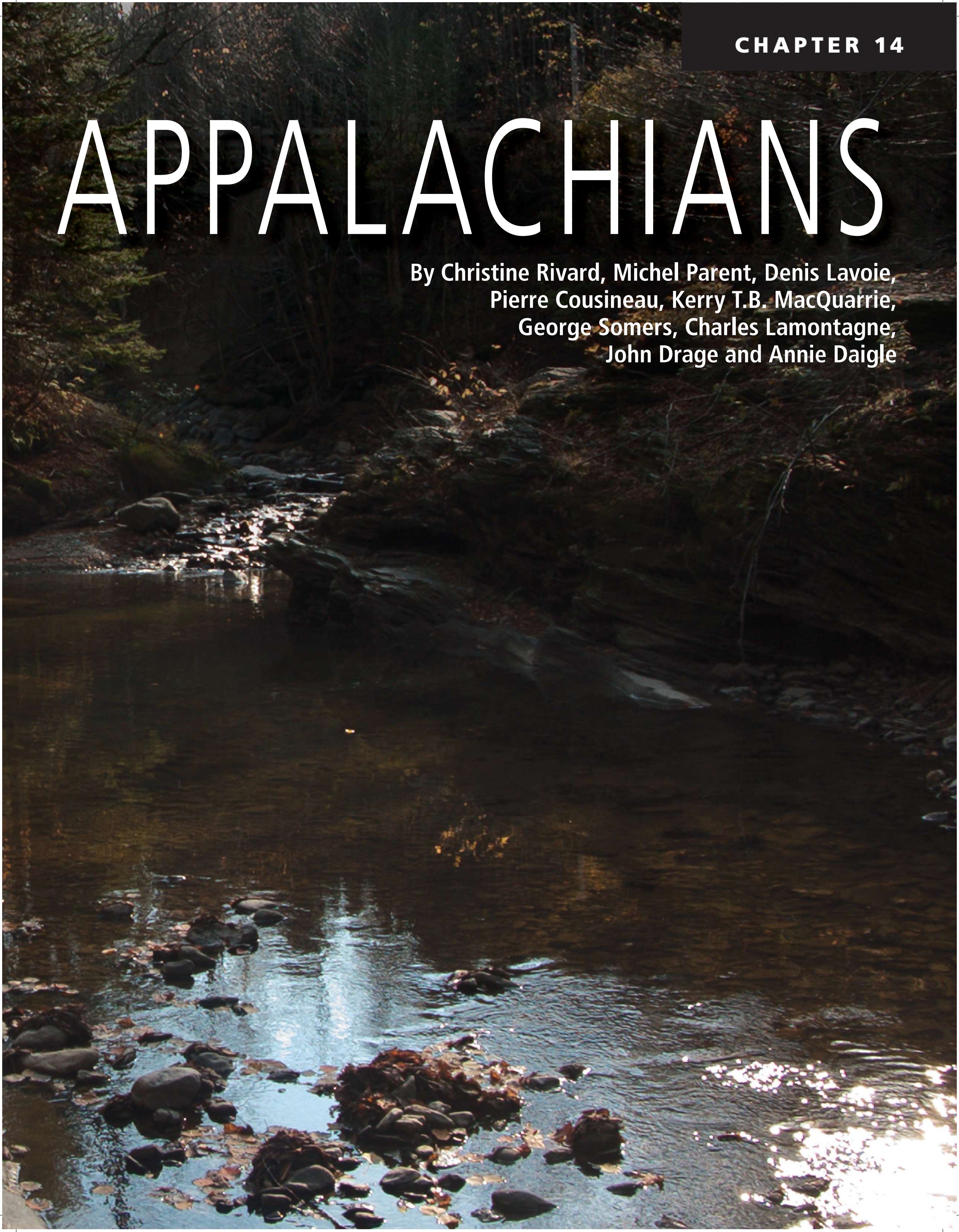

CHAPTER 14

APPALACHIANS

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14.1 DESCRIPTION OF THE APPALACHIAN REGION

The Appalachian physiographic region consists of a system of mountains and intervening uplands and lowlands, 160 to 480 km wide, extending from Newfoundland to Alabama (United States) 2,400 km to the southwest. The Canadian Appalachians comprise the three Maritime provinces (New Brunswick, Nova Scotia, and Prince Edward Island), most of the Island of Newfoundland, as well as the southeastern part of Quebec (Figure 14.1). The Quebec portion includes the south shore of the St. Lawrence River (including Estrie, Chaudière-Appalaches, Bas St-Laurent, and Gaspésie regions) and Îles-de-la-Madeleine.

The Canadian Appalachians cover a land area of 309,000 km^2. They are an ancient and eroded mountain range with rocks ranging in age from Neo-Proterozoic (Late Precambrian, 1,000 to 540 Ma; Lavoie, 2008) to Cretaceous (144 to 66 Ma; Pe-Piper and Jansa, 1987). Metamorphism is typically low grade and concentrated in the central domain of the chain. The Appalachians generally consist of elongated belts of folded and faulted, continental to shallow and deep marine sedimentary rocks, with locally intercalated tectonic slivers of ancient ocean floor, accessory plutons and volcanic rocks. The surficial sediment cover consists largely of transported sediments formed during Quaternary (2.6 Ma to modern) glacial/deglacial episodes. As a result, glacial sediments, mainly tills, are ubiquitous. The stratigraphy and architecture of these Quaternary sediments are often very complex, due to repeated erosional and depositional phases that

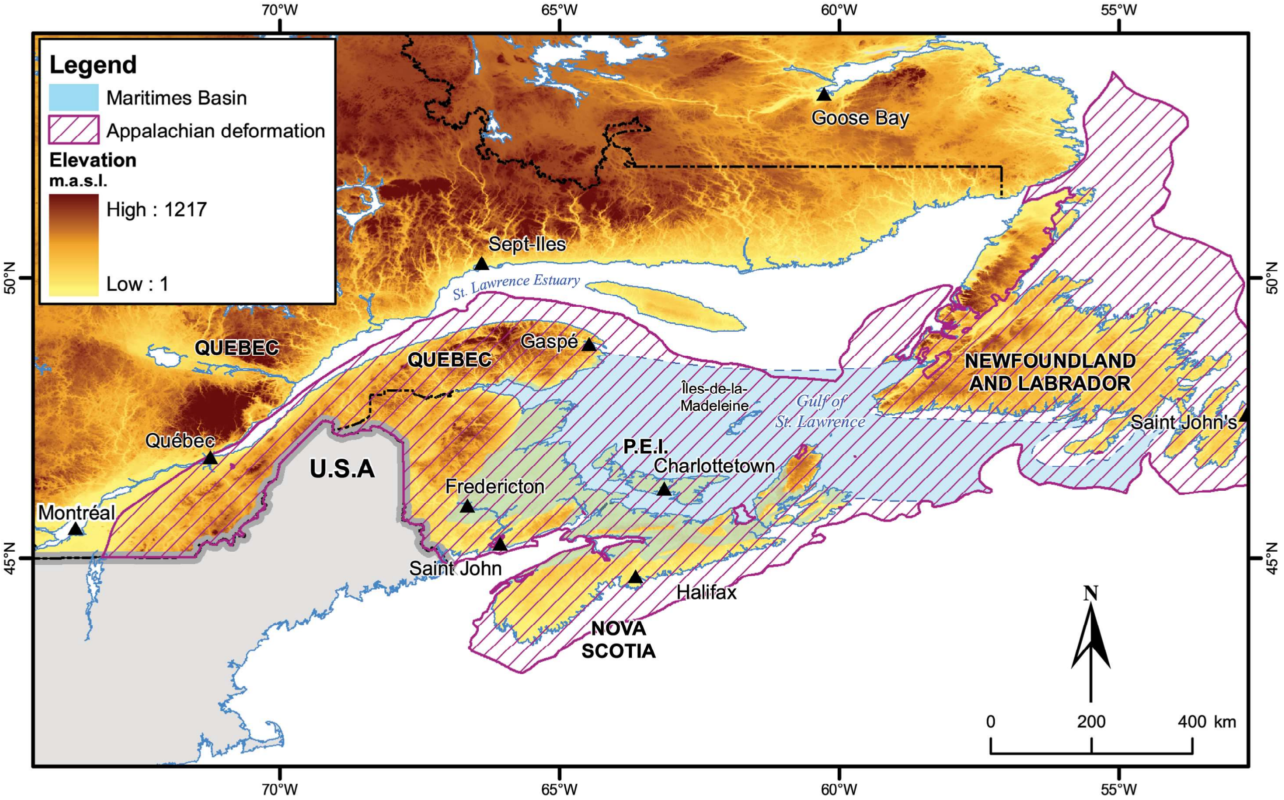

Figure 14.1 Location of the Canadian Appalachians and Maritimes Basin regions showing topography. Hatching lines illustrate the Appalachians deformed domain.

occurred during glacial advances and retreats, and also to the topographic context.

14.1.1 Physiography and hydrography

The Appalachian Mountains consist of ancient folded rock formations eroded into low, rounded mountains, dissected by valleys, and interrupted by lowland areas developed on weaker rock formations (Britannica, 2006). Much of the land in the Canadian Appalachians consists of hilly uplands with intervening, locally steep-sided valleys. Major highland areas include the Shick-shock Mountains (elevation 1,200 m) and Notre Dame Mountains (elevation 1,070 m) in Quebec, and the Long Range Mountains (elevation 800 m), as well as a dissected plateau in Newfoundland. The uplands in New Brunswick and Nova Scotia are in general lower in elevation, while Prince Edward Island is essentially a lowland area. The highest elevations for New Brunswick, Nova Scotia and Prince Edward Island are, respectively, 817 m (Mount Carleton), 532 m (Cape Breton Highlands), and 142 m (Queens County). The region's lowland areas extend mainly along the seacoast and the major rivers. The topography of the Canadian Appalachians could be described as undulating to relatively flat, with most (approximately 75%) of the region lying between sea level and 300 m (see Figure 14.1). Elevations above 600 m represent only 1% of the land area, and are mainly located in Quebec and Newfoundland.

The Canadian Appalachians are generally drained by a hydrographic network comprised of branching watercourses with a dendritic drainage pattern, common in environments characterized by uniform erosion. These inherited Tertiary networks were greatly "deranged", throughout most of the region, by successive episodes of glacial erosion and deposition. Some of the area's major rivers include the Saint John and Miramichi in New Brunswick; Saint-François, Chaudière, Temiscouata and Matapedia in Quebec; the Cornwallis, Annapolis, St. Mary's, Shubenacadie and Margaree in Nova Scotia; and the Main in Newfoundland. Major rivers in Prince Edward Island are tidal along a significant portion of their lengths, representing drowned river valleys: freshwater portions of these systems are usually relatively short and shallow. Newfoundland has a significant percentage of wetlands, covering 18% of the island, while almost 7% of New Brunswick is wetlands. It has been estimated that since Europeans began to settle here in the early 17th century (KCEDA, 2000), some 80% of the original salt marshes in the Annapolis Valley, Nova Scotia, and have been reclaimed to create agricultural land.

14.1.2 Climate

The four Atlantic Provinces have a humid continental climate and are subjected to the influence of both continental and oceanic air masses. Because of the region's relatively low relief, distance to the sea is often the major influence on local weather. Coastal areas are cooled in the summer and warmed in the winter by the ocean; typically, the warmest and coldest months are August and February, respectively. Winter ice cover in the Gulf of St. Lawrence, however, may reduce the ocean's warming influence to some degree, especially in Prince Edward Island. Proximity to the ocean generates a fairly mild and humid climate, with sudden temperature changes, high humidity (often >85%), and frequent freeze-thaw cycles during winter. Snowfalls are often heavy, with accumulations in excess of 50 cm during a single storm not uncommon. Inland parts of this region are shut

TABLE 14.1 CLIMATIC CONDITIONS IN THE APPALACHIAN REGION

PROVINCE	No. OF STATIONS	MEAN TOTAL PRECIPITATION (MIN/MAX)	MEAN ANNUAL TEMPERATURE (MONTHLY MIN/MAX)
New Brunswick	18	1172 mm/yr (1033/1531)	4.8ºC (–10.2/18.6)
Newfoundland	18	1188 mm/yr (852/1584)	3.1ºC (–9.8/15.7)
Nova Scotia	25	1398 mm/yr (1054/1700)	6.3ºC (–5.7/18.3)
Prince Edward Island	8	1143 mm/yr (1046/1241)	5.4ºC (–7.9/18.6)
Quebec (incl. 4 regions)	16	1112 mm/yr (963/1267)	4.5ºC (–11.7/18.9)

Source: http://climate.weatheroffice.ec.gc.ca/index.html

off from the ocean's tempering influence (Brown, 1967). Thus, a humid continental climate prevails, characterized by variable weather patterns, coupled with a fairly large annual range of mean monthly temperatures (about 25ºC).

The Appalachian region is one of the wettest in Canada; here, the warm moisture-laden air masses, moving in from southern latitudes, are constantly meeting cold air masses descending from the northern interior (Brown, 1967). Annual total precipitation (rain and snow) varies between 850 and 1,700 mm, with an average, over the study area, of 1,150 mm, except for Nova Scotia, where the average is around 1,400 mm. A substantial amount (20%–30%) of precipitation occurs as snowfall. Mean monthly air temperatures vary between 16ºC and 19ºC in the warmest months and between –12ºC and –6ºC during the coldest months. Table 14.1 summarises the climatic conditions, by province, of several representative weather stations within the Appalachian region. Newfoundland has the coolest weather, and Nova Scotia the warmest, with the most precipitation.

14.1.3 Population and groundwater use

The total population in the Canadian Appalachian region is 3.3 million (i.e., 11% of the total Canadian population): about half the population lives in urban areas. The population density is, on average, 18/km^2. Residents are mainly concentrated along the coastline, and in inland valleys close to major rivers. Large portions of the Appalachians (mainly inland) are forested; agricultural lands generally represent less than 7% of the total land area. These agricultural percentages are highly variable, however, being much higher (46%) in Prince Edward Island, and much lower in Newfoundland and Labrador (0.1%[1]). Farms are relatively well distributed over the land area, except in certain areas such as Prince Edward Island and in Nova Scotia's Annapolis Valley, which have significant concentrations of agricultural activity.

Groundwater is an important source of water supply within the Appalachian region. Indeed, on a provincial basis, between 34% and 100% of the population relies on this resource for potable water, either from municipal or private wells (see Table 14.2). In rural areas, these percentages are higher. In Kings County, Nova Scotia, for example, 99% of the residents draw their drinking water from groundwater (KCEDA, 2000). In Prince Edward Island and Îles-de-la-Madeleine, 100% of the population relies on groundwater. However, 90% of the population of Îles-de-la-Madeleine is supplied by municipal systems. In Prince Edward Island, which has 12 municipal supplies, this

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[1] The percentage is unknown for the island of Newfoundland.

TABLE 14.2 PERCENTAGE OF THE POPULATION SUPPLIED BY GROUNDWATER

PROVINCE	% OF THE POPULATION
New Brunswick	67%
Nova Scotia	46%
Prince Edward Island	100%
Newfoundland	34%
Quebec (Bas St-Laurent=48%; Estrie=40.7%; Gaspésie=48%; Îles-de-la-Madeleine=100%; Chaudière-Appalaches=52.8%)	≈ 48%*

Source: Groundwater use in Canada, West Coast Environmental Law, November 2004, http://www.wcel.org/sites/default/files/publications/Groundwater%20Use%20in%20Canada.pdf and http://www.mddep.gouv.qc.ca/eau/regions/.
* As a comparison, the percentage is 28% for the entire province of Quebec.

percentage drops to 45%. In New Brunswick, 56 out of 70 (80%) municipal water supply systems use groundwater in some form and 32 additional municipalities rely on groundwater from private wells. In Newfoundland, most groundwater systems are small, serving 5–40 houses.

Some of the larger municipal groundwater supplies within the study area include Sydney, Oxford, Amherst, Kentville, and Wolfville in Nova Scotia; Lac-Mégantic, St-Gédéon-de-Beauce, and Rivière-du-Loup in Quebec; Fredericton, Miramichi, Sackville, and Sussex in New Brunswick; Charlottetown and Summerside in Prince Edward Island; and Saint John's and Stephenville in Newfoundland. Several municipalities use a combination of surface water and groundwater.

14.2 GEOLOGICAL CONTEXT

14.2.1 Bedrock

14.2.1.1 Geological and structural settings

Rock units of the Appalachian geological province have been classified according to Williams' work (1979). His proposal includes zones, belts, and basins defined on the basis of rock unit ages and orogenic phases (see Figure 14.2). Rock units of Cambrian and Ordovician age are grouped into zones formed during continental rift and drift, coupled with an initial oceanic closure which produced the Taconic Orogen. Rocks of Silurian and Devonian ages are grouped into belts formed initially as successor basins following the Late Ordovician Taconic Orogeny. The Devonian period was a time of major accretion events, with the Early Devonian Acadian Orogeny (accretion of Avalonia to Laurentia) and the Late Devonian Neo-Acadian Orogeny (accretion of Meguma to Laurentia). Rocks units of Carboniferous and Permian ages are grouped into basins which originated as successor basins, later evolving into tectonically active basins, formed between the Neo-Acadian Orogeny and the Alleghenian Orogeny (this latter resulting in the assembly of the supercontinent Pangea).

Cambrian and Ordovician tectono-stratigraphic zones are believed to represent five distinct former paleogeographic areas that evolved during those geological periods. These zones, from northwest to southeast, are (1) Humber zone, relict of the former rift-passive-convergent margins of Laurentia (e.g., ancestral North America), (2) Dunnage zone, relict of the Iapetus oceanic basin, (3) Gander zone, which contains sediments partly similar to those of the Humber zone, and interpreted as the continental margin of a far travelled terrane, (4) Avalon zone, a collage of smaller blocks originating from the other side of Iapetus Ocean, and (5) Meguma zone, a fragment of the continent Gondwana (Figure 14.2).

The Taconic and Acadian Orogenies resulted from mostly orthogonal collisions producing both external and internal zones that differ in the degree

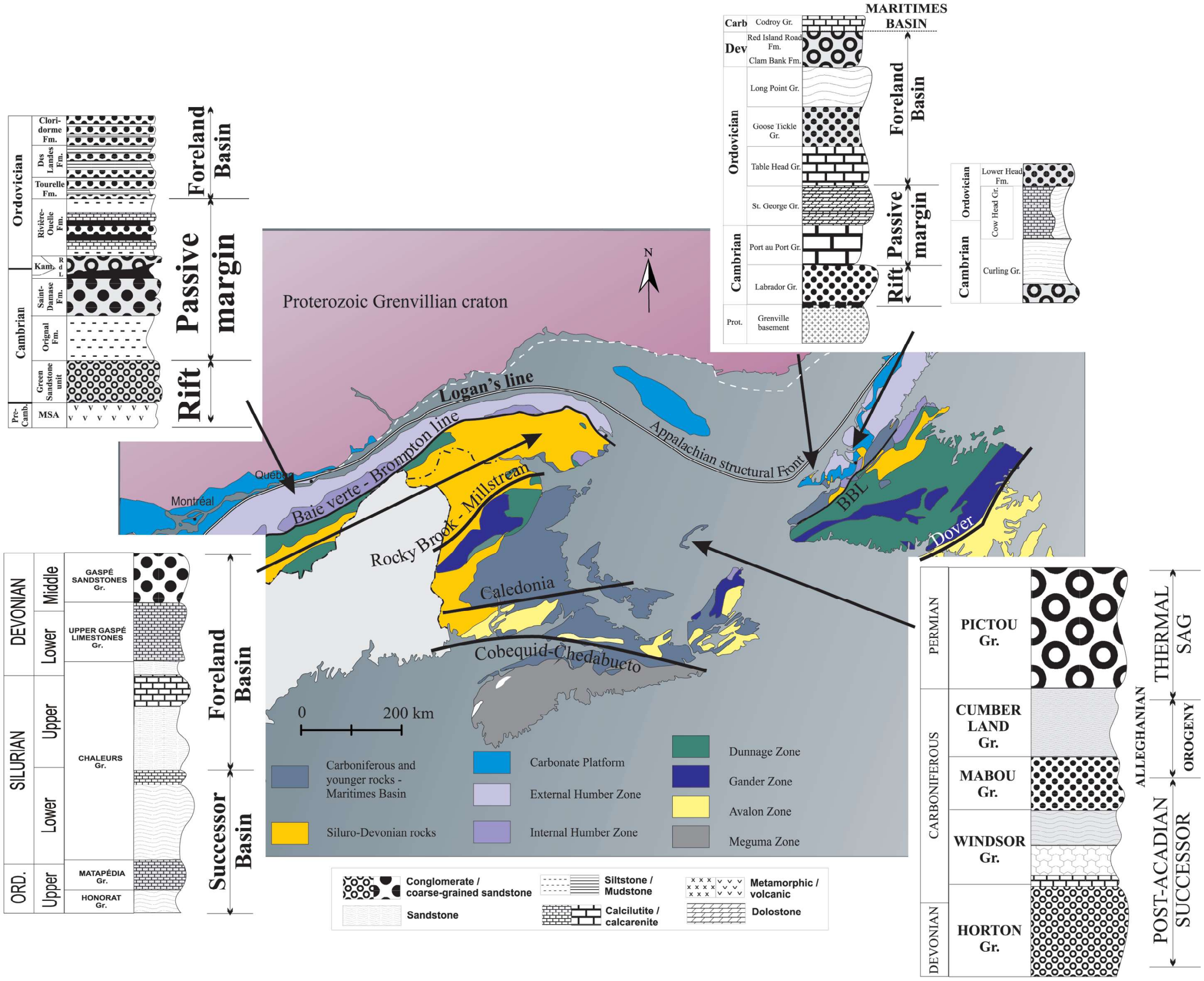


Figure 14.2 Bedrock geology showing tectono-stratigraphic zones and representative stratigraphic columns (adapted from Williams, 1979). The white dashed line marks the offshore limit between the Proterozoic Grenvillian craton to the west and northwest, and the Cambrian-Ordovician St. Lawrence platform to the east and southeast.

of deformation and metamorphism. The Acadian Orogeny was intense and its effects are generally superimposed on previously deformed rocks. There is usually a decrease in deformation from the more central zones (Dunnage and Gander) to the more peripheral Humber and Avalon (and Meguma) zones. Given the geometry of these continental collisions, most of the tectonic fabric was generated by compression or low-angle thrusting; in those areas where major faults are strike-slip in nature, deformation is largely limited to rocks adjacent to the faults. Major strike-slip faulting after the Devonian Orogeny favoured the formation of pull-apart basins in the Maritimes. The Neo-Acadian and Alleghenian Orogenies were not as intense as previous orogenies, consequently. Carboniferous and Permian rocks may be significantly less deformed and are generally found resting unconformably on older, more deformed rocks. Mesozoic rocks in the Canadian Appalachians are rare and related to the opening of the current Atlantic Ocean. Outcropping younger rocks include the Minas Basin (including the Annapolis Valley) in Nova Scotia, and the Monteregian Cretaceous alkaline intrusions which form a series of aligned plutons from Montreal to the coast of Maine.

14.2.1.2 General bedrock porosity and permeability

Aquifer classifications consider both primary and secondary porosities (Roy et al., 2006). As a first-order approximation, the younger the sedimentary rock, the better its primary (pore) porosity and, to some extent, its permeability. Secondary porosity is controlled by diagenetic and tectonic features. These include cross, longitudinal, and bedding joints in undeformed to deformed competent rocks, whether sedimentary, igneous or metamorphic. Most igneous and metamorphic rocks deformed by the Acadian and Taconic Orogenies do not appear to have developed the large interconnected fracture zones associated with good aquifers (Brown, 1967). However, synthetic and antithetic joints may be particularly well developed during brittle events occurring near minor to major fault zones (e.g., faults of the external Humber zone, see section 14.2.1.3.1). Secondary porosity in carbonate rocks may be significant, but is more difficult to predict. Secondary dolomitization and karst features, such as those related to dissolution along joint planes, may be locally important. High-relief areas are typically composed of low-porosity/low-permeability rocks that do not favour recharge. More information on bedrock porosity and permeability is available in Chapter 2.

Table 14.3 provides examples of effective porosities and estimates of maximum hydraulic conductivities for rocks (drawn mainly from Quebec samples) of a given type and age; although the samples were collected at surface, results are in the same order of magnitude as those obtained from core samples (Hu and Lavoie, 2008). Porosity values were obtained using a pressure chamber. Hydraulic conductivities (K) were estimated using water injection on 2 to 4 cm diameter samples collected from drill cores or field samples (Kmax represents the addition of the horizontal and vertical components of K). These values are theoretical, but they do provide a good picture of the prospective hydraulic conductivity and aquifer potential of these formations. From Table 14.3, we can see that sandstones have generally increasing permeability from older to younger rocks, being close to 10^{-4} m/s in Carboniferous rocks. Sandstone effective porosities vary widely from less than 1% to 11.3%.

14.2.1.3 Bedrock stratigraphy

14.2.1.3.1 Cambrian and Ordovician rocks

Humber zone

The external Humber zone forms a continuous belt extending throughout the Canadian Appalachians. This zone consists of two distinct tectono-sedimentary assemblages, the parautochthonous and the allochthonous, separated by a major fault known as Logan's Line in Quebec. The more westerly external Humber zone is moderately deformed and regional metamorphism is low, the more easterly internal Humber zone forms a nearly continuous belt in southern Quebec (and extends into the adjacent United States), but crops out sparingly as slivers or inliers elsewhere. Deformation is intense and metamorphism of higher grade. Internal stratigraphy for the latter is difficult to establish.

The parautochthonous assemblage consists of tectonic slices of shallow to deeper marine Cambrian-Ordovician St. Lawrence platform rocks (see Chapter 13 on the St. Lawrence Lowlands for detailed tectono-stratigraphic descriptions). Even

TABLE 14.3 ESTIMATES OF EFFECTIVE POROSITY (N) AND HYDRAULIC CONDUCTIVITY (K) OF DIFFERENT TYPES OF ROCKS FROM VARIOUS PERIODS (FROM LAVOIE, 2009)

PERIOD		ROCK TYPE	FORMATION OR GROUP	NO. OF SAMPLES	N (%)	K_{max} (M/S)
Carboniferous		Sandstone	Bonaventure Fm.	2	11.3	8.5E-05
Devonian	Lower-Middle	Sandstone	Battery Point Fm.	5	0.4	1.2E-05
	Lower	Sandstone	York River Fm.	5	6.3	3.5E-07
	Lower	Sandstone	Fortin Gp.	1	0.8	1.2E-07
	Lower	Limestone	Indian Cove Fm.	2	1.1	1.2E-07
	Lower	Limestone	Forillon Fm.	2	0.6	1.2E-07
Silurian - Devonian	Upper S–Lower D	Sandstone	Indian Point Fm.	1	1.9	6.9E-07
Silurian	Upper	Carbonate	West Point Fm.	13	1.7	2.6E-06
	Upper	Sandstone	Saint-Léon–Gascon Fms.	4	2.1	4.6E-07
	Lower	Carbonate	Sayabec–La Vieille Fms	24	1.7	3.5E-06
	Lower	Quartzite	Val Brillant Fm.	3	2	2.3E-06
	Lower	Sandstone	Anse Cascon Fm.	6	1.8	3.5E-07
	Lower	Sandstone	Weir Fm.	4	3.4	3.5E-07
	Lower	Sandstone	Cabano Fm.	2	1.7	3.5E-06
Ordovician - Silurian	Upper O–Lower S	Limestone	White Head Fm.	2	0.9	1.2E-07
Ordovician	Upper	Sandstone	Garin Fm.	2	0.9	1.2E-06
	Middle	Sandstone	Tourelle Fm.	2	0.5	1.2E-07
	Lower	Sandstone and limestone	Rivière-Ouelle Fm.	3	0.7	1.2E-07
Cambrian	Upper	Quartzite	Kamouraska Fm.	13	1.8	1.2E-07
	Upper	Sandstone	St. Damase Fm.	12	1.1	1.2E-07
	Lower-Middle	Sandstone	St. Roch Group	10	1.7	1.2E-07
	Lower	Sandstone		8	1.2	2.3E-07

though approximately 50 of these slices were identified in the subsurface from Montreal to Quebec City, only three of them are present at the surface (near Philipsburg, Saint-Hyacinthe, and in the Acton Vale–Upton areas). These slices commonly form small hills in a dominantly low-lying area, and are limited by faults and related joints. They represent good potential recharge areas and aquifers, given the high potential for subaerial karst dissolution of their predominantly carbonate lithologies.

The Humber zone's allochthonous assemblage is made up of weakly to moderately metamorphosed sedimentary rocks, consisting of (1) a thick Lower-Middle Cambrian succession of mudstones and green sandstones, with some basalt flows; (2) a more diversified Upper Cambrian–Lower Ordovician succession including mainly mudstones, sandstones, conglomerates with subordinate limestones; and (3) a flysch and melanges succession derived from the erosion of the westward-migrating Middle Ordovician to Late Ordovician Taconian wedge (Lavoie et al., 2003). Porosity and hydraulic conductivity values of representative Humber zone samples are found in Table 14.3 (Cambrian to Middle Ordovician samples).

The allochthonous assemblage can be subdivided into external and internal thrust sheets. Deformation and metamorphism increase from west to east, typically grading from (1) open folds affected by lower greenschist metamorphism and low-angle thrust sheets, to (2) recumbent or upright tight folds affected by upper greenschist metamorphism, and high-angle thrust, normal, or strike-slip faults. Rocks of the Humber zone are cut by numerous faults of various ages which tectonically juxtapose variably sized slivers of rocks of different composition and age. Stratigraphic units are fairly continuous laterally but may change along-strike (Cousineau and Longuépée, 2003). Rare plutons (e.g., the Devonian McGerrigle Pluton, and Cretaceous Mounts Shefford and Brome in Quebec) intrude the Humber rocks. Primary porosity and permeability in these rocks are generally very low to nonexistent. Fracture porosity is best developed near faults and expressed by synthetic and antithetic fracture networks. The local importance of this type of permeability is variable and directly related to the abundance and thickness of folded and faulted competent units present within the less competent rocks (McCormack, 1978; 1982).

Dunnage Zone

The Dunnage zone, present in Quebec, northern New Brunswick, and central Newfoundland, is a composite terrain consisting of laterally discontinuous segments that have been thrusted to the northwest. The boundary between the Humber and Dunnage zones is known as the Baie Verte–Brompton Line (BBL, see Figure 14.2), and extends throughout the Canadian Appalachians. To the east, the boundary with the Gander zone is less well established and relationships between both zones are subject to different interpretations. Most rocks of the Dunnage zone are Ordovician in age.

Structure and metamorphism in the Dunnage zone are generally less intense, but stratigraphic units are more discontinuous than in the adjacent internal Humber zone. Generally, rocks of the Dunnage zone may be grouped into four assemblages: (1) ophiolite complexes composed of mafic to ultramafic intrusive and extrusive rocks representing ancient sea-floor material thrusted over the continent; (2) shale-rich melanges of tectonic as well as sedimentary origin that contain blocks of various size, age, abundance, and composition; (3) volcaniclastic to epiclastic flysch sediments with some siliceous ("chert") and minor marine carbonate; and (4) volcanic, volcaniclastic and intrusive rocks of magmatic arc provenance. Primary porosity within these rocks is almost nonexistent and, as in the adjacent Humber zone, permeability is variable (but typically poor), being related to local abundance of fractures in fold hinges and regional faults in competent rocks. The city of Thetford Mines, Quebec, is located on these rocks (ophiolites).

Gander zone

The Gander zone consists of laterally discontinuous segments in New Brunswick, Nova Scotia (western Cape Breton Island) and central Newfoundland. The most typical sedimentary rocks of this zone are passive margin-type, Ordovician, quartz-rich sandstone and black shale. These were variously deformed and metamorphosed from greenschist to amphibolite grade during multiple phases of deformation that extended from the Cambrian to the Silurian (van Staal, 2005). Silurian and Devonian granitic intrusions may constitute about half the zone. Ordovician and Silurian volcanic rocks are locally present, especially in some parts of northeastern New Brunswick (Miramichi Highlands) and Nova Scotia (Cape Breton Highlands). The intensity in deformation and metamorphic grade of these fine-grained sedimentary rocks does not allow for significant porosity or permeability, other than fracture conduits.

Avalon zone

The Avalon zone crops out primarily in Newfoundland, where it represents the easternmost one third of the island. Numerous other disjunct segments are found, however, throughout the Appalachian Orogen, in eastern Nova Scotia (Cape Breton Island, Antigonish Highlands, Cobequid Mountains) and southern New Brunswick (Caledonian Highlands). The Avalon zone is bounded on both sides by major faults, characterized by steep ductile shears and brittle deformation zones (see Figure 14.2). There is no uniform stratigraphy throughout the zone, in part because it was an active margin for at least 100 million years (van Staal, 2005). This suggests that a substantial part of the Avalon zone is in fact a collage of smaller terranes made up of different rock types. Metamorphism is low, especially when compared to that in the Gander zone.

Stratigraphy of Newfoundland's Avalon zone is distinct from that elsewhere in the Maritimes. The upper unit is composed of terrestrial sedimentary and volcanic rocks. The youngest rocks are Cambrian and Ordovician shale and sandstone, exposed locally. In Nova Scotia and New Brunswick, the zone's younger, often more widespread rocks, consist of Upper Precambrian volcanic and volcaniclastic, and sedimentary rocks. Porosity and permeability values are expected to be low.

Meguma zone

The Meguma zone is restricted to the area of Nova Scotia south of the Cobequid-Chedabucto Fault. The Meguma "Supergroup" (excluding the overlying Annapolis Supergroup of Silurian and Devonian age) is Late Cambrian to Early Ordovician. Sedimentary rocks of the Meguma Supergroup are of marine origin. Quartzitic and feldspathic sandstones occur in the lowermost succession while the rest of the Supergroup is dominated by greyish muds to black shales (White et al., 2007). These rocks were mildly to moderately deformed and metamorphosed during a Devonian tectonic event. Their permeability is typically low.

14.2.1.3.2 Silurian and Devonian belts

Silurian and Devonian rocks of the Appalachians are often mildly to intensely deformed, especially in the vicinity of major faults. The stratigraphic description of the Upper Ordovician to Middle Devonian succession within the Gaspé Belt (*sensu* Bourque et al., 1995) is based on the synthesis of Bourque et al. (1995, 2001), and Lavoie (2008). The Gaspé Belt extends from southern Quebec (and northern US) to western Newfoundland; the succession is preserved in three major lithotectonic domains which are best exposed in the Gaspé Peninsula. From north to south, these are: (1) the Connecticut Valley-Gaspé synclinorium (Upper Ordovician to Middle Devonian rocks), (2) the Aroostook-Percé anticlinorium (Upper Ordovician to Lower Silurian rocks), and (3) the Chaleurs Bay synclinorium (Upper Ordovician to Upper Silurian rocks).

The stratigraphy within these major structural elements can be divided into four broad temporal and lithological assemblages (see above-cited literature for details). Main lithologic assemblages include marine clastic assemblages of mudstones, sandstones, conglomerates and limestones. Most units are characterized by low porosity and permeability, except for sandstones. (see Table 14.3). Aerial studies of these sandstone facies' distribution (not shown) reveals that they form the topmost rock unit of close to 25% of the Gaspé Peninsula's modern landscape. Fracturing and subaerial karst dissolution for carbonates can increase permeability locally, favouring groundwater circulation.

14.2.1.3.3 Carboniferous and younger rocks of the Maritimes Basin

During the Late Devonian, small fault-bounded basins opened following the Devonian Acadian and Neo-Acadian Orogenies. These individual basins are known collectively as the Maritimes Basin. With time, these small continental basins increased in size, with evidence of one major marine incursion. Sedimentation, was largely continental to marginal marine.

At the base of the statigraphic succession, the Upper Devonian to Lower Mississippian Horton Group is a thick succession dominated by coarse-grained sandstone and conglomerate near the faulted margins of individual half-graben basins (Hamblin and Rust, 1989). These sandstones have low permeability and porosity. Permeability is usually related to bedding and orthogonal joint sets, and improves where carbonate cement is dissolved. The Horton Group is abruptly and unconformably overlain by the Lower Mississippian carbonates of the Windsor Group (Giles, 1981) with major beds of deep-marine sulphates (gypsum and anhydrite) and salt (halite). Hundreds of metres of mafic volcanic flows and intrusive gabbros are found within the Windsor Group, in the central part of the Maritimes Basin and outcroppings on Îles-de-la-Madeleine. The Windsor Group is overlain by upper Lower Mississippian fine-grained clastics of the Mabou Group, and by the Pennsylvanian continental deposits, which contain abundant coal seams of the Cumberland Group.

Lower Permian clastics and aeolian sandstones of the Pictou Group occur at the top of the stratigraphic pile. These aeolian sandstones are well exposed on Prince Edward Island and on the Îles-de-la-Madeleine. Sandstones of the Mabou, Cumberland, and Pictou (and correlative units in small areas in western Newfoundland, e.g., Deer Lake and Stephenville areas) are characterized by variable porosity and permeability values. However, several of these formations can be considered good aquifers (see section 14.4). These units blanket large areas of New Brunswick, Nova Scotia, Prince Edward Island, and the Îles-de-la-Madeleine, Quebec: all are widely exploited for water supply.

14.2.2 Surficial sediments

14.2.2.1 Quaternary events and stratigraphy — A brief overview

Although the northern Appalachian region was repeatedly covered by ice sheets and ice caps during the Quaternary period, its surficial sediment cover is rather discontinuous and consists of sediments, most of which were deposited during the last glacial-deglacial cycle, the Late Wisconsinan substage (Grant, 1989). The Late Wisconsinan glacial advances, those associated with the Last Glacial Maximum (LGM), largely obliterated or buried the sedimentary record of Early to Middle Wisconsinan and earlier (Illinoian) glacial advances and/or retreats. Although these older Quaternary sediments were once regionally extensive, today they are only partially preserved in a few regions of Nova Scotia (Stea et al., 1998), New Brunswick (Rampton et.al., 1984; Lamothe et al., 1992) and southeastern Quebec (McDonald and Shilts, 1971; Shilts, 1981; Lamothe et al., 1992).

Surficial sediments in uplands and high tablelands of the region are generally thin and discontinuous, consisting primarily of glacial sediments and minor glaciofluvial sediments. The Quaternary sediment cover in lowlands, such as the Maritime Basin, is significantly thicker and more continuous. Valleys, which are locally the locus of thick Quaternary sediment fill, generally contain the best and most extensive granular aquifers of the region. Depending on the local Quaternary context, the nature and stratigraphic architecture of these sediments may range from relatively simple, terraced alluvial sediments, to quite complex assemblages, where glaciomarine or glaciolacustrine silt units may be overlain or underlain, or both, by fluvial or glaciofluvial sediments. Somewhat exceptionally, such as along parts of the Saint John, Chaudière, Nicolet or St-François Rivers (Lamothe, 1992; Shilts, 1981; Parent, 1987), these valleys may contain older Quaternary sediments buried below those deposited during the last glacial-deglacial cycle. The study of buried valleys, particularly preglacial valleys, is an important part of hydrogeological research in several glaciated terrains as these valleys generally present good hydraulic potential (Simard, 1970). Modern postglacial streams usually occupy broad valleys formed in pre-Quaternary time, although some valley segments are now located some distance from their former courses. One fairly well-known example of this phenomenon is the Saint-François River valley at East-Angus near Sherbrooke, where successive glacial advances have considerably disturbed the pre-Quaternary hydrographic pattern and clay-rich surface till and glaciolacustrine silts (McDonald, 1968) conceal a high-yield aquifer in the buried valley (Simard, 1970). The presence of rock-entrenched valley segments often indicates the nearby presence of buried preglacial valleys.

There has been extensive debate concerning the nature, timing, and extent of glaciation throughout the northern Appalachian region (Grant, 1977; Rampton et al., 1984; Dyke and Prest, 1987; Stea et al., 1998). It should be noted, however, that issues such as ice-flow patterns or glacial limits have only limited implications for hydrogeological conditions in the region (largely due to the fact that most of the contentious issues are associated to regions now lying below sea level). As in most other regions of Canada, tills are by far the most common surficial material of the Applachian region, covering about 90% of the surface area as calculated from the Surficial Materials Map of Canada (Fulton, 1995). The texture of tills, ranging from silty clay to sandy to stony is controlled by depositional processes, as well as by the lithological nature of their source rocks. Till texture has considerable relevance for regional hydrogeological conditions, and particularly for aquifer recharge. Usually, basal or lodgement tills in any given region are significantly finer grained, more compact, and less permeable than their ablation or melt-out counterparts. Those basal tills derived from Cambro-Ordovician and Siluro-Devonian rock assemblages in the Appalachians are typically rather stony with silty sand to sandy silt matrices, whereas tills overlying or derived from the Maritime Basin red beds have silty to silty sand matrices, and are relatively clast-poor.

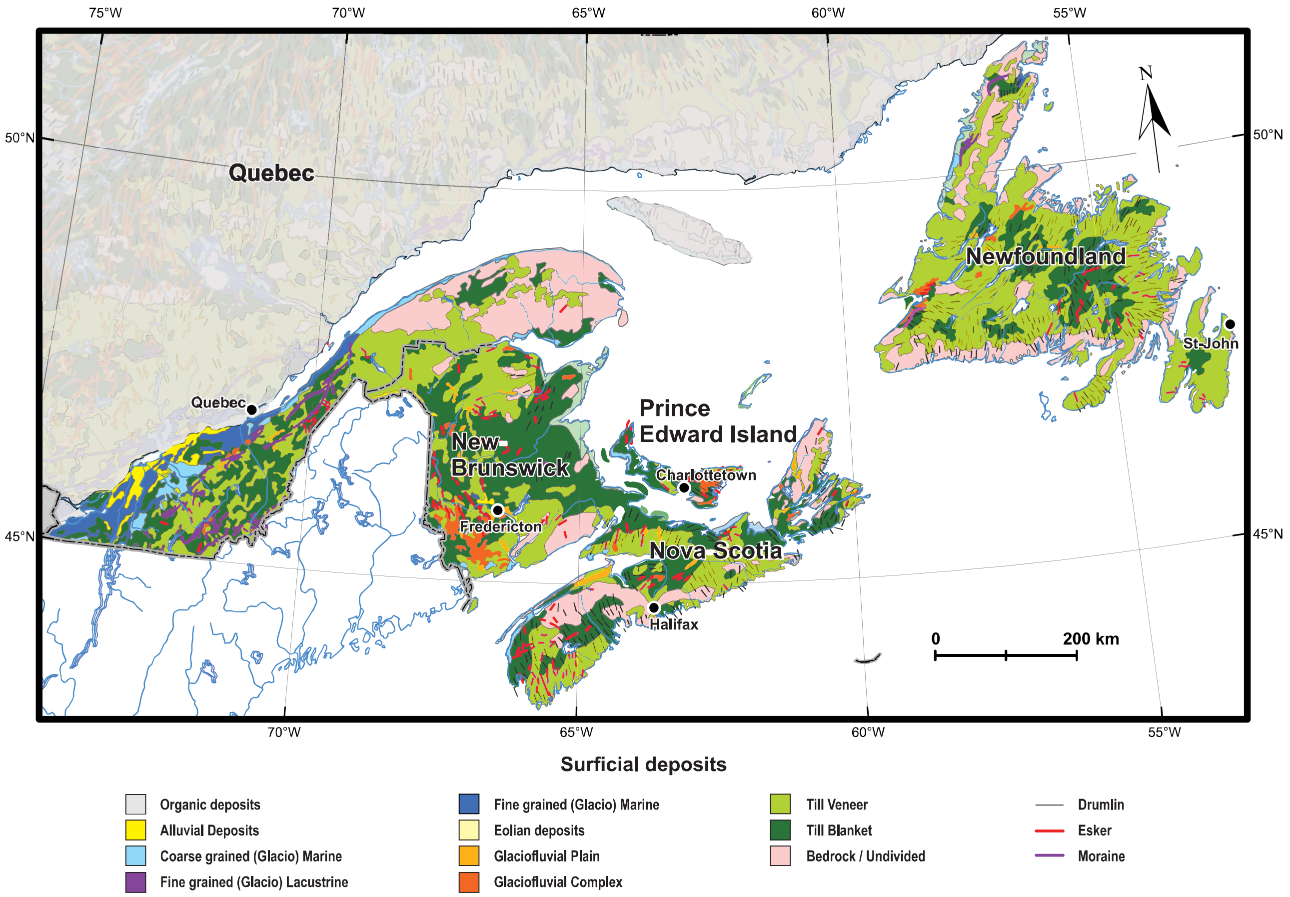


Figure 14.3 Surficial geology map of the Canadian Appalachians and Maritimes Basin region (adapted from Fulton, 1995).

The surficial geology map depicted in Figure 14.3 has been patterned after the Surficial Materials Map of Canada (Fulton, 1995). Figure 14.3 also locates those landforms, such as moraines and eskers, which often make good aquifers. Most of the eskers in this region are located in the western part of both New Brunswick and Nova Scotia, whereas moraines are usually found in the southwestern half of the Quebec Appalachians.

Coarse-grained glaciofluvial sediments, moraines and eskers constitute only a small part of the regional surface area (< 10%). Nevertheless, they provide, along with alluvial sediments, the most significant groundwater resources and some of the best aquifers of the region. Glaciofluvial sediments, mainly ice-contact sand and gravel, occur as discontinuous patches in all parts of the Appalachian region, although they are notably scarce in the lowlands of eastern New Brunswick, in Prince Edward Island, in Cape Breton Island, in Newfoundland and on the high plateaus of the Gaspé peninsula. Glaciofluvial valley trains are not a typical feature of the region, except for parts of southwestern New Brunswick. Morainal sediments, mainly end moraines consisting of ice-contact gravels, occur mostly in southern Quebec where, locally, they constitute high-yield aquifers for municipal water supply: Rivière-du-Loup (population ~ 20,000) which draws its water from an array of horizontal wells connected to a large diameter (4.9 m) production well dug into glaciofluvial sandy gravel associated with the

Saint-Antonin Moraine, a prominent regional feature (Lee, 1962), is a prime example.

Glaciolacustrine sediments are fairly uncommon in the northern Appalachians and, as a result, their role on local or regional hydrogeological conditions is often very limited. In Quebec, these sediments occur almost exclusively as rather discontinuous silty or sandy units in northward-sloping Appalachian valleys where proglacial lakes were locally impounded against the ice margin as it retreated toward the central St. Lawrence Lowlands (McDonald, 1968; Parent and Occhietti, 1988, 1999). In New Brunswick, however, glaciolacustrine sediments rarely constitute large surface units, although they do occur as subsurface units along the Saint John River valley, particularly between Grand Falls and Edmunston where they consist of silty to sandy sediments deposited in proglacial Lake Madawaska (Rampton et al., 1984).

14.2.2.2 Emergence-submergence zones and resulting stratigraphy

As the continental crust was unloaded from its glacial cover during of deglaciation, glacioisostatic recovery lagged behind global sea level rise: many coastal regions were temporarily invaded by North Atlantic marine waters. This short-lived, diachronous marine incursion left discontinuous blankets of marine sediments in many coastal regions, particularly along the estuary and northwestern Gulf of St. Lawrence. As shown in Figure 14.4, the maximum elevation reached by these postglacial seas (locally named Goldthwait, Champlain and De Geer) ranges from 0 m a. s. l. in the central regions of the Gulf of St. Lawrence (Grant, 1989) to as much as 185 m a. s. l. on the northern Appalachian front in southern Quebec (Parent and Occhietti, 1988).

The marine limit isopleths depicted in Figure 14.4 can be used to define the maximum local elevation at which coarse-grained marine sediments may be found. Fine-grained marine sediments generally occur at elevations well below the local marine limit, up to 50 m below marine limit in wave-exposed coastal areas, and less in sheltered embayments and reentrants. The 0 isopleth defines the region (zone A) where no marine sediments exist above the present-day coastline (Grant, 1989). Figure 14.4 also presents an alternate limit between zone A and zone A-B south of Îles-de-la-Madeleine; this alternate is based on unpublished findings (Parent and Dubois, unpublished data, 2007) showing post-LGM littoral sediments at elevations up to 50 m.a.s.l. Marine sediments exert a considerable role on hydrogeological conditions, in the fairly restricted (but densely inhabited) regions where they occur (zones A-B and B).

Beach, nearshore sediments, and thick, sandy marine deltas formed at the mouth of rivers entering postglacial seas, constitute extensive high-yield aquifers. On the other hand, locally extensive blankets of marine silt and clay constitute aquicludes (impermeable layers) that provide confining conditions for underlying Quaternary sediment and/or fractured bedrock aquifers. The occurrence of these fine-grained marine sediments is common along the Chaleur Bay coast in Gaspésie and New Brunswick, and in valley fills along the Saint John, Petitcodiac and Northwest Miramichi Rivers (Rampton et al., 1984; Violette, 1990; Daigle, 2005). Clayey marine sediments can also be found in valley reentrants and along a fairly narrow strip of land along the northern Appalachian front in southern Quebec.

Alluvial sediments occupy a small surface area within the Appalachian region. However, they are

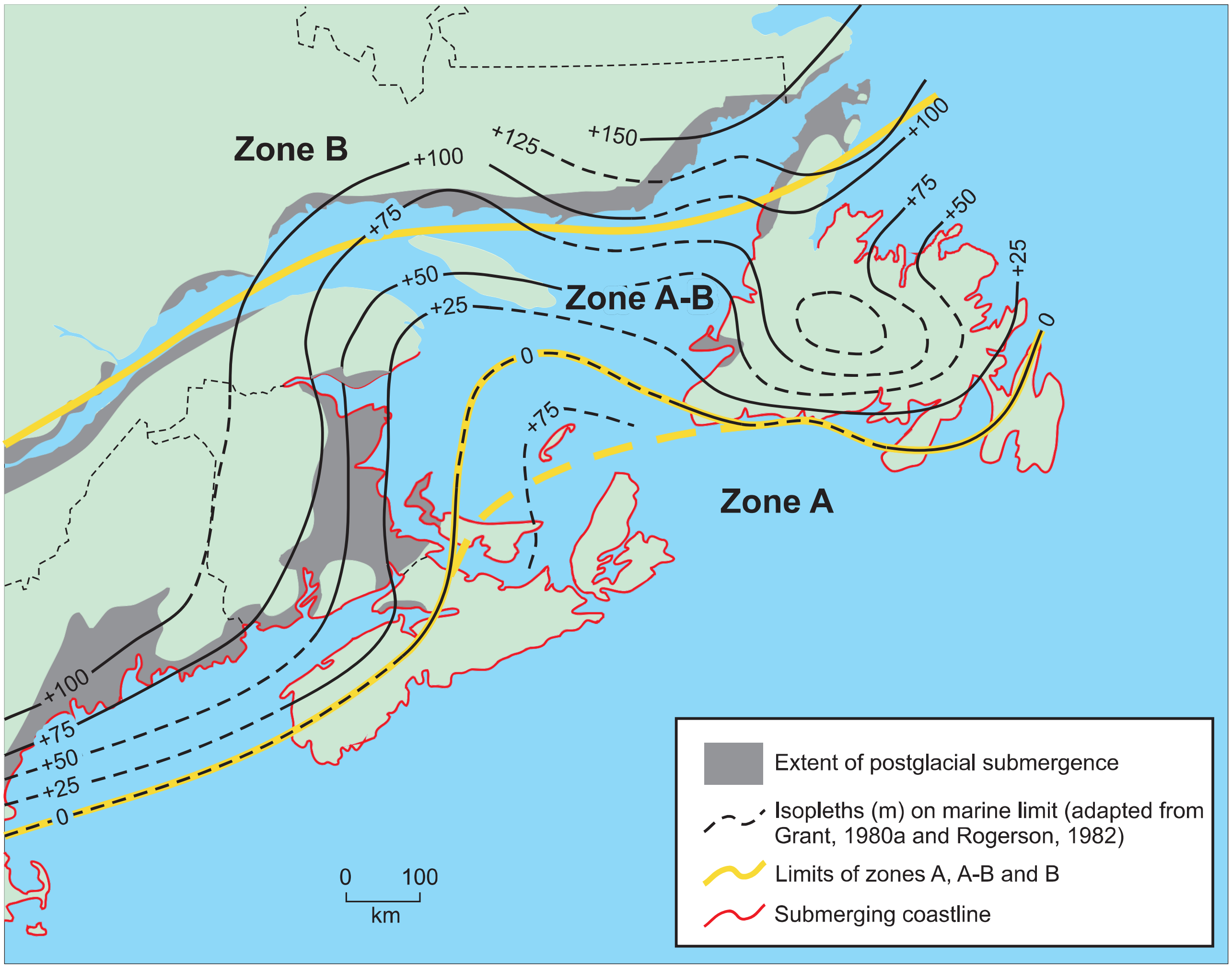


Figure 14.4 Regional distribution of Late Quaternary emergence-submergence zones (zones A, A-B and B) in Atlantic Canada and marine limit isopleths in metres (adapted from Grant, 1989).

present throughout the region and they constitute many of the best aquifers. The coarser facies, pebbly or cobbly gravels and sands, are the most interesting not only because of their high transmissivity, but also because they occur in valleys where main population centres are located. Large deposits of alluvial gravels underlie floodplains or fluvial terraces along intermediate- to low-gradient reaches of most major rivers. In the lower reaches next to the coast, alluvial sediments are commonly interstratified with finer-grained marine sediments, or overlain by silty floodplain sediments.

The Late Quaternary relative sea level history varies across the region; likewise stratigraphic and architectural relationships between alluvial and marine sediments along the coastline also vary (Figure 14.5). In zone A valleys, where relative sea level has been below present since time of deglaciation, alluvial sediments were deposited during marine lowstands and covered by intertidal muds deposited during subsequent highstands, particularly in macrotidal settings such as the St. Lawrence Estuary. In microtidal or mesotidal settings, such as along Nova Scotia's Atlantic coast, or in eastern Prince Edward Island, these valleys are generally drowned by the ongoing submergence.

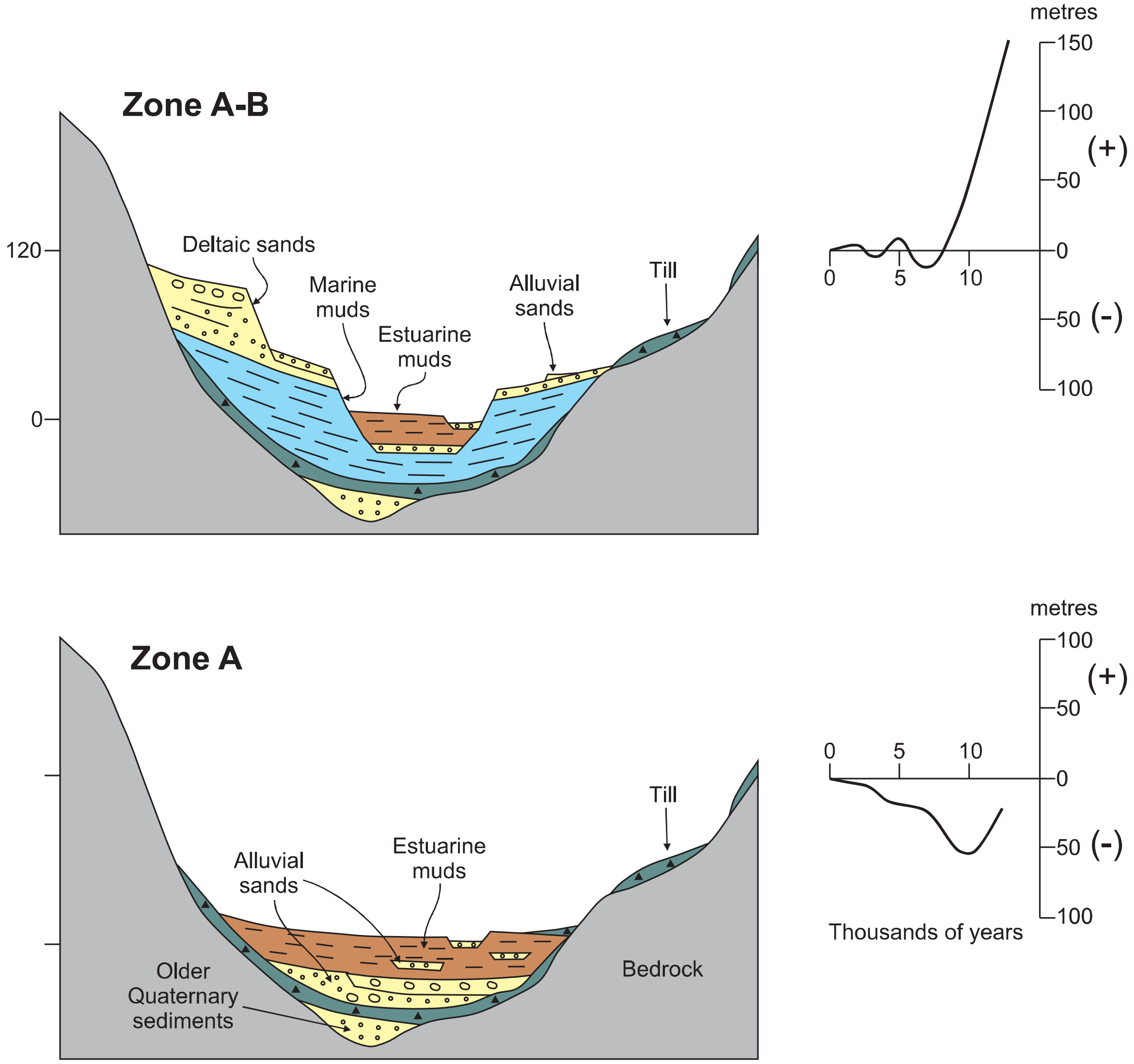


Figure 14.5 Late Quaternary relative sea level changes and resulting schematic stratigraphy in the lower reaches of valleys in zones A and A-B.

Aquifers consisting of alluvial sediments in coastal regions of zone A are commonly confined under intertidal muds; yet, because they lie below modern sea level, they are vulnerable to saltwater intrusion (Figure 14.5). Boisvert (2004) documented an aquifer confined below thick intertidal muds and containing brackish water (TDS = 5,800 mg/L) in the Memramcook valley of southeastern New Brunswick, a region of shallow postglacial submergence, where conditions are almost identical to those of zone A. In valleys of zone A-B (between isopleths 0 and 100 m) where postglacial land emergence was followed by one or several phases of submergence (continuing today), glaciomarine muds deposited earlier were incised down to below present sea level. They were subsequently covered by alluvial sediments, which were in turn overlain by intertidal muds, particularly in macrotidal settings such as in the Bay of Fundy or the St. Lawrence River estuary. Emerged coarse-grained marine sediments in zone A-B regions commonly constitute large, productive unconfined aquifers. These regions may also host various confined aquifers, either below fine-grained marine sediments

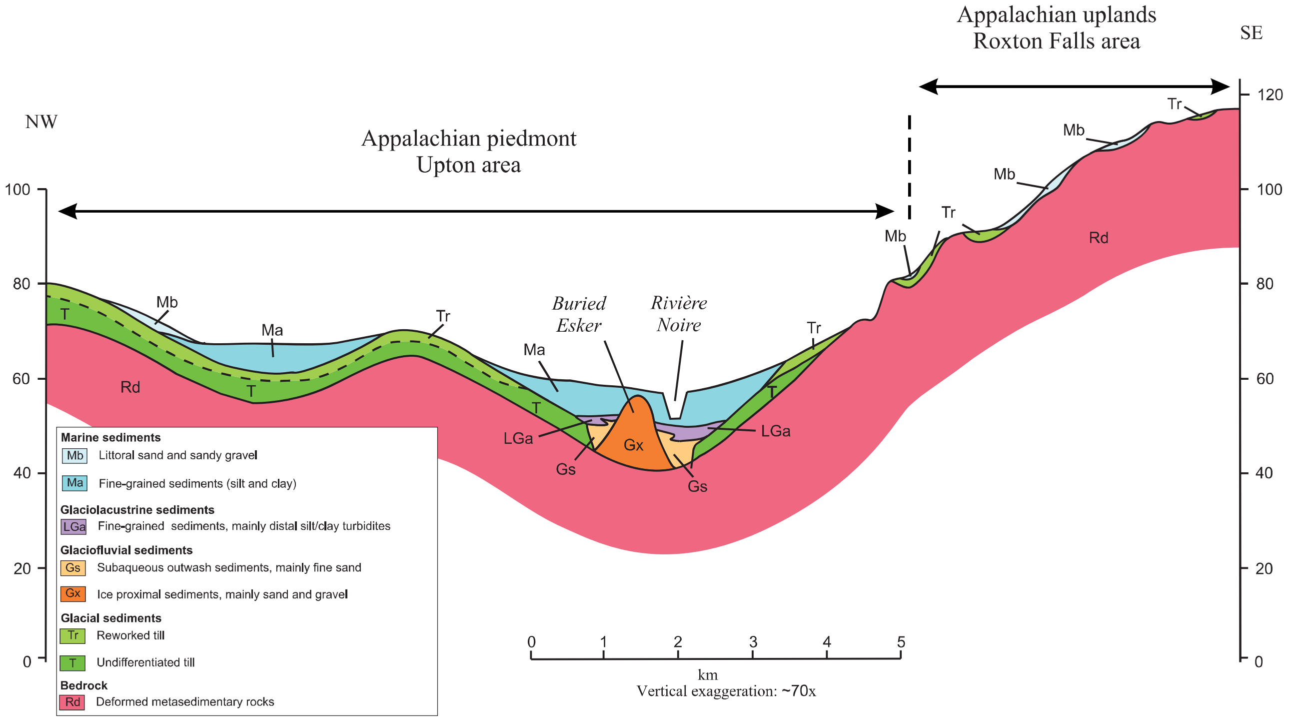


Figure 14.6 Schematic cross section of the Appalachain piedmont and uplands in southeastern Quebec.

or below intertidal muds such as in Quebec City (Lamarche et al., 2008). Large valleys, such as the York River near Gaspé, located in microtidal settings of the central Gulf of St. Lawrence, are being infilled by a prograding wedge of sandy alluvial sediments, whereas small valleys such as those on Prince Edward Island are being drowned by ongoing submergence.

14.2.2.3 Typical cross section for the Appalachian piedmont and uplands

Figure 14.6 presents a schematic cross section of the Appalachian piedmont and uplands of southeastern Quebec by illustrating the stratigraphic architecture of a typical deglacial sediment succession in the Upton-Roxton Falls region. The piedmont was invaded successively at time of glaciation by an ice-dammed lake (Glacial Lake Candona, LGa unit) and by the Champlain Sea (Ma and Mb units). The fine-grained sediments are locally underlain by discontinuous eskers (Gx unit) which often rest directly on bedrock, as the underlying till was eroded by meltwater in subglacial conduits prior to esker deposition. Such ice-contact sediment bodies, composed of sand and gravel, and the associated subaqueous outwash sands (Gs unit) usually have excellent aquifer potential. These glaciofluvial sediments may also benefit from complete or partial confinement by clayey marine sediments which provide them protection from surface contamination. Assemblages of reworked till and littoral sand are one of the main characteristics of the piedmont, where their sandy-gravelly texture and widespread occurrence favours infiltration. The compact, dense till which commonly underlies these sediments, however, has low permeability, with the result that a large part of the infiltrated water may not reach the bedrock regional aquifer below. On the other hand, infiltrated water may migrate under the silty-clay cover via sandy till, reworked till, or even bedrock subcrops, thus forming good aquifers that may supply small rural municipalities.

The common sequence of surficial sediments found in the Appalachian piedmont and uplands, as illustrated in Figure 14.6 includes, from bottom to top: 1) glacial tills which usually cover bedrock; 2) discontinuous glaciofluvial sediment bodies (e.g., eskers) found locally in Appalachian valleys; and 3) glaciolacustrine and glaciomarine silts and/or clays related to Lake Candona and the Champlain Sea, both of which covered the piedmont and valleys of the western Appalachian uplands (Parent and Occhietti, 1988; Lefebvre et al., 2011). Marine sediments are not present in the Appalachians beyond the limit of the Champlain Sea, nor are they found on the larger Monteregian hills, which formed islands.

14.3 HYDROGEOLOGICAL CONTEXTS

Three main hydrogeological contexts have been generalized to provide a framework for a more detailed description of the most important aquifer systems of the Canadian Appalachians. These contexts are based on distinctive bedrock and/or surficial geology, major tectonic episodes, and physiographic divisions. The schematic figures illustrate simplified tectono-stratigraphic zones, and geological features, in order to show differences in bedrock deformation intensity, characteristic surficial sediment-landform assemblages, and associated stratigraphic architecture. The result indicates those areas where potential aquifers and their typical extent can be found. Although the schematics depict representative geological settings from the study area, they do not correspond to a specific "real" area.

14.3.1 Context 1: Appalachian uplands with sparse glaciofluvial sediments and localized glaciolacustrine submergence

The Appalachian uplands are most commonly underlain by fractured non-porous bedrock, in which the connectivity of joints or fractures controls hydraulic conductivity. Rocks of this context are largely Cambrian to Devonian sedimentary, with some volcanic and plutonic rocks that have been metamorphosed at low grade, and more or less deformed and fractured. Many major high tablelands can be found within this context, including the Notre-Dame and Shick-shock Mountains in Quebec (which broadly coincide with the internal Humber zone), the Cobequid Mountains and Cape Breton highlands in Nova Scotia, the Newfoundland highlands (Long Range Mountains), and more localized plutonic rocks such as the Monteregians hills in Quebec, or thrust sheets with thick competent rock units (e.g., the Kamouraska quartzite in the Lower St. Lawrence Valley, Shick-shock volcanics in Gaspésie). Bedrock aquifers with good hydraulic properties are largely localized and can be expected along regional fault zones and folds in the more competent and brittle rock units. Some of these aquifers can also be found in carbonate rocks where dissolution has increased fracture porosity. The complex geology of Newfoundland and Cape Breton cannot be adequately represented in this simplified sketch, because these two areas evidence significant tectonic overprint by the Acadian and Alleghenian Orogenies.

The Quaternary sediment cover consists most commonly of thin and discontinuous till blankets, particularly on interfluves. The silty sand and sandy silt texture of this till blanket controls infiltration, allowing for significant recharge (see section 14.4.4) to the underlying bedrock aquifers.

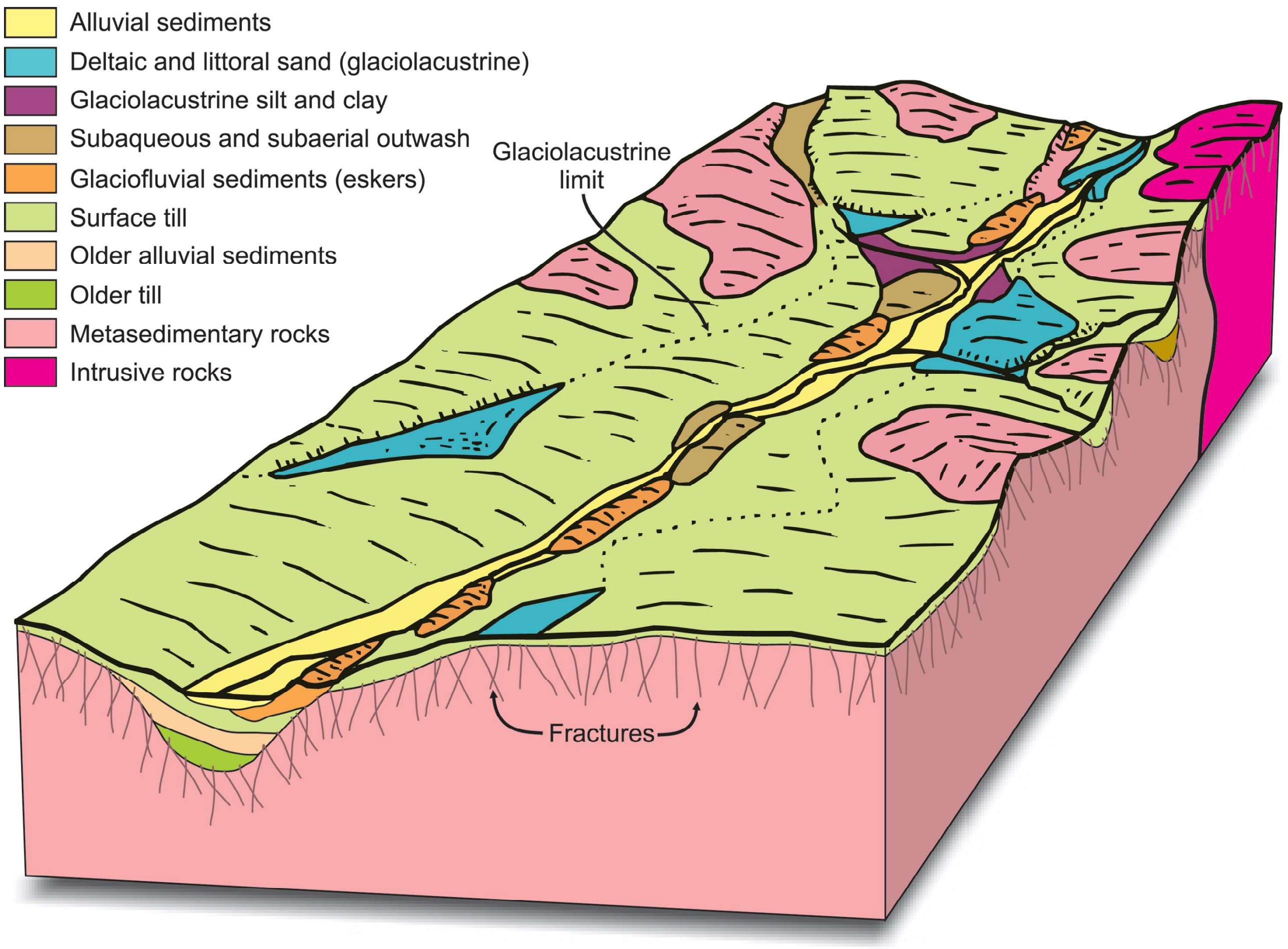


Figure 14.7 Context 1—Schematic depicting the Appalachian uplands with sparse glaciofluvial sediments and localized glaciolacustrine submergence.

Surficial aquifers are largely concentrated in valleys where the topmost Quaternary sediments consist of sandy to gravelly alluvial plains and terraces. As shown in Figures 14.4 and 14.7, eskers and other glaciofluvial sediment bodies occupy rather limited surface areas in the Appalachian uplands, particularly in north-central New Brunswick, in central Newfoundland and in the Gaspé Peninsula. Not only are glaciofluvial sediments scarce in these upland regions, they also tend to be "dry," as groundwater is generally not retained within these highly permeable sediments. Hence the most commonly used aquifers in the uplands are unconfined or semi-confined bedrock aquifers, while in valleys, alluvial sediments provide excellent, generally unconfined surficial aquifers.

The occurrence of fine-grained glaciolacustrine sediments in some Appalachian valleys provides local confining conditions for underlying unconsolidated sediments or bedrock. Silty clay sediments were deposited in glacial lakes impounded by retreating ice margins within many Appalachian valleys, particularly those of southern Quebec (McDonald, 1968; Parent and Occhietti, 1988, 1999), but also in other regions such as Nova Scotia's Annapolis Valley (Rivard et al., 2012). Valley shoulders and slopes are locally overlain by sandy littoral and deltaic sediments deposited at or near the former glacial lake shorelines: these may constitute interesting surface aquifers. The bottom

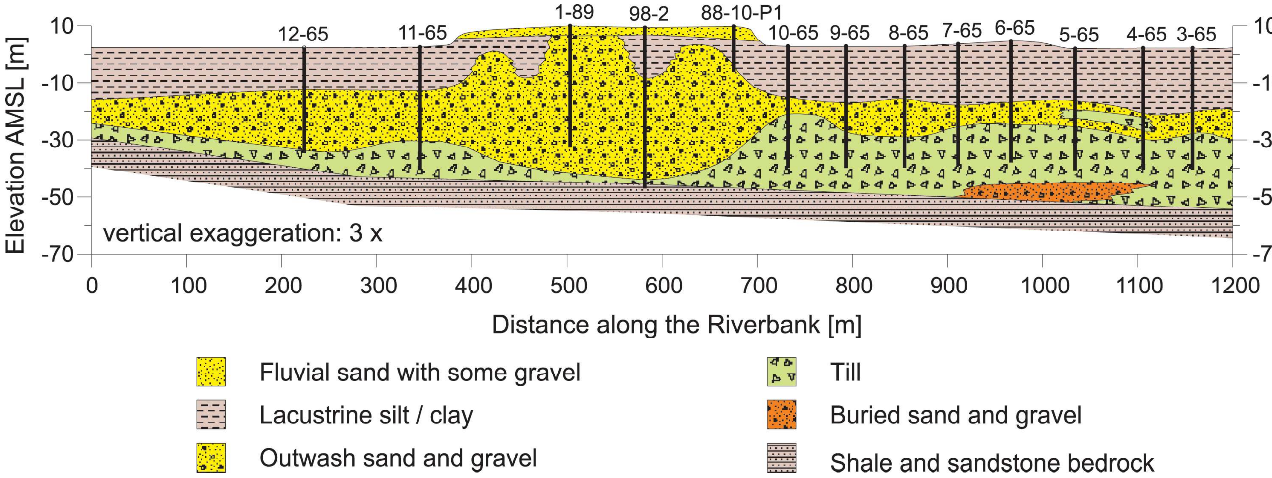


Figure 14.8 Representative cross section taken along the south shore of the Saint John River, and passing obliquely through the aquifer (outwash sand and gravel) near the Wilmot Park well field, Fredericton, New Brunswick (source: Butler et al., 2004).

of these valleys, however, is locally underlain by fine-grained sediments which commonly form discontinuous sheets as a result of subsequent fluvial incision or simply as a result of non-deposition. These confined or semi-confined valley bottom sediments may locally constitute excellent aquifers, depending on permeability, thickness and groundwater quality.

One excellent example of this phenomenon occurs in the Saint John River valley where glaciofluvial outwash sediments, partially buried by glaciolacustrine silt and clay, constitute a high-yield aquifer exploited by Fredericton for municipal water supply (Figure 14.8). Near Fredericton, the Saint John River lies in a broad bedrock valley partially filled with up to 65 m of coarse-grained Quaternary sediments. The sediments that make up the main aquifer have the morphology of a buried esker-like ridge which runs along the valley floor underneath the City of Fredericton and the Saint John River valley. The deposit thins as it spreads toward the north and south valley walls (Figure 14.8). The ridge is up to 30 m thick, and contains a wide variety of particle sizes, including sands, gravels, cobbles, and boulders (Violette, 1990; Daigle, 2005). A clay/silt aquitard, which overlies most of the aquifer, has been eroded at several locations along the crest of the ridge. These features, locally termed "windows", allow for relatively direct recharge of the aquifer.

Elsewhere in the Appalachian uplands, coarse-grained glaciofluvial sediments can constitute good aquifers, although their surface area is very limited. Moreover, these aquifers are commonly very thin because of topographic position, and, in many cases, have been compromised as a result of aggregate resource exploitation.

14.3.2 Context 2: Appalachian piedmont with localized Late Quaternary marine sediment cover

The Appalachian piedmont in much of southern Quebec was invaded by a postglacial marine incursion (Champlain and Goldthwait seas), which produced hydrogeological conditions partly shared by the adjacent St. Lawrence Lowlands, as well as by the southern edge of the Canadian Shield. The bedrock units underlying the Quaternary sequence correspond predominantly to the external Humber zone. Their permeability is primarily controlled by

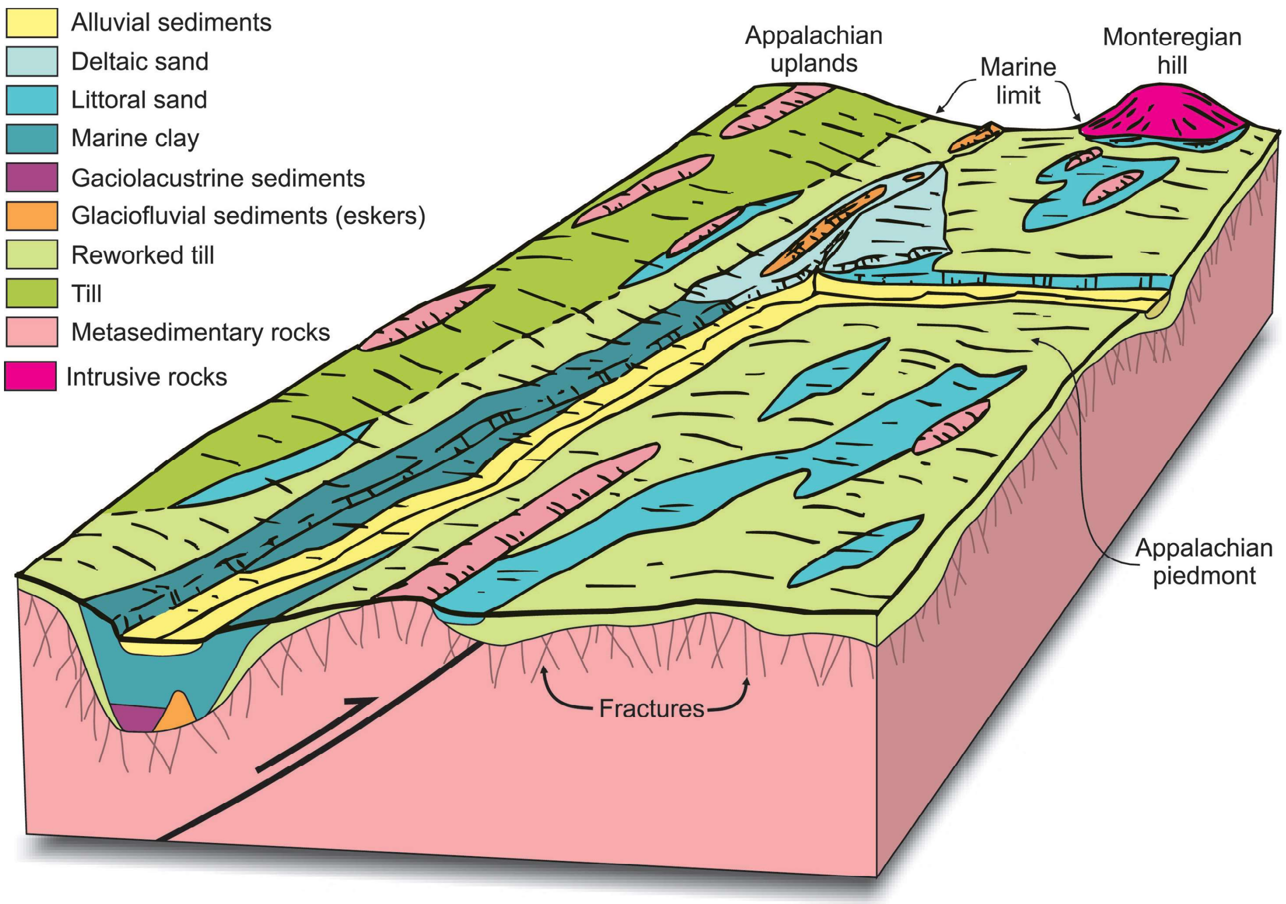


Figure 14.9 Context 2—Schematic illustrating the Appalachian piedmont with localized Late Quaternary marine sediment cover.

fracture porosity, much like those of the internal Humber zone of context 1 (Figure 14.7). However, key components of the marine incursion context (Figure 14.9) are related to (1) surface occurrence of fairly thick (5–10 m) fine-grained deposits which form widespread aquitards and produce confining conditions in the underlying sediment or rock units; (2) occurrence of large sheets of prograding sandy deltaic and offlap littoral sediments that may constitute large unconfined aquifers; (3) widespread wave action and current related winnowing and reworking of glacial sediments which increase the rate of infiltration in these sediments over vast areas below the marine limit. Towns such as Upton (Qc) and Sainte-Hélène-de-Bagot (Qc), as well as small cities such as Rimouski (Qc) are only a few examples of municipal water supply in granular or bedrock aquifers underlying marine clays.

Although the sedimentary platform of the Maritimes Basin could, in theory, be included in this context of marine incursion, it seems best to exclude it because the marine limit was generally too low or too short-lived to allow widespread deposition of fine-grained marine sediments. For instance, detailed investigations in the Moncton region (Boisvert et al., 2002; Boisvert, 2004), as in much of eastern New Brunswick (Rampton et al., 1984), have provided no evidence for fine-grained marine sedimentation nor for significant wave-washing or winnowing of tills.

14.3.3 Context 3: Maritimes Basin

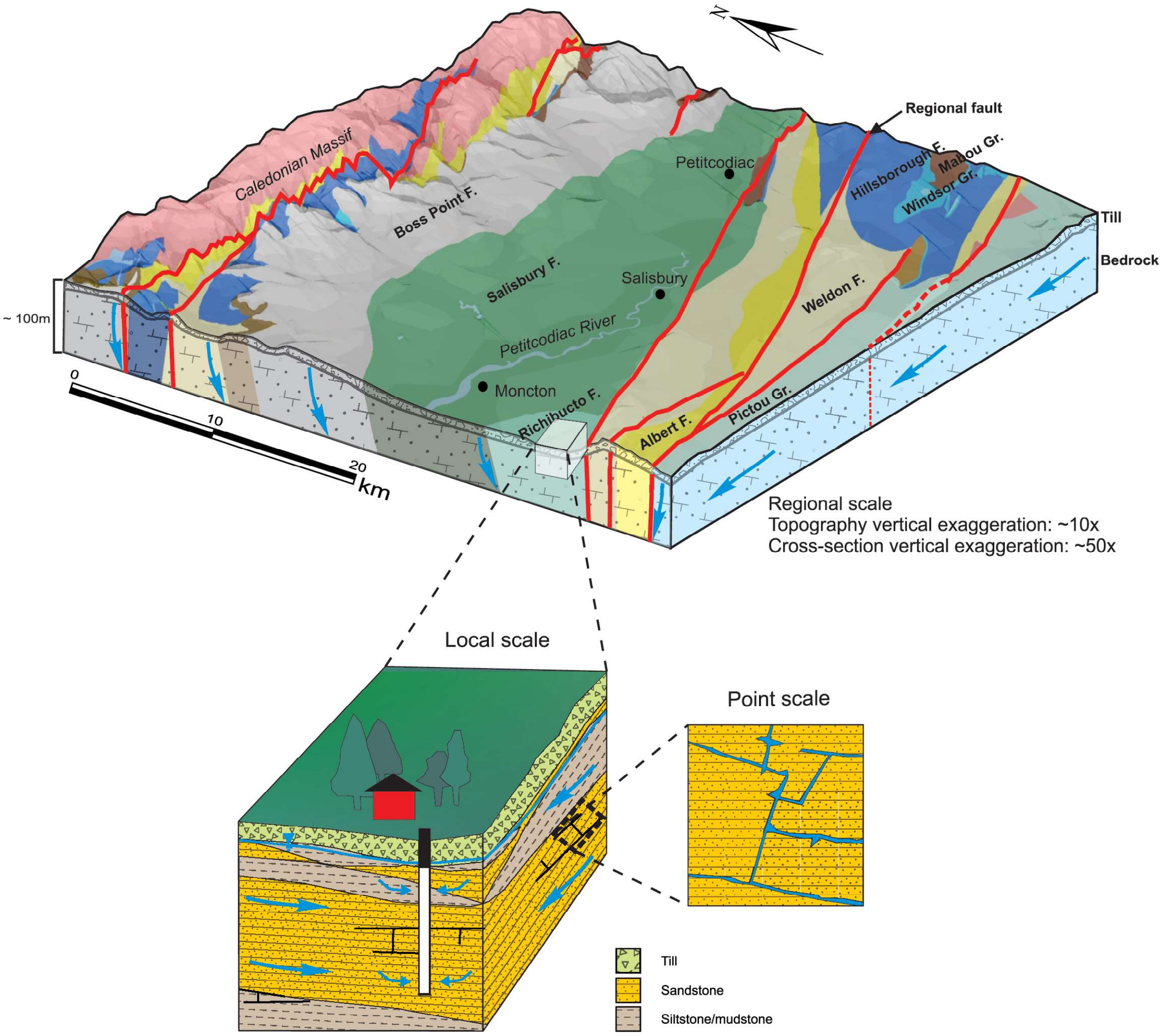
The Maritimes Basin represents one of the main regional aquifer systems in Canada. It includes Prince Edward Island, the northern part of Nova Scotia (including a portion of Cape Breton Island), the eastern part of New Brunswick, Îles-de-la-Madeleine, as well as two small areas east and south of the Long Range Mountains in Newfoundland (see Figure 14.1). In total, this basin covers 46,000 km^2. It is composed largely of Carboniferous and younger sedimentary rocks, consisting mostly of sequences of lenticular bodies of sandstone, shale, siltstone, and conglomerate, in varying proportions, in different lithostratigraphic units. There are also some volcanic rocks (basalts) present in Îles-de-la-Madeleine and along the Bay of Fundy in Nova Scotia (North Mountain). A thin layer of glacial till (mostly 4–8 m, but reaching locally up to 20 m in thickness) usually covers these formations. The main till properties strongly reflect the lithology and colour of the underlying bedrock units.

This basin is characterized by significant and rapid lateral and vertical facies changes, as in most continental to marginal marine successions. These weakly consolidated rocks constitute a vast regional aquifer with modest to significant yields. Good aquifers can also be found in the glaciofluvial sand and gravel units, as well as in fluvial valley fills, but these are notably scarce in the Maritimes Basin. Bedrock aquifers are often confined, mainly depending on the bedrock composition, layering, and fracturing. Although the porosity of these Carboniferous, Permian and Triassic rocks is usually much higher than that of older rock units elsewhere in the Appalachian region, groundwater still circulates, largely through fractures. Almost all residential wells are shallow, open holes (about 20 m), cased only through surficial sediments. Preferential groundwater recharge occurs where bedrock is overlain by sandy till.

Figure 14.10 provides a schematic representation for the particular geological context near Moncton, New Brunswick. Three scales (regional, local, and point) were used in Rivard et al. (2007; 2008) to describe the main hydrogeological characteristics of the surficial sediments and sedimentary rock units of the basin. At the region scale, each formation can be considered as only one hydrostratigraphic unit with uniform properties, although generally anisotropic. Anisotropy may indeed have a significant impact on flow system behaviour, as laterally extensive and sometimes thick impermeable strata are present. At the regional scale, however, fractures are often probably sufficiently connected to provide an equivalent porous media. Faults are interpreted to play a key role in the regional flow, based on results of numerical flow modelling.

At the local scale, each hydrostratigraphic unit has its own set of characteristic structural and hydrogeologic properties. Layering of the various strata with contrasting hydraulic properties leads to an aquifer/aquitard sequence for many geological formations. Due to this layering, and also to fracturing, these porous fractured aquifers are locally heterogeneous and anisotropic. Nevertheless, based on pumping test results, they appear to behave as equivalent porous media.

Work performed at the point scale indicated that most fractures consist of shallow-dipping joint sets generally oriented in a northeasterly direction, in agreement with regional structures. More specifically, water-bearing fractures are commonly related to bedding planes and lithological changes.



14.4 CURRENT KNOWLEDGE OF HYDROGEOLOGY

14.4.1 Most important aquifer systems

Bedrock aquifers are frequently exploited in the Canadian Appalachians. As discussed in Chapter 2, water in bedrock aquifers, may come from fractures alone (referred to as secondary porosity) such as in igneous rocks (e.g., basalts, granite), or it can be stored and circulated through pores (referred to as primary porosity) and fractures, as is often the case with sedimentary rocks such as sandstones. Fractured porous media (mainly sandstone and conglomerate) usually provide better yields and aquifer potential than strictly fractured aquifers because the latter have no primary porosity. Nevertheless, strictly fractured aquifers can supply significant yields locally, when sufficient interconnected fractures or a thick cover of saturated Quaternary sediments is present. Bedrock, in most places in the Appalachian region, is overlain by a thin layer of glacial sediments (generally till less than 10 m thick) that does not yield large quantities of water. Sand and gravel units, which have very good hydraulic potential, are present only over a limited area (<10% of the land area).

Recently, two regional hydrogeologic studies have been carried out over formations of the Maritimes Basin: the Maritimes Groundwater Initiative (Rivard et al., 2005, 2008) and the Annapolis-Cornwallis Aquifer Study (Rivard et al., 2007, 2012). The Maritimes Groundwater Initiative (MGWI) project covered a land surface of 10,500 km^2, of which 9,400 km^2 is underlain by Carboniferous and younger rocks, including the southeastern part of New Brunswick, the western part of Prince Edward Island and the northern part of Nova Scotia. The Annapolis-Cornwallis Aquifer Study (hereafter called "Annapolis") covered 2,100 km^2, including the Annapolis Valley proper and parts of North and South Mountains in Nova Scotia. The MGWI project mainly focused on permeable formations of the Pictou, Cumberland and Prince Edward Island Groups, whereas formations of the Triassic-Jurassic Fundy Group were of main interest in the Annapolis project (i.e., the Wolfville Formation underlying the valley floor and the Blomidon and North Mountain formations constituting North Mountain).

In Nova Scotia, 14 published regional groundwater resource studies characterizing different counties were carried out between 1968 and 1986 (they are available at the Nova Scotia Environment website http://www.gov.ns.ca/nse/groundwater/groundwaterresources.asp). Agriculture and Agri-Food Canada (AAFC) recently conducted a few studies in the Annapolis Valley (e.g., AAFC-PFRA, 2003). Several theses were also devoted to more or less local areas in all provinces (e.g., Carr, 1969; Trescott, 1968; Brown, 1971). Numerous local hydrogeological studies have also been undertaken throughout the Canadian Appalachians with results generally available through provincial databases.

14.4.1.1 Bedrock aquifers

The most important bedrock aquifers of the Canadian Appalachians are hosted by Carboniferous or younger rocks (Figure 14.2), located in the Maritimes Basin (Context 3, Figure 14.10). Formations in this basin consist of discontinuous layers of sedimentary rocks, forming an inter-layered suite of permeable, and almost impermeable, strata with a shallow northeastern dip (see section 14.3.3). Individual beds range in thickness from a few centimetres to several metres: their lateral extent is variable.

Most bedrock formations outside the Maritimes Basin cannot supply high-yield wells. Rocks of Contexts 1 and 2 (Figures 14.7 and 14.9), since they mainly depend on fracture porosity (very poor primary or intrinsic porosity), commonly only provide yields sufficient to supply one to a few houses. Therefore, several wells may need to be drilled to provide sufficient water to supply an industry or a community, as is the case throughout much of Newfoundland. Some igneous (e.g., granites) and sedimentary rocks, however, can provide good yields on a local basis. For instance, in the Gaspé Peninsula and in the southern part of Quebec, some Silurian and Devonian sandstones and carbonates have high hydraulic conductivities (see section 14.2.1.3.2), although the region underlain by these rocks (Figure 14.2) is rather sparsely populated, and few wells other than residential have been drilled; as a result, aquifer properties are not well known. Quartzites in other parts of the Silurian and Devonian belt, may offer some aquifer potential due to the fact that they can be quite fractured, as opposed to more ductile and finer-grained sedimentary rocks, even when the latter have been subjected to folding and fracturing. Bedrock in the Chaudière watershed (6,682 km^2), located south of Quebec City, consists mainly of schist, slate, mudstone, and sandstone, with local volcanic or intrusive rocks belonging to the Humber zone, and is thus not very permeable. The most intensely fractured and folded rocks in this area can only provide yields varying from 0.8 to 1.5 L/s (i.e., sufficient for average household use or for a (very) small central system or some commercial uses), unless they have been overlain by sufficiently thick, permeable surficial sediments.

Surficial sediments in many areas of this region are too thin or too impermeable to provide adequate yields. This fact, coupled with the prohibitive costs of construction and operation of filtration plants necessary for surface water treatment, means that groundwater from poorly permeable rocks often represents the only economically viable solution for many small municipalities, even if several wells or combined systems must be developed.

14.4.1.2 Surficial aquifers

The Appalachian region's surficial geology is usually very complex, largely because this area has been subjected to several glaciation/deglaciation cycles. As a result, the region is characterized by the presence of different landform-sediment assemblages, including rare, locally preserved sequences of interglacial/interstadial sediments (see section 14.2.2). Each glacial/deglacial cycle in the Appalachian region tended to erode surficial sediments deposited during previous cycles; hence Quaternary sediments are generally thin throughout the region, in contrast to other regions such as the Prairies where each glacial/deglacial cycle generally added to the total thickness of the Quaternary sediment pile.

There are exceptions, where Quaternary sediments can be quite thick locally, reaching up to about 100 m near Lac-Mégantic in the Upper Chaudière valley, and near Saint-Antonin in the Bas-St-Laurent region, Quebec; and 50 m in a few areas of New Brunswick (e.g., Fredericton) and Nova Scotia (e.g., Kentville).

Surficial units, with yields > 1.5 L/s, capable of supplying the needs of municipalities, industries or institutions are typically isolated sand and gravel deposits of diverse origin. These units often constitute excellent aquifers, and in the Appalachians, they consist mainly of alluvial or glaciofluvial sediments (see section 14.2.2), which provide potable water supplies for a number of fair-sized municipalities throughout the region (Fredericton, Wolfville, Parrsboro, Lac-Mégantic and most of the municipalities along the St. Lawrence estuary, as well as Stephenville in Newfoundland). Sand and gravel deposits usually occur (1) along river valleys, (2) in buried or partly buried valleys, or (3) as glaciofluvial sediment bodies (e.g., deltas, moraines, eskers), which also tend to be concentrated in valleys.

The main valleys hosting sand and gravel aquifers within the region are: the Saint John and Kennebecasis Rivers in New Brunswick, the Chaudière, Matapedia, and Bonaventure Rivers in Quebec, and the Cornwallis and Musquodoboit Rivers in Nova Scotia. Some deltas, moraines, and eskers are also exploited for water supply (the esker ridge near Sussex, New Brunswick, the St-Antonin moraine ridge in Rivière-du-Loup, and the Saint-Césaire esker in Quebec). Buried or partly-buried valleys can be found in various areas of the five provinces (in the Moncton area, and near

Lac-Mégantic and East-Angus, Quebec). These valleys have the advantages of (1) being commonly confined and thus, naturally protected from surface contamination, and (2) containing usually better-sorted, coarser-grained sediments than their overlying units, which usually consist of glacial sediments. However, buried valley aquifers are often not exploited for a variety of reasons, including poor water quality (mainly excessive iron and manganese content) and/or distance from populated areas.

Sand and gravel units sometime provide remarkably high groundwater yields, despite having only a few metres of saturated thickness. One good example of this is in Quebec's Saint-Hubert-de-Rivière-du-Loup. This municipality exploits a sand and gravel unit, 4 m thick and extending over 0.19 km^2, to supply more than a thousand people. This exploited glaciofluvial unit is assumed to belong to the Saint-Antonin Moraine, which is also present at Rivière-du-Loup. The Moraine constitutes a small enclave surrounded by till, and underlain by a clayey gravel, considered to be the base of the aquifer (Arrakis Consultants Inc., 1991). Monitoring of water levels has shown large variations between the minimum and maximum levels relative to aquifer thickness (min=1.2 m and max=2.9 m based on six observation wells). The extraction system consists of a very shallow dug well with four horizontal radial collector drains. Several similar systems are also in use within the region.

Aquifer potential of surficial sediments in the Appalachian piedmont of Quebec is currently under investigation (Lefebvre et al., 2011), particularly in valleys, where fairly thick (~5 to 10 m) permeable sediments underlie low-permeability (protective) glaciolacustrine or glaciomarine sediments (as illustrated in Figure 14.6). Scientists are paying particular attention to the extent and aquifer potential of eskers concealed under the Champlain Sea clay cover. Aquifer potential of the coarse-grained littoral sediments surrounding the Monteregian Hills is also being documented (Lefebvre et al., 2011).

14.4.2 Hydraulic properties and aquifer potential

The quantity of water yielded by any given well depends on the type of geological material, the thickness of the saturated zone, the number of transmissive fractures and/or the porosity and thickness of permeable layers encountered, well depth, recharge available, and storage capacity. The location of the well with respect to boundary conditions (proximity to a river that can feed the well, or to a less permeable boundary, as, for example, a valley wall limiting the extent of the aquifer) is also important. Hydraulic conductivity (K) is a critical parameter in hydrogeologic investigation because it provides a quantitative estimate of the ability of the formation to convey water to the well. Most commonly, however, K values are not directly available and must be derived from transmissivity values (T). These are an integration of K over the saturated thickness (b) of the assessed aquifer (T=K*b), and are commonly provided in provincial databases and reports. Transmissivities are best estimated from observed water level drawdown/recovery rates during long-duration pumping tests. Most jurisdictions only require long-term pump tests for relatively high capacity wells, or for multiple user wells. More details on these hydraulic properties are provided in Chapter 2.

1,600 transmissivity values (1,300 for bedrock and 300 for surficial aquifers) were used in the Appalachian region to depict hydraulic properties of the formations. Transmissivity values were collected from provincial databases (for New Brunswick, Prince Edward Island, and Nova Scotia), and from reports (for Quebec). No data was available for Newfoundland. Transmissivities, rather than hydraulic conductivities, have been presented here, because, as noted above, this parameter is usually the one provided in databases, and the screen and/or casing length required to estimate saturated thickness is not always provided to estimate K values. Wells often have approximate locations, as they were either located using a provincial grid system (with a precision of approximately 1 km^2) or by using the centroid of the municipality, when no other information was available. Several wells are often located in clusters and thus, cannot be distinguished at the scale of the Appalachians.

14.4.2.1 Bedrock aquifers

Transmissivity and porosity in bedrock aquifers varies according to the type of rocks, their age, and their tectonic history (see section 14.2.1). Carboniferous and younger sedimentary rocks of the Maritimes Basin (Context 3) often have moderate to high ($>10^{-4}$ m^2/s) transmissivities, especially where sandstone and conglomerate are present. Because of aquifer and aquitard layering, many formations have variable aquifer potential[2], showing poor to moderate hydraulic conditions in those areas where shale and siltstone predominate. As a general rule, the greater the presence of sandstone and conglomerate, the more permeable the bedrock will be (although this does depend on the matrix characteristics). Wide ranges in hydraulic properties are due both to the presence or absence of fractures, and to layering. Carbonate rocks (e.g., limestones in the Gaspé peninsula, Quebec; the Scots Bay Formation, at the top of the Fundy Group succession, Nova Scotia), evaporites (those of the Windsor Group near Windsor, Nova Scotia); Salt Springs evaporite (deposits near Sussex, New Brunswick), and finer-grained strata (e.g., shale and siltstone) can also yield water, mainly from fractures, bedding planes, and cavities. Their aquifer potential is typically poor to moderate, except for water-soluble rocks such as evaporites or carbonates, where large fractures or karstic features caused by dissolution can significantly increase potential, although the groundwater quality within soluble rocks can be affected (e.g., brackish water from evaporites, enhanced hardness from carbonates).

Igneous rocks such as granites, basalts, gneiss, and gabbro typically have a relatively poor aquifer potential (with $T<10^{-5}$ m^2/s), but these rocks can locally provide good yields if fractures are well interconnected. One of the municipal wells of Lawrencetown, Nova Scotia, constructed in granite, has a transmissivity on the order of 5×10^{-5} m^2/s. Highly fractured basalts of the North Mountain in Nova Scotia may also supply moderate to significant yields in some areas. Metamorphic rocks, such as slates of the Meguma Group in Nova Scotia, and schists of the Humber zone in Quebec, also commonly have a poor aquifer potential with transmissivities in the order of 10^{-6} to 10^{-7} m^2/s; typically, they can only provide water for a single house.

Figure 14.11a presents the minimum, maximum, and median bedrock transmissivity values obtained for each province. Figure 14.11b presents the same data, but using tectono-stratigraphic zones to illustrate ranges of values. Transmissivities mainly

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[2] The classification "variable aquifer" means that good hydraulic potential can be found in certain areas, while poor transmissivities (or low yields) are observed in other parts of the formation, likely where fractures and sandstone layers are less abundant.

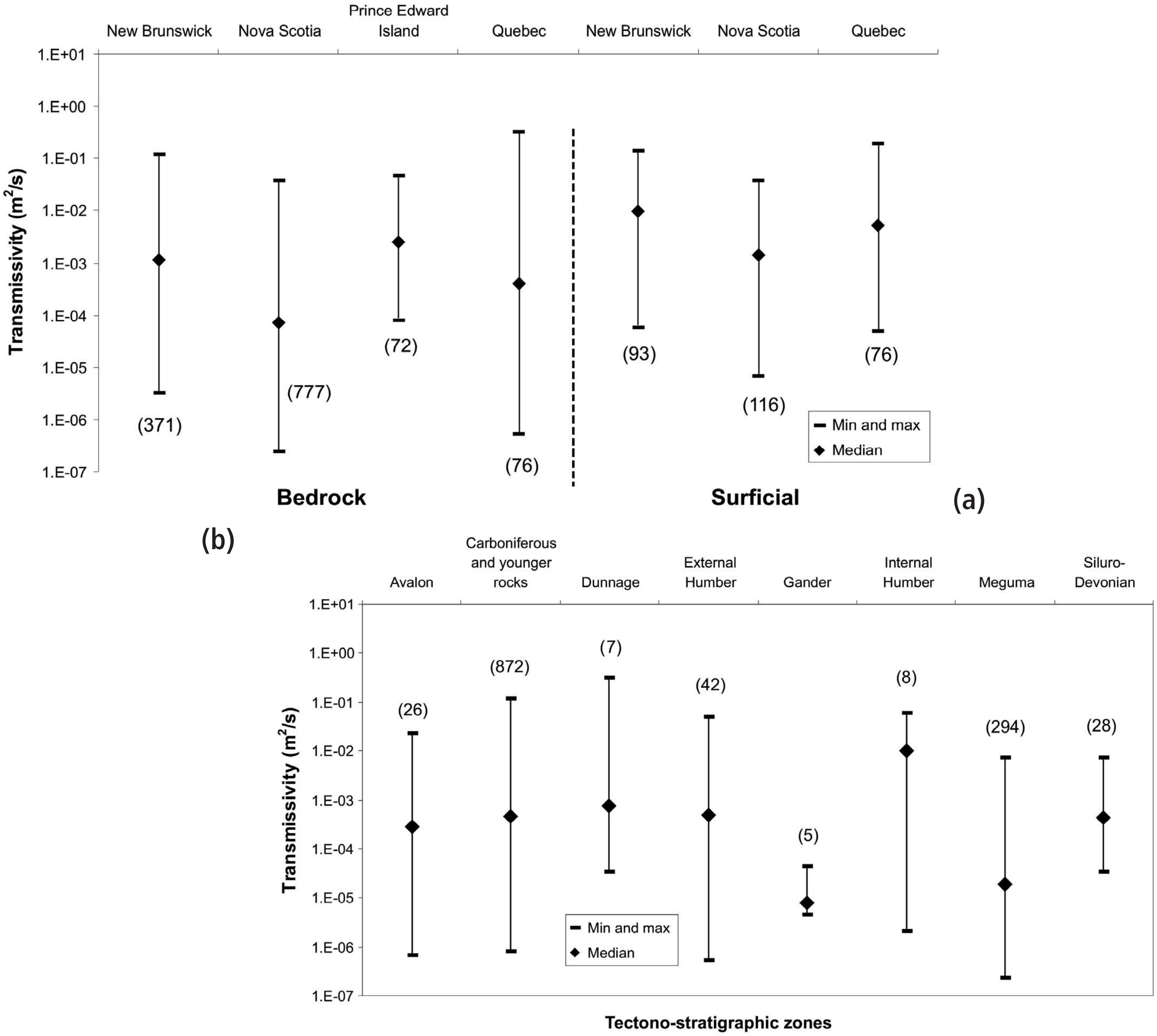

Figure 14.11 Minimum, median, and maximum values of transmissivity (m^2/s): (a) by province for bedrock and surficial sediments and (b) by tectono-stratigraphic zones. Note that there are no major high-yield wells in surficial sediments on Prince Edward Island.

range between 10^{-6} and 10^{-1} m^2/s, with most values varying between 10^{-5} and 10^{-2} m^2/s based on statistical distributions (not shown). This indicates that a relatively good hydraulic capacity is available throughout the Appalachian region. It must be kept in mind, however, that these reported values are probably positively biased, especially for less permeable bedrock formations, because only relatively productive wells are tested, and often several wells must be drilled and abandoned before finding the required yield; these "failed" wells are not included in databases. As a result, reported values likely tend to overestimate the median transmissivity of the formations. Nevertheless, figure 14.11 demonstrates that moderate to good transmissivities may, perhaps surprisingly, be found in all bedrock formations, mainly due to local fracturing.

Figure 14.12 illustrates the spatial distribution of bedrock permeability using three transmissivity (T) classes. The diagram shows that

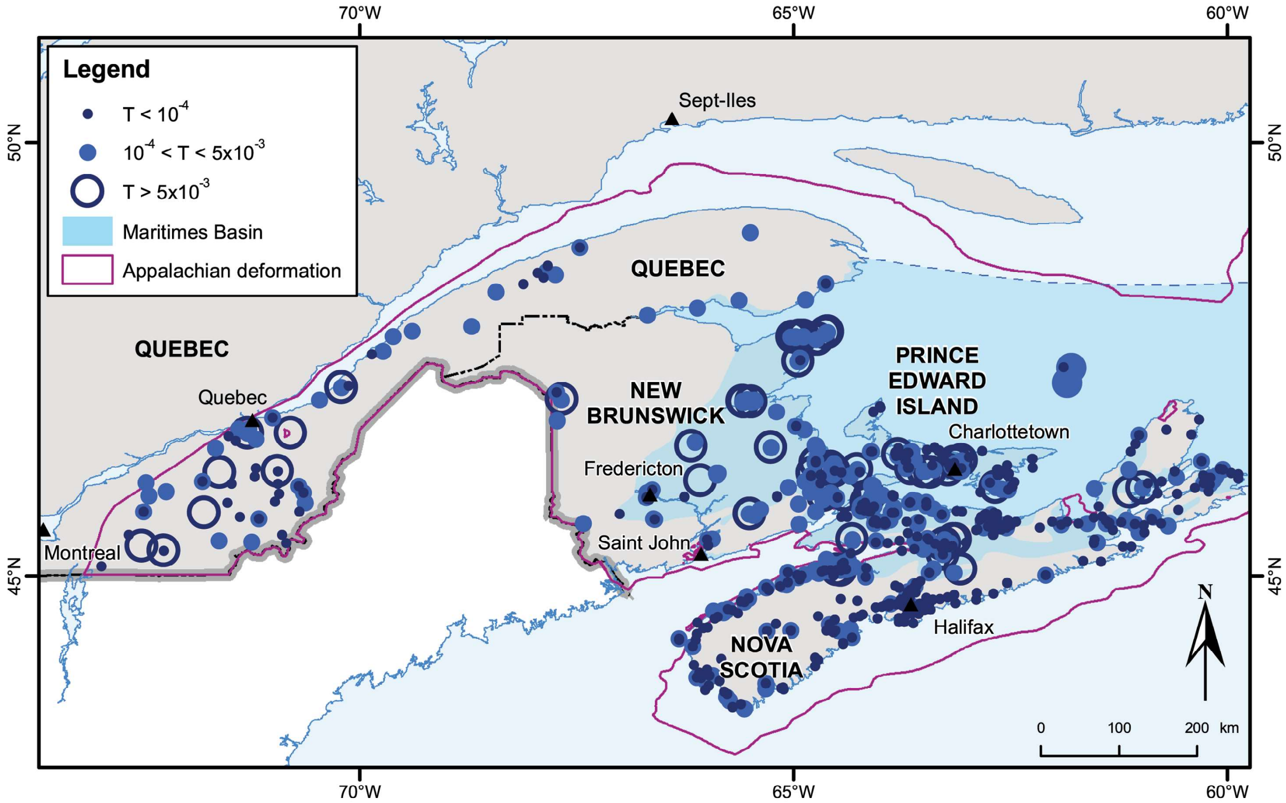

Figure 14.12 Spatial distributions of transmissivities (in m^2/s) in bedrock aquifers (data taken from provincial databases and reports).

moderate- to high-transmissivity values ($T>10^{-4}$ m^2/s) can be found in almost any municipality of the Appalachian region. Several sedimentary formations of the Maritimes Basin, including those of Prince Edward Island, Îles-de-la-Madeleine, the eastern Annapolis Valley and the Acadian littoral of New Brunswick show large values ($>10^{-3}$ m^2/s), typical of high-capacity formations. Other high values may be found on the south shore of the St. Lawrence River in Quebec, probably associated with local tectonic features. Large variations between geological formations of the same group and even within each individual stratum in sedimentary rocks have been observed. This variability attests to the important heterogeneity of bedrock aquifers and asserts the strong influence of both fracturing and layering (Rivard et al., 2008).

Areas where no data are available do not necessarily correspond to regions with poor aquifer potential; rather they usually relate to sparsely populated areas, or to areas where surface water, not groundwater, is the main water source. Long-term pump tests are required only for multi-user wells (for industrial, municipal, and institutional supplies): information for areas where demand is small is thus limited. Nonetheless, Figure 14.12 provides a good indication of where high transmissivities may be found.

Storage coefficient values, which provide an indication of the degree of confinement of an aquifer, are rarely available. This is largely because pumping tests are often performed without using observation wells. Moreover, the storage coefficient value is often questionable, as the tests do not extend over a sufficient time period. Reported storage coefficients have an overall average of

4×10^{-4}. Values typically range between 5×10^{-5} and 5×10^{-2}, showing a relatively high variability due to surficial sediment composition, bedrock layering and fracturing heterogeneity. Despite the uncertainty, these figures provide yet another indication that several bedrock formations are under confined conditions (under pressure) due to overlying fine-grained strata or to the absence of well-interconnected fractures. Such aquifers may therefore be better protected against surface contamination (see section 14.4.7 on vulnerability).

Field measurements from bedrock aquifers in the Maritimes Basin have shown that the movement of groundwater is predominantly controlled by fractures/bedding planes, although some sandstones and conglomerates may have preserved significant primary porosity (Rivard et al., 2012). The pattern, strike, dip and frequency of the fractures vary widely in the various geological formations due to differing primary lithologies and later tectonic stresses. In major aquifers of the area, fractures and bedding planes have been found to be mostly gently northeasterly dipping (toward the Northumberland Strait or the Bay of Fundy), and striking of 45º, in agreement with regional structures. Conversely, wells located in basalts or granites indicate the fact that water seems to be supplied predominantly by sub-vertical fractures, again preferentially striking in a northeastern direction.

Rocks in the Taconian zones and the Acadian Gaspé Belt (i.e., most rocks outside the Maritimes Basin) have been subjected to multiple phases of deformation associated with the Ordovician and Devonian orogenic events. These rocks are commonly folded and thrust-faulted over significant distances (see section 14.2.1) with younger rocks being tectonically overlain by older ones. The main hydrogeological differences between the internal and external domains of the Humber zone are that, within the internal domain, fractures and faults are often sub-vertical, folds are generally tight, and primary porosity is rather low to inexistent, whereas, in the external domain, fractures can be horizontal to vertical, and folds are relatively open. Deformation in external domains is less extensive, rocks are less crystallized and both primary and secondary porosities can be locally preserved, although in lower percentage and absolute values when compared to Carboniferous and younger rocks. General observations indicate that topographic highs often correspond to rocks of the internal domain.

According to water-well drillers, provincial hydrogeologists, and some reports (e.g., Francis and Gale, 1988; Chi et al., 2003), fractures in the Maritimes Basin appear to decrease with depth, both in number and in aperture. As a result, the permeability of these aquifers should generally decrease with depth. Many wells, in recharge areas drilled deeper than 100 m, yielded little or no water beneath this depth (Carr, 1969). This suggests that fractures, which account for a large part of the aquifer permeability, tend to be less frequent, less interconnected and/or have progressively smaller aperture with depth, presumably due to increasing lithostatic pressures.

In addition to the influence of fracturing, the total porosity of each rock type also varies widely, mainly due to the presence of calcite or other cements within pores, to dissolution and to diagenetic processes. The MGWI and Annapolis projects compiled estimated total porosities for the Maritime Basin formations, mainly through thin sections, coming up with values ranging between 0% and 28%. Total porosity was also evaluated by Hu and Dietrich (2008) through detailed analyses of geophysical well logs and core data in six deep wells within Carboniferous rocks (onshore and offshore) of the basin. They reported similar porosity values in the upper levels (~0–400 m), generally ranging from 3% to 25% and averaging 15% to 20%: the highest values typically corresponded to the highest percentage of sandstone in the rock. Kinematic (effective) porosity, however, may be smaller than 10%. Chi et al. (2003) showed that the total porosity of Prince Edward Island formations decreases significantly with depth, from some 20% at surface to about 12% at depths of about 1 km. This finding compares well with results obtained by Hu and Dietrich (2008) who discovered average porosity values of 15% to 20% at shallow depths (above 1,000 m), with a decrease to 10% or less below depths of about 2,000 m.

These relatively high porosity values (mainly due to the matrix, but sometimes including significant fracturing) could lead one to expect that the Maritimes Basin flow system would react hydraulically like a double-porosity medium. Typically, relatively short-term (72 h and less) well tests do not exhibit such a double-porosity behaviour, but rather demonstrate drawdown curves representative of equivalent porous media (Rivard et al., 2012). This may be caused by the presence of very well developed fracture networks (at least in the vicinity of tested wells), having themselves enough storage to act as equivalent porous media at a scale relevant to such investigations. However, longer-term pumping tests (where available) frequently reveal delayed drainage effects associated with dual porosity aquifers. Little literature on this topic is found for the region. Scientists also suspect that anisotropy has a significant impact on flow system behaviour at both local and regional scales, due to the strike of main fractures (north-east) and/or the predominance of shallow-dipping bedding plane fractures, coupled with aquifer/aquitard layering of some geological formations (Francis, 1989; Paradis et al., 2006; Rivard et al., 2012). Effective porosities of rock samples obtained in fractured rocks of Quebec are generally lower, varying between 0.4% and 11.3%, with a median of 1.7% (Table 14.3).

14.4.2.2 Surficial deposits

A solid knowledge of hydraulic properties of surficial sediments is key information for studies of the Appalachian region, and is required to identify areas with both high and low hydraulic conductivities. Areas with high hydraulic conductivities correspond to preferential recharge zones and potential aquifers, unfortunately with little protection against potential pathways for surface contaminants. In those areas with low hydraulic conductvities, or low permeability, the deposits have limited (or no) water supply potential, but offer good protection to underlying aquifers, and contaminants are unlikely to enter the hydrogeological system.

Fine-grained sediments such as glaciomarine and intertidal sediments can often play a role in the confinement of bedrock aquifers. One good example of this interplay can be found in the vicinity of Fredericton's municipal well field, where McGuigan (2005) obtained vertical hydraulic conductivity values for the overlying clay/silt aquitard (Figure 14.8) on the order of 2×10^{-9} m/s, using conventional consolidation tests, flexible wall permeameter tests, and a piezocone test. At the other end of the spectrum, sand and gravel units often have very high permeabilities ($K > 10^{-4}$ m/s or $T > 5 \times 10^{-3}$ m^2/s, see Figure 14.13). Pumping tests conducted in the Fredericton municipal well field have yielded transmissivity values as high as 10^{-2} to 10^{-1} m^2/s (Violette, 1990; GEMTEC, 1989,

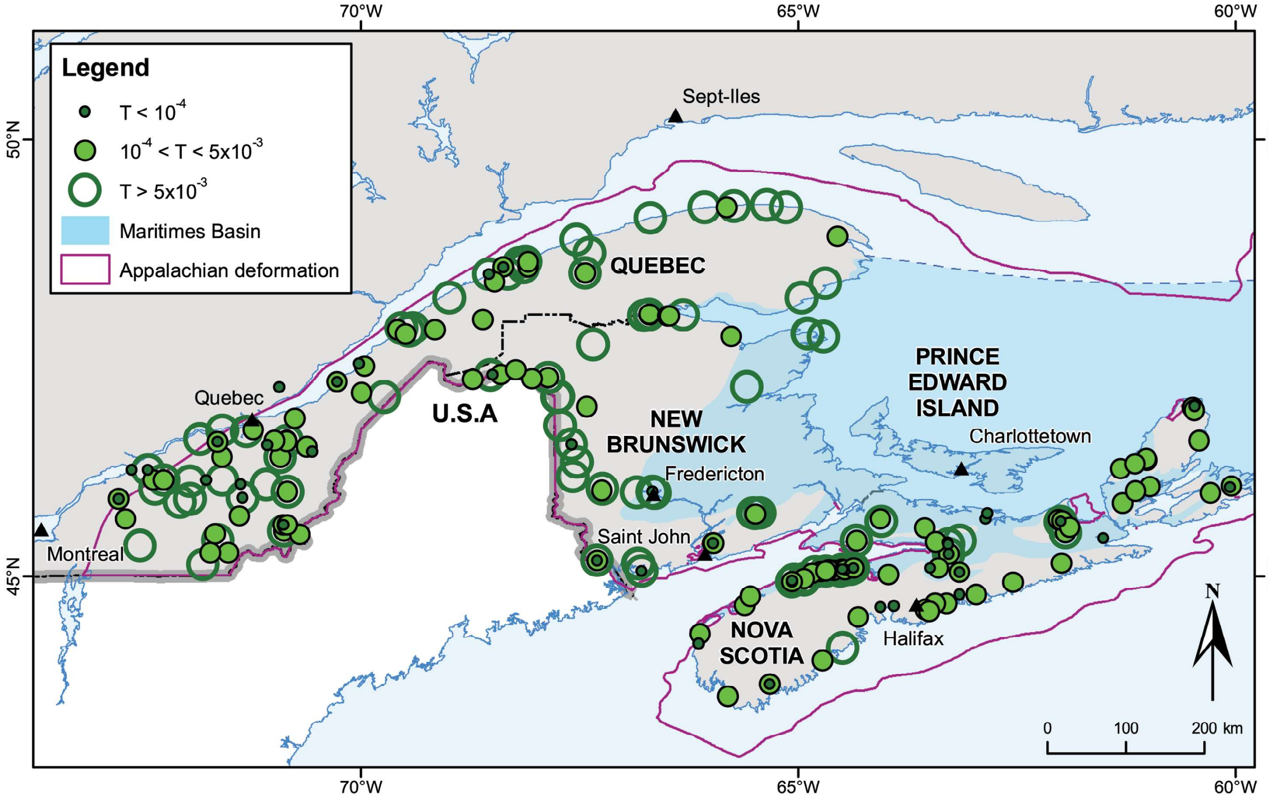

Figure 14.13 Spatial distributions of transmissivities (in m²/s) in surficial deposits (values classified into three ranges).

1992, 1999; unpublished data, University of New Brunswick, 2005).

Figure 14.13 shows that the high-permeability surficial deposits (sand and gravel) generally have T values higher than bedrock units for a given province, with medians varying between 10^{-3} and 10^{-2} m^2/s (see Figure 14.11a). Reported storage coefficients are typically higher than those for bedrock wells, with an overall average of 1×10^{-2}. This suggests that surficial aquifers may often be unconfined. Values are still quite variable, ranging usually between 10^{-4} and 0.5.

Tills are the most widespread surficial sediments within the Appalachian region, but they cannot provide high yields, mainly because of the broad grain-size distribution of their matrix, relatively high silt and clay content, and limited saturated thickness. Numerous permeameter tests (testing the first metre of soil) in the MGWI and Annapolis projects, have confirmed that these tills have a wide range of hydraulic conductivities, varying from 10^{-9} to 5×10^{-5} m/s (Boisvert, 2004; Rivard et al., 2012). Despite their poor capacity to deliver water to a well, tills play a major role in aquifer recharge, due to their ubiquitous presence, and to the fact that they generally act as a storage reservoir for bedrock aquifers. Indeed sandy tills have been shown to act as preferential paths for infiltration in the MGWI project (see section 14.4.4 for recharge values). Widespread expanses of till in Quebec's Appalachian piedmont are also believed to constitute significant regional groundwater recharge areas, particularly when they occur in low-relief regions and were reworked by wave action during the marine episode. Significant recharge is also inferred to occur locally in valleys of the Appalachian uplands (Lefebvre et al., 2011).

Till cover, because of its prevalent occurrence throughout the Appalachians, is thought to provide the main recharge pathways to bedrock aquifers. It is well known that tills exert considerable control over recharge rates, with sandier tills allowing higher recharge rates and silty/clayey tills significantly limiting recharge. Moreover, since storage capacity of many bedrock units (containing little or no primary porosity) is low, sustainable yields of some bedrock wells should decrease sharply when the water table lies below the till layer (Randall et al., 1988).

Based on these considerations, areas that could be regionally mapped as good potential aquifers are: the Maritimes Basin and areas located along major fault zones for bedrock (Figure 14.2) and alluvial, glaciofluvial, and coarse-grained marine deposits for surficial sediments (Figure 14.3). Other formations can be used for significant water supply, but their extent is limited and these do not appear as major features at the current Canadian Appalachian scale.

14.4.3 Groundwater levels and flow, well depths and yields

Most residential bedrock wells are 150 mm in diameter and average 30 m in depth; they are typically cased only through the surficial sediments and are of open hole construction except where friable wall-rock conditions, or known contamination problems, dictate greater casing lengths. Dug wells are usually less than 10 m deep and most often are made from 90 cm diameter precast concrete rings (referred to as crocks) that can store large amounts of water. Municipal and other high capacity, multi-user wells are typically in the order of 50 to 100 m deep for bedrock wells and, on average, less than 26 m deep for surficial wells (see Table 14.4 for provincial averages).

Average yields are highly variable for each province, varying from 0.25 L/s in Newfoundland to 11.4 L/s in New Brunswick for bedrock wells, and from 0.8 to 9.8 L/s for surficial wells. Values in Table 14.4 only include multi-user wells (thus excluding residential wells). From this table, both bedrock and surficial formations of Newfoundland appear

TABLE 14.4 SUMMARY OF MULTI-USER WELL CHARACTERISTICS FOR EACH PROVINCE

PROVINCE	NO. OF WELLS AVAILABLE	AVERAGE WELL DEPTH (M)	AVERAGE STATIC WATER LEVEL (M)	AVERAGE WELL YIELD (L/S)
BEDROCK				
New Brunswick	371	88.4	7.2	11.36
Newfoundland*	809	50.1	–	0.25
Nova Scotia	777	71.6	5.8	1.21
Prince Edward Island	72	70.4	7.2	13.3
Quebec	76	53	7.1	2.73
SURFICIAL **				
New Brunswick	93	21.3	4.0	1.64
Newfoundland*	8*	–	–	0.76
Nova Scotia	116	15.2	2.7	4.55
Quebec	95	26	3.2	9.83

* Values for Newfoundland correspond to averages obtained for a group of wells for a given municipality. "-" means that the value was not available.
** No high-capacity well taps surficial deposits in Prince Edward Island.

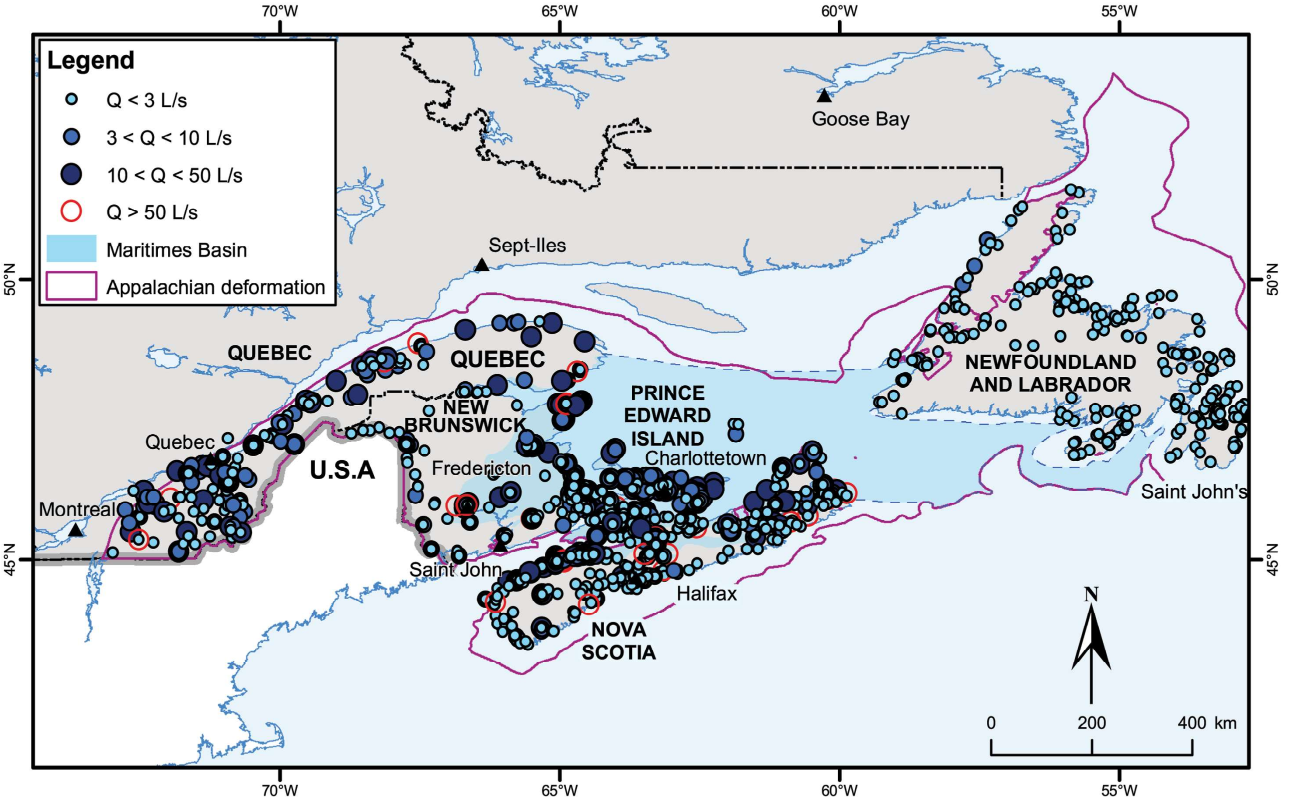

Figure14.14 Well yields from high-capacity (multi-user) wells, including both bedrock and surficial aquifers.

to be the least productive. Very few wells in this province have a yield larger than 3 L/s and very few tap surficial deposits (<1%).

Figure 14.14 presents well yields of high-capacity (i.e., multi-user) wells, from both bedrock and surficial aquifers. Therfore, the available information on well yields provides an approximate picture of groundwater withdrawals only for populated areas (where high yields are required). The yields used for Figure 14.14 were classified into four categories, according to their values. Most wells (63%) have a yield less than 3 L/s; only 21% have a yield higher than 10 L/s, and 2.7% above 50 L/s. In Newfoundland, typical yields are very small (less than 0.5 L/s), with slightly higher yields located in the Long Range Mountains.

Groundwater levels in the Appalachian region vary from flowing artesian conditions, to depths reaching as much as 50 m below the ground surface. Because of the fracturing and/or lenticular arrangement of beds, wells in fractured aquifers can show significant water level differences over a very short distance (revealing high vertical hydraulic gradients). In spite of this wide range of conditions, the water table is most often found within about 7 m from the surface, although usually deeper in high-relief areas.

Figure 14.15 presents the bedrock piezometric map produced by the MGWI project. Piezometric maps provide estimates of the spatial distribution of hydraulic heads and groundwater flow direction, based on water level measurements. They are key pieces of information and are typically one of the first outputs to be produced. Hydraulic heads are estimated by subtracting groundwater levels (depths) from ground surface elevations.

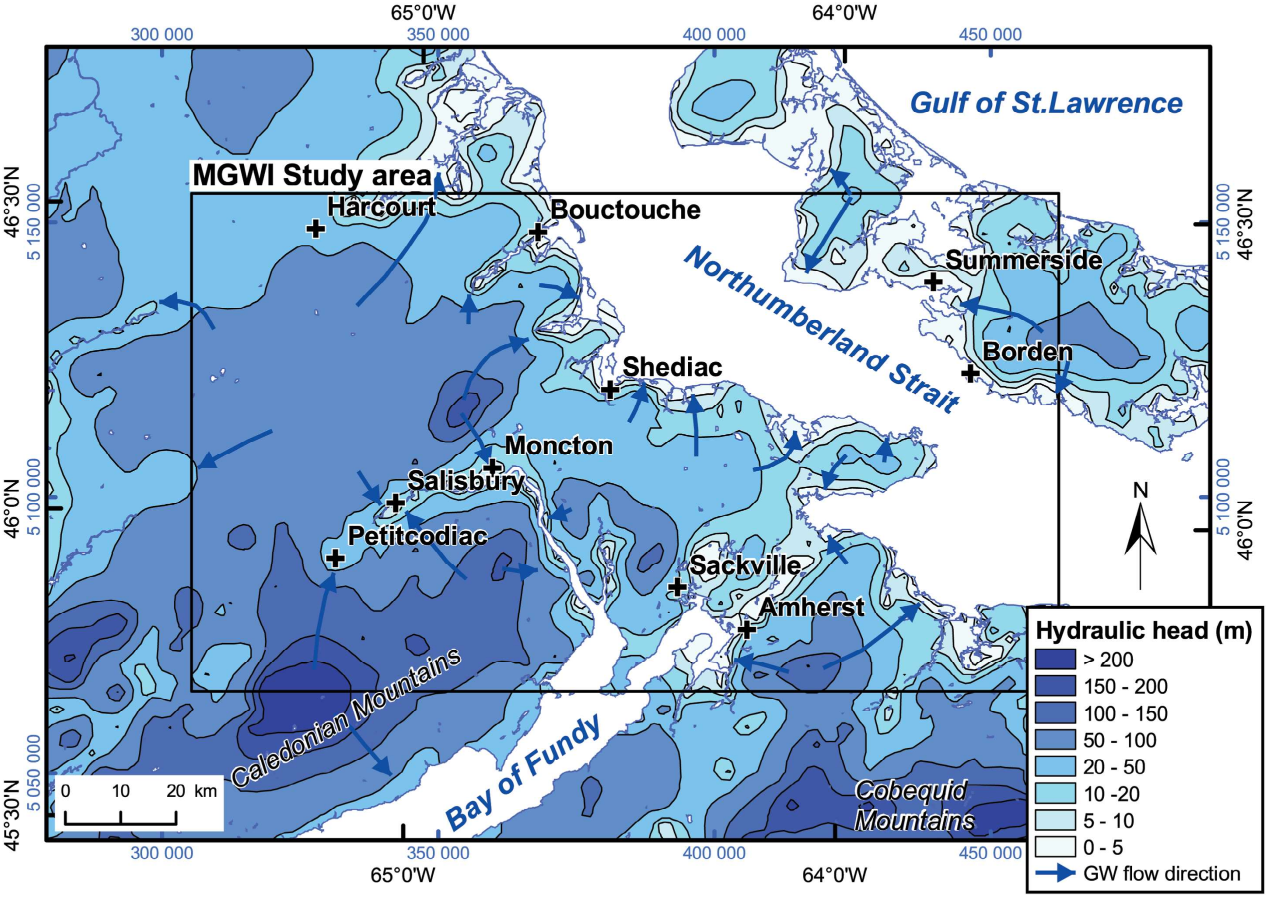

Figure 14.15 Piezometric map of the bedrock aquifers in the MGWI Project area of the Maritimes Basin (arrows indicate general flow directions) (adapted from Rivard et al., 2008).

Groundwater levels used for Figure 14.15 were collected from various sources, such as provincial databases, field campaigns and reports. Maps developed in the MGWI and Annapolis projects show that groundwater flow in bedrock aquifers is mainly regional and topographically driven (i.e., that water follows the topography), generally flowing toward the main river of a given watershed or to the ocean. Boundaries of individual groundwater flow systems essentially mimic surface watershed boundaries. These observations could likely be extended to a large part of the Maritimes Basin. Groundwater flow in the Appalachian piedmont is assumed to be mainly regional, and more local in the uplands; however, more work is necessary to confirm the role of valleys in the piedmont (Lefebvre et al., 2011).

The proportion of groundwater discharge to rivers may be quantified from river hydrograph separation. It is estimated that groundwater discharge in the Appalachian region accounts for about 60%, and maybe even up to 70%, of annual stream flow (Randall et al., 1988; Benson et al., 2007; Rivard et al., 2012). Many municipal wells are, or used to be, located in close proximity to streams and rivers to ensure that enough water was available for well recharge, and also because granular formations are often present along such water courses. Recharge to the Saint John River valley aquifers, for example, is often dominated by pumping-induced influx of river water, contrary to more regionally-extensive aquifers. This is the case for Fredericton, the largest municipality within the Canadian Appalachian region to use groundwater from surficial deposits exclusively. Hodder and MacQuarrie (2004) have noted that this form of recharge is also likely dominant for the Grand Falls, Edmundston, Perth/Andover and Woodstock municipal aquifers of New Brunswick. It has been estimated that 66% to 70% of recharge to the aquifer supplying the Fredericton well field was derived from the Saint John River (Violette, 1990; Thomas et al., 1994).

It is a known fact that microbial pathogens can travel from surface water to a nearby pumping well. Some provinces (notably New Brunswick, Nova Scotia and Quebec) have established detailed investigation procedures to evaluate any potential hydraulic connection and to test whether particulates or bacteria which might be present in the well water would be indicative of surface water influences (called "GUDI" conditions, i.e., Groundwater Under the Direct Influence of Surface Water). Such conditions may affect the design or construction of a treatment plant.

14.4.4 Water budgets

A water budget reflects the relationship between input and output of water through a region. It is crucial information to have in order to support the development of a water management plan. Values for the individual parameters included in a water budget, however, can vary widely and may be difficult to estimate with accuracy, especially for recharge. Several methods are normally used to obtain ranges for each budget parameter. Precipitation is high in the Appalachian region, on the order of 1,150 mm/year (even more for Nova Scotia), and till at the surface usually allows a fair amount of this water to infiltrate. Therefore, it is often (erroneously) assumed, in initial estimates, that evapotranspiration, surface runoff, and infiltration each represent one third of available water. This fraction may not adequately reflect the infiltration rate, however, depending on parameters such as slope of the ground surface, soil texture, timing and intensity of precipitation, and land use. Furthermore, not all the infiltrated water reaches bedrock aquifers, which means that recharge to the regional aquifer is often much less than 33% of precipitation, except where permeable deposits overlie permeable rocks. In general, aquifers supply water to streams in eastern Canada, even during the summer. Figure 14.16 presents a summary of plausible value ranges for the Maritimes Basin water budget.

According to Peters (1981), the proportion of the total precipitation that infiltrates the Maritimes Basin varies from 1% to 50%, and as much as half of this infiltration is expected to occur during the spring period. The MGWI study estimated recharge to bedrock between 130 and 165 mm/year over the entire study area (varying from 300–400 mm/year over Prince Edward Island to ~22 mm/year over the basement Complex). This represents 13% of precipitation on average.

Estimated values of infiltration for the Annapolis study ranged from 73 to 430 mm/year, with a probable average bedrock recharge over the entire study area of 80–175 mm/year (Rivard et al., 2013a). Recharge to bedrock aquifers represented approximately 7%–15% of the precipitation, whereas recharge to sand and gravel aquifers (probably close to the upper limit, i.e., 350–400 mm/year), represented about one third of total precipitation. In both studies, recharge rates were

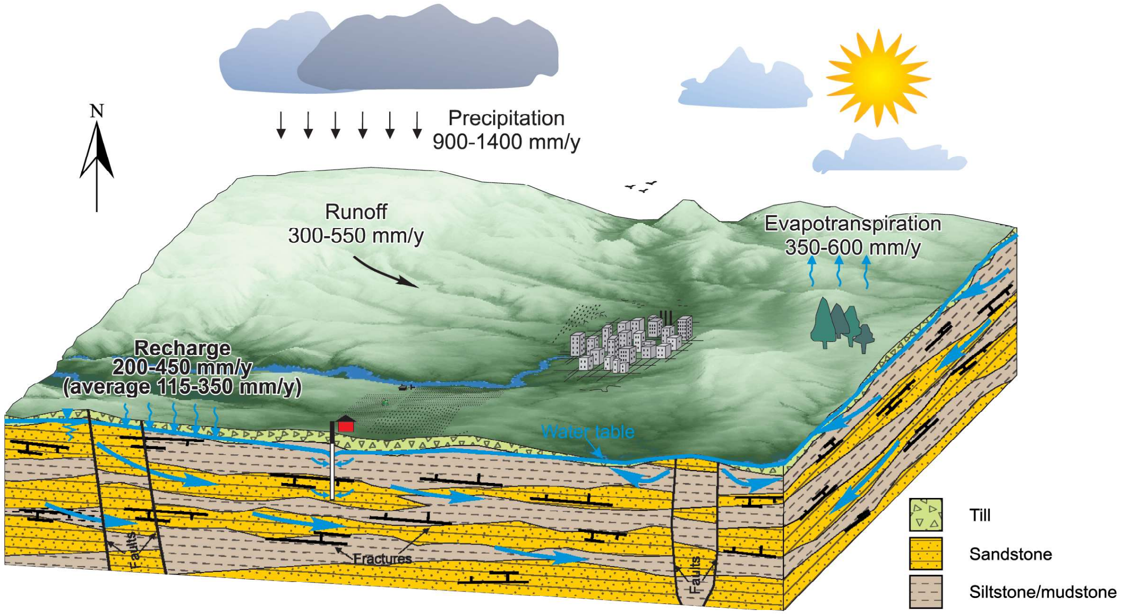

Figure 14.16 This schematic depicts representative ranges for water budget parameters of the Maritimes Basin. Recharge over large regions would be on the order of 115 to 250 mm/year, but can reach 300 to 400 mm/year on Prince Edward Island (adapted from Rivard et al., 2008).

evaluated using three approaches: hydrograph separation, water balance method, and modelling. The highest values were obtained using river hydrograph separation. However, recharge rates estimated by this method commonly reflect groundwater circulation through till and thus, may overestimate recharge to bedrock (Randall et al., 1988) when tills are saturated.

Local studies in New Brunswick have provided recharge values of 15% and 13% of precipitation for the town of Sussex and the Fredericton area, respectively (Jacques Whitford Environment Ltd., 1995; Gemtec Ltd. and FGA Ltd., 1994). Brown (1971) estimated the recharge rate near Shippagan (Taylor Island, in northern New Brunswick) to be 500 mm/year, where till is generally very thin (0.5 m) or absent, and rocks are highly fractured and weathered in the uppermost part. For Prince Edward Island, Francis (1989), using hydrograph separation, estimated that the recharge rate of the central portion of the island should be between 21% and 43% of annual precipitation, while Jacques Whitford and Associates Ltd. (1990) suggested 30% as a mean value for the entire island. On Îles-de-la-Madeleine, all reported values provided a recharge close to 230 mm/year (Groupe Madelin'Eau, 2004), also representing approximately 30% of precipitation. The minimum annual groundwater recharge in Nova Scotia was estimated between 125 mm to 150 mm over a watershed (the province being divided into 44 watersheds), or approximately 10% of the mean annual precipitation (Nova Scotia Museum of Natural History, 1996). Using the same 44 watersheds, Kennedy et al. (2010) have also recently presented recharge and groundwater use values for the province. Recharge values, illustrated in Figure 14.17, were based on baseflow estimates; they provided values ranging from 14% to 25% of total precipitation. Values reported in an NSE (Nova Scotia Environment) database, range from 8% to 30%, depending on the local context. All values are summarized in Table 14.5.

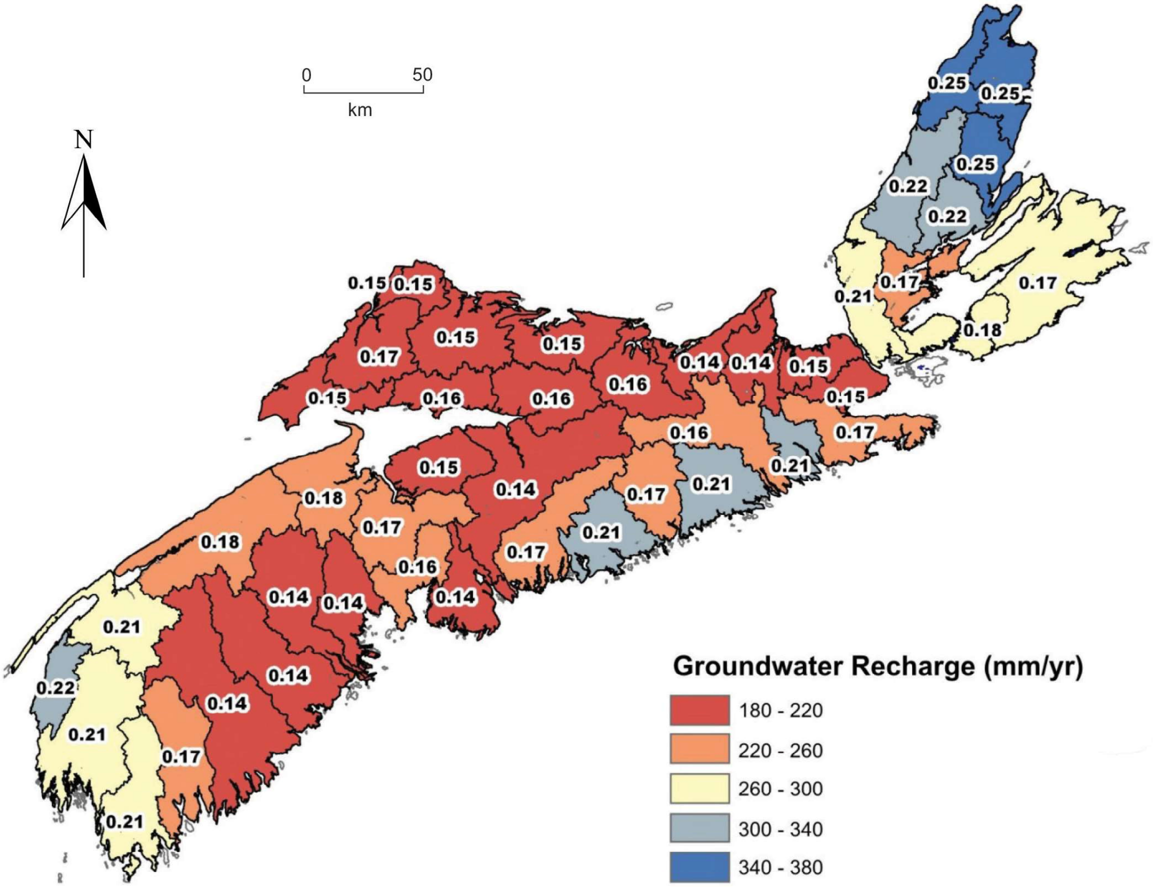

Figure 14.17 Estimated groundwater recharge across Nova Scotia (taken from Kennedy et al., 2010). Recharge ratios are also provided inside each watershed.

Recharge rates are important information for the management of groundwater resources, although, by themselves, are not sufficient to determine sustainability: the effects of changes in groundwater level on groundwater discharge rates, and aquifer storage, must also be considered (Healy, 2010). Sustainable yields must be estimated using ecological, demographical, economical, and cultural considerations. The percentage of groundwater demand (or use) as a fraction of recharge is an important parameter and is required in order to estimate the sustainability of any groundwater resource.

Although first-order estimates of groundwater use in each province are available, these values are usually less well known at the local scale, and little or no information is available on spatial distribution. Recently, Nova Scotia has made an effort (Kennedy et al., 2010) to estimate groundwater usage at the provincial scale using three major types of groundwater users (municipal, residential, and others) in 44 watersheds, based on methodology developed during a pilot study in the Annapolis Valley (CBCL Limited, 2009).

Results of the MGWI and Annapolis regional studies did not indicate overexploitation on a regional basis. Overall groundwater use in the MGWI study was estimated to be on the order of 5% of recharge. As a result, groundwater extraction in many regions could probably be increased

TABLE 14.5 SUMMARY OF REPORTED RECHARGE VALUES

LOCATION	RECHARGE RATE* (%)	SCALE	SOURCE
New Brunswick	1–50	Provincial	Peters, 1981
Nova Scotia	Min=10	Provincial	Nova Scotia Museum of Natural History, 1996
Nova Scotia	8–30	Provincial	NSE database
Nova Scotia	14–25	Provincial	Kennedy et al., 2010
Prince Edward Island	21–43	Provincial	Francis, 1989
Prince Edward Island	30	Regional	Jacques Whitford and Associates. Ltd., 1990
Maritimes Basin (MGWI study)	13	Regional (10,500 km^2)	Rivard et al., 2008
Annapolis Valley, NS	11–15	Regional (2,100 km^2)	Rivard et al., 2007; 2012; 2013a
Îles-de-la-Madeleine, QC	30	Regional	Groupe Madelin'Eau, 2004
Chaudière, QC	6	Regional (3,615 km^2)	Benoit et al., 2008
Sussex, NB	15	Local	Jacques Whitford Environment Ltd., 1995
Fredericton, NB	13	Local	Gemtec Ltd. and FGA Ltd., 1994
Shippagan, NB	50	Local	Brown, 1971

* In % of total precipitation. All values are for bedrock aquifers, except for Sussex and Fredericton, which are surficial aquifers.

significantly without jeopardizing other activities and natural habitats. Literature-based water use surveys for the Annapolis Valley, together with regional estimates, provided preliminary groundwater use estimates ranging from 3% to 42%, with an average at 21.5%, of the overall recharge to bedrock. These values were later refined in a consultant report carried out using questionnaires and existing data from the provincial database (CBCL Limited, 2009). Based on numbers provided in this report, groundwater use for the area represents about 7% of recharge, lying at the lower end of the range estimated by the Annapolis study. However, groundwater use, in the more populated and intensely farmed areas of the eastern part of the Valley, likely reaches more than 50%, a matter of some concern to local authorities because of the possible impacts of groundwater level lowering, including decreasing baseflow rates and altered aquatic habitats. Kennedy et al. (2010) found that groundwater use throughout Nova Scotia may range between 0.1% and 13% of recharge. As stated by these authors, although groundwater use seems to be significantly less than groundwater recharge on a regional scale, groundwater quantity issues are demonstrated in the province by the increasing number of water servicing requests and well modifications to improve yield.

Groundwater/surface water use should be known with a fair degree of confidence prior to developing an effective water management plan. Currently, this is an evident knowledge gap that must be addressed in the near future, especially in view of predicted population growth, economic development, and climate change that are expected to exert more pressure on groundwater resources, especially those in coastal areas in future years.

14.4.5 Monitoring wells and long-term behaviour

All Canadian provinces have numerous monitoring wells to observe groundwater level changes on

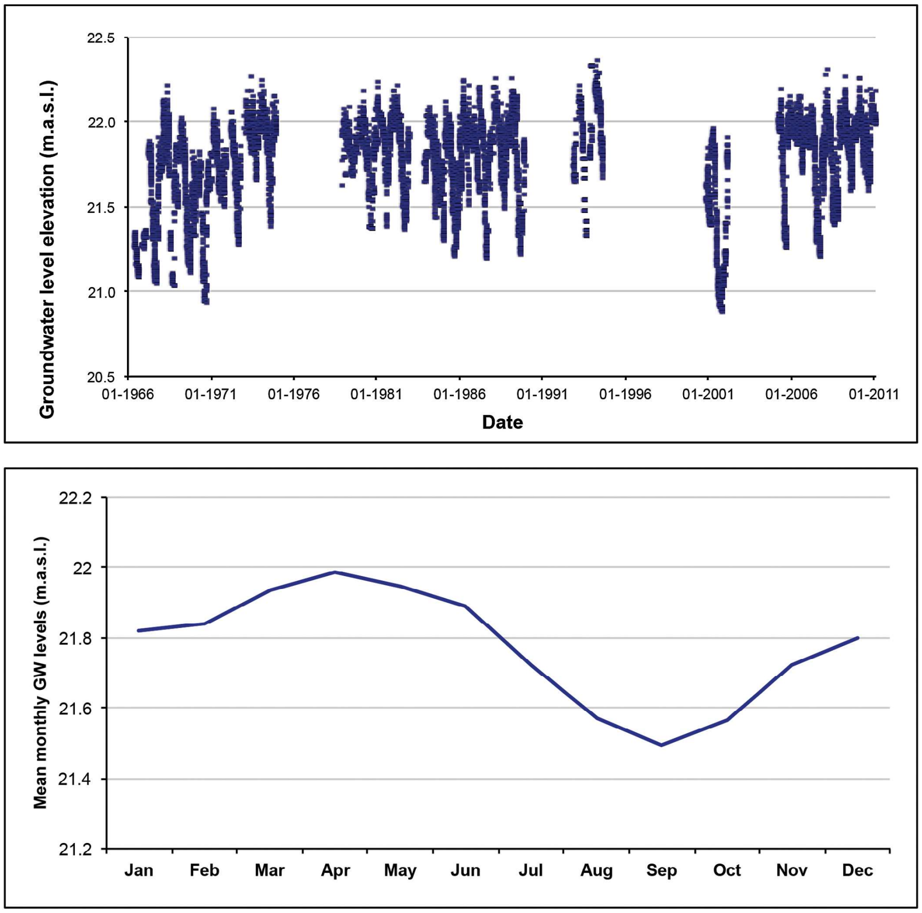

Figure 14.18 Historical data of groundwater levels from a provincial monitoring well in Greenwood, Nova Scotia a)on a daily basis; b) on a monthly basis, averaged over the entire record.

a long-term basis. The length of these records, and the number of short- and long-term data gaps, vary widely, and the specifications of these monitoring wells are not always fully documented. Several well monitoring programs were abandoned in the 1980s and 1990s due to budget constraints. In the Appalachian region, Quebec currently has 9 active monitoring wells (with 17 new wells soon be added, consult http://www.mddep.gouv.qc.ca/eau/piezo/index.htm), New Brunswick has 10, Nova Scotia has 38, Prince Edward Island has 13, and the island of Newfoundland has 10. Many of these monitoring wells are quite recent (installed after the year 2000) and most are now equipped with automated data-loggers. The number of observation wells appears to be low, at least in some areas, for such a diverse hydrogeologic region.

Mean annual water-level fluctuations typically range from 1 to 4 m (McIntosh, 1984; Francis, 1989; New Brunswick Department of the Environment, 1992). Well hydrographs usually show water-level responses to seasonal patterns: a major spring recharge event followed by a decline during the summer, a smaller recharge event during the fall, and, finally, a decline during the winter. Some recharge events, caused by winter thaws and rainfall, may take place during winter in coastal areas and areas with micro-climates (e.g., Annapolis Valley, Nova Scotia). Figure 14.18a charts an example of a daily hydrograph from a monitoring well located in a sand and gravel unit in Greenwood, Nova Scotia; Figure 14.18b shows monthly fluctuations estimated over a year, using the entire record (28 years).

A Canada-wide study by Rivard et al. (2009) employed trend statistical analysis of historical series of baseflow and groundwater levels as long-term recharge indicators, based on the commonly used non-parametric Mann-Kendall test. Series of 30, 40, and 50 years were selected. Although mixed trends were often observed across Canada, both baseflow and groundwater level data evidenced either no trend, or decreasing trends in

Atlantic Canada (and thus in the Appalachians), suggesting a recharge decrease within the region. Only six monitoring wells in the region had sufficiently long series, and four of those (two in PEI and two in NS) showed downward trends. Following this statistical study, a modelling exercise was carried out in the Annapolis Valley using the quasi-2D hydrological model HELP, and climate scenarios from a regional climate model, to define plausible projected ranges of both inter- and intra-annual variability (Rivard et al., 2013b). The model runs predicted an increase in annual recharge over the 2041–2070 period, contrary to the historical trend. However on a seasonal basis, a significant recharge decrease was observed during the summer, mainly due to a drop in precipitation, consistent with historical trends, while winter recharge increased over the same period in response to a temperature increase. These results are in general agreement with modelling studies such as those of Jyrkama and Sykes (2007) and Toews and Allen (2009) for other parts of Canada. Discrepancies in results based on the two approaches (statistical and modelling) may be due to the fact that historical series may not be representative of future climatic trends, or perhaps, to large uncertainties (both hydrological and climatic) within the models.

14.4.6 Groundwater quality

14.4.6.1 General groundwater quality and naturally occurring ions

Groundwater quality is generally excellent throughout most of the Canadian Appalachians. Natural groundwater quality used for water supply purposes usually meets Canadian drinking water guidelines (Health Canada, 2010), although concerns have been raised over the past few years regarding naturally occurring fluoride, arsenic, and uranium concentrations, and, to a lesser extent, iron and manganese concentrations. Most of these concerns are related to agricultural pollution, leaks from hydrocarbon-storage tanks, sewage and waste disposal, induced seawater intrusion, and road deicing activities. Several major and minor ions, trace metals, hardness, acidity (pH), and total dissolved solids (TDS) were mapped during the MGWI and the Annapolis projects. The results are available in atlases (Rivard et al., 2005, 2007). Hydrogeochemical data for these projects was provided largely from provincial databases. The New Brunswick Department of Environment has published a groundwater chemistry atlas depicting 28 general chemical parameters in private drinking water wells compiled from 1994 to 2007 data (New Brunswick Department of Environment, 2008). A geochemical study of the Montérégie Est area (Beaudry, 2013) that includes contexts 1 and 2 (see section 14.3 Hydrogeological contexts) defined different water types based on recently collected data, which helped better understanding groundwater flow.

Until recently, the occurrence of iron and manganese was not thought to be a threat to health, and most information collected about these metals was largely concerned with aesthetic limits. Contemporary studies, however, suggest a potential link between elevated Mn concentrations and the intellectual impairment of children (Wasserman et al., 2006; Bouchard et al., 2011). Aesthetically, elevated Mn concentrations give water a metallic taste, in addition to posing problems for laundry (black stains) and pipes (clogging). As a result, these concentrations must be lowered. Production wells in the Fredericton aquifer produce groundwater that may contain dissolved manganese concentrations

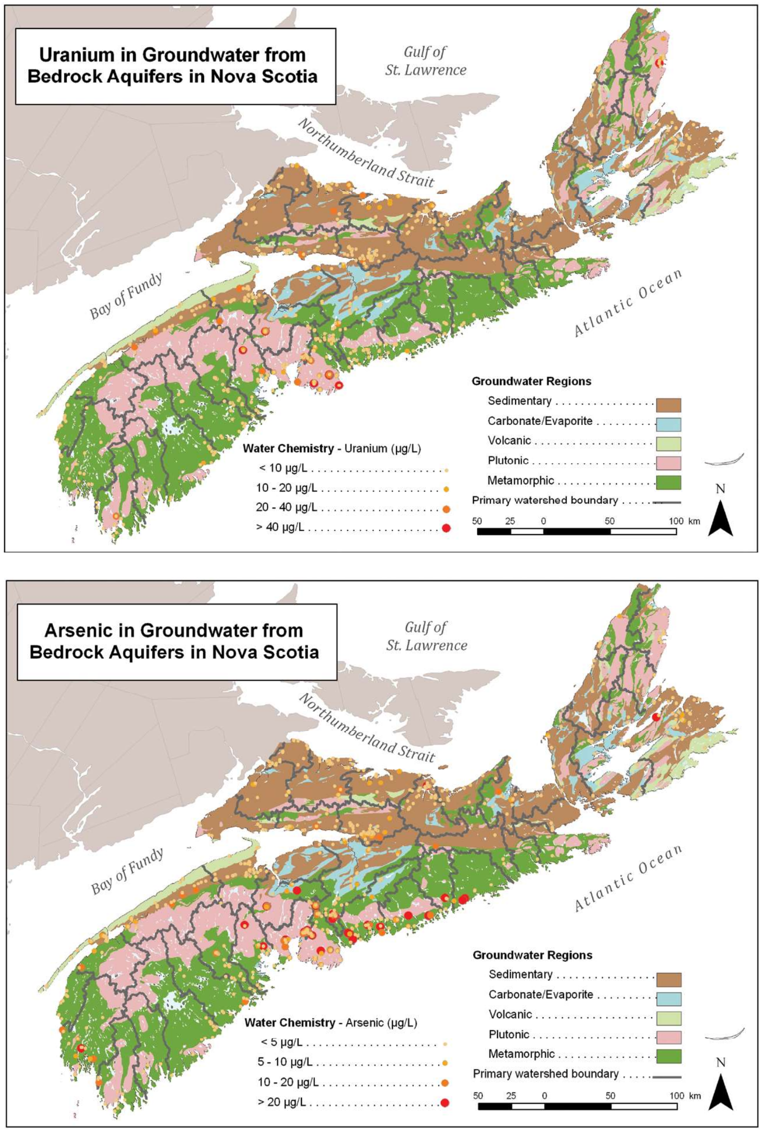

Figure 14.19 Natural occurrence of uranium and arsenic in Nova Scotia groundwater (taken from Kennedy and Finlayson-Bourque, 2011a, 2011b).

up to approximately 2 mg/L (Thomas et al., 1994), whereas the aesthetic objective is 0.05 mg/L (see Box 14-2). The water must be treated to remove manganese prior to distribution.

Elevated concentrations of fluoride, arsenic, and uranium are known to have impacts on human health. These elements are present in drinking water when groundwater dissolves the minerals that carry them. Fluoride, arsenic, and uranium are more likely to be found in drilled wells than in surficial wells, because they are present in different types of rocks and because the reducing conditions (low redox potential), more typical of bedrock groundwater, maintain them in solution (Fe^{2+}, Mn^{2+}). In sparsely located areas, such as in the municipality of Maria, in Gaspésie, and some municipalities east of Montreal, in Montérégie Est (Québec), fluoride concentrations exceed the acceptable drinking water limit of 1.5 mg/L; this is also true of areas along the Petitcodiac and Saint John Rivers, and the coast of Baie des Chaleurs in New Brunswick. Arsenic problems have been documented in a few areas of New Brunswick (on the Kingston Uplift) and Quebec (Saint-Gédéon in Beauce and Kingsbury in Estrie). Occurrences of slightly elevated arsenic and uranium concentrations in groundwater are relatively common in Nova Scotia, New Brunswick, and Newfoundland,. Nova Scotia has mapped the spatial distribution of these parameters (Figure 14.19), while Newfoundland has mapped areas of their potential occurrence (Figure 14.20). In Nova Scotia, arsenic concentrations most commonly exceed the drinking water guideline in metamorphic rock, whereas uranium concentrations most commonly exceed the guideline in plutonic rock.

When a well is constructed in New Brunswick, sending water samples to the Department of Environment is mandatory, whereas in Nova Scotia and Prince Edward Island, water analyses on private wells are provided to the government on a voluntary basis, except in the case of public

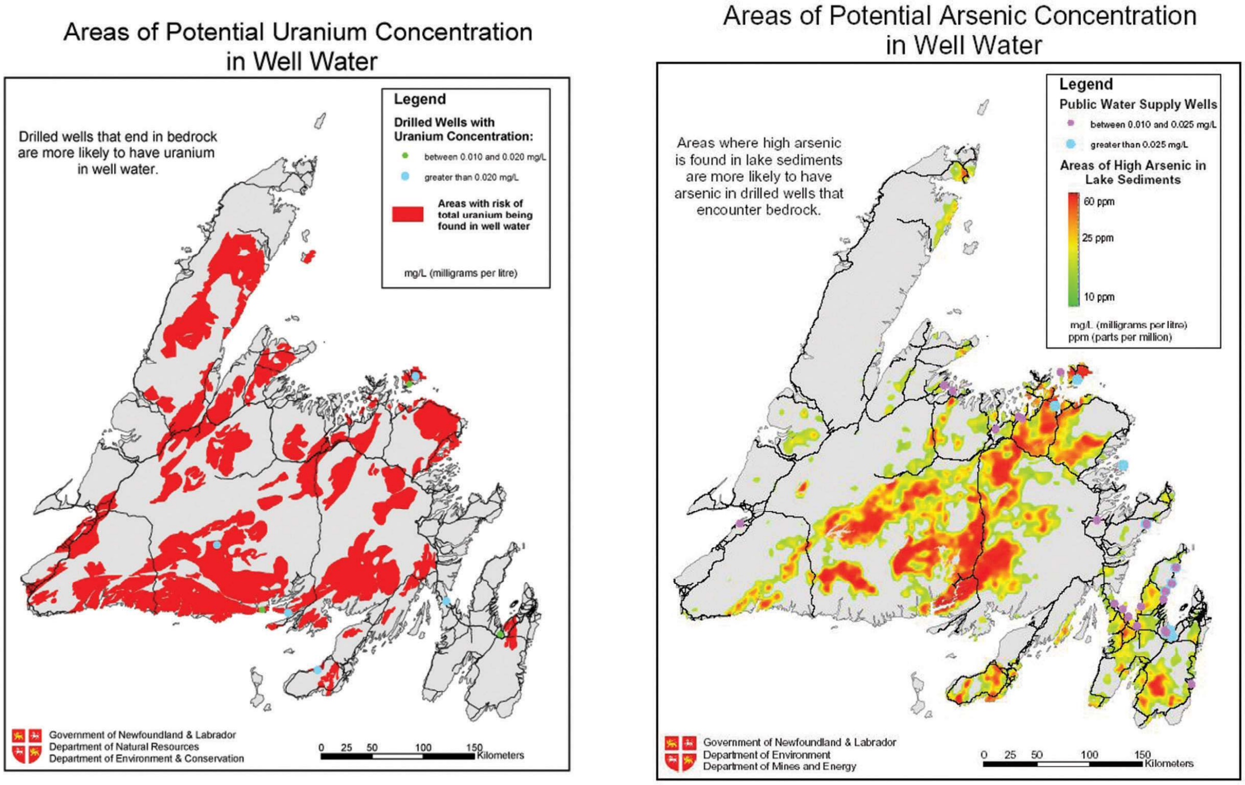

Figure 14.20 Areas of potential uranium and arsenic concentrations in well water (taken from NL Department of Environment and Conservation website http://www.env.gov.nl.ca/env/waterres/cycle/groundwater/well).

drinking water supplies where these analyses are mandatory. Some 5% of all drilled water wells in Newfoundland are randomly sampled during routine provincial inspections of new wells; this helps provide the province with a representative picture of groundwater quality. All municipal wells in Quebec are closely monitored and water analyses have been mandatory for all new wells since 2003.

Figure 14.21 presents a Piper plot of geochemical data compiled from public wells in four provinces (Nova Scotia, New Brunswick, Prince Edward Island, and Quebec). All analytical procedures available after the 1980s have been used to calculate medians, with the results classified according to exploited aquifer. Therfore several analyses are usually applicable for any given well.

Groundwater flowing in porous sedimentary bedrock typically has a higher total dissolved solids content, alkalinity, and hardness than water that flows through fractured rocks with low primary porosity, and water flowing through surficial sediments, mainly because of greater potential mineral dissolution, and longer residence times. In the Maritimes Basin, however, groundwater flowing through bedrock usually seems to be moderately to weakly mineralized, and thus, groundwater circulating in igneous and metamorphic rocks has a similar concentration of dissolved chemical species (Figure 14.21). This may be due to the fact that the siliciclastic rocks which constitute most aquifers are chemically stable and that most wells are supplied by relatively shallow, young water. Tritium dating results from Nova Scotia monitoring wells seem to corroborate the latter assumption, since only 5 of the 18 wells showed water older than 1954. Multi-level tritium dating in a 85 m deep well near

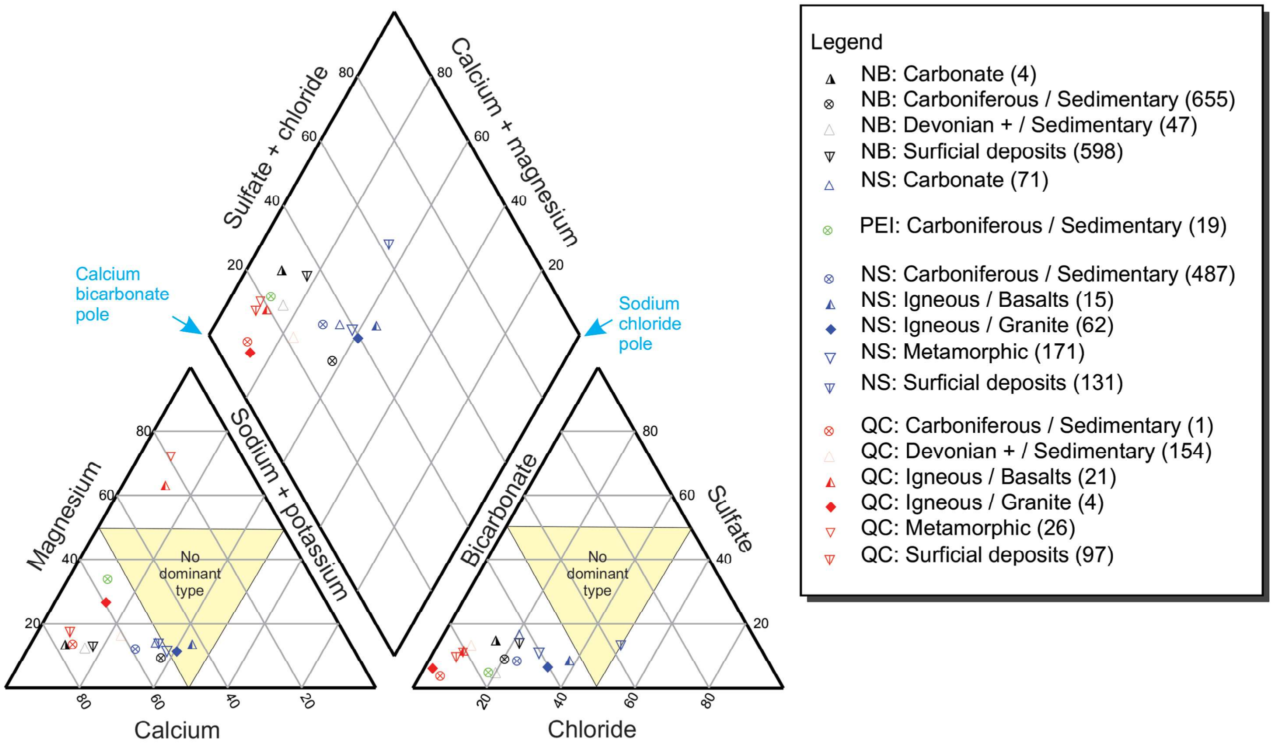

Figure 14.21 Piper plot of median water quality values for surficial deposits and bedrock types in Nova Scotia, New Brunswick, Prince Edward Island and Quebec. In the legend, "Carboniferous" is used to represent Carboniferous and younger rocks, whereas "Devonian +" refers to Devonian and older rocks.

Wilmot, Prince Edward Island, indicated a shallow (≈50 m) zone with tritium presence (therefore less than 50 years of age); carbon 14 analyses indicated older water (5,000–7,000 yr) for the lower 50 to 85 m of that well (Paradis et al., 2007).

Groundwater in the Appalachian region appears to be either of the calcium-bicarbonate type or to have no dominant type. Water from Quebec wells comes closest to the calcium-bicarbonate pole, while water from Nova Scotia wells is the furthest (closer to the middle, i.e., no dominant type). Groundwater found on Prince Edward Island's western side is typically of the calcium-bicarbonate (Ca-HCO$_3$) type, which can be attributed to calcite cements. Groundwater in the central and eastern portions of the island is characterized by Ca-Mg-HCO$_3$, attributed to dominantly dolomitic cements (Somers et al., 1999). Sedimentary rocks in provinces of NB, NS, QC or PEI tend to be closest to the calcium-bicarbonate pole, likely due to dissolution of the dolomitic cement which binds the sandstone dominating horizons where water is tapped. Water in surficial deposits and basalts usually has the lowest bicarbonate content (or alkalinity), whereas sedimentary and carbonate rocks have the highest. Chloride and sodium concentrations are normally low in bedrock, but can increase in coastal areas or in specific local regions because of evaporites (such as in the Windsor Group) or other minerals contained in rocks, or because of depth. Sodium-chloride type water is present at varying depths near the coast (<500 m).

Except for waters from carbonate rocks that are more highly mineralized, compiled data show that groundwater typically has total dissolved solids (TDS) ranging from 130 to 200 mg/L, hardness varying between 50 and 150 mg/L, and a conductivity less than 400 µS/cm (see the example for Nova

Scotia in Figure 14.22, that may be considered representative of the geochemistry across the study area for these rock types). The mean acidity (pH) approaches neutral, but is usually slightly alkaline, between 7 and 8, probably quite representative of most rock units in the Canadian Appalachians. As a comparison, median TDS of fractured nonporous bedrock was reported to be on the order of 115 mg/L, and 220 mg/L for porous sedimentary bedrock in New England (USA), a region that also belongs to the northeastern Appalachians (Randall et al., 1988). Water in surficial sediments shows values similar to those of less mineralized igneous and metamorphic rocks.

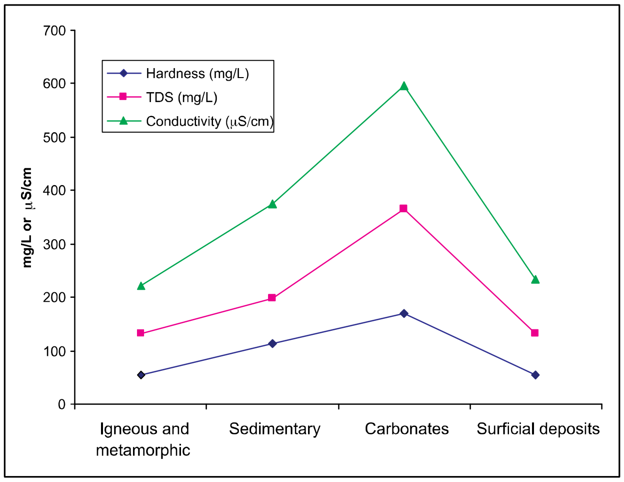

Figure 14.22 Median values for hardness, TDS, and conductivity in Nova Scotia.

14.4.6.2 Point source and diffuse pollution

Diverse point source contaminants have affected a number of municipal and residential water supplies within the Appalachian region. One of the most famous contamination cases is the Tar Ponds in Sydney, Nova Scotia. One hundred years of steel and coke production left more than a million tonnes of contaminated soil and sediment in the estuary, thereby affecting groundwater. Acid rock drainage has also been a cause of surface water and groundwater contamination in some areas of New Brunswick and Nova Scotia. The issue of acid rock drainage has been encountered not only at mine sites, but also in construction projects such as highways and the Halifax Airport. Populations located along coastlines are also at risk for saltwater intrusion, especially during the summer months when pumping increases significantly due to tourism-related activities.

Cases of municipal well groundwater contamination as a result of human activities include Sussex, New Brunswick, where groundwater in a sand and gravel aquifer in the Kennebecasis River valley was contaminated by the solvent perchloroethylene (or PCE, Broster and Pupek, 2001); and Miramichi in New Brunswick, where water was contaminated by polycyclic aromatic hydrocarbons (PAHs) believed to be linked to a pressure-treated wood facility. Industrial and commercial activities have also led to local contamination. These can be associated with deicing salts (storage or application); bacteria (e.g., Haldimand and Sandy-Beach area in Gaspésie, Quebec); organic contaminants (Trichloroethylene, or TCE, linked to a solvent bottling plant near Granby and TCE associated with tool production at Roxton Pond, Quebec); PCE from a dry cleaning business in the Greenwood area, Nova Scotia; and petroleum products from inappropriate storage or storage facility leaks as in Cap-aux-Meules on Îles-de-la-Madeleine, Quebec, in Kensington and Tignish, Prince Edward Island, and in Greenwood and Nictaux Falls, Nova Scotia.

Microbiological results from New Brunswick private wells suggested that, on average, approximately one third of wells may currently be affected, or have been affected at one time or another, by total coliforms, while 2.5% (of 4,823 wells) indicated the presence of *E. coli* (New Brunswick Department of

Environment, 2002). Similar numbers were found for the 2000–2009 period in Prince Edward Island (PEI Department of Environment, Energy and Forestry, 2011), while the presence of *E. coli* was observed in 8.8% of the 274 tested wells in the Chaudière watershed (6,682 km^2, Gouvernement du Québec, 2004). The main causes for the presence of total coliform organisms in a well include lack of well disinfection and direct surface water infiltration into poorly constructed wells. The presence of *E. coli* is likely attributable to malfunctioning or improperly maintained sewage disposal systems.

Diffuse (or non-point source) pollution can be a problem in a few locations, especially in intensive agricultural regions. In some areas of Prince Edward Island, in the upper Saint John River valley in New Brunswick, Montérégie Est in Quebec, and in the Annapolis Valley in Nova Scotia, problems related to farming activities are of great concern, particularly nitrate contamination.

Pesticides, while of great public concern, do not seem to be as large a problem, although they have been found to occur in groundwater at low concentrations, typically well below levels of health concern (Briggins and Moerman, 1995; Keizer et al., 2001; MDDEP, 2010; Mutch et al., 1992). There are exceptions, such as the study conducted by Priddle et al. (1989) between 1985 and 1988 beneath two potato fields on Prince Edward Island. Total aldicarb concentrations in this study exceeded maximum acceptable concentrations in 12% of 48 monitoring well samples at certain times of the year. A province-wide study of wells in Prince Edward Island, which sampled approximately 100 drinking wells annually, showed a gradual increase of pesticide detection incidences, from 7% in 2004 to 16% in 2009, with the exception of 2008 where 10% were found (PEI Department of Environment, Energy and Forestry, 2011).

Nitrate concentrations exceeding the 10 mg/L NO_3-N guideline have been found in 4.5% of Prince Edward Island's wells, and in more than 10% of wells in intensively farmed watersheds. 15% of wells in the Annapolis Valley exceed the 10 mg/L NO_3-N guideline (Rivard et al., 2012). The percentage of tested wells exceeding ambient (or natural) concentrations probably provides a more accurate picture of groundwater degradation, as it highlights those wells already affected by anthropogenic activities (suggesting possible increases in subsequent following years, should corrective measures not be taken). Accordingly, 81% of the wells for Prince Edward Island and 65% of the wells for the Annapolis Valley exceed 1 mg/L. These percentages have generally been attributed to intensive agricultural activities, and to the absence of significant attenuation, such as de-nitrification, in the underlying tills or bedrock.

An opposite situation occurs in Quebec's Appalachian piedmont region, where excess nutrients derived from intense farming operations have significantly impaired surface water quality (with the result that the Yamaska River is widely known as the province's most polluted river), yet, to date, groundwater does not seem to be significantly impacted (Lefebvre et al., 2011; Beaudry et al., 2011a). It has been suggested that this is due, at least in part, to the presence of dense, compact till underlying looser, more permeable reworked till at the surface, and to the dense network of collector drains that evacuate water rapidly from the subsurface (Thériault et al., 2013). Additionally, fertilizer contamination may be too young (less than 60 years) to have reached the deeper bedrock wells. This particular issue is currently under

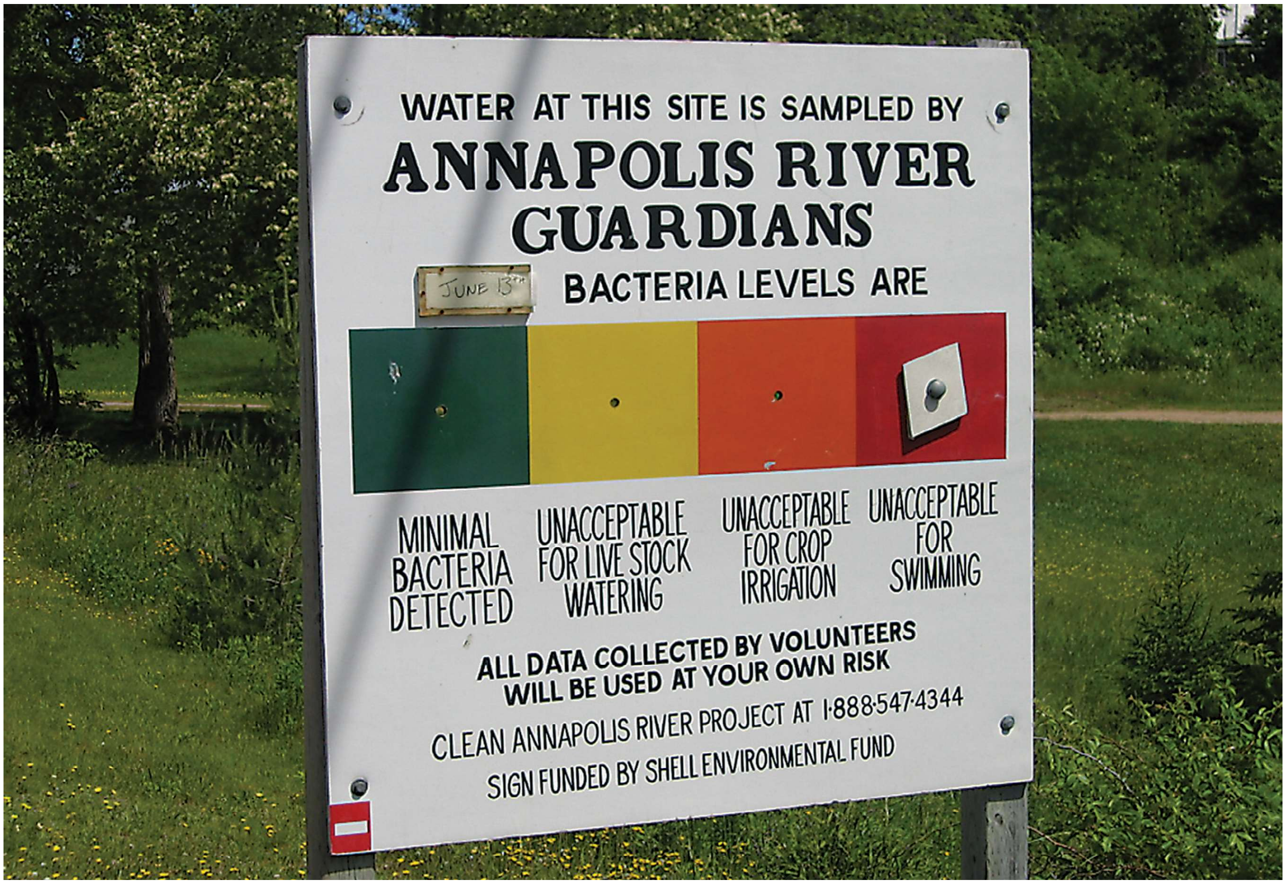

Figure 14.23 Indication of the surface water quality in the Annapolis Valley, Nova Scotia (summer 2004).

investigation as part of a regional hydrogeological study (Lefebvre et al., 2011; Beaudry et al., 2011a).

A recent study on the nitrogen cycle conducted in a region of intensive row crop production in Prince Edward Island found that nitrates in groundwater come mainly from chemical fertilizers, or mineralization and nitrification of plant residues (depending on season), and, to a lesser extent, from manure, and septic systems (Savard et al., 2007). Relative importance of specific nitrate sources in other rural regions may be expected to change, according to different land use characteristics, such as crop or livestock production.

Other concerns about nitrates and bacteria are usually related to poorly constructed or maintained septic systems, the density of these systems, and removal of riparian vegetation by agricultural and forestry operations. Elevated nitrate concentrations attributed to septic system malfunctions (Groupe Madelin'Eau, 2004) are found on Îles-de-la-Madeleine, especially in Pointe-aux-Loups and Île d'Entrée.

Surface water quality may also reflects groundwater deterioration because a significant portion of surface water is derived from baseflow. Surface water in the Annapolis Valley, during summer months, is sometimes too polluted for irrigation and even for swimming (see picture in Figure 14.23). Discharge of nitrate-rich groundwater is considered to be the major pathway for nitrogen to reach surface waters in PEI, with negative (and increasing) consequences for eutrophication of ecologically and economically important estuaries (e.g., Danielescu and MacQuarrie, 2011).

14.4.6.3 Saltwater intrusion and residual marine water

Saltwater intrusions, which can occur as a natural process in coastal areas, may be exacerbated by human-induced activities such as pumping. Brackish or saline groundwater has been reported in some areas, notably in Îles-de-la-Madeleine, Quebec, on the island of Lamèque, New Brunswick, as well as in scattered areas along the New Brunswick coastline. Notwithstanding these reports, saltwater intrusions do not seem to be a major problem, probably because of the abundant recharge that pushes saltwater back to the ocean. Nonetheless, several coastal municipalities which have not yet experienced any such problem are concerned that increasing extraction rates in the future could create a seawater zone encroachment. In Îles-de-la-Madeleine, the saltwater encroachment issue has forced municipalities to apportion pumping among several wells, and to limit pumping rates so as to avoid large drawdowns, and the subsequent upwelling of saline waters. A few PEI wells impacted by saltwater intrusion are deliberately exploited by the aquaculture and fish processing sectors due to adequate salinities, good microbiological quality and constant temperatures, factors which make this groundwater more attractive than surface water. The main risk of saltwater intrusion in the Atlantic region is likely high water demand.

Predicting location of saltwater-freshwater interfaces can be very difficult because of the stratified nature of Maritimes Basin's bedrock. This results in a succession of very distinct horizontal permeabilities, combined with confined and unconfined conditions, and complicated by the fact that water flows mainly through fractures (e.g., Carr, 1969; van der Kamp, 1981). As a result, information on the distribution of saline or brackish water comes mainly from descriptions of discrete occurrences, and the phenomenon remains poorly known and understood. It seems that the influence of saltwater intrusions can be observed only within a few tens to hundreds of metres from the coast (Rivard et al., 2008). Carr (1969), however, noted saltwater intrusions up to 350 m inland in Prince Edward Island, indicating that the zone of diffusion can encroach a considerable distance into an aquifer at shallow depths, even when the area involved has no large groundwater withdrawals. Brown (1971) and van der Kamp (1981) observed that groundwater salinity generally rises sharply in the dry period, and falls during the autumn, as abundant precipitation recharges the aquifer, increases the water table elevation and flushes out the saline water.

Climate change is expected to cause a rise in sea level to between 0.18 and 0.59 m above present by the end of the 21st century (IPCC, 2007). This increase will force changes in the position of the freshwater-saltwater interface in many coastal aquifers and could threaten water supplies. These effects will be amplified by potential reduction in water table elevation due to increases in temperature and thus evapotranspiration, and greater groundwater withdrawals (increased anthropogenic demand for groundwater). It is expected that some aquifers will react very quickly to such changes, while others may take centuries or millennia to respond. There is currently no consensus on how different aquifers within this region will behave. Several climate change–seawater intrusion studies are underway in the Atlantic Provinces under the Atlantic Climate Adaptation Solutions Association (ACASA) groundwater theme (http://atlanticadaptation.ca/groundwater).

Aquifers underlying regions below marine limit (submergence zones shown in Figure 14.4) became saline or at least brackish during the postglacial marine invasion, due to the migration and mixing of seawater with groundwaters underlying the Goldthwait, Champlain and De Geer Seas. Cloutier et al. (2010) estimated that the Champlain Sea had a TDS concentration of ~11,300 ppm, corresponding approximately to 34% seawater and 66% fresh water coming from glacial meltwater and precipitation. Since marine waters essentially withdrew from present land areas about 9,500 years ago, saline groundwater has gradually been replaced by fresh water as a result of recharge from precipitation. TDS concentrations in the Appalachian piedmont are now typically below 1,000 mg/L (Beaudry et al., 2011a). A few areas of the piedmont, however, still have TDS concentrations above 1,000 mg/L (or chloride >250 mg/L), thus above aesthetic drinking water guidelines, likely due to locally lower groundwater velocity, or to weak recharge rates. These areas are illustrated in Beaudry et al. (2011b). Similar zones with significant salt content, though usually below the saline threshold (TDS of 4,000 or 5,000 mg/L), are likely to occur in other regions subjected to postglacial submergence. Location of these zones is not well known, mainly because wells with easily detected poor water quality are abandoned and sealed without any further geochemical analysis, with the result that these occurrences are not reported in provincial databases. Work is currently being conducted to identify the origin and specific causes of the presence of brackish groundwater in southeastern Quebec (Beaudry et al., 2011a).

14.4.7 Aquifer vulnerability

Vulnerability to surface contamination is largely influenced by the nature and thickness of the surficial sediment cover, recharge rate, and water table depth. Surficial aquifers are generally more vulnerable to surface contamination than bedrock aquifers, because of their shallow depth and the common absence of confining, low-permeability units.

Both regional studies carried out in the Maritimes provinces (MGWI and Annapolis) used the DRASTIC methodology (Aller et al., 1987) to present an evaluation of the relative vulnerability of the groundwater to current and potential contamination problems. DRASTIC is a widely used groundwater vulnerability mapping method (Al-Zabet, 2002), although, for the MGWI project, only a simplified version, treating the two most variable parameters (recharge and hydraulic conductivity of the till layer) for this specific hydrogeological context was used to indicate groundwater vulnerability. Both studies concluded that bedrock aquifers of the Maritimes Basin may generally be considered as moderately to highly vulnerable. As expected, results also showed that the aquifer units with the greatest production potential also correspond to higher vulnerability potential, due to elevated values of permeability and recharge. “High” vulnerability scores (indices) were obtained for unconfined coarse-grained surficial sediments, such as the glaciofluvial sediment aquifers of the eastern part of the Annapolis Valleys, and for bedrock aquifers of Prince Edward Island, and those underlying the Annapolis Valley floor (i.e., the Wolfville Formation, supplying most of the Valley’s residents). Nevertheless, it must be emphasized that the classes obtained with DRASTIC are relative; sandy till covering PEI, for instance, probably protects the underlying bedrock formations better than a sand cover alone would.

Near surface contamination in the Fredericton area has resulted from past hydrocarbon and chlorinated solvent releases (Violette and MacQuarrie, 1993; Craig et al., 1993), although such contamination has typically been limited to the surficial fluvial sand unit overlying a clay/silt aquitard: to date, this has not posed a threat to deeper production wells, and a protection plan regulating certain activities and potential contaminants within designated well field protection areas has been implemented. In Îles-de-la-Madeleine, the vulnerability of the aquifers combined with the presence of large freshwater users (fish and seafood processing plants and the tourist industry in the summer) have forced municipal authorities to execute a unique, secure water supply management plan. All provinces have recently developed programs to help municipalities implement well protection areas around production wells in order to avoid groundwater contamination problems at these sites.

14.4.8 Knowledge gaps and recommendations

Most eastern Canadian aquifers are not over-exploited, so there is opportunity to act in a proactive manner by conducting groundwater inventories, establishing monitoring networks and creating management programs to ensure that groundwater extraction remains within sustainable yields. Additional inventories, for any given region, would provide information such as a water budget, aquifer characteristics (e.g., hydraulic conductivity, storage coefficient, effective porosity, and anisotropy), and an overview of water quality, aquifer vulnerability, and groundwater depths. The main knowledge gaps, perhaps shared by all provinces, are typically overlooked in groundwater studies: these include groundwater use data, climate change impact, and groundwater–surface water interactions. Collecting this information is financially demanding, and resource intensive, because this information requires more fieldwork and more computer time. It is, however, essential to understand fully the dynamics of a hydrogeologic system and to develop well informed groundwater management and protection programs. Lack of groundwater quality information, partly due to privacy concerns associated with samples taken from private wells, is another information gap, made more difficult to overcome because it is not mandatory in all provinces to send geochemical results of new residential wells to provincial authorities.

Challenges associated with filling groundwater knowledge gaps include 1) developing tools and expertise to study interactions between various water resources, including bedrock, surficial sediments, surface water, and aquatic ecosystems; 2) collecting accurate groundwater use data through water use surveys; 3) estimating sustainable yields of aquifers; 4) developing standard approaches to account for climate change; 5) estimating water budgets and therefore, aquifer recharge, at local and regional scales; 6) converting old hard copy groundwater data to electronic databases and developing common database formats to facilitate data sharing and analysis; and 7) improving public access to groundwater data on the internet. Another knowledge gap more specific to coastal areas is the effects of climate change and increasing population (and thus water demand) on saltwater intrusion.

In addition to existing regulations for public water supplies, we recommend the following:

1) Each municipality should equip production wells and selected observation wells with groundwater level probes or pressure transducer dataloggers to measure water levels

regularly. Records of groundwater levels on a long-term basis would allow detection of problems, such as declining water levels, caused by over-exploitation, or by additional pumping at nearby sites. These records would also provide accurate and reliable historical data which would allow a better understanding of the hydrodynamics of any given aquifer.

2) All drillers should be equipped with a GPS unit (as in Nova Scotia) to provide an accurate geographical location for each new well.
3) A better knowledge of current monitoring well stratigraphy and construction should be acquired, or new monitoring wells with known characteristics should be added to observe the potential impacts of climate change and anthropogenic activities, both for groundwater levels and groundwater quality (mainly nitrates and chlorides) in areas at greater risk.
4) All acquired groundwater quality data (laboratory analysis reports) should be automatically transmitted by laboratories to provincial environmental agencies in electronic format.

Finally, greenhouse gas emissions could be reduced by promoting open- and closed-loop groundwater heat pump systems (see Box 14-3). Completing feasibility studies in representative hydrostratigraphic units could support and encourage the use of geothermal energy.

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BOX 14-1 NATURALLY OCCURRING RADIONUCLIDES IN GROUNDWATER IN NOVA SCOTIA

Naturally occurring uranium was first identified in Nova Scotia's groundwater in 1978. In 2002, lead-210 (a daughter product of the uranium-238 decay series) was identified in the water of a school near Halifax, and, as a result, a province-wide radionuclide testing program was initiated. The initial finding indicated that lead-210 and uranium could exceed drinking water guidelines in wells drilled into granite and Upper Carboniferous sandstone and shale. Subsequent investigations, however, revealed that lead-210 testing methods did not provide a realistic indication of lead-210 levels because radon gas in the water samples was rapidly decaying to lead-210. The lead-210 sampling protocol has since been modified in Nova Scotia to eliminate radon effects. The majority of water supplies which originally exceeded the lead-210 guideline were below guidelines when they were re-tested using the modified sampling protocol. For more details, see Drage et al. (2005a, 2005b).

BOX 14-2 OCCURRENCE OF ELEVATED MANGANESE LEVELS IN THE CITY OF FREDERICTON'S WELLS

Water quality from production wells in the Fredericton aquifer is generally good, with the exception of elevated dissolved manganese (Mn), which may exceed 2 mg/L (Thomas et al., 1994). This occurrence has been attributed to the flux of dissolved organic carbon (DOC) that enters the aquifer during river water infiltration through windows that exist beneath the Saint John River. These windows are regions where the clay/silt aquitard is absent (Figure 14.24), thus creating a relatively direct hydraulic connection between the river and the water supply aquifer. Pumping of the production wells causes river water infiltration and introduces DOC, which in turn, creates *in situ* conditions suitable for reductive dissolution of Mn-oxides (Petrunic et al., 2005; Al et al., 2005). Investigation of the unconsolidated sand and gravel sediments, and pore waters, beneath the riverbed windows confirms that there is a diverse microbial community possessing the ability to reduce Mn-oxides (Haveman et al., 2005), a

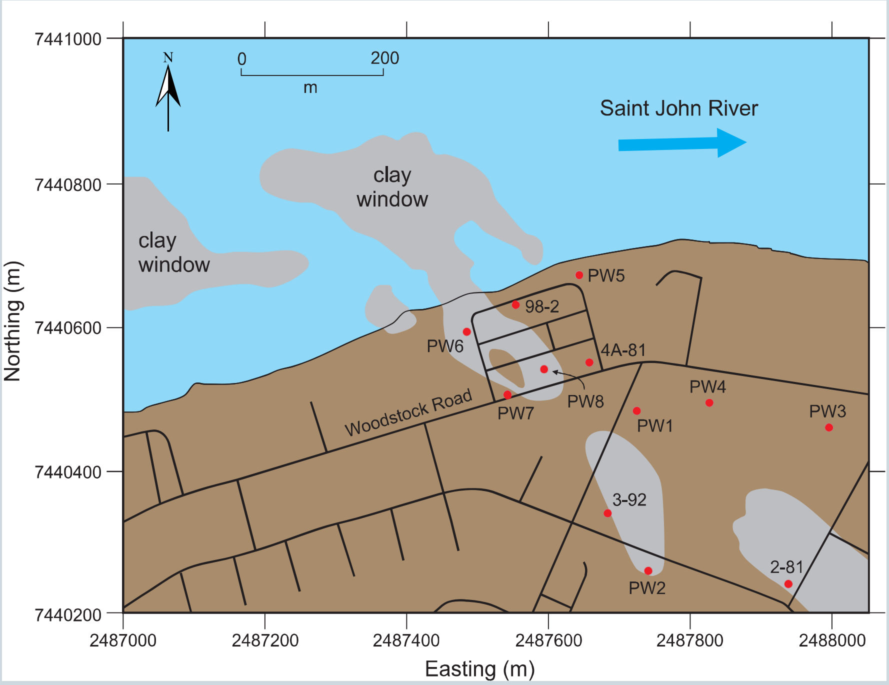


Figure 14.24 Extent of selected clay/silt windows in the Fredericton aquifer. The average thickness of the aquitard is about 15 m. For the windows that extend into the Saint John River, the aquifer is directly exposed at the river bed. There are eight production wells (PW). Selected monitoring wells are also shown.

community which is well suited to the changing redox conditions that occur as the infiltrating water temperature varies throughout the year.

Although reductive dissolution of Mn-oxides is still occurring after approximately 40 years of continuous river water infiltration, it is expected that Mn-oxide mineral depletion will eventually occur in the aquifer sediments (Al et al., 2005). The trend of Mn concentrations at some production wells suggest that this depletion may have begun. For example, in well PW5, located approximately 30 m from the river's bank (Figure 14.24), Mn concentrations increased from approximately 0.1 mg/L in the 1960s to a peak of near 2 mg/L during the early 1980s; since that time concentrations have been steadily declining. The time frame for complete Mn-oxide mineral depletion and the potential resultant water quality changes requires further investigation (MacQuarrie and Al, 2007).

BOX 14-3 HEATING AND COOLING WITH GEOTHERMAL MINE WATER

Geothermal energy from floodwater in abandoned coal mines is used to provide heating and cooling at a plastic packaging company's facility in Springhill, Nova Scotia. Although the use of mine water as a heat source is not a new concept in other parts of the world, this was the first industrial site in Canada to demonstrate its economic and technical viability. The project began in 1988.

Over 200 years of subsurface coal mining in Nova Scotia has left many square kilometres of old workings, often located directly beneath towns that grew at the pitheads. These workings have gradually filled with water over the years. Gravity circulation within the workings brings this heated water up closer to the surface where it is accessible through short drilled wells, thus providing a suitable energy source for ground source heat pumps. The heated water is a renewable source, displacing carbon emissions from coal-fired electricity or oil-fired heating.

At this site, mine water, with its temperature of 18°C, is pumped at a rate of 4 L/s and passed through a heat pump system before reinjection into another interconnected mine (i.e., in a closed-loop system). Inside the plant, 10 heat pumps with individual control thermostats provide heating and cooling. The cost of the heat pump system for the new plant was 110 K$ (Canadian dollars), compared with a cost of 70 K$ for a conventional or propane heating system. This extra capital cost was, however, offset by a saving of 110 K$, an expenditure that would have otherwise been required for dehumidifiers. The net savings in the new plant are in excess of 45 K$ annually, equivalent to a saving of about 600,000 kWh.

Source: http://oee.nrcan.gc.ca/publications/infosource/pub/ici/caddet/english/r122.cfm?attr=20

BOX 14-4 STABLE ISOTOPES REVEAL SEASONAL CHANGES IN NITRATE PRODUCTION AND SIGNIFICANT WINTER TRANSFER FROM AGRICULTURAL SOILS TO GROUNDWATER IN TEMPERATE SETTINGS

Contamination of water resources by nitrate (N) of agricultural origin is a serious problem in many temperate agricultural regions. Reducing risk of further groundwater (GW) quality degradation depends on our understanding of how nitrate (N) is transferred from agricultural lands to GW. A study combining seasonal sampling over two years with nitrate dual isotopes (δ^{15}N and δ^{18}O) recently addressed these questions in the Wilmot watershed (west-central PEI), characterized by intensive cultivation of potatoes and heavy reliance on chemical fertilizers (Savard and Somers, 2007; Savard et al., 2008).

The rapid response of the Wilmot aquifer to recharge events allows detection of seasonal characteristics with respect to nitrate δ^{18}O ratios in GW, shedding light on the timing of bacterially mediated nitrification, as the process involves oxygen from the atmosphere (constant δ^{18}O value) and soil water (δ^{18}O values varying with seasonal characteristics of precipitation). The shift in δ^{18}O values from summer/fall to winter/spring periods is inferred to represent nitrification of crop residues using soil water derived from warm season to cold season precipitation respectively, highlighting the importance of nitrification even during the winter (Figure 14.25). The nitrate δ^{18}O and δ^{15}N values of GW and key N sources in the watershed suggest striking differences in the relative seasonal contribution of N sources to the aquifer (Figure 14.26). While inorganic fertilizers are the most important anthropogenic N source in the watershed, they marginally dominate the summer/fall GW load. Nitrate produced by the degradation of crop residues dominates the winter/spring period and accounts for almost 60% of the total nitrate load transported to the aquifer on an annual basis.

These findings highlight the role of soil organic matter as a key transitory reservoir in the N cycle. Understanding the role of this reservoir helps in the development of remedial strategies to reduce agricultural impacts on GW quality.

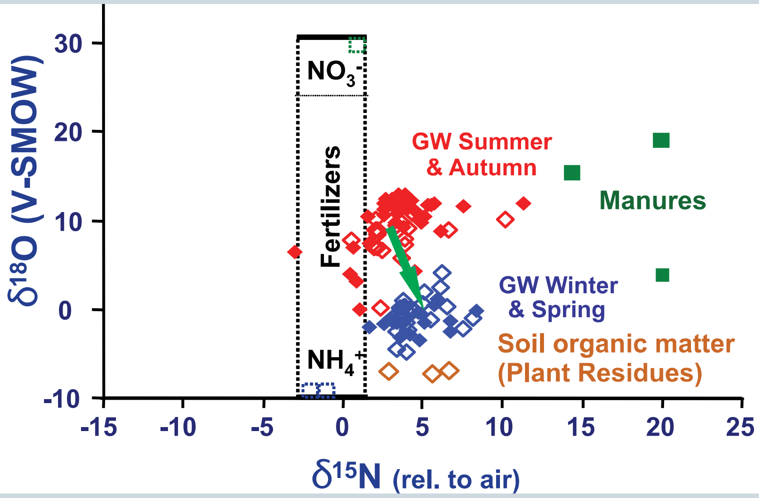
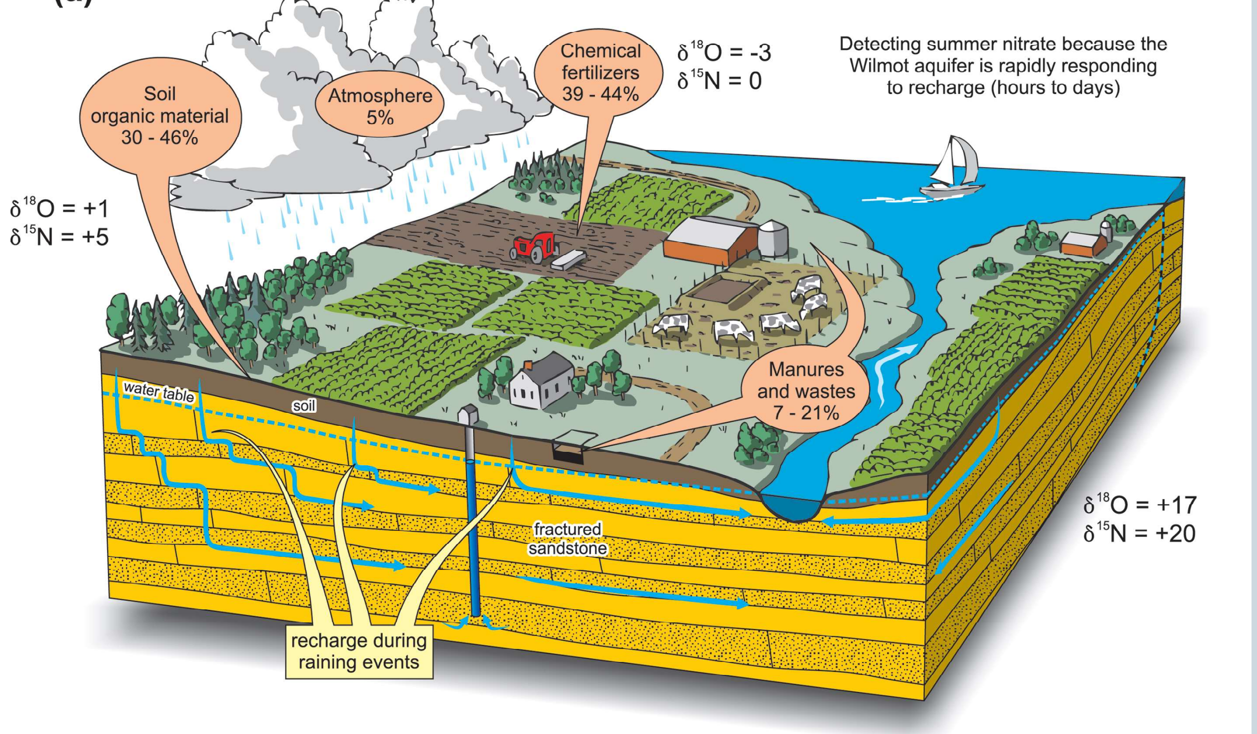


Figure 14.25 Nitrate isotope results for seasonal groundwater samples from the Wilmot watershed compared with measured values for key N-sources and chemical fertilizer domain from literature. The green arrow illustrates a shift of -10.2 per mil in oxygen isotope ratios in nitrate between summer-fall samples and winter-spring samples (modified from Savard et al., 2007).

(a) Summer/Fall - Wilmot Watershed



(b) Winter/Spring - Wilmot Watershed

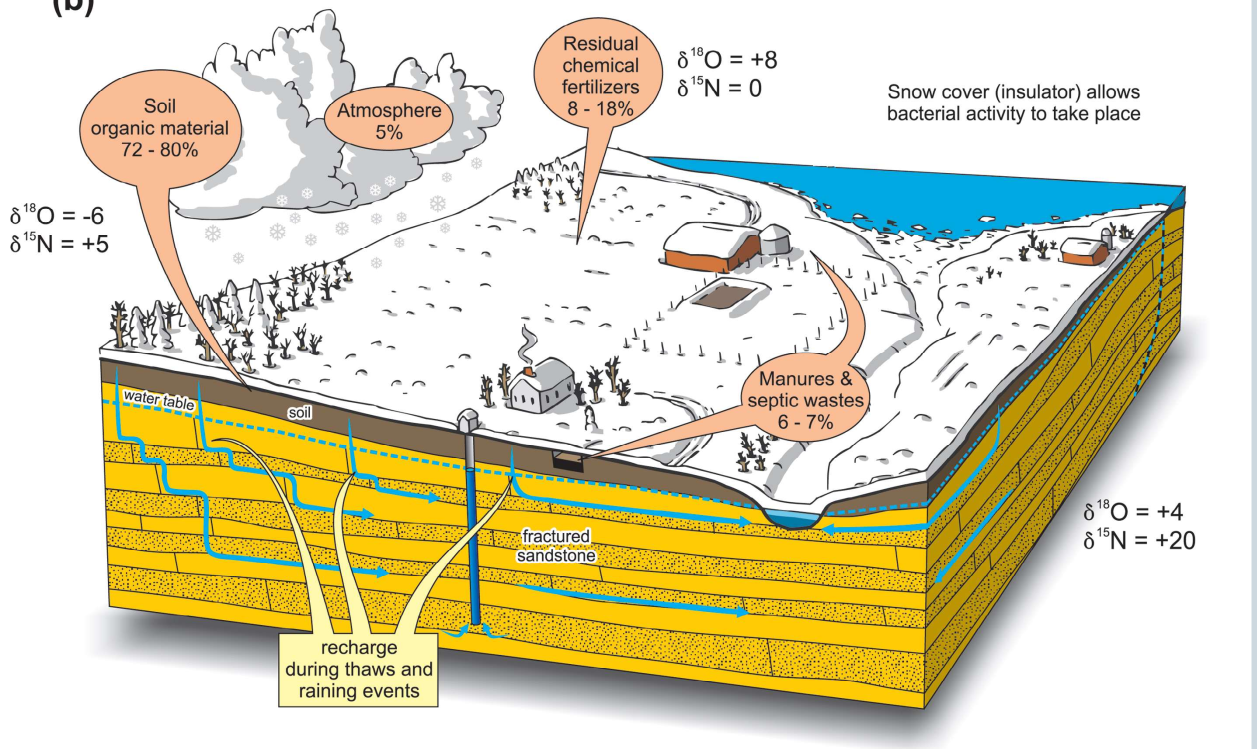


Figure 14.26 Estimated nitrate source contributions for (a) summer/fall and (b) winter/spring conditions (adapted from Savard and Somers, 2007).

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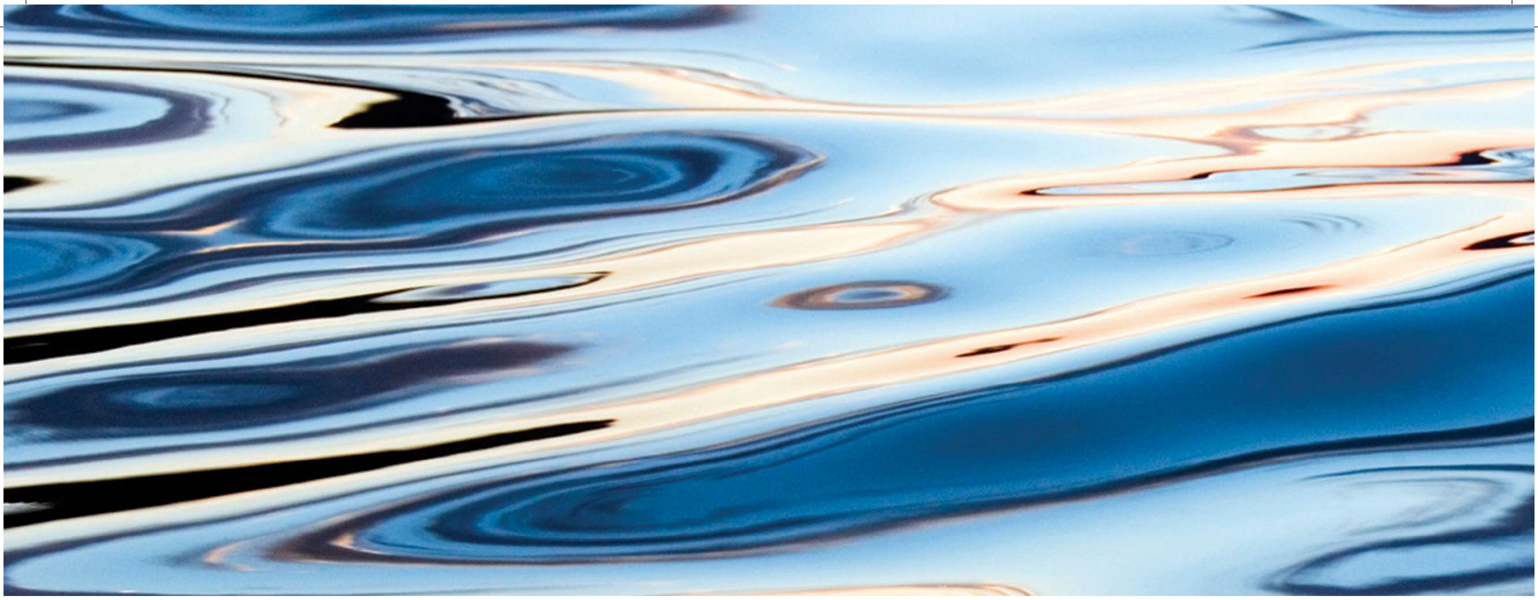

CHAPTER 3 AN APPROACH TO REGIONAL ASSESSMENTS OF GROUNDWATER

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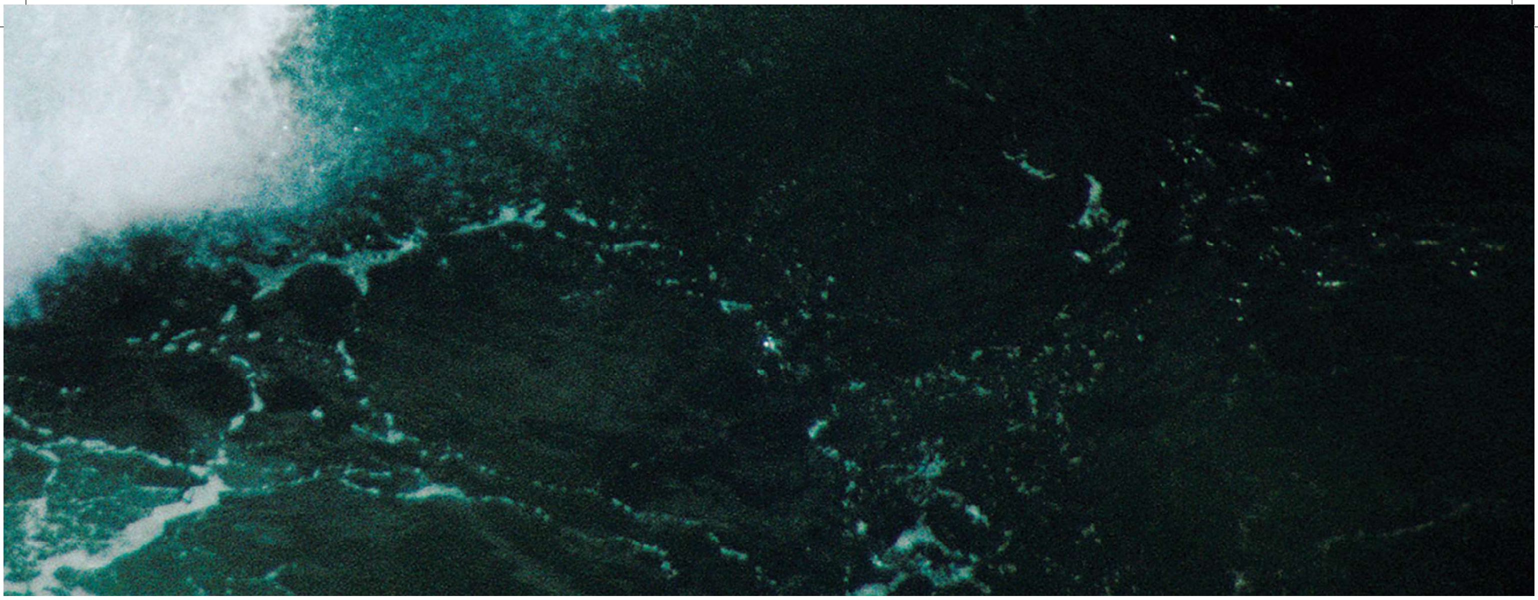

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