If the method is proved to be an important groundwater management tool it can be replicated for other regions.

SYNTHESIZE GROUNDWATER SCIENCE

The Module 1 review was generalized in order to favor the drafting of a general and holistic theoretical framework. ***We recommend that further groundwater-related scientific reviews are developed in the future*** when more specific details are required to support robust groundwater governance.

REFERENCES

Presented by Modules

CONTEXT AND INTRODUCTION

Côté, F. (2006). Freshwater management in Canada: IV. Groundwater (document PRB 05-54E). Science and Technology Division. Parliamentary information and research service. Canada.17 pp. Retrieved from https://bdp.parl.ca/content/lop/ResearchPublications/prb0554-e.html

Government of the Northwest Territories (2010). Northern Voices, Northern Waters: NWT Water Stewardship Strategy, for guiding long-term stewardship of water resources. May 2010. Retrieved from http://www.enr.gov.nt.ca/sites/default/files/strategies/nwt_water_stewardship_strategy.pdf

Government of the Northwest Territories (2011). NWT Water Stewardship: A plan for action, 2011-2015. Retrieved from http://www.enr.gov.nt.ca/sites/enr/files/reports/nwt_water_strategy_action_plan.pdf

Government of the Northwest Territories (2016). NWT Water Stewardship Strategy, Action Plan 2016-2020. Retrieved from http://www.enr.gov.nt.ca/sites/enr/files/resources/nwt_water_stewardship_strategy_plan_for_action_2016-2020.pdf

Mackenzie River Basin Bilateral Water Management Agreement, Alberta – Northwest Territories (2015a). March 18th, 10 pp. Retrieved from http://www.enr.gov.nt.ca/sites/enr/files/ab-nwt_water_management_agreement_final_signed_2.pdf

Mackenzie River Basin Bilateral Water Management Agreement, British Columbia – Northwest Territories (2015b). October 15th, 12 pp. Retrieved from http://www.enr.gov.nt.ca/sites/enr/files/nwt-bc_transboundary_water_management_agreement_oct_15_2015.pdf

Morse, P. D. (comp.) (2017). *Report on the Permafrost and Hydrogeology Interactions meeting*, 14 November 2016, Yellowknife, NWT; Geological Survey of Canada, Open File 8192,60 p. (also Northwest Territories Geological Survey, NWT Open Report 2017-010). https://doi.org/10.4095/299674

Trainer, M. A., Baveye, P., & Syme, G. (2010). Goals, gaps and governance: The holy grail in preserving Canada's hidden liquid gold. *Journal of Hydrology*, *380*(1): 1-3. https://doi.org/10.1016/j.jhydrol.2009.09.031

MODULE 1

Achtziger-Zupančič, P., Loew, S., & Mariéthoz, G. (2017). A new Global Data Base to Improve Predictions of Permeability Distribution in Crystalline Rocks at Site Scale. *Journal of Geophysical Research: Solid Earth, 122*(5), 3513-3539. https://doi.org/10.1002/2017JB014106

Alley, W. M., Healy, R. W., LaBaugh, J. W., & Reilly, T. E. (2002). Flow and storage in groundwater systems. *Science, 296*, 1985-1990. https://doi.org/10.1126/science.1067123

Andersland, O.B. & Ladanyi, B. (2004). *Frozen ground engineering* (2e edition). American Society of Civil Engineers. Hoboken, New Jersey: John Wiley & Sons.

Azmatch, T. F., Sego, D. C., Arenson, L. U., & Biggar, K. W. (2012a). Using soil freezing characteristic curve to estimate the hydraulic conductivity function of partially frozen soils. *Cold Regions Science and Technology, 83-84*, 103-109. https://doi.org/10.1016/j.coldregions.2012.07.002

Bear, J., Tsang, C-F., & de Marsily, G. (1993). *Flow and contaminant transport in fractured rock*. Cambridge, MA: Academic Press, Inc. 560 pp.

Benedek, K., Bőthi, Z., Mező, G., & Molnár, P. (2009). Compartmented flow at the Bátaapáti site in Hungary. *Hydrogeology Journal, 17*, 1219–1232. https://doi.org/10.1007/s10040-009-0440-4

Bense, V. F., Gleeson, T., Loveless, S. E., Bour, O., & Scibek, J. (2013). Fault zone hydrogeology. *Earth-Science Reviews, 127*, 171-192. https://doi.org/10.1016/j.earscirev.2013.09.008

Bhuwani, P., & Baolin, W. (2010). Freeze-thaw effect on consolidation properties of fine grained soils from the Mackenzie valley, Canada. *GEO2010 conference*, Calgary, AB.

Bonnaventure, P. P., & Lamoureux, S. F. (2013). The active layer: A conceptual review of monitoring, modelling techniques and changes in a warming climate. *Progress in Physical Geography, 37*(3), 352-376. https://doi.org/10.1177/0309133313478314

Bour, O., & Davy, P. (1997). Connectivity of random fault networks following a power law fault length distribution. *Water Resources Research, 33*(7), 1567-1583. https://doi.org/10.1029/96WR00433

Brown, J., Ferrians jr, O. J., Heginbottom, J. A., & Melnikov, E. S. (2001). *Circum-arctic map of permafrost and ice ground conditions*. Boulder, Colorado: National Snow and Ice Data Center.

Cable, W.L., Romanovsky, V.E., & Jorgenson, M.T. (2016). Scaling-up permafrost thermal measurements in western Alaska using an ecotype approach. *The Cryosphere, 10*, 2517-2532. https://doi.org/10.5194/tc-10-2517-2016

Cardenas, M. B., & Jiang, X. W. (2010). Groundwater flow, transport, and residence times through topography-driven basins with exponentially decreasing permeability and porosity. *Water Resources Research, 46*. https://doi.org/10.1029/2010WR009370

Ehlers, J., Gibbard, P. L., & Hughes, P. D. (2011). *Quaternary Glaciations - Extent and Chronology: A Closer Look*. Elsevier B.V. 1126 pp.

Ehrenberg, S. N., & Nadeau, P. H. (2005). Sandstone vs. carbonate petroleum reservoirs: A global perspective on porosity-depth and porosity-permeability relationships. *AAPG Bulletin, 89*(4), 435-445.

England, C. B., & Stephenson, G. R. (1970). Response units for evaluating the hydrologic performance of rangeland watersheds. *Journal of Hydrology, 11*(1), 89-97. https://doi.org/10.1016/0022-1694(70)90118-6

Fleckenstein, J. H., Krause, S., Hannah, D. M., & Boano, F. (2010). Groundwater-surface water interactions: New methods and models to improve understanding of processes and dynamics. *Advances in Water Resources, 33*, 1291-1295. https://doi.org/10.1016/j.advwatres.2010.09.011

Fortier, D., Allard, M., & Shur, Y. (2007). Observation of rapid drainage system development by thermal erosion of ice wedges on Bylot Island, Canadian Arctic Archipelago. *Permafrost and Periglacial Processes, 18*, 229-243. https://doi.org/10.1002/ppp.595

Freeze, R.A., & Cherry, J.A. (1979). *Groundwater*. Englewood Cliffs, NJ: Prentice Hall. 604 pp.

French, H. (2007). *Periglacial environment* (3rd edition). Hoboken, NJ: Wiley. 478 pp.

French, H. M., & Shur, Y. (2010). The principles of cryostratigraphy. *Earth Science Reviews*, *101*(3-4), 190-206. https://doi.org/10.1016/j.earscirev.2010.04.002

Gilbert, G. L., Kanevskiy, M., & Murton, J. B. (2016). Recent Advances (2008–2015) in the Study of Ground Ice and Cryostratigraphy. *Permafrost and Periglacial Processes, 27*(4), 377-389. https://doi.org/10.1002/ppp.1912

Gleeson, T., Befus, K. M., Jasechko, S., Luijendijk, E., & Cardenas, B. (2016). The global volume and distribution of modern groundwater. *Nature Geoscience, 9*, 161-167. https://doi.org/10.1038/ngeo2590

Gleeson, T., Marklund, L., Smith, L., & Manning, A. H. (2011). Classifying the water table at regional to continental scales. *Geophysical Research Letters, 38*. https://doi.org/10.1029/2010GL046427

Gleeson, T., Smith, L., Moosdorf, N., Hartmann, J., Dürr, H. H., Manning, A. H., van Beek, L. P. H., & Jellinek, A. M. (2011). Mapping permeability over the surface of the Earth. *Geophysical Research Letters, 38*. https://doi.org/10.1029/2010GL045565

Golder Associates (2015). *Central Mackenzie surface water and groundwater baseline assessment.* Report 1: technical state of knowledge. Report to the Government of the Northwest Territories. May 21st, 2015.

Guodong, C. (1983). The mechanism of repeated-segregation for the formation of thick-layered ground ice. *Cold Regions Science and Technology, 8*(1), 57-66. https://doi.org/10.1016/0165-232X(83)90017-4

Hantush, M. S. (1964). Drawdown around Wells of variable discharge. *Journal of Geophysical Research, 69*(20), 4221-4235. https://doi.org/10.1029/JZ069i020p04221

Hiscock, K. M., & Bense, V. F. (2014). *Hydrogeology: Principles and Practice* (2nd Edition). Chichester, UK: John Wiley & Sons Ltd. 544 pp.

Kokelj, S. V., & Jorgenson, M. T. (2013). Advances in thermokarst research. *Permafrost and Periglacial Processes, 24*(2), 108-119. https://doi.org/10.1002/ppp.1779

Krauss, T. W. (1995). *The Mackenzie GEWEX study (MAGS): Basic information and critical characteristics of the Mackenzie River Basin and its energy and water fluxes*. University of Saskatchewan.

Lachassagne, P., Wyns, R., & Dewandel, B. (2011). The fracture permeability of Hard Rock Aquifers is due neither to tectonics, nor to unloading, but to weathering processes. *Terra Nova, 23*, 145-161. https://doi.org/10.1111/j.1365-3121.2011.00998.x

Lécuyer, C. (2014). Water: A Molecule Endowed with Extraordinary Physicochemical Properties. In A. Mariotti and J. Pomerol (Eds.), *Water on Earth*. http://dx.doi.org/10.1002/9781118574928

Lide, D. R. (ed.) (2004). *CRC Handbook of Chemistry and Physics*. 84th Edition. Boca Raton, FL: CRC Press. 2475 pp.

Marshak, S. (2013). *Essentials of Geology* (4th Edition). New York, NY: W.W. Norton & Company Inc. 565 pp.

Meinzer, O. E. (1923). *The occurrence of ground water in the United State*s. U.S. Geological Survey Water-Supply Paper 489. Washington, D.C., 321 pp. Retrieved from https://pubs.er.usgs.gov/publication/wsp489

McCauley, C. A., White, D. M., Lilly, M. R., & Nyman, D. M. (2002). A comparison of hydraulic conductivities, permeabilities and infiltration rates in frozen and unfrozen soils. *Cold Region Science and Technology, 34*(2), 117-125. https://doi.org/10.1016/S0165-232X(01)00064-7

Murton, J. B. (2013). Ground ice and cryostratigraphy. In J. F. Schoder (Ed.), Treatise on geomorphology. Vol. 8. *Glacial and periglacial geomorphology*. Academic Press, San Diego, CA. pp. 173–201.

NASA (2017). *Understanding Earth: What's up with precipitation?* Retrieved from https://pmm.nasa.gov/education/articles/understanding-earth-whats-precipitation

Peulvast, J-P., Bétard, F., & Lageat, Y. (2009). Long-term landscape evolution and denudation rates in shield and platform areas: a morphostratigraphic approach. *Géomorphologie, 15*(2), 95-108.

Pradeep Kumar, P. (2014). Cryopeg. In V.P. Singh, P. Singh and U.K. Haritashya (Eds). *Encyclopedia of Snow, Ice and Glaciers*. Dordrecht, Netherlands: Springer. https://link.springer.com/referenceworkentry/10.1007%2F978-90-481-2642-2_90

Qi, J., Vermeer, P. A., & Cheng, G. (2006). A Review of the Influence of Freeze-thaw Cycles on Soil Geotechnical Properties. *Permafrost and Periglacial Processes, 17*, 245-252. https://doi.org/0.1002/ppp.559

Rowland, J. C., Jones, C. E., Altmann, G., Bryan, R., Crosby, B. T., Hinzman, L. D., & Geernaert, G. L. (2010). Arctic Landscapes in Transition: Responses to Thawing Permafrost. *Eos, Transactions American Geophysical Union, 91*(26), 229-230. https://doi.org/10.1029/2010EO260001

Sanchez-Vila, X., Guadagnini, A., & Carrera, J. (2006). Representative hydraulic conductivities in saturated groundwater flow. *Reviews of Geophysics, 44*, RG3002, 1-46. https://doi.org/10.1029/2005RG000169

Scesi, L., & Gattinoni, P. (2007). *Water circulation in rocks*. Dordrecht, Netherland: Springer Science + Business Media B.V. 165 pp.

Schulze-Makuch, D., Carlson, D. A., Cherkauer, D. S., & Malik, P. (1999). Scale dependency of hydraulic conductivity in heterogeneous media. *Groundwater, 37*(6), 904-919. https://doi.org/10.1111/j.1745-6584.1999.tb01190.x

Shur, Y. L., & Jorgenson, M. T. (2007). Patterns of permafrost formation and degradation in relation to climate and ecosystems. *Permafrost and Periglacial Processes, 18*(1), 7-19. https://doi.org/10.1002/ppp.582

Smith, S. L., & Burgess, M. M. (2002). *A digital database of permafrost thickness in Canada*, Open File 4173. Ottawa, ON: Geological Survey of Canada. 38 pp.

Spaans, E. J. A., & Baker, J. M. (1996). The soil freezing characteristic: Its measurement and similarity to the soil moisture characteristic. *Journal of soil science society of America, 60*(1), 13-19. https://doi.org/10.2136/sssaj1996.03615995006000010005x

Stephani, E., Fortier, D., Shur, Y., Fortier, R., & Doré, G. (2014). A geosystems approach to permafrost investigations for engineering applications, an example from a road stabilization experiment, Beaver Creek, Yukon, Canada. *Cold Regions Science and Technology, 100*, 20-35. https://doi.org/10.1016/j.coldregions.2013.12.006

Toth, J. (1963). A theoretical analysis of groundwater flow in small drainage basins. *Journal of Geophysical Research, 68*(16), 4795-4812. https://doi.org/10.1029/JZ069i020p04221

UCAR – University Corporation for Atmospheric Research - Center for Science Education (2011). *The Water Cycle*. Retrieved from https://scied.ucar.edu/longcontent/water-cycle

USGS (2016). *Contaminants Found in Groundwater*. https://water.usgs.gov/edu/groundwater-contaminants.html

USGS (2017). *Summary of the Water Cycle*. https://water.usgs.gov/edu/watercyclesummary.html

Viklander, P. (1998). Permeability and volume changes in till due to cyclic freeze/thaw. *Canadian Geotechnical Journal, 35*(3), 471-477. https://doi.org/10.1139/t98-015

Walker, R. G., & James, N. P. (1992). *Facies Models; Response to Sea Level Change*. St-John, NL: Geological Association of Canada. 409 pp.

Walvoord, M. A., & Kurylyk, B. L. (2016). Hydrologic Impacts of Thawing Permafrost—A Review. *Vadose Zone Journal, 15*(6). https://doi.org/10.2136/vzj2016.01.0010

Watanabe, K., & Mizoguchi, M. (2002). Amount of unfrozen water in frozen porous media saturated with solution. *Cold Regions Science and technology, 34*(2), 103-110. https://doi.org/10.1016/S0165-232X(01)00063-5

Wilkinson, B. H., McElroy, B. J., Kesler, S. E., Peters, S.E., & Rothman, E.D. (2009). Global geologic maps are tectonic speedometers — Rates of rock cycling from area-age frequencies. *GSA Bulletin*, *121*(5/6), 760-79. https://doi.org/10.1130/B26457.1

Williams, P. J. (1964). Unfrozen Water Content Frozen Soil Moisture Suction. *Géotechnique, 14*(3), 231-246. https://doi.org/10.1680/geot.1964.14.3.231

Winter, T. C., Harvey, J. W., Franke, O. L., & Alley, W. M. (1998). *Ground Water and Surface Water; A Single Resource*. U.S. Geological Survey Circular 1139.

Woo, M. K. (Ed.) (2008). *Cold Region Atmospheric and Hydrologic Studies*. The Mackenzie GEWEX Experience: Volume 2, Hydrologic Processes. Springer International Publishing AG.

Woo, M. K. (Ed.) (2012). *Permafrost hydrology*. Berlin, Germany: Springer-Verlag. 563 pp. https://doi.org/10.1007/978-3-642-23462-0

Worthington, S. R. H., Davies, G. J., & Alexander Jr., E. C. (2016). Enhancement of bedrock permeability by weathering. *Earth-Science Reviews, 160*, 188-202. https://doi.org/10.1016/j.earscirev.2016.07.002

Zhang, Y., Chen, W. and Riseborough, D.W. (2006). Temporal and spatial changes of permafrost in Canada since the end of the Little Ice Age. *Journal of Geophysical Research, 111*. https://doi.org/10.1029/2006JD007284

MODULE 2

Alaska Department of Environmental Conservation (2017). *Documents - North Pole Refinery*. Division of Spill Prevention and Response, Juneau, Alaska. Retrieved from http://dec.alaska.gov/spar/csp/sites/north-pole-refinery/documents.htm#GW16

AMAP (2003). *AMAP Assessment 2002: the influence of global change on contaminant pathways to, within, and from the Arctic*. Arctic Monitoring and Assessment Program (AMAP), Oslo, Norway.

AMAP (2010). *Assessment 2007: Oil and Gas Activities in the Arctic - Effects and Potential Effects*, Volume 2. Arctic Monitoring and Assessment Program (AMAP), Oslo, Norway.

AMEC (2005). *Status Report for the Historic Northern Transportation Route*. Submitted to Low-Level Radioactive Waste Management Office, Port Hope, Ontario. AMEC Earth & Environmental, Calgary, Alberta. Retrieved from https://www.andra.fr/dvd_radium/pdfs/Status%20Report%20for%20the%20Historic%20Northern%20Transportation%20Route%20redacted%20colour.pdf

AMEC (2014). *Central Mackenzie Valley subsurface groundwater baseline study*. Report to Government of Northwest Territories. NWT Open File No. 2014-07.

AANDC (2015). *Northern Contaminated Sites Program*. Performance Report 2012-2013. Minister of Aboriginal Affairs and Northern Development. Retrieved from https://www.aadnc-aandc.gc.ca/eng/1100100035316/1100100035317

ARCADIS (2013). *Flint Hills Resources Alaska, LLC Conceptual Site Model*. North Pole Refinery North Pole, Alaska. December 2013. Retrieved from http://dec.alaska.gov/spar/csp/sites/north-pole-refinery/docs/2013OffsiteSCRAppendix%201-Acsm.pdf

AREVA Resources Canada Inc. (2014). *Environmental Impact Statement, Kiggavik Project FEIS*, September 2014. Tier 3 Technical Appendix 5B: Geology and Hydrogeology Baseline. Saskatoon, SK.

ARKTIS Solutions Inc. (2011). *Report on current state of solid waste management and facilities in Nunavut and cost-benefit analysis of selected solid waste management approaches*. GN-CGS PROJECT #2010-27, March 30, 2011. Report to Government of Nunavut.

ARKTIS Solutions Inc. (2016). *Preliminary state of groundwater knowledge in the transboundary region of the Mackenzie River Basin*, Northwest Territories.

Auditor General of Canada (2002). *Report of the Commissioner of the Environment and Sustainable Development to the House of Commons*. Chapter 3, Abandoned Mines in the North. Office of the Auditor General of Canada, Ottawa.

Barnes, D. L. (2014). *Movement of oil and petroleum products in permafrost impacted soils. University of Alaska, Fairbanks.* Oil Spill Conference 2014. Retrieved from http://dec.alaska.gov/spar/ppr/docs/aosts/Barnes_Oil%20Spill%20Conference-2014.pdf

Barr Engineering Company (2012). *Site Characterization Report, through 2011 - FINAL*. Prepared for Flint Hills Resources Alaska, LLC, December 2012, Minneapolis, MN, USA.

Barrie, L. A., Gregor, D. J., Hargrave, B., Lake, R., Muir, D., Shearer, R., Tracey, B., Bidleman, T. F., (1992). Arctic contaminants: sources, occurrence and pathways. *The Science of the Total Environment*, *122*, 1-74. https://doi.org/10.1016/0048-9697(92)90245-N

Bathurst, R. J., Rowe, R. K., Zeeb, B., & Reimer, K. (2006). A geocomposite barrier for hydrocarbon containment in the Arctic. *International Journal of Geoengineering Case Histories*, *1*(1), 18-34.

Batu, V. (1998). *Aquifer Hydraulics: A Comprehensive Guide to Hydrogeologic Data Analysis.* Wiley. 752 pp.

Becklumb, P., Chong, J., & Williams, T. (2015). *Shale Gas in Canada: Environmental Risks and Regulation* (Background Paper). Economics, Resources and International Affairs Division Parliamentary Information and Research Service, Library of Parliament, Ottawa, Canada, 2015, Publication No. 2015-18-E. Retrieved from http://www.lop.parl.gc.ca/content/lop/ResearchPublications/2015-18-e.html

Bedmar, A., Donnellan, A., Mawer, H., Meire, A., & Twomey, R. (2011). *The effect of mining and permafrost thaw on sediments of Lake Skankelenjaure*. Umeå University, Sweden. Retrieved from http://www.umu.se/digitalAssets/86/86705_bedmar-et-al-project-work-arctic-geoecology-2011.pdf

Bense, V. F., & Person M. A. (2008). Transient hydrodynamics within intercratonic sedimentary basins during glacial cycles. *Journal of Geophysical Research, 113*. https://doi.org/10.1029/2007JF000969

Bieber, C., Chorley, D., Zawadzki, W., & Reinson, J. (2006). *Hydrogeologic data collection and development of conceptual models to predict mine inflow quantity and quality at the Diavik diamond mine, NWT*. In Proceedings of 59th Canadian geotechnical conference and 7th joint CGS/IAH-CNC groundwater specialty conference, Vancouver, BC, Canada, M6-B Data Collection II, 1644-1651.

Biggar, K. W. (2004). *Contaminant Behaviour and Impact in Permafrost Soils: A Review of Processes and Potential Impacts*, Environment Canada Report.

Biggar, K. W., Haidar, S., Nahir, M., Jarrett, P. M. (1998). Site Investigations of Fuel Spill Migration into Permafrost. *Journal of Cold Regions Engineering*, *12*(2), 84-104.

Boyle, R. W. (1961). *The geology, geochemistry, and origin of the gold deposits of the Yellowknife District*. Geological Survey of Canada, Department of Mines and Technical Surveys, Memoir 310.

Bright, D. (2015). *Terra Mine Site Reclamation, NWT: The Importance of understanding contaminant mass balance and predicted changes in environmental flux*. HEMMERA, presentation Oct 2015. Retrieved from http://www.esaa.org/wp-content/uploads/2015/10/15-Bright1.pdf

Brown, R. J. E. (1973). *Influence of climatic and terrain factors on ground temperatures at three locations I the permafrost region of Canada.* Permafrost, Second International Conference (13-28 July 1973, Yakutsk, U.S.S.R.), North American contribution, National Academy of Sciences, Washington, D.C., 27-34.

Brown, W. G., Johnston, G. H., & Brown, R. J. E. (1964). Comparison of observed and calculated ground temperatures with permafrost distribution under a northern lake. *Canadian Geotechnical Journal*, *1*(3), 147-154. Canadian Geotechnical Journal, 1964, 1(3): 147-154, https://doi.org/10.1139/t64-009

Bucher, K., & Stober, I. (2010). Fluids in the upper continental crust. *Geofluids*, *10*, 241–253.

Canadian Nuclear Safety Commission (2017). Historic nuclear waste. Retrieved from http://nuclearsafety.gc.ca/eng/waste/historic-nuclear-waste/index.cfm

Carlson, A. E., & Barnes, D. L. (2011). Movement of trichloroethene in a discontinuous permafrost zone. *Journal of Contaminant Hydrology*, *124*(1-4), 1-13. https://doi.org/10.1016/j.jconhyd.2010.11.002

Caron, M-E., Grasby, S. E., & Ryan, M. C. (2008). Spring water trace element geochemistry: A tool for resource assessment and reconnaissance mineral exploration. *Applied Geochemistry, 23*(12), 3561–3578. http://dx.doi.org/10.1016/j.apgeochem.2008.07.020

Cecile, M. P., Goodfellow, W. D., Jones, L. D., Krouse, H. R., & Shakur, M. A. (1984). Origin of radioactive barite sinter, Flybye springs, Northwest Territories, Canada. *Canadian Journal of Earth Sciences*, *21*, 383-395. https://doi.org/10.1139/e84-042

Chouinard, A., Yates, C. N., Balch, G. C., Jørgensen, S. E., Wootton, B. C., & Anderson, B. C. (2014). Management of Tundra Wastewater Treatment Wetlands within a Lagoon/Wetland Hybridized Treatment System Using the SubWet 2.0 Wetland Model. *Water*, *6*, 439-454. https://doi.org/10.3390/w6030439

Clark, I. D., & Raven, K.G. (2004). Sources and circulation of water and arsenic in the Giant Mine, Yellowknife, NWT, Canada. *Isotopes in Environmental and Health Studies, 40*(2), 115–128. http://dx.doi.org/10.1080/10256010410001671014

Collins, C. M., Racine, C. H., & Walsh, M. (1993). *Fate and effects of crude oil spilled on subarctic permafrost terrain in Interior Alaska fifteen years later*. CRREL Report 93-13, U.S. Army Cold Regions Research and Engineering Laboratory. Retrieved from http://www.dtic.mil/dtic/tr/fulltext/u2/a270030.pdf

Connon, R. F., Quinton, W. L., Craig, J. R., & Hayashi, M. (2014). Changing hydrologic connectivity due to permafrost thaw in the lower Liard River Valley, NWT, Canada. *Hydrological Processes, 28*, 4163–4178. http://dx.doi.org/10.1002/hyp.10206

Laurent, C. (2015). *Tracing the origin of mercury contamination in the lakes and fish of the Jean Marie River First Nation lands*. Compendium of Research in the Northwest Territories. Retrieved from http://nwtresearch.com/sites/default/files/compendium_2015_web.pdf

Dawson, R. F., & Morin, K. A. (1996). *Acid mine drainage in permafrost regions: issues, control strategies and research requirements*. Canadian Mine Environment Neutral Drainage Program MEND Report 1.6.1.2. Report prepared for the Department of Indian and Northern Affairs, Ottawa.

de Smecht, L. M., Bérubé, Y., & Laguitton, D. (1975). Control of arsenic level in gold mine waste waters. Arctic Land Use Research Program, Northern Natural Resources and Environment Branch, Dept. of Indian Affairs and Northern Development, Ottawa.

DeBeers Canada Mining Inc. (2002). *Snap Lake Diamond Project*. Baseline hydrogeology report. Retrieved from http://www.reviewboard.ca/upload/project_document/EA1314-02_Snap_Lake_Water_Licence_Amendment_-_Table_of_Contents.pdf

DeBeers Canada Mining Inc. (2010). *Gahcho Kué project environmental impact statement*. Section 11.6 subject of note: permafrost, groundwater and hydrogeology. December 2010.

DeBeers Canada Mining Inc. (2013). *De Beers Snap Lake Mine - ii - November 2013*. Environmental Agreement Annual Report. Nov 2013. Retrieved from http://www.slema.ca/wp-content/uploads/2015/07/2012-Environmental-Agreement-Annual-Report.pdf

Douglas, M., Clark, I. D., Raven, K., & Bottomley, D. (2000). Groundwater mixing dynamics at a Canadian Shield mine. *Journal of Hydrology, 235* (1-2), 88–103. http://dx.doi.org/10.1016/S0022-1694(00)00265-1

Downey, J. S., & Sinton, P. O. (1990). *Geohydrology and ground-water geochemistry at a subarctic landfill, Fairbanks, Alaska*. Water-Resources Investigations Report 90-4022. US Geological Survey.

Dubnie, A. (1972). *Northern mining problems with particular reference to unit operations in permafrost*. Technical Bulletin TB 148, Department of Energy, Mines and Resources Mines Branch, Ottawa.

Dugan, H. A., Gleeson, T., Lamoureux, S. F., & Novakowski, K. (2012). Tracing groundwater discharge in a High Arctic lake using radon-222. *Environmental Earth Sciences, 66*(5), 1385-1392. http://dx.doi.org/10.1007/s12665-011-1348-6

Dyke, L. D. (2001). Contaminant migration through the permafrost active layer, Mackenzie Delta area, Northwest Territories, Canada. *Polar Record*, *37*(202), 215-228.

Eagles, D. (2012). *DEW Line Clean Up (DLCU) Lessons Learned*. DEW Line Clean Up Project. DND, Ottawa, Canada (presentation).

EBA Engineering Consultants Ltd. (2010). *Town of Hay River solid waste management facility operations plan*. Report to Town of Hay River, Y22101145, July 2010, Yellowknife, NWT. Retrieved from http://registry.mvlwb.ca/Documents/MV2009L3-0005/MV2009L3-0005%20-%20Town%20of%20HR%20-%20Landfill%20Operation%20and%20Maintenance%20Plan%20(LOMP)%20-%20Jan05-11.pdf

Elberling, B. (2004). Disposal of mine tailings in continuous permafrost areas: environmental aspects and future control strategies. In *Cryosols Permafrost-Affected Soils*, J. M. Kimble (Ed.), Springer, New York.

Ellis & Associates Inc. (2004). *Drilling waste management recommended best practices*. March 2004**.** DRILLING WASTE in the Mackenzie Delta (Inuvialuit Settlement Region) Region. Edition 1. Environmental Studies Research Funds (ESRF). Retrieved from http://publications.gc.ca/Collection/NE22-4-152-2004E.pdf

Emerson, D., Bessler, J., Podolski, M., & Mahoney, J. (2006). *Hydrogeological characterization of Gahcho Kue Diamond Project*. Sea to Sky Geotechnique 2006. 1723–1728. Retrieved from http://www.mahoneygeochem.com/Portals/0/PDF/06EmeBesPodMah.pdf

Environmental Sciences Group (1993). *The environmental impact of the DEW Line on the Canadian Arctic.* Victoria, BC. North Warning Systems Office, Department of National Defence.

Environmental Sciences Group (1994). *Environmental Study of Abandoned DEW Line Sites: II.* Six Intermediate Sites in the Eastern Arctic, Volume 2. Royal Roads Military College, Victoria, BC.

Environmental Sciences Group (2009). *Site Investigation and Remedial Action Plan for BAR-B, Stokes Point, Ivvavik National Park, Yukon Territory*. Environmental Sciences Group, Royal Military College Kingston, Ontario.

Environmental Sciences Group (2012). *DEW Line Clean Up Project Landfarm*. Summary Report Environmental Sciences Group, Royal Military College Kingston, Ontario. RMC-CCE-ES-12-04. Retrieved from http://www.environmentalsciencesgroup.ca

Espley, G. H. (1969). *Experience with permafrost in gold mining*. In R. J. E. Brown (ed.), Proceedings of the Third Canadian Conference on Permafrost 14 and 15 January 1969. Technical memorandum no. 96, Associate Committee on Geotechnical Research, National Research Council of Canada, 59-64. Retrieved from http://pubs.aina.ucalgary.ca/cpc/CPC3-59.pdf

Everitt, R., Brown, A., Ejeckam, R., Sikorsky, R., & Woodcock, D. (1998). Litho-structural layering within the Archean Lac du Bonnet Batholith, at AECL's Underground Research Laboratory, Southeastern Manitoba. *Journal of Structural Geology, 20*(9/10), 1291-1304. https://doi.org/10.1016/S0191-8141(98)00068-6

Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction (2014). *Environmental Impacts of Shale Gas Extraction in Canada*. Council of Canadian Academies, Ottawa, 44 pp. Retrieved from http://www.scienceadvice.ca/uploads/eng/assessments%20and%20publications%20and%20news%20releases/shale%20gas/shalegas_fullreporten.pdf

Falk, M. R., Miller, M. D., & Kostiuk, S. J. M. (1973). *Biological effects of mining wastes in the Northwest Territories*. Department of the Environment, Fisheries and Marine Service, Fisheries Operations Directorate, Central Region. Technical Report Series No.: CEN/T-73-10.

Flewelling, S. A., Tymchak, M. P., & Warpinski, N. (2013). Hydraulic fracture height limits and fault interactions in tight oil and gas formations. *Geophysical Research Letters, 40*, 3602-3606. http://dx.doi.org/10.1002/grl.50707

Freifeld, B. M., Chan, E., Onstott T. C., Pratt L. M, Johnson, A., Stotler, R., Holden B., Frape, S., Pfiffner, S. M., DiFurio, S., Ruskeeniemi, T., & Neill, I. (2008). *Deployment of a Deep Borehole Observatory at the High Lake Project Site, Nunavut, Canada*. Proceedings of the Ninth International Conference on Permafrost University of Alaska Fairbanks, June 29–July 3, 2008, Volume 1 (Eds. Kane D.L., Hinkel K.M.), Institute of Northern Engineering University of Alaska Fairbanks.

French, H. (1980). Terrain, land use and waste drilling fluid disposal problems, Arctic Canada. *Arctic*, *33*, 794-806.

Gartner Lee Ltd. (2006). *Appendix A: Hydrogeological modelling of the Proposed High Lake Mine*. Prepared for Wolfden Resources.

Gascoyne, M., Davison, C. C., Ross, J. D., & Pearson, R. (1987). Saline groundwaters and brines in plutons in the Canadian Shield. In: *Saline Water and Gases in Crystalline Rocks* (Eds: Fritz, P., Frape S. K.), Geological Association of Canada Special Paper, Ottawa. 53-68.

Gascoyne, M. (2000). *A review of published literature on the effects of permafrost on the hydrogeochemistry of bedrock*. Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Co.), Report R-01-56, Stockholm, Sweden. Retrieved from http://www.skb.se/publication/19100/R-01-56.pdf

Gassiat, C., Gleeson, T., Lefebvre, R., & Mckenzie, J. (2013). Hydraulic fracturing in faulted sedimentary basins: Numerical simulation of potential long term contamination of shallow aquifers. *Water Resources Research, 49*, 8310-8327. https://doi.org/10.1002/2013WR014287

Gerber, R. E., & Howard, K. (2002). Hydrogeology of the Oak Ridges Moraine aquifer system: implications for protection and management from the Duffins Creek watershed. *Canadian Journal of Earth Sciences, 39*, 1333-1348. https://doi.org/10.1139/e02-058

Ghomshei, M. M. (2007). *Geothermal energy from Con Mine for Heating the City of Yellowknife, NWT: A concept study*. Norman B. Keevil Institute of Mining Engineering, Yellowknife, 2007, 18pp. Retrieved from www.enr.gov.nt.ca/sites/enr/files/geothermalstudyfinalreport.pdf

GIN – Groundwater Information Network (2017). *Hydrogeological regions of Canada*. Retrieved from http://gin.gw-info.net/service/api_ngwds:gin2/en/hydroreg/hg.html Gleeson, T., & Novakowski, K. (2009). Identifying watershed-scale barriers to groundwater flow: Lineaments in the Canadian Shield. *GSA Bulletin, 121*(3/4), 333–347.

Golder Associates (2012). *Geotechnical and hydrogeological feasibility report*. Case V-V1 A21 Open pit design Diavik Diamond Mines. Report to Diavik Diamond Mines Inc. October 16, 2012.

Golder Associates (2015a). *Central Mackenzie surface water and groundwater baseline assessment*. Report 1: technical state of knowledge. Report to the Government of the Northwest Territories. May 21, 2015.

Golder Associates (2015b). *Central Mackenzie surface water and groundwater baseline assessment*. Report 2: plain language summary. Report to the Government of the Northwest Territories, May 21 2015.

Golder Associates (2017). *Liard and Petitot River Basins State of Knowledge Report*. British Columbia- Northwest Territories Bilateral Water Management Agreement. March 2017. Report submitted to ENR-GNWT, Yellowknife, NWT.

Government of Canada (2016). *Radionuclides in groundwater: federal contaminated sites advisory bulletin*. Retrieved from https://www.canada.ca/en/environment-climate-change/services/federal-contaminated-sites/advisory-bulletin-radionuclides-groundwater.html

Government of Quebec (2014). *Rapport Synthèse*. Comité de l'évaluation environnementale stratégique sur le gaz de schiste Evaluation environnementale stratégique sur le gaz de schiste. Bibliothèque et Archives nationales du Québec, 2014. Retrieved from http://www.mddelcc.gouv.qc.ca/evaluations/Gaz-de-schiste/rapport-synthese.pdf

Government of the NWT (2012). *Northwest Territories Source Water Assessment and Protection (SWAP) Guidance Document*. Feb 2012. 26 pp. Retrieved from https://www.nwtwaterstewardship.ca/sites/default/files/SWAP_Guidance_web.pdf

Government of NWT (2017a). *Hazardous Materials Spill Database*. Environment Division of ENR. Yellowknife, NWT. Retrieved from https://mvlwb.com/sites/default/files/mvlwb/documents/Spills%20NWT%202016-201709-03-2017.pdf

Government of the NWT (2017b). NWT Drinking Water Information. Arsenic. Retrieved from http://www.nwtdrinkingwater.ca/faqwd/arsenic/

Grant S. A., & Iskandar, I. K. (2000). *Contaminant Hydrology, Cold Regions Modeling*. CRC Press, Boca Raton, Fl. 262 pp.

Grasby, S., & Chen, Z. (2005). Subglacial recharge into the Western Canada Sedimentary Basin—Impact of Pleistocene glaciation on basin hydrodynamics. *Geological Society of America Bulletin, 117*, 500-514. https://doi.org/10.1130/B25571.1

Greene, S., Battye, N., Clark, I., Kotzer, T., & Bottomley, D. (2008). Canadian Shield brine from the Con Mine, Yellowknife, NT, Canada: Noble gas evidence for an evaporated Palaeozoic seawater origin mixed with glacial meltwater and Holocene recharge. *Geochimica Cosmochimica Acta, 72*, 4008-4019. https://doi.org/10.1016/j.gca.2008.05.058

Hamilton, J., & Ford, D. (2002). Karst geomorphology and hydrogeology of the bear rock formation - a remarkable dolostone and gypsum megabreccia in the continuous pemafrost zone of Northwest Territories, Canada. *Carbonates and Evaporites, 17*, 114-115.

Hardy BBT Ltd., & Stanley Associates Engineering Ltd. (1988). *Handling and disposal of waste drilling fluids from on-land sumps in the Northwest Territories and Yukon*. Environmental Studies Research Funds Report No. 093. Ottawa. 58 pp.

Hayes, J. R., & Dunn, J. (2012). *Deep subsurface saline aquifer characterization, Central Mackenzie Valley, Northwest Territories*. NWT Geoscience Office, NWT Open File 2012-07.

Hinzman, L. D., Johnson, R. A., Kane, D. L., Farris, A. M., & Light, G. J. (2000). Measurements and modeling of benzene transport in a discontinuous permafrost region. Chapter 14, 175-237, In: *Contaminant Hydrology: Cold Regions Modeling*, S. A. Grant, I. K. Iskandar (Eds.), Proceedings of a workshop held in Anchorage, Alaska in August 1995. CRC Press LLC.

Hivon, E. G., & Sego, D. C. (1993). Distribution of saline permafrost in the Northwest Territories, Canada. *Canadian Geotechnical Journal*, *30*, 506-514.

INAC (2005). *Discovery Mine, Remediation Project*. Retrieved from http://www.reviewboard.ca/upload/project_document/EA0506-004_Discovery_Mine_Reclamation_Presentation.pdf

INAC (2007). *CAM-F Sarcpa Lake Long-Term Monitoring Plan*. January 23, 2007. Indian and Northern Affairs Canada. 30 pp.

INAC (2008a). *Big Picture 2008. Contaminated Sites in the NWT*. Indian and Northern Affairs Canada. Published by the Minister of Public Works and Government Services Canada.

INAC (2008b). *Abandoned Military Site Remediation Protocol, Volume I – Main Report*. December 2008. Indian and Northern Affairs Canada.

INAC (2010). *Big Picture 2010. Contaminated Sites in the NWT*. Indian and Northern Affairs Canada. Published by the Minister of Public Works and Government Services Canada. QS-Y248-000-EE-A4, Catalogue: R71-69/2010E-PDF. 47 pp. Retrieved from https://www.aadnc-aandc.gc.ca/DAM/DAM-INTER-NWT/STAGING/texte-text/tbp10_1362178908715_eng.pdf

INAC (2017). *Giant Mine Remediation Project*. Retrieved from https://www.aadnc-aandc.gc.ca/eng/1100100027364/1100100027365

Ing, J. (2015). *Occurrence and Origin of Methane in Shallow Groundwater in Alberta, Canada*. MSc thesis, University of Calgary, Alberta.

Iwakun, O., Biggar, K., Van Stempvoort, D., Bickerton, G., & Voralek, J. (2008). Fuel contamination characterization in permafrost fractured bedrock at the Colomac mine site. *Cold Regions Science and Technology*, *53*(1), 56-74. https://doi.org/10.1016/j.coldregions.2007.10.001

Iwakun, O., Biggar, K., & Sego, D. (2010). Estimation of actual LNAPL thickness at a fuelcontaminated Arctic mine site. *Cold Regions Science and Technology*, *60*, 212–220. https://doi.org/10.1016/j.coldregions.2009.10.005

Iwakun, O., Ulrich, A., Biggar, K., & Sego, D. (2012). Groundwater Geochemical Characterization of a Fuel-Contaminated Fractured Bedrock in a Permafrost Environment. *Journal of Environmental Engineering*, *138*(9), 958-971. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000552

Janicki, E. (2001). *A brief history of hydrocarbon exploration in the Northwest Territories*. Northern Geosciences Centre, NWT Geosciences Office.

Johnson, P., & Matz, A. (2011). *Environmental contaminants and climate change: new challenges for Alaska*. Alaska Climate & Human Health - Ecosystem Impacts to Health Inter-agency Work Group May 26, 2011. Retrieved from https://www.fws.gov/alaska/fisheries/contaminants/pdf/climate_change_contam_poster.pdf

Johnson, K., & Wilson, A. (1999). *Sewage treatment systems in communities and camps of the Northwest Territories and Nunavut*. In Proceedings of 1st Cold Regions Specialty Conference of the Canadian Society for Civil Engineering, Edmonton, Alberta, Canada, 2 June 1999.

Johnson, L. A., Sparrow, E. B., Jenkins, T. F., Collins, C. M., Davenport, C. V., & McFadden, T. T. (1980). *The fate and effect of crude oil spilled on subarctic permafrost terrain in interior Alaska*. Alaskan Projects Office, US Army Cold Regions and Engineering Laboratory, Fairbanks, Alaska, EPA-600/3-80-040, March 1980.

Jones, A. T. (2016). *Impacts of Permafrost Melting on Arsenic Mobility in Groundwater in Fairbanks, Alaska*. Carnegie Mellon University Pittsburgh, Pennsylvania. Retrieved from http://www.cmu.edu/cee/adaptation/research/publications/images/Impacts%20of%20Permafrost%20Melting%20on%20Arsenic%20Mobility%20in%20Groundwater%20in%20Fairbanks.pdf

Kadlec, R.H. (2009). Wastewater treatment at the Houghton lake wetland: Hydrology and water quality. *Ecological Engineering, 35*, 1287-1311. https://doi.org/10.1016/j.ecoleng.2008.10.001

Kalinovich, I., Rutter, A., Poland, J.S., Cairns, G., Kerry Rowe, R. (2008). Remediation of PCB contaminated soils in the Canadian Arctic: Excavation and surface PRB technology. *Science of the Total Environment*, *407*, 53-66.

Klaminder, J., Hammarlund, D., Kokfelt, U., Vonk, J. E., & Bigler, C. (2010). Lead contamination of subarctic lakes and its response to reduced atmospheric fallout: Can the recovery process counteracted by the ongoing climate change? *Environmental Science & Technology*, *7*(44), 2335-2340. https://doi.org/10.1021/es903025z

Klassen, R. A., Douma, S. L., Ford, A., Rencz, A., & Grunsky, E. (2009). *Geoscience modelling of relative variation in natural arsenic hazard potential in New Brunswick*. Geological Survey of Canada, Current Research 2009-7, 9 pp. Retrieved from http://publications.gc.ca/collection_2010/nrcan/M44-2009-7-eng.pdf

Kohnert, K., Serafimovich, A., Metzger, S., Hartmann, J., & Sachs, T. (2014). *Regional variability of methane fluxes in the permafrost landscape of the Mackenzie River Delta, Canada derived from airborne measurements*. DUE Permafrost 2014 workshop, 12th of February 2014, Frascati, Italy. Retrieved from http://www.climate-cryosphere.org/media-gallery/1161-2014-02-12-14kkohnert?album_id=51

Kokelj, S. (2014). *Evaluating the environmental impacts of permafrost mega-disturbances along the Dempster Highway, NWT*. Compendium of Research in the Northwest Territories. Retrieved from http://nwtresearch.com/sites/default/files/compendium_2014.pdf

Kokelj, S. V., & GeoNorth Ltd. (2002). *Drilling mud sumps in the mackenzie delta region: construction, abandonment and past performance*. Report for Department of Indian Affairs and Northern Development, NWT. 52 pp. Retrieved from https://www.aadnc-aandc.gc.ca/eng/1100100024132/1100100024182

Kokelj, S. V., Riseborough, D., Coutts, R., & Kanigan, J. C. N. (2010). Permafrost and terrain conditions at northern drilling-mud sumps: Impacts of vegetation and climate change and the management implications. *Cold Regions Science and Technology*, *64*, 46-56.

Kopczynski, S. E., Lawson, D. E., Arcone, S. A., & Snyder, C. F. (2003). Predicting the extent of discontinuous permafrost and affiliated ground water aquifers. In: *Permafrost*, (Eds. Phillips, Springman & Arenson). Swets & Zeitlinger, Lisse, ISBN 90 5809 582 7.

Krauss, T. W. (1995). *The Mackenzie GEWEX study (MAGS): Basic information and critical characteristics of the Mackenzie River Basin and its energy and water fluxes*. University of Saskatchewan.

Kuchling, K., Chorley, D., & Zawadzki, W. (2000). *Hydrogeological modeling of mining operations at the Diavik Diamonds Project.* Diavik Diamond Mines & Golder Associates. In Proceedings of the Sixth International Symposium on Environmental Issues and Waste Management in Energy and Mineral Production, University of Calgary, Calgary AB. Retrieved from http://kuchling.com/wp-content/uploads/2015/04/Hydrogeological-Modeling-at-Diavik-2000.pdf

Kurlyk, B., Hayashi, M., Quinton, W., McKenzie, J. M., & Voss, C. (2016). Document Influence of vertical and lateral heat transfer on permafrost thaw, peatland landscape transition, and groundwater flow, *Water Resources Research*, *52*(2). http://dx.doi.org/10.1002/2015WR018057

Lawson, D. E., Arcone, S. A., Delaney, A. J., Strasser, J. D., Strasser, J. C., Williams, C. R., & Hall, T. J. (1998). *Geological and Geophysical Investigations of the Hydrogeology of Fort Wainwright, Alaska.* Part II: North-Central Cantonment Area. US Army Corps of Engineers, Cold Regions Research & Engineering Laboratory, Alaska. CRREL Report 98-6.

Lee, K. *(chair),* Boufadel, M., Chen, B., Foght, J., Hodson, P., Swanson, S., & Venosa, A. (2015). *Expert Panel Report on the Behaviour and Environmental Impacts of Crude Oil Released into Aqueous Environments.* Royal Society of Canada, Ottawa, ON.

Lefebvre, R., Hockley, D., Smolensky, J., & Gelinas, P. (2001). Multiphase transfer processes in waste rock piles producing acid mine drainage. 1: Conceptual model and system characterization. *Journal of contaminant hydrology*, *52*(1-4), 137-164. http://dx.doi.org/10.1016/S0169-7722(01)00156-5

Lemieux, J.-M., Sudicky, E. A., Peltier, W. R., & Tarasov, L. (2008). Dynamics of groundwater recharge and seepage over the Canadian landscape during the Wisconsinian glaciation. *Journal of Geophysical Research*, *113*.

Liblik, L. K., Moore, T. R., Bubier, J. L., & Robinson, S. D. (1997). Methane emissions from wetlands in the zone of discontinuous permafrost: Fort Simpson, Northwest Territories, Canada. *Global Biogeochemical Cycles*, *11*(4), 485-494. http://dx.doi.org/10.1029/97GB01935

Livingstone, S. (2016). Evaluation of Crude Oil Spills and 70 years of Natural Reclamation along the Historic Canol Oil Pipeline, NWT. ARCADIS. PIPELINES 2016 Conference Kansas City, Missouri July 17-20. ASCE. Retrieved from http://www.esaa.org/wp-content/uploads/2016/10/16-Livingstone.pdf

Macdonald, R. W., Barrie, L. A., Bidleman, T. F., Diamond, M. L., Gregor, D. J., & Semkin, R. G. ... *Yunker, M. B.* (2000). Contaminants in the Canadian Arctic: 5 years of progress in understanding sources, occurrence and pathways. *The Science of the Total Environment, 254*, 93-234. https://doi.org/10.1016/S0048-9697(00)00434-4

Macdonald, R. W., Harner, T., Fyfe, J., Biddleman, T. F., & Stow, J. P. (2005). Recent climate change in the arctic and its impacts on contaminant pathways and interpretation of temporal trend data. *Science of the Total Environment*, *342*(1-3), 5-86. https://doi.org/10.1016/j.scitotenv.2004.12.059

Mackie, D. (2002). *Multi-level data as a key component for a hydrogeological conceptual model of an underground mine.* SRK Consulting (Canada) Inc. Retrieved from http://www.srk.com/files/File/newsletters/groundwater/PDFs/3DMackie.pdf

Mailath, S. B. (2015*). In-situ remediation of hydrocarbon impacted groundwater in permafrost terrain at a remote site in the Northwest Territories*. 2015 RPIC Federal Contaminated Sites Regional Workshop, Assessment and Remediation on Remote or Northern Sites, June 3-4, Edmonton, Alberta.

Martel, E., Turner, E. C., & Fischer, B. J. (editors) (2011). Geology of the central Mackenzie Mountains of the northern Canadian Cordillera, Sekwi Mountain (105P), Mount Eduni

(106A), and northwestern Wrigley Lake (95M) map-areas, Northwest Territories. NWT Special Volume 1, NWT Geoscience Office, 423 pp.

Mathieu, J., Turner, E. C., & Rainbird, R. H. (2013). *Sedimentary architecture of a deeply karsted Precambrian-Cambrian unconformity, Victoria Island, Northwest Territories*. Geological Survey of Canada, Current Research 2013-1, 15 pp.

Mayer, J. M., Allen, D. M., Gibson, H. D., & Mackie, D. C. (2014). Application of statistical approaches to analyze geological, geotechnical and hydrogeological data at a fractured-rock mine site in northern Canada. *Hydrogeology Journal, 22*(7), 1707–1723. http://dx.doi.org/10.1007/s10040-014-1140-2

McCarthy, K., L. Walker, & L. Vigoren, (2004). Subsurface fate of spilled petroleum hydrocarbons in continuous permafrost. *Cold Regions Science and Technology*, *38*(1), 43-54. http://dx.doi.org/10.1021/es0305149

McDonald, D. C. (1953). *Mining at Giant Yellowknife*. The Canadian Mining and Metallurgical, Annual General Meeting, Edmonton, AB, April 1953, Transactions Volume LVI. 199-209.

Mcguigan, C. F., Hamula, C. L. A., Huang, S., Gabos, S., & Le, X. C. (2010). A review on arsenic concentrations in Canadian drinking water. *Environmental Reviews*, *18*, 291-307. https://doi.org/10.1139/A10-012

McKenzie, J., & Voss, C. (2013). Permafrost thaw in a nested groundwater-flow system. *Hydrogeology Journal, 21*(1), 299-316. https://doi.org/10.1007/s10040-012-0942-3

Mercer, A. (2015). Compendium of Research in the Northwest Territories 2014. Aurora Research Institute. Fort Smith, NWT. 150 pp. Retrieved from http://nwtresearch.com/sites/default/files/compendium_2014.pdf

Mercer, A., Allooloo, S., & Dutton, J. (2014). Compendium of Research in the Northwest Territories 2013. Aurora Research Institute. Fort Smith, NWT. 145 pp. Retrieved from https://nwtresearch.com/sites/default/files/compendium_2013_final.pdf

Michel, J., Gareis, J., Benson, K., Owen, C., & Hille, E. (2015). Compendium of Research in the Northwest Territories 2015. Aurora Research Institute. Fort Smith, NWT. 150 pp. Retrieved from http://nwtresearch.com/sites/default/files/compendium_2015_web.pdf

Minsley, B. J., Abraham, J. D., Smith, B. D., Cannia, J. C., Voss, C. I., Jorgenson, T., Walvoord, M. A., Wylie, B. K., Anderson, L., Ball, L. B., Deszcz-Pan, M., Wellman, T. P., & Ager, T. A. (2012). Airborne electromagnetic imaging of discontinuous permafrost. *Geophysical Research Letters*, *39* (2). https://doi.org/10.1029/2011GL050079

Morin, K. (2003). Problems with acid rock drainage predictions at the Ekati Diamond Mine, Northwest Territories, Canada. Proceedings of 6th ICARD Conference, Cairns, Queensland, Australia, July 12-18 2003, 663-669. Retrieved from http://www.mdag.com/MDAG%20Paper%20Database/M0062%20-%20Morin%202003%20-%20Ekati%20Paper.pdf

Morse, P. D. (2017). *Report on the Permafrost and Hydrogeology Interactions meeting*, 14 November 2016, Yellowknife, Northwest Territories. Geological Survey of Canada Open File 8192, Northwest Territories Geological Survey Nwt Open Report 2017-010.

Muir, A. K. (1951). *Underground Storage of Dry Arsenic Tri-oxide*. Feb 24, 1951 letter to GEB Sinclair, Dept. of Resources and Development, Ottawa. Giant Yellowknife Gold Mines Ltd., Yellowknife, NWT. 4 pp. Obtained from document titled: Giant Mine Environmental Assessment, Information Request Response. May 31 and June 17, 2011.

NCP (2003). *Sources, Occurrence, Trends and Pathways in the Physical Environment*. Northern Contaminants Program, Canadian Arctic Contaminants Assessment Report II. Bidleman T., Macdonald R., Stow J. (Eds.), INAC, Ottawa. Minister of Public Works and Government Services Canada.

NCP (2012). *Mercury in Canada's North*. Canadian arctic contaminants assessment report iii. Chételat, J. & Braune, B. (Eds.), Northern Contaminants Program. Aboriginal Affairs and Northern Development Canada, Ottawa ON.

NCP (2013). Cana*dian Arctic Contaminants Assessment Report on Persistent Organic Pollutants – 2013*. Muir, D., Kurt-Karakus, P., Stow, J. (Eds). Northern Contaminants Program, Aboriginal Affairs and Northern Development Canada, Ottawa ON. Retrieved from http://pubs.aina.ucalgary.ca/ncp/79027.pdf

Neuner, M., Smith, L., Blowes, D. W., Sego, D. C., Smith, L. D. J., Fretz, N., & Gupton, M. (2013). The Diavik Waste Rock Project: Water flow through mine waste rock in a permafrost terrain. *Applied Geochemistry*, *36*, 222–233.

Nixon, J. F. (1998). Recent applications of geothermal analysis in northern engineering. Proceedings of 7th International Conference on Permafrost, Yellowknife, Canada. *Collection Nordicana*, *55*. 833-846.

Nova Scotia Independent Panel on Hydraulic Fracturing (2014). Report of the Nova Scotia Independent Panel on Hydraulic Fracturing. Report submitted to: The Province of Nova Scotia Department of Energy. Cape Breton University, Sydney, Nova Scotia. Retrieved from https://energy.novascotia.ca/sites/default/files/Report%20of%20the%20Nova%20Scotia%20Independent%20Panel%20on%20Hydraulic%20Fracturing.pdf

OxyTek (2013). Final Remediation Pre-Treatment Assessment, James Creek Maintenance Camp, Highway No.8, NWT. Report to Dept. of Transportation, Government of NWT. March 28, 2013. Retrieved from http://registry.mvlwb.ca/Documents/G13H004/G13H004%20-%20Assessment%20Report%20-%20Jul%201013.pdf

Palmer, M. J., Galloway, J. M., Jamieson, H. E., Patterson, R. T., Falck, H., & Kokelj, S. V. (2015). The concentration of arsenic in lake waters of the Yellowknife area; Northwest Territories Geological Survey, NWT Open File 2015-06. 25 p. Retrieved from http://www.nwtgeoscience.ca/sites/ntgs/files/nwt_open_file_2015-06.pdf

Peapples, P., Astley, B., Lawson, D., Delaney, A., Arcone, S., Bigl, S., Staples, A., Wilkinson, J., Epps, S., Snyder, C., & Sauceda, J. (2000). *Bedrock and structure characterization: Birch Hill Tank Farm and Truck Fill Stand, Fort Wainwright, Alaska*. CRREL Contract Report. Hanover NH: US Army Cold Regions Research and Engineering Laboratory.

Pham, N., Amos, R., Blowes, D., Smith, L., & Sego, D. (2015). *The Diavik waste rock project: Heat transfer in a large scale waste rock pile constructed in a permafrost region*. 10th International Conference on Acid Rock Drainage & IMWA Annual Conference 2015. Retrieved from https://www.imwa.info/docs/imwa_2015/IMWA2015_Pham_147.pdf

Pierce, K. L., & Falck, H. (2015). *Delineation of watersheds in the Mackenzie Mountains*. Northwest Territories Geological Survey, NWT Open Report 2015-007.

Piteau Engineering Ltd. (1989). G*roundwater resources protection from drilling waste, Northwest Territories and Yukon.* Northern Affairs Program (Canada), Canada. Department of Indian Affairs and Northern Development. Ottawa: Supply and Services Canada, 1989.

Poland, J.S., Mitchell, S., Rutter, A. (2001). Remediation of former military bases in the Canadian Arctic. *Cold Regions Science and Technology, 32*, 93-105. https://doi.org/10.1016/S0165-232X(00)00022-7

POSIVA. (2003). *Baseline conditions at Olkiluoto*. POSIVA report 2003-02, Finland: POSIVA OY

Queen's University (n.d.) Environmental Projects. Analytical Services Unit. Retrieved from http://www.queensu.ca/asu/arctic-projects

Rescan (2014). *Back River Project: Cumulative Permafrost Baseline Data Report* (2007 to May 2014). Prepared for Sabina Gold & Silver Corp. by Rescan Environmental Services Ltd., an ERM company.

ReSDA (2016). *ReSDA Atlas: Summary of Northwest Territories Mines*. Compilation of summary information of mines past and present for the Northwest Territories. Retrieved from http://yukonresearch.yukoncollege.yk.ca/resda/wp-content/uploads/sites/2/2013/12/NWT-Mine-Summaries-for-web.pdf

Rhen, I., Follin, S., & Hermanson, J. (2003). *Hydrogeological Site Descriptive Model—A strategy for its development during site Investigation*s. SKB Report R-03-08.

Roy, J. W., & Bickerton, G. (2011). Comment on "Estimation of actual LNAPL thickness at a fuel-contaminated Arctic mine site" by Olumide Iwakun, Kevin Biggar and David Sego. *Cold Regions Science and Technology*, *65*, 269-270. https://doi.org/10.1016/j.coldregions.2010.09.007

Royle, M. (2007). Giant Mine: Identification of Inflow Water Types and Preliminary Geochemical Monitoring during Reflooding. *Mine Water and the Environment*, *26*(2), 102-109. https://doi.org/10.1007/s10230-007-0156-4

Rudolph, D. L., Lotimer, A. R., & Barker, J. F. (2016). *Baseline hydrogeological evaluation of Central Mackenzie Valley, oil and gas exploration areas, Sahtu Region, Northwest Territories*. Final report to the Government of the Northwest Territories. 35 pp.

Ruskeeniemi, T., Ahonen, L., Paananen, M., Frape, S., Stotler, R., Hobbs, M., Kaija, J., Degnan, P., Blomqvist, R., Jensen, M., Lehto, K., Moren, L., Puigdomenech, I., & Snellman, M. (2004). *Permafrost at Lupin: Report of Phase II.* Geological Survey of Finland, Nuclear Waste Disposal Research. Report YST-119, 89.

Rydberg, J., Klaminder, J., Rosén, P., & Bindler, R. (2010). Climate driven release of carbon and mercury from permafrost mires increases mercury loading to sub-arctic lakes. *Science of the Total Environment, 20*(408), 4778-4783. https://doi.org/10.1016/j.scitotenv.2010.06.056

Samuelson, G. M. (1998). Water and waste management issues in the Canadian arctic: Iqaluit, Baffin Island. *Canadian Water Resources Journal*, *23*(4), 327-338. https://doi.org/10.4296/cwrj2304327

Sandlos, J., & Keeling, A. (2012*). Giant Mine: Historical Summary.* Memorial University. Retrieved from http://reviewboard.ca/upload/project_document/EA0809-001_Giant_Mine__History_Summary.PDF

Seburn, D. C., & Kershaw, P. (1997). Changes in the active layer of subarctic right-of-way as a result of a crude-oil spill. *Canadian Journal of Earth Sciences*, *34*, 1539-1544. https://doi.org/10.1139/e17-125

Shaikh, A. (2015). In-situ remediation of hydrocarbon impacted groundwater in permafrost terrain at a remote site. Tibbitt to Contwoyto winter road, Northwest Territories. Presentation, Tetra Tech EBA Inc.

Sharpe, D. R., Russell, H. A. J., Grasby, S. E., & Wozniak, P. R. J. (2008). *Hydrogeological regions of Canada: Data release*. Geological Survey of Canada, Open File 5893. 20 pages, 1 CD-ROM.

Silke, R. (2009). The operational history of mines in the Northwest Territories, Canada. NWT Geoscience Office. Retrieved from http://www.miningnorth.com/_rsc/site-content/library/NWT_Mines_History_RSilke2009.pdf

Singhal, B. B. S., & Gupta, R. P. (1999). *Applied hydrogeology of fractured rocks*. Dordrecht, Netherland, Springer Science + Business Media. https://doi.org/10.1007/978-94-015-9208-6

Smith, S. L., Romanovsky, V. E., Lewkowicz, A. G., Burn, C. R., Allard, M., Clow, G. D., Yoshikawa, K., & Throop, J. (2010). Thermal state of permafrost in North America - A contribution to the International Polar Year. *Permafrost and Periglacial Processes*, *21*, 117-135. https://doi.org/10.1002/ppp.690

Smith, S. L., Riseborough, D. W., Ednie, M., & Chartrand, J. (2013). *A map and summary database of permafrost temperatures in Nunavut, Canada*. Geological Survey of Canada, Open File 7393. https://doi.org/10.4095/292615

St-Onge, D.A. (2012). Late Wisconsinan Morphosedimentary Sequences of the Lower Coppermine River Valley, Nunavut and Northwest Territories. *Journal of the Geological Association of Canada, 39*(3). https://journals.lib.unb.ca/index.php/GC/article/view/18973/23197

SRK Consulting (2002a). *Giant Mine Hydrogeology*. Report Prepared for DIAN Dept., NWT, Canada. Government of Canada.

SRK Consulting (2002b). *Giant Mine Hydrogeology*. Supporting Document C1. Supporting Document 2 to SRK 2002**.** Report Prepared for DIAND, NWT, Canada. Government of Canada. Retrieved from http://registry.mvlwb.ca/Documents/MV2007L8-0031/SD%20C1Giant%20Mine%20Hydrogeology2002.pdf

SRK Consulting (2002c). *Supporting Document 9. Giant Mine Ground Freezing*. Report Prepared for DIAND, NWT, Canada. Government of Canada. Dec 2002. Retrieved from http://registry.mvlwb.ca/Documents/MV2007L8-0031/SD_9.pdf

SRK Consulting (2004). *Groundwater Monitoring System: November 2004 Monitoring Update*. Supporting Document C4. Giant Mine Arsenic Trioxide Management Project. Prepared for:

Giant Mine Project Team Department of Indian Affairs and Northern Development. Retrieved from http://registry.mvlwb.ca/Documents/MV2007L8-0031/SD%20C4Groundwater%20Monitoring20070917.pdf

SRK Consulting (2005). *Preliminary surface infrastructure design, Doris North Project, Hope Bay Nunavut Canada.* Prepared for Miramar Hope Bay Ltd. Submitted to Nunavut Impact Review Board 2005.

SRK Consulting (2007a). *Structural Geology. Supporting Document 1.* Giant Mine Arsenic Trioxide Project. Retrieved from http://registry.mvlwb.ca/Documents/MV2007L8-0031/SD_1.pdf

SRK Consulting (2007b). *Water Quality Model, Doris North Project, Hope Bay, Nunavut, Canada*. Prepared for Miramar Hope Bay Ltd. March 2007.

SRK Consulting (2010). *Cold Regions Cover Research - Phase 2*. MEND Report 1.61.5b. Prepared for Indian and Northern Affairs Canada and Mine Environment Neutral Drainage (MEND). November 2010. Retrieved from http://mend-nedem.org/wp-content/uploads/2013/01/1.61.5b.pdf

SRK Consulting (2011). *Groundwater Inflows and Inflow Water Quality Used for the Revised Doris North Project Amendment Package No. 3 to Water License No. 2AM-DOH0713 - AMENDED*. Memo, Nov 4, 2011 to Patterson B, Hope Bay Mining Ltd. Retrieved from ftp://ftp.nwb-oen.ca/registry/2%20MINING%20MILLING/2A/2AM%20-%20Mining/2AM-DOH1323%20TMAC/1%20APPLICATION/2011%20Amendment%20PC%20(withdrawn)/120104%202AM-DOH0713%20Amendment%20J%20Appendix%209-IMLE.pdf

SRK Consulting (2012). *Back River 2012 Geotechnical and Hydrogeological drilling program factual data report*. Report Prepared for Sabina Gold & Silver Corporation. Nov 2012. Retrieved from http://backriverproject.com/wp-content/themes/gold/assets/pdfs/English%20Posters/BackRiver_FactualData_Report_2CS031.002_BG_RG_20121109_FNL.pdf

SRK Consulting (2013). *Giant Mine Remediation Project–Arsenic Trioxide Management*. Pan–Territorial Permafrost Workshop – November 5-7, 2013.

SRK Consulting (2016). *Hydrogeological Characterization and Modeling of the Proposed Boston, Madrid South and Madrid North Mines, Hope Bay Project, Nunavut*. Prepared for TMAC Resources Inc. Project No: 1CT022.004, December 2016. Retrieved from http://www.nwb-oen.ca/public/registry/2%20MINING%20MILLING/2A/2AM%20-%20Mining/2AM-HOP----%20TMAC/1%20APPLICATION/161228%202AM-HOP----%20Phase%202%20DEIS%20For%20NIRB-IAAE/Vol%203%20Appendices/161228%202AM-HOP----%2012MN001%20V3%204B%20Groundwater%20Report%20Part%201-IAAE.pdf

SRK Consulting & SENES Consultants (2007). *Giant Mine Remediation Plan*. Giant Mine Remediation Project Team Department of Indian Affairs and Northern Development. *Prepared for:* Indian and Northern Affairs Canada Giant Mine Remediation Project. July 2007. SRK Project Number 1CI001.013. Retrieved from http://reviewboard.ca/upload/projectdocument/EA0809-001GiantMineRemediationPlan1328900464.pdf

Stantec (2016). *State of Aquatic Knowledge for the Hay River Basin*. Prepared for: Government of the Northwest Territories Department of Environment & Natural Resources, Yellowknife, NWT. March 32, 3026.

Stevenson, D. R., Brown, A., Davison, C. C., Gascoyne, M., McGregor, R. G., Ophori, D. U., Scheier, N. W., Stanchell, F., Thorne, G. A., & Tomsons, D. K. (1996). *A revised conceptual hydrogeologic model of a crystalline rock environment, Whiteshell Research Area, SE Manitoba, Canada*. Atomic Energy of Canada report AECL-11331, COG-95-271.

Stotler, R. L., Frape, S. K., Ruskeeniemi, T., Ahonen, L., Onstott, T. C., & Hobbs, M. Y. (2009). Hydrogeochemistry of groundwaters in and below the base of thick permafrost at Lupin, Nunavut, Canada. *Journal of Hydrology, 373*(1-2), 80-95. http://dx.doi.org/10.1016/j.jhydrol.2009.04.013

Stotler, R. L., Frape, S. K., Freifeld, B. M., Holden, B., Onstott, T. C., Ruskeeniemi, T., & Chan, E. (2011). Hydrogeology, Chemical and Microbial Activity Measurement Through Deep Permafrost. *Groundwater, 49*(3), 348-364. http://dx.doi.org/10.1111/j.1745-6584.2010.00724.x.

Su, X., Booshehrian, A., & Wan, R. (2013). *Numerical Simulation of the Issues Related to Uranium Mining and Tailings Management in Continuous Permafrost Zones in Nunavut, Canada*. American Geophysical Union, Fall Meeting 2013, San Francisco, California. Abstract #C41A-0584.

Thienpont, J. R., Kokelj, S. V., Korosi, J. B., Cheng, E. S., Desjardins, C., Kimpe, L. E., Blais, J. M., Pisaric, M. F. J., & Smol, J. P. (2013). Exploratory hydrocarbon drilling impacts to arctic lake ecosystems. *PLOS ONE*, *8*(11). https://doi.org/10.1371/journal.pone.0078875

Thury, M., Gautschi, A., Mazurek, M., Müller, W. M., Naef, H., Pearson, F. J., Vomvoris, S., & Wilson, W. (1994). *Geology and hydrogeology of the crystalline basement of northern Switzerland*. Nagra technical report NTB 93-01, Wettingen, Switzerland.

Tilsworth, T., & Smith, D. W. (1984). Cold climate facultative lagoons. *Canadian Journal of Civil Engineering*, *11*, 542-555. https://doi.org/10.1139/l84-073

Tsang, C.-F., Neretnieks, I., & Tsang, Y. (2015). Hydrologic issues associated with nuclear waste repositories. *Water Resources Research, 51*, 6923-6972. https://doi.org/10.1002/2015WR017641

US EPA – US Environmental Protection Agency (2012). *Study of the potential impacts of hydraulic fracturing on drinking water resources*. Progress Report, EPA 601/R-12/011. United States Environmental Protection Agency, Office of Research and Development, Washington, D.C. Retrieved from https://www.epa.gov/sites/production/files/documents/hf-report20121214.pdf#page=140

USGS (2001). *Ground-water studies in Fairbanks, Alaska—a better understanding of some of the United States' highest natural arsenic concentrations*. USGS Fact Sheet FS-111-01. November 2001.

Utting, N., Clark, I., Lauriol, B., Wieser, M., & Aeschbach-Hertig, W. (2012). Origin and Flow Dynamics of Perennial Groundwater in Continuous Permafrost Terrain using Isotopes and Noble Gases: Case Study of the Fishing Branch River, Northern Yukon, Canada. *Permafrost and Periglacial Processes*, *23*, 91–106. http://dx.doi.org/10.1002/ppp.1732 van Everdingen, R. O. (1991). Physical, chemical, and distributional aspects of Canadian springs. *Memoirs of the Entomological Society of Canada*, *123*(S155), 7-28. https://doi.org/10.4039/entm123155007-1

Veska, E., & Eaton, R. S. (1991). Abandoned Rayrock uranium mill tailings in the Northwest Territories: environmental conditions and radiological impact. *Health Physics, 60*(3), 399-409.

Walvoord, M. A., Day-Lewis, F. D., Lane Jr, J. W., & Voss, C. I. (2015). *Improved understanding of permafrost controls on hydrology in Interior Alaska by integration of ground-based geophysical permafrost characterization and numerical modeling*. SERDP Project RC-2111. Department of Defense Strategic Environmental Research and Development Program. Retrieved from http://www.dtic.mil/dtic/tr/fulltext/u2/a621851.pdf

Wan, R., Booshehrian, A. (2015). *Permafrost degradation within continuous permafrost zones due to mining disturbances in canadian northern regions*. Department of Civil Engineering University of Calgary Calgary, Alberta. April 2015.

Welch, A. H., Westjohn, D. B., Helsel, D. R., & Wanty, R. B. (2000). Arsenic in ground water of the United States-- occurrence and geochemistry. *Ground Water*, *38*(4), 589-604. https://doi.org/10.1111/j.1745-6584.2000.tb00251.x

Westbay Instruments (2017). Information website: http://www.westbay.com

Woo, M-K. (2012). *Permafrost Hydrology*. Springer-Verglag Berlin Heidelberg. https://doi.org/10.1007/978-3-642-23462-0

Workman, P. (2016). *Water and Sanitation Summary for Northwest Territories-Canada. Presentation*. Department of Health and Social Services, Government of Northwest Territories, Yellowknife, NWT. Proceedings of WIHAH Conference, Water Innovations for Healthy Arctic Homes. Anchorage, Alaska September 18-21, 2016. Retrieved from http://wihah2016.com/wp-content/uploads/2016/10/Workman-Peter_WIHAH-Country-Comparison-North-West-Territories-Canada.pdf

Wrye, L. A. (2008). *Distinguishing between natural and anthropogenic sources of arsenic in soils from the Giant Mine, Northwest Territories and the North Brookfield Mine, Nova Scotia*. MSc thesis, Queen's University Kingston, Ontario, Canada.

Yates, C. N. (2012). *Developing an understanding for wastewater treatment in remote communities in Nunavut, Canada*. *Investigating the performance, planning practice and function of tundra and constructed treatment wetlands*. PhD thesis, University of Waterloo, Ontario. Retrieved from https://uwspace.uwaterloo.ca/bitstream/handle/10012/6682/Yates_Colin.pdf?sequence=1D

Yunker, M. B., Backus, S. M., Graf Pannatier E., Jeffries, D. S., & Macdonald, R. W. (2002). Sources and significance of alkane and PAH hydrocarbons in Canadian Arctic rivers. *Estuarine, Coastal and Shelf Science*, *55*, 1-31. https://doi.org/10.1006/ecss.2001.0880

MODULE 3

Presented by jurisdictions

Nelson, R., & Quevauviller, P. (2016). Groundwater law. In: Jakeman, A. J. (Ed.) *Integrated groundwater management.* Springer, Berlin. p. 173-196, Chapter 7. Retrieved from https://link.springer.com/content/pdf/10.1007%2F978-3-319-23576-9_7.pdf

Federal (Canada)

Canadian Council of Ministers of the Environment – CCME (1999). *Canadian water quality guidelines for the protection of aquatic life*. Canadian environmental quality guidelines. Publication No. 1299. Retrieved from http://ceqg-rcqe.ccme.ca/

Canadian Council of Ministers of the Environment – CCME (2007a). *Canadian Environmental Quality Guidelines*. A protocol for the derivation of water quality guidelines for the protection of aquatic life 2007. Publication No. 1299; ISBN 1-896997-34-1. Retrieved from http://ceqg-rcqe.ccme.ca/download/en/342/

Canadian Council of Ministers of the Environment – CCME (2007b). *Summary of a protocol for the derivation of environmental and human health soil quality guidelines* (CCME 2006). Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health. Canadian Environmental Quality Guidelines. Retrieved from http://ceqg-rcqe.ccme.ca/download/en/342/

Canadian Council of Ministers of the Environment – CCME (2008). *National Classification System for Contaminated Sites Guidance Document*. ISBN 978-1-896997-80-3 PDF. Winnipeg. Retrieved from http://www.ccme.ca/files/Resources/csm/pn_1403_ncscs_guidance_e.pdf

Canadian Council of Ministers of the Environment – CCME (2016). Guidance Manual for Environmental Site Characterization. In *Support of Environmental and Human Health Risk Assessment*. Volume 1 Guidance Manual. PN 1551 / ISBN 978-1-77202-026-7 PDF. Retrieved from http://www.ccme.ca/en/files/Resources/csm/Volume%201-Guidance%20Manual-Environmental%20Site%20Characterization_e%20PN%201551.pdf

Canadian Council of Ministers of the Environment – CCME (2017). *Canadian Environmental Quality Guidelines*. Canadian Council of Ministers of the Environment. Retrieved from http://ceqg-rcqe.ccme.ca/en/index.html

Environment and Climate Change Canada (2013). *Groundwater*. Web-based resources for the public. Date modified: 2013-09-09. Retrieved from https://www.ec.gc.ca/eau-water/default.asp?lang=En&n=300688DC-1

Environment and Climate Change Canada (2017). *Environment solid waste management for northern and remote* communities. Planning and technical guidance document, March 2017. Environment and Climate Change Canada, Government of Canada, Cat. No.: En14-263/2016E-PDF. Retrieved from http://publications.gc.ca/site/eng/9.826705/publication.html

Government of Canada (2009a). *Guidelines for designing and implementing aquatic effects monitoring programs for development projects in the Northwest Territories: Overview Report*. June 2009 version. Retrieved from http://www.aadnc-aandc.gc.ca/eng/1316200324333/1316201794319

Government of Canada (2009b). *Recommended procedures for developing detailed designs for aquatic effects monitoring programs*. AEMP Technical Guidance Document Volume 4 Indian and Northern Affairs Canada Yellowknife, Northwest Territories. June 2009 Version. Retrieved from http://www.enr.gov.nt.ca/sites/default/files/aemp_technical_guidance_document_volume_4.pdf

Government of Canada (2016a). *Guidance Document on Federal Interim Groundwater Quality Guidelines for Federal Contaminated Sites*. May 2010, Revised June 2016 (Version 4). Federal Contaminated Sites Action Plan (FCSAP). Government of Canada, Cat. no. En14-91/2013E-PDF.

Government of Canada (2016b). *Federal Contaminated Sites Action Plan (FCSAP). Decision-Making Framework*. April 2016. Federal Contaminated Sites Action Plan (FCSAP). Government of Canada, Cat. No. En14-89/2013E-PDF. Retrieved from http://publications.gc.ca/collections/collection_2017/eccc/En14-89-2016-eng.pdf

Government of Canada (2017a). *Guidelines for Canadian Drinking Water Quality - Summary Table*. Prepared by the Federal-Provincial-Territorial Committee on Drinking Water of the Federal-Provincial-Territorial Committee on Health and the Environment, February 2017. Retrieved from https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/water-quality/guidelines-canadian-drinking-water-quality-summary-table-health-canada-2012.html

Health Canada (2012), *Guidelines for Canadian Recreational Water Quality, Third edition,* April 2012. Prepared by the Federal-Provincial-Territorial Working Group on Recreational Water Quality of the Federal-Provincial-Territorial Committee on Health and the Environment. Retrieved from https://www.canada.ca/content/dam/canada/health-canada/migration/healthy-canadians/publications/healthy-living-vie-saine/water-recreational-recreative-eau/alt/pdf/water-recreational-recreative-eau-eng.pdf

MVLWB/AAND (2013). *Guidelines for the Closure and Reclamation of Advanced Mineral Exploration and Mine Sites in the Northwest Territories November 2013*. Mackenzie Valley Land and Water Board / Aboriginal Affairs and Northern Development Canada. Retrieved from https://mvlwb.com/sites/default/files/documents/wg/WLWB_5363_Guidelines_Closure_Reclamation_WR.pdf

Northwest Territories

Government of Canada (2016b). *Mackenzie Valley Resource Management Act. S.C. 1998, c. 25* Current to April 12, 2017. Last amended on September 1, 2016. Published by the Minister of Justice. Retrieved from http://laws-lois.justice.gc.ca/eng/acts/M-0.2/

Government of Canada (2016c). *Mackenzie Valley Federal Areas Waters Regulations* (SOR/93-303). Current to April 12, 2017 Last amended on June 13, 2016. Published by the Minister of Justice. Retrieved from http://laws-lois.justice.gc.ca/eng/regulations/SOR-93-303/index.html

Government of the Northwest Territories (2003). *Environmental Guideline for Contaminated Site Remediation*, Nov 2003. Retrieved from http://www.enr.gov.nt.ca/sites/default/files/guidelines/siteremediation.pdf

Government of the Northwest Territories (2004). *Guideline for Industrial Waste Discharges in the NWT*. April 2004. Retrieved from http://www.enr.gov.nt.ca/sites/default/files/guidelines/industrial_waste_guidelines.pdf

Government of the Northwest Territories (2011a). *Water Supply Systems Regulations* (R-108-2009, Public Health Act). Printed by Territorial Printer, Northwest Territories Yellowknife, N.W.T. Retrieved from https://www.justice.gov.nt.ca/en/files/legislation/public-health/public-health.r7.pdf

Government of the Northwest Territories (2011b). *A Guide to the Spill Contingency Planning and Reporting Regulations*. Environment and Natural Resources, March 2011. 6 p. Retrieved from http://www.enr.gov.nt.ca/sites/default/files/reports/guide_to_spill_contingency_planning_and_reporting.pdf

Government of the Northwest Territories (2012). *Northwest Territories Source Water Assessment and Protection (SWAP) Guidance Document*. Feb 2012. 26 pp. Retrieved from http://www.enr.gov.nt.ca/sites/default/files/source_water_assesment_and_protection_swap_guidance.pdf

Government of the Northwest Territories (2014a). *Managing water after devolution*. Devolution newsletter, March 2014, Issue #4. Retrieved from http://devolution.gov.nt.ca/wp-content/uploads/2012/04/Devolution-Newsletter-4-Water.pdf

Government of the Northwest Territories (2014b). *Environmental Protection Act*, R.S.N.W.T. 1988, c.E-7. Printed by Territorial Printer, Northwest Territories Yellowknife, N.W.T., 2014. 34 p. Retrieved from https://www.justice.gov.nt.ca/en/files/legislation/environmental-protection/environmental-protection.a.pdf

Government of the Northwest Territories (2016a). *Waters Act, S.N.W.T. 2014, c.18.* Territorial Printer Yellowknife, N.W.T., 2016. 54pp. Retrieved from https://www.justice.gov.nt.ca/en/files/legislation/waters/waters.a.pdf

Government of the Northwest Territories (2016b). *NWT Water Stewardship Strategy Action Plan 2016-2020*. Retrieved from http://www.enr.gov.nt.ca/sites/enr/files/resources/nwt_water_stewardship_strategy_plan_for_action_2016-2020.pdf

Government of the Northwest Territories (2017). *Water Boards in the Northwest Territories*. Online table. Retrieved from http://www.enr.gov.nt.ca/sites/default/files/nwt_water_boards.pdf

INAC (2010). *The BIG Picture: Contaminated Sites in the NWT*. Indian and Northern Affairs Canada. Retrieved from http://www.aadnc-aandc.gc.ca/eng/1362175540271/1362175765271

INAC (2013). *Overview of Land and Resource Management in the NWT*. Retrieved from http://www.nwtboardforum.com/wp-content/uploads/2013/05/NWTBoardForumPPT.pdf

Kent, R., Marshall, P., and Hawke, L. (2003). Guide*lines for the Planning, Design, Operations and Maintenance of Modified Solid Waste Sites in the Northwest Territories*. Prepared for Government of Northwest Territories, Department of Municipal and Community Affairs. Retrieved from http://www.enr.gov.nt.ca/sites/enr/files/guidelines/solidwaste_guidelines.pdf

Mackenzie Valley Water Board (2011). Guid*elines for Developing a Waste Management Plan*. March 31, 2011. Retrieved from https://mvlwb.com/sites/default/files/documents/MVLWB-Guidelines-for-Developing-a-Waste-Management-Plan-Mar-31_11-JCWG.pdf

MVLWB (2017). *Mackenzie Valley Water Board*. Retrieved from https://mvlwb.com/

YUKON TERRITORY

Golder Associates (2011). Guida*nce Document on Water and Mass Balance Models for the Mining Industry.* Report submitted to Yukon Government. Dec 19, 2011. Retrieved from http://www.env.gov.yk.ca/publications-maps/documents/mine_water_balance.pdf

Government of Yukon (1999). *Sewage Disposal Systems Regulation* (O.I.C. 1999/82 Public Health and Safety Act). Jun 30, 1999. Retrieved from http://www.gov.yk.ca/legislation/regs/oic1999_082.pdf

Government of Yukon (2002a). *Contaminated Sites Regulation*. O.I.C. 2002/171 Environment Act. Sept. 30/02. Retrieved from http://www.gov.yk.ca/legislation/regs/oic2002_171.pdf

Government of Yukon (2002b). *Public Health and Safety Act*. Revised Statutes of the Yukon 2002. Queen's Printer for the Yukon. 17 pp. Retrieved from http://www.gov.yk.ca/legislation/acts/puhesa.pdf

Government of Yukon (2003). *Waters Act*, Chapter 19. Statutes of the Yukon 2003. Queen's Printer for the Yukon. Retrieved from http://www.gov.yk.ca/legislation/acts/waters.pdf

Government of Yukon (2006). *Assessment Guideline for Well Water or Groundwater Under the Direct Influence of Surface Water (GUDI).* Environmental Health Services, Health and Social Services, Government of Yukon. Feb 2006. 3pp. Retrieved from http://www.hss.gov.yk.ca/pdf/well_ground_guidelines.pdf

Government of Yukon (2014a). *Groundwater and Aquifers*. Last updated 2014 Nov 03. Retrieved from http://yukonwater.ca/understanding-yukon-water/water-facts-and-information/groundwater-and-aquifers

Government of Yukon (2014b). *Water Wells*. Last updated 2016 May 4. Retrieved from http://yukonwater.ca/understanding-yukon-water/drinking-water/water-wells

Government of Yukon (2015). *Domestic Water Well Program Guidelines*. Yukon Community Services. April 2015. 7pp. Retrieved from http://www.community.gov.yk.ca/pdf/Domestic_Water_Well_Program_Guidelines_2015.pdf

Government of Yukon (2017). *Environment Act*. Unofficial Consolidation of the Statutes of Yukon. Retrieved from http://www.gov.yk.ca/legislation/acts/environment_c.pdf

NUNAVUT TERRITORY

Government of Canada (2016d). *Nunavut General Monitoring Plan (NGMP), Nunavut General Monitoring Blueprint Compendium 2013*. Indigenous and Northern Affairs Canada, Iqaluit. Date modified: 2016-12-06. Retrieved from http://www.ngmp.ca/DAM/DAM-PSGN-NGMP/STAGING/texte-text/monitoringBlueprint_1424179146631_eng.pdf

Government of Canada (2016e). *Nunavut Waters and Nunavut Surface Rights Tribunal Act* (S.C. 2002, c. 10). Current to April 12, 2017 Last amended on June 19, 2016. Published by the Minister of Justice. Retrieved from http://laws-lois.justice.gc.ca/eng/acts/N-28.8/

Government of Canada (2017b). *Nunavut Waters Regulations* (SOR/2013-69). Current to April 12, 2017. Published by the Minister of Justice. Retrieved from http://laws-lois.justice.gc.ca/eng/regulations/SOR-2013-69/index.html

Government of Nunavut (2002). *Guideline: Contaminated Site Remediation*. Environmental Protection Service, Department of Sustainable Development Government of the Nunavut, January 2002. 12pp. Retrieved from ftp://ftp.nwb-oen.ca/other%20documents/Guidelines/090728%202002%20Guideline%20for%20Contaminated%20Site%20Remediation-IMLE.pdf

Nunavut Water Board (2017). *Nunavut Water Board – Sustaining the integrity of Nunavut's fresh water for the future*. Retrieved from http://www.nwb-oen.ca

PROVINCE OF QUEBEC (INCLUDING THE NUNAVIK REGION)

Gouvernement du Québec (2011). *Politique nationale de l'eau* (National water policy). Rapport synthèse d'évaluation de la Politique nationale de l'eau pour la période 2003-2009. Juin 2011. Bibliothèque et Archives nationales du Québec, 2011 ISBN : 978-2-550-62815-6 (PDF). Retrieved from http://www.mddelcc.gouv.qc.ca/eau/politique/bilan/rapport-synthese2003-2009.pdf

Gouvernement du Québec (2016a). *Guide de réalisation des analyses de la vulnérabilité des sources destinées à l'alimentation en eau potable au Québec* (A guide to implementing vulnerability analyzes for drinking water supply in Quebec). Bibliothèque et Archives nationales du Québec ISBN 978-2-550-77217-0 (PDF) (2e édition, 2016). Retrieved from http://www.mddelcc.gouv.qc.ca/Eau/prelevements/guide-analyse-vulnerabilite-des-sources.pdf

Gouvernement du Québec (2016b). *Guide sur les principes d'atténuation et de compensation des activités agricoles relativement aux installations de prélèvement d'eau* (A guide to principles of mitigation and compensation of agricultural activities relating to water extraction facilities). Updated March 2016. Retrieved from http://www.mddelcc.gouv.qc.ca/Eau/souterraines/Guide_compensation.pdf

Gouvernement du Québec (2017a). *Loi sur la qualité de l'environnement* (Environment Act) (1978), c. 94, a. 1. Chapitre Q-2. Éditeur officiel du Québec, Feb 1, 2017. Retrieved from http://legisquebec.gouv.qc.ca/fr/ShowDoc/cs/Q-2/

Gouvernement du Québec (2017b). *Loi affirmant le caractère collectif des ressources en eau et visant à renforcer leur protection* (Collectice character of water Act). Chapitre C-6.2. Éditeur officiel du Québec, Feb 1, 2017. Retrieved from http://legisquebec.gouv.qc.ca/fr/ShowDoc/cs/C-6.2

Gouvernement du Québec (2017c). *Règlement sur le prélèvement des eaux et leur protection* (RPEP) (Regulation on water extraction and protection). Chapitre Q-2, r. 35.2. Éditeur officiel du Québec, Feb 1, 2017. Retrieved from http://www.mddelcc.gouv.qc.ca/Eau/prelevements/reglement-prelevement-protection/index.htm

Gouvernement du Québec (2017d). *Politique de protection des sols et de réhabilitation des terrains contaminés: Plan d'action 2017-2021* (Policy on soil protection and contaminated land reclamation: Action plan 2017-2021). Ministère du Développement durable, de l'environnement et de la Lutte Contre les Changements Climatiques. 34 pp. Retrieved from http://www.mddelcc.gouv.qc.ca/sol/terrains/politique/politique.pdf

Gouvernement du Québec (2017e). *Critères applicables aux cas de contamination des eaux souterraines* (Criteria applicable in case of groundwater contamination). Retrieved from http://www.mddelcc.gouv.qc.ca/sol/terrains/politique/annexe_2.htm

Chapuis, R. P. (2007). *Guide sur les essais de pompage et leurs interprétations* (Guide to pump testing and interpretation). Bibliothèque et archives nationales du Québec, 2007. ISBN 978-2-550-50664-5 (PDF). Retrieved from http://www.mddelcc.gouv.qc.ca/eau/souterraines/guide_pompage/index.htm

Province of Alberta

Alberta Environment & Sustainable Resource Development (ESRD) (2014). *Environmental Quality Guidelines for Alberta Surface Waters*. Water Policy Branch, Policy Division. Edmonton. 48 pp. Retrieved from http://aep.alberta.ca/water/education-guidelines/documents/EnvironmentalQualitySurfaceWaters-2014.pdf

Alberta Environment and Parks (AEP) (2016). Alb*erta Tier 1 Soil and Groundwater Remediation Guidelines*. Land Policy Branch, Policy and Planning Division. 197 pp. Retrieved from http://aep.alberta.ca/lands-forests/land-industrial/inspections-and-compliance/documents/AlbertaTier1Guidelines-Feb02-2016A.pdf

Government of Alberta (2003). *Water for life*. Retrieved from http://aep.alberta.ca/water/programs-and-services/water-for-life/strategy/documents/WaterForLife-Strategy-Nov2003.pdf

Government of Alberta (2006). *The Water Allocation and Conservation Guideline (and Policy) for Oilfield Injection*. PUB NO. I/969. 8 pp. Retrieved from http://aep.alberta.ca/water/programs-and-services/groundwater/regulation-and-policy/documents/WaterConservationOilfieldInjectionPolicy.pdf

Government of Alberta (2010a). *Alberta Tier 1 Soil and groundwater remediation guidelines*. Alberta Environment, Edmonton, Alberta. December 2010. 58 pp. and appendices. Retrieved from https://extranet.gov.ab.ca/env/infocentre/info/library/7751.pdf

Government of Alberta (2010b). *Alberta Tier 2 Soil and groundwater remediation guidelines*. Alberta Environment, Edmonton, Alberta. December 2010. 77 pp. and appendices. Retrieved from https://extranet.gov.ab.ca/env/infocentre/info/library/7752.pdf

Government of Alberta (2010c). *Guidelines for licensing water diversion projects*. Retrieved from http://aep.alberta.ca/water/education-guidelines/documents/LicensingWaterDiversionProjects-Guide.pdf

Government of Alberta (2011). *Alberta environment guide to groundwater authorization*. Retrieved from http://aep.alberta.ca/water/education-guidelines/documents/GroundwaterAuthorization-Guide-2011.pdf

Government of Alberta (2014). *Water Act*. Revised Statutes of Alberta 2000 Chapter W-3 current as of December 17, 2014. Published by Alberta Queen's Printer. Retrieved from http://www.qp.alberta.ca/documents/Acts/w03.pdf

Government of Alberta (2015). *The Water (Ministerial) Regulation*. Alberta Regulation 205/1998 with amendments up to and including Alberta Regulation 185/2015. Published by Alberta Queen's Printer. Retrieved from http://www.qp.alberta.ca/documents/Regs/1998_205.pdf

Government of Alberta (2017a). *Environmental Protection and Enhancement Act*. Revised Statutes of Alberta 2000 Chapter E-12, current as of March 31, 2017. Published by Alberta Queen's Printer. Retrieved from http://www.qp.alberta.ca/documents/Acts/E12.pdf

Government of Alberta (2017b). *Publication list on the subject of Groundwater*. Retrieved from https://extranet.gov.ab.ca/env/infocentre/info/listing.asp?subcategoryid=92

Province of British Columbia

Berardinucci, J., & Ronneseth, K. (2002). *Guide to Using the BC Aquifer Classification Maps for the Protection and Management of Groundwater*. BC Ministry of Water, Land and Air Protection, Victoria, British Columbia. Retrieved from http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/reports/aquifer_maps.pdf

British Columbia Ministry of Environment (2017). A*n Aquifer Classification System for Ground Water Management in British Columbia.* Province of British Columbia. Retrieved from http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/Aq_Classification/Aq_Class.html

Government of British Columbia (1996a). *Water Protection Act (WPA)*. [RSBC 1996] Chap. 484. Current to April 19, 2017. Queen's Printer, Victoria, British Columbia, Canada. Retrieved from http://www.bclaws.ca/EPLibraries/bclaws_new/document/ID/freeside/00_96484_01

Government of British Columbia (1996b). *Geothermal Resources Act* [RSBC 1996] Chapter 171, Current to April 19, 2017. Queen's Printer, Victoria, British Columbia, Canada. Retrieved from http://www.bclaws.ca/civix/document/id/complete/statreg/96171_01

Government of British Columbia (2000). *Well Protection Toolkit*. Retrieved from http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/wells/well_protection/wellprotect.html

Government of British Columbia (2003). *Environmental Management Act (EMA)*. [SBC 2003] CHAPTER 53. Current to April 19, 2017. Queen's Printer, Victoria, British Columbia, Canada. Retrieved from http://www.bclaws.ca/Recon/document/ID/freeside/03053_00

Government of British Columbia (2015). *Guidance document for determining ground water at risk of containing pathogens (GARP) (including Ground Water Under Direct Influence of Surface Water (GWUDI))*, Version 2. Health Protection Branch, Population and Public Health Division, Ministry of Health. Retrieved from http://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/documents/garp_assessment_v2_dec1_2015_final.pdf

Government of British Columbia (2016a). *Contaminated Sites Regulation*. BC Reg. 375/96, O.C. 1480/96. [includes amendments up to BC Reg. 184/2016, July 19, 2016]. Effective April 1, 1997. Queen's Printer, Victoria, British Columbia, Canada. Retrieved from http://www.bclaws.ca/EPLibraries/bclaws_new/document/ID/freeside/375_96_00

Government of British Columbia (2016b). *Water and Air Baseline Monitoring Guidance Document for Mine Proponents and Operators*. Prepared by the Ministry of Environment, Version 2 - June 2016. Retrieved from https://www.google.co.jp/search?client=safari&rls=en&q=Water+and+air+baseline+monitoring+guidance+document+for+mine+proponents+and+operators&ie=UTF-8&oe=UTF-8&gfe_rd=cr&ei=rLwBWYGFF6GL8Qe1rJDYAw

Government of British Columbia (2017a). *Water Sustainability Act* [SBC 2014] CHAPTER 15, current to April 19, 2017. Queen's Printer, Victoria, British Columbia, Canada. Retrieved from http://www.bclaws.ca/civix/document/id/complete/statreg/14015

Government of British Columbia (2017b). *Groundwater Protection Regulation*. BC Reg. 39/2016 O.C. 113/2016 [includes amendments up to BC Reg. 152/2016, June 10, 2016], current to April 25, 2017. Queen's Printer, Victoria, British Columbia, Canada. Retrieved from http://www.bclaws.ca/civix/document/id/complete/statreg/39_2016

Government of British Columbia (2017c). *Groundwater Protection Regulation*. BC Government's website with simplified summary and links to brochures. Retrieved from http://www2.gov.bc.ca/gov/content/environment/air-land-water/water/laws-rules/groundwater-protection-regulation

Government of British Columbia (2017d). *Summary of Water Quality Guidelines: Drinking water sources. Summary table*. Water Protection & Sustainability Branch Ministry of Environment. Retrieved from http://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/waterquality/wqgs-wqos/approved-wqgs/bcenv_drinkingwaterguidelines_summarytable.pdf

Government of British Columbia (2017e). *British Columbia Approved Water Quality Guidelines: Aquatic Life, Wildlife & Agriculture*. Summary Report. Water Protection & Sustainability Branch, Ministry of Environment. Retrieved from http://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/waterquality/wqgs-wqos/approved-wqgs/final_approved_wqg_summary_march_2016.pdf

Government of British Columbia (2017f). *Groundwater Wells: Information for Property Owners*. Retrieved from http://www2.gov.bc.ca/gov/content/environment/air-land-water/water/groundwater-wells/information-for-property-owners

Liggett, J., Lapcevic, P., & Miller, K. (2011). *A Guide to the Use of Intrinsic Aquifer Vulnerability Mapping*. British Columbia Ministry of Forests, Lands and Natural Resource Operations, and the Cowichan Valley Regional District. Retrieved from http://cvrd.bc.ca/DocumentCenter/Home/View/7838

Todd, J., Wei, M., & Lepitre, M. (2016). *Guidance for Technical Assessment Requirements in Support of an Application for Groundwater Use in British Columbia*. Water Science Series, WSS2016-08. Prov. BC, Victoria BC Retrieved from http://a100.gov.bc.ca/appsdata/acat/documents/r50847/TechAssess_1473197338159_3194880156.pdf

Wei, M., Allen, D., Kohut, A., Grasby, S., Ronneseth, K., & Turner, B. (2009). Understanding the types of aquifers in the Canadian Cordillera hydrogeologic region to better manage and protect groundwater. *Streamline Watershed Management Bulletin, 13*(1), 1-18. Retrieved from http://forrex.org/sites/default/files/publications/articles/Streamline_Vol13_No1_Art3.pdf

Wels, C., Mackie, D., & Scibek, J. (2012). *Guidelines for Groundwater Modelling to Assess Impacts of Proposed Natural Resource Development Activities*. Prepared for British Columbia Ministry of Environment. Retrieved from http://www.env.gov.bc.ca/wsd/planprotectsustain/groundwater/groundwatermodellingguidelinesfinal-2012.pdf

State of Alaska (USA)

Alaska Department of Environmental Conservation (2000). *Guidance for Cleanup of Petroleum Contaminated Sites*. Division of spill prevention and response, Contaminated sites program. June 9, 2008. Retrieved from http://dec.alaska.gov/spar/csp/guidance/petr2000.pdf

Alaska Department of Environmental Conservation (2006a). *Natural Condition Guidance and Tools*. Retrieved from http://dec.alaska.gov/Water/wqsar/wqs/NaturalConditions.html

Alaska Department of Environmental Conservation (2006b). *Guidance for the Implementation of Natural Condition-Based Water Quality Standards*. Alaska Department of Environmental Conservation, Division of Water. November 15, 2006. Retrieved from http://dec.alaska.gov/Water/wqsar/pdfs/NaturalConditionsGuidance.pdf

Alaska Department of Environmental Conservation (2008). *Cleanup Levels Guidance. Division of spill prevention and response, Contaminated sites program*. June 9, 2008. Retrieved from https://dec.alaska.gov/spar/csp/guidance/cleanuplevels.pdf

Alaska Department of Environmental Conservation (2009). *Implementation Guidance: 2006 Mixing Zone Regulation Revisions*. As amended through February 3, 2009. Retrieved from http://dec.alaska.gov/Water/wqsar/wqs/pdfs/MixingZoneGuidance2-3-09.pdf

Alaska Department of Environmental Conservation (2017a). *Water Quality Standards*. Amended as of February 5, 2017. Document 18 AAC 70. Retrieved from http://dec.alaska.gov/commish/regulations/pdfs/18-AAC-70.pdf

Alaska Department of Environmental Conservation (2017b). *Mixing Zones*. Retrieved from http://dec.alaska.gov/Water/wqsar/wqs/mixingzones.html

Alaska Department of Environmental Conservation (2017c). *On-site Disposal Systems*. Information website. Retrieved from http://dec.alaska.gov/water/wwdp/onsite/

Alaska Department of Environmental Conservation (2017d). *User's Guide to the Alaska Department of Natural Resources, Division of Mining, Land & Water*. Alaska Hydrologic Survey (AHS) Water Well Log Tracking System (WELTS). revised on 1/30/2017. Retrieved from https://dnr.alaska.gov/welts/includes/helpers/welts_user_guide.pdf

Alaska Department of Natural Resources (2006). *Fact Sheet: Water rights in Alaska*. Department of Natural Resources, Water Resources Section Anchorage Office. Retrieved from http://dnr.alaska.gov/mlw/factsht/wtr_fs/wtr_rght.pdf

Alaska State Legislature (2011). *Water Use Act. 2011 Alaska Statutes, Title 46*. Water, Air, Energy, And Environmental Conservation, Chapter 46.15. Retrieved from http://www.legis.state.ak.us/basis/folio.asp

Reilly, T. E., & Harbaugh, A. W. (2004). *Guidelines for evaluating ground-water flow models*. U.S. Geological Survey Scientific Investigations Report 2004-5038, 30 pp. Retrieved from https://pubs.usgs.gov/sir/2004/5038/PDF/SIR20045038_ver1.01.pdf

US EPA – United States Environmental Protections Agency (1991). *Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells*. EPA160014-891034 March 1991. Retrieved from https://www.epa.gov/sites/production/files/2015-06/documents/fieldsamp-wellshandbook.pdf

US EPA – United States Environmental Protections Agency (2017). *Protecting Underground Sources of Drinking Water from Underground Injection (UIC)*. United States Environmental Protection Agency. Retrieved from https://www.epa.gov/uic

MODULE 4

Aller, L., Bennett, T., Lehr, J. H., & Petty, R. J. (1987). *DRASTIC - A standardized system for evaluating ground water pollution potential using hydrogeologic settings*. U.S. Environmental Protection Agency, report EPA/600/2-85/018.

Anderson, M. P., Woessner, W. W., & Hunt, R. J. (2015). *Applied Groundwater Modeling: Simulation of Flow and Advective Transport* (2nd Edition). Academic Press, London, UK. Retrieved from http://www.sciencedirect.com/science/book/9780120581030

Annan, A. P. (2005). GPR methods for hydrogeological studies (pp. 185-213). In Y. Rubin and S. Hubbard (Eds.) *Hydrogeophysics*. Water Science and Technology Library Series, Vol. 50. Springer, The Netherlands. Retrieved from https://link.springer.com/chapter/10.1007/1-4020-3102-5_7

ArcGIS (2015). *Canada Ecodistricts (Data Basin Dataset)*. Retrieved from https://www.arcgis.com/home/item.html?id=74719ba7a7a246f197f4990b6046eb3a

ASTM D3385. (2003). *Standard test method for infiltration rate of soils in field using double-ring infiltrometer*. Annual book of ASTM standards, vol. 4.02. ASTM International.

Barbour, S. L. (1998). Nineteenth Canadian Geotechnical Colloquium: The soil-water characteristic curve: a historical perspective. *Canadian Geotechnical Journal, 35*(5), 873-894. https://doi.org/10.1139/t98-040

Bavusi, M., Lapenna, V., Loperte, A., Gueguen, E., De Martino, G., Adurno, I., Catapano, I., & Soldovieri, F. (2013). Groundwater Monitoring and Control by Using Electromagnetic Sensing Techniques. In : A. Scozzari and E. Dotsika (Eds.), *Threats to the Quality of Groundwater Resources: Prevention and Control*, Volume 40 of the series The Handbook of Environmental Chemistry, 193-224. https://doi.org/10.1007/698_2013_243

Beaujean, J., Jean-Michel Lemieux, J-M., Dassargues, A., Therrien, R., & Brouyere, S. (2014). Physically Based Groundwater Vulnerability Assessment Using Sensitivity Analysis Methods. *Groundwater, 52*(6), 864–874. http://dx.doi.org/10.1111/gwat.12132

Becker, M. W. (2006). Potential for Satellite Remote Sensing of Ground Water. *Groundwater, 44*(2), 306-318. https://doi.org/10.1111/j.1745-6584.2005.00123.x

Benkert, B., Fortier, D., Kennedy, K., Lewkowicz, A., Bonnaventure. P., deGrandpré, I., Grandmont, K., Laxton, S., Light, E., Sliger, M., & Pope, G. (2013). *Burwash Landing and Destruction Bay landscape hazards: Geological mapping for climate change adaptation planning*. Northern Climate ExChange, Yukon Research Centre, Whitehorse, YT, Canada, 66 pp.

Bloschl, G., & Sivapalan, M. (1995). Scale issues in hydrological modelling: A review. *Hydrological Processes, 9*, 251-290. https://doi.org/10.1002/hyp.3360090305

Boydell, A. N., Rutter, N. W. (1980). S*urficial Geology and Geomorphology, Root River, District of Mackenzie*. Geological Survey of Canada, Preliminary Map 12-1979, 1 sheet. Retrieved from http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/downloade.web&search1=R=108884

Bonnaventure, P. P., & Lamoureux, S. F. (2013). The active layer: A conceptual review of monitoring, modelling techniques and changes in a warming climate. *Progress in Physical Geography, 37*(3), 352-376. https://doi.org/10.1177/0309133313478314

CCME - Canadian Council of Ministers of the Environment (2006). *A Canada-wide Framework for Water Quality Monitoring.* Publication No. 1369. Retrieved from http://www.ccme.ca/files/Resources/water/water_quality/wqm_framework_1.0_e_web.pdf

CCME - Canadian Council of Ministers of the Environment (2011). *Protocols manual for water quality sampling in Canada*. Publication No. 1461. Retrieved from http://www.ccme.ca/files/Resources/water/water_quality/protocols_document_e_final_101.pdf

CCME - Canadian Council of Ministers of the Environment (2015). *Guidance manual for optimizing water quality monitoring program design* (document # PN 1543). 78 pp. Retrieved from http://www.ccme.ca/files/Resources/water/water_quality/Guidance%20Manual%20for%20Optimizing%20Water%20Quality%20Monitoring%20Program%20Design_1.0_e.pdf

Chanasyk, D. S., & Naeth, M. A. (1996). Field measurement of soil moisture using neutron probes. *Canadian Journal of Soil Science, 76*, 317-323. https://doi.org/10.4141/cjss96-038

Cloutier, V, Rosa, E., Nadeau, S., Dallaire, P-L., Blanchette, D. Roy, M., Rey, N., & Bondu, R. (2015). Regional hydrogeological mapping in Abitibi-Temiscamingue, Quebec, Canada: from groundwater knowledge to land management (Paper GW-8). *Proceedings of the 5th GEOINDO 2015 Conference, 23-24th Nov.* Khon Kaen, Thailand.

Cocking, R. B., Deblonde, C., Kerr, D. E., Campbell, J. E., Eagles, S., Everett, D., Huntley, D. H., Inglis, E., Laviolette, A., Parent, M., Plouffe, A., Robertson, L., Smith, I. R., & Weatherston, A. (2016). *Surficial Data Model, version 2.2.0: Revisions to the science language of the integrated Geological Survey of Canada data model for surficial geology maps*. Geological Survey of Canada, Open File 8041, 45p. Retrieved from http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/downloade.web&search1=R=298767

Condesso de Melo, M. T., Custodio, E., Edmunds, W. M., & Loosli, H. H. (2008). Monitoring and characterization of natural groundwater quality. In W. M. Edmunds and P. Shand (Eds.), *Natural Groundwater Quality*. Blackwell Publishing. http://dx.doi.org/10.1002/9781444300345

Corniello, A., Ducci, D., & Napolitano, P. (1997). Comparison between parametric methods to evaluate aquifer pollution vulnerability using GIS: An example in the "Piana Campana", Southern Italy. In: Marinos PG, Koukis GC, Tsiambaos GC, and Stournaras GC (Eds), *Engineering Geology and the Environment*, Balkema, Rotterdam, 1721-1726.

DeBell, L., Anderson, K., Brazier, R. E., King, N., & Jones, L. (2016). Water resource management at catchment scales using lightweight UAVs: current capabilities and future perspectives. *Journal of Unmanned Vehicle Systems, 4*, 7-30, https://doi.org/10.1139/juvs-2015-0026

Denny, S. C., Allen, D. M., & Journeay, J. M. (2007). DRASTIC-Fm: a modified vulnerability mapping method for structurally controlled aquifers in the southern Gulf Islands, British Columbia, Canada. *Hydrogeology Journal, 15*(3), 483–493. http://dx.doi.org/10.1007/s10040-006-0102-8

Dobriyal, P., Badola, R., Tuboi, C., & Hussein, S. A. (2016). A review of methods for monitoring streamflow for sustainable water resource management. *Applied Water Science*. https://doi.org/10.1007/s13201-016-0488-y

Duk-Rodkin, A. (2009). *Surficial geology, Dahadinni River (95N/SE), Northwest Territories*. Geological Survey of Canada, Open File 6008, 1 sheet. Retrieved from http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/downloade.web&search1=R=261324

Erwin, M. L., & Tesoriero, A. J. (1997). *Predicting groundwater vulnerability to nitrate in the Puget Sound Basin*. U.S. Geological Survey Fact Sheet 061-97, 4 p.

Eschbach, D., Piasny, G., Schmitt, L., Pfister, L., Grussenmeyer, P., Koehl, M., Skupinski, G., & Serradj, A. (2017). Thermal-infrared remote sensing of surface water–groundwater exchanges in a restored anastomosing channel (Upper Rhine River, France). *Hydrological Processes, 31*, 1113–1124. https://doi.org/10.1002/hyp.11100

Fitch P., Brodaric B., Stenson M., Booth N. (2016) Integrated Groundwater Data Management. In: Jakeman A. J., O. Barreteau, R. J. Hunt, J. D. Rinaudo and A. Ross A. (eds) *Integrated Groundwater Management*. Springer.

Focazio, M. J., Reilly, T. E., Rupert, M. G., & Helsel, D. R. (2002). *Assessing Ground-Water Vulnerability to Contamination: Providing Scientifically Defensible Information for Decision Makers*. U.S. Geological Survey Circular 1224. Retrieved from https://pubs.usgs.gov/circ/2002/circ1224/pdf/circ1224ver1.01.pdf

Fortier, D., Veuille, S., Sliger, M., Verpaelst, M. Davesne, G., Charbonneau, S., & Grandmont, K. (2016). *Évaluation des impacts de l'écoulement souterrain sur la dégradation du pergélisol et la stabilité des infrastructures routières*. Rapport Final (préparé pour Transports Canada). Laboratoire de géomorphologie et de géotechnique des régions froides (Géocryolab), Université de Montréal, Montréal, QC, Canada, 116 pp.

French, H. M., & Shur, Y. (2010). The principles of cryostratigraphy. Earth Science Reviews, 101(3-4), 190-206. https://doi.org/10.1016/j.earscirev.2010.04.002

Frind, E. O., Molson, J. W., & Rudolph, D. L. (2006). Well vulnerability: A quantitative approach for source water protection. *Groundwater, 44*(5), 732–742. http://dx.doi.org/10.1111/j.1745-6584.2006.00230.x

Fritz, M., Deshpande, B. N., Bouchard, F., Högström, E., Malenfant-Lepage, J., & Morgenstern, A. . . . Weege (2015). Brief communication: Future avenues for permafrost science from the perspective of early career researchers. *Cryosphere, 9*: 1715–1720. https://doi.org/10.5194/tc-9-1715-2015

Gardner, C. M. K., Dean, T. J., & Cooper, J. D. (1998). Soil Water Content Measurement with a High-Frequency Capacitance Sensor. *Journal of agricultural Engineering Research, 71*(4), 395-403. https://doi.org/10.1006/jaer.1998.0338

Geological Survey of Canada (2014a). Surficial geology of Canada; Geological Survey of Canada, Canadian Geoscience Map 195 (preliminary, Surficial Data Model v. 2.0 conversion of Map1880A), scale 1:5 000 000. https://doi.org/10.4095/295462

Geological Survey of Canada (2014b). Surficial geology, Lac de Gras, Northwest Territories, NTS 76-D. Geological Survey of Canada, Canadian Geoscience Map 184, (ed. 2, Preliminary, Surficial Data Model V.2.0 Conversion), 1 sheet. Retrieved from http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/downloade.web&search1=R=295497

Gogu, R., Carabin, G., Hallet, V., Peters, V., & Dessarques, A. (2001). GIS-based hydrogeological databases and groundwater modelling. *Hydrogeology Journal*, *9*(6): 555-569. https://doi.org/10.1007/s10040-001-0167-3

Gogu, R. C., & Dassargues, A. (2000). Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. *Environmental Geology, 39*(6), 549-559. http://dx.doi.org/10.1007/s002540050466

Golder Associates Ltd. (2010). *Fractured Bedrock Field Methods and Analytical Tools* (Main Report), Submitted to the Science Advisory Board for Contaminated Sites in British Columbia, Project No. 08-1436-0101, 99 pp. Retrieved from http://www.sabcs.chem.uvic.ca/May%2024%20Final%20FBRock%20ReportFBFMAT-Vol1.pdf

Government of Canada (2017a). *Terrestrial Ecodistricts of Canada*. Original publication date: 2013-05-21. Retrieved from http://open.canada.ca/data/en/dataset/fe9fd41c-1f67-4bc5-809d-05b62986b26b

Government of Canada (2017b). *Hydrogeological Regions*. Original publication date: 2010-12-31. Retrieved from http://open.canada.ca/data/en/dataset/dc2dbd30-8893-11e0-b77b-6cf049291510

Grandmont, K., Cardille, J. A., Fortier, D., Gibéryen, T. (2012). Assessing land suitability for residential development in permafrost regions: A multi-criteria approach to land-use planning in Northern Quebec, Canada. *Journal of Environmental Assessment Policy and Management, 14* (01): 73-9. https://doi.org/10.1142/S1464333212500032

Grasby, S., Osadetz, K., Betcher, R., Render, F. (2000). Reversal of the regional-scale flow system of the Williston basin in response to Pleistocene glaciation. *Geology*, *28*, 635-638. https://doi.org/10.1130/0091-7613(2000)28<635:ROTRFS>2.0.CO;2

Grenier, C., Roux, N., Anbergen, H., Collier, N., Costard, F., & Ferry, M. . . . *Vidstrand* (2015). *The InterFrost benchmark of thermo-hydraulic codes for cold regions hydrology—First inter-comparison results*. European Geosciences Union Assembly - EPSC2016, Vienna, Austria. Abstracts 17: EGU2015-9723.

Hiscock, K. M., & Bense, V. F. (2014). *Hydrogeology: Principles and Practice* (2nd Edition). John Wiley & Sons Ltd., Chichester, UK.

Hoffman, P., & Hall, L. (1993). Geology map of the Slave Craton and environs, District of Mackenzie, Northwest Territories. Geological Survey of Canada, Open File 2559. 1 sheet; 1 CD-ROM. https://doi.org/10.4095/183951

Holding, S., & Allen D. M. (2015). *Shallow Groundwater Intrinsic Vulnerability Mapping in Northeast British Columbia*. Final Report, November 2015, Simon Fraser University, Burnaby, BC.

Huisman, J. A., Hubbard, S. S., Redman, J. D., & Annan, A. P. (2003). Measuring soil water content with ground penetrating radar: A review. *Vadose Zone Journal, 2*(4), 476-491. https://doi.org/10.2113/2.4.476

Ireson, A. M., van der Kamp, G., Ferguson, G., Nachshon, U., & Wheater, H. S. (2013). Hydrogeological processes in seasonally frozen northern latitudes: understanding, gaps and challenges. *Hydrogeology Journal, 21*(1): 53-66. https://doi.org/10.1007/s10040-012-0916-5

Kalbus, E., Reinstorf, F., & Schirmer, M. (2006). Measuring methods for groundwater - surface water interactions: a review. *Hydrology and Earth System Science, 10*(6), 873-887. https://doi.org/10.5194/hess-10-873-2006

Karami, G. H., & Younger, P. L. (2002). Analysing step-drawdown tests in heterogeneous aquifers. *Journal of Engineering Geology and Hydrology, 35*, p.295-303.

Koch, K. R., & Long, A. J. (2012). *Microgravity methods for characterization of groundwater-storage changes and aquifer properties in the karstic Madison aquifer in the Black Hills of South Dakota, 2009–12*. Scientific Investigations Report 2012–5158. U.S. Geological Survey, Reston, VA. 22pp. Retrieved from https://pubs.usgs.gov/sir/2012/5158/sir2012-5158.pdf

Kurylyk, B. L., Hayashi, M., Quinton, W. L., McKenzie, J. M., & Voss, C. I. (2016). Influence of vertical and lateral heat transfer on permafrost thaw, peatland landscape transition, and groundwater flow. *Water Resources Research, 52*(2): 1286-1305. https://doi.org/10.1002/2015WR018057

Latorre, B., Moret-Fernández, D., & Peña, C. (2013). Estimate of soil hydraulic properties from disc infiltrometer three-dimensional infiltration curve: theoretical analysis and field applicability. *Procedia Environmental Sciences, 19*, 580–589. https://doi.org/10.1016/j.proenv.2013.06.066

Legchenko, A., Baltassat, J-M., Beauce, A., & Bernard, J. (2002). Nuclear magnetic resonance as a geophysical tool for hydrogeologists. *Journal of Applied Geophysics, 50*(1-2), 21-46. https://doi.org/10.1016/S0926-9851(02)00128-3

Legchenko, A., Baltassat, J-M., Bobachev, A., Martin, C., Robain, H., & Vouillamoz, J-M. (2004). Magnetic Resonance Sounding Applied to Aquifer characterization. *Groundwater, 42*(3), 363-373. https://doi.org/10.1111/j.1745-6584.2004.tb02684.x

Liggett, J. A., & Allen, D. M. (2011). Evaluating the sensitivity of DRASTIC using different data sources, interpretations and mapping approaches. *Environmental Earth Sciences, 62*(8), 1577-1595. http://dx.doi.org/10.1007/s12665-010-0642-z

Liggett, J., & Gilchrist, A. (2010). *Technical summary of intrinsic vulnerability mapping methods in the regional districts of Nanaimo and Cowichan Valley*. Geological Survey of Canada. Open file 6168. 64 p.

Liggett, J., Lapcevic, P., & Miller, K. (2011). *A Guide to the use of intrinsic aquifer vulnerability mapping*. British Columbia Ministry of Forests, Lands and Natural Resource Operations, and the Cowichan Valley Regional District. Retrieved from http://cvrd.bc.ca/DocumentCenter/Home/View/7838

Luscombe, D. J., Anderson, K., Gatis, N., Grand-Clement, E., & Brazier, R. (2015). Using airborne thermal imaging data to measure near-surface hydrology in upland ecosystems. *Hydrological processes, 29*, 1656-1668. https://doi.org/10.1002/hyp.10285

Ma, J. (2015). Review of permeability evolution model for fractured porous media. *Journal of Rock Mechanics and Geotechnical Engineering, 7*(3), 351-357. http://dx.doi.org/10.1016/j.jrmge.2014.12.003

Matsushima, D., Kimura, R., & Shinoda, M. (2012). Soil Moisture Estimation Using Thermal Inertia: Potential and Sensitivity to Data Conditions. *Journal of Hydrometeorology, 13*, 638-648. https://doi.org/10.1175/JHM-D-10-05024.1

McKenzie, J., Voss, C., & Siegel, D. (2007). Ground-water flow with energy transport and water-ice phase change: numerical simulations, benchmarks and application to freezing in peat bogs. *Advances in Water Resources, 30*(4): 966-983. https://doi.org/10.1016/j.advwatres.2006.08.008

McKim, H. L., Walsh, J. E., & Arion, D. M. (1980). *Review of techniques for measuring soil moisture in situ* (special report 80-31). United States Army Corp of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, U.S.A. 22 pp. Retrieved from http://www.dtic.mil/dtic/tr/fulltext/u2/a089974.pdf

Ministry of Environment of British Columbia (2017). Water Stewardship Information Series; Guide to Conducting Well Pumping Tests. Retrieved online: http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/guide_to_conducting_pumping_tests.pdf

Muskett, R. R., & Romanovsky, V. E. (2011). Alaskan permafrost groundwater storage changes derived from GRACE and ground measurements. *Remote Sensing, 3*, 378–397. http://dx.doi.org/10.3390/rs3020378

National Research Council (2014). *Opportunities to use remote sensing in understanding permafrost and related ecological characteristics*. Report of a workshop, Polar Research Board. Committee on Opportunities to Use Remote Sensing in Understanding Permafrost and Ecosystems. The National Academies Press, Washington, D.C.

Natural Resources Canada (2017). *Water*. Selected thematic maps. Produced by the Government of Canada. Retrieved from http://www.nrcan.gc.ca/earth-sciences/geography/atlas-canada/selected-thematic-maps/16888

Nawaz, M. F., Bourrié, G., & Trolard, F. (2013). Soil compaction impact and modelling: A review. *Agronomy for Sustainable Development, 33*(2), 291-309. https://doi.org/10.1007/s13593-011-0071-8

Nelson, P. H. (1994). Permeability-porosity relationships in sedimentary rocks. *The Log Analyst, 35*(3), 38-62. Retrieved from http://www.pe.tamu.edu/blasingame/data/z_zCourse_Archive/P324_03A/Lecture_Refs_(pdf)/P324_Mod1_01_Nelson_(Log_Analyst_May_June_1994).pdf

Neukum, C., Hoetzl, H., & Himmelsbach, T. (2008). Validation of vulnerability mapping methods by field investigations and numerical modelling. *Hydrogeology Journal, 16*(4), 641–658. http://dx.doi.org/10.1007/s10040-007-0249-y

Normandeau, P. X. (2017). Personal communication. Northwest Territories Geological Survey. Government of the Northwest Territories.

Northwest Territories Geological Survey (NTGS) (n.d.a). Geological map compilation of the Northwest Territories. Produced by the Government of Northwest Territories. Retrieved from http://www.nwtgeoscience.ca/services/geological-map-compilation-northwest-territories

Northwest Territories Geological Survey (NTGS) (n.d.b). Surficial Geology. Produced by the Government of Northwest Territories. Retrieved from http://www.nwtgeoscience.ca/project/summary/surficial-geology

Pfeffer, J., Boucher, M., Hinderer, J., Favreau, G., Boy, J-P., de Linage, C., Cappelaere, B., Luck, B., Oi, M., & Le Moigne, N. (2011). Local and global hydrological contributions to time-variable gravity in Southwest Niger. *Geophysical Journal International, 184*(2), 661-672. https://doi.org/10.1111/j.1365-246X.2010.04894.x

Pinder, G. F., & Celia, M. A. (2006). *Subsurface hydrology*. John Wiley & Sons. Inc., Hoboken, NJ.

Plummer, R., de Loe, R., & Armitage, D. (2012). A systematic review of water vulnerability assessment tools. *Water Resources Management, 26*(15) 4327–4346. http://dx.doi.org/10.1007/s11269-012-0147-5

Pochon, A., Tripet, J.-P., Kozel, R., Meylan, B., Sinreich, M., & Zwahlen, F. (2008). Groundwater protection in fractured media: a vulnerability-based approach for delineating protection zones in Switzerland. *Hydrogeology Journal, 16*, 1267–1281. http://dx.doi.org/10.1007/s10040-008-0323-0

Portnoy, J. W., Nowicki, B. L., Roman, C. T., & Urish, D. W. (1998). The discharge of nitrate-contaminated groundwater from developed shoreline to marsh-fringed estuary. *Water Resources research, 34*(11), 3095-3104. https://doi.org/10.1029/98WR02167

Pride, S. R. (2005). Relationships between seismic and hydrological properties. p. 259-290. In Y. Rubin & S. Hubbard (Eds.) *Hydrogeophysics*. Water Science and Technology Library Series, Vol. 50. Springer, The Netherlands. Retrieved from https://link.springer.com/chapter/10.1007/1-4020-3102-5_9

Ramsahoye, L. E., & Lang, S. M. (1961). *Ground-water hydraulics: A Simple Method for Determining Specific Yield from Pumping Tests.* U.S. Geological Survey Water-supply Paper 1536-C. Retrieved from https://pubs.usgs.gov/wsp/1536c/report.pdf

Remondino, F., Barazzetti, L., Nex, F., Scaioni, M., & Sarazzi, D. (2011). *UAV photogrammetry for mapping and 3D modeling*. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. 38(1/C22), ISPRS ICWG I/V UAV-g (unmanned aerial vehicle in geomatics) conference, Zurich, Switzerland. Retrieved from http://3dom.fbk.eu/sites/3dom.fbk.eu/files/pdf/Remondino_etal_UAV2011.pdf

Rice, E. W., Baird, R. B., Eaton, A. D., & Clesceri, L. S. (Eds.) (2012). *Standard methods for the examination of water and wastewater*, 22nd edition. Co-Published by American Public

Health Association, American Water Works Association, and Water Environment Federation. Washington, D.C.

Riseborough, D., Shiklomanov, N., Etzelmüller, B., Gruber, S., & Marchenko, S. (2008). Recent advances in permafrost modelling. *Permafrost and Periglacial Processes, 19*(2): 137-156. https://doi.org/10.1002/ppp.615

Robinson, D. A, Campbell, C. S., Hopmans, J. W., Hornbuckle, B. K., Jones, S. B., Knight, R., Ogden, F., Selker, J., & Wendroth, O. (2008). Soil Moisture Measurement for Ecological and Hydrological Watershed-Scale Observatories: A Review. *Vadose Zone Journal, 7*(1), 358-389. https://doi.org/10.2136/vzj2007.0143

Rosen, L. (1994). A study of the DRASTIC methodology with emphasis on Swedish conditions. *Groundwater, 32*(2): 278-285. http://dx.doi.org/10.1111/j.1745-6584.1994.tb00642.x

Roux, N., Costard, F., & Grenier, C. (2017). Laboratory and Numerical Simulation of the Evolution of a River's Talik. *Permafrost and Periglacial Processes, 28*(2): 460-469. https://doi.org/10.1002/ppp.1929

Rowland, J. C., Travis, B. J., & Wilson, C. J. (2011). The role of advective heat transport in talik development beneath lakes and ponds in discontinuous permafrost. *Geophysical Research Letters, 38*(17). https://doi.org/10.1029/2011GL048497

Rühaak, W., H. Anbergen, C. Grenier, J. McKenzie, B. Kurylyk, J. Molson, N. Roux, I. Sass, (2015). Benchmarking Numerical Freeze/Thaw Models. *Energy Procedia*, *76*: 301-210.

Rupert, M. G. (2001). Calibration of the DRASTIC ground water vulnerability mapping method. *Groundwater, 39*(4), 625–630. http://dx.doi.org/10.1111/j.1745-6584.2001.tb02350.x

Sarsby, R. (2000). *Environmental geotechnics*. London, UK: Thomas Telford.

Schönberger, J. L., & Frahm, J-M. (2016). Structure-from-Motion Revisited (pp. 4104-4113). Proceedings of the 2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 27-30th June. Las Vegas, NV. http://dx.doi.org/10.1109/CVPR.2016.445

Scibek, J., Allen, D. M., Cannon, A., & Whitfield, P. (2007). Groundwater-surface water interactions under scenarios of climate change using a high-resolution transient model. *Journal of Hydrology, 333*(2-4): 165–181. http://dx.doi.org/10.1016/j.jhydrol.2006.08.005

Shoja, G. D., Mehdi, H., & Willibald, L. (2015). Towards using pedotransfer functions for estimating infiltration parameters. *Hydrological Sciences Journal, 61*(8)1477-1488. https://doi.org/10.1080/02626667.2015.1031763

Smith, I. R. (2003). Surficial geology, Etanda Lakes, Northwest Territories - Yukon Territory. Geological Survey of Canada, Open File 1671, 1 sheet. Retrieved from http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/downloade.web&search1=R=214291

Smith, S. L., & Burgess, M. M. (2002). A *digital database of permafrost thickness in Canada. Geological Survey of Canada*, Open File 4173. Retrieved from http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/downloade.web&search1=R=213043

Snyder, D. T., Wilkinson, J. M., & Orzol, L. L. (1998). *Use of a ground-water flow model with particle tracking to evaluate ground-water vulnerability, Clark County, Washington*. U.S. Geological Survey Water-Supply Paper 2488.

Soil Classification Working Group (1998). *The Canadian System of Soil Classification*, 3rd ed. Agriculture and Agri-Food Canada Publication 1646.

Stevenazzi, S., Masetti, M., Nghiem, S.V., & Sorichetta, A. (2015). Groundwater vulnerability maps derived from a time-dependent method using satellite scatterometer data. *Hydrogeology Journal, 23*(4), 631. http://dx.doi.org/10.1007/s10040-015-1236-3

Stevens, C. W., Kerr, D.E., Wolfe, S.A., & Eagles, S. (2017). *Predictive surficial geology, Yellowknife and Hearne Lake, Northwest Territories, NTS 85-J and NTS 85-I*. Geological Survey of Canada, Canadian Geoscience Map 200, (ed. 2, preliminary), 1 sheet. Retrieved from http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/downloade.web&search1=R=299516

St-Onge, M. R., Harrison, J. C., Paul, D., Tella, S., Brent, T. A., Jauer, C. D., & Maclean, B. C. (2015). *Tectonic map of Arctic Canada*; Geological Survey of Canada, Canadian Geoscience Map 187 (preliminary), scale 1:4 000 000. https://doi.org/10.4095/295945

Sykes, J. F., Normani, S. D., Jensen, M. R., & Sudicky, E. A. (2009). Regional-scale groundwater flow in a Canadian Shield setting. *Canadian Geotechnical Journal, 46*(9), 813–827. http://dx.doi.org/10.1139/T09-017

Taylor, A., Burgess, M., Judge, A., Allen, V., & Wilkinson, A. (1998). Canadian Geothermal Data Collection - Deep permafrost temperatures and thickness of permafrost. In International Permafrost Association, Data and Information Working Group, comp. Circumpolar Active-Layer Permafrost System (CAPS), version 1.0. CD-ROM available from National Snow and Ice Data Center, Boulder, Colorado. Retrieved from http://nsidc.org/data/docs/fgdc/ggd503_boreholes_ncanada/paper.html

Thomas W, Gregory A, Gager J, Kuo I-L, Wackerow A., & Nelson C (2009). Data Documentation Initiative (DDI) technical specification part I: overview, pp 1–103. Retrieved online from: http://www.ddialliance.org/

Topp, G. C. (2003). State of the art of measuring soil water content. *Hydrological Processes, 17(*14), 2993–2996. https://doi.org/10.1002/hyp.5148

Tsoflias, G. P., Halihan, T., & Sharp Jr., J. M. (2001). Monitoring pumping test response in a fractured aquifer using ground-penetrating radar. *Water resources research, 37*(5), 1221-1229.

U.S. Geological Survey (2016). Groundwater Techniques, Methods, and Models. Retrieved from https://water.usgs.gov/ogw/techniques.html

Van Stempvoort, D., Ewert, L. & Wassenaar, L. (1993). Aquifer vulnerability index: a GIS-compatible method for groundwater vulnerability mapping. *Canadian Water Resources Journal, 18*, 25–37. http://dx.doi.org/10.4296/cwrj1801025

Veuille, S., Fortier, D., Verpaelst, M., Grandmont, K., & Charbonneau, S. (2015) *Heat advection in the active layer of permafrost: Physical modelling to quantify the impact of subsurface flow* *on soil thawing*. 7th Canadian Conference on Permafrost and 68th Canadian Conference on Geotechnic, September 20-23, Quebec City, Canada.

Walvoord, M. A., & Kurylyk, B. L. (2016). Hydrologic Impacts of Thawing Permafrost—A Review. *Vadose Zone Journal, 15*(6). http://dx.doi.org/10.2136/vzj2016.01.0010

Walvoord, M. A., Voss, C. I., & Wellman, T. P. (2012). Influence of permafrost distribution on groundwater flow in the context of climate-driven permafrost thaw: Example from Yukon Flats Basin, Alaska, United States. *Water Resources Research, 48*(7), W07524. http://dx.doi.org/10.1029/2011WR011595

Wang, S., Fernandes, R., Latifovic, R., Charbonneau, F., Huang, J., Canisius, F., Maloley, M., Pouliot, D., Leblanc, S., Wang, J., & Chalifoux, S. (2012). *Remote sensing in support of groundwater Studies* (Cat. No. M114-20/2011E-PDF). Natural Resources Canada, Canada Centre for Remote Sensing. 2pp. Retrieved from http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/earth-sciences/files/pdf/geomatics/11-0440-Groundwater-studies_eng.pdf

Warner, B. G., & Rubec, C. D. A. (1997). *Canadian Wetland Classification System* (2nd ed). Waterloo, ON: Wetlands Research Centre, University of Waterloo.

Water, P, Greenbaum, D, Smart, P. L., & Osmaston, H. (1990). Applications of remote sensing to groundwater hydrology. Remote Sensing Reviews, 4(2), 223-264. https://doi.org/10.1080/02757259009532107

WMO - World Meteorological Organization (2008) Guide to hydrological practices. WMO, Geneva. Retrieved from http://www.whycos.org/hwrp/guide/

Xu, X., Lewis, C., Liu, W., Albertson, J. D., & Kiely, G. (2012). Analysis of single-ring infiltrometer data for soil hydraulic properties estimation: Comparison of BEST and Wu methods. *Agricultural Water Management, 107*, 34-41. https://doi.org/10.1016/j.agwat.2012.01.004

Zhang, D., & Zhou, G. (2016). Estimation of Soil Moisture from Optical and Thermal Remote Sensing: A Review. *Sensors, 16*(8), 1308. https://doi.org/10.3390/s16081308

Zhou, Y., & Li, W. (2011). A review of regional groundwater flow modeling. *Geoscience Frontiers, 2*(2): 205-214. https://doi.org/10.1016/j.gsf.2011.03.003

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Morse, P. D. (comp.), (2017). *Report on the Permafrost and Hydrogeology Interactions meeting*, 14 November 2016, Yellowknife, NWT; Geological Survey of Canada, Open File 8192,60 p. (also Northwest Territories Geological Survey, NWT Open Report 2017-010). https://doi.org/10.4095/299674