CHAPTER 9

CORDILLERAN HYDROGEOLOGICAL REGION

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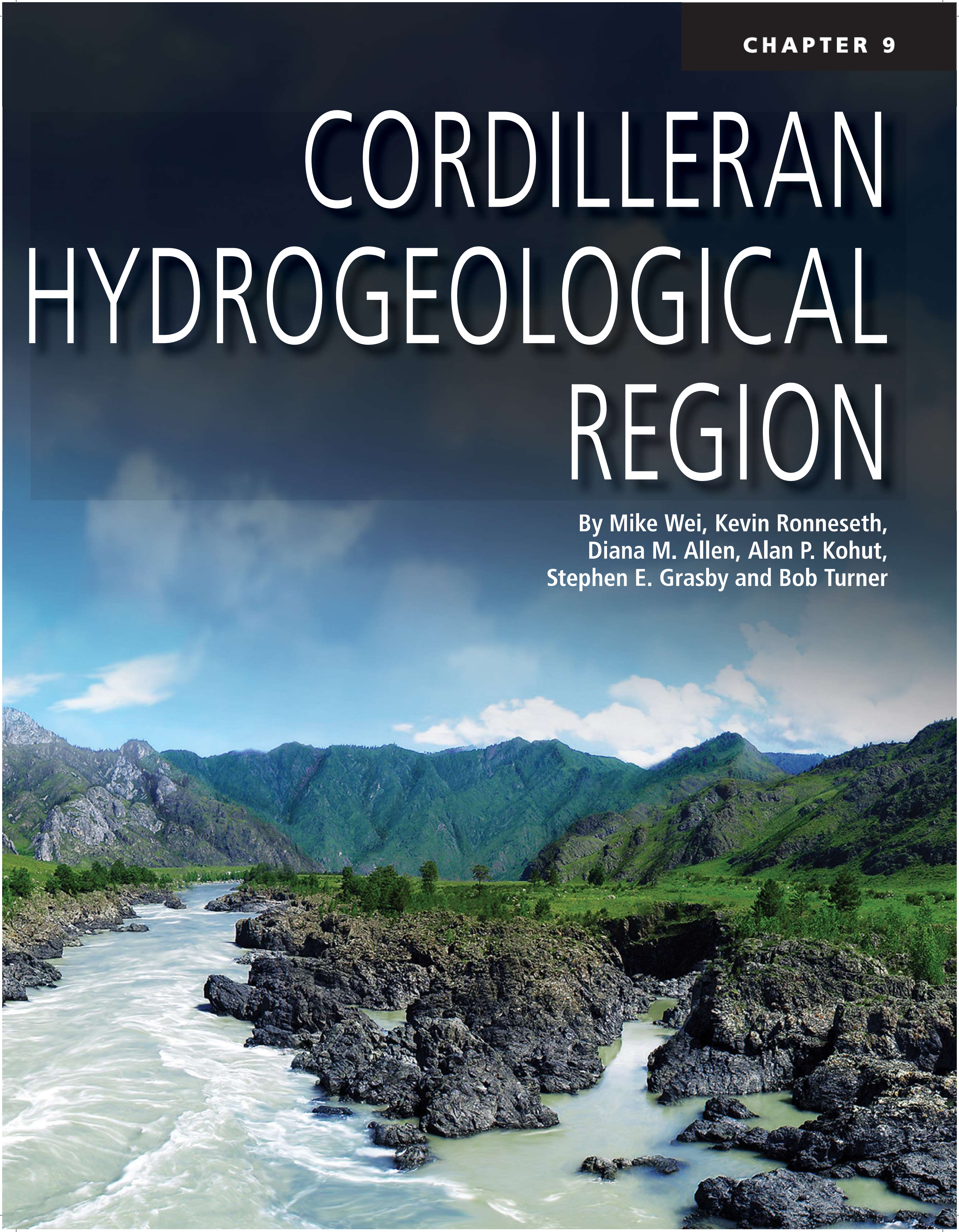

9.1 INTRODUCTION

9.1.1 Previous studies

The Cordilleran Hydrogeological Region (referred to as the "Cordillera" or the "Region" in this chapter) was first described by Halstead in *Groundwater in Canada* published by the Geological Survey of Canada (Halstead, 1967a). Subsequently, it was discussed as part of the Cordilleran region of North America, published by the Geological Society of America (Back et al., 1988). The Canadian Cordillera covers an area of ~1.4 million km^2 and includes parts of two provinces and two territories: most of the Province of British Columbia (except the Peace River region of northeastern British Columbia), part of the Yukon, the Rocky Mountains and Foothills of western Alberta and the western part of the Northwest Territories (Figure 9.1). The Region is vast and physiographically and geologically diverse.

The information and understanding of aquifers in the Cordillera presented in this chapter is based mostly on available local (and a few regional) studies in British Columbia (BC) and on the existing inventory of aquifers classified by the province of BC. BC began conducting groundwater studies in the Region during the 1950s, mostly to support development of groundwater supplies in local communities, and, within the last two decades, to assess local groundwater quality issues. Many of these groundwater reports can be accessed through the Ministry of Environment's Ecological Reports Catalogue—EcoCat http://www.env.gov.bc.ca/ecocat/. In 1994, *Groundwater Resources of British Columbia* provided a region-by-region overview of groundwater conditions in the various physiographic regions in BC (BC Environment and Environment Canada, 1994). The Federal government has also conducted groundwater studies in the Cordillera since the mid-1950s. These early studies focused mainly on describing groundwater conditions of parts of Vancouver Island (Halstead and Treichel, 1966; Halstead, 1967b), the Lower Fraser Valley, east of Vancouver (e.g., Halstead, 1957; Halstead, 1959; Halstead, 1961; Halstead, 1964; Halstead, 1986; Armstrong and Brown, 1963), other locales (Lawson, 1968; Brandon, 1964) as well as on thermal and mineral springs (van Everdingen, 1972). In the 1990s the Geological Survey of Canada characterized the aquifer at Langley (Ricketts and Makepeace, 2003). Recent regional groundwater studies, including many completed by Simon Fraser University in partnership with federal, BC, and local governments, have focused on aquifers at Abbotsford in the Lower Mainland (Liebscher et al., 1992; Hii et al., 1999; McArthur and Allen, 2005; Scibek and Allen, 2005; Scibek and Allen, 2006a; 2006b, Chesnaux and Allen, 2007; Chesnaux et al., 2007), Grand Forks in the southern interior, along the Canada-USA border (Allen, 2000; Allen, 2001; Allen et al., 2004a; 2004b; Scibek and Allen, 2003; 2004; 2006c; Scibek et al., 2004; Scibek et al., 2007; Wei et al., 2004), the Gulf Islands between Vancouver and Vancouver Island (Allen, 2004; Allen et al., 2003; Allen et al., 2002; Allen and Suchy, 2001a; 2001b; Allen and Matsuo, 2001; Dakin et al., 1983; Denny et al., 2007; Mackie, 2002; Surrette and Allen, 2008; Surrette et al., 2008), and most recently, in the Okanagan Basin (Carmichael et al., 2008; Liggett, 2008; Liggett and Allen, 2010, 2011; Liskop and Allen, 2005; Neilson-Welch and Allen, 2007; Toews, 2007; Smerdon et al., 2009, 2010; Voeckler and Allen, 2012). These study areas are heavily dependent on groundwater and have ongoing quality and quantity concerns.

In 1994, the Province of British Columbia developed the *Aquifer Classification System* to identify and classify *developed*[1] aquifers as a means of providing summary information to assist with groundwater management in BC (Kreye and Wei, 1994; see Box 9-1). Aquifers were identified and classified on the basis of available well records, geologic mapping and groundwater reports on file at the time. 888 aquifers were identified and classified in the BC Cordillera, as of December 31, 2007. This work has resulted in a numbered inventory of developed aquifers and their basic characteristics for a large part of the Cordillera where groundwater is being used. These aquifers can be viewed at the BC Water Resources Atlas website http://webmaps.gov.bc.ca/imf5/imf.jsp?site=wrbc. Although numerous developed aquifers exist in the Region, only a small percentage have been sufficiently studied. As a result, our discussion of aquifers in the Cordillera does not follow a region-by-region approach: instead we decided to present and discuss them based on aquifer type, profiling a few of the better studied examples within these type categories. For discussion, the Cordillera's 888 classified aquifers can be grouped according to lithologic, morphologic, stratigraphic, and structural criteria. Each aquifer type is expected to have unique hydrogeological characteristics: nature of its origin, size and location, depths, yields, permeability and vulnerability and potential connection to surface water.

9.2 PHYSICAL SETTING AND CLIMATE

The Cordilleran Hydrogeological Region comprises massive mountain ranges, highlands, foothills, plateaus, basins, and lowlands. The region extends westerly to the Pacific Ocean, from an eastern boundary with the Interior Plains region of Alberta and northeastern British Columbia, and is bounded by the international border with the United States of America to the south (Figure 9.1). The Cordillera has the highest relief in Canada—5,959 m (from sea level at the coast to Mount Logan in the Elias Mountains of the Yukon Territory). The Region includes three major physiographic areas (Holland, 1976) from west to east:

1. Western system of northwesterly-trending coast mountain ranges, coastal lowlands and basins
2. Interior system comprising several major and minor mountain ranges, plains, plateaus, and basins
3. Eastern system of northwesterly-trending Rocky Mountain ranges, foothills and the Liard plateau

The climate of the Cordillera varies from semi-Mediterranean conditions along the southern west coast to polar conditions at high mountain elevations in the north. Mean annual precipitation (Environment Canada, 2006) generally decreases from west to east (following the general movement of the weather fronts), varying, for example, from 1,403 mm at Sandspit in the Queen Charlotte Islands to 293 mm at Kamloops, to 472 mm at Banff Alberta (refer to the graphs in Figure 9.1). Annual precipitation generally increases with elevation in any given area, due to orographic effects. Figure 9.1 includes a graphical summary of average monthly precipitation and, where available, groundwater level data for several long-term climate stations and observation wells. Average monthly climate data for other locations is available from Environment Canada's website: http://www.climate.weatheroffice.ec.gc.ca/index.html.

Seasonal climatic variations control the annual amount and form of precipitation (i.e., rain or

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[1] *Developed* aquifers are aquifers wherein wells have been completed to utilize groundwater.

snow) falling in drainage areas, thereby affecting runoff and the amount and timing of groundwater recharge. Coastal regions experience highest precipitation during the winter months. Much of this precipitation falls as rain (temperatures are above freezing), except at higher elevations where it generally falls as snow (temperatures below freezing). Much of the groundwater recharge in these coastal regions tends to occur during the winter months when the rate of transpiration is at its seasonal lowest. Consequently, natural groundwater levels in aquifers located within coastal regions show a seasonal high during winter or early spring, and generally decline from spring to late fall (see the average monthly groundwater levels for Nanaimo and Abbotsford in Figure 9.1). In contrast, interior stations have their highest precipitation during the summer months (mostly as rain). Much of this precipitation is not available for recharge because evaporation and transpiration are highest during the summer months (when the mean daily air temperature is highest). As well there is no excess water available to infiltrate past the root zone for aquifer recharge (e.g., Liggett and Allen, 2010; Toews and Allen, 2007; Smerdon et al., 2009, 2010). In these interior regions, snow accumulations during winter months, and at higher elevations, are important for recharge during spring and early summer months when snowmelt occurs. Natural aquifer groundwater levels in the interior are generally at a seasonal high in late spring or early summer and then decline over the summer and early fall. The groundwater level usually reaches a seasonal low during the winter months in these areas because precipitation at the land surface is frozen and not available for recharge (see the monthly groundwater levels for Kelowna and Cranbrook in Figure 9.1).

9.3 GEOLOGIC SETTING

9.3.1 Surficial geology

Despite their geological and physiographical diversity and complexity, aquifers in the Cordillera can be grouped into two broad types: *unconsolidated* or *surficial* aquifers, and *bedrock* aquifers. Most unconsolidated aquifers in the Region are formed by deposition of sand and/or gravel in moving water under a *fluvial* or, if by moving water during glacial times, a *glaciofluvial* environment. Surficial geology and glacial history have a major influence on the *lithology*, form or *morphology*, and *stratigraphic* location of sand and gravel deposits (location of the geologic deposit in relation to other geologic deposits). Therefore, the occurrence and characteristics of unconsolidated sand and gravel aquifers. The *lithology* of the sands and gravels—e.g., the grain size, sorting, and porosity—affects its primary permeability and storativity, while the mineralogical make-up can influences the natural chemical quality of the groundwater. The morphology of the sand and gravel deposit influences its thickness, shape, and extent and its stratigraphic location (relative to other less permeable, surficial deposits, such as clay, till) determines whether a particular deposit will be shallow or deep, confined or unconfined, vulnerable or not vulnerable, and directly influenced by or connected to surface water or not.

The Cordillera has experienced several periods of glaciation (BC Environment and Environment Canada, 1994; Armstrong, 1981; Fulton, 1975). The surficial geology and unconsolidated aquifers of the Region, however, mostly reflect the last glaciation period (Fraser Glaciation), which occurred during the Late Wisconsinan (about 30,000 years to 10,000 years ago) (Clague, 1994). Ice built up rapidly, especially during the climatic

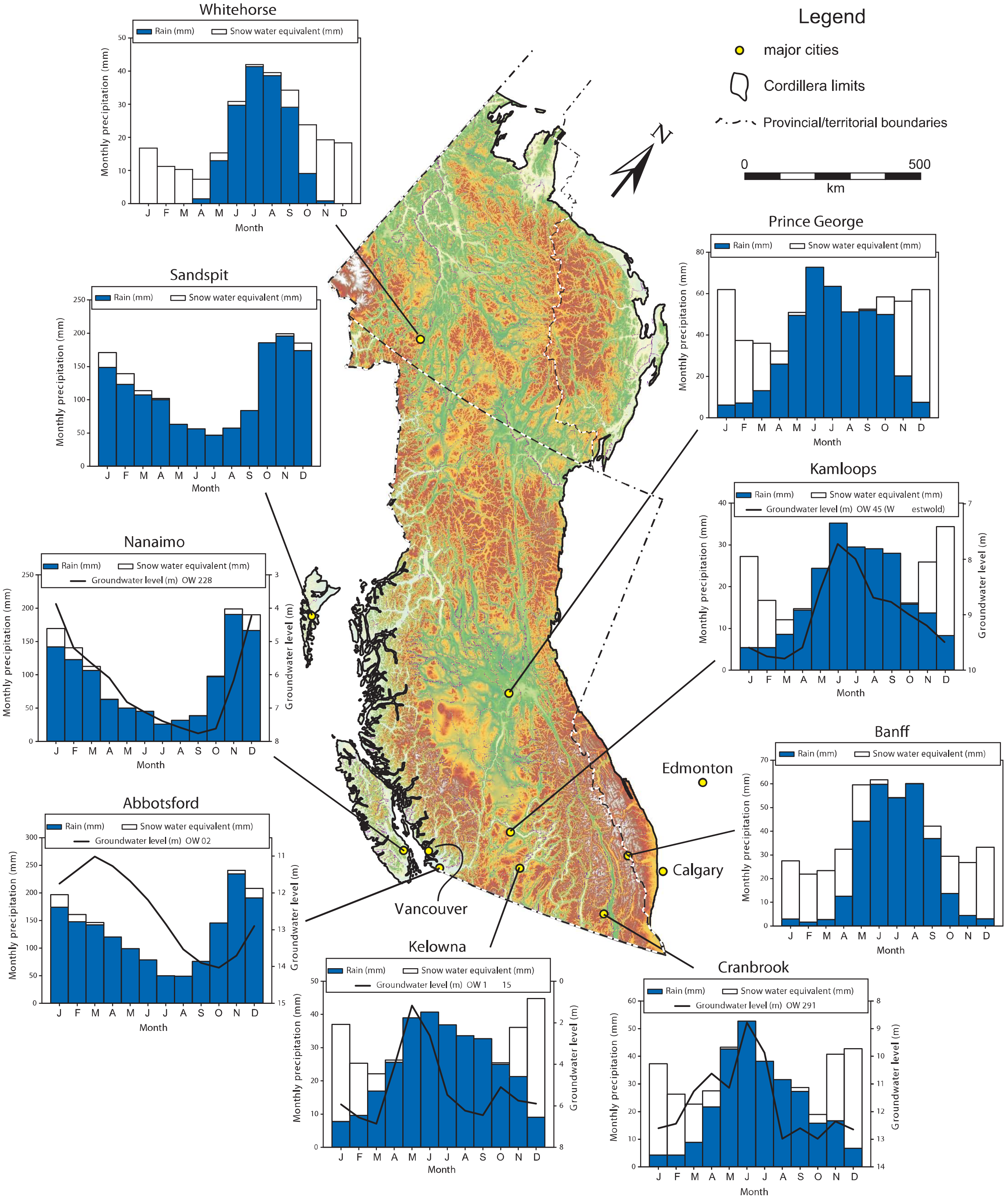

Figure 9.1 Map of the Cordilleran Hydrogeological Region and information on select climate stations and observation wells.

Vashon Stade[2] (18,000–12,000 years ago). In less than 4,000 years glaciers advanced down mountains to coalesce in lowlands and plateaus, creating a vast continental ice sheet that covered the entire Region. At maximum glaciation, the Cordilleran ice sheet covered BC, Yukon, and Southern Alaska and stretched south to Puget Sound in Washington State (Clague, 1994). This sheet developed in the high areas of the Coast Mountains and extended across the entire Pacific coast, achieving a thickness of approximately 2,000 m in the major valleys. Only the highest mountain tops and a few locations near the western margin of the ice sheet were not covered.

Ice sheet melt was much more rapid than ice sheet growth. Between 16,000 years and 12,000 years ago, the ice began to disappear as the climate warmed: melting exceeded ice build-up. Retreat began at the continental shelf, proceeding eastward and northward. Glaciers were active near the end of the Fraser Glaciation, and were restricted to valleys and fjords. Less than 1,000 years after the beginning of deglaciation, present-day Vancouver and Victoria were ice-free. Lowlands were free of ice 12,500–13,000 years ago, and by about 9,500 years ago, glaciers had essentially the same extent as they do today.

The various ice advances removed most

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[2] Period of glacial advance.

sediments deposited during previous glaciations. Much of the removed material was "reworked" by the ice and deposited under the ice as till. Generally only sediments from the most recent period of glaciation (the Fraser Glaciation) remain. Older surficial deposits have mostly been obliterated, existing only in isolated locations and as sediments at depth (see the lower orange-coloured aquifer in Figure 9.2a). Knowledge of glacial and inter-glacial surficial deposits prior to the Fraser Glaciation is minimal.

Sands and gravels deposited by meltwaters at the margins of advancing glaciers during the onset of the Fraser Glaciation formed productive aquifers. The advancing glaciers overrode these same sands and gravels, depositing a layer of till on top. Sand and gravel deposits were confined by the till above (see the orange-coloured aquifers confined directly above by the greenish till in Figures 9.2a and 9.3a). The lithology and morphology of these "advance" glaciofluvial sand and gravel deposits are quite varied, and depend on such factors as size of the glaciated area, the steepness and topography of the underlying ground, amount of meltwater, availability of sands and gravels, and distance of sediment transport. One well-studied example of an advance-type glaciofluvial sand and gravel deposit is the Quadra Sand, which occurs along the east coast of Vancouver Island and the BC Coastal Mainland, a principle aquifer in the local area (Clague, 1977). The Quadra Sand was formed by deposition of sand from meltwater streams as a tongue of the Cordilleran ice sheet advanced south along the depression of what is now the Strait of Georgia (the upper orange-coloured aquifer in Figure 9.2a). Similar glaciofluvial sand and gravel deposits formed at the onset of the Fraser Glaciation are evident from well records where sand and gravel occur directly beneath till. Glaciers also dammed drainage courses in many major valleys of the Region's interior, causing glacial lakes to form behind them (the South Thompson River valley, Okanagan Lake, Nicola Lake). Vast amounts of fine-textured silt and clay sediments were transported from tributary streams into these glacial lakes and deposited in the lake's stillwater (*glaciolacustrine*) environment. These silt and clay deposits covered the till beneath the lake and provided a thick confining layer (in addition to the till) above advanced sand and gravel deposits in these interior valleys (see the brown-coloured silt and clay layer in Figures 9.3a). Examples of these silt and clay deposits can be seen beside the South Thompson River east of Kamloops along Highway 1, or beside Lake Okanagan near Penticton.

Unconsolidated aquifers associated with glaciofluvial coarse sands and gravels deposited at the end of the Fraser Glaciation, as glaciers were melting, are typically some of the most productive aquifers in the Region. Meltwaters formed streams capable of moving vast quantities of gravel and sand, depositing them along present-day river valley bottoms (see the yellow-coloured aquifer in Figure 9.3a). Many of these deposits are evident along river valley bottoms as terraces, and are hydraulically connected to the river (e.g., at Grand Forks). Sands and gravels were also deposited onto outwash plains (e.g., at Abbotsford) or deltas (and often rose above present local sea or lake levels as a result of land rising after the ice melted). Since these sands and gravels were deposited at the end of glaciation, many of them have not been covered over by other less permeable deposits and, therefore, are unconfined (see the yellow-coloured aquifer on the left in Figure 9.2a). The Abbotsford-Sumas Aquifer is an example of an unconfined

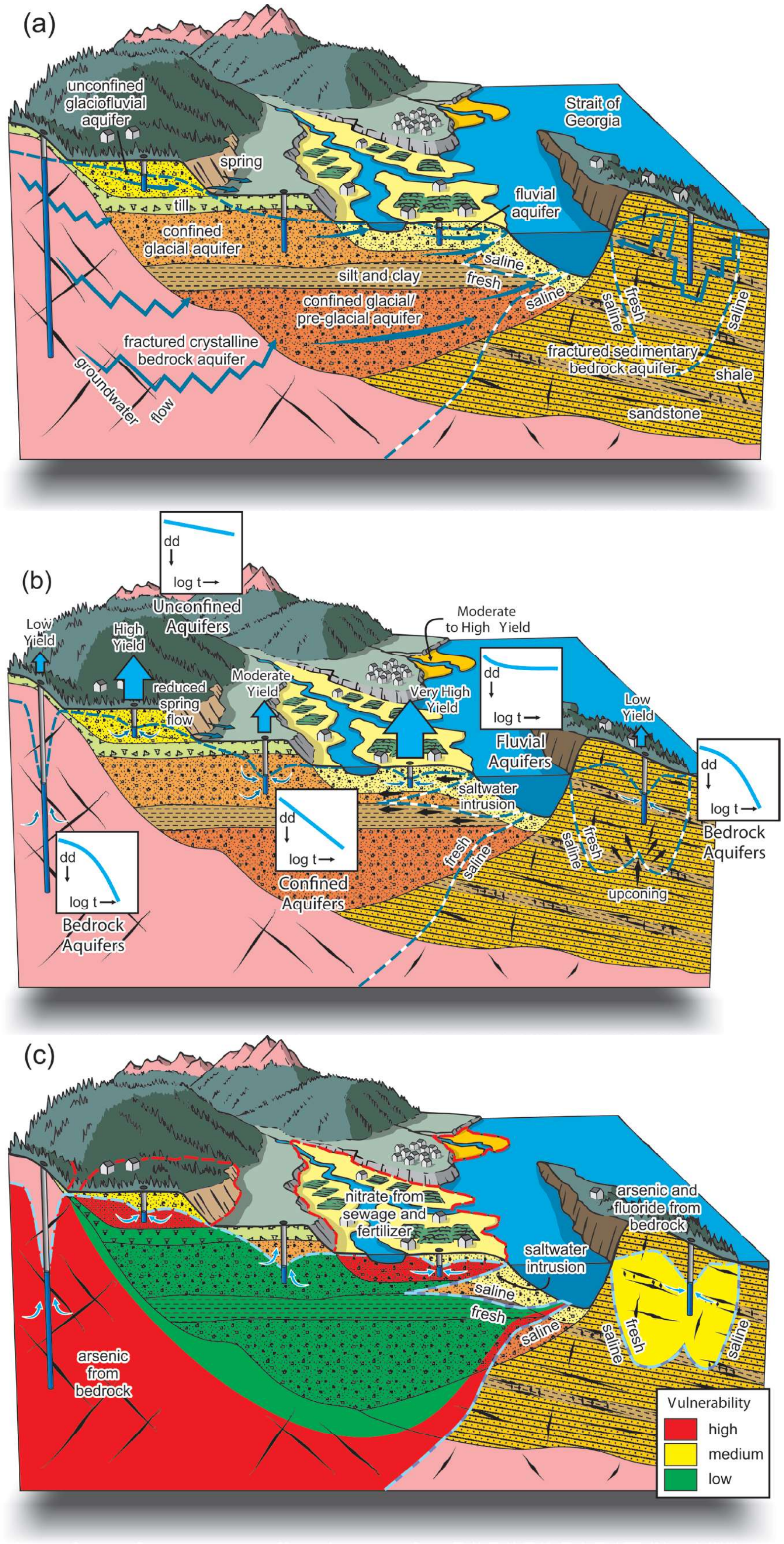

Figure 9.2 Schematic diagram of aquifers in a coastal setting, with respect to **(a)** general geologic, **(b)** hydraulic, and **(c)** vulnerability characteristics. In **Figure 9.2(b)**, the graphs represent how the groundwater level in the well is expected to draw down (dd) over time during pumping, for wells drilled into some of the different types of aquifers.

glaciofluvial sand and gravel outwash deposit formed at the end of the Fraser Glaciation (see Box 9-2). Sands and gravels were also deposited onto existing ice during glacial time. As the underlying glacier melted away, the sand and gravel deposits later collapsed to form kames (e.g., aquifers at O'Keefe Valley and Grandview Flats near Armstrong, BC).

Other important unconsolidated aquifers in the Cordillera include more recent fluvial sand and gravel examples, formed during the last 10,000 years (see the yellow-coloured aquifer in the centre of Figure 9.2a). These sands and gravels are deposited by rivers and streams and comprise floodplains (along the Fraser River, the Cowichan River in southern Vancouver Island, the Bow River near Banff, or along smaller streams), deltas (sand and gravel deposited at the mouth of Adams River, famous for its sockeye salmon run, at Shuswap Lake), or alluvial fans (the Vedder River fan at the town of Chilliwack). Although fluvial deposits tend to be unconfined, they can be locally confined in those areas where moving water has slowed and silt or clay has been deposited. Because these sands and gravels are deposited by present-day rivers and streams, they are usually hydraulically connected to the adjacent river or stream.

Sand and gravel deposits are also found along steep mountainous slopes. These colluvial deposits are primarily formed, not solely from water deposition but rather by gravity. Although colluvial deposits are coarse-textured, they tend to be less well-sorted than fluvial or glaciofluvial deposits and, with their typically limited extent and thickness, are of more limited potential as aquifers.

9.3.2 Bedrock geology

The bedrock geology of the Cordillera is extremely varied and complex due to the Region's geologic, tectonic, and volcanic history. Holland (1976) generalized the Cordillera's bedrock geology into six main types (see Figure 9.4):

1. Intrusive igneous rocks
2. Flat-lying lava, and some sedimentary rocks
3. Flat or gently-dipping sedimentary rocks
4. Folded sedimentary rocks
5. Folded and faulted volcanic and sedimentary rocks
6. Foliated metamorphic rocks

The Western system is comprised mostly of intrusive igneous rocks (the light pink rock in Figure 9.4). This is the main rock type forming the Coast Mountains. Vancouver Island, however, is comprised mostly of folded and faulted volcanic and sedimentary rocks (grey-green and yellow, respectively in Figure 9.4). The southern east coast of Vancouver Island and the Georgia Basin, including the Gulf Islands, are comprised of gently-dipping sedimentary rocks, the Nanaimo Group (Mustard, 1994), overlying older basement rocks.

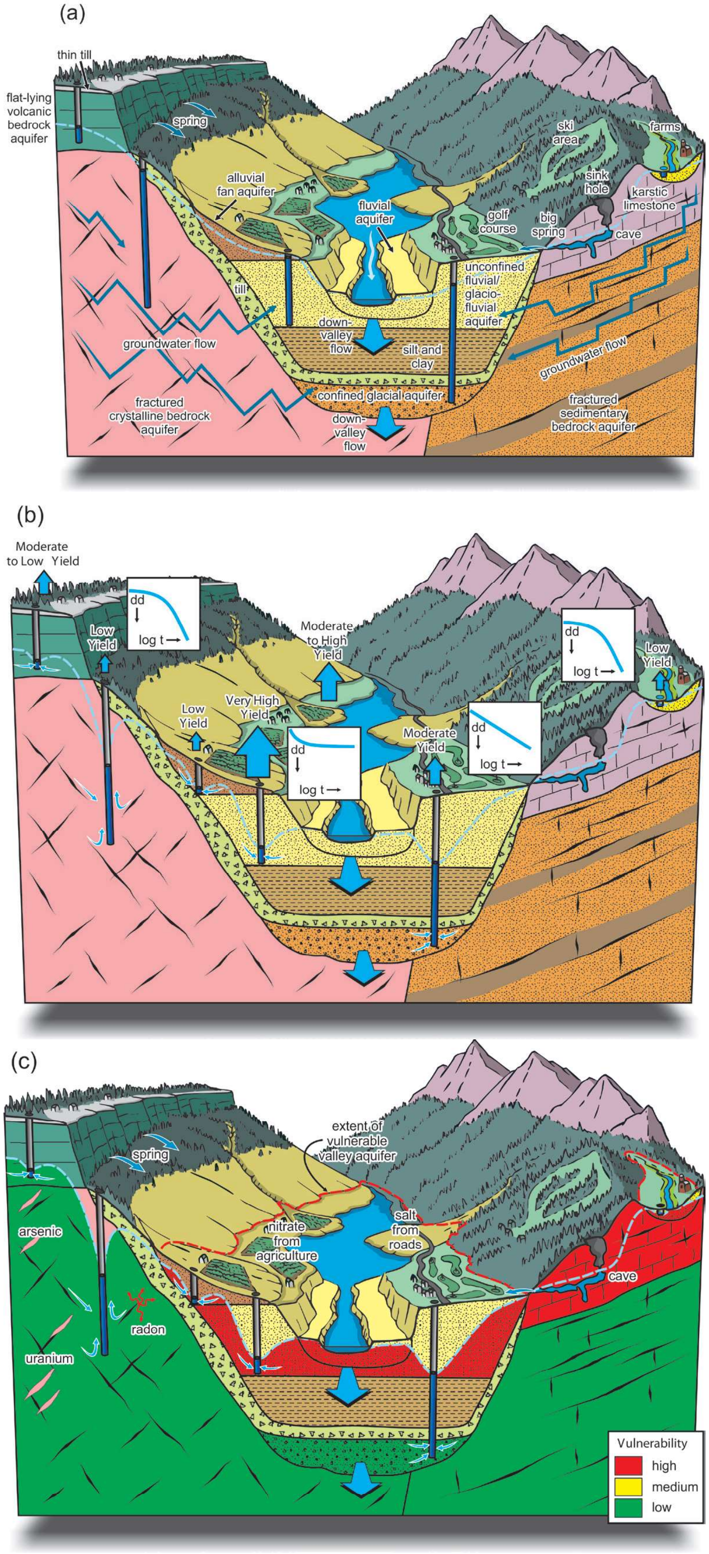

Figure 9.3 Schematic diagram of aquifers in an interior setting, with respect to **(a)** general geologic, **(b)** hydraulic, and **(c)** vulnerability characteristics. In Figure **9.3(b)**, the graphs represent how the groundwater level in the well is expected to draw down (dd) over time during pumping, for wells drilled into some of the different types of aquifers.

Groundwater from these bedrock aquifers is an important source of water supply on Vancouver Island and in the Gulf Islands.

The Eastern system is mostly comprised of folded sedimentary rocks, which form the spectacular Canadian Rocky Mountains (yellow in Figure 9.4). The Interior system is comprised of all six bedrock types, much of which is folded and faulted volcanic and sedimentary rock. A few notable exceptions are the flat-lying lava in the central interior (grey-green in Figure 9.4), foliated metamorphic rocks (as part of the crystalline rock, the light-pink in Figure 9.4) in the Okanagan and Shuswap areas, and flat or gently-dipping sedimentary rocks in the north (in the Spatsizi Plateau and in the area north of Takla Lake).

Despite the presence of different types of bedrock in the Cordillera, permeability exists mostly as a result of development of interconnected porosity, after bedrock formation. This secondary porosity developed either as fractures or faults from tectonic forces or, in limestone, dissolution cavities. Here fractures and faults developed in igneous intrusive, foliated metamorphic, and folded and faulted volcanic and sedimentary rocks, giving these types of rocks sufficient *secondary permeability* to form aquifers (see Figure 9.2a). This permeability, therefore, is generally *anisotropic* (permeability dependent on direction of groundwater flow) because the fractures or faults are discrete and have specific orientations in the bedrock. Porosity and storativity of fractured or faulted bedrock are also very low (a porosity of less than a few percent). We know fractures and faults can store and transmit groundwater because, since the 1970s, drillers, using air rotary drilling rigs, have observed and recorded the fractures and their water yield in their well record when drilling in bedrock.

Limestone sedimentary rock formations may have significant secondary permeability because of large *karst* openings or cavities in rock created as a result of fracture dissolution by water. These cavities can allow huge amounts of groundwater flow through the limestone. Although there are some springs in limestone formations in the Rocky Mountains with flows of up to several tens of litres per second (see Figure 9.3a), the occurrence and extent of karst limestone aquifers in the Cordillera are not well known.

Extensive areas of central British Columbia are underlain by relatively unaltered, flat-lying lava of Tertiary age (e.g., the Fraser and Nechako Plateaus in the central part of the Region). These are mostly basalts and individual flows that can be hundreds of metres thick. This lava serves as an aquifer because groundwater typically occurs in joints, as well as fractured and weathered contact zones between the lava flows (see Figure 9.3a).

9.4 MAJOR AQUIFER TYPES AND THEIR GENERAL CHARACTERISTICS

There are six main aquifer types (four with subcategories) within the Cordilleran Region:

Unconsolidated aquifers

Type 1 Unconfined sand and gravel aquifers of fluvial or glaciofluvial origin occurring along rivers or streams

a. Aquifers occurring along large rivers
b. Aquifers occurring along mid-size rivers or streams
c. Aquifers along small streams

Type 2 Predominantly unconfined deltaic sand and gravel aquifers

Type 3 Predominantly unconfined alluvial fan, colluvial sand and gravel aquifers

Type 4 Sand and gravel aquifers of glacial or

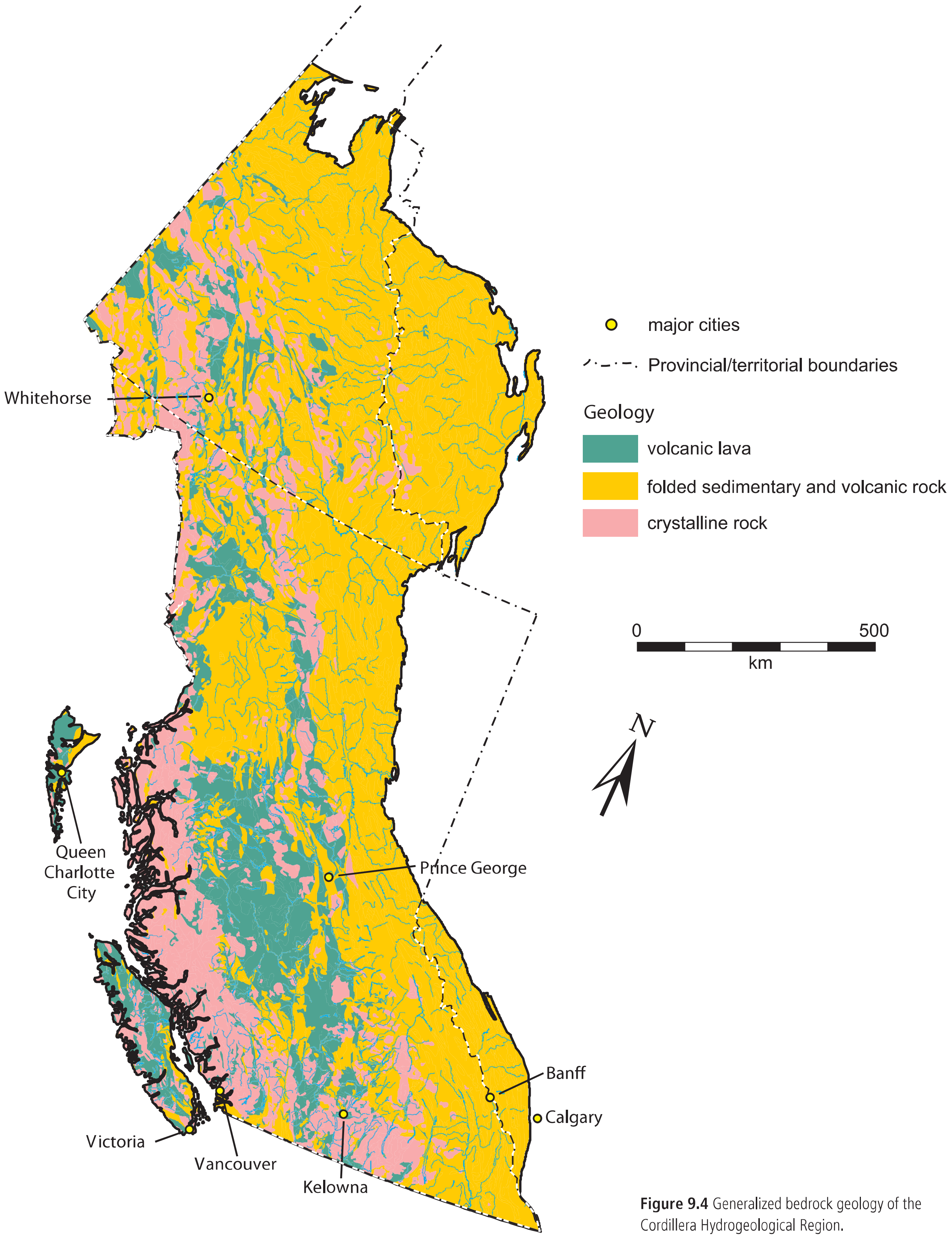

Figure 9.4 Generalized bedrock geology of the Cordillera Hydrogeological Region.

preglacial origin

  a. Unconfined sand and gravel aquifers of glaciofluvial origin (These types of aquifers do not generally occur adjacent to present-day rivers.)
  b. Confined sand and gravel aquifers of glacial or preglacial origin
  c. Confined sand and gravel aquifers associated with glaciomarine environments

Bedrock aquifers

Type 5 Sedimentary bedrock aquifers

  a. Fractured sedimentary bedrock aquifers
  b. Karstic limestone aquifers

Type 6 Crystalline bedrock aquifers

  a. Flat-lying or gently-dipping volcanic flow rock aquifers
  b. Crystalline granitic, metamorphic, metasedimentary, meta-volcanic and volcanic rock aquifers

These categories and subcategories of aquifer types are based on geologic and hydrologic, as well as data availability considerations. Many of the aquifer types are illustrated in Figures 9.2a (coastal setting in the Region) and 9.3a (interior setting in the Region). General characteristics for the types of aquifers found in the Region are summarized in Table 9.1.

The main geologic factor in these descriptions is the type of the geologic deposit which comprises an aquifer (e.g., unconsolidated sand and gravel deltaic aquifer at the mouth of a river or a plutonic granitic fractured bedrock aquifer). Geologic deposit is important because it governs an aquifer's hydraulic properties, such as hydraulic conductivity and specific storage.

Another consideration for unconsolidated aquifers is origin and location with respect to surface water bodies, such as rivers, because location may allow a direct hydraulic connection with surface water. Direct hydraulic connection can impact potential well yields because pumping may induce surface water infiltration into these aquifers.

Other possible implications include direct impact on the baseflow of rivers from well pumping or the influence of groundwater quality from the river or lake water. A practical consideration, particularly for unconsolidated buried and gravel aquifers overlain by other unconsolidated deposits, is that it is often difficult to identify their origin based on current limited well record data. It is usually challenging, for example, to determine whether a buried unconsolidated sand and gravel aquifer occurring beneath till or clay is a delta, alluvial fan, or glaciofluvial deposit. Such an aquifer would be lumped into Type 4b as a confined unconsolidated sand and gravel aquifer of glacial or preglacial origin. Similarly, there is no distinction between fluvial or glaciofluvial unconsolidated sand and gravel deposits occurring along river valley bottoms.

9.4.1 Predominantly unconfined aquifers of fluvial or glaciofluvial origin along river or stream valleys (Type 1)

Many river or stream valleys in the Cordillera have shallow, fluvial sands and gravels recently deposited by the river or stream (fluvial origin) as well as sands and gravels deposited at the end of the last glaciation period (glaciofluvial origin). Often these two types of deposits are adjacent and sometimes mixed due to re-working of the sediment. Together they form unconfined aquifers along river or stream valley bottoms.

Aquifers of this type can be further divided into three subcategories. Each has distinctly different characteristics, such as hydraulic connection to the river or stream, yield, and degree of confinement and vulnerability:

a. **Aquifers found along major rivers of higher stream order with potential to be hydraulically influenced by the river**
   These rivers are generally of low gradient and depositional energy which results in deposition of sand and silt (e.g., at the lower reaches of the Fraser River).
b. **Aquifers found along rivers of moderate stream order with the potential to be hydraulically influenced by the river** (see the yellow-coloured aquifer underlying the river in Figure 9.2a)
   These rivers have higher gradients compared to large rivers. Here the depositional energy is high enough to cause deposition of sand and gravel (e.g., the fluvial sand and gravel deposit along the Cowichan River on the east coast of Vancouver Island at Duncan, and the fluvial and terraced glaciofluvial sand and gravel deposits along Kettle River in the southern interior community of Grand Forks).
c. **Aquifers found along lower order (< 3–4) streams in narrow valleys with relatively undeveloped floodplains, where aquifer thickness and lateral extent are more limited** (e.g., fluvial or glaciofluvial deposits along a mountain stream—see the yellow-coloured aquifer on the right in Figure 9.3a).

9.4.1.1 Occurrence, identification and size characteristics

One hundred and twenty-eight (or 14.4%) of the 888 aquifers identified and classified in the Region) are unconsolidated aquifers of fluvial or glaciofluvial origin occurring along river or stream valleys. 3.8% of these are Type 1a, 8.2% are Type 1b, and 2.4% are Type 1c. Table 9.1 suggests, as might be expected, that the areal extent of these aquifers decreases from those located adjacent to large rivers to those next to small-order streams.

Aquifers occurring adjacent to large or moderate-sized rivers (Types 1a and 1b) can generally be identified from a 1:50,000 scale topographic map or from aerial photographs. These aquifers are located along the river floodplain— i.e., the generally flat valley bottom between the river and its surrounding uplands (see Figures 9.2a and 9.3a). Aquifers occurring adjacent to large rivers (the Fraser, Columbia, or Skeena) are predominantly fluvial in origin, formed by deposition of river sediments. Aquifers occurring adjacent to moderate-sized rivers (the Cowichan on Vancouver Island, the Kettle River, or the Okanagan River) can either be fluvial or fluvial/glaciofluvial in origin. The aquifer at Grand Forks, for example, occurs adjacent to the Kettle River and is comprised of both fluvial sediments deposited recently by the river and, more predominantly, glaciofluvial terraced sands and gravels deposited by the river at the end of the last glaciation. Aquifers occurring along smaller streams (Type 1c) may not be as easy to identify from 1:50,000 scale topographic maps or even aerial photographs because some may only be several tens of metres to a few hundred metres wide, and the surrounding floodplain not extensively developed.

Unconsolidated aquifers of fluvial or glaciofluvial origin occurring along river or stream valleys are generally shallow; the average median well depths are 22 m (Type 1a), 22 m (Type 1b), and 19 m (Type 1c) for the three aquifer subtypes (Table 9.1). The depth to water table is also usually shallow, with average median depths of 5 m (Type 1a), 8 m (Type 1b), and 9 m (Type 1c), respectively.

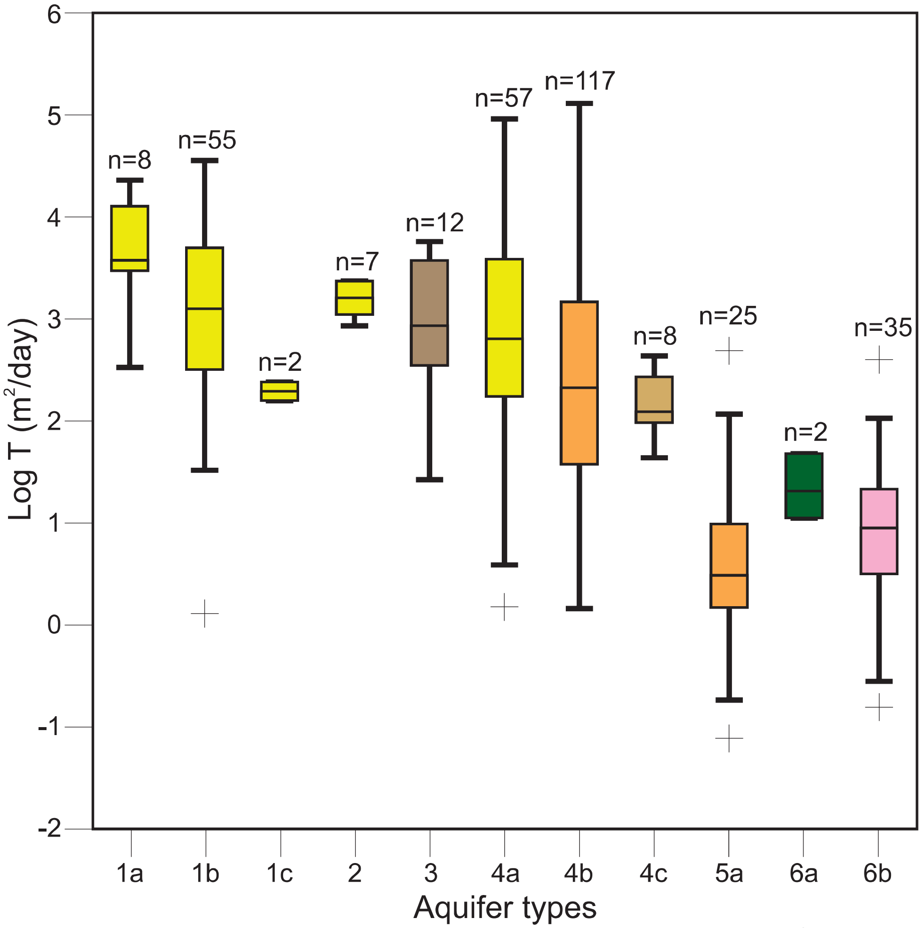

Figure 9.5: Graph depicting maximum, minimum, and geometric mean log transmissivity reported for each aquifer type where data are available.

9.4.1.2 Productivity characteristics and importance as a water supply

Aquifers adjacent to large or moderate-sized rivers (i.e., Types 1a and 1b) can be some of the most productive aquifers in the Cordillera because they comprise sands, or sands and gravels, which are highly permeable (reported transmissivities can range up to over 22,000 m^2/d for aquifers adjacent to major rivers and over 36,000 m^2/d for aquifers along moderate-sized rivers, with geometric mean transmissivities of 4,500 to 1,300 m^2/d, respectively (Table 9.1 and Figure 9.5).

Reported well yields for these aquifers range up to 92 L/s (Type 1a) or 215 L/s (Type 1b), with average median reported yields of 3.5 L/s (Type 1a) and 5.7 L/s (Type 1b), respectively. Another factor which augments an aquifer's productivity is the direct hydraulic connection between the aquifer and its adjacent river. Pumping lowers the hydraulic head in the aquifer and, in turn, can induce infiltration of river water thereby stabilizing pumping drawdown (Figures 9.2b and 9.3b). In such cases, there is also the potential for any significant pumping to negatively impact streamflows in moderate-sized rivers, particularly during summer and fall low flow season.

Aquifer adjacent to moderate-sized rivers, provide drinking water to many communities. Some notable examples include the fluvial aquifer along the lower reaches of the Nechako River (aquifer classification # 92), which provides the water for the City of Prince George (population 77,000); the fluvial aquifer along the lower reaches of the Cowichan River (aquifer classification # 186), which supplies the City of Duncan (population 5,000) on the southern east coast of Vancouver Island; the glaciofluvial aquifers along the Okanagan River in the southern Okanagan Basin (aquifer classification # 254 and 255—Toews, 2007; Wei, 1985; also see Box 6-3 in Chapter 6), which supply the Town of Oliver and surrounding agricultural area; and the fluvial aquifer along the Similkameen River (aquifer classification # 259),

which supplies small towns and farms of the area.

Most aquifers adjacent to large rivers are located along the Fraser River, and with the exception of the aquifer at Quesnel which supplies that town (aquifer classification # 117), most are not heavily used. Other developed aquifers of this type occur near Windermere, along the Columbia River in the East Kootenay, and at Terrace, along the Skeena River, in northwest coastal BC.

Aquifers adjacent to small creeks and streams, due to their small size (and possibly of lesser thickness), are less important sources of community water supply. Consequently, they are less well studied. These aquifers, however, remain an important local water supply for residents, small communities, and farms. Reported well yields range up to 101 L/s and the average median reported yield is 4 L/s. Transmissivity values are available for only 2 aquifers—240 m^2/d (aquifer classification # 482) and 160 m^2/d (aquifer classification # 713). One of the most important aquifers of this type is along the Bonaparte River, which supplies the Village of Cache Creek (aquifer classification # 134; west of Kamloops, with a population of just over 1,100). Although there is generally little data for these types of aquifers, it is possible that some of them may be in direct hydraulic connection with the adjacent creek or stream.

9.4.1.3 Aquifer vulnerability and water quality characteristics

The generally shallow depth of unconsolidated aquifers of fluvial or glaciofluvial origin located beside rivers or streams means that these types of aquifers are usually unconfined or partially confined. Most of them (95%) have been classified as highly (71%) or moderately (24%) vulnerable. The degree of partial confinement seems to be greatest for those aquifers adjacent to small creeks and streams (Type 1c aquifers). Some of these may result from interlayering with less permeable deposits occurring along valley bottom slides.

Local nitrate concerns have been reported in three unconfined sand and gravel aquifers adjacent to moderate-sized rivers: Merritt (aquifer classification # 74); Grand Forks (aquifer classification # 158; Maxwell et al., 2002; Wei et al., 1993); and near Oliver (aquifer classification # 254; Hodge, 1992). Fluoride is known to occur near Cranbrook in the East Kootenay (aquifer classification # 538) and arsenic levels approaching drinking water guideline limits has been detected in the Chilliwack-Rosedale area (aquifer classification # 6; Graham, 2006).

Aquifers adjacent to large rivers appear to have higher proportions of reported concerns related to elevated iron and manganese. One hypothesis suggests that groundwater flow in these aquifers may be relatively slower (due to lower gradient, finer, less permeable sand, and existence of confining layers and lenses at depth) which can result in the possibility of less oxygenated environments and greater dissolution of iron and manganese into the groundwater.

9.4.1.4 Profile: Aquifer at Grand Forks

The unconsolidated aquifer at Grand Forks (aquifer classification # 158), a prime example of a Type 1b aquifer, is located along the Canada-US boundary adjacent to the moderate-sized Kettle River. This aquifer consists of terraced glaciofluvial sands and gravels, and serves as the water supply for the City of Grand Forks and surrounding irrigation districts (population ~8,000). Hydrogeological mapping and modelling work by Allen (2001; 2000), Allen et al. (2004a; 2004b), Scibek and Allen (2006b; 2006c), and Scibek et al. (2007) indicates that groundwater flow is in close hydraulic connection to the Kettle River (see Box 4-1 in Chapter 4 for a discussion of direct and indirect recharge of the Grand Forks Aquifer). Regional groundwater flow is from west to east, in the general direction of the Kettle River flow. The Kettle River appears to be an important source of recharge at the aquifer's upgradient (west) end, although groundwater discharges back out into the Kettle River at the aquifer's downgradient (east) end where the aquifer's thickness pinches out.

There are 24 public water supply wells supplying water to the city, the surrounding irrigation districts, and mobile home parks (Wei, 1999). Reported well yields range up to 189 L/s and transmissivity ranges up to 11,000 m^2/d. Most of the high-yielding wells are located in the western half of aquifer, where the thickness is greatest (up to 80–100 m thick; Wei et al., 2004). Under pumping conditions, significant water infiltration from the Kettle River into the aquifer is expected under regular pumping conditions. Numerical modelling (Allen, 2001; 2000) indicates significant water increase from the Kettle River in the water budget under pumping conditions. Capture zones from all the large-capacity pumping wells (some located more than a kilometre away from the river) extend to the Kettle River. Actual pumping test data from these wells reveal stabilization of the water level in the well during pumping, an indication that the Kettle River is connected to the aquifer and is an important source of infiltration recharge during pumping.

The Grand Forks aquifer illustrates the generally high vulnerability of these aquifer types. Mapping of aquifer vulnerability using DRASTIC (Aller et al., 1986) reveals that most of the Grand Forks aquifer is highly vulnerable, with DRASTIC scores of 140 or greater. The eastern part of the aquifer, where depth to water is the shallowest (within 10 m from the ground surface), has the highest vulnerability (DRASTIC score of generally 180 or greater). Elevated nitrate levels exist locally within the aquifer as a result of nutrient leaching from human activities. (Maxwell et al., 2002; Wei et al., 1993).

9.4.2 Predominantly unconfined deltaic sand and gravel aquifers (Type 2)

9.4.2.1 Occurrence, identification and size characteristics

Twenty-three of the 888 aquifers (or 2.6%) identified and classified in the Region are developed sand and gravel deltaic aquifers (Type 2). This type excludes older deltaic aquifers buried at depth under till/ silt, or clay deposits for the reasons stated in section 9.4 (buried deltaic aquifers are categorized as Type 4b). Type 2 aquifers also exclude larger river deltaic environments (e.g., the lower hydraulic energy environment found in the Lower Fraser River where aquifers are categorized as Type 1a) and those aquifers found in delta kame deposits (Type 4a).

Deltaic aquifers, as the name implies, are commonly found in deltas where a stream or smaller river flows into a standing body of water. Of the 23 deltaic aquifers in the inventory, the ocean is the standing body of water for 13. Deltas can be readily identified from 1:50,000 scale topographic maps by their distinguished deltaic or fan shape (see Figure 9.2a). A delta in profile is much less steep than an alluvial fan, and the material, well-sorted by weight and volume, often results in definite graded layers sloping to standing water. Seasonal variations in stream discharge can result in further stratification of the deposits, as a stream's higher and lower hydraulic energy affects where different materials are deposited.

Type 2 deltaic aquifers are predominantly shallow and unconfined, comprised of sand and gravel and usually local in extent, ranging in area from <1 km^2 to 19 km^2, averaging 5 km^2 (Table 9.1). Well depth and depth to water in a deltaic aquifer are generally less than in alluvial fan aquifers. Wells drilled into deltaic aquifers range in depth from 2 m to 68 m deep, with an average median depth of 12 m. The water table depth in deltaic aquifers is generally shallow (average median depth to water of 3 m) but ranges from <1 m to 43 m.

9.4.2.2 Productivity characteristics and importance as a water supply

Hydrogeologists have determined that it is generally more feasible to develop wells from deltaic aquifers to supply a greater volume of water than that required for domestic use. Well yields for deltaic aquifers have been reported to be as high as 44 L/s: the Lost Shoe Creek aquifer serving the town of Ucluelet, on the west coast of Vancouver Island, near Pacific Rim National Park, has an average median well yield of 6.1 L/s. Reported transmissivity values (7 values from 5 aquifers) range from a minimum of 960 m^2/d to a maximum of 2,400 m^2/d, with a geometric mean of 1,500 m^2/d (see Table 9.1 and Figure 9.5).

In addition to meeting private domestic needs, these aquifers typically supply water to small communities (e.g., aquifer classification #

159—Ucluelet, #189—Mesachie Lake, and #419—Fanny Bay), water utilities, farming, commercial and industrial operations (aquifer classification #67—North Vancouver) including fish hatcheries (aquifer classification # 297, 412, 414, and 419).

In those locations where direct hydraulic connection exists with surface water, significant pumping from wells can induce surface water infiltration into the aquifer in the direction of the pumping wells. This connection may allow higher capacity wells to be developed because pumping drawdown usually reaches equilibrium within hours or days. When, however, the direct hydraulic connection exists with the ocean, there is always the concern that over-pumping could result in saltwater intrusion.

Although deltaic aquifers are fairly productive (most of the deltaic aquifers in the inventory are classified as highly or moderately productive), one aquifer in the inventory was reported to have a water quantity concern. The Trout Creek aquifer, underlying the delta on Okanagan Lake (aquifer classification # 297), is comprised of a higher than average percentage of lower-permeability silts and clays as compared to most developed deltaic aquifers within the Cordillera. A lower energy hydraulic regime and source materials of lower permeability may explain the many wells reported as dry holes, or those wells within this aquifer which report lower than average yields.

9.4.2.3 Aquifer vulnerability and water quality characteristics

The unconfined or partially confined nature of deltaic aquifiers is due to a number of factors including aquifier composition, genesis and shallow depths. Most developed deltaic aquifers in the BC Cordillera have been classified as highly (71%) or moderately (29%) vulnerable.

Although half of the developed deltaic aquifers within the Cordillera have overlying commercial or industrial activity, only isolated reports of water quality concerns have been identified. Four of the aquifers support salmonoid fish hatcheries. Three of these hatcheries (sourcing groundwater from aquifers #412, 414, and 419) are located on the east coast of Vancouver Island and operate to enhance Pacific salmon stocks. The other hatchery (sourcing groundwater from aquifer #297) in Summerland (Okanagan Valley) is one of several provincial trout hatcheries operated to support the provincial trout stocking program for recreational fisheries. Many of the Cordillera's deltaic aquifers are located in rural areas and have minimal land use activities over them.

As a general rule, the natural flow rate of fresh water moving to the sea in coastal deltaic aquifers is sufficient to mitigate any negative effects from existing pumping wells (e.g., saltwater intrusion). One well however, constructed in the Sechelt area (aquifer classification # 556), was reported to have "very brackish" water at depth, although we do not know whether this brackish water is due to over-pumping or occurs naturally.

9.4.3 Alluvial, colluvial sand and gravel aquifers (Type 3)

9.4.3.1 Occurrence, identification and size characteristics

Fifty-six of the 888 aquifers identified and classified in the Region (6.3%) are developed alluvial fan aquifers. To date there have been no colluvial aquifers identified and classified within the Region. Older alluvial fan aquifers buried beneath till, silt or clay are categorized under sand and gravel aquifers of glacial or preglacial origin aquifer (Type 4b).

Alluvial fan aquifers typically occur at or near

the base of mountain slopes, either alongside valley bottoms, or, if formed during the last period of glaciation, raised above the valley floor (see the alluvial aquifer in Figure 9.3a). Alluvial fans are formed by sediment deposition from tributary streams as they enter the main valley. Sediments of alluvial fans tend to be coarse, somewhat sorted (e.g., sands and gravels) and permeable, particularly at the head or apex of the fan; sediments tend to be finer and less permeable at the fan's distal end. Alluvial fans can be readily identified from a 1:50,000 scale topographic maps by their distinguished fan shape (see Figure 9.3a). Alluvial fan aquifers are usually local in extent, ranging in area from <1 km^2 to 54 km^2, with an average area of 5 km^2 (Table 9.1).

Wells drilled into alluvial fan aquifers range in depth from 1 m to 141 m deep, with an average median depth of 24 m. The water table depth in alluvial fan aquifers is usually shallow, with an average median depth to water of 9 m, although it can range from <1 m to 99 m.

9.4.3.2 Productivity characteristics and importance as a water supply

Developing wells drilled into alluvial fan aquifers to supply domestic quantities of water has usually proved feasible. Reported well yields can range up to a maximum of 189 L/s (Vedder River Fan aquifer at the City of Chilliwack, 85 km east of Vancouver), with an average median well yield of 4 L/s. Reported transmissivity values (14 values from 8 aquifers) range from a minimum of 25 m^2/d to a maximum of 5,600 m^2/d, with a geometric mean of 710 m^2/d (see Table 9.1 and Figure 9.5).

Because many alluvial fan aquifers are usually small and shallow, they are typically used to supply water to farming and/or commercial operations, and smaller communities. One of the most important alluvial fan aquifers in the Region, from a water supply perspective, however, is the Vedder River Fan Aquifer, which is the water supply source for the City of Chilliwack (population 73,000). This aquifer is 25 km^2 in area and can yield up to 200 L/s to municipal wells. One of the reasons for the Vedder River Fan Aquifer's productivity is its location, adjacent to the Vedder River. It is either in direct hydraulic connection with the river or receives infiltration recharge from the river immediately upstream (one of the City of Chilliwack's municipal well fields is located near the river, at the head of the fan). When direct hydraulic connection exists in alluvial fan aquifers, significant pumping from wells in proximity to surface water can induce infiltration of surface water into the aquifer toward the pumping wells. This connection may allow higher-capacity wells to be developed as pumping drawdown usually reaches equilibrium within hours or days. A number of alluvial fans (aquifer classification # 387, 388, 393, and 394) are sources of water supply for the Resort Municipality of Whistler.

9.4.3.3 Aquifer vulnerability and water quality characteristics

Alluvial fan aquifers are usually characterized as unconfined, or partially confined, as a result of their location at the land surface, and their generally shallow depth. Most developed alluvial fan aquifers in the BC Cordillera (86% of the alluvial fan aquifers) have been classified as highly (54%) or moderately (32%) vulnerable. The Vedder River Fan Aquifer's vulnerability was mapped by Golder Associates (1997) using the GOD vulnerability mapping methodology (Foster, 1987), as part of the work in developing a well protection plan for the City of Chilliwack. This mapping indicated that the Vedder River Fan Aquifer is of “high” to “extreme” vulnerability throughout.

To date, there are only isolated reports of water quality concerns for developed alluvial fan aquifers, a likely reflection of the current lack of intensive land use activities over these generally small, largely rural unconfined water sources.

9.4.4 Sand and gravel aquifers of glacial or preglacial origin (Type 4)

This category contains known surface glaciofluvial sand and gravel aquifers, other sand and gravel aquifers identified in well records as occurring underneath till or glaciolacustrine deposits, and glaciomarine sand, sand and gravel aquifers. These aquifers were deposited by glacial meltwater streams either directly in front of, or in contact with glacier ice. These types of aquifer occur throughout the Region, varying widely in size and represent two-thirds of all unconsolidated aquifers within inventory. The category is subdivided further into three subcategories:

(a) Unconfined glaciofluvial outwash or ice contact sand and gravel aquifers, generally formed near or at the end of the last period of glaciation (see the yellow-coloured aquifer on the left in Figure 9.2a). The Abbotsford-Sumas Aquifer, 65 km east of Vancouver (see Box 9-2 in this chapter) is perhaps the most well-known and studied aquifer of this type in the Cordilleran Region.

(b) Confined sand and gravel aquifers underneath till, in between till layers, or underlying glaciolacustrine deposits (see the orange-coloured aquifers in Figures 9.2a and 9.3a). The

Quadra Sand, which occurs in the Georgia Depression on the east coast of Vancouver Island and along the southern mainland coast, is an excellent example of a confined glaciofluvial sand and gravel aquifer. It is comprised of advanced glaciofluvial sand and gravel deposited as the glacier ice advanced south along the Georgia Depression. Other aquifers occur between till layers, indicating they were deposited during glaciation. Still others may be fluvial, alluvial or colluvial deposits from a time prior to glaciation (and therefore lie underneath till or glaciolacustrine deposits). Unless a confined sand and gravel aquifer has been well studied, it is often hard to determine its geologic origin and morphology based on limited data. Therefore, any water-bearing sand and gravel aquifer occurring underneath till, in between till layers or under glaciolacustrine deposits has been included in this subcategory.

(c) Sand and gravel aquifers occurring underneath known sand, silt and clay deposited under a marine environment near the coast. The few known aquifers of this category occur in the marine sediments at depth in the Fraser Lowland near the mouth of the Fraser River, southeast of Vancouver where marine sediments are interbedded with estuarine and fluvial deposits consisting of fine sand, silt and clayey silts (Halstead, 1986; 1978). The presence of marine shells and remains of other organisms in these aquifers usually confirms their marine origin.

9.4.4.1 Occurrence, identification and size characteristics

Unconsolidated aquifers of glaciofluvial or preglacial origin comprise 413 of the 888 aquifers identified and classified in the Region (46.5%; 7.9% Type 4a, 37.6% Type 4b, and 1.0% Type 4c). Their general hydrogeological characteristics are summarized in Table 9.1. The extent of unconfined Type 4a aquifers can be readily identified from available surficial geology and soils mapping. Known Type 4a aquifers range from <1 to 90 km^2 with an average area of 8 km^2 (Table 9.1) and well depths ranging from 3 to 112 m with an average median depth of 24 m. Mapping the extent of confined Type 4b and 4c aquifers requires greater subsurface information from well records, and examination of geologic exposures in stream valleys or escarpments. Confined sand and gravel aquifers can vary considerably in size and may be relatively large as elongate deposits buried in major river valleys or along coastal areas. Mapped areas for Type 4b and 4c aquifers range from <1 to 332 km^2 and 2 to 194 km^2, respectively with average areas of 13 and 32 km^2, respectively. Well depths for Type 4b aquifers range from 4 to 378 m (average median depth of 39 m) and from 6 to 130 m (average median depth of 61 m) for Type 4c aquifers. The average median depth to water levels in Type 4a aquifers is 10.7 m. Water levels can be within a few metres of land surface or relatively deep (several 10's of metres) depending upon topographic conditions, aquifer thickness and subsurface flow conditions. The average median depths to water levels in confined Type 4b and 4c aquifers are 18 m and 14 m, respectively.

9.4.4.2 Productivity characteristics and importance as a water supply

Glaciofluvial aquifers are an important source of water. They occur throughout the Region and can be found near surface and within economical depths for drilling. The larger and more productive aquifers are able to supply all sectors including industrial, municipal, agricultural and domestic. Reported median well yields for unconfined Type 4a aquifers range up to 126 L/s with an average median of 3 L/s. Highest individual well yields for Type 4a aquifers of 126 L/s are reported for the Abbotsford-Sumas Aquifer and at Mackenzie in northern British Columbia. Reported median well yields for confined Type 4b aquifers range from 4 to 265 L/s with an average median of 2.3 L/s. Maximum well yield of 265 L/s was reported for a well completed in an exceptional confined aquifer under flowing artesian conditions at Fort St. James situated at the mouth of Stewart Lake in northern British Columbia. Reported median well yields for confined Type 4c aquifers range up to 31.5 L/s with an average median of 0.6 L/s. The maximum well yield reported for a Type 4c aquifer in the Hazelmere Valley, 40 km southeast of Vancouver, is 31.5 L/s.

Transmissivity values for Types 4a and 4b aquifers show a wide range from 1.6 to 89,000 m^2/d and 1.5 to 120,000 m^2/d respectively. The geometric mean transmissivity for Type 4a aquifers is 690 m^2/d, for Type 4b aquifers 250 m^2/d, and for Type 4c aquifers is 150 m^2/d (see Table 9.1 and Figure 9.5).

9.4.4.3 Aquifer vulnerability and water quality characteristics

The unconfined or partially confined nature of glaciofluvial Type 4a aquifers makes them especially vulnerable to contamination from land use activities when water tables are relatively shallow (Chesnaux and Allen, 2007; Chesnaux et al., 2007; Wassenaar, 1995; Wassenaar et al., 2006). As a result most aquifers (79%) have been classified as highly vulnerable while 21% aremoderately vulnerable. Local and regional water quality concerns, including nitrates and bacteria, are reported for 8 (11%) of the Type 4a aquifers. Major aquifers affected occur at Abbotsford and Osoyoos (in the Okanagan Basin).

Most confined Type 4b aquifers (74%) are classified as low vulnerability with 25% as moderately vulnerable. There was only one aquifer (out of the 333 Type 4b aquifers) with reported local water quality concerns related to nitrate (aquifer #356 in the north Okanagan). The majority (89%) of Type 4c aquifers are classified as low vulnerability: 11% are regarded as moderately vulnerable, with a report of only one aquifer (aquifer #32 in the Lower Mainland) experiencing local chloride concerns.

9.4.5 Sedimentary bedrock aquifers (Type 5)

9.4.5.1 Occurrence, identification and size characteristics

There are 101 (11.4% of 888 mapped aquifers) developed sedimentary bedrock aquifers identified and classified in the Region (see the brown-coloured aquifers in Figures 9.2a and 9.3a). These are divided into two subcategories (a) fractured sedimentary rocks (95 aquifers) and (b) (potential) karstic limestone (6 aquifers).

The Cordillera Region's complex tectonic history has given rise to a diversity of geological settings in which sedimentary rocks are found in association with old sedimentary basins, as volcanic sediments, or as pockets/slivers of exotic terrains that were accreted onto the North American landmass. The Rocky Mountains are comprised primarily of sedimentary rock, ranging from Proterozoic clastics and carbonates deposited in ancient continental basins, to Cambrian and/or Jurassic shelf and slope carbonate and shale deposited on and near the ancient North American continental margin, to Late Jurassic, and to early Cenozoic marine and/or non-marine clastics eroded from the uplifting Omenica and Foreland Belts (Monger and Price, 2002). These rocks were folded and thrust eastward over the ancient continental margin to form the Rocky Mountains.

Various rock assemblages within the Omenica, Intermontane and Coast Belts are usually metamorphosed, but also include sedimentary rocks formed in island arc and marginal basin settings, or deposited during uplift (Monger and Price, 2002).

Sedimentary rocks within the Insular Belt range in age from the latest Proterozoic to mid-Cretaceous, formed mainly in mostly island arc settings, to mid-Cretaceous and younger clastics eroded from the Coast Belt, to late Jurassic to Holocene clastic-rich accretionary complexes (Monger and Price, 2002).

Fractured sedimentary bedrock aquifers classified within the region range significantly in size from <1 km^2 to 700 km^2, with an average size of 24 km^2 (Table 9.1). Wells drilled into these aquifers range in depth up to a maximum of 331 m, with an average median depth of 56 m. The water table depth is moderate (average median depth to water of 10 m) but can range from 0 m to 155 m. The most likely reason for such large differences is fracturing variations encountered during drilling. One single fracture situated at relatively shallow depth can provide adequate supply for domestic purposes. However, when productive fractures are not encountered at shallow depth, it is necessary to drill deeper. It is not uncommon in fractured sedimentary rock to have two immediately adjacent wells that are vastly different in depth. Fractures at depth often exhibit artesian pressures, leading to shallower water level depths and, sometimes, even flowing artesian conditions. Likewise, springs are typically found in association with fractures that extend from depth up to surface. This can lead to thermal springs (e.g., Banff, Radium, etc.; see Allen et al., 2006; Grasby et al., 2000; 2002; van Everdingen, 1972), when the temperature at depth is high and the transport to surface rapid.

Karst limestone aquifers are often productive aquifers with hard water chemistry. Karst limestone aquifers are capable of moving large quantities of water over great distances in relatively short periods of time. Karst environments can be identified by features such as cave entrances, sinkholes, sinking streams, and karst springs. Occurrence of karstic limestone aquifers in the Cordillera has not been well studied. Carbonate rocks (approximately 80% of which exists as limestone, 20% as dolomite) of variable composition make up approximately 10% of the Cordillera landscape. Most of these soluble rocks are found as extensive belts along the Rocky Mountains, the Purcell Mountains, the southern end of the Interior Plateau, east of Takla Lake in the Cassiar Mountains, on Vancouver and the Queen Charlotte Islands, in addition to other smaller occurrences scattered throughout the Region. The existence of karst springs in the Kananaskis region of the Rockies and limestone caves at Horne Lake Caves Provincial on Vancouver Island suggest karst limestone aquifers may exist in those areas.

The occurrence of potential karstic limestone aquifers has been inferred by overlaying sedimentary bedrock aquifer polygons with a karst potential map (available through the BC Ministry of Forests; Stokes, 1994). Potential karst polygons were initially screened so as to include only those polygons where the likelihood of karst-forming bedrock occurrence was greater than 50% (highest rating), and the estimated intensity of karst development potential was moderate to high. Whenever an 80% overlap between bedrock aquifer polygons and potential karst polygons was found, the aquifers were categorized as potential karstic limestone aquifers.

Based on this approach, six potential karstic limestone aquifers (Type 5b), ranging in size from 2 km^2 to 19 km^2, with an average size of 8 km^2 (Table 9.1) have been identified (see the example column in Table 9.1), although the well logs for these aquifers do not report the existence of solution channels (larger void spaces). The aquifer size likely reflects the area of well development and not the full extent of karstic limestone formation. Wells drilled into these aquifers range in depth up to a maximum of 183 m, with an average median depth of 75 m. The water table depth is moderate (average median depth to water of 16 m) but ranges from <1 m to 96 m.

9.4.5.2 Productivity characteristics and importance as a water supply

Sedimentary bedrock aquifers found within the region typically have limited *primary porosity*, mostly because the rocks are quite old and may have undergone some minor chemical and physical alteration (i.e., low-grade metamorphism). Consequently, aquifer productivity hinges on the degree to which they are fractured or, in the case of karstic limestone, the degree to which dissolution has created solution channels (*secondary porosity*).

Deformation following deposition or emplacement of sedimentary rocks invariably leads to fracturing at a range of scales, from micro-scale cracks to regional-scale faults and fracture zones. Fractures are heterogeneously distributed, depending on the tectonic history of an area. When these fractures are open, they provide pathways for groundwater flow and enhance the aquifer's local permeability. Several factors modify the degree of fracture openness: 1) the amount of precipitate infill, 2) the degree to which mineral dissolution has enhanced fracture size, and 3) the direction of the current stress regime.

Mineral precipitation (e.g., calcite) usually occurs in fractures as a result of changes in the chemical conditions encountered during fluid flow. Such precipitates can essentially seal off fractures and render them impermeable. Similarly, minerals previously precipitated within fractures may dissolve, leading to enhanced permeability. Such dissolution within carbonate rocks, such as limestone, may be so extreme as to lead to open dissolution channels, cavities, and caves, typical of karstic terrain. Current stress regime also plays a major role in determining if fractures are open or closed. Fractures oriented perpendicular to regional compressive stresses will tend to be closed, whereas those oriented perpendicular to regional tensional stresses will be open. Thus, in addition to identifying the direction and intensity of fracturing within an aquifer, it is also important to consider other factors which may serve to modify its permeability.

Sedimentary bedrock aquifers are generally a solid source for the development to supply domestic water even though they have significant ranges in productivity. Reported well yields in fractured sedimentary bedrock aquifers range up to a maximum of 12.6 L/s (Ford Creek area southeast of the City of Chilliwack), with an average median yield of 0.3 L/s. Reported transmissivity values (25 values from 11 aquifers) range from a minimum of 0.1 m^2/d to a maximum of 480 m^2/d, with a geometric mean of 3.7 m^2/d (see Table 9.1 and Figure 9.5). Thus, aquifer productivity is generally quite good but typically lower than that of unconsolidated aquifers.

Well productivity is generally enhanced when the well intersects a fracture zone. On the Gulf Islands, higher-yielding wells have been associated both with mapped lineaments corresponding to fracture zones and near contacts between formations (Mackie, 2002; Allen et al., 2002). Pumping tests conducted in fractured rock aquifers often display linear type flow behaviour, where drawdown effects propagate along the length of a fracture, as opposed to radially away from the well (Allen et al., 2003). This type of flow behaviour occurs because the fracture zone is more permeable than its surrounding rock matrix. In such situations, it is not uncommon for transmissivity values to be higher, on average, although there is also a greater likelihood of interference between wells situated along the same fracture.

Productivity of karstic limestone aquifers can also be expected to be quite high, although no data is currently available to confirm this. Well yields in the six potential karstic limestone aquifers of the region range from 0.01 L/s to 1.26 L/s, with an average median yield of 0.3 L/s— similar to other fractured bedrock types. To date, we have no available estimates of transmissivity for these potential karstic limestone aquifers.

Another well within a karst aquifer of the Dead Man Flats, Bow River valley, Alberta, had a reported yield of 0.3 L/s. Although this well is situated near a karst spring flowing at 11.7 L/s (Toop and de la Cruz, 2002), it failed to tap the spring's source. Reported flows of 30 L/s and 40 L/s from other karst springs (Railside and Watridge springs[3] respectively) in the Kananaskis area, Alberta, suggest that future productive karst aquifers to be identified and developed.

9.4.5.3 Aquifer vulnerability and water quality characteristics

Fractured sedimentary bedrock aquifers have been mapped as unconfined, partially confined, and confined aquifers. The majority are mapped as partially confined, due to the absence of a continuous low-permeability cover layer and a hydraulic response that suggests mostly confined conditions (i.e., these aquifers display a Theis type response for at least part of a pumping test). Consequently, most (44%) are of moderate vulnerability, with roughly equal distribution between high vulnerability (26%) and low vulnerability (29%). Isolated, local and regional reports of water quality concerns have been identified: the most commonly reported local is saltwater (13 cases). Regionally, saltwater is a problem in four aquifers. Other water quality concerns include sulphur, fluoride, and manganese and iron (Allen and Matsuo, 2001; Allen and Pelude, 2001; Kohut et al., 1986). Most of these concerns have been identified in the Gulf Islands, where water quality is affected by proximity to the coast (saltwater intrusion) (Allen and Suchy, 2001b; Dakin et al., 1983) and geological processes such as submergence (Liteanu, 2003), which have given rise to unique water chemistry (Allen and Suchy, 2001b; Allen, 2004; Earle and Krogh, 2006). The vulnerability of the Gulf Islands aquifers (Journeay et al., 2003) was linked to aquifer architecture (Mackie, 2002), and mapped by Denny et al. (2007) to take into account regional structure. Ffracture zones and faults play an important role in determining aquifer vulnerability due to saltwater intrusion and to surface contamination (see Box 6-2 in Chapter 6).

Of the six potential karstic limestone aquifers within the Region, two have been identified as

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[3] For more information on Watridge spring, please see Hike # 71 in Gillean Daffern's *Kananaskis Country Trail Guide, Volume 1* (1996).

confined and four have unknown confining conditions. None have low vulnerability, 50% are of moderate vulnerability and 50% are of high vulnerability. There is a greater likelihood that karstic limestone aquifers will have moderate to high vulnerability due to the potential for solution cavities (created by infiltrating water from surface) which can extend to the surface thus creating potential pathways for surface contaminants to enter the aquifer. Rapid transit times and limited natural cleansing and filtering mechanisms associated with solution channels can readily allow transport of any contaminants or sediments very quickly from one area to another. There are no reports of quality or quantity issues in any of the six potential karst limestone aquifers found in the BC portion of the Cordillera.

9.4.5.4 Profile: Fractured sedimentary aquifers of the Gulf Islands

The most extensively studied Type 5a sedimentary bedrock aquifers in the Cordillera are those located on the Gulf Islands, in the Strait of Georgia on the southwest coast of British Columbia. These islands range in area from approximately 20 to 60 km^2, with elevations up to 400 m above sea level. Their topography is primarily characterized by northwest-southeast trending ridges and valleys. Rocks comprising the islands belong to the *Late Cretaceous* Nanaimo Group (~91–66 Ma) and consist of alternating sequences of interbedded sandstone-dominant and mudstone (or siltstone)-dominant formations (Mustard, 1994). Contacts between the formations are typically transitional and are usually characterized by the presence of interbeds. While massive sandstone units are common, massive mudstone units are not; mudstone is typically interbedded with sandstone. The primary porosity of the Nanaimo Group is low and is considered to be of minor importance in the storage and flow of groundwater (Dakin et al., 1983; England, 1990). As a result, permeability is thought to be derived primarily from fractures (*secondary porosity*).

Four major tectonic features exist in the sedimentary rocks of the Nanaimo Group: these provide the secondary porosity necessary for groundwater movement. From oldest to youngest, these features include 1) northwest trending and northeast dipping thrust faults associated with compression by a southwest vergent thrust system (England and Calon, 1991; Mustard, 1994; Journeay and Morrison, 1999); 2) northwest trending buckle folds associated with northeast vergent thrust faults resulting from southeast directed extension (Journeay and Morrison, 1999); 3) shallow dipping features representing bedding plane partings, which are believed to have formed during uplift and/or isostatic rebound after deglaciation (Mackie, 2002); and 4) northeast trending fault and fracture zones as well as bedding perpendicular jointing, present at local scales (Mustard, 1994; Mackie, 2002).

Mackie (2002) used fracture measurements from rock exposures on the Gulf Islands to arrive at a conceptual model that could describe the range of potential permeability within the different sedimentary units. He defined hydrostructural domains on the basis of fracture intensity measured in the less fractured sandstone (LFSS), the interbedded mudstone and sandstone (IBMS-SS), and in association with faults and fracture zones (FZ).

Surrette and Allen (2008) used the fracture data to estimate potential permeability for each. Based on the results of fracture flow modelling, Surrette and Allen (2008) demonstrated that the two highly fractured domains (IBMS-SS and FZ) have an average permeability, on the order of 10^{-13} m^2 (hydraulic conductivity of 10^{-6} m/s), due to enhanced fracture-network connectivity. In contrast, the LFSS domain has an average permeability of 10^{-14} m^2 (hydraulic conductivity of 10^{-7} m/s). Surrette and Allen also observed anisotropy within the permeability, with maximum permeability generally aligned in a northwest-southeast direction, consistent with regional tension perpendicular to this direction.

The possibility of increased infiltration rates within FZ domains, coupled with a high-storage potential relative to other domains suggests that fault zones with similar characteristics are likely zones of recharge. As a result, these recharge zones have an increased capacity to store and transmit infiltrated water throughout the interconnected fracture-network. Surrette et al. (2008) showed that in a regional sense, there is a weak, but consistent, pattern of increasing permeability in both modelled and observed data toward the southeast along the chain of islands, from Galiano Island in the northwest to Saturna Island in the southeast. Values also tended to increase in proximity to the hinge of a large-scale antiformal fault propagation fold structure running parallel to the islands and superimposed high-angle brittle fault structures. This work has shown that fracturing is heterogeneous within the sedimentary layers and depends on the nature of the bedding (i.e., finer bedding gives rise to higher fracture intensity). Consequently, the finer grained interbedded mudstones and sandstones have a higher potential permeability. Furthermore, regional scale structure and current stress regime imparts heterogeneity and anisotropy to fracturing and, thus, contributes to permeability.

9.4.6 Crystalline bedrock aquifers (Type 6)

This category covers crystalline bedrock of various ages ranging from the younger and extensive basaltic lava flows of the *Tertiary* age to older igneous and metamorphic “basement” type rocks (see Figures 9.2a and 9.3a). Crystalline bedrock aquifers are subdivided into two subcategories: flat-lying to gently-dipping volcanic flow aquifers (Type 6a) and fractured crystalline rocks (Type 6b). Groundwater flow in crystalline rocks is through fractures. Flow in flat-lying to gently-dipping volcanic rocks can also be through broken, scoriaceous and weathered contact zones between lava flows. Interflow zones in some areas may also contain granular deposits such as sand and gravel.

9.4.6.1 Occurrence, identification and size characteristics

Sixteen (16) of the 888 aquifers (2%) identified and classified in the Region are developed Type 6a—flat-lying to gently-dipping volcanic flow aquifers. Extensive areas of central British Columbia are underlain by relatively unaltered, flat-lying lava of the Tertiary age (e.g., the Fraser and Nechako Plateaus in the central part of the Region). A smaller developed basalt flow aquifer occurs in the Grant Hill region (aquifer classification # 19) of the Lower Mainland in British Columbia. These lava flow areas often have obvious geological boundaries which define the aquifer’s areal extent locally. The developed extent varies from <1 to 6,546 km^2, with an average area of 484 km^2 (Table 9.1).

The largest single continuous aquifer in the Cordillera is the flat-lying or gently-dipping volcanic flow rock aquifer in the 100 Mile House area of the Fraser Plateau region (aquifer classification #124). When this aquifer is completely mapped, its area is expected to cover more than 7,000 km^2.

Wells drilled here range in depth up to 242 m deep, with an average median depth of 62 m. Water table depth is relatively shallow (average median depth of 19 m) but ranges from <1 m to 130 m.

One hundred and fifty four of the 888 aquifers (17.3%) identified and classified in the Region are developed Type 6b crystalline aquifers. This subcategory includes igneous intrusive or metamorphic rocks (such as the coast granitic pluton north of Vancouver). Because the meta-sedimentary, older volcanic and meta-volcanic rocks are most similar in hydrogeological properties to granitic and metamorphic rocks, they have been included in this subcategory. Groundwater flow in fractured crystalline rocks is mostly along joints, fractures, and faults. Typically there is negligible internal primary porosity so storage is limited.

These Type 6b aquifers occur over a broad portion of the Region. They do not have obvious geological boundaries to define their extent locally. Groundwater production is typically from fractures and joints. Fracture nature and density is controlled by both regional and local stress fields in addition to ancient tectonic features, making it difficult to develop predictive aquifer models. There are also significant heterogeneities between wells within a defined aquifer area, as variability in the nature and orientation of individual fracture relative to a well influences production rates and degree of interference between wells. The developed extent of these aquifers varies from <1 to 538 km^2, with an average area of 31 km^2 (Table 9.1). Wells drilled into Type 6b crystalline aquifers can be up to 268 m deep, with an average median depth of 71 m. The water table depth is relatively shallow (average median depth of 15 m) but ranges from <1 m to 213 m.

9.4.6.2 Productivity characteristics and importance as a water supply

Groundwater production in flat-lying to gently-dipping volcanic rocks is primarily through joints and fractures, although it also occurs in broken, weathered zones between flows. High yielding groundwater zones within the lavas are the “brecciated or erosional zones,” which are like interconnecting “fingers”. Yield of a given well will depend on whether or not these brecciated/erosional zones are present. Regional fractures or fault zones are also significant as major groundwater supply sources (Brown, 1969).

Permeability of these aquifers sometimes exists as *primary porosity* due to the vesicular nature of the rock, and the interconnected porosity, after bedrock formation. This *secondary porosity* developed as a result of fractures, joints or faults formed by tectonic forces. Permeability also exists, largely, as within interflow zones which occur between lava flows. This porosity may result from weathering, fracturing from extreme heat in contact zones, or, in some cases, deposition and subsequent burial of unconsolidated sediments by lava flows.

The interflow zones within these aquifers vary in nature, with some zones exhibiting only centimetres of weathering, while others a significant thickness of trapped alluvial sands and gravels when an old stream channel has been covered by a basaltic flow (Livingston, 1967). Variabilities in fracturing, thickness, and extent of unconsolidated material found in the interflow zones result in significant heterogeneities between wells within any defined aquifer area. Variability in the nature and orientation of individual fracture, or interflow zone relative to a well influences production rates and the degree of interference between wells.

Well yields for flat-lying lava aquifers vary widely, with a range from <1 to 15 L/s reported. The average median well yield is, however, relatively low at 0.3 L/s. Reported transmissivity values (3 values from 1 aquifer) range from a minimum of 11 m^2/d to a maximum of 47 m^2/d, with a geometric mean of 23 m^2/d. Water quantity concerns with flat-lying to gently-dipping volcanic rock aquifers are uncommon. The Tertiary basalt flow rocks of central British Columbia probably represent the largest reserve of good-quality ground water in the province (Livingston, 1967). Only a few reports of poor water supplies exist for any of the wells completed in these lavas. High hardness values (286 mg/L) were reported in one of the community wells for 100 Mile House (Foweraker, 1981).

The dominant use of Type 6a aquifers in the Cordillera is for drinking water (domestic and municipal) and for minor farming purposes. These aquifers are typically considered moderate to low in vulnerability and also have moderate to low demand.

Well yields for Type 6b crystalline aquifers vary widely. Ranges from <1 to 126 L/s have been reported, although the average median well yield is relatively low at 0.4 L/s. Well yield is dependent on the well encountering water-bearing fractures within the drill hole. Kenny (2004) examined whether the proximity to mapped lineaments, well depth, and well location could influence well yield of crystalline aquifers in the Victoria area.

Voeckler and Allen (2012) used outcrop measurements of fractures, lineament data from orthophotos, and Landsat imagery to model fracture distributions within crystalline rocks in the Okanagan Basin. Their results estimated hydraulic conductivities in the range of 10^{-8} to 10^{-7} m/s.

Reported transmissivity values (35 values from 19 aquifers) range from a minimum of 0.2 m^2/d to a maximum of 400 m^2/d, with a geometric mean of 9.2 m^2/d (see Table 9.1 and Figure 9.5). Transmissivity of crystalline aquifers is also expected to be anisotropic. For example, Kohut et al. (1983) reported on the highly directional drawdown observed during the pumping test of an irrigation well in a granitic aquifer (aquifer classification # 608) north of Victoria.

The dominant use of the Cordillera's type 6b crystalline aquifers is for drinking water. These aquifers are typically considered moderate to low in vulnerability, with a moderate to low demand. Roughly two-thirds of these aquifers are classified as low productivity. Water quality concerns with developed crystalline aquifers are uncommon. There have been, however, isolated issues over non-health related problems relating to high sulphur and iron content, as well as seawater intrusions in coastal areas. Twelve aquifers (8%) report concerns with high arsenic content (typically from aquifers in fractured granite, likely related to naturally occurring arsenic bearing minerals). No issues regarding radioactive elements as noted in other granite hosted aquifer systems have been reported.

9.4.6.3 Aquifer vulnerability and water quality characteristics

The majority of Type 6a flat-lying volcanic rock aquifers (69%) are classified as low vulnerability; 25% are classified as moderately vulnerable and 6% as highly vulnerable.

The majority of Type 6b crystalline aquifers (56%) are classified as moderately vulnerable and 13% as highly vulnerable. Vulnerability of crystalline bedrock aquifers depends on the nature, extent and thickness of the unconsolidated sediments overlying the bedrock aquifer. Where exposed at surface, crystalline bedrock aquifers can be directly

TABLE 9.1 SUMMARY OF HYDROGEOLOGICAL CHARACTERISTICS OF THE MAJOR AQUIFER SYSTEM TYPES IN THE CORDILLERAN HYDROGEOLOGICAL REGION (BASED ON BC'S INVENTORY OF CLASSIFIED AQUIFERS)

AQUIFER TYPE	NO. OF AQUIFERS (% OF TOTAL INVENTORY)	RANGE; AVERAGE SIZE (KM^2)	AVERAGE RANGE; AVERAGE MEDIAN WELL DEPTHS (M)	AVERAGE RANGE; AVERAGE MEDIAN WELL YIELDS (L/S)	RANGE; GEOMETRIC MEAN TRANSMISSIVITY (M^2/D)	HYDRAULIC CONNECTIONS WITH SURFACE WATER	EXAMPLES OF AQUIFER TYPES
1. Unconfined aquifers of fluvial or glaciofluvial origin along river valley bottoms							
a. Aquifers along higher-order rivers	34 (3.8%)	<1–142; 27	12–82; 22	1.8–17; 3.5	350–22,000; 4,500	Common	Agassiz, Chilliwack-Rosedale
b. Aquifers along moderate-order rivers	73 (8.2%)	<1–120; 15	11–53; 22	1.5–41; 5.7	1.0–36,000; 1,300	Common	Grand Forks, Duncan, Chemainus, Nechako, Merritt
c. Aquifers along lower-order streams	21 (2.4%)	<1–23; 7	9–43; 19	1.4–22; 4.0	160–240; 200 (based on 2 values)	Unknown	Cache Creek, Little Fort
2. Unconfined deltaic aquifers	23 (2.6%)	<1–19; 5	5–27; 12	1.5–15; 6.1	960–2,400; 1,500	Common	Scotch Creek near Chase
3. Unconfined alluvial, colluvial fan aquifers	56 (6.3%)	<1–54; 5	13–47; 24	1.6–23; 4.0	25–5,600; 710	Common in aquifers adjacent to surface water	Vedder River Fan at Chilliwack
4. Aquifers of glacial or preglacial origin							
a. Unconfined glaciofluvial aquifers	70 (7.9%)	<1–90; 8	12–59; 24	1.3–22; 3.0	1.6–89,000; 690	Common in aquifers adjacent to surface water	Abbotsford, Langley, Hopington
b. Confined glacial or preglacial aquifers	334 (37.6%)	<1–332; 13	20–83; 39	0.8–12; 2.3	1.5–120,000; 250		Quadra Sand aquifers in the Georgia Basin, Okanagan and Coldstream valleys
c. Confined glaciomarine aquifers	9 (1.0%)	2–194; 32	23–176; 61	0.1–14; 0.6	45–410; 150	Limited	Nicomekl-Serpentine in Surrey and Langley
5. Sedimentary bedrock aquifers							
a. Fractured sedimentary bedrock aquifers	95 (10.7%)	<1–700; 24	22–139; 56	0.1–2.5; 0.3	0.1–480; 3.7	Limited	Nanaimo Group aquifers in the Gulf Islands and east coast of Vancouver Island
b. Karstic limestone aquifers	6 (0.7%)	2–19; 8	35–125; 75	0.1–1; 0.3	N/A	Unknown, but possible	Limestone aquifers in the Canadian Rockies, Sorrento, Fort St. James
6. Crystalline bedrock aquifers							
a. Flat-lying volcanic flow rock aquifers	16 (2%)	<1–6,546; 484	21–129; 62	0.1–3.2; 0.3	11–47; 23 (based on 3 values)	Limited	Aquifer classification # 124 around 70 Mile House, British Columbia
b.Crystalline granitic, metamorphic, meta-sedimentary, meta-volcanic and volcanic rock aquifers	154 (17.3%)	<1–538; 31	28–152; 71	0.1–4.8; 0.4	0.2–400; 9.2	Limited	Saanich granodiorite, granitic aquifers along Sunshine Coast, metabasalt aquifer at Metchosin near Victoria

impacted by surface land use activities. Since these aquifers are dominated by fracture permeability and fracture induced porosity, travel times for contaminants can be quick, and opportunities for attenuation low.

9.5 GROUNDWATER USE IN THE REGION

Groundwater is an important water supply source within the Region. Throughout the Cordillera, there are some unique motivations for using groundwater as a supply:

1. Surface water resources in some areas are fully allocated (for example, in some watersheds in the southern interior of BC).
2. Communities develop groundwater supplies to avoid the cost of treating surface water.
3. Groundwater quality and quantity are generally excellent (see Section 9.7).

It is estimated that 1 million people[4] in the Cordillera Region rely on groundwater for drinking water. This supply ranges from municipal systems to private residential wells. Communities such as Abbotsford (population 129,000), Township of Langley (population 100,000), and Chilliwack (population 73,000) in the Lower Mainland, Parksville-Qualicum Beach (population 21,000) on Vancouver Island, Prince George (population 77,000) and Quesnel (population 11,000) in Central BC, and Banff (population 6,700) and Jasper (population 4,600) in the Canadian Rockies are examples of communities relying on groundwater as their water source. Spatially, groundwater use has historically been focused in valley bottoms and plateaus throughout the main settlement corridors (see locations of reported wells in Figure 9.6).

Throughout this Region, groundwater has historically been used largely (by volume) for industrial processing (mineral, pulp, and paper), agriculture, and aquaculture (Wei and Allen, 2004; Hess, 1986; Foweraker et al., 1985), and is, therefore, vitally important in sustaining the region's economy. Overall figures in BC indicate that approximately 55% of the water volume pumped annually is for industrial use, 20% for agricultural and 25% for municipal and rural uses (Hess, 1986). The high industrial use of groundwater is unique to BC and to the Cordillera. Groundwater is also increasingly used as a viable source of low-temperature geothermal energy.

9.6 WATER STORED IN DEVELOPED AQUIFERS WITHIN THE REGION

The amount of groundwater potentially stored in developed aquifers within the Cordilleran Hydrogeological Region is estimated to be 7.9–19.6 km^3. This volume[5] represents capacities from developed aquifers identified and classified in the BC Cordillera only covering approximately 20,000 km^2 (<2%) of the entire 1.4 million km^2 of the Cordilleran Hydrogeological Region (Table 9.2). The volume of groundwater stored in undeveloped aquifers (e.g., in remote, undeveloped areas) and in developed aquifers in the Region where aquifers have not been mapped and classified has not been included in the volumes in Table 9.2. The amount of groundwater stored in developed aquifers within the Region was calculated from the following general equation (Rivera, 2007):

$$V = S \times A \times h_o \quad (9.1)$$

where:

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[4] This number is estimated from: Nowlan (2005).

[5] By volume stored, we mean the volume of groundwater that is stored and can potentially be released from an aquifer when the groundwater level is lowered.

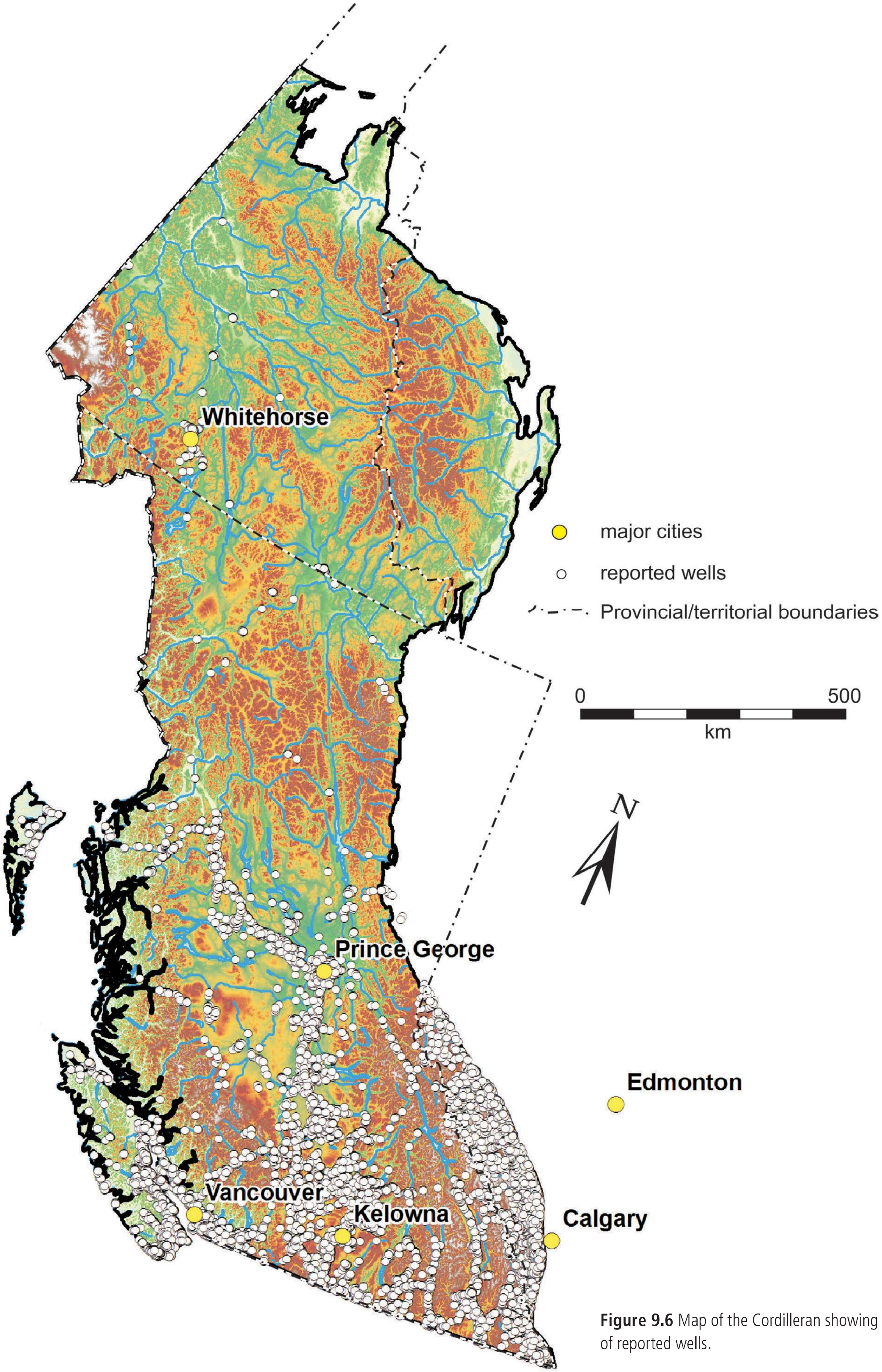

Figure 9.6 Map of the Cordilleran showing location of reported wells.

TABLE 9.2 TOTAL SURFACE AREA AND ESTIMATED TOTAL VOLUME OF GROUNDWATER STORED IN DEVELOPED AND CLASSIFIED AQUIFERS (BY AQUIFER TYPE)

AQUIFER TYPE	TOTAL SURFACE AREA OF DEVELOPED AND CLASSIFIED AQUIFERS (KM^2)	ESTIMATED TOTAL VOLUME IN DEVELOPED AND CLASSIFIED AQUIFERS (KM^3)
1a	932	2.67–6.24
1b	1,110	2.76–6.46
1c	168	0.27–0.64
2	116	0.14–0.32
3	292	0.67–1.56
4a	566	1.08–2.52
4b	3,997	0.01–0.05
4c	291	0.001–0.01
5a	2,007	0.05–0.14
5b	51	0.002–0.02
6a	6,779	0.09–0.26
6b	4,426	0.14–1.33
Total	**20,735**	**7.88–19.55**

V is the volume of water stored in an aquifer;

S is the aquifer storativity, or if an aquifer is unconfined, the specific yield;

A is the mapped areal extent of the aquifer; and

h_o is the groundwater level above the bottom of the aquifer.

In estimating the volume of groundwater in each type of aquifer, representative values and range of values of storativity or specific yield were assumed for each aquifer type: the difference between the average depth to water and average well depth was used to represent the average groundwater level above the bottom of the aquifer. Since the average well depth is shallower than the bottom of the aquifer, the use of the difference between depth to water and well depth is conservative. The total volume of groundwater stored in each type of aquifer is presented in Table 9.2. Table 9.2 shows that, generally, unconfined, unconsolidated aquifers can store and release more groundwater than confined, unconsolidated aquifers and fractured bedrock aquifers. The relatively small average volume of groundwater in confined, unconsolidated aquifers (Types 4b and 4c) reflects the low value of aquifer storativity used in the calculation compared to the larger specific yield value used for unconfined, unconsolidated aquifers. In total, fluvial sand and gravel aquifers (Types 1a and 1b), alluvial fan aquifers (Type 3) and glaciofluvial aquifers (Type 4a)—all generally unconfined aquifers—comprise over 80 to over 95% of the total groundwater stored in developed aquifers and reflect their importance as developed water supply aquifers in the Region. The total volume of groundwater in the Region is undoubtedly much greater.

9.7 WATER QUALITY

The Cordilleran Hydrogeological Region is blessed with many aquifers with the potential to yield large quantities of water to serve domestic, industrial, and agricultural requirements.

TABLE 9.3 SUMMARY OF RESULTS FROM THE WATER QUALITY CHECK PROGRAM—PHYSICAL PARAMETERS

PARAMETER	NUMBER OF SAMPLES	RANGE	MEDIAN	PERCENT OF SAMPLES EXCEEDING DRINKING WATER QUALITY GUIDELINES
TDS	5,013	<10 to >9,800 mg/L	185 mg/L	12% (>500 mg/L)
Hardness	11,550	<10 to >7,700 mg/L	77 mg/L	3.5% (>500 mg/L)[6]
Total Alkalinity	11,600	<10 to 7,734 mg/L	110 mg/L	10% (>300 mg/L)[7]
pH	11,606	<5 to >10	7.6	9.7% (pH<6.5); 6.2% (pH>8.5)

The natural chemical quality within these aquifers is excellent, for the most part. Between 1977 and 1993, the province of British Columbia provided over 11,000 subsidized laboratory analyses through the BC Water Quality Check Program (WQCP) to residents in the BC Cordillera relying on well water. Laboratory analyses were performed on a limited range of water quality parameters concerning health issues, or as general indication of water quality. Although this data set has an inherent spatial bias (e.g., more data may be from the west coast volcanic belts as opposed to the eastern Cordillera carbonate areas; more data from the south than the north), the analysis nevertheless contains the widest geographic coverage of the Region from where groundwater is used, over an extended period of time. The overview of groundwater quality provided in this section is primarily based on data set from the BC Water Quality Check Program (1977–1993), as well as on documented water quality concerns identified through aquifer classification mapping and other available groundwater quality studies. Groundwater quality data for the Cordillera outside of BC and for public water supply wells was not readily accessible and these areas have not been included in the summary for the Region.

9.7.1 General groundwater quality in the Region

According to the data, total dissolved solids (TDS) in the Cordillera range from as low as <10 mg/L to over 9,800 mg/L, with a median of 185 mg/L (see Table 9.3 and Figure 9.7a), reflecting the generally low total mineralization of groundwater in the Region. 90% of the samples had TDS of <650 mg/L. The highest reported TDS was found in coastal bedrock aquifers and may reflect wells drilled into brackish groundwater close to the ocean.

Water hardness (expressed as $CaCO_3$) ranged from <10 mg/L to over 7,700 mg/L (see Table 9.3 and Figure 9.7b). Water hardness in most groundwater is occurring naturally from weathering of limestone, sedimentary rock, and calcium bearing minerals. Over 50% of the samples had hardness of <80 mg/L, indicating water in the Region is generally soft. Over 90% of the samples had hardness of <340 mg/L, while 3.5% had hardness concentrations over 500 mg/L, while (the limit above which water is considered unacceptable). Soft water tended to be found in areas with mainly igneous rock formations, whilehardness in areas with mainly sedimentary rock tended to be greater. Water is also generally softer along the coast than in the interior

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[6] No numerical guideline; 80 to 100 mg/L as $CaCO_3$ is acceptable; over 200 mg/L as $CaCO_3$ is poor but can be tolerated; over 500 mg/L as $CaCO_3$ is normally unacceptable.

[7] No guideline.

of the Region.

Total alkalinity, expressed as $CaCO_3$, ranged from <10 mg/L (generally low pH waters) to >7,700 mg/L, with a median value of 110 mg/L (see Table 9.3 and Figure 9.7c). 90% of the samples had total alkalinity values of <325 mg/L.

The pH values ranged from <5 to >10 (see Table 9.3 and Figure 9.7d). 84.1% of the samples had pH values of between 6.5 and 8.5 (the pH range within the Guidelines for Canadian Drinking Water Quality, known as GCDWQ, for pH), 9.7% of the groundwater samples had pH values < 6.5, and 6.2% of the samples had pH value > 8.5. pH values of lower than 6.5 were all found along the coastal areas of the Region; pH values of greater than 8.5 were found in the Lower Mainland, Gulf Islands (likely wells intersecting seawater as a fraction) and Vancouver Island, as well as in the interior of the Region.

9.7.2 Common water quality concerns in the Region

Of the 888 aquifers classified and mapped in the Cordillera Region, 4% (38 aquifers) have documented health-risk related quality concerns (including nitrate, arsenic, fluoride, boron), and 4% (39) have "salty water". These issues are isolated, local, or regional in extent. Table 9.4 (adapted from Cui and Wei, 2000) lists the groundwater quality parameters of concern, range of values and median from the analytical results, and percentages of samples exceeding Canadian Drinking Water Guidelines. Generally, only a small portion of groundwater samples had certain water quality parameters above Canadian Drinking Water Guidelines.

Although several water quality concerns (both naturally occurring and as a result of human activity) exist in the Region (e.g., fecal coliform bacteria and *E. coli*, metals, volatile organics), there are a few that have occurrence with potential aquifer-wide impact: nitrate, arsenic, fluoride and boron, and salty water (sodium, chloride).

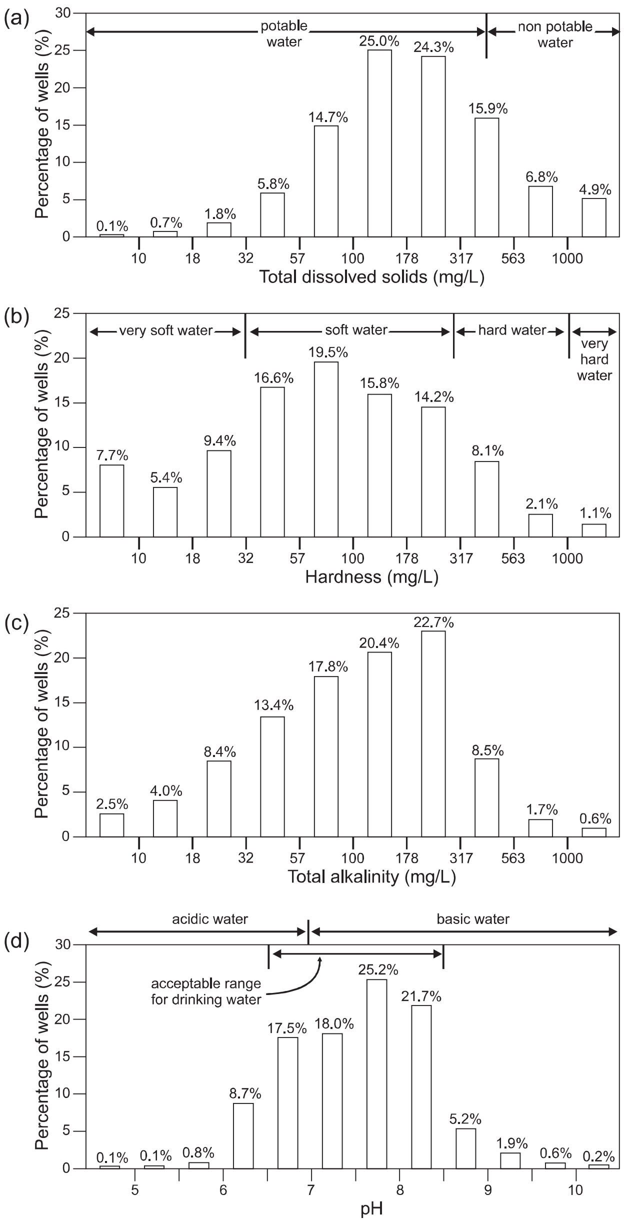

Figure 9.7 These graphs depict, from top to bottom, (a) total dissolved solids (TDS), (b) hardness, (c) total alkalinity, and (d) pH in wells in the Cordilleran Hydrogeological Region, sampled as part of the BC Water Quality Check Program between 1977 and 1993. Please note that the horizontal axis for the TDS, hardness, and alkalinity graphs shows the distribution of values on a logarithmic scale.

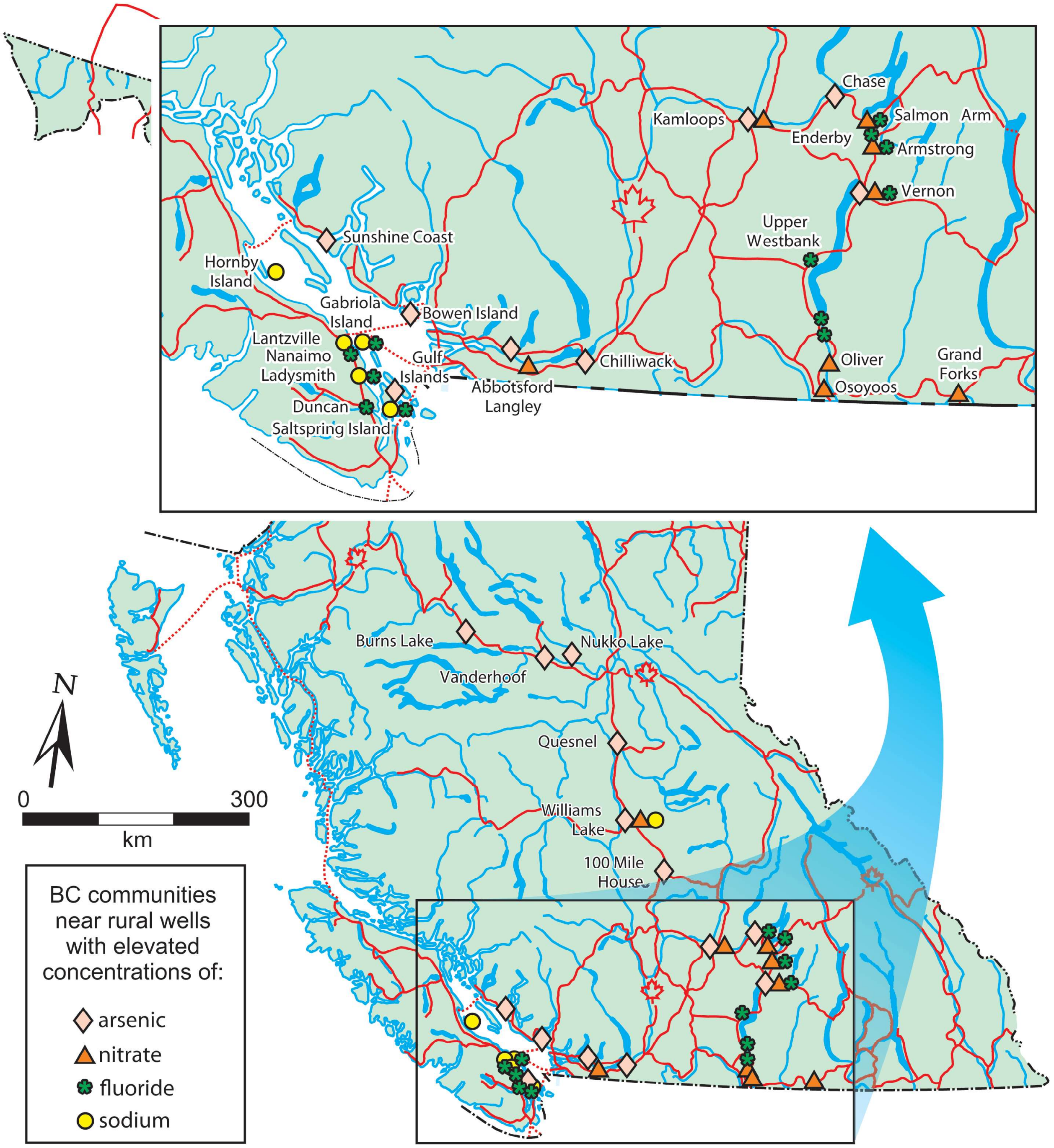

Figure 9.8 Areas of known elevated arsenic, sodium, fluoride and nitrate-nitrogen in wells within the Cordilleran Hydrogeological Region (based on data from the BC Water Quality Check Program).

9.7.2.1 Nitrate

Nitrate (NO_3) is the most significant non-point source contaminant in the Cordillera Region. Nitrate ranges from non-detectable to over 100 mg/L NO_3-N (Table 9.4). The median NO_3-N value is 0.05 mg/L. Less than 2% of the samples tested contained nitrate-nitrogen (NO_3-N) higher than the Canadian Drinking Water Guideline; 7%

of the samples had NO_3-N values of above 3 mg/L, the concentration above which groundwater quality is interpreted to be affected by human activities. Elevated nitrate is known to occur in some aquifers within the Lower Fraser Valley (e.g., Carmichael et al., 1995; Hii et al., 1999; 2005; Liebscher et al., 1992; McArthur and Allen, 2005), near Langley and Abbotsford, for example, plus the Southern Okanagan interior of the Region (Hodge, 1992; 1985a; 1985b), and Grand Forks (Maxwell et al., 2002; Wei et al., 1993). Nitrates also occur in other areas, but in isolated cases (see Figure 9.8). Most exceedances occur in areas of intensive agricultural activity, or at locations where septic tanks are the main method of sewage disposal.

Localized to widespread nitrate typically occurs in unconfined, unconsolidated aquifers—Types 1b (3 aquifers) and Type 4a (8 aquifers); these are the most vulnerable aquifers in the Cordillera. These unconfined aquifers also occur along valley bottoms and in plains, where agricultural activities exist. Localized nitrate may also be found in confined, unconsolidated aquifers—Type 4b (1 aquifer), although windows in the confining layer may allow nitrate to be transported downward into the aquifer. To date, no bedrock aquifers show any significant nitrate contamination.

Nitrate is usually introduced into groundwater through diffuse and/or widespread sources (non-point sources) to pinpoint. They include leaching of chemical fertilizers or animal manure. Point sources of nitrate include septic and sewage discharges. Recent studies have used nitrogen isotopes to distinguish between different sources of nitrate-nitrogen in groundwater (to differentiate between chemical fertilizer versus manure fertilizer, for example, Wassenaar, 1995; Wassenaar et al., 2006; Wei, 1992); human waste and septic sources, however, produce nitrate that is indistinguishable from animal waste (Kendall, 1998). In addition to nitrate, pesticides at trace levels have been detected in Cordillera well water, although only in isolated instances (e.g., Lower Mainland – Carmichael et al., 1995; Liebscher et al., 1992).

9.7.2.2 Arsenic

A total of 112 samples from the 2226 Water Quality Check Program sample results (5%) had arsenic present at concentrations above the historic laboratory method detection level of 0.4 mg/L. Current analytical methods have much lower detection limits, and, as a result, these results provide an incomplete picture of arsenic occurrence within the Region. The GCDWQ is 0.010 mg/L.

The most common source of naturally occurring elevated arsenic levels in groundwater is the weathering of arsenic bearing minerals and ores. Arsenic is found primarily in areas with arc, back-arc, and oceanic volcanic rocks or meta-volcanic rocks (i.e., crystalline bedrock aquifer types). There are, however, recent reported occurrences in sedimentary rock (on Saturna Island and Saltspring Island in the Gulf Islands) and in unconsolidated aquifers (the aquifer underneath the San Juan River on southern Vancouver Island, and the aquifer at Chilliwack-Rosedale (Graham, 2006), in the Lower Mainland. Localized high arsenic concentrations have been found in well water from several areas within the Region (Figure 9.8); these are almost always associated with arsenic-containing bedrock formations. Arsenic concentrations above the drinking water guideline have been found in some rural wells near the communities of 100 Mile House, the Sunshine Coast, Powell River and the Howe Sound (Mattu and Schreier, 2000; Carmichael, 1995), the Okanagan Valley (e.g., Vernon), and other parts of the interior of the Region (e.g., Burns Lake, Chase, Kamloops, Quesnel, Vanderhoof, and Williams Lake). Elevated arsenic has been found in isolated wells on Saltspring Island, the Lower Mainland (Zubel, 2002), and near Nukko Lake (Figure 9.8). Arsenic levels above the drinking water guideline may be identified in other areas of the Region as more water quality results become available.

9.7.2.3 Fluoride and boron

Some 3% of the samples tested contained fluoride concentrations above the drinking water limit of 1.5 mg/L while 0.7% had boron above the drinking water limit of 0.5 mg/L (Table 9.4). Fluoride is found in some sedimentary, volcanic, and crystalline bedrock aquifers. High concentrations of fluoride in groundwater were observed in rural wells near the communities of Armstrong, Duncan, Enderby, Gabriola Island, Ladysmith, Nanaimo, Okanagan Falls, Penticton, Salmon Arm, Saltspring Island, and Vernon (BC Environment and Environment Canada, 1994; see Figure 9.8). On the east coast of Vancouver Island and the adjacent Gulf Islands, Earle and Krogh (2006) observed a strong correlation between fluoride and pH, also with boron. Their study contained 30 samples with pH greater than 8.5, 17 had fluoride levels greater than 1.5 mg/L.As a result, Earle and Krogh proposed that these elevated concentrations were the result of base-exchange softening, as discussed by Allen and Suchy (2001b). Fluoride in groundwater in the Cordillera can also result from runoff and infiltration of chemical fertilizers in agricultural areas.

9.7.2.4 Salty water (sodium and chloride)

The most common natural sources of elevated sodium levels in groundwater are the erosion of salt deposits and sodium bearing rock minerals; the naturally occurring brackish water of some aquifers, and salt water at depth in coastal areas. Ambient concentration of sodium in groundwater within the Region typically ranges from a few mg/L to over 100 mg/L. Samples with high sodium concentrations (>200 mg/L), generally associated with "salty water", were found either along coastal areas, where seawaters were the possible sources, or in areas where road salts might be the contributors (Figure 9.8). High values of chloride are often found in conjunction with high sodium; however, concentrations of sodium can be increased due to base-exchange or water-softening processes (Allen and Suchy, 2001b).

Naturally occurring brackish or saline groundwater has been found in deep marine sediments (Type 4c) in the Lower Mainland (Halstead, 1978), locally in some sedimentary bedrock aquifers (e.g., Nanaimo Group—Type 5a) or in crystalline bedrock aquifers (Type 6b) on the Gulf Islands and Vancouver Island (Kohut et al., 1986; Allen and Suchy, 2001a), and those aquifers associated with thermal springs (Grasby and Lepitzki 2002, Grasby et al., 2000; Allen et al., 2006). Saline groundwater is typically characterized by high levels of sodium and chloride, although elevated sulphate may also be present. Unconsolidated aquifers underneath the San Juan River and Cowichan River (Kohut, 1981) also have documented concern about salty water in the estuary.

Sodium and chloride contamination, due to saltwater intrusion, is a threat to groundwater supplies located within coastal areas. In some instances, saltwater intrusion has already occurred, most notably in the Gulf Islands (Allen and Suchy, 2001a), where a number of wells (e.g., Gabriola

TABLE 9.4 SUMMARY RESULTS FROM THE WATER QUALITY CHECK PROGRAM —PARAMETERS OF HEALTH CONCERNS

PARAMETER	NUMBER OF SAMPLES	RANGE*	MEDIAN	PERCENT OF SAMPLES EXCEEDING DRINKING WATER QUALITY GUIDELINES
Nitrate-nitrogen	11,660	ND to >100 mg/L	0.05 mg/L	1.6% (>10 mg/L)
Arsenic	2,226			5% (>0.04 mg/L Detection Limit)[8]
Fluoride	8,349	ND to >100 mg/L	0.1 mg/L	3.2% (>1.5 mg/L)
Boron	10,343	ND to >75 mg/L	0.01 mg/L	0.69% (>5 mg/L)
Sodium	2,209	<1 to 3,000 mg/L	9.3 mg/L	Sodium - 5.1% (>200 mg/L)
Total Coliform	11,321	<1 to 24,000 CFU	ND CFU	15.3% (>10 CFU)

* ND= Not Detected

Island, Hornby Island, Saturna Island, Mayne Island, Saltspring Island) have Na concentrations up to thousands of mg/L depending upon the location and depth of the well (Allen and Suchy, 2001a; Allen and Matsuo, 2001; Kohut et al., 1986; Dakin et al., 1983).

Typically, saltwater intrusion occurrences are restricted to narrow islands and peninsulas where land for groundwater recharge is limited. However, closely-spaced residential lots serviced by individual private wells along the coast are also at risk of groundwater quality degradation. Elevated concentrations of sulphate have also been observed in certain areas of the Gulf Islands (Allen and Suchy, 2001a; Allen and Matsuo, 2001). An increase in the groundwater content of sodium or chloride above ambient or natural levels in non-coastal areas may indicate pollution from point or non-point sources, such as from the application of road salt or from nearby landfills.

9.7.2.5 Bacteria

The presence of coliform bacteria in well water either reflects naturally occurring sources, anthropogenic sources, such as septic tank effluent, or inadequate disinfection. Occurrence of coliform bacteria in the Cordillera Region appears to be generally local in extent. Of the 12,000 samples analyzed for total coliform bacteria (Water Quality Check Program), 15% had concentrations greater than the drinking water guideline of 10 CFU (colony forming unit) per 100 mL water, 80% of the samples taken had between 1 and 10 CFU/100 mL and 5% of samples had less than or equal to 1 CFU/100 mL. There was no geographic occurrence pattern for total coliform organisms above the guideline. Twelve sites sampled in the Abbotsford-Sumas aquifer during 2004 showed the presence of fecal coliform, and 111 sites were found to have elevated total coliforms (as high as 1,500 CFU per 100 mL) (Hii et al., 2005). The distribution of bacteria contamination, however, appeared to be localized to a few specific wells and not reflective of overall aquifer water quality.

9.7.2.6 Other parameters

Iron, manganese, and hydrogen sulphide gas are problematic in some parts of the Cordillera

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[8] Historically, samples from the WQCP were analyzed using a method with a detection limit that is higher than the current Guideline for Canadian Drinking Water Quality for arsenic (current guideline is 0.010 mg/L). Therefore, historic values likely range from Not Detected (ND) to hundreds of parts per billion (mg/L).

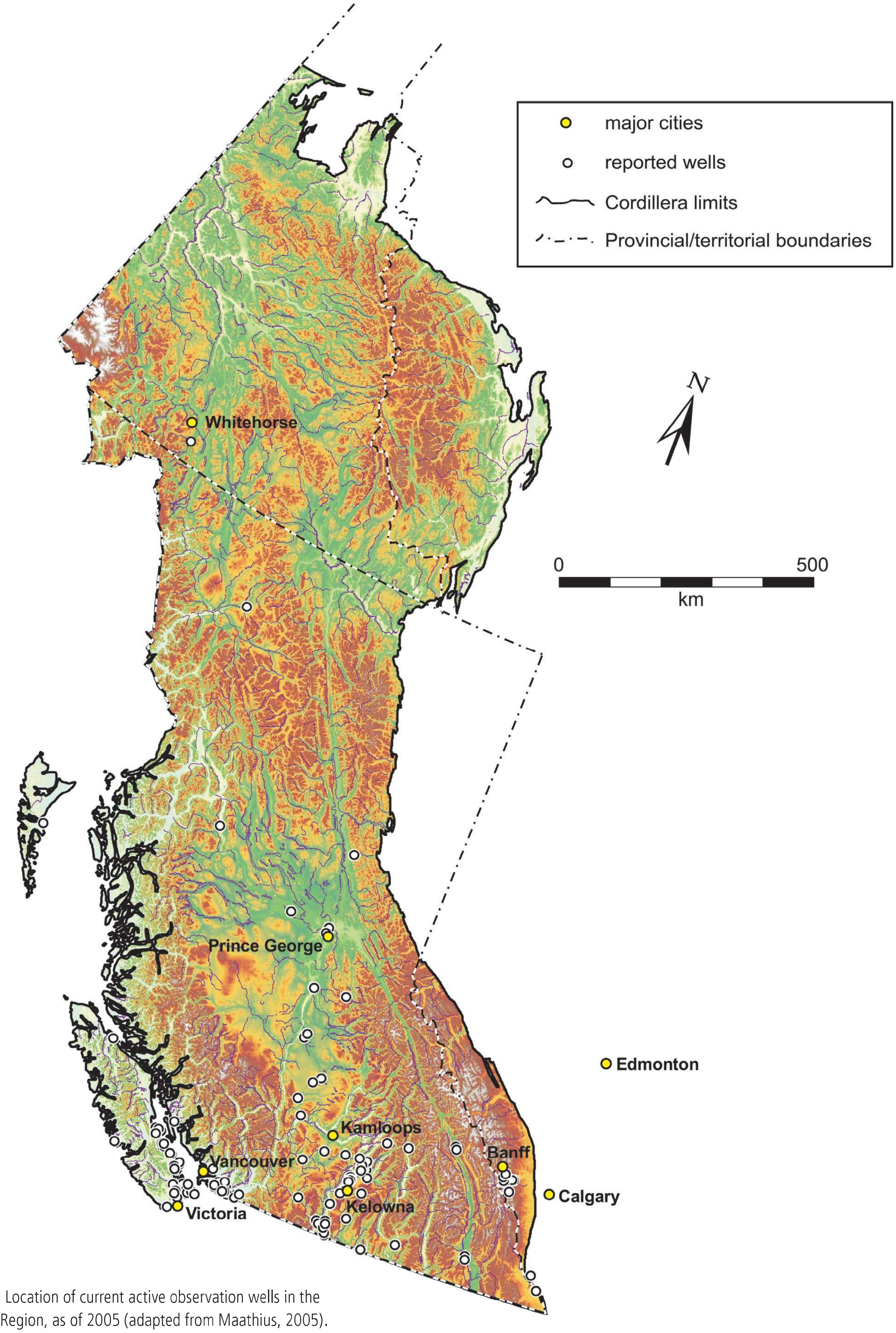

Figure 9.9 Location of current active observation wells in the Cordilleran Region, as of 2005 (adapted from Maathius, 2005).

Region. The most common groundwater sources of iron and manganese occur naturally, from weathering of iron and manganese bearing minerals and rocks. Industrial effluent, acid mine drainage, sewage and landfill leachate may also contribute. The concentration of iron and manganese in well water can fluctuate seasonally and will vary with the well depth and location, and the geology of the area. Iron and manganese are found naturally in groundwater containing little or no oxygen, typically in deeper wells (but not always), in areas where groundwater flow is slow, and in those areas where groundwater flows through soils rich in organic matter. Locally, concentrations of iron and manganese can range up to several mg/L. In one residential area south of Revelstoke, historical observations suggest iron and manganese in well water fluctuate with the level of the nearby Columbia River (as fluctuation of the river may affect the groundwater rate of flow to the river and, therefore, the amount of oxygen in the groundwater; Wei, 1983). Concentrations of Mn exceeding the MAC (maximum allowable concentration) have been found in roughly one third of the wells sampled on the Gulf Islands (Allen and Pelude, 2001).

Groundwater containing dissolved hydrogen sulphide (H_2S) gas imparts a characteristic “rotten egg” odour and taste. Although not normally analyzed during a routine chemical analysis, hydrogen sulphide gas is often detected by smell during sampling. It has been noted on some of the Gulf Islands (e.g., Saturna and Hornby Island), and likely is present in other parts of the Region.

Phosphorous, a principal constituent of concern in septic tank effluent has been detected in groundwater entering lakes in the Okanagan Valley (BC Environment and Environment Canada, 1994).

When the BC Ministry of Health tested household basements for radon gas (BC Ministry of Health, 2007), a number of communities, mostly within BC’s interior of BC, had levels above 200 Bq/m^3. Although no groundwater sampling for radon gas has been done in these areas, it is possible that concentrations could be similarly high.

9.8 GROUNDWATER MONITORING IN THE CORDILLERAN HYDROGEOLOGICAL REGION

Four different senior levels of government within the Cordillera—Yukon and Northwest Territories, the province of Alberta and the province of British Columbia—have groundwater level and ambient quality monitoring responsibilities for the Region. We will address, in this section, the distribution of observation wells within the Region, both spatially and by aquifer types. Much of the information presented here is derived from *Groundwater Observation Well Networks in Canada* compiled by Maathius (2005).

In 2005, there were 162 observation wells existing in the Cordillera (153 of these wells were operated by the province of British Columbia, 8 by the province of Alberta, and 1, in Whitehorse, by the Yukon Territory) to monitor groundwater conditions in the Miles Canyon Basalt aquifer. Most of these wells are located in developed areas, largely in the southern half of the Region, where groundwater development has historically been most intensive (Figure 9.9). Figure 9.10 charts the proportion of active observation wells by aquifer types. Most of the active observation wells monitor groundwater levels in Type 1b, 4a, 4b, 5a, and 6b aquifers. Distribution of the Observation Well Network in BC was recently reviewed (Kohut, 2007).

Groundwater levels for BC’s observation wells reported online (http://www.env.gov.bc.ca/wsd/

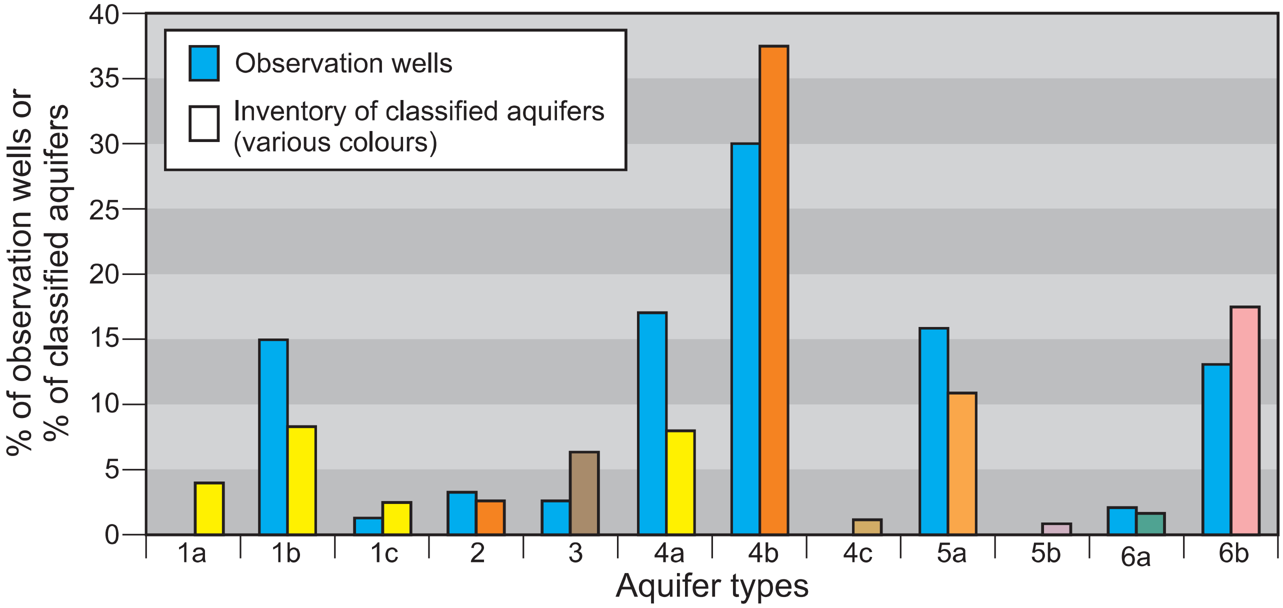

Figure 9.10 Percentage of current observation wells compared to percentage of classified aquifers by aquifer types.

data_searches/obswell/map/obsWells.html, and groundwater level data for all observation wells in BC can be downloaded from the web: http://www.env.gov.bc.ca/wsd/data_searches/obswell/map/obsWells.html.

Moore et al. (2007) undertook a review of the historic climate, hydrometric and groundwater level data throughout BC, to examine groundwater trends. Decreasing groundwater levels during late summer in naturalized settings coincided with decreasing streamflow in many parts of the province (Allen et al., 2008). The 2007 Environmental Trends Report http://www.env.gov.bc.ca/soe/indicators/water/ for BC revealed the fact that groundwater levels in BC are declining over time in a number of observation wells within the Cordillera. Between 2000 and 2005, some 35% of observation wells monitoring groundwater levels affected by human activities (e.g., local pumping industry, agriculture or drinking water) showed declining water levels.

The 2000 to 2005 reporting period also revealed a notable increase in observation wells showing declining groundwater levels due to human activities compared to previous reporting periods (1995–2000, 1990–1995, and 1985–1990). It is not yet known if this increase can be attributed to additional observation wells being installed in heavily developed aquifers, or to a general increase in human activities over these aquifers, or both.

The provinces of BC and Alberta also monitor ambient groundwater quality. Most observation wells in BC are sampled regularly either every year to every few years in this regard. BC also operates an Ambient Groundwater Quality Monitoring Network comprised of private residential, municipal, and monitoring wells in areas where non-point sources of contamination occur, or in IA—heavily developed, highly vulnerable aquifers. To date, this network covers the Lower Mainland (Abbotsford, Langley, Hopington, Belcarra), Whistler, Southern Interior (Merritt, Oliver, Osoyoos, Cache Creek, Armstrong, Grand Forks, Scotch Creek), Vancouver Island and Gulf Islands (Hornby Island, Gabriola, Chemainus, Cowichan River). Data for Ambient Groundwater

Quality Network is available online (http://www.env.gov.bc.ca/emswr/).

9.9 CONCLUSIONS

The Cordilleran Hydrogeological Region occupies four jurisdictions—British Columbia, Alberta, Yukon and Northwest Territories, and is one of the most diverse and unique in Canada with respect to relief, climate, and hydrogeology. Our discussion of aquifers within the Region has been based largely on the inventory of developed aquifers mapped and classified since 1994 by the province of British Columbia, as well as more comprehensive study reports of select aquifers. Records indicate six major types of aquifers (with subtypes) within the Region, each with its own unique hydrogeological characteristics:

Unconsolidated aquifers

Type 1. Unconfined sand and gravel aquifers of fluvial or glaciofluvial origin occurring along rivers or streams
  a. Aquifers occurring along large rivers
  b. Aquifers occurring along mid-size rivers or stream
  c. Aquifers along small streams

Type 2. Predominantly unconfined deltaic sand and gravel aquifers

Type 3. Predominantly unconfined alluvial fan, colluvial sand and gravel aquifers

Type 4. Sand and gravel aquifers of glacial or preglacial origin
  a. Unconfined sand and gravel aquifers of glaciofluvial origin (These types of aquifers do not generally occur adjacent to present-day rivers.)
  b. Confined sand and gravel aquifers of glacial or preglacial origin
  c. Confined sand and gravel aquifers associated with glaciomarine environments

Bedrock aquifers

Type 5. Sedimentary bedrock aquifers
  a. Fractured sedimentary bedrock aquifers
  b. Karstic limestone aquifers

Type 6. Crystalline bedrock aquifers
  c. Flat-lying or gently-dipping volcanic flow rock aquifers
  d. Crystalline granitic, metamorphic, meta-sedimentary, meta-volcanic and volcanic rock aquifers

One of the unique characteristics of unconsolidated sand and gravel aquifers within the Region is the small size (ranging from an average size of 5 km^2—Type 2 and 3—to 27 km^2—Type 1a in average size); these are not considered "regional" aquifers but nonetheless constitute some of the most productive and important aquifers in Canada (with reported average median well yields of up to 6.1 L/s and geometric mean transmissivities ranging from 200 to 4,510 m^2/d). Many of the unconsolidated sand and gravel aquifers (Types 1, 2, 3 and 4a) were formed at or after the end of the last period of glaciation these are shallow, predominantly unconfined, comprised of coarse-textured sediments, and therefore, highly vulnerable to contamination from the land surface. Older, deeper unconsolidated sand and gravel aquifers formed during or at the advance stages of the last period of glaciation (Type 4b), or of glaciomarine origin (Type 4c), are generally confined and much less vulnerable.

Bedrock aquifers within the Region generally exhibit fractured flow, and possibly channelized flow (potential karstic limestone aquifers—Type 5b). The largest bedrock aquifer is the volcanic flow aquifer (aquifer classification # 124) situated in Central British Columbia which occupies at least

6,546 km^2 (known mapped area). Bedrock aquifers usually yield lesser quantities of groundwater (average median yields range from 0.3 to 0.4 L/s) and have lower transmissivities (geometric mean transmissivities of 3.7 to 23 m^2/d) than unconsolidated sand and gravel aquifers. The vulnerability of bedrock aquifers within the Region varies depending on the nature, amount, and extent of overlying unconsolidated sediments present.

Groundwater quality of the Region is normally excellent with respect to TDS (median of 185 mg/L), hardness (median of 77 mg/L), total alkalinity (median of 110 mg/L), and pH (average of 7.6), although concerns exists about elevated nitrate, arsenic, fluoride, and salty water in specific aquifers. Elevated nitrate is usually found in predominantly unconfined, unconsolidated sand and gravel aquifers (mostly Types 1b and 4a). Elevated arsenic and fluoride appear to be naturally occurring. Elevated arsenic is found in crystalline and some sedimentary bedrock aquifers (Types 5a and 6b) but also in unconsolidated aquifers (Type 1a). Elevated fluoride is found in sedimentary and crystalline bedrock aquifers (Type 5a and Type 6). Elevated salty water occurs in unconsolidated glaciomarine aquifers (Type 4c) in the Fraser Lowland near Vancouver, as well as sedimentary (Type 5a) and crystalline bedrock (Type 6b) aquifers in coastal areas such as the Gulf Islands and Vancouver Island.

Although much has been learned about aquifers within the Canadian Cordillera over the last 50 years, more studies are required, especially at the local scale. This will result in specific place-based science to support management and/or protection of local groundwater resources within the Region. Given the unique characteristics of many of the Cordillera Region's aquifers, and the increasing demand and pressures on the groundwater resource they provide, we recommend the following:

- Detailed local mapping (at 1:20,000 to 1:50,000 scale) and characterization of specific high-priority aquifers or basins, including a better understanding of the relationship between surface water and groundwater for specific high-priority Type 1, 2 and 4a aquifers
- Expand groundwater level monitoring in developed aquifers, especially in the northern and eastern portion of the Region to monitor groundwater use, resource development, and any effects on groundwater availability
- Regional vulnerability mapping of developed aquifers given the numerous unconfined, unconsolidated aquifers that exist in the Region to influence appropriate local land use planning and practices
- Develop and expand acquisition of groundwater quality data in the Region to gain greater understanding about the occurrence and origin of naturally occurring chemicals and microbiological species of concern in groundwater, such as arsenic and bacteria
- Engage local communities to support use of place-based hydrogeological information in local decision making
- Establish regular dialogue between federal, provincial, and territorial governments to promote exchange of information and coordinate activities, where appropriate

ACKNOWLEDGEMENTS

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Financial and in-kind support from the BC Ministry of Environment and Geological Survey of Canada for this work is also greatly appreciated.

BOX 9-1 BRITISH COLUMBIA AQUIFER CLASSIFICATION SYSTEM

The British Columbia aquifer classification system was developed in 1994 (Kreye and Wei, 1994). Its main objective was to interpret and synthesize raw well construction report (well record) data to identify and classify developed aquifers to

- Provide a framework to direct detailed aquifer mapping and assessment
- Provide a method of screening and prioritizing management, protection and remedial efforts on a provincial, regional and local level
- Identify the level of management and protection an aquifer requires
- Build an inventory of developed aquifers in the province
- Increase public knowledge and understanding of the groundwater resource

Data used for classifying aquifers come from various sources (primarily available well records, geologic mapping, and specific groundwater reports). The aquifer classification system contains two main components:

a) Classification component

b) Ranking value component (see Figure 9.11).

The classification and ranking value components are determined for the aquifer as a whole, and not for parts of aquifers.

The **classification component** characterizes an aquifer on the basis of groundwater resource development and level of vulnerability to contamination. The **ranking value component** assigns a number value indicating the aquifer's relative importance.

Classification Component

The classification component categorizes aquifers based on current level of groundwater development (categories I, II, and III for high, moderate and light development, respectively) and vulnerability to contamination (categories A, B, and C for high, moderate, and low vulnerability, respectively). The combination of the three development and three vulnerability categories results in nine aquifer classes, ranging from IA to IIIC as seen in the Figure 9.12.

These nine aquifer classes have an implied priority from IIIC, the lowest priority for management and protection to IA, the highest.

Specific management objectives also set priorities. Should the objective be assurance of a sustainable water supply then heavily developed I aquifers (i.e., IA, IB, IC) should be given attention.

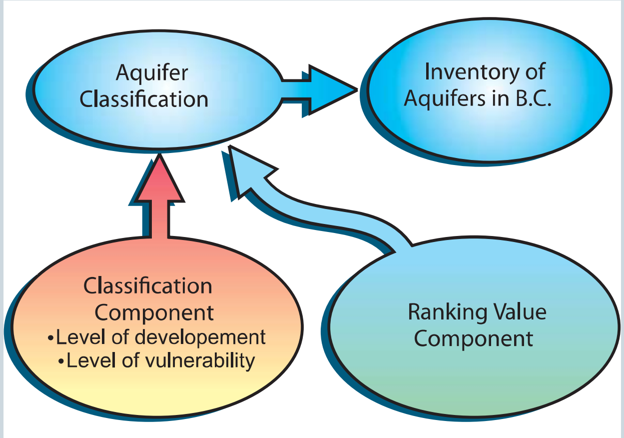
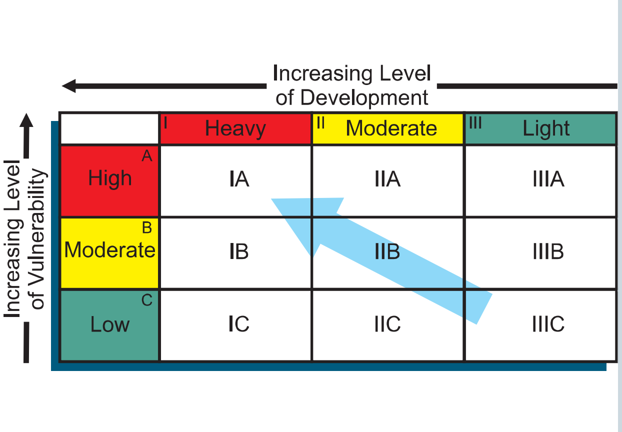


Figure 9.11 The British Columbia Aquifer Classification System.



	I Heavy	II Moderate	III Light
A High	IA	IIA	IIIA
B Moderate	IB	IIB	IIIB
C Low	IC	IIC	IIIC

Figure 9.12 Aquifer classes.

When the objective is protection of groundwater quality, then highly vulnerable A-aquifers (i.e., IA, IIA, IIIA) become primary concerns.

Level of development, a relative and subjective term, compares the amount of groundwater withdrawn from an aquifer (demand) to the aquifer's inferred ability to supply groundwater for use (productivity). Levels of development are usually determined subjectively by assessing well density, water use and aquifer productivity (calculated from reported well yield and specific capacity), and recharge sources.

An aquifer's **level of vulnerability** is a measure of its vulnerability to any contaminant introduced at the land surface. Vulnerability in such a system is considered to be intrinsic to the aquifer, based on hydrogeology: it does not consider existing type of land use or nature of potential contaminants.

Assessment of vulnerability is not an assessment of the risk of contamination. An aquifer's level of vulnerability is qualitative and based on type, thickness and extent of geologic sediments overlying the aquifer, depth to water (or depth to top of confined aquifers), and porosity (when reporting on bedrock aquifers), and type of aquifer material.

Ranking Value Component

The ranking value component assigns a number value indicating the relative importance of an aquifer. Assigned values are derived from seven criteria: 1) aquifer productivity, 2) aquifer vulnerability to surface contamination, 3) aquifer area, 4) demand on the resource, 5) type of groundwater use, and known documented groundwater concerns related to 6) quality, and to 7) quantity.

This point value is determined by summing each criterion, with the lowest ranking value possible being 5 and the highest-ranking value possible being 21. Generally, the aquifer with the highest-ranking value has the greater priority. Table 9.5 shows the ranking values applied for each criterion.

TABLE 9.5 AQUIFER RANKING VALUES

Increasing ranking value →

	1	2	3
Productivity	low	moderate	high
Vulnerability	low	moderate	high
Area	< 5 km^2	5 - 25 km^2	> 25 km^2
Demand	low	moderate	high
Type of use	non-drinking water	drinking water	multiple
Quality concerns	isolated	local	regional
Quantity concerns	isolated	local	regional

All hydrological and water use criteria are of equal weight. Each is assigned a point value ranging from 1 to 3 according to the magnitude of concern or importance. Exceptions are quality and quantity concerns, where the point values range from 0 to 3. A zero value (0) is assigned if no known or documented concerns exist. Once individual values have been assigned, all other values are summed to obtain an overall ranking for the specific aquifer.

Productivity describes yield from wells and springs and the abundance of groundwater in any given aquifer. Indicators of productivity (e.g., reported well yields, specific capacity of wells, and transmissivity of the aquifer) are used to infer potential productivity of that aquifer.

Vulnerability is the potential for an aquifer to be degraded. The higher an aquifer's vulnerability, the greater the potential for degradation, necessitating a higher priority for directing protection and management efforts to that aquifer.

Aquifer size refers to the areal extent (in square kilometres) of the aquifer. Usually, larger aquifers have more regional importance when compared to smaller aquifers. For those aquifers straddling the international border, size is generally reported only for that portion located within Canada.

Demand is assessed subjectively, based on domestic well density, number and type of production wells, and general knowledge of groundwater use (such as for drinking water or irrigation) and land use within the area.

Type of water use of an aquifer reflects the variability and diversity of the resource as a supply. Categories of water use include non-drinking, drinking (municipal or domestic), and multiple (both drinking and other applications such as commercial, industrial, and agricultural).

Quality concerns are defined by the presence of contaminants in the aquifer that pose a health risk. Contaminates may include nitrate, pesticides, volatile organic compounds, fluoride, arsenic or sea water intrusion. Contaminants may be naturally occurring or introduced by human activities.

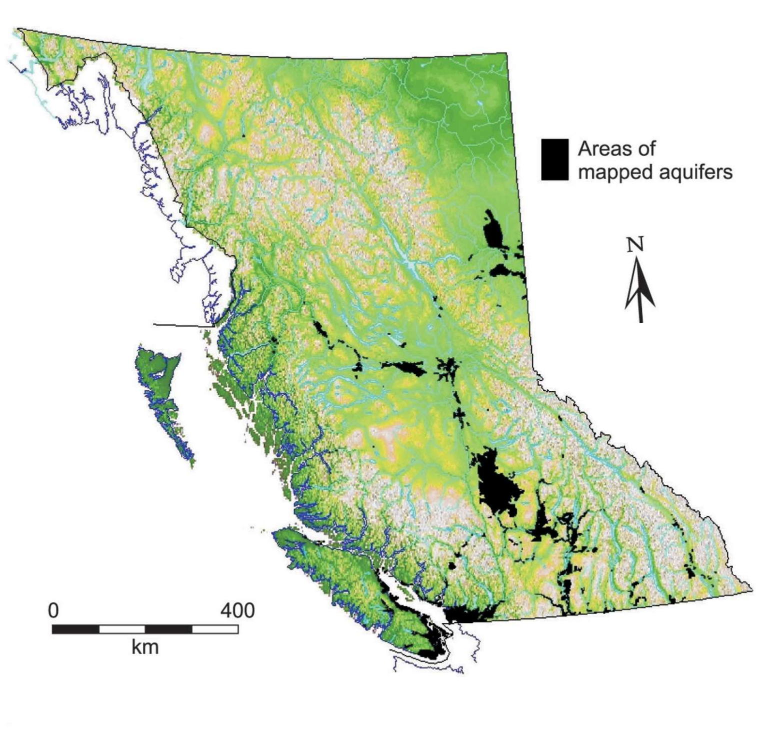


Figure 9.13 Mapped developed aquifers in BC (as of 2007).

Quantity concerns are defined by demand exceeding supply. Evidence of demand exceeding supply includes instances of well interference or aquifer mining, presence of dry wells, and situations in which primary source aquifers are unable to meet demands on a seasonal or cyclical basis.

Ranking values for the aquifers ranged from a high of 21 to a low of 5. Only 5% of all aquifers have a ranking value of 14 or greater. The highest ranking values were associated with unconsolidated aquifers and were attributable to quality/quantity concerns, aquifer size, productivity, and level of demand on those aquifers.

Aquifer classification has now been completed in most areas of BC where groundwater resources have been developed. Once a new aquifer is classified, it is added to the Province's aquifer inventory. As of 2007, 888 developed aquifers have been identified, mapped, and classified within the BC Cordillera (Figure 9.13).

The inventory of aquifers shows:

Unconsolidated aquifers:	70%
Bedrock aquifers:	30%
IA aquifers (highly developed & highly vulnerable):	4%
I aquifers (heavily developed):	8%
A aquifers (highly vulnerable):	27%
B aquifers (moderately vulnerable):	31%

The high percentage of unconsolidated aquifers identified reflects the association between population distribution and river valley locations where aquifers are typically developed in sand and gravel deposits. Bedrock aquifers are generally found on valley sides or in upland and plateau areas where the population is more sparse. Almost 30% of unconsolidated aquifers were reported as highly productive, versus less than 1% of bedrock aquifers.

17% of classified aquifers have documented quantity and/or health-risk related quality concerns. 107 aquifers have reported quality concerns, 63 have reported quality concerns; some aquifers have both. These concerns may be isolated, local, or regional in extent.

Development of the classification system stimulated a demand for aquifer information far greater than expected because the information was accessed by a myriad of other user groups beyond the target group of hydrogeologists, planners and water managers. A guidance document (Berardinucci and Ronneseth, 2002) was produced to promote the appropriate use of the aquifer classification system and to assist users in interpreting and using the aquifer maps. This document can be found at: http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/reports/aquifer_maps.pdf. These aquifer maps, and other hydrological information, are also available on-line on the web at: http://webmaps.gov.bc.ca/imf5/imf.jsp?site=wrbc.

BOX 9-2 ABBOTSFORD-SUMAS AQUIFER

The Abbotsford-Sumas aquifer, located in Lower Fraser Valley in southwest British Columbia and northwest Washington State is approximately 161 km^2 (62 sq. miles) in area, roughly bisected by the Canada-USA border (Figure 9.14). The aquifer spans uplands and three river valleys. The uplands are centred on the City of Abbotsford, and extend westward through Langley, and south to Lynden, WA. The Sumas Valley, which borders the aquifer to the east, is a large sediment-filled deep bedrock valley that receives aquifer discharge. The Nooksack River valley, to the south, receives the largest discharge component from the uplands and the aquifer. To the north is Fraser River floodplain, where a small component of groundwater discharge from the aquifer occurs (Cox and Kahle, 1999).

The aquifer is highly productive and provides water supply for nearly 10,000 people in the USA (towns of Sumas, Lynden, and scattered agricultural establishments) and 100,000 people in Canada, mostly in the city of Abbotsford, but also in the Township of Langley. Almost half the groundwater is pumped to supply fish hatcheries in Abbotsford, BC. Industrial use is becoming important as evidenced by the construction of a power plant near Sumas, WA. Pumping is significant, and is on the order of 1/7 to 1/8 of total annual recharge.

The coastal climate is humid and temperate, with significant rainfall over most of the year. Recharge to the aquifer is primarily from direct precipitation, mostly from October to May. Recharge varies spatially and is estimated to range from 650 to 1000 mm/year, with greater recharge occurring to the north, coinciding with the strong precipitation gradient across the Region (Scibek and Allen, 2006a). Groundwater discharge occurs through spring flow, and seepage to small streams and rivers.

The aquifer is composed of uncompacted sands and gravels of the Sumas Drift, a glacial deposit formed at the end of the last period of glaciation. There is significant heterogeneity of the geologic units, resulting in potentially complex groundwater flowpaths. The thickness of Sumas Drift can be up to 65 m; its thickest dimension is in the northeast where glacial terminal moraine deposits are found. The deepest part of the aquifer system in this Region is located along the Canada-USA border south of the city of Abbotsford, toward Lynden, WA; the most productive areas are near Sumas, WA in southwest end of the Sumas Valley. The transmissivity of the aquifer averages 109 m^2/d, with a specific yield of 0.1.

This particular aquifer is largely unconfined, although part of the aquifer within Sumas Valley is confined. The aquifer under discussion is underlain by a glaciomarine stony clay deposit (Armstrong et al., 1963), which reaches ground surface to its western boundary; this unit is believed to act as a regional aquitard and is referred to as the Fort Langley Formation. There is a regional groundwater divide to the north, centred on the Langley uplands. To the south, the aquifer is bounded by the Nooksak River, and to the east and southeast, the aquifer is bounded by Tertiary bedrock, which

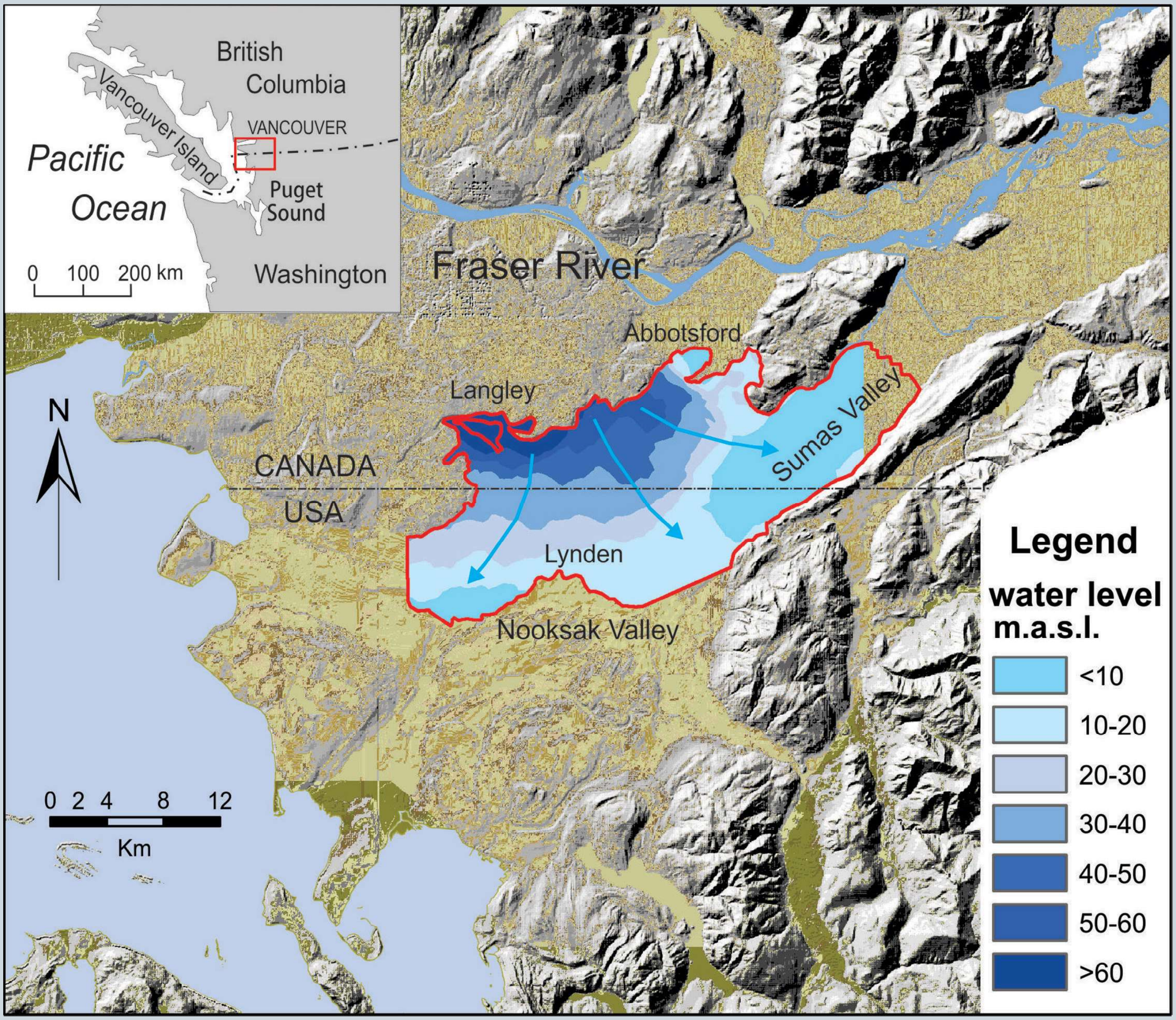


Figure 9.14 Topography of the Lower Fraser Valley, and outline of Abbotsford-Sumas aquifer. Groundwater flows south from areas of high water table (dark blue) to areas of low water table (light blue).

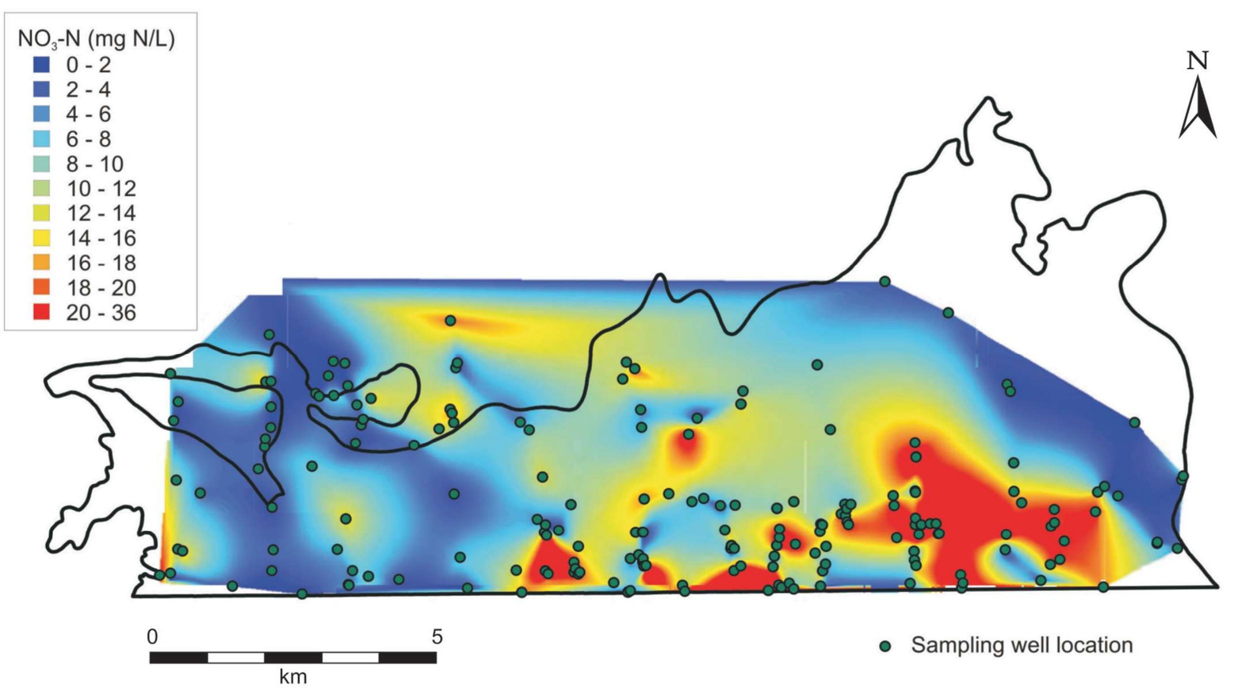


Figure 9.15 Nitrate distribution for the period 2002 to 2004 in the Abbotsford-Sumas Aquifer.

outcrops as mountains on both sides of Sumas Valley (Figure 9.14).

Elevated concentrations of nitrates have been documented in the Abbotsford-Sumas aquifer since the early 1970s (Kohut et al., 1989; Liebscher et al., 1992). The maximum allowable concentration (MAC) guideline as set by Health Canada (2008) for nitrate-nitrogen (NO_3-N) in drinking water is 10 mg/L: approximately 40% of 300 wells sampled in 2005 had concentrations that surpassed this value (Hii et al., 2005). Figure 9.15 shows a map of nitrate concentration from the period 2002–2004 for the Canadian portion of the aquifer.

The main source of nitrate is attributed to agricultural activities: raspberries are the predominant crop above the Canadian portion of the aquifer. Fertilizer application practices associated with raspberry production have been identified as significant contributors to nitrates within the aquifer (Liebscher et al., 1992; Hii et al., 1999; Zebarth et al., 1998; Mitchell et al., 2003). There are also a significant number of poultry farms present in the area, and manure produced from these operations is another potential source of nitrate contamination. Septic system sources are not considered to be a major contaminant source for this particular aquifer.

A study of nitrogen origin and fate within the aquifer (Wassenaar, 1995) indicates that soil nitrate was predominantly derived from nitrification of manure and, to a lesser extent, from ammonium-based fertilizers. Later work by Wassenaar et al. (2006) suggests a shift in nitrogen sources, away from manure sources toward inorganic fertilizer sources, following a recent (since 1992) shift in agricultural practice away from the use of manure fertilizer to synthetic fertilizer (as a response to a challenge to the industry to reduce nitrate loading). Hii et al. (2005) indicated that the farming industry as a whole responded to this challenge, although results of the latest survey (Hii et al., 2005) indicate that the extent of nitrate contamination throughout the aquifer has not changed dramatically.

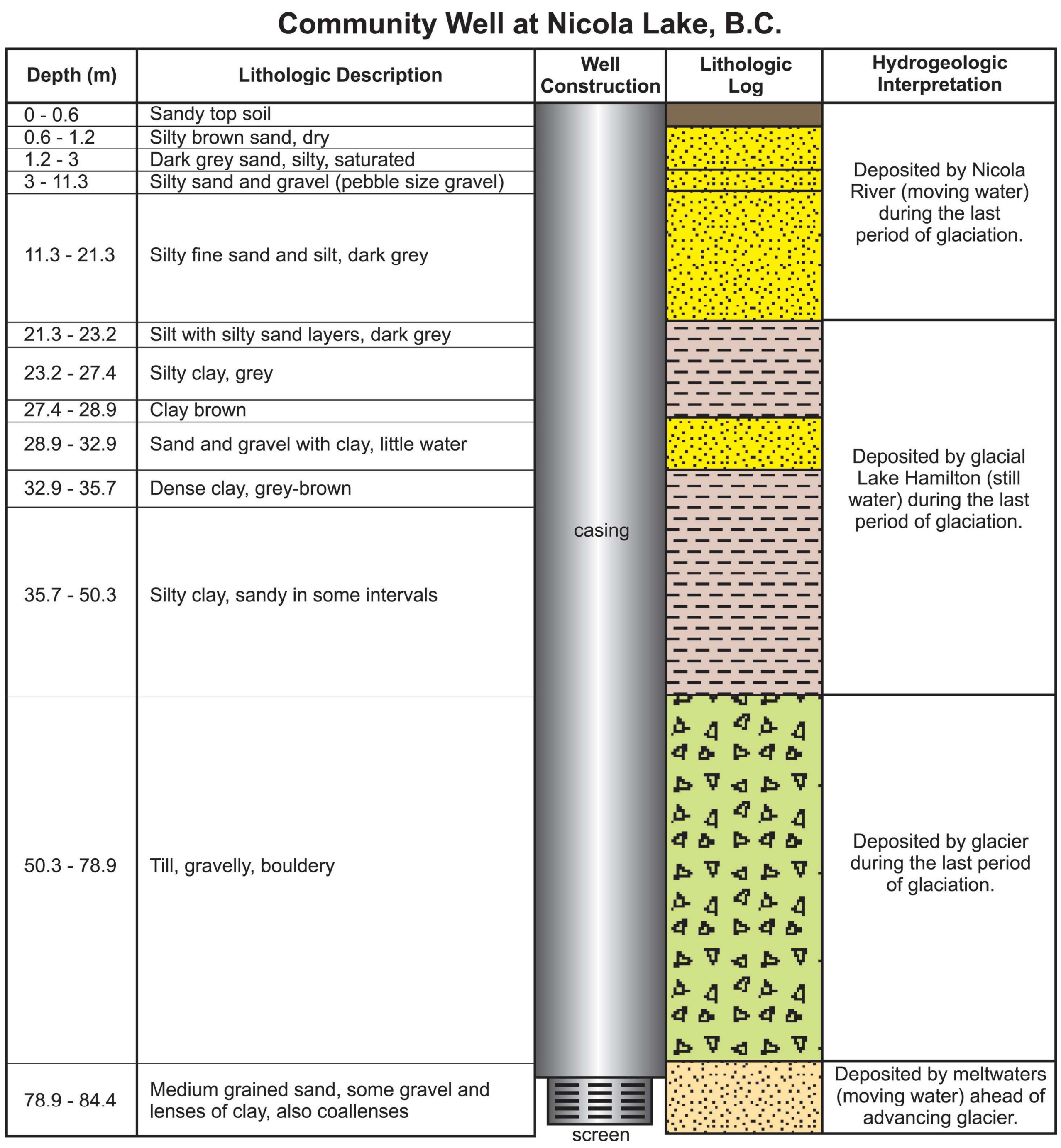
Chesnaux and Allen (2007) and Chesnaux et al. (2007) simulated nitrate leaching through the vadose zone and found that nitrate mobilization to the water table is rapid, on the order of only a couple of months, but that ongoing loading at the surface continues to yield high nitrate concentrations within the aquifer.

Wassenaar et al. (2006) measured the age of groundwater in wells using isotopic $^3H/^3He$ dating techniques to discover groundwater ages upward of 30 years. Wei (1989) similarly determined a chemical response time constant of ~10 years for the aquifer. Both studies suggest that it may take a decade, or more, for an aquifer to show changes in NO_3-N levels in response to nitrate loading changes.

BOX 9-3 INTERPRETING LOCAL SURFICIAL GEOLOGY AND UNDERSTANDING THE LOCAL GROUNDWATER RESOURCES FROM WATER WELL RECORDS

We would like to pay tribute to Canadian well drillers for contributing to the knowledge of groundwater resources throughout this country. Drillers record lithology encountered during drilling, depth of water-bearing units, groundwater level, and estimate of well yield. This information allows hydrogeologists to begin assembling pictures of the aquifers and the hydrogeology of a local area in order to help develop and protect local groundwater resources. This information, when interpreted, is also valuable in understanding how specific aquifers may have been formed.

Surficial geologic history and hydrogeology of a specific area within the Cordillera (or elsewhere in Canada) can often be inferred from the lithology contained in a well record and a knowledge of the area's glacial history. The degree to which scientists can interpret geologic history depends on the depth of the well, the method of drilling, and quality of lithologic description recorded by the driller. Figure 9.16 depicts the lithologic description for a community well (Kala, 1983) at Nicola Lake, northeast of Merritt in the southern Interior System. This description, together with a knowledge of the surficial geology and glacial history of the area (Fulton, 1975), allows the on-site surficial geologic history to be inferred. The well cited here is located in the Nicola River floodplain and the saturated sand, to 21.3 m depth, is interpreted to be deposited by the Nicola River at the end of or after the last period of glaciation. This sand is inferred to have been deposited in a fluvial environment to form an unconfined, unconsolidated aquifer (Type 1b) here. Beneath the sand, from 21.3 m to 50.3 m depth, are mostly clay and silt deposits. These sediments must have collected within a still-water environment, most likely during the last period of glaciation when the area was submerged under Nicola Lake (Glacial Lake Hamilton). The layer of sand and gravel between 28.9 m and 32.9 m depth may reflect an episode where the lake receded and coarser-textured sediments were deposited in a fluvial environment. A layer of till exists between 50.3 m and 78.9 m depth, most likely deposited by the local glacier during the last period of glaciation. Saturated sand and gravel found beneath the till (below 78.9 m) is interpreted to be glaciofluvial sand and gravel deposited by meltwaters ahead of the advancing glacier. This deeper sand and gravel unit is a confined, unconsolidated aquifer (Type 4b) and the source of water for the well (which is completed with a screen intake opposite this unit). Had the well been only 20 m



Depth (m)	Lithologic Description	Well Construction	Lithologic Log	Hydrogeologic Interpretation
0 - 0.6	Sandy top soil	casing		Deposited by Nicola River (moving water) during the last period of glaciation.
0.6 - 1.2	Silty brown sand, dry			
1.2 - 3	Dark grey sand, silty, saturated			
3 - 11.3	Silty sand and gravel (pebble size gravel)			
11.3 - 21.3	Silty fine sand and silt, dark grey			
21.3 - 23.2	Silt with silty sand layers, dark grey			Deposited by glacial Lake Hamilton (still water) during the last period of glaciation.
23.2 - 27.4	Silty clay, grey			
27.4 - 28.9	Clay brown			
28.9 - 32.9	Sand and gravel with clay, little water			
32.9 - 35.7	Dense clay, grey-brown			
35.7 - 50.3	Silty clay, sandy in some intervals			
50.3 - 78.9	Till, gravelly, bouldery			Deposited by glacier during the last period of glaciation.
78.9 - 84.4	Medium grained sand, some gravel and lenses of clay, also coallenses	screen		Deposited by meltwaters (moving water) ahead of advancing glacier.

Figure 9.16 Graphical representation of a well log for a community well at Nicola Lake, illustrating how the local surficial geology and presence of aquifers can be interpreted from the lithologic description.

deep, interpretation of the surficial geologic history would have been much more limited. One can also appreciate that the driller's description is also critical in allowing the surficial geologic history to be correctly and less ambiguously interpreted.

BOX 9-4 AQUIFER RESPONSE TIMES

One important question water resource managers or communities ask themselves is: “How quickly can we expect to detect a change in groundwater level from a drought?” or “If nutrient source controls were implemented, how quickly would we be able to see a change in the nitrate concentration within the aquifer?”

How quickly an aquifer responds to a change in hydraulic stress (e.g., increase or decrease in the amount of water input or increase in well pumping) or chemical stress (e.g., decrease in nitrogen loading) can be estimated by calculating an aquifer’s hydraulic or chemical response time, a concept presented by Gelhar and Wilson (1974).

We do know that hydraulic response time can be calculated, knowing the key aquifer parameters (see equation 9.2 below):

$$\tau_h = S \times L^2 / \beta \times T \qquad (9.2)$$

where:

τ_h is the aquifer’s hydraulic response time;

S is the aquifer’s storativity, or if an aquifer is unconfined, the specific yield;

L is the length of groundwater flowpath in an aquifer;

β is a geometric shape factor of an aquifer (generally varies between 2.5–3.5); and

T is the aquifer transmissivity.

Equation 9.2 shows that the greater the length of the groundwater flow system (or the larger the aquifer size), or the lower the transmissivity of an aquifer, the longer the aquifer’s hydraulic response time would be. Small, highly transmissive aquifers (such as those in the Cordillera) are expected to have relatively quick hydraulic response times and they react quickly to changes in hydraulic inputs or outputs.

Hydraulic response times have been calculated for 33 different aquifers within the Cordillera, including unconsolidated aquifers, usually unconfined (Types 1b and 4a), unconsolidated confined aquifers (Types 4b) and bedrock aquifers (Types 5a and 6b), where data are available. Hydraulic response times for these 33 aquifers range from less than a year to up to 8 years. All of the confined, unconsolidated aquifers (16 aquifers), 7 of the 9 unconfined, unconsolidated aquifers, and 7 of the 8 bedrock aquifers had response time of less than 2 years, suggesting they react very quickly to hydraulic inputs and outputs. The rapid response times for all the aquifers are mostly attributable to their generally localized extent, resulting in the development of limited flow systems.

Figure 9.17 plots hydraulic response times for some unconfined, unconsolidated aquifers. Also plotted are curves that allow hydraulic response times to be estimated graphically for various values of transmissivity, given the length of the groundwater flowpath. Based on equation 9.2 (similar curves can be generated for unconsolidated, confined aquifers and bedrock aquifers using equation 9.2 by substituting the appropriate storativity or specific yield for confined and bedrock aquifers, respectively). Note that in Figure 9.17, all the aquifers have estimated flowpaths of only a few kilometres in length. For unconfined, unconsolidated aquifers, the rapid response times are also explained by the relatively high transmissivity of these aquifer types. Confined, unconsolidated aquifers have even faster response times because the storage ability of confined systems is smaller than the specific yield of unconfined systems. The

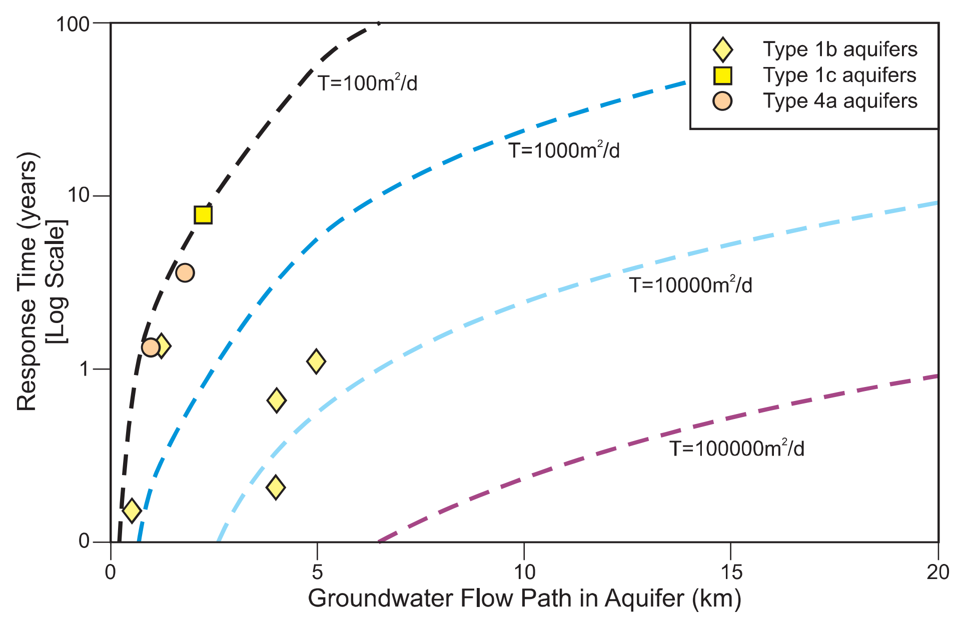


Figure 9.17 Hydraulic response times for specific aquifers and hydraulic response time curves for varying transmissivity values (m^2/d) for unconfined, unconsolidated aquifers.

quick response times for bedrock aquifers reflects not only the limited length of their flow systems but also the small specific yield corresponding to the low fractured porosity typical of bedrock aquifers in the Cordillera.

The equation for chemical response time is:

$$\tau_c = n \times h_o / N \qquad (9.3)$$

where:

τ_c is the aquifer's chemical response time;

n is the porosity of the aquifer;

h_o is the groundwater level above the bottom of the aquifer; and

N is the recharge.

Equation 9.3 shows that lower porosity, thinner aquifers, and greater recharge lead to faster aquifer chemical response times. A thin aquifer in a wet, coastal setting with greater recharge would be expected to have relatively quick chemical response times.

Chemical response times were calculated for 12 aquifers. These times ranged from less than a year to over 60 years. For the 4 unconsolidated aquifers in the study, chemical response times ranged from years to decades. Limited aquifer thickness and low recharge for aquifers in arid regions of the Cordillera were identified as the main factors in increasing chemical response times. In fractured bedrock aquifers, the generally quick chemical response times may be explained by the low-fracture porosity typically found in bedrock.

Although response time calculations only provide a crude estimate of how an aquifer, responds to changes in hydraulic, and chemical inputs and outputs, the results do illustrate that hydraulically and chemically, many aquifers within the Cordillera can be expected to react quickly to changes in stresses. This is because of the generally limited size, specific aquifer physical properties (e.g., transmissivity, specific yield and porosity, degree of confinement) and climate (which affects recharge).

BOX 9-5 THERMAL SPRINGS OF THE CORDILLERAN REGION

One interesting groundwater anomaly of the Cordilleran Hydrogeological Region is the fact that over 140 thermal springs occur in the area, the only region in Canada to have such features (including the Cordilleran portion of the Northern Region—Grasby and Hutcheon 2001, Grasby et al., 2000; Allen et al., 2006; Caron et al., 2008; Figure 9.18). These springs, with a few, rare exceptions, occur in the bottoms of the major valley systems.

Although thermal springs are normally associated with regions of high heat flow, this is by no means a prerequisite. Thermal springs can be associated with 1) high heat flow areas, including the volcanic belts of the west coast and high heat flow region of the McKenzie Mountains, 2) crustal scale Eocene normal faults, found across southern BC, and 3) anomalous structural features that locally enhance permeability, like the thermal springs found in the Rocky Mountains. The thermal springs at Banff, for example, occur in one of the lowest heat flow regions of the Cordillera. The anomalous structure at Cascade Mountain, however, enhances permeability along the Sulphur Mountain thrust, allowing deep groundwater circulation (Grasby et al., 2003). Stable isotope data indicates that all of these springs originate as meteoric water. The high temperatures reflect circulation of groundwater to depth, where the water is heated before returning to surface (Figure 9.19).

Temperature of any thermal spring outlet reflects a combination of local geothermal gradient, circulation depth, and flow rate. The variability in heat flow and geothermal gradients within the southern Rocky Mountain Trench affecting thermal springs has been shown by Allen et al. (2006). Lower gradients require greater circulation depths for groundwater to obtain heat. The depth of groundwater circulation is typically restricted by the strength of the rock it is flowing through; increasing stress at depth closes fracture networks, thus inhibiting circulation. Empirical evidence suggests a practical limit for circulation at around 5 km. This observation is consistent with the deepest estimated circulation depths for springs in the Cordillera. Research has shown that when groundwater circulates too fast, advective heat transport will cool the region, while when the circulation is too slow, the groundwater will cool during its ascent to surface (Ferguson et al., 2009; Foster and Smith, 1988).

Unique aquatic ecosystems are a common feature of thermal spring outlets. The northern limit of most plant and animal species is often a function of climatic factors (e.g., how cold a winter can these organisms survive). The discharge of thermal waters in Canada's northern climate creates microclimates which

Figure 9.18 A pool of warm water at the Meager Creek Hot spring, Southwestern British Columbia.

often support rare and unique ecosystems. The warm microclimates of thermal springs allow plant species (e.g. the southern Maiden Hair Fern at the Fairmont Spring) to survive as isolated communities at climates much farther north than their normal distribution. There are also documented cases of unique animal species (e.g., the Banff Springs Snail) evolving to adapt to thermal waters (Grasby and Lepitzki, 2002). Along with hosting rare ecosystems, spring outlets often develop extensive travertine mounds as unique hydrogeological features. These mounds are typically formed by calcium carbonate precipitating from solution in response to degassing of carbon dioxide (CO_2) as the waters equilibrate to atmospheric pressure (Figure 9.20). This degassing can result in the local formation of extensive structures which grow and spread over thousands of years.

The unique and rare occurrence of thermal springs is appreciated by all that find them—it is very difficult to encourage a moose soaking in a hot pool to leave so you can sample the water! People likewise enjoy these features; over 10 thermal spring resorts have been developed across the Cordillera Region. The majority of these thermal springs are situated in remote locations and found in mostly a natural state.

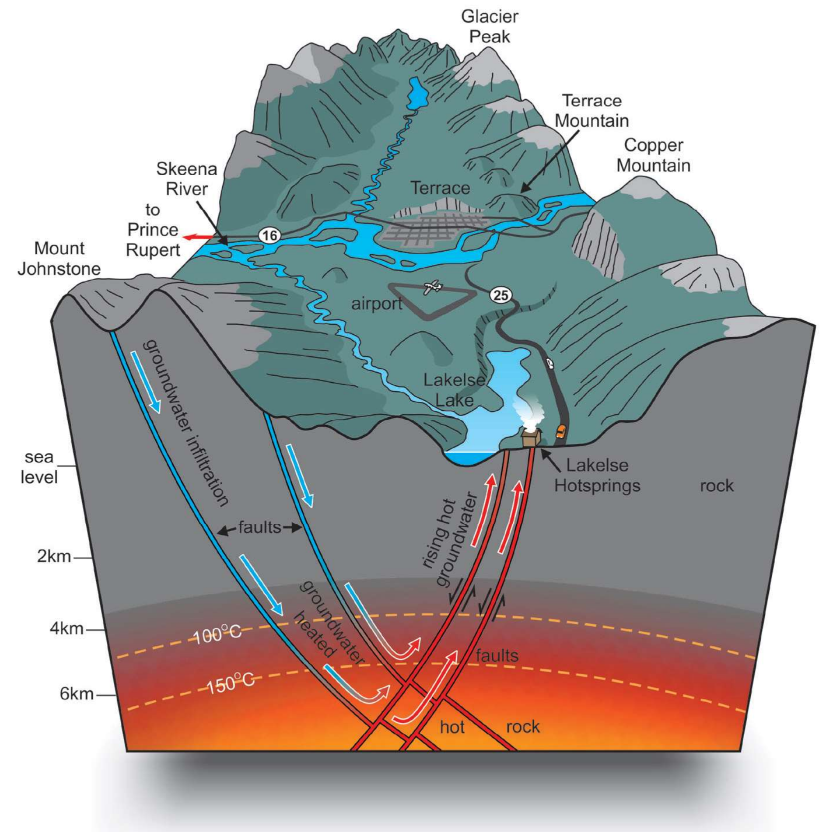


Figure 9.19 Schematic diagram showing the occurrence of the Lakelse Hot Spring in Northwest British Columbia.

Figure 9.20 Travertine mound forming at the Sculpin warm spring, McKenzie Mountains, Northwest Territories.

CANADA'S
GROUNDWATER
RESOURCES

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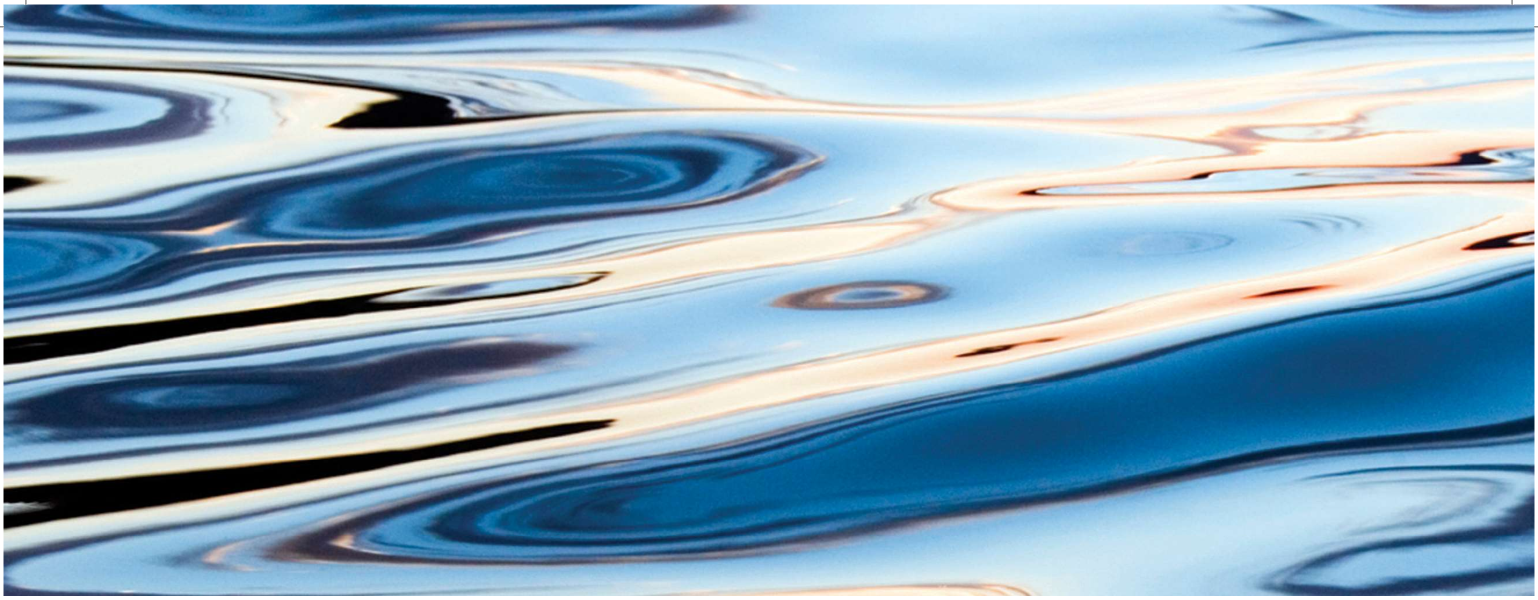

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