CHAPTER 15

PERMAFROST GROUNDWATER REGION

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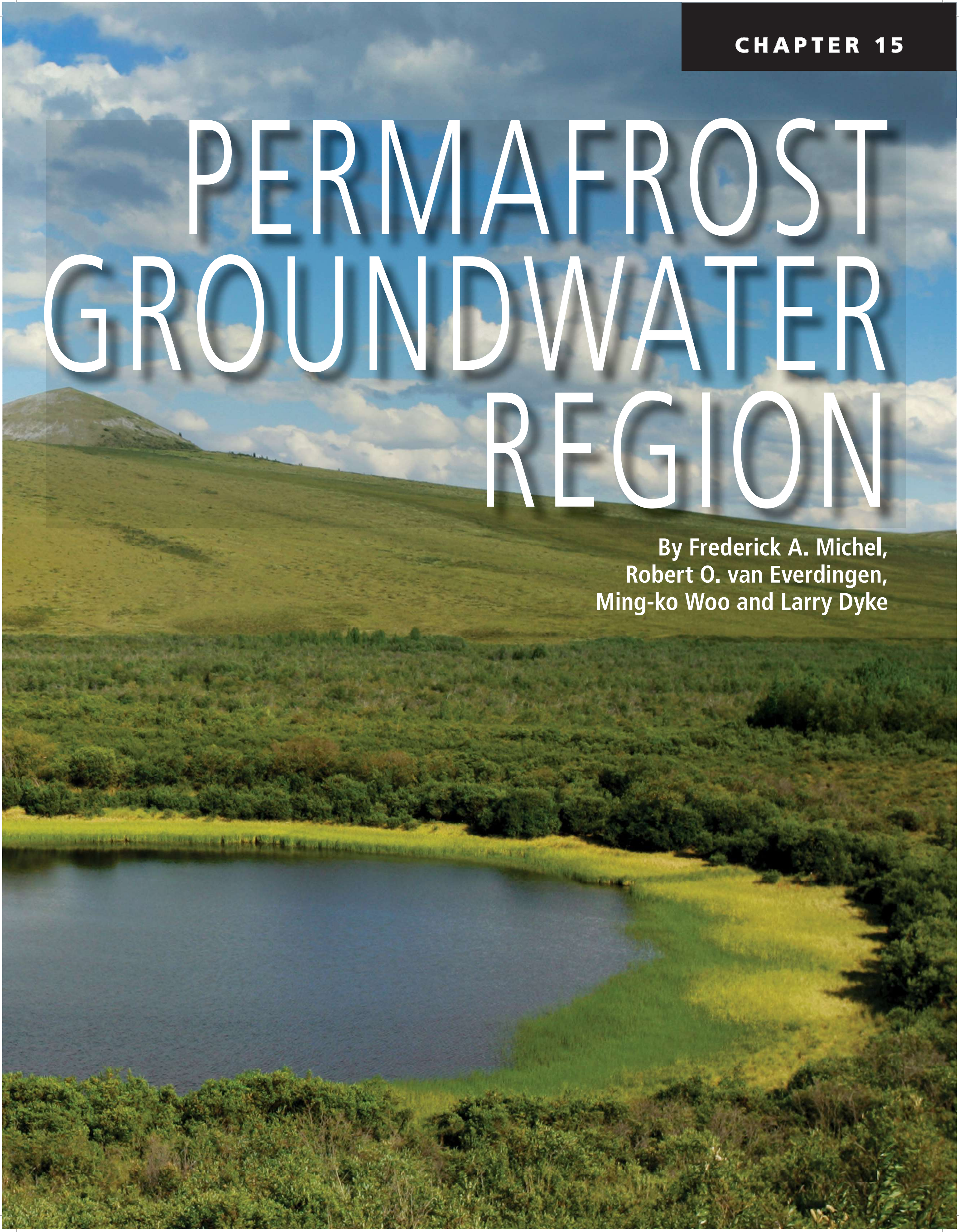


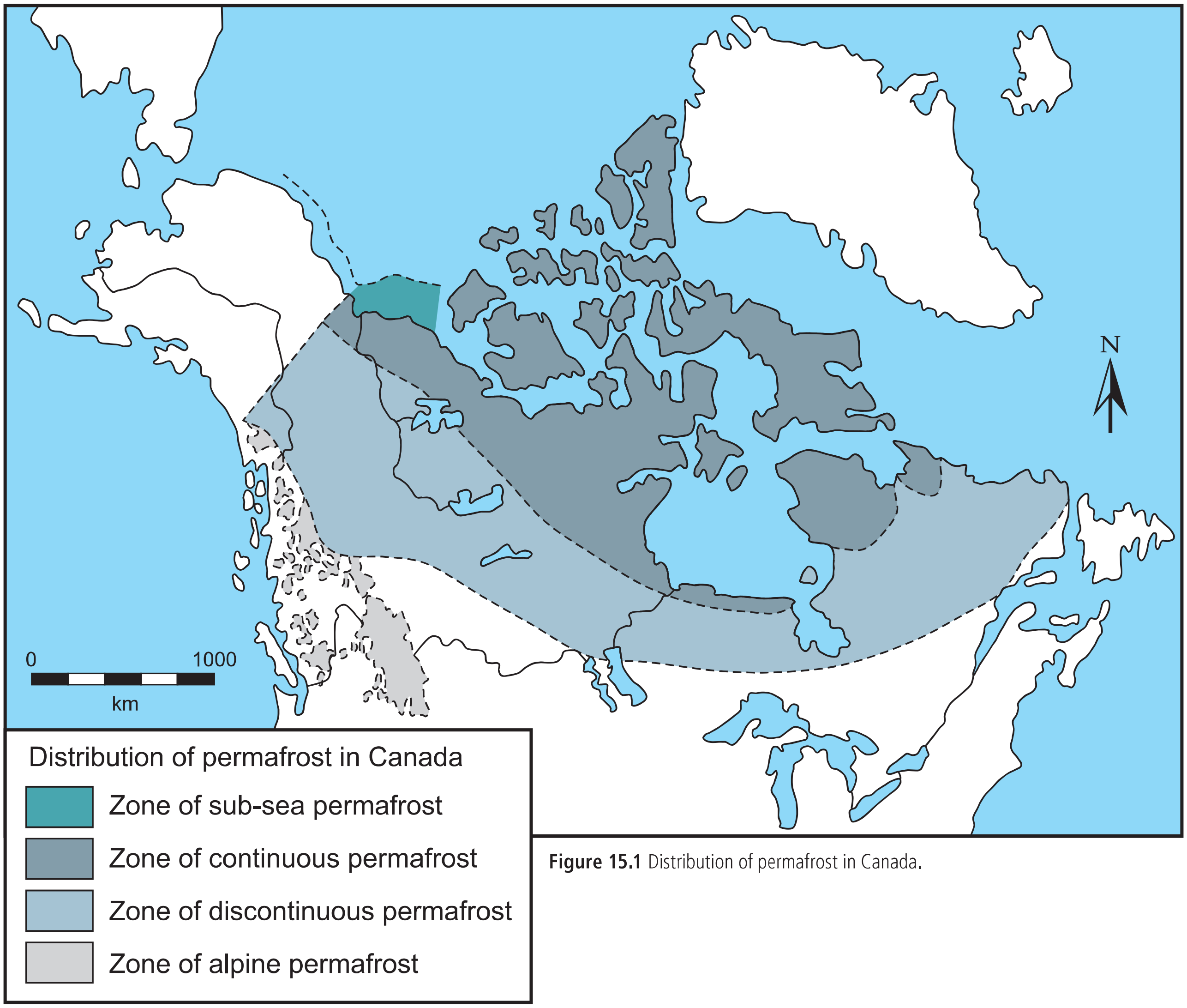


Figure 15.1 Distribution of permafrost in Canada.

15.1 INTRODUCTION

15.1.1 Permafrost

The northern groundwater region was first described by Brown (1970) as that portion of Canada north of the southern limit of discontinuous permafrost. Permafrost (or perennially frozen ground) is defined as the region exhibiting temperatures in rock or soil that remain below 0°C continuously for two or more years (Muller, 1943).

The distribution of permafrost is determined most closely by climate and its effects on the local ground thermal regime. Other influencing factors include geology, topography, slope aspect, vegetation, surface water bodies, snow cover and glacial history. The polar and subpolar regions north of the tree line are within the zone of continuous permafrost, where virtually all terrain exhibits permafrost conditions to depths ranging from tens to hundreds of metres (Figure 15.1). The continuous zone grades southward into the thinner discontinuous zone where permafrost and non-permafrost areas are interspersed. Further south, permafrost occurs only sporadically in isolated favourable settings, such as peat bogs or on north-facing slopes. Extensive relict permafrost, formed during the last ice age, has also been documented in offshore regions such as the

Beaufort Sea (Judge, 1974).

In his delineation of the northern region, Brown (1970) included areas with very patchy or sporadic permafrost, even though the territory contained large intervening areas where permafrost was absent. As a result, the northern region comprises over 50% of the land mass of Canada. Since the non-permafrost portions are similar to the more southern parts of Canada that experience only seasonal frost penetration, and since the presence of permafrost is one of the major distinguishing characteristics of the northern region, most of this chapter will focus on the region north of the southern limit of widespread discontinuous permafrost (Figure 15.1).

15.1.2 Moisture conditions in permafrost

A wide range of moisture conditions can exist in permafrost. Water contained in pores and fractures within permafrost is often frozen as ice due to the negative ground temperatures; however, unfrozen water may occur at temperatures several degrees below 0°C due to the presence of dissolved salts or if the water is under pressure. Permafrost can also be dry and contain no ice, particularly in well-drained coarse-grained clastic material and in massive unfractured crystalline rock. Therefore, the 0°C temperature condition used to define permafrost does not necessarily indicate the physical state of the moisture content.

Permafrost has often been considered as simply an impermeable barrier (or aquiclude) to groundwater movement because the pore spaces and fractures may be filled with ice. As a consequence, many people consider northern Canada to lack active groundwater flow systems. Permafrost does have a significant impact on groundwater flow regimes, especially the recharge component; however, active groundwater flow can be found to varying degrees throughout the permafrost regions of Canada. As permafrost areas become more discontinuous, isolated and patchy, the influence of permafrost on the hydrogeologic regime also decreases. Throughout all of Canada, seasonal ground freezing will affect the local groundwater regimes to some extent during the winter months.

15.2 THE NORTHERN REGION

15.2.1 Physiography and geology

The permafrost region of Canada encompasses all of Nunavut (NU), Northwest Territories (NWT), and Yukon Territory (YT), as well as the northern portions of the western provinces from British Columbia to Manitoba, and the northern half of Ontario, Quebec, and most of Labrador (Nfld). Four broad physiographic subregions are defined on the basis of diverse geology and topography; they are the Canadian Shield, northern Interior Platform, northern Cordillera, and Arctic Archipelago (Figure 15.2).

The Canadian Shield is the most extensive region, spanning the northern portions of Saskatchewan, Manitoba, Ontario, Quebec, and Labrador (Nfld), the eastern half of NWT, and much of the mainland and Baffin Island of Nunavut. The gently undulating to rugged terrain of the Shield is predominantly composed of Precambrian-age igneous and metamorphic crystalline rocks with smaller, relatively undeformed, Proterozoic-age sedimentary basins (e.g., the Thelon and Athabasca Basins). Younger undeformed Paleozoic sedimentary rocks form a broad basin that blankets the Shield rocks throughout Hudson Bay and is best exposed along the northern Ontario coast (see Chapter 11).

Bordering the Shield to the west in the NWT are the relatively undeformed flat-lying sedimentary

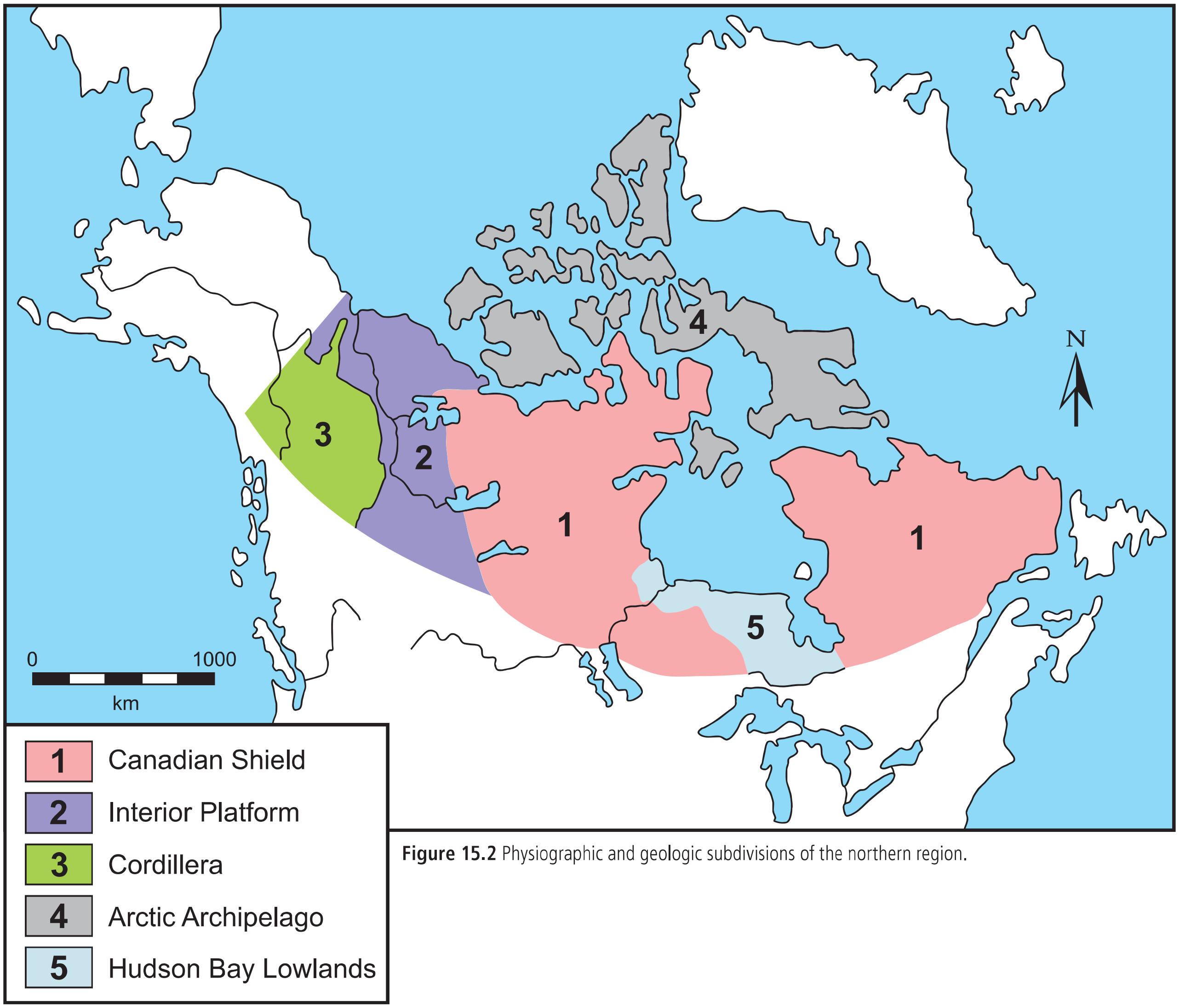


Figure 15.2 Physiographic and geologic subdivisions of the northern region.

rocks of the northern Interior Platform. This wedge of Paleozoic-age rocks is the northern extension of the broader platformal sequence that underlies the Prairies (see Chapter 10). These rocks are composed of clastics (sandstones to shales), evaporites (gypsum/anhydrite and halite), and a dominant carbonate (limestone and dolostone) sequence. The sedimentary rocks of the Mackenzie Valley are a westward continuation of the Interior Platform, but have been affected by foreland thrusting of the Cordillera. The Mackenzie Valley is a broad plain 15 to 40 km wide, bounded on the east by the low-lying Franklin Mountains and to the west by the Mackenzie Mountains of the Cordillera.

The Cordillera represents an accumulation of accretionary slices that contain a mix of crystalline rocks and steeply folded and faulted sedimentary and volcanic rocks (see Chapter 9). The northern Cordillera is composed of the Mackenzie and Yukon Mountains. The Cordilleran geosynclines experienced their main folding events during the Triassic in the Yukon Plateau region and in the late Cretaceous to early Tertiary in the Mackenzie Mountains. In northern Yukon, the British Mountains rise to over 2,000 m above sea level, while the Ogilvie and Wernecke Mountains reach 2,200m. The St. Elias Mountains, along the southwest Yukon/ Pacific coast, peak at 5,959 m with Mount Logan, the highest elevation point in Canada.

The Arctic Archipelago includes a series of islands that contain a younger wedge of folded and faulted platformal sedimentary rocks north of the Canadian Shield. The western islands are composed of less deformed low-lying terrain under 600 m in elevation, while the northern islands are mountainous, rising to over 2,000 m on Axel Heiberg and Ellsemere Islands.

With the exception of northern and western Yukon, the northern region has been affected most recently by continental and alpine glaciation during the latest Wisconsinan ice age. The Canadian Shield and Interior Platform were scraped bare of most soil cover and are now blanketed with a thin veneer of stony glacial moraine and numerous eskers radiating out from the centres of glacial retreat. Adjacent to Hudson Bay, especially the southwest portion, there is a sequence of marine clay-rich sediments and abandoned shorelines. Mountainous areas have bare to talus-covered peaks, whereas thick complex sequences of glacial and glaciofluvial sediments blanket the valley floors. The Mackenzie Valley is covered with unconsolidated Tertiary and Quaternary clastic sediments that include fine-grained glaciolacustrine sediments deposited by proglacial lakes that temporarily flooded the valley during deglaciation. The Mackenzie Delta and near-shore Beaufort Sea contain the largest and thickest accumulation of unconsolidated sediments in the northern region.

15.2.2 Population

The total population of the three territories comprising the northern region (north of 60° latitude) was 101,310 in 2006 (Statistics Canada, 2007), with 30% living in Yukon, 41% in NWT, and 29% in Nunavut. The total population for those portions of the provinces contained within the northern region was estimated at approximately 40,500 in 2001.

In Nunavut, most communities are small Inuit settlements located adjacent to the coastline; Baker Lake is a notable exception. Increased mineral exploration and development eventually will lead to the development of small local mine site populations inland that will exist for the duration of mining activity. Iqaluit, as the centre of the territorial government, is the largest community in Nunavut with a population of 6,184 in 2006.

Population centres in NWT are located primarily adjacent to inland waterways such as the Mackenzie River. Yellowknife, located on Great Slave Lake, originally developed as a mining community, later grew as the seat of the territorial government and as a major supply point for smaller northern communities. The recent development of diamond mines north of Yellowknife has led to continued growth in the city's population, which increased to 18,700 in 2006. Norman Wells was established during the 1940s to develop local oil reserves for the war effort. Inuvik was established in the 1950s as a more stable site for the local aboriginal population, and as a supply point for resource development in the Mackenzie Delta. Communities based solely on resource development tend to be abandoned following the cessation of mining activities (e.g., Pine Point).

The population of Yukon is more diverse with a mix of small communities primarily located in river valleys. In addition to native and resource-based communities, tourism is a major driver of the local economy. The city of Whitehorse is the largest community in Yukon (22,898), serving as a legislative and administrative centre for activities throughout the territory.

15.2.3 Water supply

An estimated 9 million Canadians (30.3%) relied on groundwater for their domestic water supply in 1996. According to Environment Canada's analysis of Statistics Canada 1996 data, 47.9% of Yukoners and 28.1% of the residents in Nunavut and NWT utilized groundwater as their supply source (Rutherford, 2004). Over 99% of Yukoners rely at least partially on groundwater for their domestic supply and 75.4% of the total licensed water use in Yukon is from groundwater sources (Rutherford, 2004).

Groundwater use within the northern region is restricted by the presence and extent of frozen ground and depends on groundwater availability. No communities within the zone of continuous permafrost utilize groundwater as a water supply (with the exception of Old Crow, YT; see Box 15-1), either in the low-relief areas of the Canadian Shield, or in the mountainous areas of the Arctic Archipelago and northern Labrador (Nfld). Groundwater of good quality is available in the mountainous Cordillera of Yukon and in western NWT, where local-scale groundwater flow systems are active and permafrost is discontinuous. Freezing conditions can create problems during drilling and maintenance of wells, while deep freezing reduces recharge to aquifers, in addition to seasonally cutting off water supply to shallow wells. Shallow wells completed within the active layer are also very susceptible to contamination.

In areas of crystalline rocks, where groundwater flow is restricted to weathered zones, fractures and faults, the potential for obtaining a year-round supply is generally much reduced because yield generally decreases with depth, and near-surface zones are subject to annual freezing. As a result, it is the alluvial and coarse-grained glacial deposits that provide the only potential source for groundwater supplies on the Canadian Shield.

Bedrock aquifers generally have not been exploited in those areas underlain by sedimentary rocks. Tertiary sands and gravels, in addition to Paleozoic sandstones, limestones, and dolostones are potential aquifers due to their intergranular and/or fracture permeability. Michel (1986a) identified the dolostones of the Bear Rock, Franklin Mountain, and Mount Kindle Formations in the Mackenzie Valley as the most suitable bedrock aquifers on the basis of water quality. Most communities along the Mackenzie and Liard Rivers rely at least partially (seasonally) on groundwater supplies; however, these wells are completed within unconsolidated fluvial or glaciolacustrine sand and gravel aquifers. Van Everdingen (1974) noted that fine-grained sediments associated with lakes and ponds generally have too low a permeability for development.

Sediment type greatly influences water quality, as demonstrated at the community of Wrigley along the Mackenzie River. Michel (1977) reported that the airport well, completed prior to 1960, in sand and gravel, at a depth of nearly 46 m, with the lowermost 12 m screened, produced good-quality calcium bicarbonate water. The nearby community well was completed in 1974 at a depth of 40 m, most likely in a finer-grained glaciolacustrine unit. Water quality in this second well was of much poorer quality, with a dominantly sodium bicarbonate composition that included significant concentrations of chloride and sulphate.

Groundwater extraction has been dominated in the NWT by mining operations. The former

Cominco mining operation at Pine Point in the discontinuous permafrost of southern NWT was the largest groundwater user in the entire northern region. The municipal supply for the community averaged 1,260 m^3/day, while the mill operations at the mine utilized an additional 18,000 m^3/day. Dewatering of the mine site required the extraction of another 157,000 m^3/day (van Everdingen, 1974). These quantities reflect the large flow capacities of the karstic limestone present at the site and draw attention to the large water requirements associated with mining, requirements that must be attained from either groundwater or surface water sources.

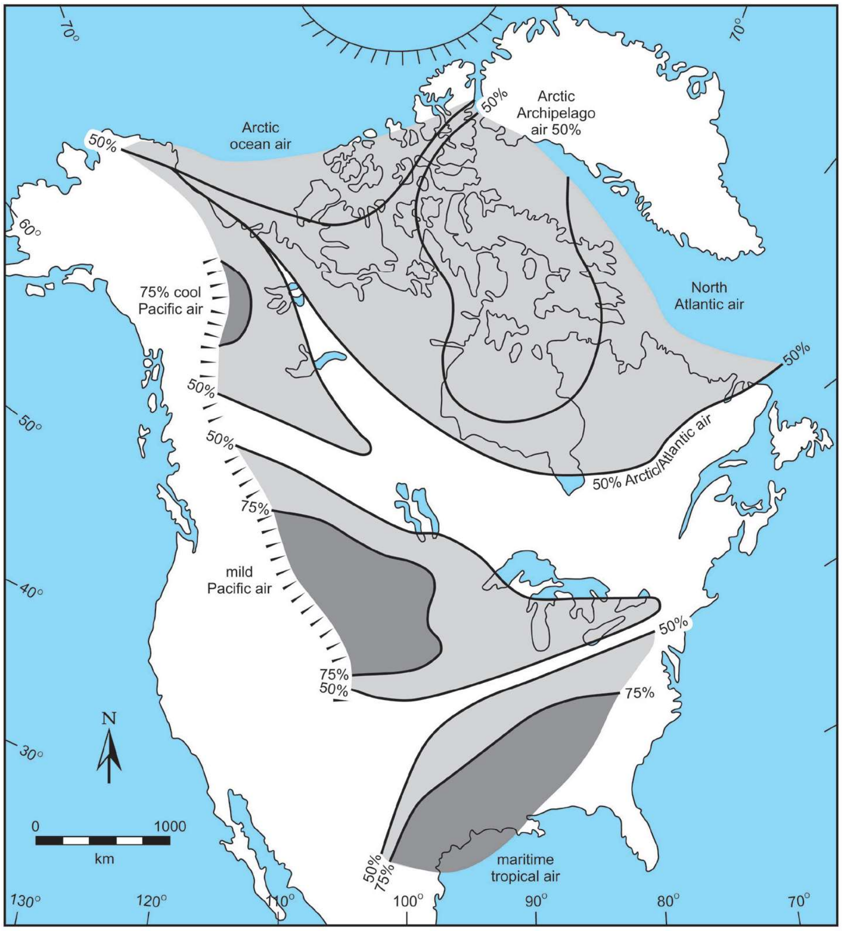


Figure 15.3 Distribution of dominant air masses in North America. The 50% frequency lines correspond to mean frontal positions in July (modified from Barry and Chorley, 1982).

According to the Yukon government's "State of the Environment Report" (Yukon government, 1999), not much is known about the quality or quantity (capacity) of groundwater aquifers throughout the Territory; however, alluvial and glaciofluvial unconsolidated deposits generally provide adequate quantities of good-quality groundwater for most communities. Within Yukon, almost all communities currently rely on groundwater, and most rural residents have wells. Carcross is the only exception because its groundwater supply was found to contain elevated arsenic concentrations. As a result, its citizens now rely on Lake Bennett for their water supply. Groundwater in several other communities contains elevated concentrations of manganese, but this is seen as more of an aesthetic issue.

The community of Old Crow, located within the continuous permafrost region of northern Yukon, has utilized a bedrock aquifer (limestone and dolostone) since 1982 for its water supply because permafrost extended throughout the thickness of the alluvium intended as the original target (see Box 15-1). Further south, in Dawson City, where permafrost is absent in the alluvium immediately adjacent to the Yukon River, the community has drilled wells in the alluvium for their water supply. Pumping of these wells induces infiltration of the river water through the alluvium where it is naturally filtered to remove any suspended particles.

Historically, Whitehorse obtained its municipal water supply from Schwatka Lake and

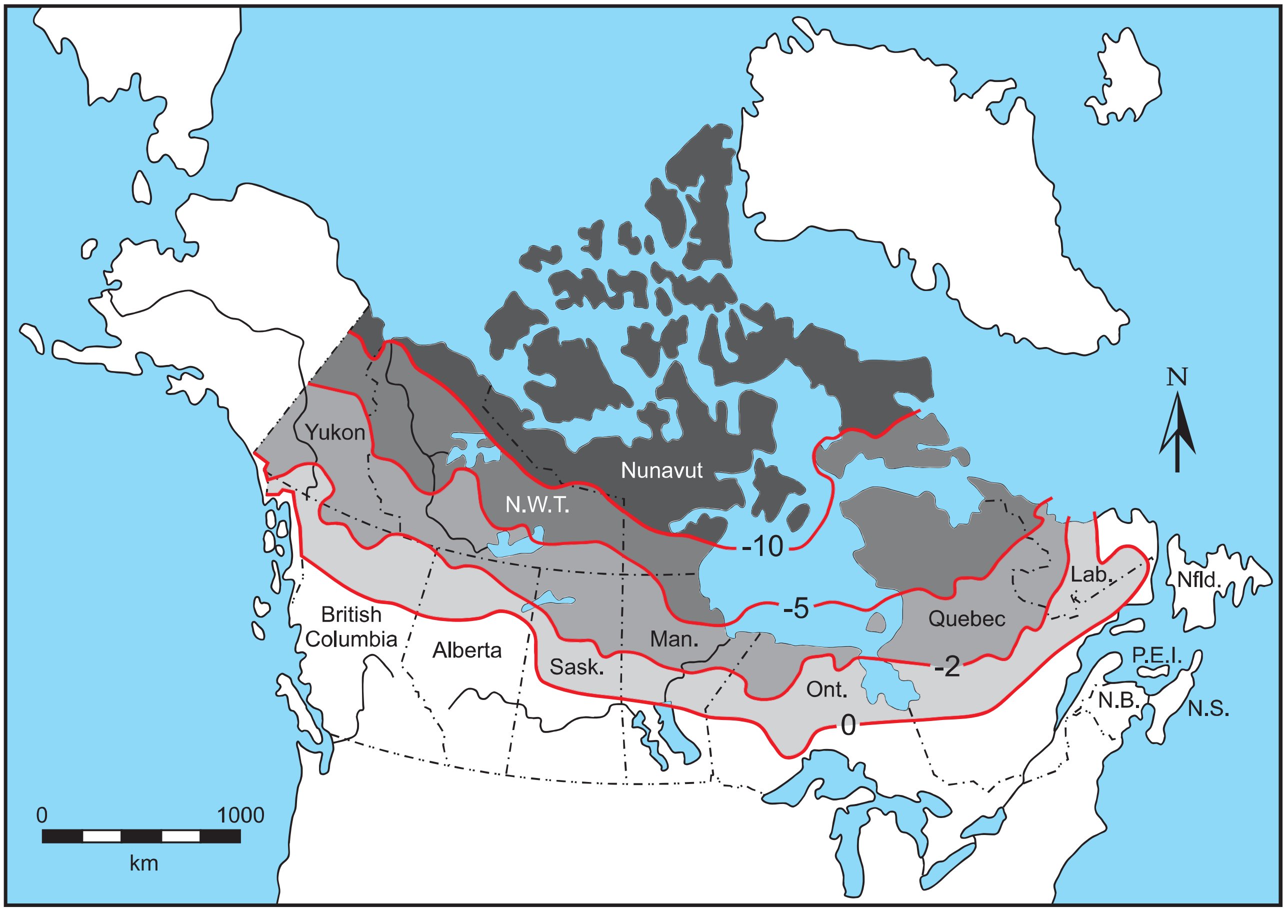


Figure 15.4 Distribution of mean annual air temperature (MAAT) in Canada (from NRCan website, 2012). The –5°C and 0°C MAAT correspond with the boundaries of continuous and discontinuous permafrost, respectively as seen in Figure 15.1.

two local aquifers, the Selkirk and the deeper Whitehorse. In 1997, approximately 30% of the total supply was from groundwater; in December 2009, the city switched entirely to groundwater. The groundwater aquifers provide a reliable, good-quality supply, but their best attribute is the constant positive temperature that they produce. Previously, Whitehorse's groundwater was mixed with the cold surface water supply to raise water temperatures and prevent freezing of pipes during winter, and to reduce the silt load found in the surface water during spring melt. Constant water flow through the bleeder systems during winter, coupled with water loss due to leakage from pipes, meant that the average consumption of water in Whitehorse in 1998 was 842 litres/person/day, compared to the Canadian average of 326 litres/person/day (Yukon Government, 1999). The switch to 100% groundwater and recent pipe repairs are expected to reduce this rate of usage significantly.

Installation and operation of monitoring wells within and through permafrost can result in changes in the thermal regime, which in turn can cause local changes to the groundwater flow system. Frost heave acting on the well casings can cause significant frost jacking (changing the elevation of the casing), potentially breaking pipe joints, and allowing migration of water between aquifers (J. Miller, personal communication).

15.2.4 Climate

The northern permafrost region encompasses the arctic (tundra) and subarctic (boreal) climatic regions where winters are long and cold, while summers are short (2 to 3 months) and cool. The boundary between the two regions is delineated by the tree line, which corresponds to a mean July temperature of approximately +10°C, a mean annual air temperature (MAAT) of –8.5°C, and a mean annual ground temperature of –5°C. This boundary also approximates the division between continuous and discontinuous permafrost.

The climate of the North American continent is controlled by three major air masses originating in the Arctic/North Atlantic, Pacific, and Gulf of Mexico (Barry and Chorley, 1982) (Figure 15.3). Each of these air masses dominates at different times of the year, resulting in differing temperatures and precipitation patterns across the continent. The northern region corresponds to that area dominated by the cold and relatively dry Arctic/North Atlantic air mass. The mountains of the northern Cordillera form a partial barrier that results in a stronger Pacific influence for southern Yukon. Within the mountainous regions of the Cordillera and Arctic Archipelago, temperature inversions occur during winter: when the coldest air sinks to valley floors, higher elevations are somewhat warmer.

Negative winter air temperatures cause near-surface ground freezing throughout Canada. These seasonally frozen soils thaw completely in southern Canada, as temperatures rise during the spring. In northern Canada, the near-surface frozen soils also thaw gradually, during the short summer season of above 0°C temperatures, to form an unfrozen active layer (which can range from 0.2 to 2.0 metres in thickness) above the permafrost. The rate of thaw depends primarily on air temperature, ice content of the soil, and vegetation and snow (insulation) cover. Within the continuous permafrost region, the lower boundary of the active layer usually corresponds to the upper permafrost surface (table) where ground temperatures remain below 0°C. Depending on the ground thermal regime, the permafrost table in the region of discontinuous or sporadic permafrost may be deeper than the active layer zone of annual freeze/thaw. Winter temperatures often below –30°C ensure refreezing of the active layer and result in MAAT as low as –20°C in the Arctic Islands (Figure 15.4).

Mean annual precipitation (MAP) is relatively low throughout northern Canada, ranging from 500 to 600 mm per year in central Quebec, Labrador (Nfld), and southwest Yukon, to less than 100 mm per year in the high Arctic Islands, thereby creating a polar desert. Snowfall accounts for 35 to over 80% of the total annual precipitation in the permafrost region and provides a moisture store that is released rapidly during the melt period each spring. Evapotranspiration exceeds 60% of the total precipitation over most of the region (see Figure 4.3).

15.3 SURFACE HYDROLOGY

15.3.1 Surface ponding

Surface ponding and wetland formation are prevalent in flat terrain because deep percolation is inhibited by the presence of frozen ground. Thermokarst lakes are produced by permafrost thaw (Mackay, 1992). The presence of these lakes increases the open water area, thus enhancing evaporation. Where lake density is high, the regional energy and water fluxes can be affected. Nagarajan et al. (2004) observed this relationship in the northern Mackenzie Basin. Increased evaporation from lake areas provides more moisture to the atmosphere, which is then recycled back as precipitation, thus accelerating the land-atmosphere water circulation. Lake ice regime has a significant effect on annual lake evaporation because a long ice-covered period shortens the evaporation season. A warmer climate will lead to a longer evaporation season and can raise the lake water temperature which, when transmitted to the lake bottom, will promote development of a deeper active layer or a talik below the lake.

Tundra lakes are sensitive to changes in the permafrost. A recent study by Smith et al. (2005) found that in the continuous permafrost zone of western Siberia, there has been an increase in both the number and the area of tundra lakes, attributable to climate warming and thermokarsting. In the discontinuous permafrost zone further south and where the permafrost is thin, continued deepening of the active layer may lead to lake drainage by thawing.

Areas with abundant surface water storage also support wetland development. Wetlands in the continuous permafrost zone are areas with extraordinarily rich and diverse flora. Winter freezing of saturated soil in wetlands yields considerable seasonal ground ice. In the discontinuous permafrost zone, valley wetlands are also prone to icing formation, with water supplied by lateral drainage from adjacent hill slopes. For almost all wetlands, the accumulation of peat insulates the ground against deep thaw in the summer; peat holds large amounts of ground ice which requires much latent heat to melt. The consequence is preservation of a shallow thawed zone in the organic terrain (Woo et al., 2006a), thus limiting the subsurface storage capacity and enabling the water table to rise and saturate the entire active layer. Feedback between soil saturation and slow thaw of ground-ice–rich terrain ensures that wetlands are a self-sustaining system (Woo et al., 2006b).

15.3.2 Streamflow

Depending on the primary water sources or the water storage mechanisms that influence the temporal pattern of flow, three groups of streamflow regimes (or seasonal rhythm of streamflow) can be recognized within the permafrost region.

15.3.2.1 Nival regime

Snow in permafrost regions accumulates over many winter months without melt interruption. In spring, most or all of the snow melts within days or weeks, yielding large quantities of water in a short time. Because shallow ground thaw inhibits infiltration, runoff responds quickly to snowmelt to produce sharp hydrograph rises. Surface flow is prevalent, efficiently delivering abundant runoff to nearby streams. The dominance of snowmelt runoff in the seasonal rhythm of streamflow is evident in most rivers of the permafrost region (Figure 15.5a). This pattern of flow was termed the nival regime by Church (1974) to signify the importance of snowmelt contribution.

High flows in Arctic rivers are complicated by deep snow drifts in the channels (Xia and Woo, 1992). In subarctic rivers, breakup of river ice intensifies the magnitude of floods (Prowse and Ferrick, 2002). Once the flow begins, it usually exhibits a marked diurnal rhythm, reflecting the daily melt cycle. A spell of warm, sunny days will generate increasingly high daily flows, while the onset of cool, overcast conditions will curtail snowmelt, thus leading to a decline in streamflow. After the snow is melted, spring high flows recede rapidly to baseflow. Low flows are occasionally interrupted

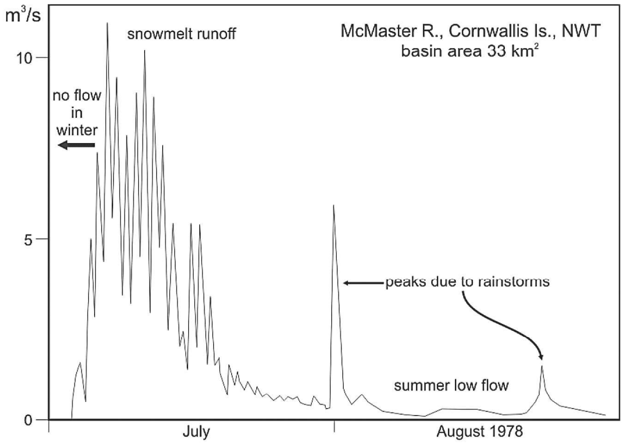


Figure 15.5a Typical streamflow regimes in permafrost areas: Nival regime, with example from McMaster River, Cornwallis Island (after Woo, 1986).

by hydrograph rises, caused by rainfall or summer snowfall, but the summer peaks are generally lower than those in the spring.

Flow patterns can be further subdivided into arctic and subarctic nival regimes. The subarctic regime is distinguished from its arctic counterpart by a longer streamflow season and more prominent summer peaks generated by heavy rainfall events. Taliks in the discontinuous permafrost permit winter flows to be maintained by the discharge of subpermafrost and intrapermafrost groundwater. In some areas, river icing formation is enhanced by a continuous discharge of groundwater supplied from deep sources. The result can be an extensive and thick icing covering a large part of the local valley (Clark and Lauriol, 1997).

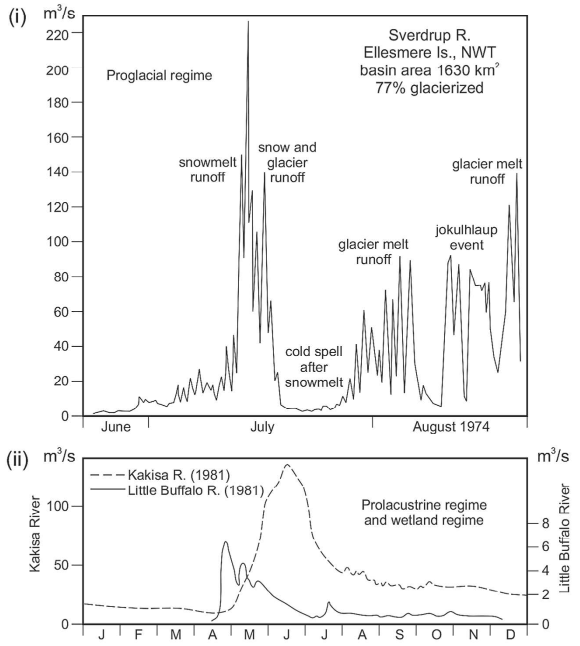


Figure 15.5b Typical streamflow regimes in permafrost areas: (i) modifications of nival regime— proglacial regime of Sverdrup River, Ellesmere Island; (ii) prolacustrine regime of Kakisa River, NWT; and wetland regime of Little Buffalo River, NWT (after Woo, 1986).

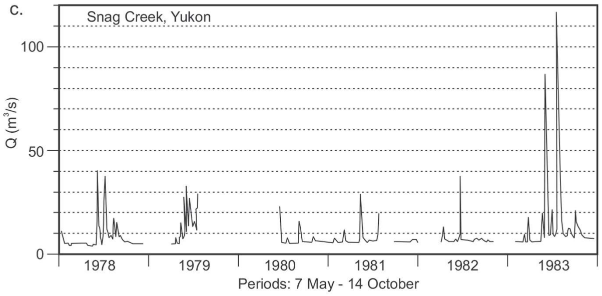


Figure 15.5c Typical streamflow regime in permafrost areas: spring-fed regime, Snag Creek, Yukon (after van Everdingen, 1988).

15.3.2.2 Modifications of the nival regime

The presence of glaciers, lakes, and extensive wetlands modifies the summer low flows of the nival regime (Figure 15.5b). Glaciers provide an available water source after the basin snow cover is depleted, so that snowmelt runoff is extended and superseded by glacier melt contribution. Rivers issuing from glaciers show a proglacial regime (Church, 1974), with the summer yield controlled largely by the energy available for ice melt. Lake storage reduces the magnitude of peak inflows, but enhances the low flow discharges. Consequently, compared with the nival regime, a lake-modified or prolacustrine regime has lower peaks and higher baseflows. Timing of peak flow in response to rainfall or snowmelt is also delayed. Wetland storage is far less effective than lakes in regulating runoff. Streams with a wetland regime are fed by poorly drained areas which, when thawed, may have relatively large water-retention capacity in their peaty soil to attenuate high flows. This detention mechanism is ineffective in spring, however, when the wetland is frozen (Woo, 1988), and storage is then provided only by surface depressions and ponds.

15.3.2.3 Spring-fed regime

Deep-seated groundwater within or below the permafrost may be connected to the ground surface via taliks, and emerge locally as mineral springs, or as a water supply to streambeds (van Everdingen, 1987). Streams fed principally by this water source are found mainly in carbonate terrain. They have a stable baseflow which is maintained throughout the year (e.g., Figure 15.5c charts Snag Creek, Yukon, described by van Everdingen [1988], with a baseflow rate of approximately 4 m^3/s); the hydrographs may contain spikes induced by snowmelt and rainfall inputs.

15.4 GROUNDWATER

15.4.1 Permafrost hydrogeology

The hydrogeology of the northern region has received little attention over the years. Brown (1970) provided a brief summary based on early work by Brandon (1965), permafrost investigations by R.J.E. Brown and G.H. Johnston of the National Research Council, and discussions with mine operators. Van Everdingen (1974) published the first comprehensive review of groundwater in the permafrost regions of Canada, coauthored reviews for North American studies of groundwater in permafrost (Williams and van Everdingen, 1973; Sloan and van Everdingen, 1988), and authored report chapters on northern groundwater hydrology (van Everdingen, 1987, 1990). Similar reviews written for Alaska (Williams, 1965, 1970; Zenone and Anderson, 1978; Heath, 1984) and Russia (Tolstikhin and Tolstikhin, 1974) provide the basis for our understanding of groundwater systems in permafrost regions.

The knowledge of permafrost hydrogeology in Canada has been limited largely to observations of karstic recharge (Brook, 1976, 1983; Michel, 1977; Michel and van Everdingen, 1988; van Everdingen, 1981); groundwater discharge as springs, seeps, and related phenomena (Brandon, 1965; Gulley, 1993; Hamilton, 1990; Hamilton et al., 1988, 1991, 2003; Michel, 1977, 1986a,1986b; Michel and Paquette, 2003; Michel and van Everdingen, 1987; Pollard, 1983; Pollard et al., 1999; van Everdingen, 1974, 1978, 1981, 1982, 1988); mine studies (Douglas et al., 2000; Frape and Fritz, 1987; Ruskeeniemi et al., 2004), and data from municipal water supply wells (Brandon, 1965; Trimble et al., 1983). Detailed surface hydrology studies examining potential infiltration through the active layer and upper permafrost are more numerous (e.g., Carey and Woo, 1999, 2000; Marsh, 1988; Marsh and Woo, 1993; Woo, 1988; Zhao and Gray, 1999) because of the impact of frost heave on man-made structures, and the potential for rapid contamination of the surface environment.

Groundwater movement direction and rate in permafrost regions are generally dependent on the same physical parameters as in areas without permafrost. However, the presence of permafrost constitutes a low-permeability layer and exerts a significant but variable influence on groundwater recharge and discharge. It is important, therefore, to place aquifers in a context of their position relative to the permafrost zone, and scientists find it convenient to group aquifers into three categories related to that position: suprapermafrost, intrapermafrost, or subpermafrost (Figure 15.6).

Suprapermafrost aquifers are situated above the permafrost. In areas of continuous and widespread discontinuous permafrost, the seasonally frozen active layer above the permafrost forms the suprapermafrost aquifer. Thickness of this layer, usually consisting of organics and weathered mineral soil, is generally restricted to less than two metres. Refreezing of the active layer during winter makes it unsuitable for water supply considerations; however, suprapermafrost water plays a significant role in geotechnical problems involving frost heave and slope instability (Williams, 1979; Williams and Smith, 1989). Where degradation of the upper permafrost surface has occurred, such that winter freezing does not reach the permafrost table, a perennially unfrozen zone will exist that may contain coarse-grained material to form a near-surface aquifer capable of providing groundwater year round. Areas covered by surface water bodies that retain some unfrozen water throughout the year (water depths greater than 2.0 to 2.5 m) are especially important since they provide a source of heat to maintain a relatively thick unfrozen zone beneath. These suprapermafrost aquifers are capable of providing annual water supplies and form important conduits for groundwater discharge as baseflow in rivers.

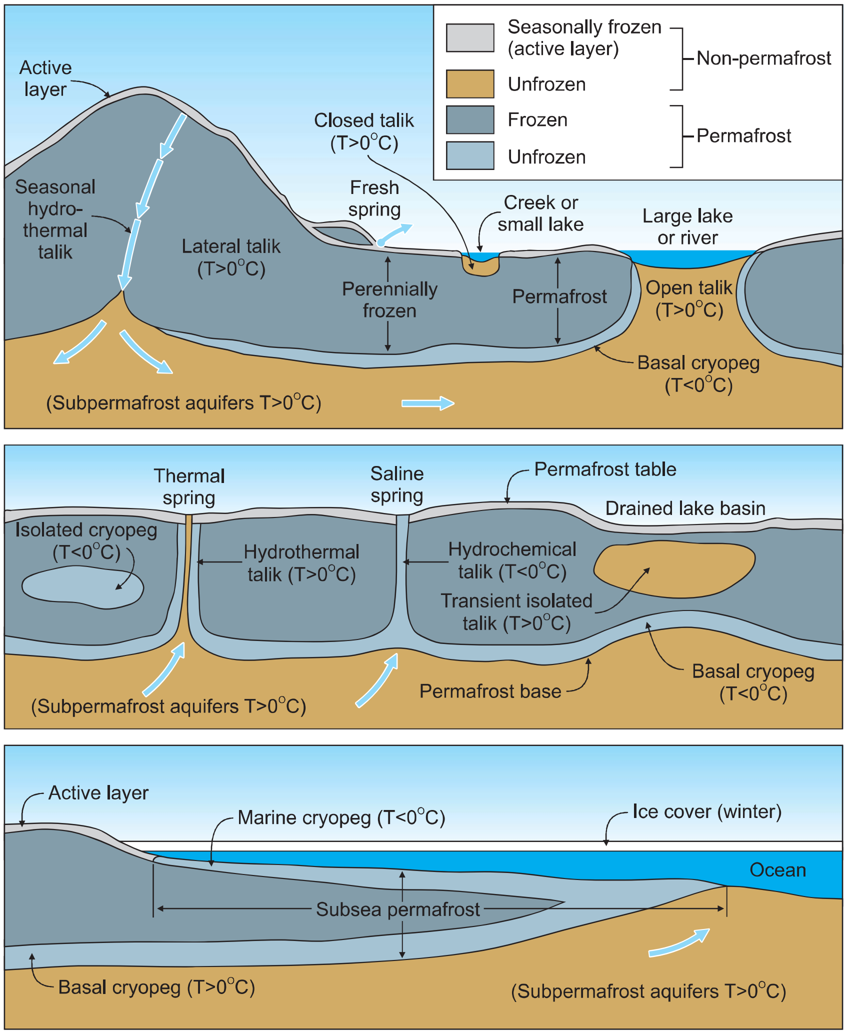


Figure 15.6 Cross sections illustrating terminology for groundwater flow in a permafrost environment (from van Everdingen, 1998).

Intrapermafrost aquifers exist within the zone of permafrost and are not subject to seasonal freezing. Their extent is usually relatively constant, being affected primarily by long-term climatic trends. Water temperatures are usually above 0°C and are maintained by the upward flow of deeper, warm groundwater or downward heat flow from large surface water bodies (lakes and major rivers). Depending on the size and depth of the surface water body, unfrozen zones can extend through the entire thickness of the local permafrost as an open talik, which connects groundwater flow above and below the permafrost, or as a thaw bulb (closed talik) containing suprapermafrost water. Where permafrost aggradation is occurring, such as beneath the bottom of a recently drained lake or abandoned river channel, taliks can become isolated and gradually decrease in size as freezing continues. Unfrozen water can also exist in intrapermafrost aquifers at subzero temperatures if the dissolved solids content is sufficient to cause a freezing-point depression. Intrapermafrost aquifers represent permeable zones through which unfrozen water can migrate. They may take the form of an open karst passageway, a fault zone, or a permeable geologic unit.

Subpermafrost aquifers comprise all permeable materials below the base of the permafrost, and contain water with above 0ºC temperature. As a result of salt expulsion during freezing, a thin zone of unfrozen saline water may exist within the bottom portion of the permafrost, forming a basal cryopeg where the temperature is still below 0ºC. Within areas of thick permafrost, subpermafrost aquifers will be restricted to bedrock. In the igneous and metamorphic terrain of the Canadian Shield, groundwater flow will be limited to interconnected fractures and fault zones. In the western and northern areas of the northern region with thick sedimentary sequences, subpermafrost groundwater flow will be similar to non-permafrost regions. Valleys containing alluvial sediments that exceed the thickness of the permafrost provide ideal targets for water supply wells. However, because of the length of time it may have been in the ground, subpermafrost water may contain an elevated dissolved-solids concentration, making it unacceptable for human consumption. Residence times can vary greatly. Michel (1977) found that most groundwater within the active flow systems of the Mackenzie Valley are postglacial in age, while some ice from within permafrost contains isotope signatures indicative of water recharged during glacial times (Michel and Fritz, 1978; Michel, 1982).

15.4.2 Infiltration and recharge

Infiltration, or water entry into the ground, is the principal mechanism of recharge, which is predicated upon the amount of water supply and the capacity of the land to accept the water. Light drizzle on vegetation, and on the land surface, is largely lost to evaporation and becomes unavailable for infiltration. Rapid release of ample water such as during heavy rain or intense snowmelt, on the other hand, often exceeds the infiltration capacity, with the result that much of the water may run off instead of recharging the ground. In permafrost areas, snowmelt and rainfall are the common water sources, although, locally, water can be supplied by lateral overland flow.

The bulk of water input in the permafrost region arrives in spring (from snowmelt)when the ground is frozen. Infiltration into frozen soil is a major consideration of recharge. The work of Gray's team (Granger et al., 1984), although conducted in Saskatchewan for seasonally frozen soil, is equally applicable to all permafrost areas when the active layer is frozen during the snowmelt period.

Infiltration into frozen soil can be unlimited, as in the case of gravels or peat without interstitial ice, restricted, as in ice-rich clay or silt where the soil pores are sealed with ice to prevent water entry, or limited, in which case the cold soil permits some infiltration (Figure 15.7a). Zhao et al. (1997) noted that infiltration into frozen soil occurs in two phases: an early transient regime of larger heat and water fluxes than the later steady-state regime, when infiltration is more subdued (Figure 15.7b).

Zhao and Gray (1999) provided an equation to describe cumulative infiltration into frozen soil of limited infiltrability (INF in mm):

$$INF = cS_{o}^{2.92}(1-S_{I})^{1.64}[(273.15-T_{I})/273.15]^{-0.45}t_{o}0.44 \qquad (15.1)$$

where c is a coefficient, S_o is surface saturation minus moisture content at the soil surface, T_I (in degree K) and S_I are, respectively, average temperature and average soil saturation (water and ice) of 0–40 mm soil layer at the start of infiltration, and t_o is infiltration opportunity time (in hours). Here, S_I is the ratio of the volumetric soil moisture content to the soil porosity. When the active layer is thawed, infiltration is governed by the intrinsic soil property, since ground ice no longer plays a role in blocking the soil pores within the active layer. However, ice contained in the permafrost, at the base of the active layer, still restricts deeper penetration of the infiltrating water.

The presence of soil cracks can greatly enhance infiltration. Woo et al. (1990) measured infiltration in silty soils of Hot Weather Creek area, Ellesmere Island, and found that, in the absence of cracks, silt has the lowest infiltration rate, followed by gravel and silt mixture, while sandy soil allows the highest infiltration. The presence of small cracks in silt initially permits a high rate of infiltration, although infiltration declines when silt swells to close the cracks, (Figure 15.7c). A high infiltration rate is maintained, however, when the silt has large cracks. Another feature that affects infiltration is the presence of a surface layer with highly porous organic materials that may include living plants and peat. The abundance of pores, unless filled with ice in the spring or saturated during the thawed season, allows ready infiltration of meltwater or rainwater. When the substrate is frozen and impervious, however, the infiltrated water can quickly saturate the thawed layer, causing infiltration to cease.

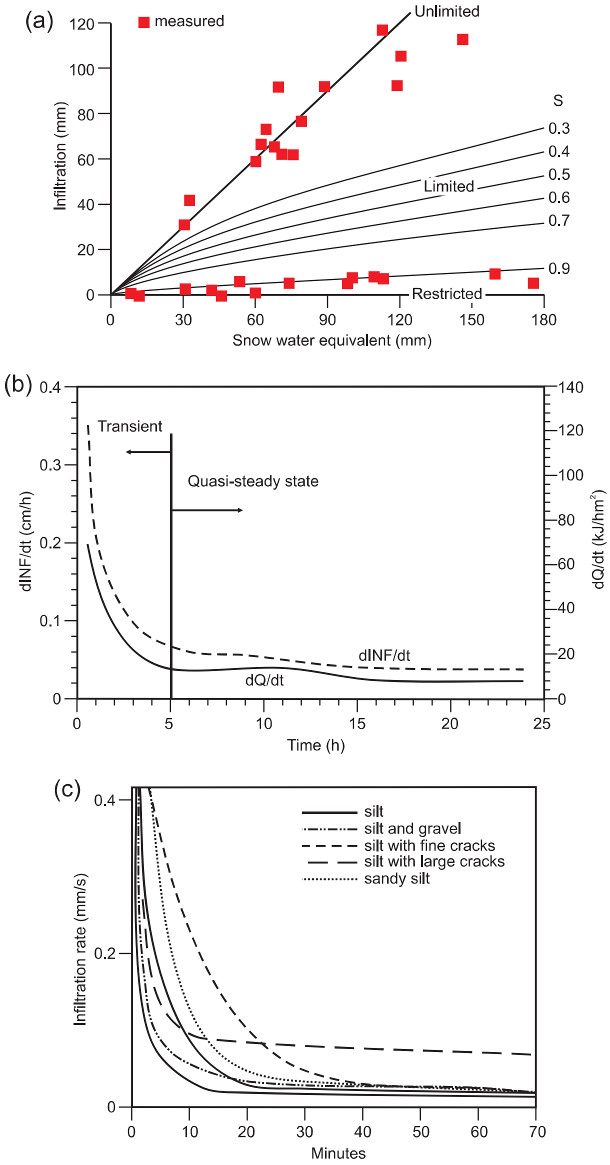


Figure 15.7 Infiltration into frozen soil: **(a)** unlimited, limited and restricted infiltration versus snow water equivalent; **(b)** variations in infiltration rate (dINF/dt) and heat flux rate (dQ/dt) plotted against time, for limited infiltration; and **(c)** infiltration curves for frozen soils with and without cracks. Figures after Granger et al. (1984), Zhao et al. (1997) and Woo et al. (1990).

Frozen, coarse materials have a higher infiltration capacity than fine-grained soils. In Resolute,

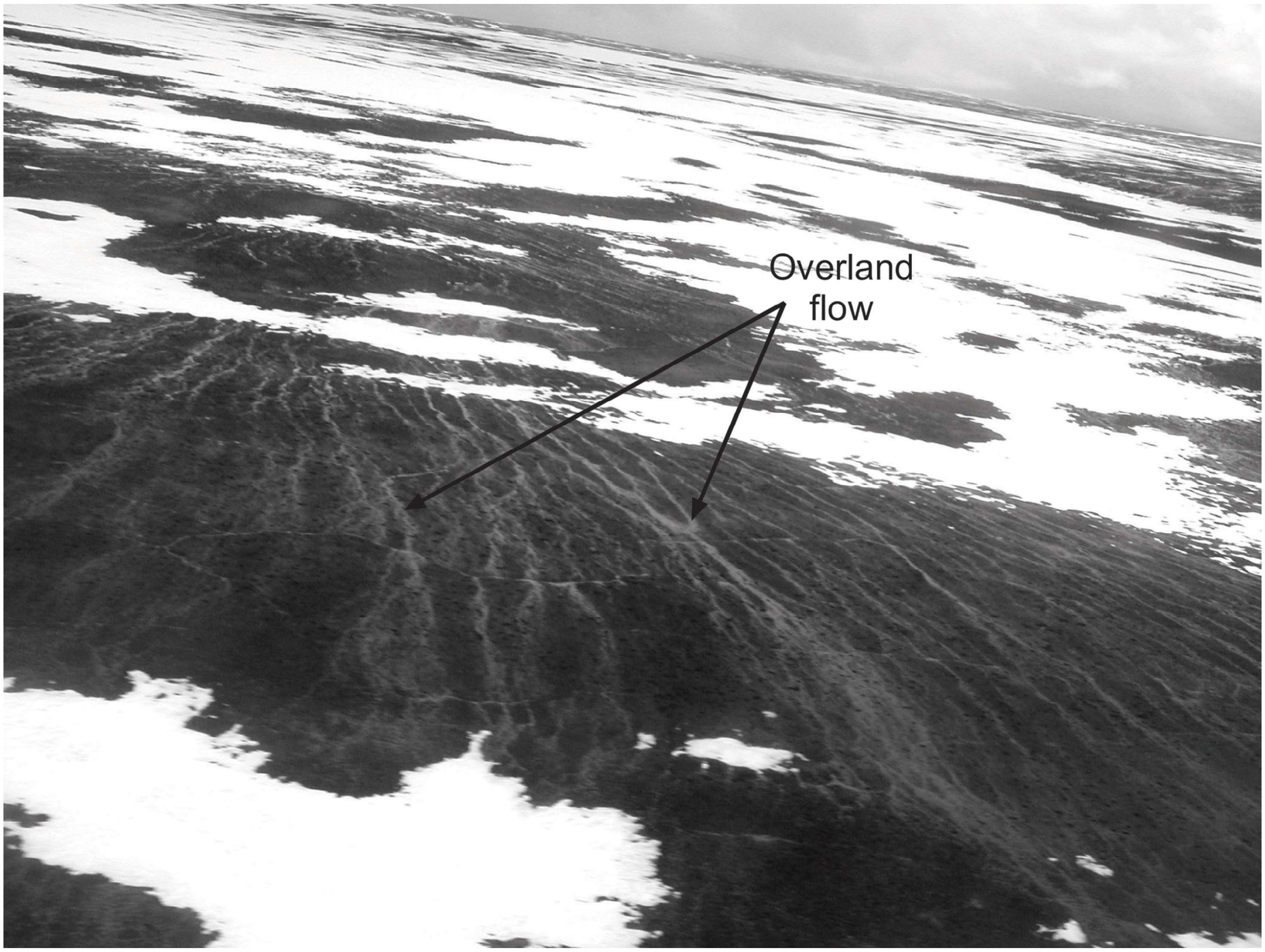


Figure 15.8 Extensive overland flow occurring during snowmelt due to limited infiltration of meltwater into frozen soil, eastern Bathurst Island, Nunavut (photo: M. K. Woo).

Nunavut, for example, a site with 70% gravel and 20% sand content had 3.5–4 times more water infiltrate than an adjacent site with 30% gravel and 40% sand (Marsh and Woo, 1993). Infiltration in continuous permafrost areas represents a small portion (about 5% to 20%) of total snowmelt, although the infiltration rate in some frozen coarse sand has been found to be high enough that little surface runoff remains (Marsh, 1988). In many areas with discontinuous permafrost, meltwater infiltrates along soil cracks and through the lichen and moss cover to be stored in the organic mat (Kane et al., 1981). This infiltrated water usually freezes in the interstitial spaces within the soil, thus increasing soil imperviousness.

Downward percolation is generally considered to be restricted by imperviousness of the frozen substrate. This is predicated upon the pores and cracks in the permafrost or the frozen active layer being filled by ground ice. However, Burt and Williams (1976) have shown that infiltration can occur even when ice is present because of the large thermal gradients present in the upper permafrost. Michel (1982) and Burn and Michel (1988) found that young tritiated water exists in the uppermost ice-rich permafrost; some of this tritiated water may also be related to an aggrading permafrost table caused by changing climatic conditions (Michel, 2008).

Intrapermafrost taliks can provide conduits for deep percolation. Similarly, karst terrain, with many solution openings in its carbonate rocks, allows easy movement of groundwater. One example was provided by Brook (1983), who observed flooding of depressions in the Nahanni karst area during the snowmelt season; when the ice blocking the drainage routes melted in autumn, these temporary ponds (measuring over 100 m in length) disappeared quickly as the water drained through the subterranean passages. Similar observations reported by van Everdingen (1981) for the karst of the Interior Platform east of Norman Wells demonstrate the importance of recharge in the late summer and autumn when maximum thaw conditions exist.

The general imperviousness of frozen soils limits infiltration and deep percolation, thus enhancing surface runoff, particularly for snow meltwater. Widespread surface flow of this nature (Figure 15.8) occurs in the continuous permafrost region during and immediately after the snowmelt season, when the considerable volumes of meltwater cannot be absorbed by the thin layer of thawed soil (Woo and Steer, 1982). During summer, the thawed zone within the active layer can be too shallow to accommodate inputs from intense rain events; as a result, the suprapermafrost water table rises to the ground surface and generates overland flow.

Frozen and unfrozen ground coexist in areas with discontinuous permafrost; this can give rise to large spatial contrasts in runoff. Many permafrost-free (e.g., south-facing) slopes with little ground ice allow meltwater and rainwater to infiltrate, and then percolate deeply. These slopes seldom generate surface runoff (Carey and Woo, 1999; Kane et al., 1981). Slopes underlain by permafrost are often covered by peat and living moss and lichen. Snow meltwater may enter the porous organic layer, but cannot penetrate the frozen substrate containing pore ice and segregated ice. Consequently, the organic layer becomes saturated, permitting surface flow and/or rapid lateral drainage in the organic soils. Runoff concentrates along rills and soil pipes, most of which develop at the organic-mineral soil interface (Carey and Woo, 2000).

15.4.3 Karst systems

Active groundwater flow through sedimentary rocks of carbonate or evaporite composition in northern Canada has increased the development of karstic terrain. Enlargement of channelways by the dissolution of exposed outcrops and near-surface bedrock is important for recharge, and continuation of these discrete channels (as taliks) through the subsurface often yields large-volume cold-water spring discharges. To a large extent, dissolution of near-surface carbonates within the Arctic islands has been confined to enlargement of joints since deglaciation (Bird, 1963). Saline springs discharging on Axel Heiberg Island are considered to represent groundwater flow through karstified gypsum domes (Beschel, 1963; Pollard et al., 1999), where the evaporites form a sink for meltwater runoff from nearby alpine glaciers. Discharge temperatures of the springs are above 0°C, but quickly drop during winter as the water flows over the ground surface. Downstream unfrozen water temperatures as low as –12°C have been recorded (Heldmann et al., 2003) as a result of the high concentration of dissolved salts in the groundwater.

Groundwater flow through well-developed karstic terrain within the Cordillera is confined to carbonates. Extensive networks of poljes, caves,

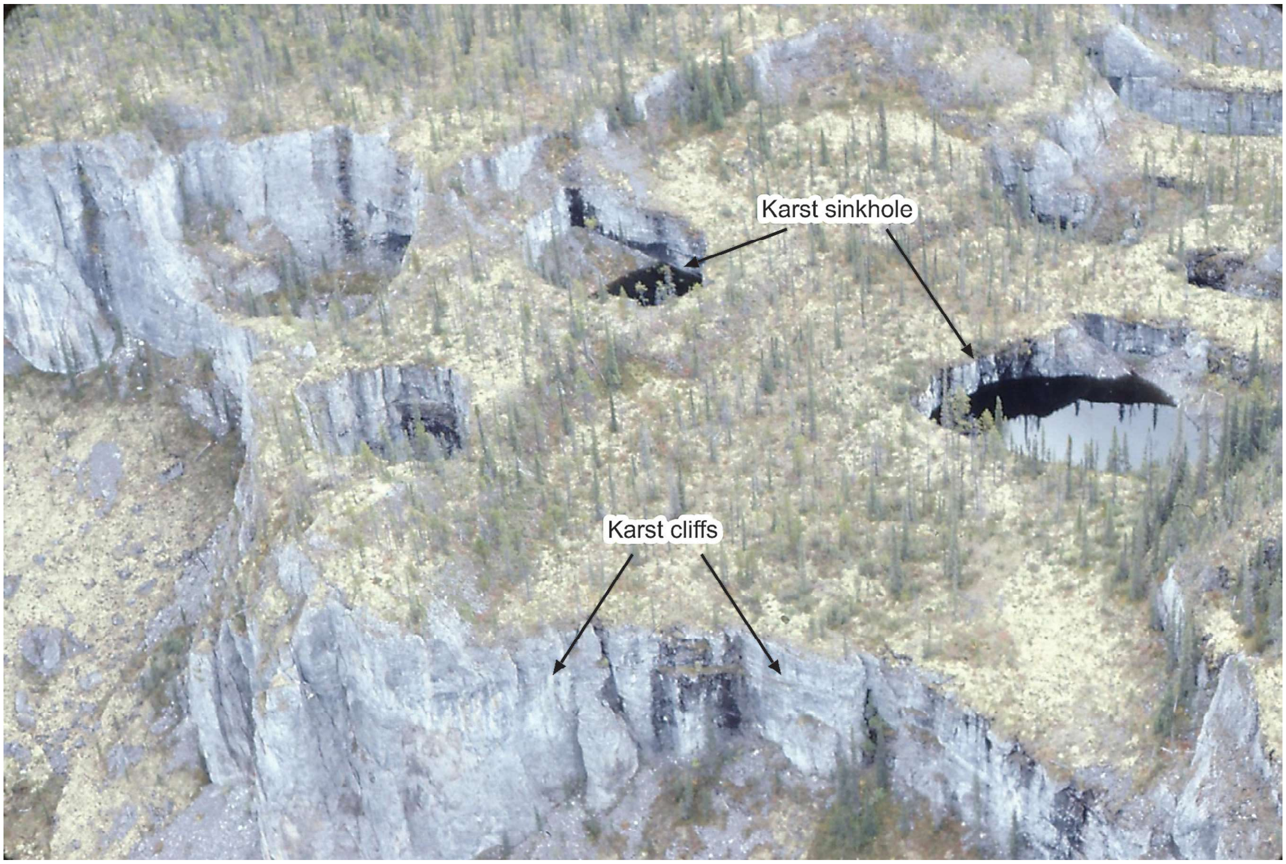


Figure 15.9a Photos of karst-related features, showing: (a) karst terrain of Nahanni North (photo: F. A. Michel).

Figure 15.9b, c Photos of karst-related features, showing: (b and c) full and empty lake in Nahanni North Karst North (photo: F. A. Michel).

Figure 15.9d Photos of karst-related features, showing: (d) White Spray spring discharging into the South Nahanni River (photo: F. A. Michel).

and deep canyons have developed in response to the large topographic relief (Figure 15.9a). The best-developed area, adjacent to the eastern edge of Nahanni National Park, has been well documented by Brook (1976, 1983). Several large poljes in the Nahanni North Karst area typically fill with water during spring melt and, after heavy summer rainfall events, form temporary lakes (Figure 15.9b) that then gradually drain through conduits in the floor (Figure 15.9c), ultimately discharging locally as large-volume cold springs (Figure 15.9d). Further west, Hamilton et al. (1988) reported the development of immature high-altitude karst near the upper end of Nahanni National Park. Northward, within the Cordillera, karst has also been studied west of Norman Wells, and in northern Yukon (Williams and van Everdingen, 1973; Lauriol and Clark, 1993).

Karstic terrain and groundwater flow have also been reported in association with carbonate and evaporite formations in the Mackenzie Valley and the adjacent northern Interior Platform (Great Bear Plain) by Michel (1977) and van Everdingen (1981).

Figure 15.9e Photos of karst-related features, showing: (e) drained Lake 142 east of Norman Wells (photo: R. O. van Everdingen).

Figure 15.9f Photos of karst-related features, showing: (f) Vermilion Creek sinkhole south of Norman Wells North (photo: R. O. van Everdingen).

The platform rocks range in age from Cambrian to Devonian and are dominated by carbonates, but do contain two evaporite units: gypsum/anhydrite in the Lower Devonian Bear Rock Formation, and halite and gypsum/anhydrite in the Upper Cambrian Saline River Formation. The evaporites display evidence of dissolution where exposed; groundwater chemistry of spring discharges also indicates significant subsurface dissolution of both evaporite units.

The majority of sinkholes in this area are associated with dolostones of the Ordovician Mount Kindle Formation and Upper Cambrian Franklin Mountain Formation, but these may, in part, be due to the collapse of karst developed within the underlying evaporites. Sinkholes are most easily identified when associated with surface water bodies, either a stream that disappears into a sinkhole, or temporary snowmelt lakes that drain through sinkholes in the lake floor once ice plugs have melted due to the heat input from the lake water (Figure 15.9e) (van Everdingen, 1981). Detailed examination of bedrock exposures in this area indicates that carbonate dissolution and early stages of karstification are widespread and some well-developed sinkholes already exist (Figure 15.9f). Most of the groundwater discharges locally in topographic lows; however, some flow systems may be more regional in extent. The development of karstic terrain and saline groundwater discharges (springs) has been reported as far south as Wood Buffalo National Park by Brandon (1963).

15.4.4 Groundwater discharge

Groundwater flow, from recharge to discharge, is driven by differences in the hydraulic head and the resulting hydraulic gradient. Discharge in the northern region, as in non-permafrost regions, is expressed as springs, seeps, and baseflow into rivers, streams, and lakes. The location of discrete discharge points is usually controlled by structural or stratigraphic (aquifer/aquitard) features, while baseflow is often topographically controlled. The presence of permafrost in the northern region acts as a low-permeability layer with frozen pore waters: this layer can be considered as a continuous to discontinuous aquitard of varying thickness and depth. Beneath larger lakes and rivers, taliks are usually through-going and permafrost is absent; thus there is no impediment of subpermafrost groundwater movement to the surface. Subpermafrost groundwaters, and some intrapermafrost groundwaters, usually discharge throughout the year and form perennial springs.

Since most field investigations are conducted during the summer, Sloan and van Everdingen (1988) prepared criteria to identify subpermafrost groundwater likely to discharge perennially. They considered all springs with a temperature greater than 10°C; most springs with discharge rates exceeding 5 L/s; and most springs with a TDS concentration greater than 1 g/L (1,000 mg/L) to represent subpermafrost water. Where present, permafrost will control groundwater flow as an aquitard and restrict the amount of groundwater discharging into shallow lakes, ponds, and streams.

This discharge, which may be seasonal due to winter freeze-back, will frequently be suprapermafrost water, which often has a low temperature, low flow rate, and low TDS content.

Major regional studies of groundwater flow in the north have been confined primarily to two areas: the east side of the Mackenzie Valley, along the proposed highway and pipeline transportation

Figure 15.10a Photos of groundwater discharge features: vegetation at Meilleur River Hot Spring showing deciduous trees (photo: F. A. Michel).

Figure 15.10b Photos of groundwater discharge features showing carbonate terrace of South Redstone Hot Springs (photo: F. A. Michel).

Figure 15.10c Photos of groundwater discharge features showing Rabbitkettle carbonate deposit in Nahanni National Park (photo: F. A. Michel).

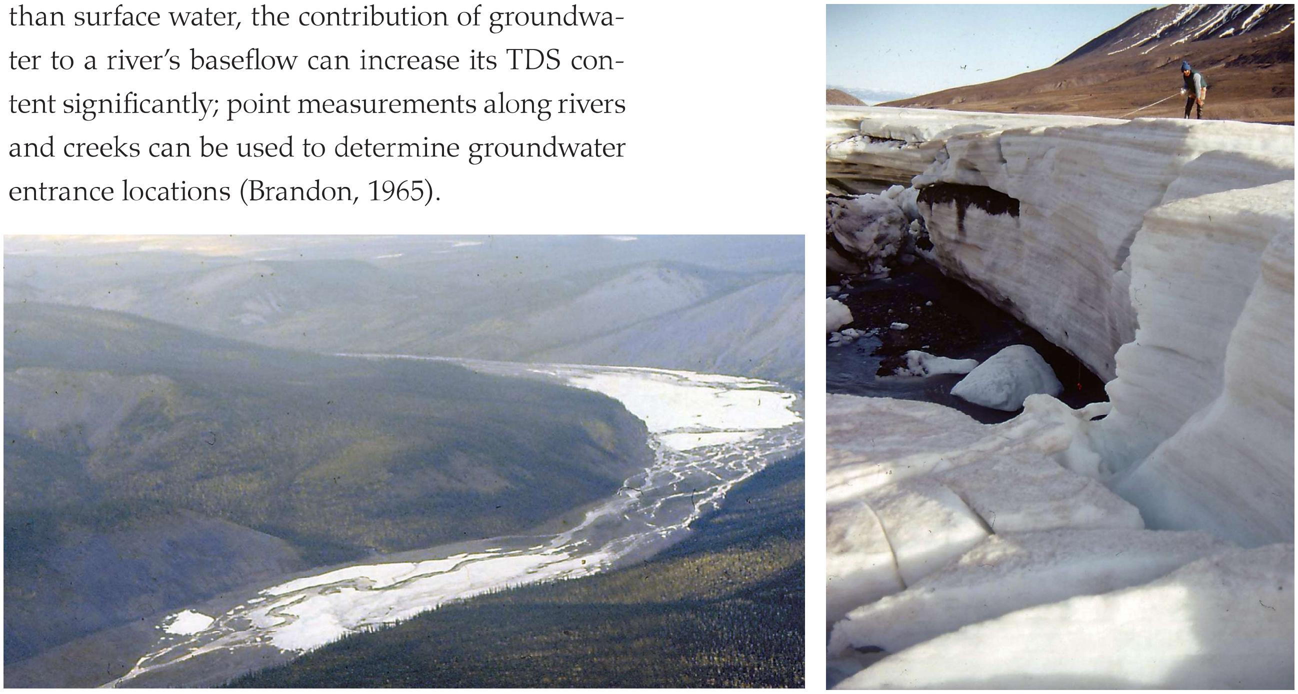
Figure 15.10d Photos of groundwater discharge features showing Iron Spring near Flat River, NWT (photo: F. A. Michel).

corridor investigated during the mid-1970s (Michel, 1977, 1986b), and the area including and adjacent to Nahanni National Park, examined as part of a mineral resource evaluation program in the late 1980s (Jefferson and Spirito, 2003). Both groups of studies focused on the identification and sampling of springs and seeps as discrete points of groundwater discharge. For the Mackenzie Valley (and north Yukon coast), some consideration was also given to baseflow in major rivers as it related to the impact on fish overwintering locations (Templeton Engineering, 1973).

Over 100 distinct groundwater discharge sites were visited in each of the study areas. Many locations were identified by the sudden increase in water flow, vegetation, deposition of precipitates, water colour, or, in the case of thermal springs on a cool day, misty water vapour rising from the vents. Spring flow rates varied from less than 0.1L/s to several hundred litres per second and emanated from a single source or numerous outlets. Vegetation adjacent to springs is often different due to the creation of microclimatic conditions at the vent (Figure 15.10a). Plants can vary from larger growth, to deciduous trees instead of spruce, to bright-green mosses and, occasionally, to exotic vegetation such as wild mint. Halophytic vegetation may be present when the discharging groundwater is highly mineralized or saline. Tan-coloured travertine deposits and terraces are common where groundwater is carbonate rich (Figures 15.10b, c); iron-rich springs precipitate reddish brown amorphous oxides (Figure 15.10d); sulphurous springs may deposit white precipitates, and thermal springs related to granitoid intrusives often have noticeable whitish alteration minerals (clays) on the rocks adjacent to the vent. Where highly mineralized water discharges into a small pool or pond, the water colour may be milky white (sulphurous) or green (reduced iron or carbonate) as a result of changes in the chemistry that occur upon discharge.

Streams and rivers receiving diffuse groundwater discharge are likely to continue to flow even during dry periods. Baseflow can be derived from the melting ice in the active layer, or from suprapermafrost flow throughout the summer, but it is the addition of subpermafrost water that maintains many rivers throughout the entire year. Williams and van Everdingen (1973) estimated that groundwater contributes on average 2.0 to 5.0 L/s/km^2 of drainage basin in the discontinuous permafrost zone. MacKay and Loken (1974) estimated that the groundwater contribution to surface runoff (streamflow) in areas of discontinuous permafrost is 20% to 40%, and decreases to less than 10% in areas of continuous permafrost. Baseflow can also occur as the discharge of water from lakes. Since the groundwater tends to be more mineralized than surface water, the contribution of groundwater to a river's baseflow can increase its TDS content significantly; point measurements along rivers and creeks can be used to determine groundwater entrance locations (Brandon, 1965).

Major springs discharging subpermafrost water can provide a significant baseflow to rivers even in winter. Williams and van Everdingen (1973) reported that a large spring on a tributary of the Porcupine River in northern Yukon maintained open-water conditions on the river for 30 km downstream during the middle of winter. Such areas form important overwintering locations for fish populations. The open-water area depends on volume of flow, the TDS content of the mixed water, groundwater temperature, air temperature, and the channel configuration. Continual flow of water from the spring provides a constant supply that will eventually freeze once the water cools sufficiently. Continued freezing of this constant supply builds up along the river to form an icing, or aufeis/naled, deposit (Figures 15.10e, f). Most icings are related to perennial springs, and the size of the icing will depend on the volume of water flow during the winter. Large springs can produce thousands of cubic metres of ice that persist into



Figures 15.10e and **15.10f** Photos of groundwater discharge features showing icing in river valley (photos: F. A. Michel and B. J. Moorman).

Figures 15.10g and **15.10h** Photos of groundwater discharge features showing pingos in the Mackenzie Delta region (photos: F. A. Michel).

the summer and are readily visible on aerial photographs or satellite imagery.

Van Everdingen (1990), with reference to long-term studies of icings in Russia by Sokolov (1973), approximated the volume of an icing with the equation:

$$Vi = 0.96Ai^{1.09} \tag{15.2}$$

where Vi is the ice volume in 100 m^3, and Ai is the icing area in 100 m^2. If the time period over which the icing formed is known, then it is also possible to calculate the average groundwater discharge rate. Melting of the icing provides an additional input of water to the stream during the spring and early summer.

Depending on the channel geometry, icings may block the normal river flow and force the water to cut channels through the ice. The restriction in flow caused by icing during the period of high-volume snowmelt runoff in spring will slow the river flow sufficiently to allow it to drop some of its sediment load and develop a braided stream drainage network across the icing footprint. This area of braided channels is in stark contrast to the usual single stream channel found upstream and downstream of the icing area, and the change in the stream pattern can facilitate identification of icing areas even after the ice has melted completely.

When stream water freezes entirely to the underlying sediment, it

Figure 15.10i Photos of groundwater discharge features showing frost blisters at North Fork Pass, Yukon (photo: F. A. Michel).

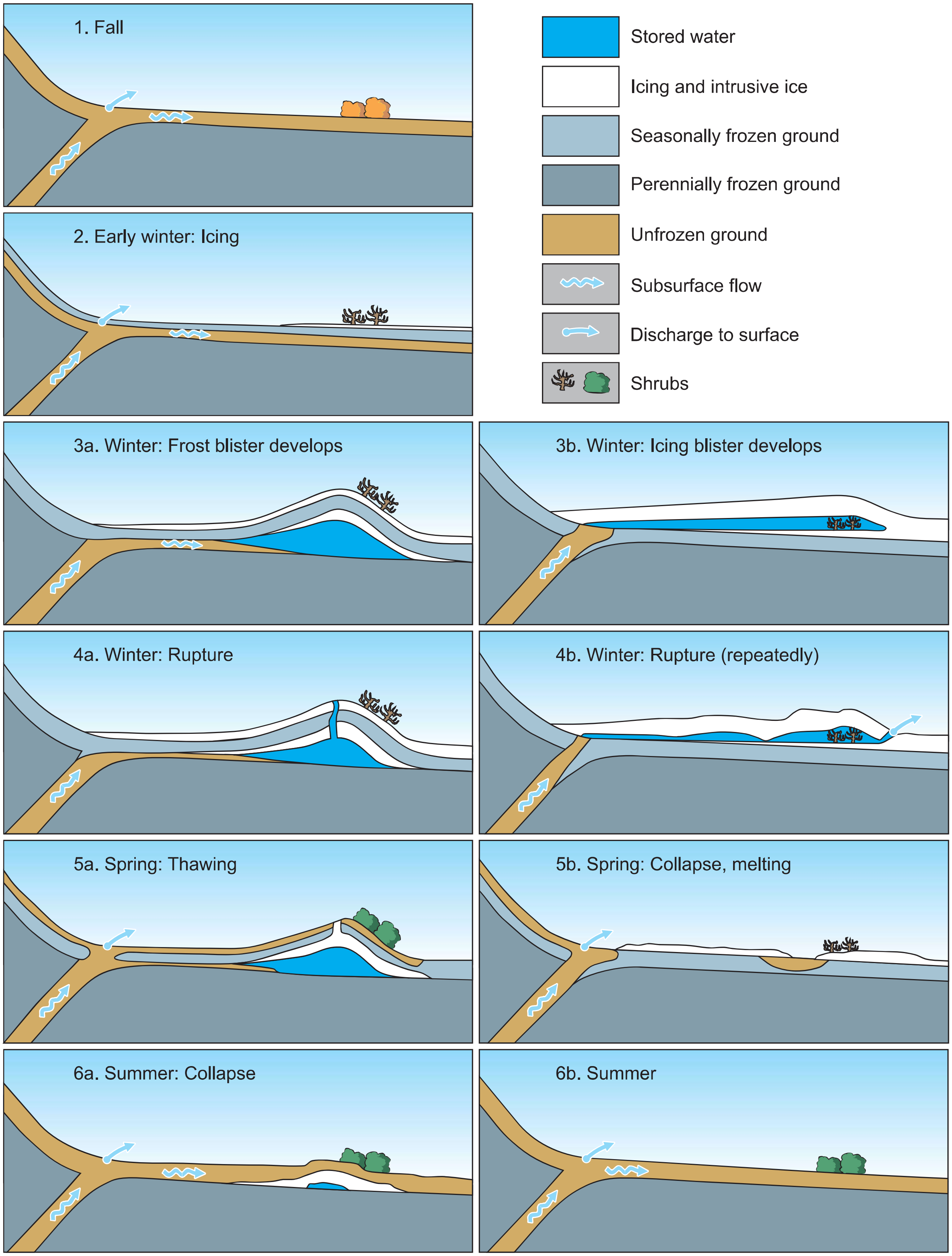


Figure 15.11 Formation and decay of frost blisters and icing blisters (from van Everdingen, 1998)

can form anchor ice, which coats the stream bed. This ice may persist into the period of spring melt, causing changes to streamflow and even, perhaps, affecting local groundwater discharge.

When groundwater discharges directly into the stream bed sediments, and the point of discharge becomes covered by the icing, hydraulic pressure of the contained water can build up to create an icing blister (a pocket of water under pressure) within the icing; this blister will gradually freeze as a small mound, and, as it does so, dissolved solids within the water will eventually precipitate onto the blister floor (Michel and Paquette, 2003).

Icings can also form downstream from glaciers as a result of early winter freezing of late-draining water from the glacier's internal plumbing (Elver, 1994); or from baseflow provided to rivers from lakes during winter as the river channel shallows. These icings are not indicative of groundwater additions to baseflow and can usually be identified on the basis of their geographic setting.

Closed-system pingos (Figure 15.10g), common in the low-relief continuous permafrost terrain of the Mackenzie Delta, are related to the freezing of suprapermafrost groundwater found in closed taliks beneath recently drained lakes (Mackay, 1979, 1985). After lake drainage, the unfrozen lake bed begins to refreeze, forming a surficial confining layer. As groundwater in the talik freezes to form pore ice, its volume expands, placing the remaining water under pressure. The combination of pressure and volume expansion results in an upward heave of the lake bottom sediments. Migration of this pressurized water to the stabilized freezing front creates a separate pure ice core (Figure 15.10h). Continued heave of the lake bed over a period of years forms the characteristic dome-shaped pingo. Open-system pingos, described by Hughes (1969), are another subpermafrost groundwater discharge phenomenon in areas of discontinuous permafrost with significant topographic relief.

Groundwater migrating through a suprapermafrost aquifer also experiences annual refreezing during winter. As in non-permafrost regions, the suprapermafrost groundwater often forms seeps and springs at the break in slope near the floor of a valley. When winter freezing creates a surficial confining layer, the residual flowing suprapermafrost water from springs becomes restricted, resulting in an increase in hydraulic pressure. Provided the surficial frozen layer is sufficiently strong, this hydraulic pressure can increase until the ground starts to heave (Figures 15.10i and 15.11), forming a frost blister with a water-filled core (van Everdingen, 1978, 1982; Pollard, 1983; Michel, 1986a). If the frozen ground is not strong enough to contain the pressurized water, the blister can rupture and allow the water to escape. Freezing of the confined water will form a separate ice core, similar to a pingo, which causes further heave due to the volume expansion. Blisters (both frost and icing) tend to be annual features that collapse every summer.

15.4.5 Geothermal systems

All geothermal waters reported in the literature for the northern region are spring discharges located in the mountains of the Cordillera and the adjacent Mackenzie Valley. These spring discharges can be subdivided into two main groups; those associated with Cretaceous-age granitoid intrusions, and those discharging along fault structures. The maximum reported temperature for the intrusion-related springs is 63.5°C (Hamilton et al., 1988), while that for structurally controlled springs is 53.5°C (Michel, 1977). A compendium of known localities was compiled by Crandall and Sadlier-Brown (1976) as part of a geothermal resource inventory, and recently updated by Woodsworth (1997) (see Chapter 7).

Thermal springs, such as the Takhini hot springs near Whitehorse, the MacArthur hot springs in central Yukon, and the Cache Creek thermal springs in northern Yukon (van Everdingen, 1974), can be found throughout the Yukon portion of the Cordillera. Elsewhere in the Cordillera, a number of thermal springs have been identified in the Tungsten area; these are primarily associated with young intrusions (Williams and van Everdingen, 1973; Crandall and Sadlier-Brown, 1976; Hamilton et al., 1988; Hamilton, 1990). With the high heat flow from these intrusions, groundwater circulation depths are probably only a few hundred metres.

A second group of travertine-precipitating thermal springs in the Tungsten area has been described by Atchison (1964), Gabrielse et al. (1973), Bowman (1990), Hamilton (1990), and Gulley (1993). The latter study focused on the rate of travertine accumulation and groundwater flow history for the spectacular Rabbitkettle hot springs site in Nahanni National Park (Figure 15.10c). Hamilton (1990) also discovered a previously unreported fault-related travertine thermal spring along the Meilleur River at the east end of the Park.

Further north, two groups of structurally controlled hot springs along the Redstone River were reported by Gabrielse et al. (1973). Michel (1977) described the main group of these springs in detail. Multiple spring outlets discharge water at temperatures between 31.3°C and 53.5°C; these combine into a single stream prior to flowing into the South Redstone River. Total flow, estimated at over 30 L/s, makes this one of the largest known hot springs in the northern region. Given the high elevation and northern location of this site, the springs have created an ecological oasis just below tree line, with travertine deposits and terraces covering an area of over 30,000 m^2.

Brandon (1965) and Michel (1977) investigated thermal discharges within the Mackenzie Valley near Wrigley, where thermal waters, with temperatures as high as 31.3°C, were found discharging into the Mackenzie River via a thrust fault cutting across the river. Geochemical investigations indicate that precipitation recharged in the mountains flows primarily through the Bear Rock Formation until it reaches the thrust fault along which the thermal groundwater rises.

All of the structurally controlled thermal water discharges indicate that deep regional-scale groundwater flow systems are active where topographic relief is substantial. Elevated water temperatures have caused permafrost adjacent to the groundwater flowpath (talik) to disappear, and not affect the location of discharge. Many thermal springs have probably never been identified or reported because of the region's remoteness.

15.4.6 Groundwater chemistry

Most municipal groundwater supplies have low total dissolved solids (TDS) concentrations and are dominantly calcium bicarbonate in composition. However, some communities may be forced to utilize marginally acceptable waters from wells that intersect subpermafrost aquifers. Tulit'a (formerly Fort Norman), at the junction of Great Bear River with the Mackenzie River, originally relied on a shallow hand-dug well, which was located near the Roman Catholic mission, and collected active-layer water. High nitrate concentrations (55 mg/L) provided the impetus for a deeper drilled

TABLE 15.1 CHEMICAL ANALYSES (IN MG/L) FOR SELECTED SPRINGS IN THE NORTHERN REGION

NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13
NAME	WHITE SPRAY	GRIZZLY LAKE SPRINGS	GYPSUM HILL	MVP MILE 359	WILLOWLAKE RIVER SPRINGS	FLAT FRUIT	MEILLEUR RIVER	PRAIRIE CREEK MINE (200 LEVEL)	GOLDEN DEPOSIT	NAHANNI HEADWATER HOT SPRING	ROCHE QUI TREMPE A L'EAU	YELLOWKNIFE CON MINE BRINE	NORMAN WELLS OIL BRINE, BEAR ISLAND
T°C	4.3	1.5	6.1	13,	10.9	8.9	5,	3,	3.7	63.5	31.3	22.5	N/A
Elec. Cond.	770,	395,	N/A	>8,000	2,050,	870,	2,730,	937,	8,700,	390,	17,800,	N/A	N/A
pH (units)	7.8	7,	N/A	7.2	7.2	6.2	3.8	7.6	2.9	7.9	7.6	5.5	N/A
Ca	39,	84,	1,823,	1,450,	522,	530,	344,	148,	341,	30,	900,	57,300,	10,300,
Mg	7.9	23,	346,	183,	70,	54.5	212,	54,	800,	0.2	149,	920,	1,700,
Na	40.3	1.4	27,100,	27,000,	7.6	29.1	14.8	0.5	500,	53,	3,240,	32,600,	35,600,
K	<0.2	1,	25,	106,	1,	5.6	2.1	0.5	7,	1.5	49,	495,	N/A
Fe	0.136	0.25	N/A	N/A	0.32	0.028	1.4	0.337	220,	0.026	0.21	18.6	Trace
Mn	<0.01	N/A	N/A	N/A	<0.01	0.158	5.4	0.092	6.5	<0.01	0.032	21.8	N/A
Cu	0.004	N/A	N/A	N/A	0.002	0.005	0.049	0.448	0.03	0.005	<0.001	0.81	N/A
Zn	0.01	N/A	N/A	N/A	0.017	<0.005	5.35	61.9	0.17	0.008	0.032	0.59	N/A
Ni	0.006	N/A	N/A	N/A	N/A	<0.002	2.31	0.065	N/A	<0.002	N/A	12.7	N/A
Co	0.006	N/A	N/A	N/A	N/A	0.004	0.405	0.009	N/A	<0.002	N/A	5.8	N/A
HCO3	147,	128,	32.3	204,	218,	1,918,	0,	272,	0,	79.5	177,	2,	320,
SO4	9,	176,	3,995,	3,400,	1,350,	38,	2,285,	393,	5,300,	37.9	2,920,	1,	0,
Cl	1,	1.7	42,340,	44,300,	7.3	3.8	2.5	1.2	24,	11,	5,210,	142,000,	77000,
F	0.12	N/A	N/A	N/A	1.22	0.53	0.48	0.49	0.15	7.8	2.86	26.9	N/A
SiO2	3,	N/A	N/A	8.8	6.3	15,	19,	6,	37,	83,	23,	8,	N/A
Sum	208,	415,	75,661,	76,652,	2,184,	3,371,	2,890,	874,	7,236,	313,	11,716,	237,100,	124,900,
Latitude	61°18' N	66°01' N	79°24' N	65°25'20" N	62°39' N	61°41' N	61°11' N	61°33' N	65°14' N	62°48' N	63°18' N	62°26'30" N	65°15'30" N
Longitude	124°07' W	125°25'45" W	90°43' W	127°17' W	122°57' W	127°38' W	124°48' W	124°45' W	124°52' W	128°50' W	123°37'30" W	114°24' W	126°54' W
Source Ref. #	65	114		93	2B	58	72B	67	72	38	35E	4500-6C	BI-3
Sample Date	Aug 86	21-06-75	18-08-62	21-03-75	12-06-75	July 86	Aug 86	Aug 86	15-09-75	July 86	17-06-75	1980	28-05-44
Notes:													

Data for samples, 2, 4, 5, 9, 11, and 13 from Michel (1977); samples 1, 6, 7, 8, and 10 from Hamilton (1990); sample 3 from van Everdingen (1974); and sample 12 from Frape and Fritz (1987) community well, which produced mineralized subpermafrost water dominated by sodium and chloride with an average TDS concentration of 1,250 mg/L (Michel, 1977).

Investigations of groundwater chemistry, outside of municipal communities, focus either on spring discharge locations, or on the sampling of groundwater seepage within mine workings. Most of the regional-scale research has been driven by development of a transportation corridor (highway and pipeline) through the Mackenzie Valley (Michel, 1977), and the exploration and development of potential mineral resources in the Cordillera (Hamilton, 1990): both are subregions with active regional groundwater flow systems. Studies of site-specific groundwater-related issues have been conducted elsewhere in the north, especially in association with environmental studies of new mine developments.

Water chemistry throughout the northern region can be highly variable (Table 15.1, Samples # 1–13), reflecting the vast range in geological terranes and hydrogeological conditions. Examples given in Table 15.1 include springs with low water temperature and low TDS content (Samples #1 and 2); those with low water temperature and moderate to very high TDS content (Samples # 3 to 9); those with high water temperature and low TDS content (Sample # 10); those with high temperature and high TDS content (Sample # 11); those with elevated trace metal concentrations (Samples # 7 to 9); and deep formation brines (Samples # 12 and 13).

Many of the groundwater systems studied are confined largely to the thick sequences of carbonate rocks found within the Mackenzie Valley and Cordillera. The development of karst in these carbonates channels the groundwater and often results in large-volume discharges that can exceed 100 L/s. Consequently, the pH for most of these spring waters ranges between 6.9 and 8.4; temperatures are usually <10°C; TDS contents are low to moderate; and the major dissolved ionic species are calcium, magnesium, and bicarbonate (Samples # 1 and 2).

Michel (1977) found that the groundwater chemistry, within the Mackenzie Valley, represented a mixture of three endmember groups defined as Ca-Mg-HCO_3, Ca-SO_4, and Na-Cl types. The latter two categories are the result of groundwater flow through the evaporite units of the Bear Rock (gypsum/anhydrite) and Saline River (halite + gypsum/anhydrite) Formations, which add dissolved constituents (Ca, Na, SO_4, and Cl) to the original Ca, Mg, and HCO_3 derived from the carbonates (Samples # 4 and 5). Similar evaporite sequences are not as prevalent within the Cordillera, where the groundwater chemistry is carbonate dominated. Exposed gypsum domes on Axel Heiberg Island (Sample # 3) actually produce NaCl dominated brine waters, indicating the presence of halite along the subsurface flowpath. On northern Ellesmere Island, springs discharging from the surface of an alpine glacier have been reported to precipitate calcium carbonate (as vaterite), gypsum, and native sulphur (Grasby, 2003).

Timlin (1991), Hamilton (1990), and Hamilton et al. (1991), investigated a series of lower pH (5.9 to 6.3), high pCO_2 (> 1 atm), travertine-depositing cold springs (Sample # 6) in the Flat River Valley near Tungsten. Their data suggest that the high CO_2 concentrations are generated by metamorphic decarbonation reactions adjacent to granitoid intrusives at depth. The escaping CO_2 rises along structural lineaments, and mixes with shallow circulating groundwater prior to discharge within the valley. These springs are unique in Canada, but are similar to a class of springs identified worldwide as associated with tectonic activity (Barnes et al., 1978; Hamilton, 1990).

High pH (7.5 to 9.0), low TDS hot springs discharge (Sample # 10) where these granitoid intrusions are exposed. Although the TDS concentrations are low, some trace metals associated with the plutons, such as Mo and W, are elevated, as are Si and F (Hamilton et al., 1988; Hall et al., 1988). Other thermal springs, not directly associated with exposed intrusions, are caused by the rapid ascent along structural lineaments. These springs represent deep circulation and tend to reflect the chemistry of the rocks through which the groundwater flows; thus they often have elevated TDS concentrations dominated by carbonates or, in some instances, evaporites (Sample # 11).

Iron-rich springs in the Nahanni area of the Cordillera are associated with granitoid intrusions, carbonates, sandstones, and shales (Hamilton et al., 1988), whereas in the Mackenzie Valley and northern Yukon they are primarily associated with shales. Iron springs are easily visible from a distance due to the bright red precipitates found adjacent to the discharge vents. These waters typically have a lower pH (3.0 to 6.5), a moderate electrical conductivity (350 to 1,500 µS/cm), and of course a high dissolved-iron concentration (1.0 to 122 mg/L) (Hamilton et al., 1988). The iron is usually derived from oxidation of Fe-bearing sulphides (van Everdingen et al., 1979, 1985).

The presence of elevated iron concentrations in some spring waters is often accompanied by acidic conditions and higher concentrations of other trace metals, while in other instances, elevated trace metals may be found without significant iron. The source of these metals depends on the geology. Hamilton et al. (1988) and Hall et al. (1988) identified three economically interesting metal associations in the Nahanni Park area. These were W-Mo anomalies associated with granitoid intrusions in the Tungsten area, shale-hosted waters with a suite of base metals (Fe, Mn, Ni, Co, Cd, Zn, and Cu), and a highly anomalous group of fault-related springs in shales along the Meilleur River with extremely high concentrations of Ni, Co, Cd, and Zn (Sample # 7). The geology at the latter site indicates that this area may be a southern extension from the Prairie Creek (Pb-Zn-Ag) mine where groundwater sampled within the mine was also anomalous in some trace metals (Sample # 8).

Groundwater that encounters shale-rich formations along its flowpath often undergoes cation exchange, which can significantly alter the overall chemical composition of the water. Michel and van Everdingen (1987) described a groundwater system (Sample # 9) west of Great Bear Lake where cation exchange in conjunction with pyrite oxidation resulted in a groundwater chemistry with a pH of 2.9 , an iron concentration of 220 mg/L, and dominated by sodium, magnesium and sulphate. Upon discharge, a mixture of jarosite, amorphous iron hydroxides (goethite) and clay minerals is deposited as a yellow ochre, which led to the site being referred to as the “Golden Deposit”.

Near Baker Lake in Nunavut, Urangesellschaft Canada Limited (1989) reported radionuclides being transported to local surface water bodies by water flowing through the active layer overlying a uranium-bearing deposit.

All of these examples demonstrate that analysis of groundwater chemistry has the potential to enhance mineral exploration programs in the region, providing an important window to the subsurface geology.

Deeply circulating groundwater experiences an increase in TDS concentration due to prolonged water-rock interaction times. The formation of ice in the subsurface during permafrost aggradation results in expulsion of salts into the residual unfrozen water. This creates a higher salinity fluid that lowers the freezing point, ultimately creating a chemical cryopeg below or within the permafrost. In some instances, groundwater encountered at depth, within mine workings, may be a highly saline brine migrating within taliks or in the subpermafrost zone. Groundwater investigations in the mines at Yellowknife discovered Ca-Na-Cl brines at depth with >237 g/L dissolved salts (Sample # 12) (Frape et al., 1984; Frape and Fritz, 1987; Clark et al., 2000). Detailed groundwater studies at the Lupin mine, north of Yellowknife, revealed Na-Ca-Cl brines beneath the permafrost; the highest salinity waters (39.5 g/L), however, were found within the permafrost, and concentrations decreased with depth (Ruskeeniemi et al., 2004). At the Polaris mine on Little Cornwallis Island, north of Resolute, proximity to the ocean resulted in the mining operations encountering saline waters that may be related to the overlying seawater. The highest salinity brine reported to date (324.5 g/L) was found at a depth of 1,500 m in Thompson, Manitoba, an area with only sporadic permafrost conditions (Frape and Fritz, 1987).

Brines are often considered to represent formation water that has remained in the rock for millions of years, gradually increasing its TDS content through prolonged water-rock interaction. During development of the Norman Wells oil field in the 1940s, formation water, typical of oil field formation waters throughout North America, was encountered in the reservoir rocks (Sample # 13). Comparison of this water with other saline waters encountered in the Mackenzie Valley (Sample # 4) revealed many similarities, although Michel (1977) has shown that most regional groundwater in the Mackenzie Valley is postglacial in age. This suggests that formation water may, in fact, be much younger groundwater that encountered evaporites along its flowpath, and saturated pore spaces within the reservoir rock. The Norman Wells reservoir is known to be leaky.

Drillers are often leery of using cold surface water as a circulating fluid during drilling because of the increased freezing potential in permafrost areas. As a result, they add salt to the groundwater, creating brine that will depress the freezing point. Since some of this saline drilling fluid may escape through fractures in the rock, subsequent sampling programs must be careful to identify any man-made brine present.

15.5 OUTSTANDING ISSUES

15.5.1 Construction of pipeline and highway infrastructure

The widespread distribution of perennially frozen ground throughout the northern region requires special consideration of hydrogeologic characteristics during the planning, design, and construction of buildings, roadways, and pipelines.

Buildings, storage facilities such as fuel tanks, and fixed structures like bridge abutments are susceptible to long-term frost heave. Frost heave by itself is not unique to the northern region; however, the limitations placed on the infiltration of precipitation by the presence of permafrost restricts the drainage of soils, which can result in high ice contents during re-freezing of the active layer each winter. Migration of moisture within the upper permafrost due to large thermal gradients, as demonstrated by Burt and Williams (1976), has been studied extensively and reported in the permafrost literature (Andersland and Anderson, 1978; Williams and Smith, 1989). A significant portion of the water content in a soil can remain unfrozen at subzero temperatures due to increasing solute concentrations (exclusion of salts during freezing) causing depression of the freezing point (Burt and Williams, 1976; Marion, 1995). Anderson and Tice (1972) related unfrozen water contents to the surface area of a soil, such that fine-grained soils (with a large surface area) can remain essentially unfrozen at temperatures well below 0°C. Combined with large temperature gradients in the shallow subsurface, it is possible for large quantities of unfrozen high-salinity water to migrate through the upper permafrost.

Even more critical is the melting of ground ice beneath various structures resulting from the transfer of heat into the ground. Construction projects in coastal regions and on fine-grained marine deposits, which may contain highly saline waters, are of special concern since depression of the freezing point may result in the presence of a significant proportion of unfrozen water within the permafrost. These fluids are subject to migration along strong thermal and concentration gradients, in addition to the normally considered hydraulic gradients, and may be highly corrosive to the steel piles utilized to mitigate frost heave and issues of thaw settlement.

Roadways within northern communities are normally constructed using coarse-grained aggregate or crushed rock; these materials drain water, inhibit frost heave, and insulate the ground to prevent thaw subsidence of ice-rich material. Layout of these relatively short, community roads usually avoids the ice-rich or water-saturated terrain that could result in differential settlement or heave problems. Similarly, airport runways are located and designed at sites where water migration is not an issue.

Major transportation corridors for roadways and pipelines between communities may not always be able to avoid sensitive terrain; these projects require extensive engineering design following selection of the most appropriate route. Differential heave/thaw can result in serious problems in those cases where the engineering design is inadequate; this is especially true of railroads, which have very strict tolerances. Infrastructure construction within the permafrost regions raises three major concerns that need to be considered from a hydrogeologic perspective:

1. Prevention of frost heave or thaw settlement along roadbeds should be addressed during the design phase. Construction of the road base with an adequate thickness of coarse-grained aggregate usually suffices. Pipelines, which are usually buried within the native soils, require special consideration. Unless the pipeline is to be elevated above the ground surface, as portions of Alaska's Alyeska pipeline are, soil thermal and water-migration properties must be taken into account. Uninsulated, chilled gas pipelines will cause water migration toward the pipe; this water accumulates as ice lenses beneath the pipe, and can result in significant differential frost heave along the length of the pipeline (Williams, 1979), unless large earth or rock berms are placed on top of the pipe to counteract heave and buoyancy. Heated oil pipelines can cause thawing of ice-rich permafrost, leading to subsidence. Significant subsidence by buried oil pipelines in Siberia has led to the development of drainage streams, erosion along the pipeline

right of way, and instability of adjacent ice-rich permafrost. Thermal siphons have been installed along portions of the Alyeska pipeline to prevent thaw.

2. The positioning of roadways and pipelines relative to concentrated groundwater discharge points, such as springs, and the modification of near-surface aquifers can be critical in the design of these structures. Groundwater discharge provides significant baseflow to rivers and small streams that can persist through winter at some locations. Construction of linear structures that can restrict groundwater discharge or streamflow in winter often leads to development of icings on the upstream side. Even multiple oversized culverts can become entirely blocked with ice such that subsequent water flow is ponded adjacent to the structure and eventually overflows the structure's top. Freezing of this water has led to ice masses stretching across roadways, blocking the movement of winter traffic. Freezing of the saturated roadbed aggregate can create significant pore ice and ice lenses, which can cause slumping and failure of the structure during spring melt. Restriction of near-surface aquifers, caused by compaction of soils, or the creation of a frozen barrier surrounding a chilled gas pipeline within a stream bed, can also create groundwater discharge features such as icings or frost blisters. Recognition of these groundwater discharge zones, coupled with proper design, may prevent the need for expensive annual maintenance or future reconstruction.
3. The clearing of vegetation along transportation corridors can lead to an increase in the thickness of the active layer. The maintenance of high water contents in these newly thawed soils because of underlying frozen ground and poor drainage can raise the potential for slope failure, especially on south-facing slopes. Increased water flow over the slope surface can also increase erosion rates and, as a result, increase the sediment content of adjacent streams and rivers. Re-insulation of the entire right of way and special design considerations are necessary to control these processes.

15.5.2 Mining development

Mining activity has been a major economic force in all parts of the northern region. Knowledge of and experience with groundwater flow in permafrost terrain has been gained from mining operations in discontinuous permafrost south of Great Slave Lake at Pine Poin; in the thick continuous permafrost at Polaris, north of Resolute; from Nanasivik on Baffin Island; from deep mines in the Canadian Shield at Yellowknife, Thompson, and Lupin; and from mines in the mountainous terrain of the Cordillera at Tungsten and Keno Hill. New mineral discoveries will create new mining activities throughout all the northern subregions, leading to the development and expansion of infrastructure facilities, each with its share of groundwater issues.

Construction at mine sites requires coarse-grained aggregates for roads, building pads, air strips, and cover material for tailings. Eskers and other glaciofluvial and near-shore glaciolacustrine deposits represent the main source of aggregates for many of these locations. The coarse nature of the aggregates and their higher elevation, compared to the surrounding terrain, has reduced the amount of water present, in many of these settings. Lower water contents mean less ice bonding and easier extraction. However, massive ice has been encountered in esker and deltaic sediments at some localities. This ice presence reduces the volume of material available for extraction and requires controlled drainage of the meltwater. Ice bonding within an orebody can also create additional problems for blasting operations, because of the ice's cohesive nature.

Permafrost may be beneficial in the construction of tailings facilities because of frozen ground's low-permeability characteristics. One major concern is water flow within the active layer, the unfrozen solute-rich groundwater in fine-grained tailings within permafrost, and the potential loss of contaminated tailings' fluid to nearby surface streams and lakes. Tailings embankments need to be carefully constructed to encourage permafrost aggradation. Permafrost aggradation upward through the tailings and into the cover material at the time of mine closure is important, as is the long-term maintenance of this elevated permafrost table under changing climatic conditions. Creation of permafrost conditions around open pits has also been considered as one method of reducing groundwater flow into the workings. Artificial permafrost aggradation is being examined at Yellowknife as an option to prevent groundwater flow in the upper levels of abandoned mines from interacting with large quantities of stored iron-arsenic trioxides.

Groundwater flow within mine workings, whether open pit or underground, can also be of major concern. As noted in our earlier discussion on water supply, Cominco, at its Pine Point operation, pumped 157,000 m^3/day from dewatering wells around the open pit. The karstic nature of the carbonate rocks at Pine Point, and the discontinuous nature of the permafrost, permitted significant unrestricted groundwater flow, which became a major issue for the mine operation.

The kimberlite of the new Victor diamond project, on the Attawapiskat River in northern Ontario, is also located within locally karstic Paleozoic limestones (AMEC, 2004). Permafrost in this part of the Hudson Bay Lowlands is sporadic, found mainly on peat plateaus, and totals less than 5% in areal extent. Water levels in shallow bedrock wells have been reported to fluctuate seasonally by up to 2 m, while deeper wells have flowing artesian conditions. A pumping test in the country rock surrounding the kimberlite was able to sustain a yield of 3,815 m^3/day, with only a 3 m depression in the groundwater table (AMEC, 2004). The effect on this pumping test of an adjacent fault zone, with a reported hydraulic conductivity of 500 m/day, is unknown at present. Nevertheless, development of an open-pit mine will require significant dewatering of local bedrock, which will impact the water table of a large portion of the area surrounding the mine. In addition, water quality concerns for the discharge from dewatering need to be addressed, since the deeper (200 m) groundwaters have TDS concentrations exceeding 2,000 mg/L.

Unrestricted groundwater flow has also become a serious issue for uranium mines in the Athabasca sedimentary basin of northern Saskatchewan, especially with the 2006 flooding of the Cigar Lake mine, which completely shut down operations (see Box 15-2). Again, permafrost in the area is sporadic.

At the Cadillac mine in the Nahanni region, groundwater discharging through the mine portal was considered a serious environmental issue for the adjacent Prairie Creek. However, the region experienced a major earthquake in 1985 that changed the groundwater flow regime such that there was no longer any discharge from the mine entrance after that event.

Brown (1970) reported large mineralized groundwater flows in the Yellowknife mines at depths exceeding 700 m, whereas the base of permafrost is found at a depth of just over 100 m. This flow was concentrated along fractures and faults in the shield rock. Mining operations at Tungsten, N.W.T., also encountered highly pressurized groundwater flow from faults. Detailed investigations of subpermafrost groundwater flow in fractured shield rocks at the Lupin mine were undertaken recently (Ruskeeniemi et al., 2004). Again, groundwater flow is limited to major fracture and fault zones. Structural heterogeneities across the mine site have resulted in variations in hydraulic head, and very little recharge of the subpermafrost system.

The high dissolved-solids concentrations in many of the deeper groundwaters may be the result of water-rock interactions occurring during long subsurface travel times, or, perhaps, the result of salt expulsion during permafrost aggradation. At the Polaris mine on Little Cornwallis Island, saline waters were encountered below the base of the continuous permafrost. In this case, mining beneath the adjacent bay may have intersected a through-going talik that connected the mine workings to the marine waters of the bay. The presence of brine waters associated with oil deposits at Norman Wells suggests that ancient formation waters may also be present at some localities, although as noted earlier, the Norman Wells brines may also reflect dissolution of local evaporites.

Through-going taliks are likely to exist throughout the zone of continuous permafrost in areas inland from the coast. Large deep lakes provide heat sources that can maintain such taliks, and act as point sources of recharge for subpermafrost groundwater systems. Lakes in the Arctic usually freeze to a maximum depth of approximately 2.0 to 2.5 m. Therefore, any lake deeper than 2.5 m could maintain an unfrozen section throughout the winter. Lakes with a diameter greater than about 500 m, and a depth exceeding 2.5 m, will likely form through-going taliks. Depending on the thickness of the permafrost, smaller diameter lakes may also be of concern, especially if major structural features, such as faults, connect the lake directly to subpermafrost aquifers or to subsurface mine workings. Terrain elevation differences of a few metres between proximal lakes may be sufficient to create an active groundwater flow system, with the lakes acting as recharge and discharge points.

15.5.3 Contamination issues

The sparse population of Canada's permafrost region implies that all waters there should be pristine, groundwater in particular. This is largely the case although industrial and military activities, facilitated by improvements in northern transportation since World War II, have left behind local contaminant sources, for which mining, hydrocarbon exploration, and operation of military installations are primarily responsible. Contamination originates from the waste products of these activities. Waste rock and tailings from base-metal operations release acidic leachate upon weathering. Abandoned sumps used to contain drilling fluids collapse and release drilling-mud additives. Military surveillance stations established waste dumps from station operations, including electrical components containing Polychlorinated Biphenyls (PCBs). The contaminants listed above are not unique to permafrost regions, but permafrost will play an important role in determining how these wastes disperse.

When a saturated soil is frozen, the ice-filled pores render the material essentially impermeable. This attribute has resulted in the perception that ice-bonded permafrost can serve as a waste disposal medium. Excavations are created, waste placed and allowed to freeze, and finally a cover is laid down to complete the containment. The concept is sound as long as freezing is maintained. However, departures from complete ice bonding, freezing point depression due to elevated solute concentrations, freeze-thaw processes, and the ground thermal regime of the site will reduce the effectiveness of permafrost containment. Should the fluid component of any waste escape containment, these site characteristics will act to promote further contaminant dispersal.

Permafrost is always associated with a surficial active layer that thaws in summer. This thaw zone can approach two metres in thickness in soils, deeper in rock. When thawed, the active layer functions as an unconfined aquifer above permafrost. Any fluid within this layer is free to flow during the thaw period. Although the active layer is often within fine-grained, presumably low-permeability sediments, the formation of ice lenses by ice segregation results in large water-filled pores during active-layer thaw. This pore fabric has been demonstrated to greatly increase the permeability of thawing sediments relative to the permeability that would be exhibited in the same material if never frozen. Should any contaminant reach the active layer, an avenue is available for further contaminant movement. In the case of solutes, active layer freeze-back will tend to concentrate the dissolved components (Michel, 1982). The resulting higher pore-water densities may promote contaminant movement even beneath level ground.

Where metal concentrating accompanies mining, waste residue from the mill is termed tailings. Tailings are usually placed as a slurry that forms a pond behind a specially constructed dam. In permafrost regions, the tailings pond will freeze, resulting in encapsulation of the pond contents between existing permafrost below the tailings and aggrading permafrost above. Pore-water expulsion ahead of the freezing front should tend to raise the pressure in the remaining unfrozen water, and also to concentrate salts. These processes have been observed to occur in natural settings. Although there is little documentation to date for tailings facilities, licensing conditions for new mining projects tend to include provisions for assessing the possibility of later contaminant escape. Contaminant dispersal is most likely to occur via the active layer in permafrost regions; however, subpermafrost movement is possible if contaminants enter recharge areas for subpermafrost flow.

Little documentation of aquifers confined by permafrost exists. Understanding groundwater flow under permafrost confinement would be warranted most where groundwater is produced for individual or community consumption, and where potential contaminants exist from septic or other local activities. Not only is protection of recharge areas required, but preservation of the permafrost confinement is as well, given that loss of ice bonding could radically alter the flow pattern in the vicinity of any producing well, and lead to downward migration of contaminants.

15.5.4 Climate change

The widespread existence of frozen ground within the northern region has already been shown to have a significant effect on the hydrogeology of the region. In 1990, the International

Geosphere-Biosphere Programme (IGBP, 1990) concluded that northern wetlands and permafrost regions play a vital role in the global climate system. Current global climate models (GCMs) predict that global temperatures will rise during the 21st century, and that the most dramatic changes in temperature will occur at higher (polar) latitudes. Over the long term, any significant temperature change, whether increasing or decreasing, will lead to changes in permafrost distribution, which will affect all components of the water balance in the northern region. Smith (1990) predicted that a temperature rise of 0.5ºC per decade over a 60-year period would cause permafrost degradation ranging from seven metres in ice-rich areas to complete disappearance of permafrost in areas of unsaturated frozen sand. The effects of a warming climate on permafrost hydrogeology were originally considered by Michel and van Everdingen (1994). It must be remembered that climate is dynamic and constantly changing, as evidenced by the succession of glacial and interglacial cycles during the Pleistocene, and the climatic fluctuations (warm and cold) throughout the Holocene. Such changes continuously affect the distribution and thickness of permafrost (Koster, 1993; Vaikmae et al., 1995). More recently, concerns about global cooling and the start of a new ice age (in the 1970s) have given way to concerns about global warming.

An increase in air temperature will have several important effects on the water balance, the scale of which will depend on the seasonal distribution and magnitude of the temperature change. These effects may include shifts in the ratio between rainfall and snowfall; changes in evapotranspiration rates, glacier melt, and the total amount of precipitation; and changes in the ground thermal regime. Indirect effects would include changes in vegetation, surface albedo, and runoff rates. Most GCMs predict that global warming will cause an increase in total precipitation as precipitation patterns shift northward in the northern region. This overall increase in precipitation and the seasonal redistribution of that precipitation could result in increased runoff, increased evapotranspiration, and/or increased infiltration and groundwater recharge changing the overall hydrologic balance.

In mountainous areas of the region (Yukon and the Arctic islands), global warming will most likely cause a general retreat of glaciers, although locally increased precipitation could lead to temporary surging if that precipitation falls as snow. The retreat of glaciers will expose ground that may be free of permafrost and, therefore, provide new areas for groundwater recharge. The increased rate of glacier melting will provide an increase in meltwater volumes for both surface-water drainage systems and groundwater recharge, at least over the short term.

The landscape in non-mountainous areas is dotted with numerous small lakes and ponds due to the presence of frozen ground. Degradation of the upper permafrost will remove many of the flow barriers, resulting in the development of more coherent drainage networks and possibly some lake drainage. Permafrost degradation in ice-rich areas could also lead to an increase in thermokarst activity, thereby increasing the number of small lakes and ponds. Changes in drainage could significantly affect the areal distribution of wetlands, which serve as the primary breeding grounds for many wildlife species, and are considered major carbon sinks.

Moderate increases in MAAT can lead to melting of near-surface ground ice, and increased groundwater flow within the active layer. A thicker unfrozen layer developed over a longer portion of the year would allow infiltration rates to increase and would permit longer periods of recharge to both shallow and deep groundwater flow systems. Improved drainage of the active layer, along with increased ground temperatures, also will affect the type and distribution of vegetation. A northward shift in vegetation zones, including the tree line, will impact transpiration rates, surface albedo, and snow cover, which in turn will affect runoff rates.

Lowering of the permafrost table and less freeze-back in winter will create a near-surface perennially unfrozen zone between the active layer and permafrost that will be capable of transmitting groundwater throughout the year and could alter geotechnical conditions locally. The disappearance of permafrost from some areas would increase the areal extent of recharge, and increased rates of recharge for warmer water would cause further degradation of the permafrost at its base and through the creation and enlargement of taliks. Enhanced talik development, and thus better connectivity between deeper subpermafrost aquifers and the surface, will result in more rapid groundwater circulation at both the local and regional scale, coupled with higher rates of recharge and discharge. Increased groundwater discharge will probably affect baseflow characteristics of rivers and lead to a rise in the dissolved-solids content of river water. Additional groundwater discharge enhancing baseflow could cause some rivers to maintain longer open-water seasons, or result in increased icing activity. Specific effects of climate change on any given groundwater system will depend on local characteristics and conditions.

15.6 CONCLUSIONS

The northern region comprises over 50% of Canada’s land mass, encompassing all of Canada north of the southern limit of discontinuous permafrost. The region includes a wide variety of geologic and physiographic terranes, which create a large range of groundwater conditions. Relatively little is known about the permafrost control of groundwater flow since the region is sparsely populated, and groundwater is utilized primarity as a water supply for communities within Yukon. Permafrost is known to act as a barrier to groundwater recharge when the permafrost is ice-bonded and continuous. Groundwater flow through permafrost is restricted to taliks created by the thermal or chemical conditions of the groundwater. Groundwater that discharges directly into rivers from taliks can provide perennial baseflow, and result in open reaches within the rivers during winter: these provide important fish habitat. Major issues in the region related to groundwater flow, or the effects of phase change between water and ice, include the construction of infrastructure (especially pipelines and highways), mining development, contaminant migration, and climate change.

BOX 15-1 OLD CROW, YUKON

The community of Old Crow, Yukon, is located on an old floodplain of the Porcupine River, just below the confluence of the Porcupine and Old Crow Rivers. Situated 120 km north of the Arctic Circle and 50 km east of the Yukon/Alaska border (67^{o} 33′ N, 132^{o} 52′ W), the community is within the zone of continuous permafrost. Until 1982, the community relied on the Porcupine River for its water supply.

In March 1982, drilling was undertaken in an attempt to locate a new groundwater supply from within alluvial gravels of the old river channels or adjacent to the current river. Due to the thickness of the permafrost (determined as extending to a depth of 63 m), two deep 15 cm diameter wells were drilled into bedrock to explore for a potential subpermafrost aquifer. Bedrock was encountered at depths of 37.6 m (WW #1) and 35.8 m (WW #2) in the two wells, which were drilled 17 m apart. The bedrock stratigraphy consisted of sandstone to 64 m, shale and siltstone to 79 m, and limestone/dolostone below.

The 15 m of shale and siltstone form a confining layer above the permeable carbonates. Water well #1 encountered artesian flow at 79.3 m that was estimated at 6.1 L/s (80 Igpm). The second well also encountered artesian conditions upon entering the carbonates at 79 m; however, drilling was continued to a depth of 122 m. Flow from the second well was approximately 2.3 L/s (30 Igpm). Water temperatures ranged from +0.5 ºC to +2.5ºC, stabilizing after two months of pumping at +0.8ºC. TDS values averaged 340 mg/L with elevated Mn and Fe concentrations.

Initial testing demonstrated that the two wells intersected the same hydrostratigraphic unit, but at different depths. A 72-hour pumping test was conducted on WW #1 at a rate of 17 L/s (225 Igpm), while WW #2 was employed as an observation well. The data was analyzed, using both Theis and Jacob methods, yielding transmissivity values ranging from 17.1 m^2/day to 42.2 m^2/day, and storativity values from 1.52×10^{-3} to 3.62×10^{-3}. Analysis of 20 hours of recovery data produced a transmissivity value of 122 m^2/day.

The two wells were connected to insulated shallow buried service lines to provide the community with a new groundwater supply. Both the wells and the service lines were installed with heater cables to prevent freezing. A winter-time ($T < -35$ºC) fire at the local school demonstrated that even fire hoses should contain heater cables to prevent freezing and loss of access to the water supply. For details on this work refer to Trimble et al. (1983).

BOX 15-2 CIGAR LAKE, SASKATCHEWAN

The mid-Proterozoic-age Athabasca Basin in northern Saskatchewan contains a thick sequence of relatively undeformed fluvial, quartz-rich sandstones that unconformably overlie a basement complex of deformed and metamorphosed Archean and early Proterozoic rocks. The basal unconformity hosts several known large, high-grade hydrothermal uranium deposits, primarily near the eastern margin of the basin. The Cigar Lake deposit, one of the richest in the world (up to 55% U), was the subject of a detailed study led by Atomic Energy of Canada Limited (AECL) in the 1980s and early 1990s, because the deposit was viewed as a natural analog for a nuclear waste repository. Groundwater investigations were an important aspect of the study. Thin sporadic permafrost exists in the area.

The uranium orebody, located at a depth of 430 m, was considered to be isolated from groundwater flow in the overlying permeable sandstones by a clay cap, and underlain by impermeable metamorphic rocks. The regolith along the unconformity was also estimated to have low hydraulic conductivity. Modelling of field data indicated that three flow regimes exist (local to semi-regional), all with a southwest to northeast groundwater flow direction, discharging locally into Waterbury Lake. Recharge was calculated to be approximately 5% of annual precipitation, or 25 to 30 mm/year to maintain steady-state flow conditions. Modelled flow rates were calculated to be 1 to 4 m/year in the sandstone and <0.01 m/year in the basement. However, tritium age dating suggested that at least some groundwater in the upper unconfined overburden aquifer and the two deeper confined flow systems within the sandstone was less than 45 years old, possibly due to fracture flow. Particle tracking from within the ore zone through the clay cap produced model groundwater ages of 18,000 to 85,000 years.

Observations from underground workings indicated that the regolith was much less permeable than calculated from borehole test data, that groundwater flow through fractures intersected was minimal ($Q < 19$ L/h), and that there was no connection to the permeable sandstone above. Although fractures in the rock were not pervasive, one probe hole drilled at the 420 m level in the workings encountered a 10 to 20 m wide highly permeable fracture zone with a flow of 75 L/s.

Groundwater inflow and weak rock zones were expected during development of the mine. Design plans included freezing of the ground to increase rock stability, reduce groundwater flow, and reduce radiation exposure due to radon gas dissolved in the groundwater. However, in 2006, a rockfall in the production area led to water inflow at a rate of 1,500 m^3/h. Flooding of the entire subsurface workings occurred when a steel door, installed to contain water inflow, could not be fully closed. Remediation efforts are in progress and Cameco, the mine operator, announced in February 2008 that a large concrete plug had successfully sealed the workings from further groundwater inflow at the rockfall location. The analysis was based on rising head tests conducted utilizing the shaft as a large diameter pumping/monitoring well over an 8-day period. Flooding occurred again during the summer of 2008, further delaying the start date for production until some time after 2011, more than three years behind schedule. See Cramer and Smellie (1994) for further details on the AECL-led study.

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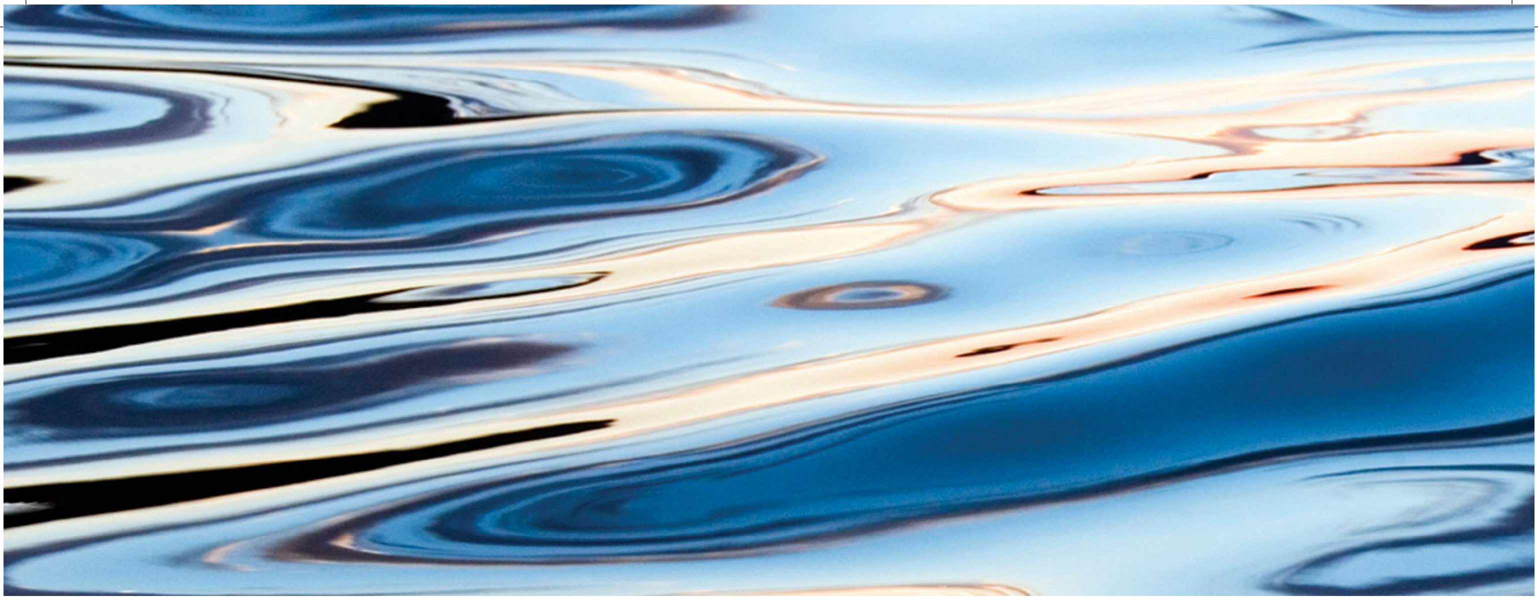

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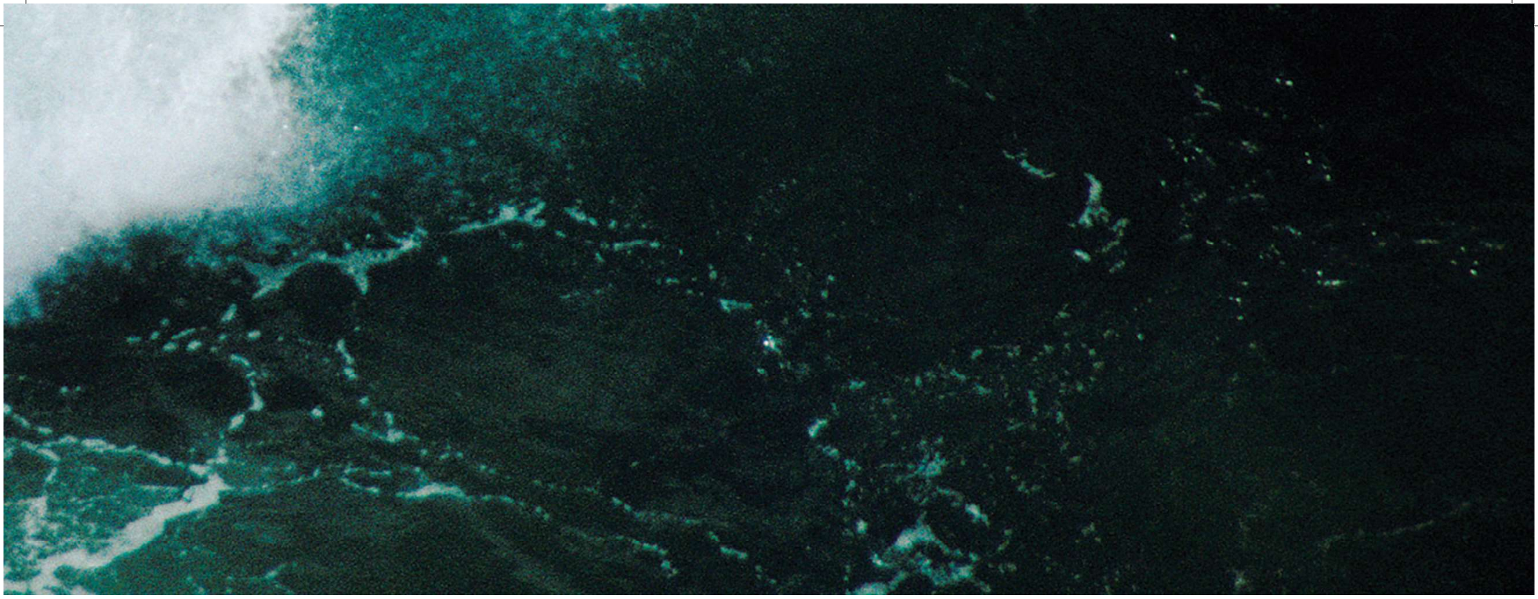

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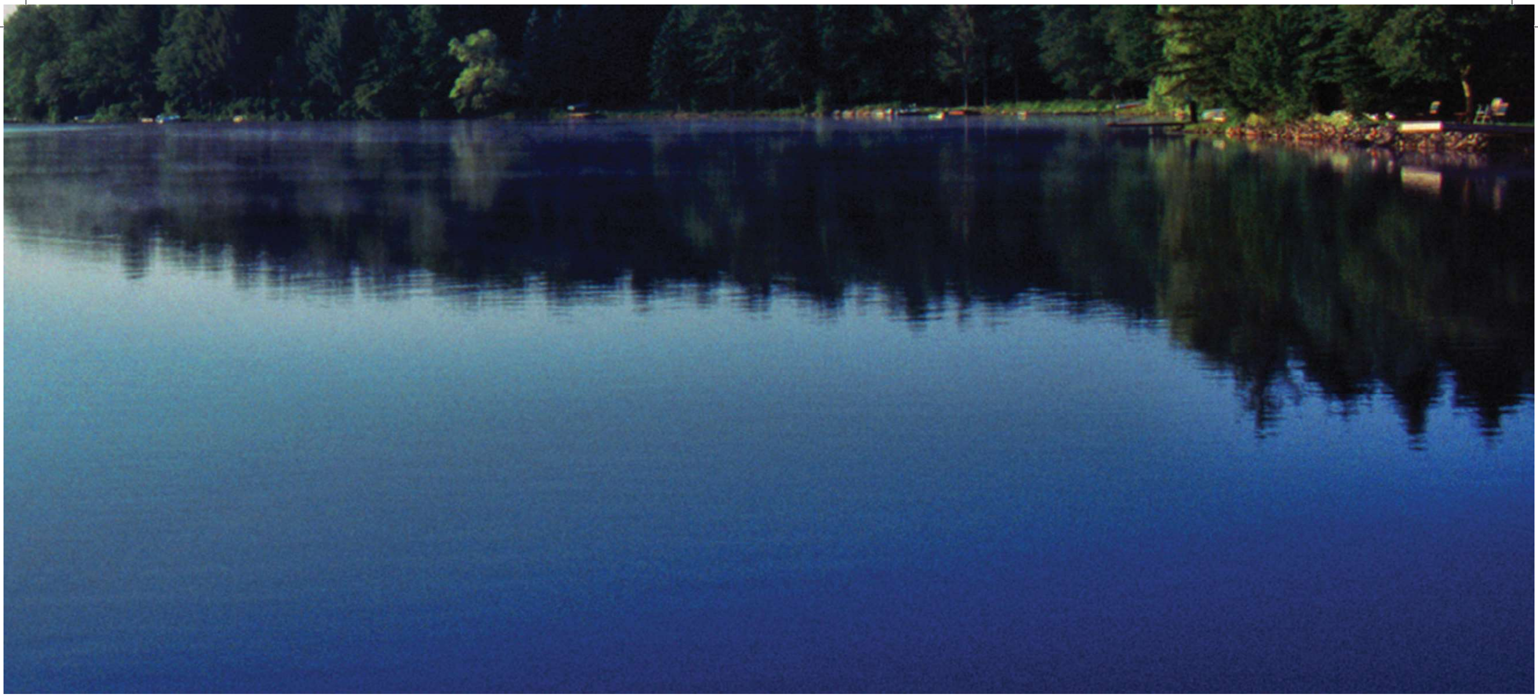

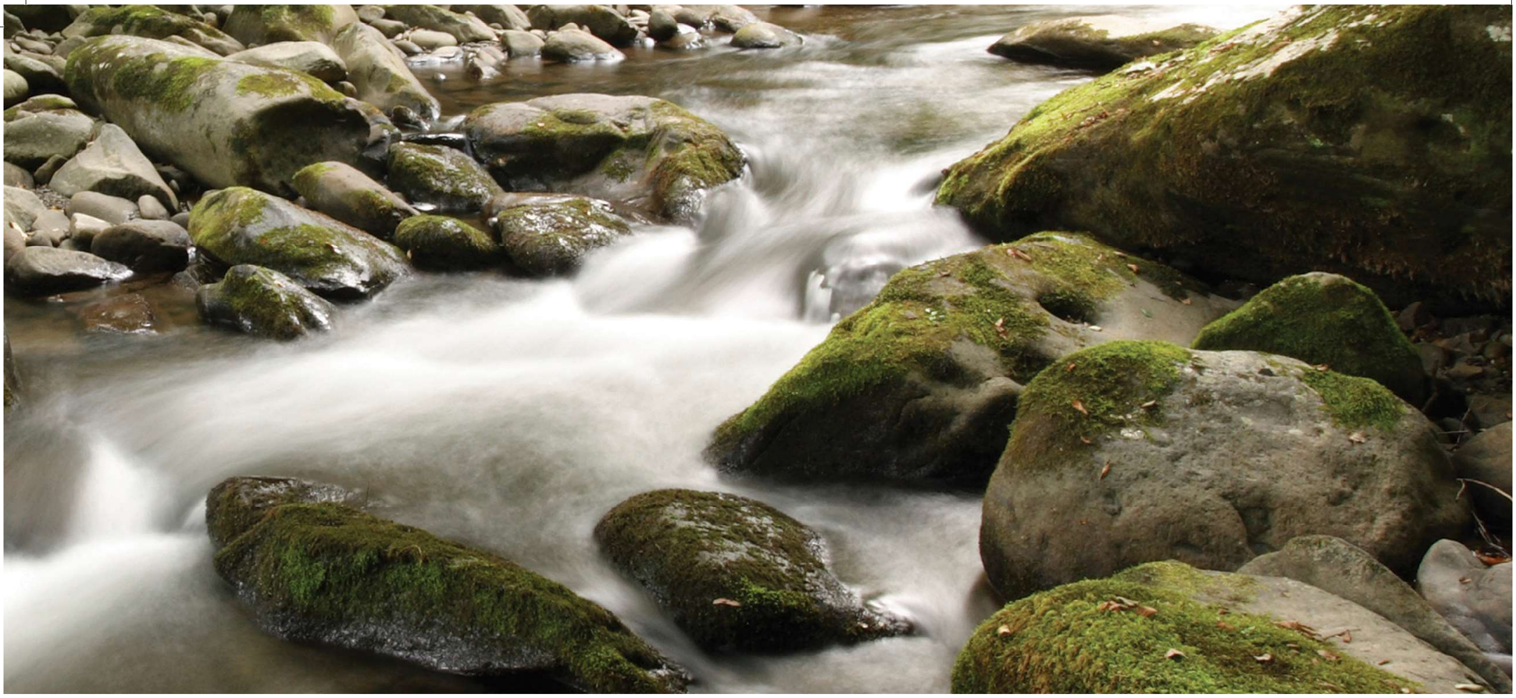

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