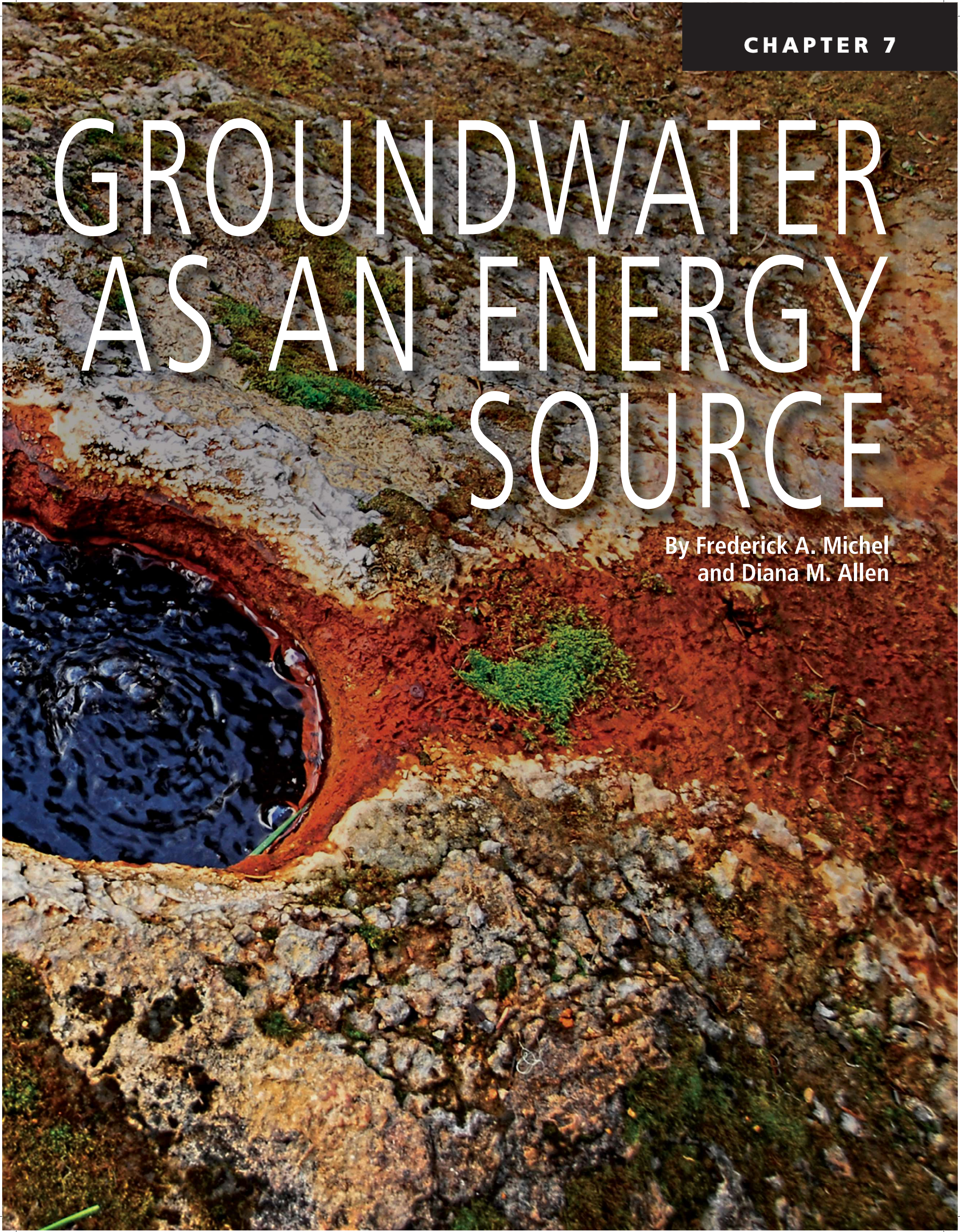

CHAPTER 7

GROUNDWATER AS AN ENERGY SOURCE

By Frederick A. Michel
and Diana M. Allen

Figure 7.1 Nahanni Headwater hot springs (64°C) near Tungsten, N.W.T. discharge from a still warm Cretaceous-age quartz monzonite intrusive.

7.1 INTRODUCTION

Rising energy costs during the past two decades have created an increasing worldwide interest in exploring and developing alternative energy sources. An adequate supply of electricity is critical for everything from of manufacturing to computers, for lighting, and for heating and cooling our buildings. As energy demands continue to climb, much of the focus today has shifted towards using renewable energy sources, such as wind, tidal, solar, hydro, biomass, and geothermal, for electricity production. The Governments of Nova Scotia and Ontario have recently announced major policy changes to significantly increase the percentage of electricity produced by renewable energy.

Surface water, flowing in rivers and lakes, is well known as an energy source. It can be contained behind dams and channeled through turbines to release energy for the generation of hydroelectricity. Groundwater also contains thermal energy, which can be harnessed as a renewable energy source through ever improving technologies. Moreover, groundwater's potential as an energy source is enormous, particularly in comparison to its current usage.

Our Earth is dominated by two sources of thermal energy: radiation from the sun and heat radiation generated within the interior of the planet itself (this latter source is known as geothermal energy, from the Greek "geo" meaning "earth" and "therme" meaning "heat"). Geothermal energy generated within the interior of the planet migrates along a geothermal gradient towards the Earth's surface, where temperatures are lower. Worldwide geothermal gradients average 25°C/km, although they can be considerably higher in tectonically and volcanically active regions, and lower in areas of stable cratons (12°C/km in the Canadian Shield). Distribution of these thermal variations is depicted in the geothermal maps of Canada provided by Grasby et al. (2009).

The migration of geothermal energy is accomplished by conduction through rock and sediment, and by convection of groundwater circulating within the outer crust. Unless the groundwater is fast moving, it remains in thermal equilibrium with the surrounding rocks and sediments through which it flows. Thus, the ground and groundwater usually have the same temperature. However, when groundwater is fast flowing, it may move out of thermal equilibrium with the surrounding geologic environment, and in such cases, we observe several interesting geothermal features. Groundwater that has been heated within the subsurface can discharge at the Earth's surface as thermal springs (warm or hot), geysers, or the fumaroles associated with volcanic activity. Figure 7.1 pictures thermal waters (with mist rising) discharging between boulders at Nahanni Headwater hot springs near Tungsten, N.W.T.

Temperature fluctuations at the Earth's surface influence shallow groundwater temperatures to depths of approximately 10 m (Figure 7.2). During spring and summer, heat from the sun warms the ground surface, and heat energy migrates downward into the ground. This causes the ground to warm, and its temperature increases progressively into the late summer months. During winter, this heat energy flow is reversed, and the ground loses heat, resulting in a cooling of ground temperatures.

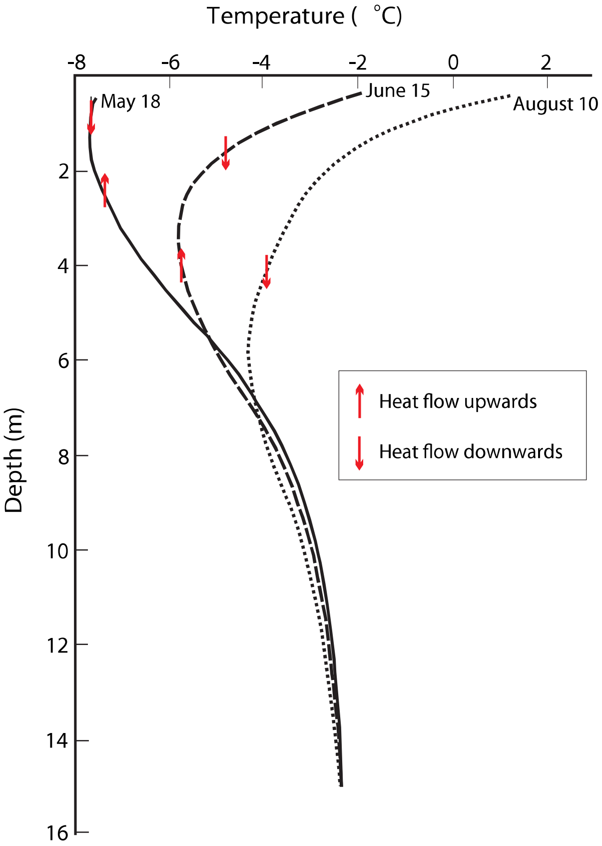

Figure 7.2 Temperature distribution with depth (adapted from Domenico and Schwartz, 1990).

Thus, shallow subsurface groundwater experiences a range of temperatures on an annual basis.

Between depths of 10 m and 20 m, however, ground and groundwater temperatures remain relatively stable year-round. The depth at which this occurs is termed "the maximum depth of annual cyclic variation".

Thermal waters have been defined as those waters with temperatures significantly (> 5°C) above the mean annual air temperature (MAAT) of the local region (White, 1957; van Everdingen, 1972), while "hot" water in the broadest definition has a temperature above that of the human body (37.0°C), although Woodsworth (1997) used 32°C to define "hot springs" in western Canada. Shallow ground and groundwater temperatures in

Canada tend to average nearly 5°C above MAAT, and it may be more appropriate to define "thermal waters" as those with a temperature of at least 5°C above the mean annual ground temperature (MAGT) of a particular area, or as Michel (1977) and Grasby and Hutcheon (2001) suggest, temperatures > 10°C above MAAT. Groundwater with a temperature below this limit would be considered as non-thermal, even though it still contains a certain amount of heat. The relatively low temperature of non-thermal waters might still make them ideal for potential heat/cooling sink applications.

Water's thermal and fluid properties make groundwater an ideal transporter of heat energy within the subsurface, while the rocks and sediments through which the groundwater migrates become the primary heat storage medium. Geothermal resources, and the groundwater associated with the heat flux are considered an important type of renewable energy source because of the constant generation and transport of heat to the Earth's surface. We will focus, in this chapter, on examining the potential to utilize groundwater as a thermal energy source/sink throughout Canada.

7.2 DISTRIBUTION OF THERMAL WATERS

When people think of geothermal water, they often imagine phenomena such as the Old Faithful geyser in Yellowstone National Park, the district heating of buildings in Iceland's capital Reykjavik (meaning Bay of Steam), or the tourist resorts and spas associated with well-known thermal and mineral springs throughout the world. Geothermal waters, however, heated to varying degrees, exist almost everywhere on Earth.

Ground temperatures below the depth of annual cyclic variation rise, in accordance with the local geothermal gradient, as the depth within the Earth

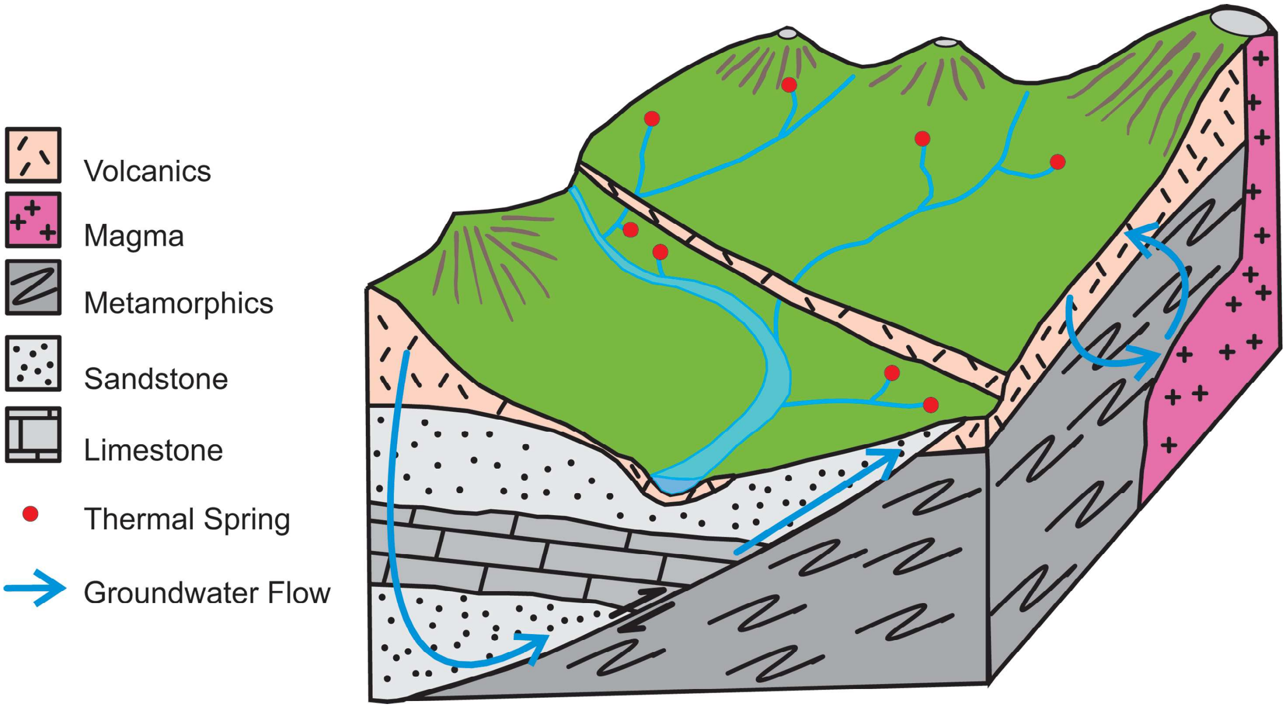

Figure 7.3 Schematic showing thermal springs resulting from deeply circulating groundwater flow discharging along a fault trace and groundwater circulation related to high-level pluton emplacement.

increases. Deep mines often encounter unbearably high rock temperatures at depths exceeding one kilometre, requiring additional ventilation and cooling to allow miners to work with some degree of comfort. Groundwater circulating within the upper 2 to 3 km of the Earth's crust is also heated as it flows through the deeper hotter rocks. The water expands as it is heated, causing a decrease in its density. This heated, lower-density groundwater rises towards the ground surface through fractured or permeable rocks, while colder, denser water migrates deeper: the thermally driven groundwater circulation carries heat towards the ground surface by convection. Depending on the depth of circulation, the local geothermal gradient, and the rate of upward flow once the water is heated, these thermal groundwaters may discharge as warm or hot springs, often along fault lineaments (also see Figure 7.3). Because the groundwater moves quickly up the fault, it falls out of thermal equilibrium with the shallow environment and thus is warm or hot relative to other near-surface groundwater. In those areas where molten magma has risen recently within the crust to form high-level plutons, or erupted onto the surface as volcanoes, the geothermal gradient is very high and groundwater heats up rapidly at relatively shallow depths (Figure 7.3). When the rate of ascent is relatively slow, much of the heat can be dissipated into the rocks through which the groundwater migrates, leaving a cool groundwater discharge. Thermal springs in Canada have been shown to originate as meteoric[1] water (Michel 1977, 1986; Grasby and Hutcheon, 2001; Grasby et al., 2000; Caron et al., 2008) which circulates to depths estimated at 0.2 to 4.8 km.

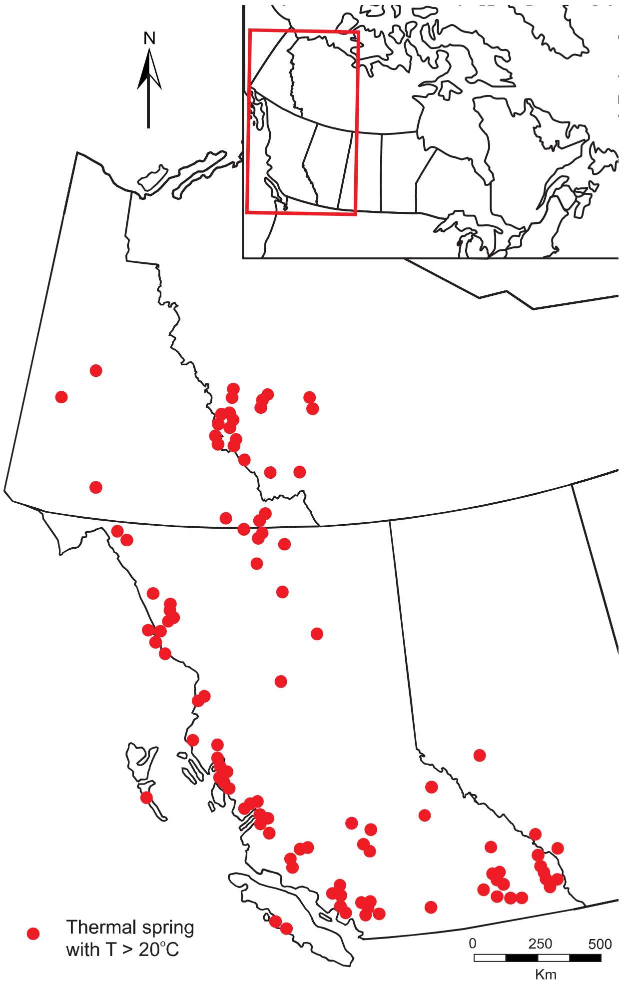

Figure 7.4 Distribution of known thermal springs in Canada with T > 20°C (after McDonald et al., 1978).

Western Canada's Cordillera hosts numerous identified occurrences of thermal springs, wherein water temperatures up to 86°C have been reported (Woodsworth, 1997). (Figure 7.4. See also van Everdingen, 1972, Crandall and Sadlier-Brown, 1977; McDonald et al., 1978; and Woodsworth 1997). Many more thermal springs remain still unidentified. A number of the more accessible springs are enjoyed by hikers, while others (e.g., Banff, Harrison, and Miette) have been developed for tourists, some of whom are attracted by a belief in the therapeutic benefits of these thermal waters. Most spring sites in Canada, however, remain relatively pristine and undeveloped.

The majority of thermal springs in the Canadian

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[1] Meteroric water is water that is derived from precipitation.

Cordillera are associated with deep circulation systems within sedimentary rock sequences, with faults providing high permeability conduits which permit the rapid ascent and concentrated discharge of the heated waters. Hot springs near Mount Meager in southern B.C. and Mount Edziza in northern B.C. are associated with recent volcanic complexes active during the past few thousand years, while others, such as those of the Tungsten, N.W.T area, are related to residual heat associated with high-level pluton emplacement during the Cretaceous.

7.3 GEOTHERMAL RESOURCE POTENTIAL

Geothermal resource potential can be divided into three main categories based on the possible application types, which are usually related to subsurface thermal conditions. These three categories are:

1. Electricity generation—with steam turbines where temperatures exceed 150°C, and with binary generation technology where temperatures are > 80°C
2. Direct utilization in space heating or industrial processes where the resource temperature is moderate to high (>60°C)
3. Space heating with or without the aid of heat pumps when the resource temperature is low (<60°C)

British Columbia's Geothermal Resources Act (GRA) defines a geothermal resource, in part, as groundwater with a surface discharge temperature exceeding 80°C. There are only two known spring localities (both in B.C.) that meet this requirement; thus, the GRA is focused on the development of deeper subsurface groundwater reservoirs for high-temperature applications, such as electricity generation. The province of Nova Scotia, on the other hand, has identified several “Geothermal Resource Areas” (as part of the Mineral Resources Act) within sedimentary basins containing flooded former coal mines with groundwater temperatures below 20°C. None of the other provinces or territories formally recognize geothermal resources, although Manitoba is encouraging development of low-temperature resources. Allen et al. (2000) summarized the status of geothermal development in Canada, and Grasby et al. (2011) demonstrated the fact that there is tremendous geothermal energy potential across the country. Future technology developments may also help develop Enhanced Geothermal Systems that could supply a significant amount of Canada’s electricity demand (Majorowicz and Grasby, 2010). Additionally, Majorowicz et al. (2009) have described significant shallow heat exchange potential across Canada.

Traditional applications in all three categories have considered only direct utilization of existing geothermal conditions, wherein groundwater at the ambient subsurface temperature is employed as the ground source fluid. Higher temperature groundwater (categories 1 & 2) can be utilized directly for space heating of local buildings and greenhouses, industrial processing, aquaculture, swimming pools and spas. These categories are also an indication of at least localized higher-than-average geothermal gradients that might potentially be tapped as high-temperature energy sources through the drilling of deeper boreholes. For instance, at B.C.’s Mount Meager, recorded bottom-hole temperatures (as high as 270°C) were sufficient to permit the construction of a 20kW test scale geothermal power plant facility designed to generate electricity (Jessop, 1998). Central Alaska’s Chena Hot Springs generates electricity utilizing groundwater temperatures as low as 74°C (B. Aho, pers. comm.).

Category 3 usually focuses on shallow boreholes (<200 m deep). These low-temperature resources can incorporate applications for both heating and cooling by employing heat exchangers and heat pumps, where heat energy is either added to or removed from the groundwater during the respective cooling and heating applications. Because of the widespread occurrence of groundwater throughout Canada, the potential for use of groundwater as a low-temperature energy source is similarly widespread.

Higher temperature resources are primarily restricted to the Cordilleran region of the country. Lower temperature groundwaters are more widespread across the entire country, and are still capable of being utilized as energy sources using our current levels of technological development (Grasby et al., 2011).

7.3.1 Direct generation of electricity

Geothermal resources suitable for the generation of electricity require a reservoir capable of providing super-heated hot water and steam at a temperature exceeding 150°C, and preferably above 200°C. The Cordillera Region, as part of the “Rim of Fire”, with its young volcanoes and recent high-level pluton emplacement related to ongoing tectonic activity, is the only region in Canada where this very high temperature potential exists.

The primary focus for the development of geothermal electrical generation within Canada has been at Mount Meager, located approximately 170 km north of Vancouver. Mount Meager is the northernmost volcano of the Cascade Mountains and is currently one of only a few Canadian locations leased for geothermal electricity production.

BC Hydro began exploratory surveys at Mount

Meager during the mid 1970s, drilling a total of 18 test holes and 3 deep full-diameter exploratory wells. In 1983, flow from one of the exploratory wells was utilized successfully in the operation of a test 20 kW generator facility, although the facility was subsequently discontinued in 1984 for several reasons, including declining energy prices and infrastructure overcapacity at BC Hydro (Jessop, 1998).

Western GeoPower Corp. undertook additional investigations in 2002 which yielded borehole temperatures of 200°C to 225°C at depths of 600 to 900 m. A follow-up program that included drilling in the period 2004 and 2005 resulted in the company stating in 2007 that the geothermal reservoir covered an area of 4.5 to 7.5 square kilometres and that the reservoir has an average temperature of 220°C to 240°C (maximum of 275°C) at a depth of 1,600 to 1,700 metres, and has a potential development capacity of 100 MW or more. As a result, feasibility for a 100 MW power plant utilizing dual-flash turbine technology with two 55 MW (gross) generating units was explored. Dual-flash turbine technology flashes hot water from the reservoir to steam by suddenly dropping its pressure. The steam is then used to drive a low-pressure turbine. The condensed steam and unflashed water are re-injected to the reservoir for reheating and to maintain reservoir pressure. In 2009, Western GeoPower Corp. was taken over by a U.S. company, Ram Power Corp., and the Mount Meager project has been moved to low priority.

More recently a project examining production of hot water from the Western Canada Sedimentary Basin was proposed to produce electricity for the remote town of Fort Liard, wherein a geothermal system would provide the town's entire electrical needs, removing its reliance on burning imported diesel fuel. The Fort Liard project is being developed by Borealis GeoPower. Discussions began in 2009; an MOU with the town was signed in 2010.

Borealis GeoPower is planning construction of the system during the summer of 2013 with the official start-up set for January 1, 2014. It is expected to generate at least 600 kW of electricity using a binary power plant (Phase 1) to replace the current diesel generators for electricity production. In Phase 2 it will provide up to 6.8 MW of geothermal heating for all 160 homes in the community (1.3 MW) and other commercial uses.

Geothermal potential is also being examined for other remote mine sites in the Yukon, in addition to geothermal leases at Knight Inlet and Canoe Reach in B.C.. At the Chena Hot Springs in central Alaska, two 200 kW Organic Rankine Cycle (ORC) power plant modules, designed and built by United Technologies Corporation (UTC) based on reverse engineering of traditional air conditioning hardware, have produced electricity at less than 20% of the cost for the previous diesel generators (< \$0.06/kW). The project has produced a flow rate of 480 gallons per minute (gpm) and flashes a binary fluid (R-134a) to vapour in order to drive the turbine and generate electricity. The binary fluid is re-condensed using local cold (4–7°C) groundwater in summer at a rate of 1,500 gpm, and air cooling in winter. The thermal water is re-injected to the subsurface to maintain reservoir pressure. In addition, the geothermal waters are utilized directly for heating of the resort buildings, its swimming pools, and greenhouses, which produce fresh vegetables for the resort (see www.chenahotsprings.com for details).

7.3.2 Moderate- to high-temperature resources

High-heat flow occurs in tectonically active regions, usually related to convergent or divergent plate margins, as evidenced by molten discharges of magma from volcanoes. Upward heat flow, however, occurs everywhere within the Earth's crust. In areas of rapid sediment accumulation, the sediment weight depresses the ground, forming a basin into which sediments continue to be deposited. Deep sedimentary basins have been identified throughout the world as potential targets for exploration of geothermal resources primarily because of the presence of significant quantities of groundwater—a major medium for transferring and transporting heat from rock at depth. Even with an average geothermal gradient of 25°C/km, groundwater at a depth of only 2,000 m will attain a temperature of 50°C. Higher temperatures can be expected when the geothermal gradient is above average, or if one looks to greater depths within the basin. Groundwater that migrates upward, either vertically or toward the basin margins, can carry additional heat closer to the ground surface than would otherwise be expected. Heat can also be trapped in the deeper reservoir rocks when the overlying sediments possess a comparatively low thermal conductivity[2] and are relatively impermeable.

Although the temperature of these deep basin groundwaters can exceed 60°C, they usually do not attain the higher values required for electrical generation. Instead, these moderate- to high-temperature groundwater resources can be utilized for direct heating applications, such as space heating of buildings and greenhouses, industrial processes, drying of agricultural products, aquaculture, and thermal spas and pools. Jessop (1976) described development of 60°C groundwater resources for space heating of apartment buildings in France's Paris Basin. Higher water temperatures provide more heat energy per volume of water extracted a factor that can substantially affect the economics of a project.

From 1976 to 1986, the Earth Physics Branch of Energy, Mines and Resources Canada (now Natural Resources Canada, or NRCan) initiated several investigations across the country to determine the potential for moderate- to high-temperature geothermal resources in deeper sedimentary basins (Figure 7.5). Canada's largest sedimentary basin is the Western Sedimentary Basin of Alberta, Saskatchewan, southwestern Manitoba, northeastern B.C. and southwestern N.W.T., with a maximum depth of nearly 5.4 km. Atlantic Canada's Cumberland Basin, part of a group of Carboniferous basins in the area, contains up to 9 km of sediment. Other smaller Carboniferous sedimentary basins in Nova Scotia and New Brunswick, the Quebec Basin, the Michigan Basin, the Mackenzie Delta–Beaufort Sea Basin, and the Sverdrup Basin in the Arctic Islands have also been investigated. Jessop (1976) provided a preliminary overview of the geothermal potential for all of these basins.

The Western Sedimentary Basin's (WSB) geothermal potential was originally evaluated by Sproule and Angus (1981) for NRCan's Earth Physics Branch: the study involved the compilation of existing data (such as bottom-hole temperatures) from exploratory oil and gas wells drilled throughout the basin. The study paid particular attention to delineating sediment thickness, thermal gradients and bottom-hole temperature distribution, as well as commenting on permeability of potential reservoirs and the geochemistry of groundwater encountered in the formations during drilling.

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[2] Thermal conductivity is a property of a medium (air, water, soil, rock) that describes the medium's ability to conduct heat. For porous media, the bulk thermal conductivity is determined by the thermal conductivities of both the minerals (and organics) along with the fluid (air or water) filling the pore space. Thermal conductivity is analogous to hydraulic conductivity in hydrogeology in that it is the property that governs conduction (heat rather than water). Typical values are: granite (2.5–3.8 W/mK), sandstone (1.5–4.3 W/mK), wet sand (2.5–3.5 W/mK), water (0.598 W/mK at 20°C).

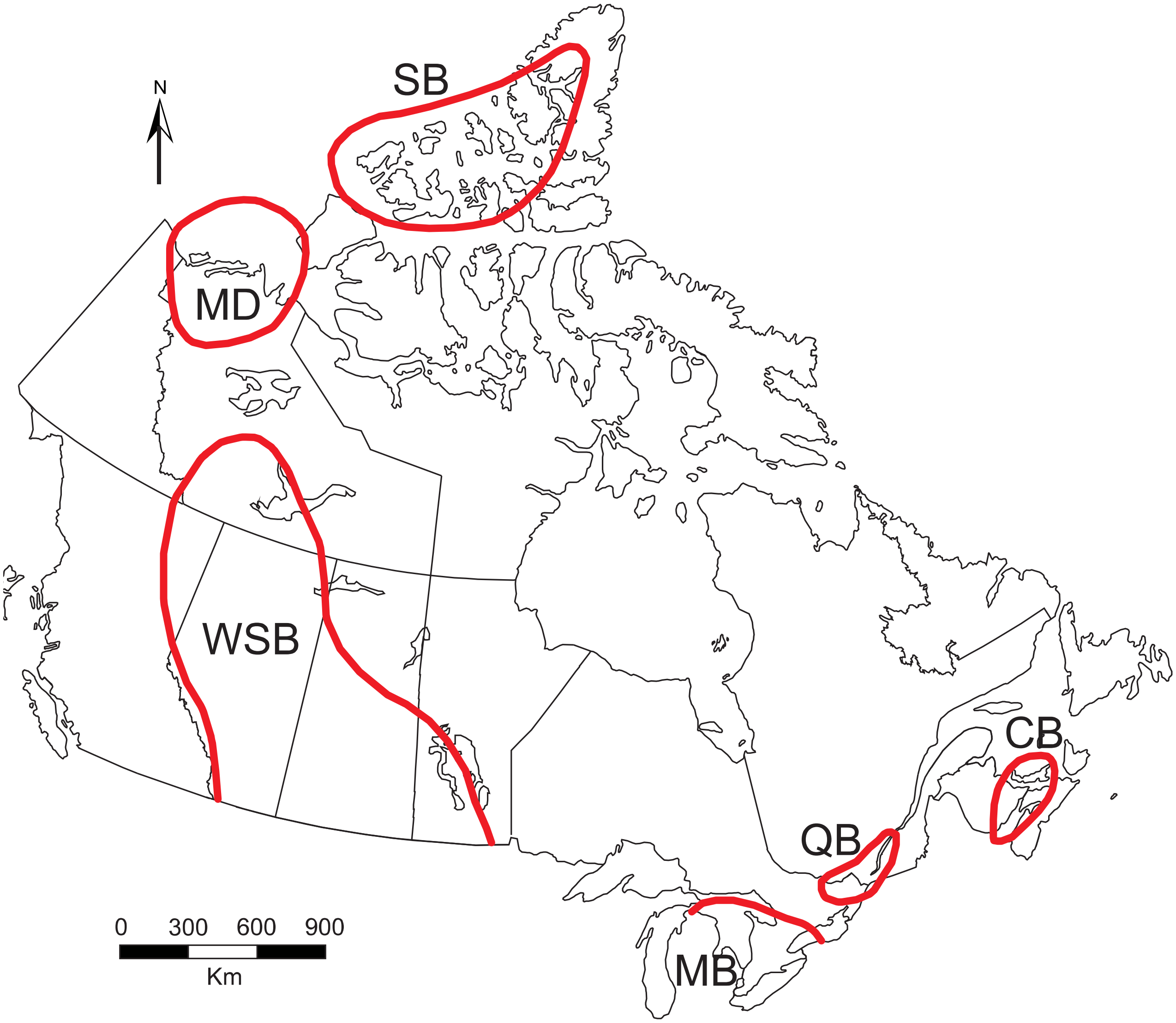

Figure 7.5 Location of major sedimentary basins in Canada discussed by Jessop (1976). Western Sedimentary Basin (WSB), Mackenzie Delta–Beaufort Sea Basin (MD), Sverdrup Basin (SB), Michigan Basin (MB), Quebec Basin (QB), and Cumberland Basin (CB).

The WSB can reach a thickness in excess of 3,000 m in a trough stretching through western Alberta, northeastern B.C. and into the south end of N.W.T. (Figure 7.6). Localized thickening of the sedimentary rocks is also present in southern Saskatchewan. Figure 7.7 depicts the approximate temperature distribution within the basin. The highest temperatures, which exceed 90°C, are found within parts of the trough containing over 3 km of sediments: the highest temperature reported was from a well at the southern end of the Yukon–N.W.T. border, where a bottom-hole temperature of 179°C was measured at a depth of 4419 m (Jessop, 1976). Temperature gradients varied from 20 °C to 50°C per km, and averaged near 30°C/km. Some of the higher gradients were reported from those areas where the basin is less than 2 km deep. The basin east of central Alberta is generally less than 1.5 km thick and temperatures measured below 60°C. In 1983, Acres Consulting Services Ltd. examined the

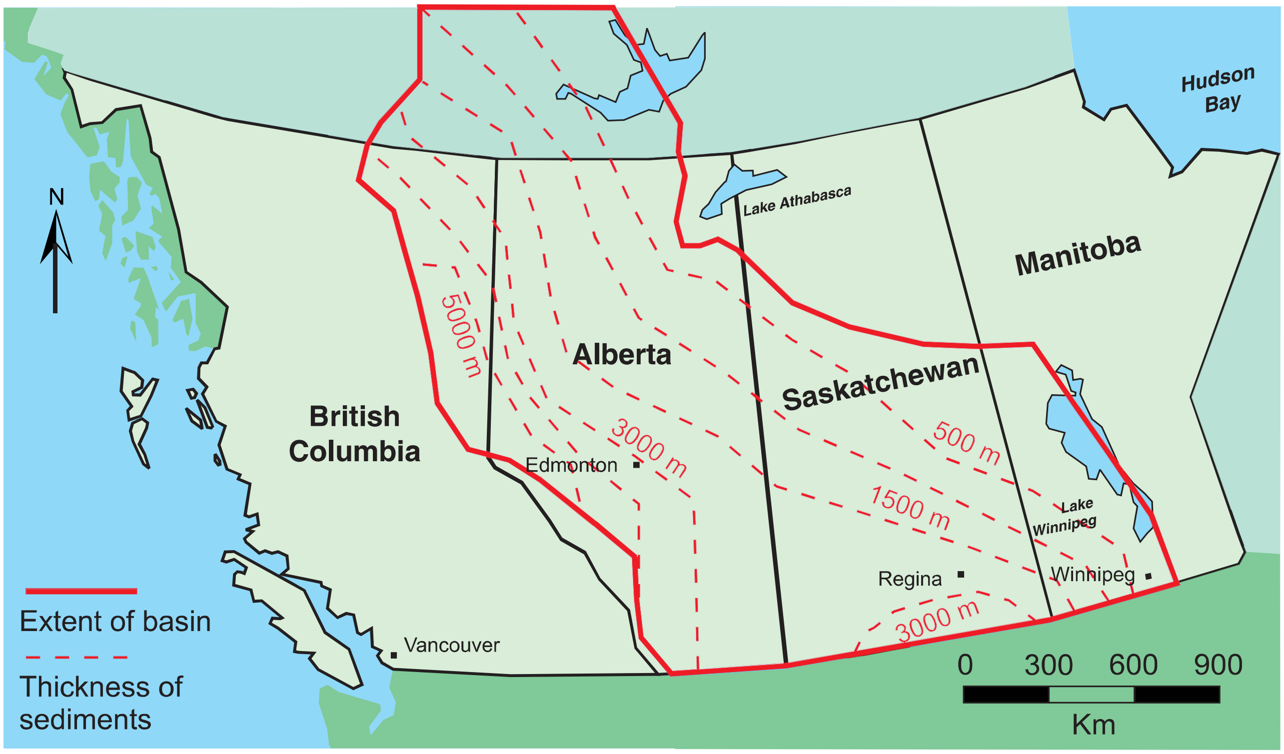

Figure 7.6 Thickness of sediments within the Western Sedimentary Basin overlying Precambrian basement (adapted from Canadian Plains Research Centre Mapping Division, 2008). The western margin of this basin forms a trough with over 3,000 m of sediment.

economic potential for low-temperature geothermal applications for the National Research Council of Canada.

Jessop (1976) reported an elevated geothermal gradient of 30°C/km for both major basins in northern Canada, but since these are not located close to any potential markets they have not received much consideration. Nevertheless, there has been recent interest in the potential to supply electricity to remote northern communities not connected to transmission grids. Additional suggestions for producing electricity from the hot water co-produced from pumping oil and gas wells before being re-injected into the ground are also under discussion.

Geothermal gradients in eastern Canada are consistently low, and average 15°C to 25 °C/km (Jessop 1976; Leslie 1981, 1982; Jessop et al., 1995). A thick sediment accumulation (up to 9 km) and an average geothermal gradient in the Cumberland Basin make this the most likely basin in Atlantic Canada to find moderate- to high-temperature groundwater at depth. Further research is required to identify potentially favorable reservoir formations.

Bottom-hole temperatures do not necessarily correspond to a geological formation which can be considered as a reservoir rock. Only a few stratigraphic formations provide sufficient permeability and storage capacity to be considered as geothermal reservoirs. Drilling represents a significant portion of geothermal system development (capital) costs and, as a result, potential target formations must be well defined early in the evaluation process. Production rates are limited by reservoir permeability, thickness, continuity, and hydraulic pressure, as well as by well design, well diameter, and pump size. Acres Consulting Services Ltd. (1983) estimated that the minimum target flow rate for geothermal systems in the WSB should be

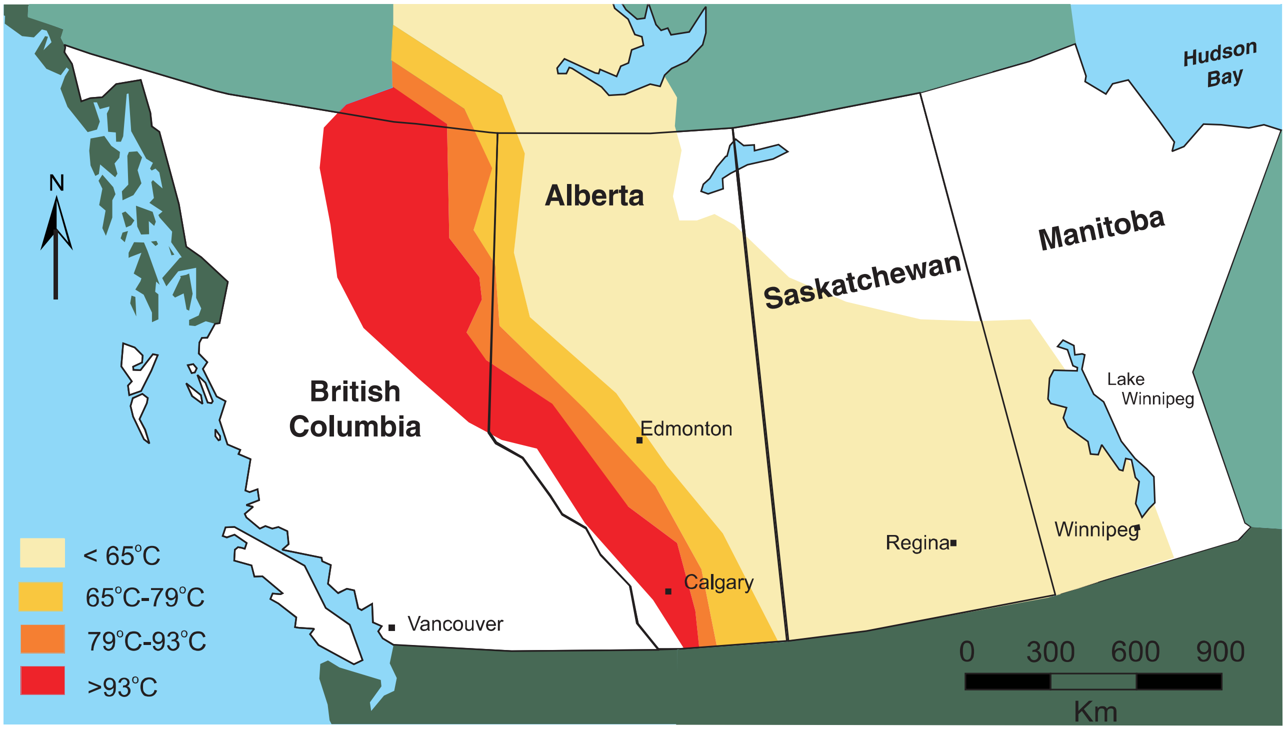

Figure 7.7 Temperature distribution in the Western Sedimentary Basin (from Allen, 2000).

100 m^3/hr. Temperatures must be closely related to potential reservoir formations and their characteristics to develop a proper evaluation for any sedimentary basin.

7.3.3 Low-temperature resources

Much of the worldwide attention for geothermal energy development has traditionally focused on electricity generation and, to a lesser extent, on the potential exploitation of hot water in deep sedimentary basins for direct space heating. In recent years, however, there has been increasing interest in the use of low-temperature resources for heating and direct cooling applications.

Low-temperature geothermal systems, whether used for heating or cooling, or for a combination of both, are known under a variety of names, including ground source heat pump systems, geo-exchange systems, ground-coupled systems, or earth energy systems. Open-loop systems, wherein groundwater is extracted using a water well and used for heating or cooling, are a particular type of low-temperature geothermal system. Closed loop systems, in contrast, involve no direct communication with the groundwater regime: heat exchange occurs through a set of horizontally buried pipes (horizontal loop) or pipe circuits placed in a series of boreholes (vertical loop).

In Canada, low-temperature geothermal resources occur everywhere in the shallow subsurface wherever mean annual ground temperatures are roughly 3°C to 5°C above the mean annual air temperature. Mean annual air temperatures for selected cities across the country are given in Table 7.1, while representative shallow groundwater temperatures across Canada are shown in Figure 7.8. Temperature rises with depth, in accordance with the local geothermal gradient, but is still relatively low even at a depth of a few hundred metres.

Air temperatures fluctuate both daily and seasonally, thus, continuous heating or cooling of buildings is required in order to maintain a constant comfortable room temperature environment. Heating and cooling, which typically accounts for 60% of all energy used for commercial, institutional and residential buildings (NRCan, 2006), represents an important component of the overall energy and greenhouse gas emission picture. Figure 7.9 illustrates the fact that groundwater temperatures remain relatively constant throughout the year, but are generally lower than normal room temperature (20°C). Many low-temperature heating applications employ heat pumps to enhance energy recovery and to make up the difference between ground temperature and room temperature.

Lower ground temperatures also permit direct cooling applications in many instances, thereby considerably lowering electrical consumption compared to standard chillers and air conditioners.

Open-loop geothermal systems extract groundwater from an aquifer using a water well, and pass it across a heat exchanger to allow transfer of energy for direct use in a building's heating/ventilation/air-conditioning (HVAC) system, typically in combination with a heat pump. The majority of open-loop systems dispose of the "used" groundwater either by discharging it to a surface water body or by injecting it back into the aquifer. These types of open-loop systems, known as pump-and-release or pump-and-dump systems, are relatively simple to implement and offer energy efficiencies which

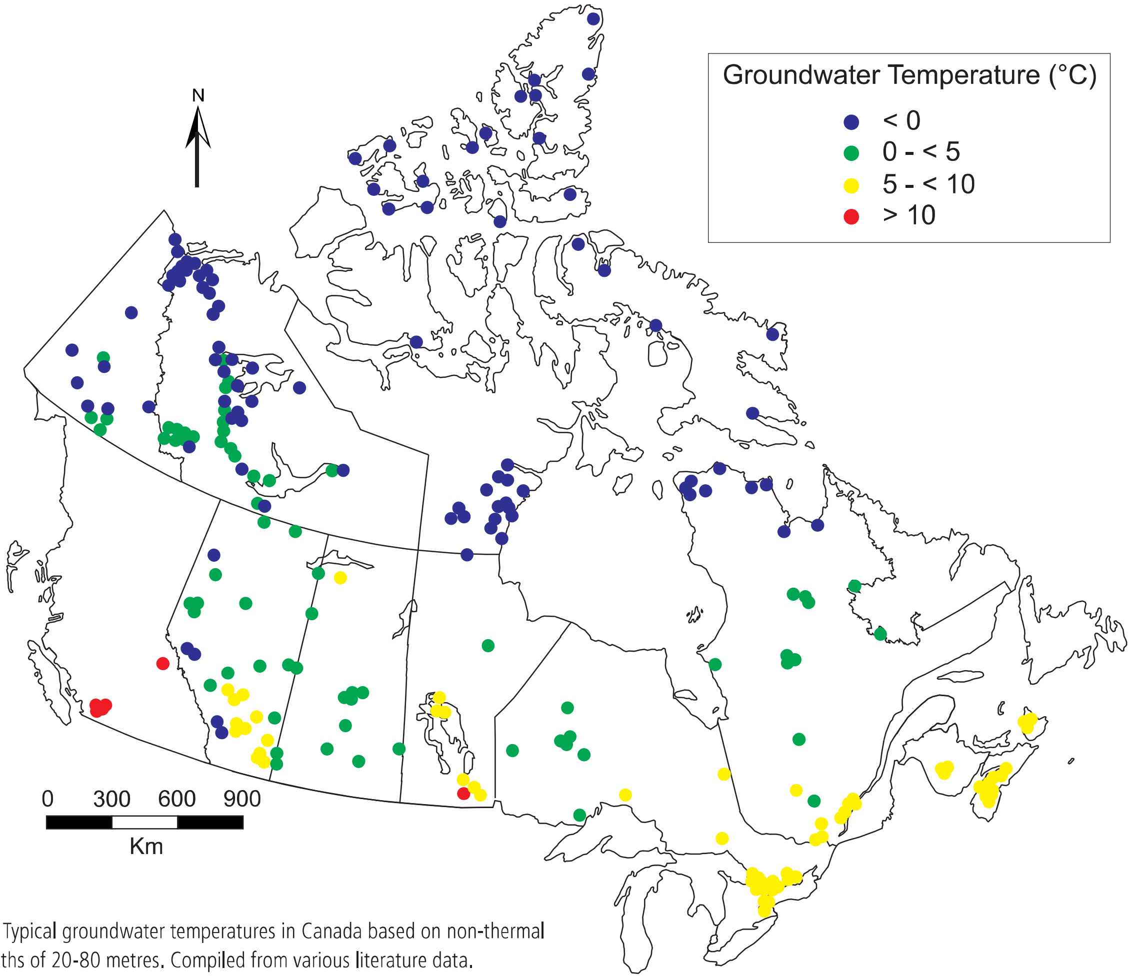

Figure 7.8 Typical groundwater temperatures in Canada based on non-thermal wells at depths of 20-80 metres. Compiled from various literature data.

TABLE 7.1 MEAN ANNUAL AIR TEMPERATURE (MAAT) FOR SELECTED CANADIAN CITIES SHOWING STANDARD DEVIATION. DATA FROM ENVIRONMENT CANADA (2006): 1971–2000 CLIMATE NORMALS

CITY	MAAT (^{0}C)
St. John's	4.7 ± 0.8
Charlottetown	5.3 ± 0.8
Halifax	6.3 ± 0.7
Fredericton	5.3 ± 0.8
Quebec City	4.4 ± 0.9
Montreal	6.2 ± 0.9
Ottawa	6.0 ± 0.8
Toronto	7.5 ± 0.9
Winnipeg	2.6 ± 1.3
Regina	2.8 ± 1.2
Calgary	4.1 ± 1.1
Edmonton	2.4 ±1.2
Vancouver	10.1 ± 0.7
Whitehorse	-0.7± 1.6
Yellowknife	-4.6 ±1.3

are comparable to closed-loop systems, but at substantially reduced capital cost (Rafferty, 2001). Nova Scotia's Acadia University, in Wolfville, currently utilizes an unconfined, unconsolidated sand and gravel aquifer to cool its research greenhouses and the adjacent environmental science building.

Open-loop geothermal systems, however, have a potential for causing environmental degradation due to the long-term warming or cooling of the material surrounding the well(s) which can be coupled with a degradation in system efficiency or system failure due to excessive warming (or cooling) of the aquifer (Bridger and Allen, 2005). This is particularly true in cases where injection of waste heat is not countered by subsequent removal of that heat, a situation which leads to excessive heat build-up. Some areas of an aquifer beneath the City of Winnipeg, for example, have warmed up by several degrees due to continued release of waste heat, largely from industrial cooling applications (Ferguson and Woodbury, 2004; 2005). When waste heat or cold energy is discharged directly into the subsurface (or surface) environment, and is unable to dissipate naturally, open-loop systems may lead to negative environmental impacts.

Depending on system design, the Earth's subsurface can also be considered as a potential store for heat (and cold) energy as discussed in the following section.

7.4 THERMAL ENERGY STORAGE (TES)

The concept of utilizing the Earth's subsurface for energy storage (especially for the purpose of providing space heating/cooling for buildings) means that we need to assess our ability to enhance and upgrade low-grade geothermal resources. A number of underground subsurface techniques utilize the Earth as a warm or cold mass storage medium (Figure 7.10): these forms of thermal mass storage include pit storage, rock-cavern storage, closed-loop pipe, duct or borehole systems in unconsolidated materials or solid rock, and open-loop aquifer or gravel-water pit storage.

Closed-loop systems, including Borehole Thermal Energy Storage (BTES) systems, offer a solid alternative when no suitable aquifers are present on site, or when the cost to determine an aquifer's suitability and the subsequent well drilling exceeds a project's budget.

Open-loop systems, including Aquifer Thermal Energy Storage (ATES) systems, are best suited to those aquifers where in situ permeability provides adequate volumes of groundwater for heat exchange operation. Worldwide use of these various techniques has shown aquifer thermal energy storage (ATES) to be one of the better methods of underground energy storage over longer-time periods (IF Technology, 1995) with respect to the storage volume achievable, the ability to transfer

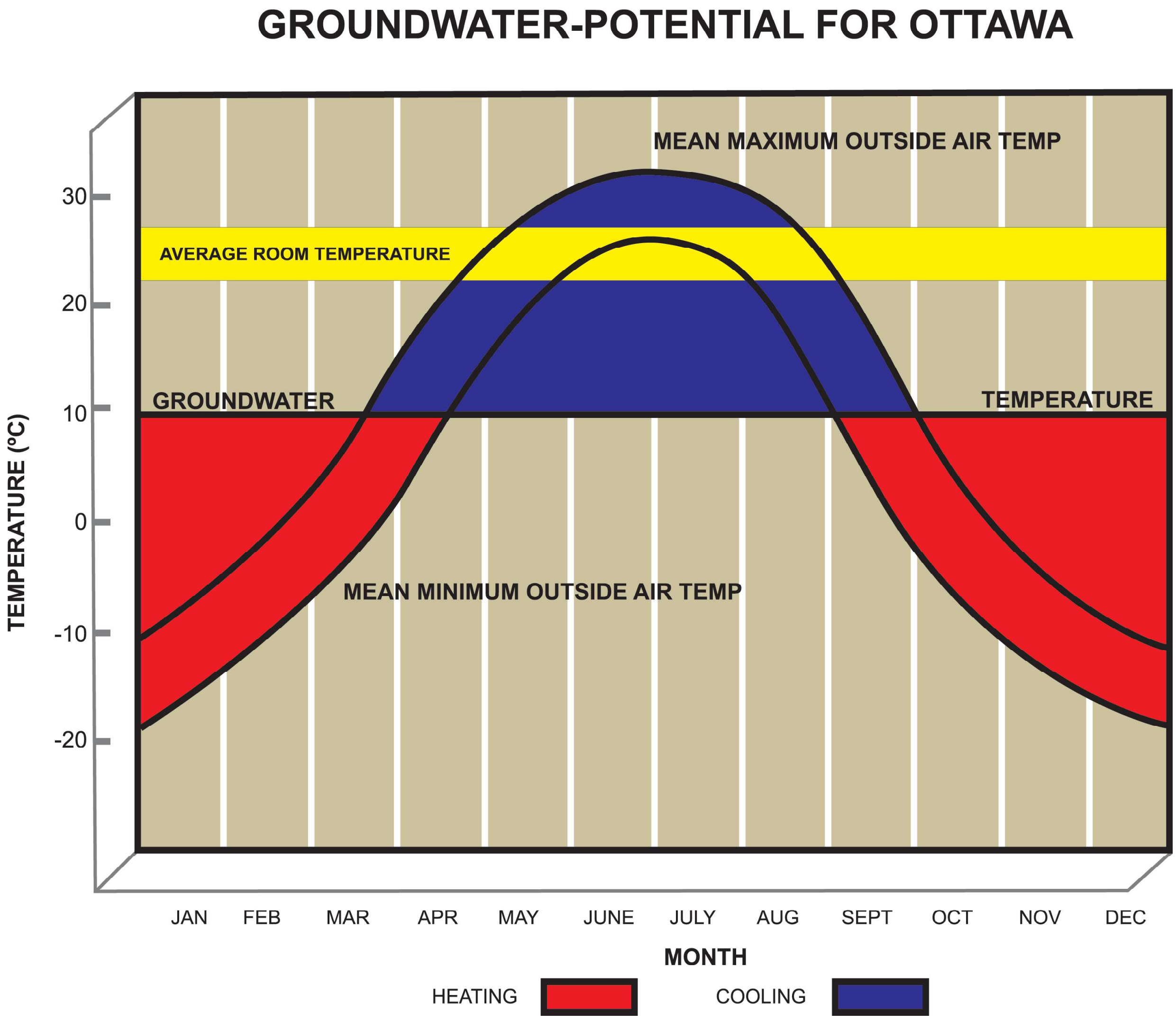

Figure 7.9 Schematic showing heating and cooling seasons superimposed with monthly air temperature range, room temperature and groundwater temperature for Ottawa, Canada.

energy, the temperature range, cost-efficiency and capital cost. Cavern Thermal Energy Storage (CTES) systems, which rely on ambient temperature groundwater stored in large caverns, have been developed at old mine sites in some areas around the world, including Springhill, Nova Scotia. All three approaches (ATES, BTES, and CTES) are being developed and utilized around the world for heating and cooling, in projects ranging from individual homes to large industrial and institutional complexes.

7.4.1 Aquifer Thermal Energy Storage (ATES)

Aquifer Thermal Energy Storage (ATES) open-loop systems offer increased energy efficiency and long-term cost savings over pump-and-dump systems and closed-loop systems because they use an aquifer as the seasonal storage reservoir for waste or excess thermal energy generated in alternate (off-peak) seasons or periods of low demand (i.e., solar energy in summer months, cold air in winter months). During periods of high heating or cooling demand, water is pumped from

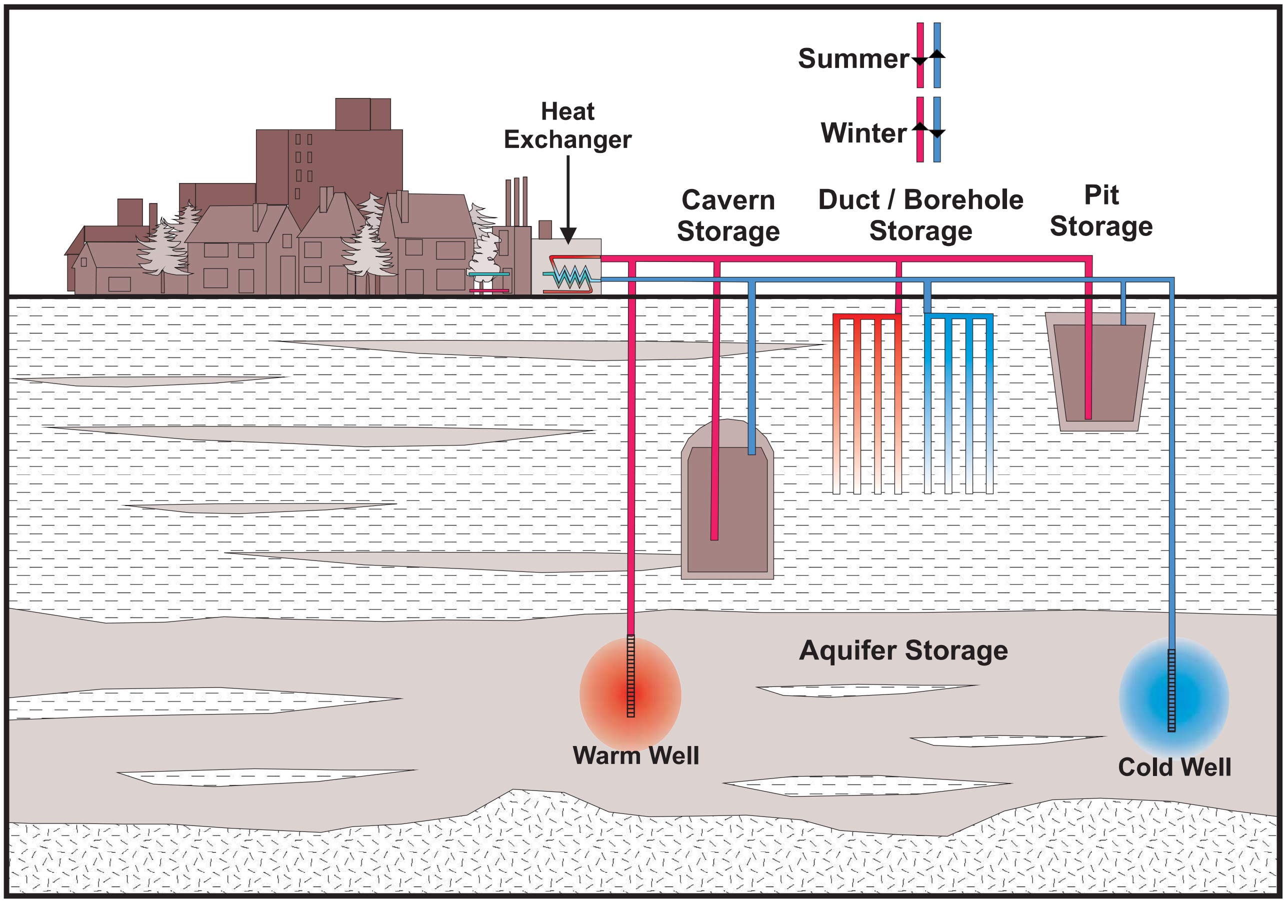

Figure 7.10 Various forms of underground thermal energy storage (adapted from IF Technology, 1995).

the aquifer to be utilized as an energy source or sink. ATES systems operate by transferring waste or excess heat or cold mass to/from groundwater via a heat exchanger. Groundwater injected back into the aquifer is heated (13°C to 120°C) or chilled (6°C to 12°C) (Figure 7.11). This water may retain a temperature higher or lower than the undisturbed ground temperature, depending on the earth's thermal properties within the specific location, and the aquifer's flow characteristics. It is difficult to maintain the thermal stores in high-gradient aquifers, because of the down-gradient drift of the thermal plumes, as illustrated in the shallow, high-gradient aquifer of Figure 7.11. However, plume capture becomes much more efficient when the hydraulic gradient is low, because the thermal plumes do not drift.

Three main ATES system types can be defined on the basis of the energy form being stored: chilled-water systems (normally referred to as cold storage), heat systems, and integrated heat and cold systems.

Cold storage involves the injection, storage and recovery of chilled/or cold water (at temperatures between 6ºC and 12ºC) in a suitable storage aquifer for periods from several hours to several months. One or more wells are used in this process, depending on energy requirements and the properties of the aquifer. Cold storage applications include air conditioning and equipment cooling (e.g., computers) on institutional (hospitals, universities/colleges, and government

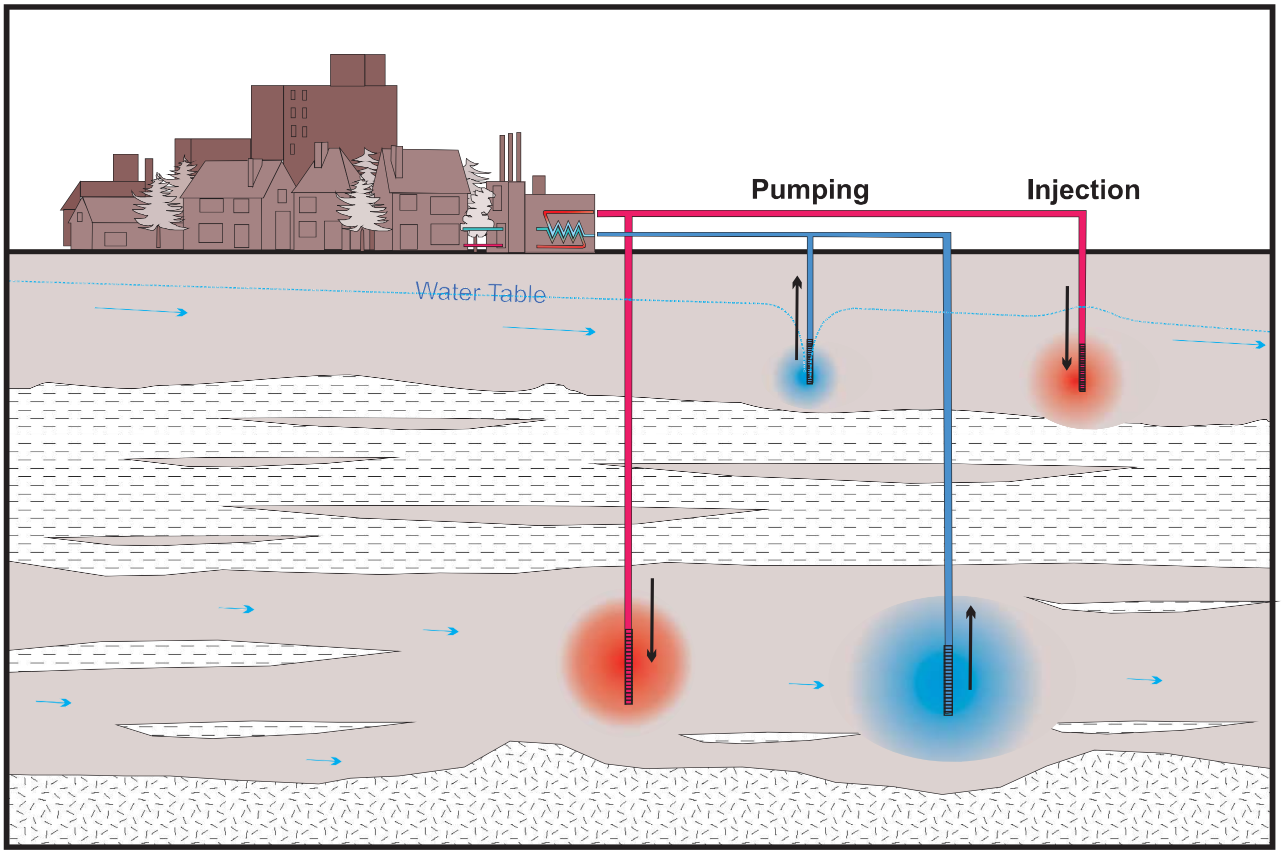

Figure 7.11 Aquifer Thermal Energy Storage (ATES) system illustrating the injection of warm water during the cooling season in a high-gradient (shallow) and a low-gradient deep aquifer. In the high-gradient aquifer, the stored heat and cold energy plumes have drifted down-gradient. In the low-gradient aquifer, the heat and cold energy plumes remain proximal to the storage wells (adapted from IF Technology, 1995).

facilities) campuses and in commercial buildings (office complexes and warehouses), and industrial process cooling (manufacturing facilities). Cold storage systems are best applied in those locations where there is a significant cooling demand for much of the year: there are many cold storage systems in operation today, both in North America and in Europe, particularly in the Netherlands.

Heat storage involves the injection, storage and recovery of heated water into and from a suitable storage aquifer. Heat storage systems are differentiated on the basis of whether they store low- to moderate-temperature heat (10˚C to 40ºC) or high-temperature heat (40˚C to 150˚C). The components, well configurations, and storage periods of heat storage ATES systems are similar to those of cold-storage systems. Aquifer heat storage is used for space heating, industrial heating, heating for agricultural purposes (e.g., greenhouses), and roadway deicing and/or snowmelting. Convective heat losses (buoyancy effects) are far greater for heat storage than for cold storage, and heat storage efficiency is typically less than that of cold storage, ranging between 50–80% (IF Technology, 1995). Wells for high-temperature heat storage are usually drilled to greater depths in order to counter the effects of higher heat losses resulting from convection currents. This system minimizes losses by using the earth above the storage aquifer as an insulator between the warm aquifer and the cooler ambient air, and through the choice of a storage medium surrounded by warmer materials (due to the geothermal gradient).

Integrated (or combined**) heat and cold ATES systems** offer increased efficiency levels over cold- or heat-only storage systems, particularly for large-scale applications. These systems are usually used in combination with heat pumps to provide heating and cooling in commercial or institutional buildings. Although the components of combined systems are essentially the same as for cold or warm mass storage, the design complexity of above-ground and below-ground components for these integrated systems usually increases dramatically. Well positioning for below-ground components becomes more important because the aquifer is used for both warm and cold mass storage (storage of warm and cold mass results in development of thermal plumes around the wells, thus increased risk of heat transfer between them, see Figure 7.11).

ATES system design ultimately reflects the variability of the local conditions present on-site, and different system configurations exist as a result. The main components of any ATES system include:

- a suitable storage aquifer
- a production well or wells (acting as pumping or injection wells)
- a low-cost or free source, or sink, of thermal energy (such as waste industrial process heat, or solar heat for heating, or cold outside air temperatures for cooling)
- a heat exchanger
- energy demand

Determining the feasibility of an ATES system requires an analysis of an aquifer's suitability to act as a storage medium for warm or cold groundwater. This can be assessed through a characterization of the aquifer's properties. Normally, aquifer characterization for an ATES project entails a detailed assessment of the aquifer's geology, physical properties, flow characteristics, and water chemistry (characteristics which are the same as those assessed for most environmental investigations or water supply studies).

Most thermal storage projects utilize unconsolidated aquifers as storage media although unfractured and highly fractured bedrock aquifers can also be used for thermal energy storage (Allen and Michel, 1997). Mapping of structural features, such as those fractures and faults which strongly influence fluid flow within these aquifers is an important goal for future research.

Bridger and Allen (2005) reviewed basic criteria for the design of ATES systems, with the following results:

First, high hydraulic conductivities are desirable in order for large flow rates of water to be withdrawn or injected from or to the aquifer with the least amount of change to hydraulic and temperature gradients around the production wells.

Second, because water has a higher heat capacity but lower thermal conductivity than rock, the storage of thermal energy in aquifers is best suited to high porosity formations which minimize conductive energy losses and increase the efficiency of the thermal store.

Third, regional groundwater flow is an important consideration in ATES system design as higher groundwater flow regimes may lead to advection or down-gradient "drift" of stored energy beyond potential recovery regions (Midkiff et al., 1992). A lower- permeability storage aquifer is required to minimize convective losses in the presence of a steep regional gradient in hydraulic head, which would correspond to faster groundwater flows. This contrasts, however, with the need for a greater-permeability medium to minimize conductive

transport. Additionally, small-scale vertical and horizontal variations in hydraulic conductivity or heterogeneity within the aquifer (resulting from changes in geology) must be considered as these will affect the thermal plume dispersion (Bridger, 2006).

Several large-scale ATES systems have been installed in Canada. Three of the earliest systems, dating back to the late 1980s, are Carleton University system in Ottawa (Allen and Michel, 1997), the Sussex Hospital in Sussex, N.B. (Cruickshanks and Adsett, 1997), and the Scarborough Centre system (Mirza, 1993).

Carleton University's system became operational in 1990, and operated until 2006. It was to be implemented in phases, which would sequentially bring in line different areas of the campus over a several-year period. Phase 1 (for the residence area) was completed in 1990. A five-well configuration supplied groundwater at a combined rate of 125 L/sec through simultaneous pumping and reinjection. The configuration was designed to be reversed on a seasonal basis, so that winter pumping wells became summer reinjection wells, and vice versa. Well rates ranged from 25 L/sec to 95 L/sec, depending on the individual well productivity. Carleton University took steps during the early 1990s towards further expansion and redesign of the system, as five additional Phase 2 wells were drilled in 1994. Nevertheless, the system continued to be operated only in a small portion of the campus. Disagreements about baseline data used to measure the effectiveness of the new system and length of the payback period caused the project to be officially terminated in 1995, although the small pilot project remained in operation until 2006.

British Columbia implemented a relatively new ATES system at its Agriculture and Agri-Food Canada laboratory facility in Agassiz (Pacific Agri-Food Research Centre, or PARC) (Allen and Bridger, 2003). This system continues to supply both heat and cold energy to a 7,000 m^2 building facility consisting of laboratory, office, industrial, and greenhouse space. In addition to climate control, the ATES system cools several large-growth chambers and freezers. The system's total cooling capacity is about 150 tons: the total heating capacity from the heat pumps is about 1 million btu/hr (1 Mbtu/hr). The building facility has a year-round demand for cooling, and consequently, a load imbalance in favour of cooling. Heating is required from late fall to early spring. The ambient groundwater temperature is roughly 10°C. Agassiz's ATES system was designed with this load imbalance in mind, and consists of four 60 m deep production wells, including two warm wells used to store warm energy (15°C to 16°C), two cold wells used to store cold energy (6°C to 9.5°C), and a dump well that is situated downgradient from the main well field and used as a heat-dissipation well during peak cooling. This system is a hybrid, achieving primary storage through ATES, but with minor pump-and-release capability to handle the annual load imbalance. The estimate of the total water pumped and injected for heating and cooling is around 70 million gallons (265,000 m^3) per year.

More recently, a large-scale $14 million project geo-exchange system has been implemented at the University of British Columbia's Okanagan campus (UBC Reports, 2005). Between 2008 and 2011, an open-loop groundwater system operated for new buildings (Phase 1); however, reliability of the groundwater supply for a larger system delayed the addition of the five original campus buildings (Phase 2). In 2011, the system was converted to a closed-loop campus District Energy System (DES) (Phase 3) with an open-loop geothermal heat exchange system, which provides heating and cooling to ten academic buildings totalling approximately 80,000 m^2. Overall 80% of all the heating and cooling on campus is generated from no to low-carbon emission sources.

7.4.2 Borehole Thermal Energy Storage (BTES)

Borehole thermal energy storage (BTES) systems involve the transfer of thermal energy between a carrier fluid and the subsurface materials into which the boreholes are drilled. Technically, these systems do not concern groundwater because they involve no water exchange. However, both the subsurface geology and groundwater have important implications for the successful storage of heat and cold energy within such systems, and for this reason BTES represents a viable option in aquitards and aquicludes (such as solid unfractured crystalline rock or massive clay).

When no aquifer is present, the Earth's subsurface materials (sediment or rock) form an aquitard through which groundwater movement is very slow and well water yield is minimal. Thermal energy in these settings migrates upward along the geothermal gradient to be transferred by conduction directly via subsurface materials and contained porewater. This subsurface thermal energy is still capable of being exploited through the use of a series of closely spaced closed-loop pipes installed in vertical boreholes or, where space exists, pipes buried as horizontal loops in the shallow subsurface (see Figure 7.10). BTES systems are most effective in such low-permeability geologic units because groundwater flow is low to absent. These types of systems do not involve pumping or reinjection of groundwater, and they operate only through circulation of a carrier fluid within a closed-pipe system, therefore, there is no opportunity to hydraulically control the thermal stores.

BTES systems often require a considerable number of boreholes to achieve sufficient surface area for heat exchange: these systems can be enlarged by the addition of more boreholes to create a store of suitable size for the intended application. Depth, spacing, and design of boreholes are modified according to the thermal properties of local subsurface materials. Thermal energy exchange is by conduction between the subsurface materials and the fluid flowing within the pipes; as a result, it is important to maximize the thermal properties of all backfill material within the boreholes. In those formations with very low permeability, open water-filled boreholes often provide the best thermal connection between the pipes and the surrounding store material. However, since these systems rely on the retention of thermal energy within a relatively confined volume of subsurface material, it is vital to identify and address (seal) any fractures or other similar high-permeability features which might cause fluid excursions. A high-silica clay or clay/cement grout is normally the backfill material of choice when water loss cannot be prevented.

BTES installations require identification of a suitable low-permeability subsurface unit (aquitard). Low-permeability saturated clays, well-compacted glacial tills, or massive poorly fractured bedrock can all be utilized as potential BTES stores. Thus, a thorough understanding of the hydrogeologic characteristics of the subsurface materials is required. National standards for the design and installation of both ATES and BTES systems were approved in 2003 (CSA, 2003). In Ontario, provincial regulations to deal with the proper completion of boreholes associated with BTES projects were implemented in 2012 as a result of drilling into natural gas bearing formations.

BTES installations are becoming more widespread in Canada. The largest system installed to date is at the University of Ontario Institute of Technology (UOIT) / Durham College in Oshawa, where 370 boreholes, 200 m deep, were drilled with a 4.5 m spacing within a current parking lot (Beatty et al., 2006). The subsurface stratigraphy consists of 40 m of silt/clay overburden overlying 14 m of hydraulically tight shale (with a hydraulic conductivity of $K = 10^{-7}$ m/s) and 146 m of massive limestone ($K = 10^{-10}$ m/s). The boreholes were filled with water after installation of the closed-loop tubing was completed.

In Dartmouth, Nova Scotia, there are investigations for a BTES system for a municipal building complex containing offices, library, and recreational facilities on the harbourfront. Temperature of the energy store (in metamorphic rocks) for this application would be lowered to provide additional cooling capacity by charging the store with cold energy from harbour waters during the winter. Buildings for the new Dartmouth campus of the Nova Scotia Community College system are also being designed to utilize BTES for heating and cooling. Extensive instrumentation for monitoring building performance will be incorporated during construction and will also be utilized in instructional coursework.

7.4.3 Cavern Thermal Energy Storage (CTES)

Most subsurface thermal energy storage (TES) applications to date have involved the development of ATES and BTES systems, and both technologies have seen a rapid rise in implementation across the

country over the past several years. However, abandoned mining operations throughout Canada have resulted in the creation of numerous subsurface mine workings that are now flooded with groundwater. Communities located adjacent to these flooded, abandoned mines can benefit from utilizing the groundwater in these subsurface workings for Cavern Thermal Energy Storage (CTES).

The extent and configuration of such workings varies considerably, and some mines extend to depths in excess of one kilometre and contain tens of kilometres of interconnected tunnels (drifts) and stopes at multiple levels. These old workings form large cavernous reservoirs that will fill with groundwater when not continuously pumped. Temperature of this groundwater equilibrates with the surrounding rock, which then represents a potentially large thermal energy resource for the community nearby. Watzlaf and Ackman (2006) reviewed the use of groundwater from old mine workings for the purpose of heating and cooling. Potential utilization of subsurface caverns (mines) as thermal energy stores in Canada was reported by Jessop et al. (1995), Michel et al. (2002), and Grasby et al. (2011).

There are two basic design concepts for seasonal storage of thermal energy in caverns (CTES), either as a single cavern system or as separate hot- (or warm-) and cold-water stores located within different parts of the workings. Theoretically, both hot and cold water could be stored simultaneously in what is known as a stratified layered system (SL system) within large isolated abandoned mine workings, such as salt mines, or deep workings with little perturbation from interconnecting groundwater flowpaths, Hot water in a SL system "floats" above the cold water because of density stratification, similar to lake water in the summer. When there is little or no perturbation of the static condition, this thermal stratification can be maintained over seasonal periods, provided the respective quantities are adequate and the cavern store remains stable. A zone of convection mixing and diffusion will occur at the boundary between the two thermal strata and the cavern depth must be deep enough to accommodate the hot- and cold-water strata, as well as the thickness of the diffuse zone. Because a single large cavern, unless properly designed, would be structurally unstable in most rock types, the store in other mine types normally consists of tunnels on several levels linked vertically by shafts and raises. Boreholes connecting the system to its aboveground infrastructure are completed at different depths for cold and hot water access, in order to minimize thermal convection.

Interconnections between levels in many abandoned mine workings which have subsequently flooded may provide pathways for deeper, geothermally heated waters to migrate upward due to their lower density, and for cooler near-surface waters to sink due to their higher density. The results are the formation of a slowly circulating convection system, similar to water in a pot being heated on a stove. One can expect a certain amount of circulation to develop in deep, well-connected mine workings, whereas isolated shallow workings will contain only cooler near-surface waters. These shallow workings often receive large influxes of snowmelt recharge during the spring, and water temperatures can be close to 0°C. In this situation, groundwater use solely for cooling may be the only consideration.

The second method of cavern thermal energy storage is to capture cold and hot thermal energy in separate water-filled caverns or two isolated sets of abandoned mine workings. Some interconnectivity between stores can be tolerated in such schemes, provided thermal mixing is of limited occurrence. The mine workings employed in this scenario may represent two adjacent mine properties with different owners or a single mine with multiple relatively isolated working levels (such as a coal mine, for instance, where the workings on individual coal seams are separated by barren poorly fractured strata).

Since 1989, Springhill, Nova Scotia has been a world leader in championing the use of groundwater from flooded coal mine workings for heating and cooling of buildings (Jessop et al., 1995). Workings on seven levels were used to extract coal from five seams to depths of 1,300 m between 1868 and 1958. The coal seams subcrop under the western edge of the community and were accessed through stopes running-down dip. Most seams were mined independently with limited connection between seams. Since 1958 the workings have been allowed to flood with groundwater. Jessop et al. (1995) estimated the total volume of groundwater in the mine workings to be approximately 4,000,000 m^3, but a more recent detailed Geographic Information System (GIS) study of mine documents by Herteis (2006) estimated that the No. 2 seam alone contains 5,500,000 m^3 of water. Groundwater temperatures measured at the time of well drilling, and/or testing in the late 1980s and early 1990s, ranged from 9°C to 19°C, averaging 15°C. The western edge of Springhill is an industrial park and most of the current eight users of this system are located in or adjacent to the park.

Jessop et al. (1995) presented data for the original user's first year of system operation from 1989 to 1990 which indicated that the company (a plastics manufacturer) calculated a net energy savings of $160,000 per year and a 50% reduction in CO_2 emissions, relative to the pre-geothermal system. The payback period for the extra capital cost was less than one year. In 2004, a new community centre and arena complex was opened, with mine water providing heating and cooling for the building and the chilling requirements for the arena ice.

Although the total volume of groundwater associated with flooded abandoned mines appears to be immense, the high degree of hydraulic connectivity associated with mine workings requires that the placement of wells be such that interference effects are minimized. This is especially critical when adjacent wells are operating at significantly different temperatures. For large multi-user systems, such as the industrial park in Springhill, it is important to co-ordinate the design, implementation, and usage of all operators in order to avoid problems. Another issue that must be considered over time for abandoned mines is the potential for roof collapse of near-surface workings. It is important to identify these possible hazards early so that buildings and equipment are located on solid ground.

7.4.4 Other considerations

In all of these systems, heat or cold energy is stored in the subsurface. The source of this thermal energy is irrelevant. Solar (heat) energy, for instance, can be transferred to the subsurface for daily or seasonal recovery at a later date. Likewise, cold energy (low temperature) from melting snow in snow dumps can be transferred to the subsurface to create a cold store which can be utilized, when required, for air conditioning. TES system design should be flexible and adapted for local conditions.

One of the key considerations for maximizing the storage potential in any of these types of systems is the efficient balancing of heating and cooling loads. Canadians require both heating and cooling, but often, there is an imbalance in this need. Typically, heating carries the heavier load, particularly for residential units: this creates an excess of cold energy that must somehow be dissipated. Industrial processes and locations where there are significant computing facilities require heavier cooling loads. From an environmental perspective, addition of cold water to the Earth's subsurface environment may not pose as significant a threat as the addition of warm water; however, future research is needed to determine the potential environmental side effects of geothermal development, particularly where there are substantial load imbalances or where cooling-only or heating-only systems are operational.

Another consideration is the potential for adverse effects on aquatic environments, particularly where geothermal waters are directed into surface water systems or where groundwater discharges into streams, lakes, and wetlands. While geothermal technology has significant advantages over other forms of conventional and green energy technologies, there remains the need to exercise caution.

Thermal regimes require information on water temperature, knowledge of the geothermal gradient, and thermal conductivity of subsurface materials. It is important in any system to understand how heat will circulate or dissipate in the subsurface, especially when storage is considered as part of the design. Subsurface materials with high thermal conductivities may enhance storage by readily transferring some heat from water to rock, where it is stored locally rather than being transported further away. When significant water flow is expected, heat will be carried by the water and will affect the thermal distribution. Upward groundwater flow in an area will transport relatively high temperatures to surface, as is the case with many of the world's hot springs. Water flow within boreholes, from one depth interval to another, can also generate false thermal gradients which must be identified during the developmental investigative stage in order to provide for proper evaluation of the resource potential and proper system design. Interference between geothermal systems has not yet become a serious issue here in Canada, but in Malmo, Sweden, there have been reported instances of losses in efficiency of ATES systems due to interference between adjacent landowners. Parts of Winnipeg have experienced subsurface warming on account of the extensive use of groundwater for industrial cooling (Ferguson and Woodbury, 2004), but to date has not resulted in interference.

Multiple aquifer strata in the Netherlands allow the Dutch to specify aquifer usage (groundwater withdrawal or recharge) by temperature.

Chemically, thermal groundwaters can dissolve relatively high concentrations of elements from the rocks through which they migrate: eventually these groundwaters will become high salinity brines when they remain in the subsurface for long periods of time. These groundwaters are also excellent and efficient scavengers of metals, and play an important role in the formation of many types of mineral deposits. We must evaluate and understand the chemical composition of any groundwater in the context of its potential utilization as an energy source. Groundwater chemistry is of interest when evaluating corrosion or scaling issues related to equipment and infrastructure and the quality of water supplyto other users (particularly if there is potential for quality deterioration as a result of mixing with poor quality water, a situation which is often encountered in coastal areas where saltwater intrusion occurs when an aquifer located in close proximity to the ocean is over pumped). Dissolved metals, such as iron and manganese, will come out of solution and precipitate as oxides when oxygen is present, leading to well screen clogging and scaling on heat exchangers. Biofouling of well screens can be particularly problematic in low-temperature geothermal systems, particularly where manganese and iron are present at moderate to high concentrations in the natural aquifer. Biofouling gradually reduces the efficiency of pumping through progressive buildup of slime on the well screen. However, biofouling is not restricted to geothermal systems; it is a pervasive problem in many pumping systems. Treatment technologies continue to improve.

7.5 CONCLUSIONS

The Earth is a major thermal energy store and geothermal represents a large, relatively undeveloped, and renewable thermal energy source. Groundwater is the dominant medium for convective transport of heat in the upper 3 to 5 km of the Earth's crust. Groundwater is generally in thermal equilibrium with the rocks and sediments through which it flows; however, where rapid upward migration occurs, groundwater can discharge at surface as warm or hot springs, geysers, or volcanic fumaroles, with temperatures well above ambient.

Groundwater with temperatures exceeding 150^{o}C has traditionally been targeted for the generation of electricity, although recent technology now makes it possible to lower the minimum temperature to about 75^{o}C. Moderate- to high-temperature groundwater resources (>60°C), associated with regions of high heat flow or deep sedimentary basins, can be utilized directly for space heating and industrial processes. Depending on the groundwater temperature and the potential application, lower temperature resources (<60°C) can be employed for space heating with or without the aid of heat pumps.

Low-temperature resources (5°C to 15°C) associated with productive aquifers or abandoned mine workings can be utilized directly with heat pumps, or enhanced through subsurface thermal energy storage (TES), to provide heating and cooling (thermal energy sink) for buildings. Likewise, poorly conductive aquitards and aquicludes are ideal for TES applications with the use of horizontal or vertical closed-loop Earth energy systems. The advantages of the low-temperature aquifer and non-aquifer systems are that they are very adaptable, they can act as a heat source or heat sink, and at least one type of hydrogeological unit (aquifer, aquitard, or aquiclude) can be found at any site.

CANADA'S GROUNDWATER RESOURCES

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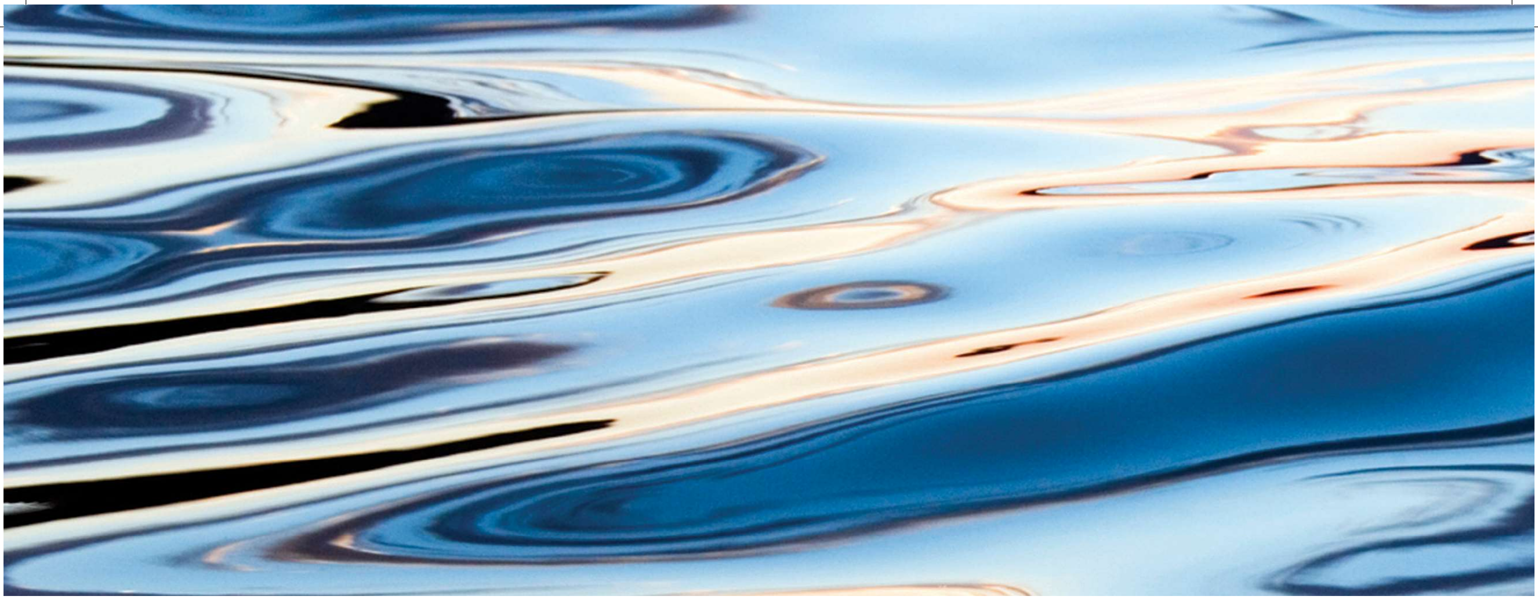

CHAPTER 3 AN APPROACH TO REGIONAL ASSESSMENTS OF GROUNDWATER

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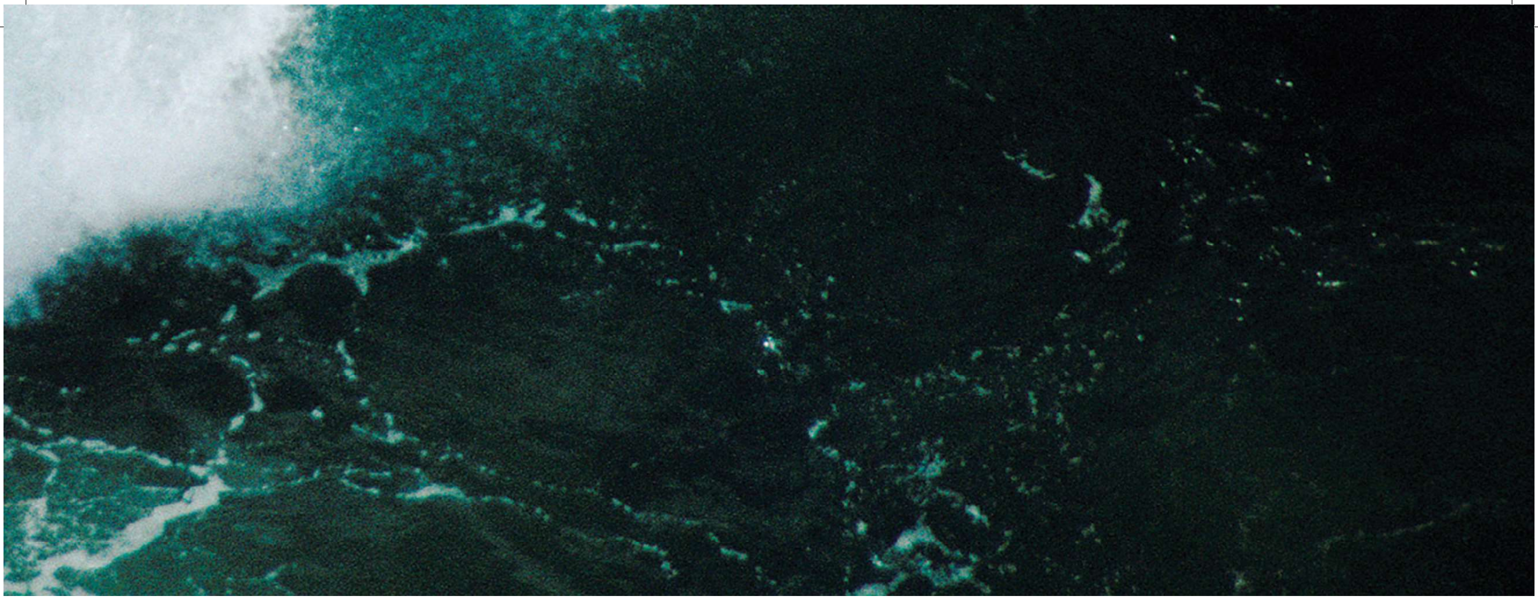

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