CHAPTER 10

PLAINS REGION

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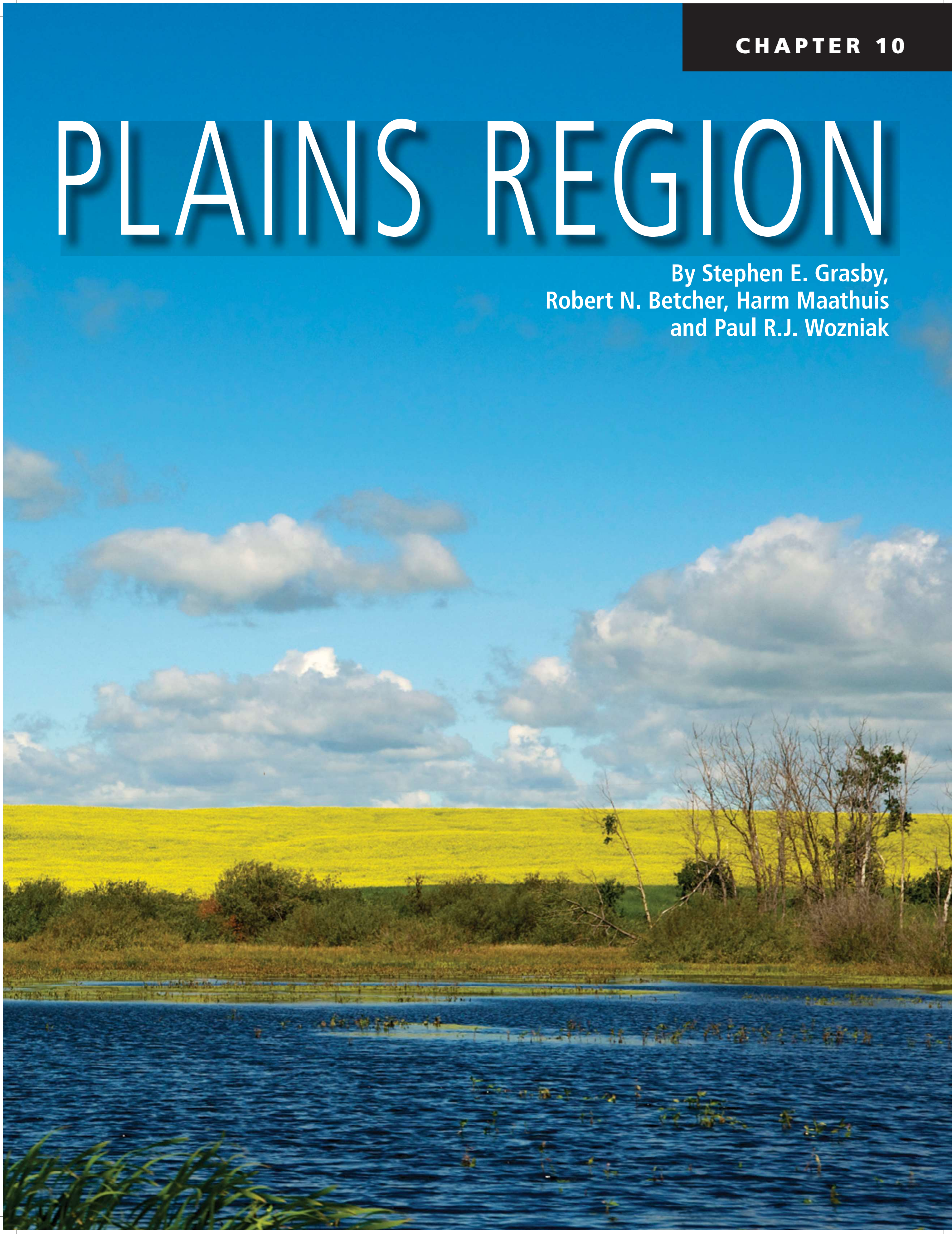


10.1 INTRODUCTION

The Plains Region (Figure 10.1), Canada's agricultural heartland, is a major world grain producer. Covering over 1.7 million km^2, the region has a sparse population of 5.2 million, the majority of which is concentrated in a few major cities. Most large urban centres are supplied by surface water, whereas rural populations rely largely on groundwater. Domestic groundwater use varies across the region and is estimated to be 23% in Alberta, 43% in Saskatchewan and 30% in Manitoba (Statistics Canada, 2003).

In the southern portion of the region, surface water is heavily used for major irrigation withdrawals, municipal use, hydroelectric power generation and small-scale industry. In some drainage basins within southern Alberta, sustainable rates of surface water withdrawal are now considered fully allocated and there are no new surface water licences available to meet growing demand associated with rapid population growth. Consequently, the demand for groundwater resources is expected to grow substantially. Given the shortage of supply and rapidly increasing demand, the southern Plains Region will probably have some of the greatest water supply challenges in Canada's near future. While there is growth in water demand in the Athabasca River Basin because of oil extraction from the oil sands of northern Alberta, total use accounts for only a minor component of the discharge to date.

10.2 PLAINS HYDROGEOLOGICAL REGION

The Plains Region is bound on the east and north by the Canadian Shield and on the west by the deformation front of the Rocky Mountain Foothills. While the interior plains extend north to the Arctic Ocean, the Plains Hydrogeological Region, as used here (Sharpe et al., 2008) and consistent with Brown (1967), has a northern boundary defined by the southern limit of continuous permafrost and a southern boundary defined by the international border.

10.2.1 Physiographic description

The entire Plains Region is characterized by low-relief landscapes and generally flat or rolling hills with some steep embankments along incised river valleys. The easternmost part is formed by the Manitoba Lowlands. This low-lying area (elevations under 400 masl) was mostly covered by glacial Lake Agassi during the retreat of the last continental ice sheet (Teller and Leverington, 2004), with lake sediments forming the flattest portion of the region. To the west, the landscape rises along the ~200-metre-high Manitoba Escarpment to the Saskatchewan Plain. The Saskatchewan Plain is characterized by thick deposits of glacial till, hummocky moraines and localized glacial lake sediments forming a rolling but generally flat landscape with elevations from 460 m to 760 masl on average. However, there are some localized areas with more topographic relief. The Cypress Hills between southern Alberta and Saskatchewan form isolated highlands up to a height of 1,460 masl Further west, the plains rise gradually to the Alberta Plain with elevations up to 1,600 masl. The Alberta Plain has more varied relief and defined erosional features than the plains to the east. Northern Alberta is characterized by forested lowlands with a series of disconnected plateaux (rising up to 1,000 masl) dissected by the Peace and Athabasca river valleys.

Vegetation zones in the Plains Region show defined patterns largely related to precipitation and temperature variations across the region. The triangle-shaped short-grass prairie region is centred roughly in the southern portion of the Alberta-Saskatchewan border. As one proceeds west, east and north from there, a transition occurs to long-grass prairie, and then into aspen parkland, with increasing net precipitation and decreasing average temperatures. These three zones form the prairie portion of the Plains Region. As one proceeds northward, one encounters aspen parkland that transitions to the northern Boreal Forest Region on the northern plains (Figure 10.2a).

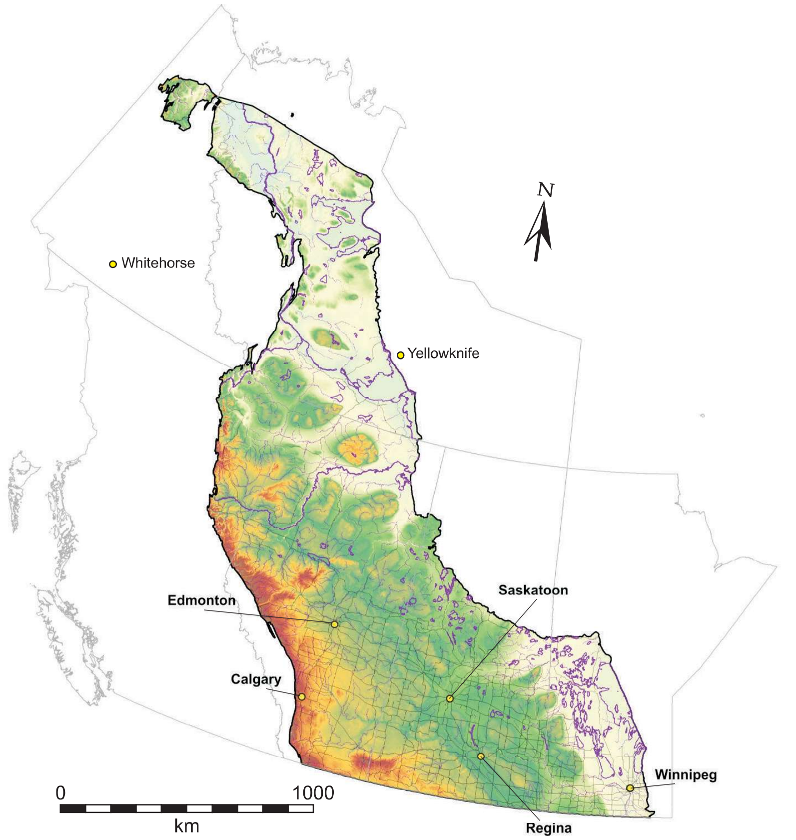


Figure 10.1 Map of Plains Hydrogeological Region, showing major rivers, political boundaries, cities, shaded topography and major road networks.

10.2.2 Demographics

According to the 2006 Census, the population of the Plains Region was about 5.2 million, a 6.5% increase over the five years from the previous census. Most of the population (about 4 million people) live in urban areas, while an additional 102,000 live in outlying urban areas and the remainder in small communities and rural settings. Urban and rural areas have approximately the same average number of inhabitants per private dwelling (2.4). Of the 5.2 million people within the Plains Region, the majority live in southern Alberta (~3 million), while Saskatchewan and Manitoba each have about 1 million people, and 57,000 people live in the plains portion of northeast British Columbia.

10.2.3 Climate

The Plains Region is characterized by long cold winters and warm dry summers. Average temperature varies across the region, with the highest annual mean temperature in the southwest and decreasing northward. Average minimum and maximum temperatures vary across the region by up to 12°C (Figure 10.2). Average annual temperatures have risen by 1.5°C during the approximately 100-year period that records have been kept (Figure 10.3). This trend has been observed in a number of locations within the region (Zhang et al., 2000; Chen et al., 2004, 2006) and has been documented in borehole temperature profiles (Majorowicz et al., 2006; Skinner and Majorowicz, 1999).

Mean annual precipitation is very low across the Plains Region, varying from 285 mm to 600 mm per year, with the lowest values recorded in southeastern Alberta and southwestern Saskatchewan (Figure 10.4). Precipitation in the region is dominated by rainfall (300 mm/year to 400 mm/year)

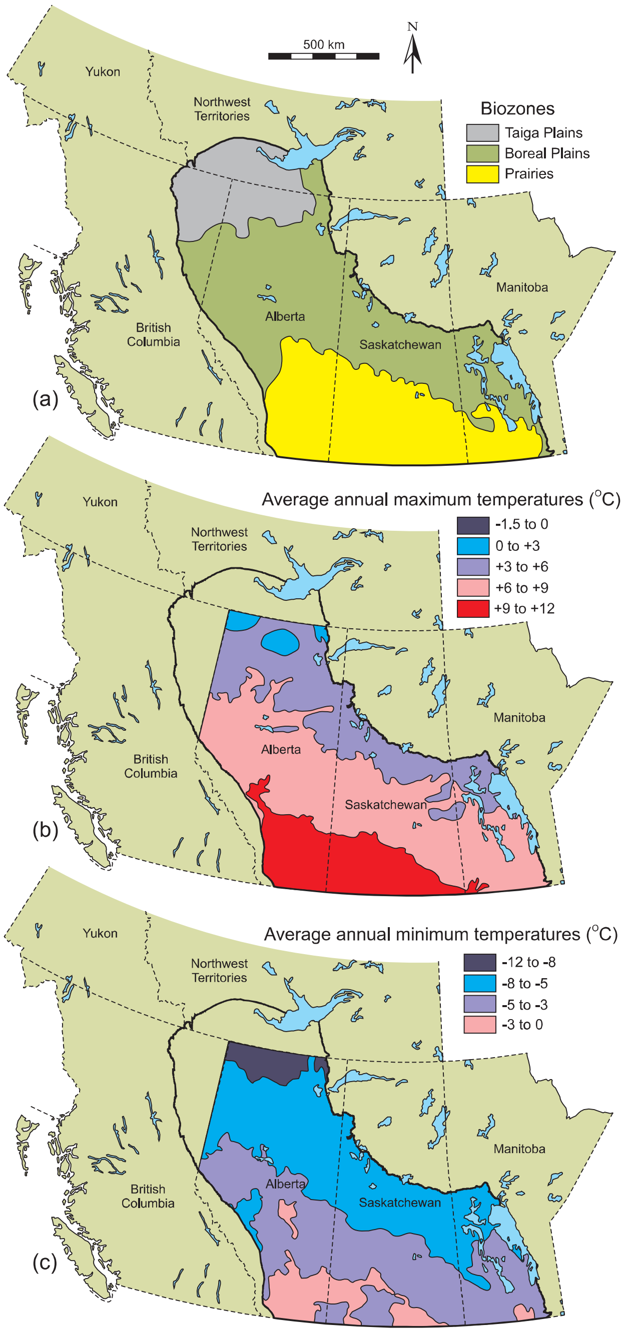


Figure 10.2 (a) Principal biozones of the southern part of the Plains Region as influenced by **(b)** Average annual maximum temperatures (°C) and **(c)** Average annual minimum temperatures (°C), calculated from daily temperatures during the 1961–1990 period (from Nyirfa and Harron, 2002).

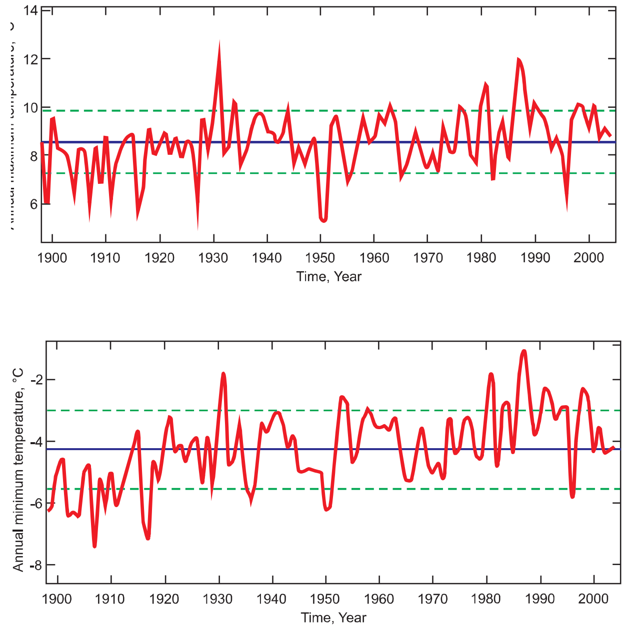


Figure 10.3 Maximum and minimum temperature time series (for Saskatoon). The annual average temperature is shown by a solid red curve with mean (blue) and plus/minus one deviation (green). Note overall the increase of approximately 1.5°C over past 100 years. Data source: Environment Canada (Adjusted Historical Canadian Climate Data).

with smaller amounts of snowfall (100 mm/year to 200 mm/year). Precipitation time series show no definitive trends over the last 100 years (Figure 10.5); however, some studies suggest that an overall increase has occurred in the northern areas (Zhang et al., 2000), while the southern Prairies have seen a decrease (Gan, 1998). Nonetheless, tree ring studies suggest that the 20th century may have been a period of higher-than-normal precipitation in the Plains Region, when comparisons are made on a 1,000-year time scale. Evidence of prolonged periods of sustained multidecadal drought has also been observed (Sauchyn and Beaudoin, 1998; Case and MacDonald, 2003; St. George and Nielsen, 2002). During the warm, dry period of the hypsithermal, before 6000 BC, prairie peatlands were less extensive (Zoltai and Vitt, 1990) and regional groundwater tables were 6 m to 15 m lower than present (Remenda and Birks, 1999). Evidence also suggests that deep groundwater circulation systems were less active (Grasby et al., 2003).

Both temperature and precipitation records indicate that relatively short-term instrumented

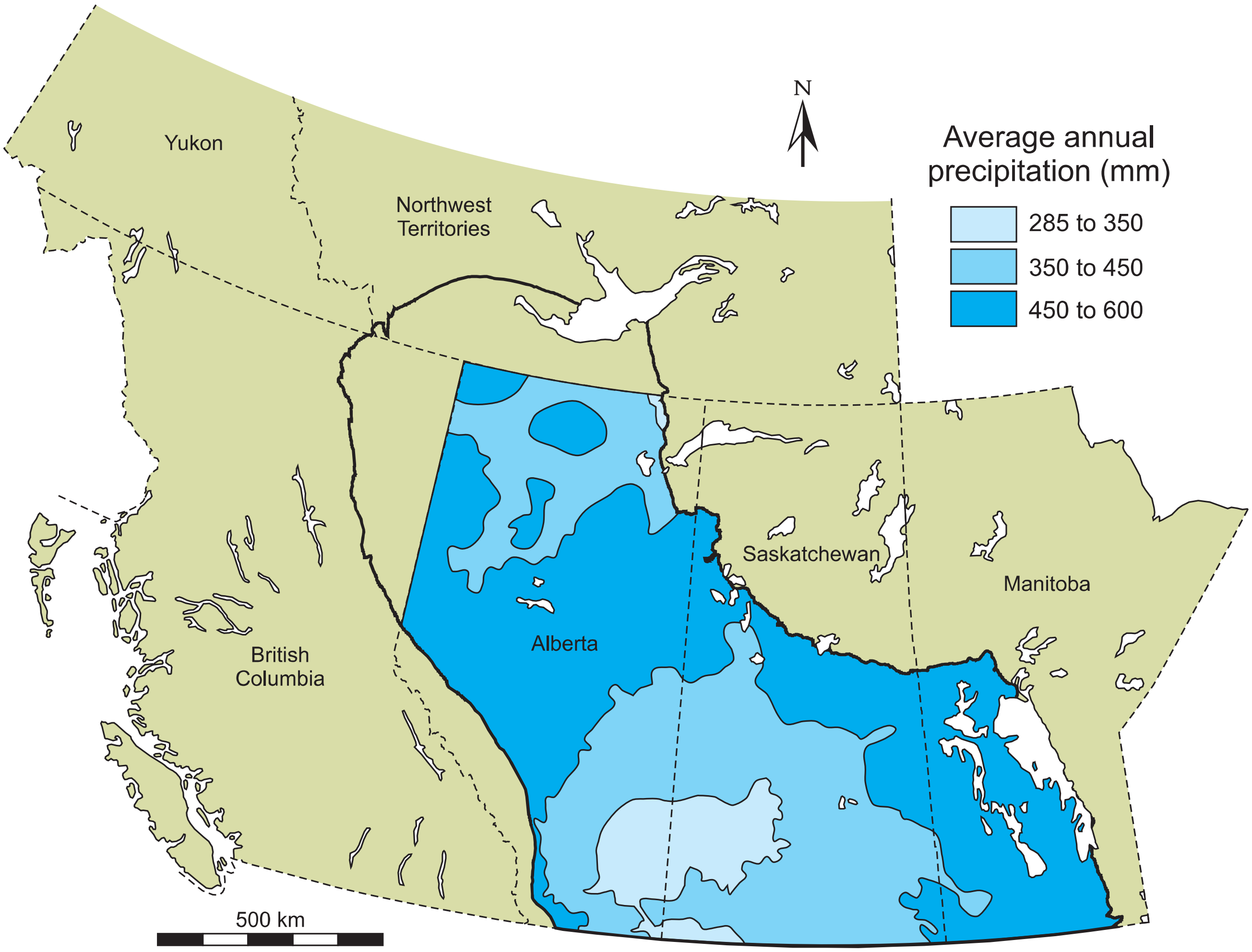


Figure 10.4 Average annual precipitation from 1961 to 1990 (from Nyirfa and Harron, 2002).

records may not be representative of longer-term climate variability (Chen and Grasby, 2009). Studies of long-term trends in groundwater levels in southern Manitoba show a strong correlation with precipitation patterns, as well as temperature, (Chen et al., 2002, 2004), indicating that changes in these parameters may have a significant impact on groundwater availability. Caution therefore needs to be exercised when using these historical climate records to model future groundwater resources.

The evapotranspiration potential within the region is high, ranging from 500 mm/year to 700 mm/year: in many places, it exceeds annual precipitation, creating a net moisture deficit (Figure 10.6). Moisture deficits in most of the southern portion of the region create semiarid conditions that limit surface water and recharge to groundwater systems. The majority of runoff moving through major river systems of the southern plains is generated in the Cordillera Region to the west rather than internally. Much of the southern Plains Region is characterized by closed basin conditions (Last, 1989).

10.2.4 Surface water

The Plains Region is drained by three major river systems—the Nelson, the Churchill and the headwaters of the Mackenzie—in addition to the relatively small headwaters portion

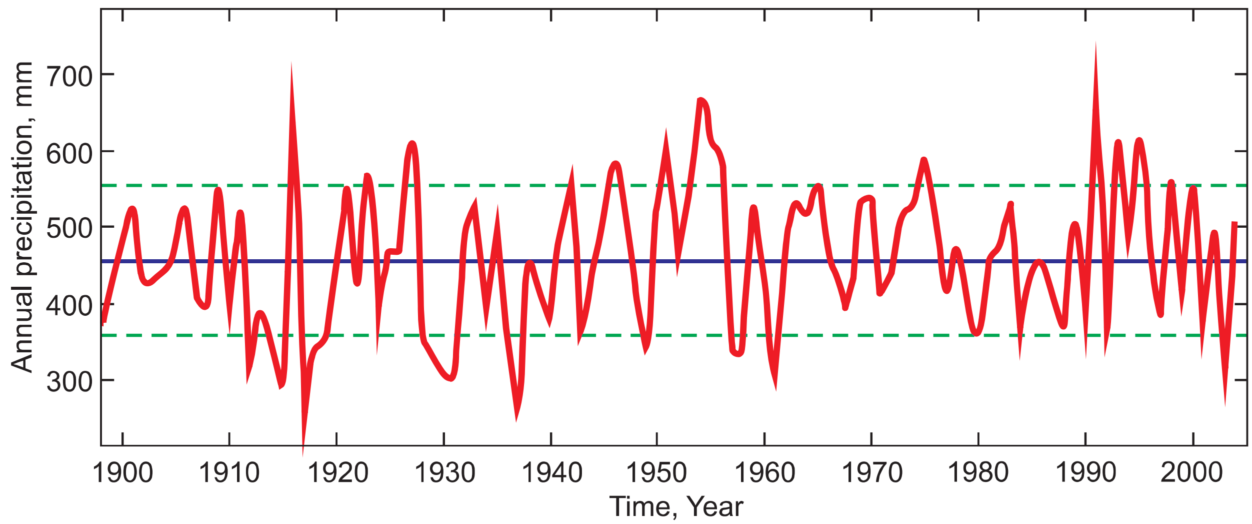


Figure 10.5 Annual precipitation at Regina, shown by the solid red curve with mean (blue solid) and plus/minus one deviation. Note no definitive trend indicated over the last 100 years. Data source: Environment Canada (Adjusted Historical Canadian Climate Data).

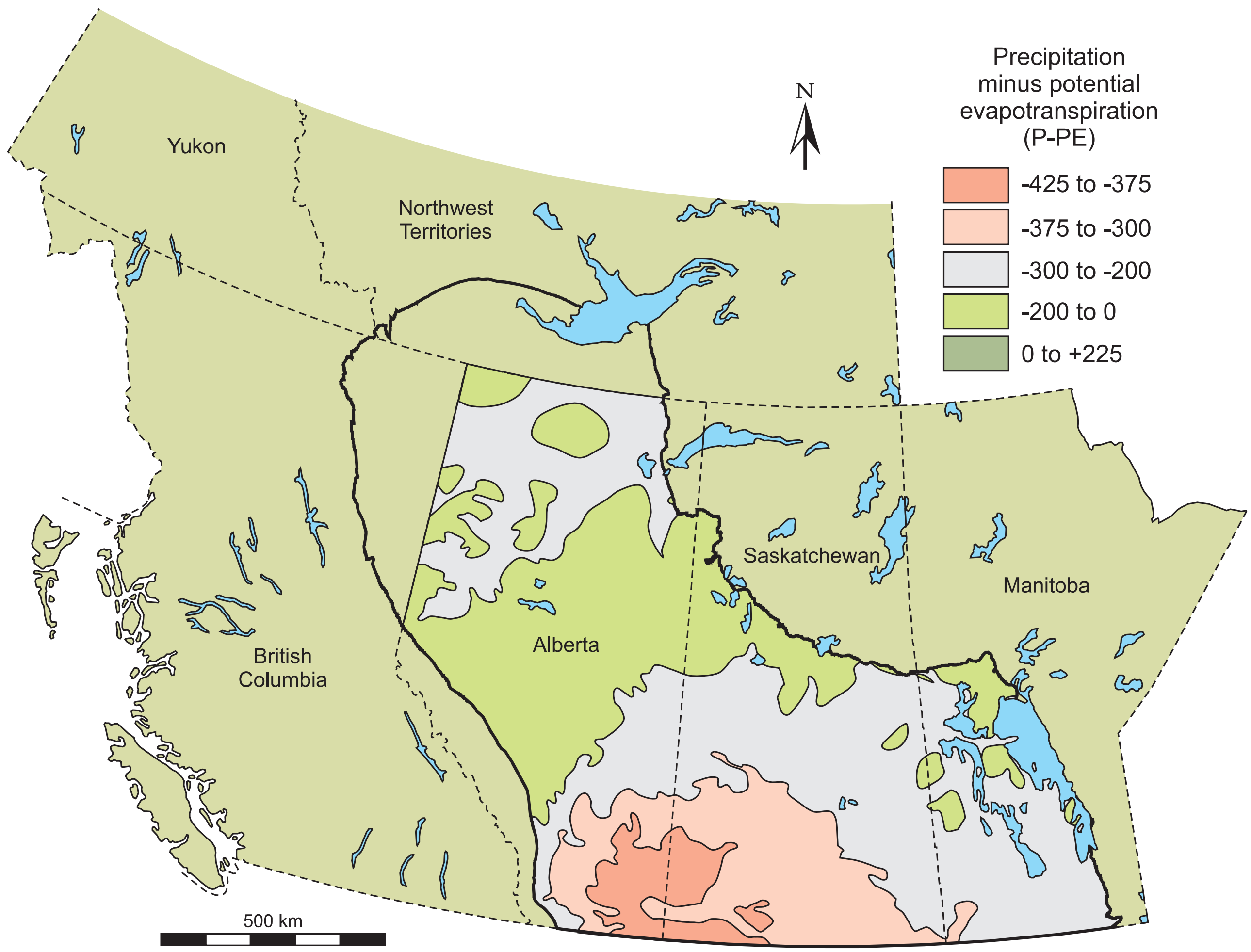


Figure 10.6 Average moisture deficit in different climate regions within the southern part of the Plains Region. The average moisture deficit is calculated from the differences between annual precipitation and potential evapotranspiration in the 1961–1990 period (from Nyirfa and Harron, 2002).

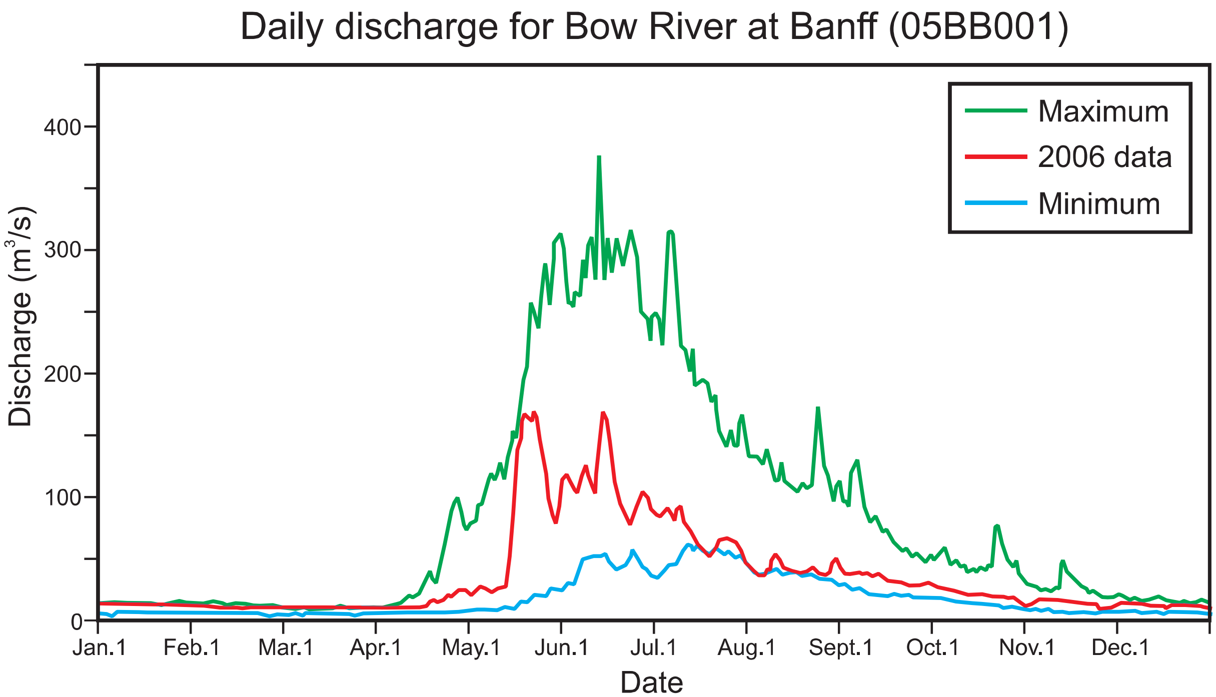


Figure 10.7 Example of annual hydrograph of streamflow for the Bow River at Banff based on 98 years of records (1908–2006).

of the Missouri River, along the southern border of Alberta and Saskatchewan (Figure 10.1), and the Red River of southern Manitoba. The Saskatchewan River is further divided into the North and South Saskatchewan basins, and the South Saskatchewan, in turn, is divided into the Oldman, Bow and Red Deer basins. Most of the region's population, agriculture and industry, are located within the Nelson Basin (including the major sub-basins of the Saskatchewan and Red Rivers). The Nelson River supplies an average of 75 km^3 of water per year, 90% of which originates as runoff from the eastern slopes of the Rocky Mountains (Martz et al., 2007). Hydrographs are characterized by a large spring peak related to snowmelt, which then tapers through the summer to winter baseflow conditions (Figure 10.7).

10.2.5 Geology

The plains are underlain by sedimentary rocks of the Western Canada Sedimentary Basin (WCSB) (Figures 10.8 and 10.9). These range in thickness from zero along the eastern erosional edge to over 4 km in the west. While all of these sediments are filled with groundwater, most of that resource is of naturally high salinity. Only rock in the near surface (typically the upper 400 m) contains water of sufficiently low salinity to be suitable for human use. A detailed description of the 700-million-year geological history of the Basin can be found in Mossop and Shetsen (1994).

The basal sedimentary units of the Basin are Cambrian sandstones and conglomerates, overlain in parts of the area by sandstone and shale of the Middle Ordovician Winnipeg Formation. This was followed by marine carbonate deposition throughout most of the Paleozoic. Extensive marine evaporites were also deposited in the central portion of the Basin, forming the thick potash accumulations found throughout central Saskatchewan and in parts of Alberta and Manitoba. Following the onset of mountain building to the west, the

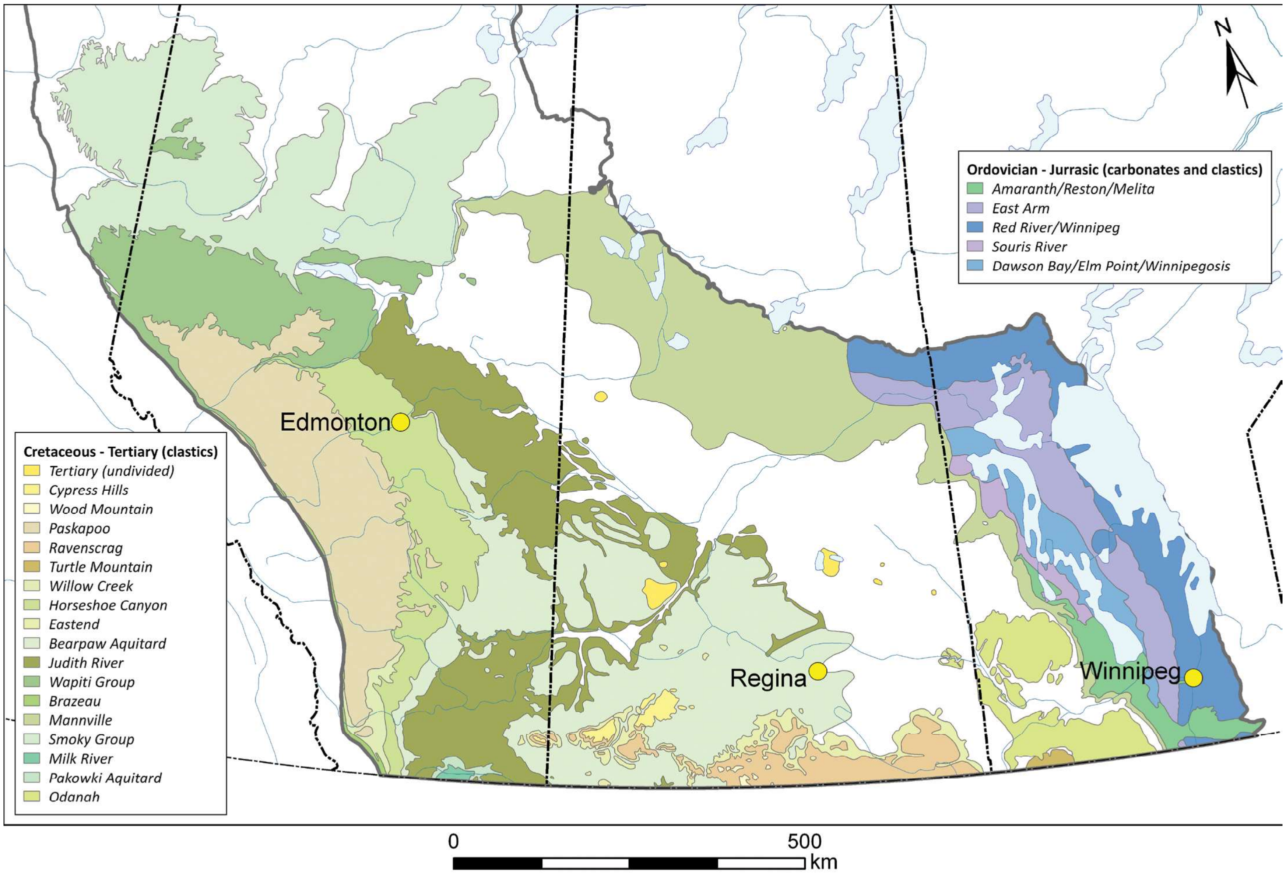


Figure 10.8 Distribution of major bedrock units in the southern part of the Plains Region (based on geology derived from Hamilton et al., 1999; Macdonald and Slimmon, 1999; Massey et al., 2005; Wheeler et al., 1997).

depositional environment changed to largely clastic inland environments throughout the Mesozoic. This sedimentation was initiated by the accumulation of thick marine shale sequences that graded into extensive marine sandstones. During the Cretaceous, deposition transitioned into fluvial systems, including extensive coal deposition in some parts of the region. The youngest bedrock sequences consist of Tertiary fluvial deposits which covered much of the region. With the end of mountain building, these units suffered significant erosion, leaving many isolated erosional remnants of Tertiary sediments across the Prairie Region (e.g., Paskapoo, Ravenscrag, Turtle Mountain Formations). In most areas, the near-surface bedrock is now dominantly shale, along with marine sandstone units and some localized areas of fluvial deposits. In Manitoba and northeastern Alberta, freshwater-bearing carbonate rocks occur near the surface, forming large aquifer systems.

Most of the Plains Region, except for the Cyprus Hills, was glaciated during the Pleistocene, leaving a complex history of till, glaciofluvial and lacustrian complexes, moraine features and other deposits related to glacial retreat, referred to collectively as glacial drift. The regional Quaternary history has been well defined in Saskatchewan (Christiansen and Schmidt, 2005; Barendregt et al., 1998; Christiansen, 1968a, b, 1979, 1992; Schreiner, 1990) and more locally in Alberta (Andriashek and Fenton, 1989) and Manitoba (Klassen, 1979, 1989; Teller and Fenton, 1980).

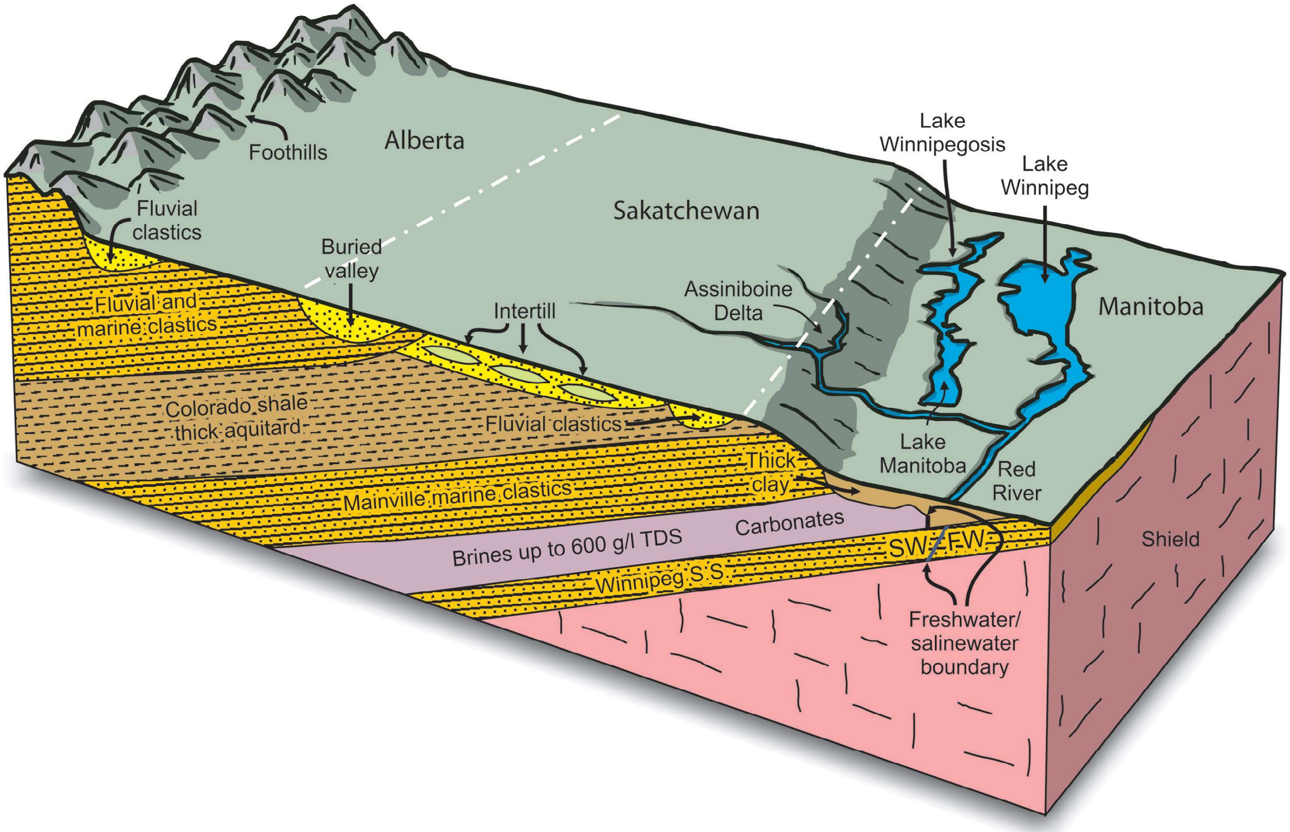


Figure 10.9 Schematic west to east cross section of the southern Plains Region showing distribution of main bedrock and surficial aquifers.

A general summary of the glacial history of the Plains Region can be found in Fenton et al. (1994). The thickness of drift cover varies extensively across the region, from zero in the unglaciated Cypress Hills to over 300 m in parts of Saskatchewan (Fenton et al., 1994). In general, drift is relatively thin in the Manitoba Lowlands, thick to very thick through Saskatchewan, while thinning toward western Alberta (Figure 10.10). The thickest accumulations of drift cover are typically found in buried preglacial valleys which today contain substantial groundwater resources.

10.2.6 Groundwater use in the Plains Region

Early regional hydrogeological studies were conducted in Manitoba and Saskatchewan (1930s to 1960s) by the Geological Survey of Canada. Although these studies mostly consisted of compiling inventory, they provided an early indication of which aquifers were being used for water supply. Manitoba expanded on this work by producing a series of 1:250,000 regional hydrogeology maps of the agricultural areas of the province from the 1970s to 1991 and is currently revising these maps. In Saskatchewan, the Saskatchewan Research Council (SRC) also carried out hydrogeological mapping on a 1:250,000 map sheet basis in the southern part of the province from 1964 to 1980. During the 1986–1999 period, the SRC prepared a series of 2nd-generation groundwater maps on a 1:100,000 scale showing individual bedrock and Quaternary aquifers (Empress Group aquifers between bedrock and the first till, inter/intra-till and surficial aquifers). In Alberta, the Alberta Research Council (ARC) conducted groundwater mapping, again on a 1:250,000 map

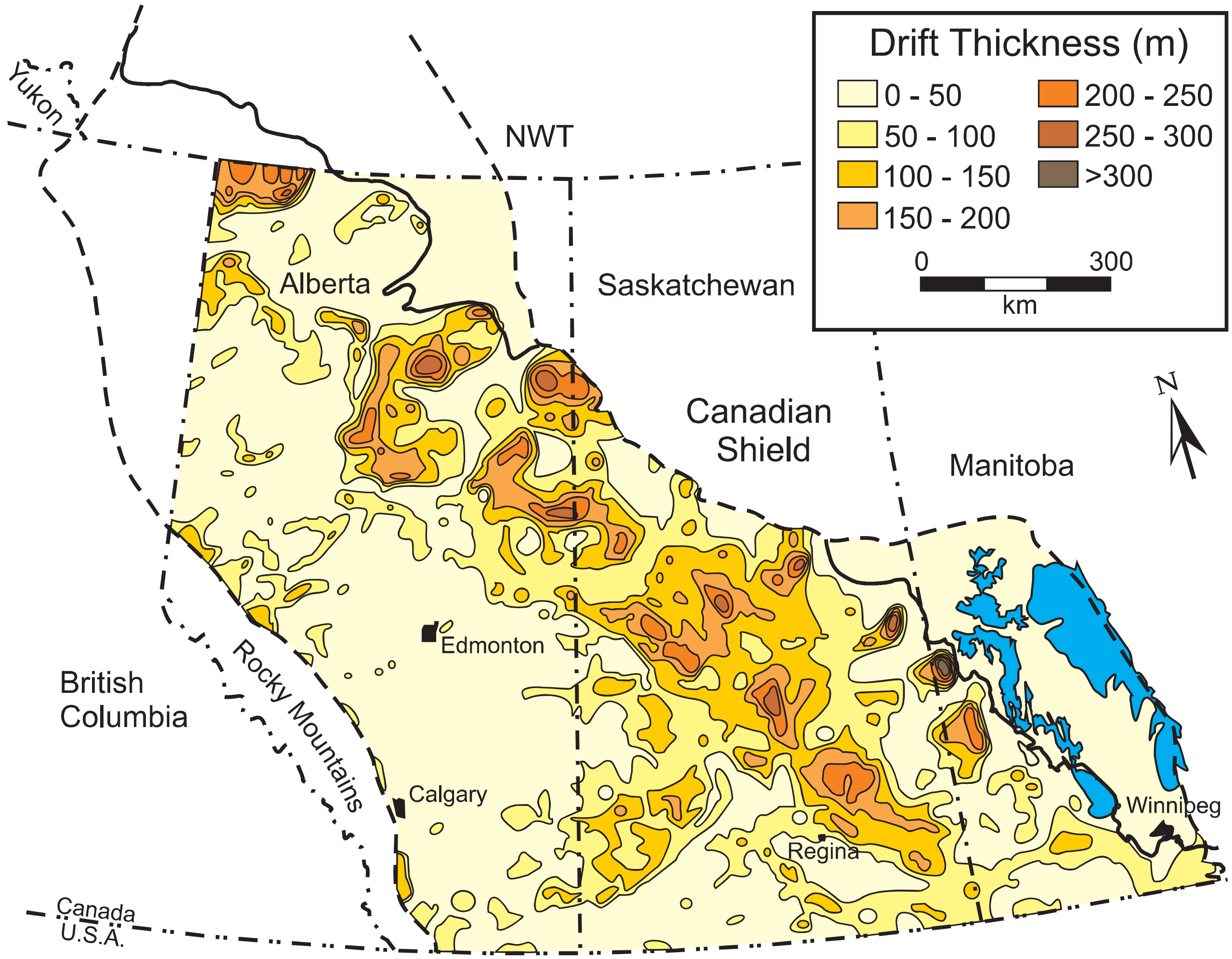


Figure 10.10 Drift thickness of the southern Plains Region (after Fenton et al., 1994).

sheet basis, from 1968 to 1982.

In addition, hydrogeological mapping and reports discussing the regional hydrogeology of all or part of the Plains Region were produced by a number of other agencies during this period, culminating with the 1967 Geological Survey of Canada's report entitled Groundwater in Canada. Maps and cross sections of areas along the Manitoba/Saskatchewan and Saskatchewan/Alberta borders were prepared by the Prairie Provinces Water Board (Tokarsky, 1985, 1986; Judd-Henrey et al., 1994, Judd-Henrey and Simpson, 2005) to show the location and extent of inter-provincial aquifers. Regional summaries of the hydrogeology of the Plains Region were prepared by Brown (1967), Lennox et al. (1988), Pupp et al. (1989, 1991) and Betcher et al. (1995). More recently, many groundwater studies have been conducted by provincial agencies. In addition, the Prairie Farm Rehabilitation Administration (PFRA) has sponsored numerous studies, including county-based groundwater reports. In recent years, there has also been a significant increase in university-based research into Plains Region groundwater systems.

The characterization of current groundwater use in the Plains Region is made difficult by the nature of the available data; however, a general overview of

TABLE 10.1 BREAKDOWN OF REPORTED WELL USE CATEGORIES BY PROVINCE SHOW THAT DOMESTIC WELLS ARE THE MOST COMMON WELLS IN THE REGION. (SOURCES: BRITISH COLUMBIA MINISTRY OF ENVIRONMENT, 2008; ALBERTA ENVIRONMENT, 2007; SASKATCHEWAN WATERSHED AUTHORITY, 2007; AND MANITOBA WATER STEWARDSHIP, 2007)

PROVINCE	DOMESTIC		MUNICIPAL		AGRICULTURAL LIVESTOCK IRRIGATION				INDUSTRIAL		OTHER			
	wells	%	wells	%	wells	%	wells	%	wells	%	wells	%	Total	%
British Columbia	826	52.91	13	0.83	0	0.00	3	0.19	26	1.67	693	44.39	1,561	0.49
Alberta	125,301	73.41	1,624	0.95	24,659	14.45	216	0.13	12,359	7.24	6,534	3.83	170,693	53.04
Saskatchewan	73,473	94.52	2,760	3.55	0	0.00	124	0.16	1,063	1.37	316	0.41	77,736	24.15
Manitoba	54,682	76.12	761	1.06	14,446	20.11	529	0.74	333	0.46	1,088	1.51	71,839	22.32
Total	**254,282**	**79.01**	**5,158**	**1.60**	**39,105**	**12.15**	**872**	**0.27**	**13,781**	**4.28**	**8,631**	**2.68**	**321,829**	

how the resource is used can still be provided. Water well databases have varying degrees of uncertainty that hamper accurate determinations of active well use. Table 10.1 provides a summary of water well usage determined for those wells that appear to be in active production. While production estimates can be derived from recommended pumping rates, this data is not available for a significant portion of the wells. Therefore, consumptive values can only be roughly estimated.

The majority of wells in the Plains Region (79%) are designated as supplying water for domestic water requirements of rural and urban populations. Although the term domestic use is not used consistently, livestock data for January 2007 combined with Alberta's consumption estimates was used to provide a rough estimate of the groundwater required for livestock use (12%). The total amount of water for domestic and livestock use represents 0.2 mm/year of recharge over the Plains Region agricultural crop and rangeland (Figure 10.11). This estimate is conservative, representing only 1,235 m^3/year of production from each of the domestic wells in the region, slightly less than the 1,250 m^3/year provided as a statutory right for household use in Alberta (Maathuis and van der Kamp, 2006).

Approximately 6% of the wells in the plains are used for municipal and industrial purposes. The number of licences and annual allocations (Maathuis and van der Kamp, 2006) provide a rough estimate of groundwater use for these two categories. The annual allocations are estimates of expected groundwater use and represent the upper limit of what might be extracted in a year, with actual production probably lower. Based on the number of wells designated as municipal or industrial (there is an average of 3 wells per licence, with an average allocation of 22,953 m^3/year per well), the average allocated production is 68,860 m^3/year per licence. The total estimated allocation for this use in the three provinces represents 0.3 mm/year of recharge over the Plains Region agricultural land (Figure 10.11a).

10.3 MAJOR AQUIFER TYPES AND PROPERTIES

There are two major aquifer types in the Plains Region: bedrock and Quaternary. Because most groundwater users extract water from the first producible zone encountered during drilling, the dominant aquifer type in any area corresponds to the nearest-to-surface aquifer system and does

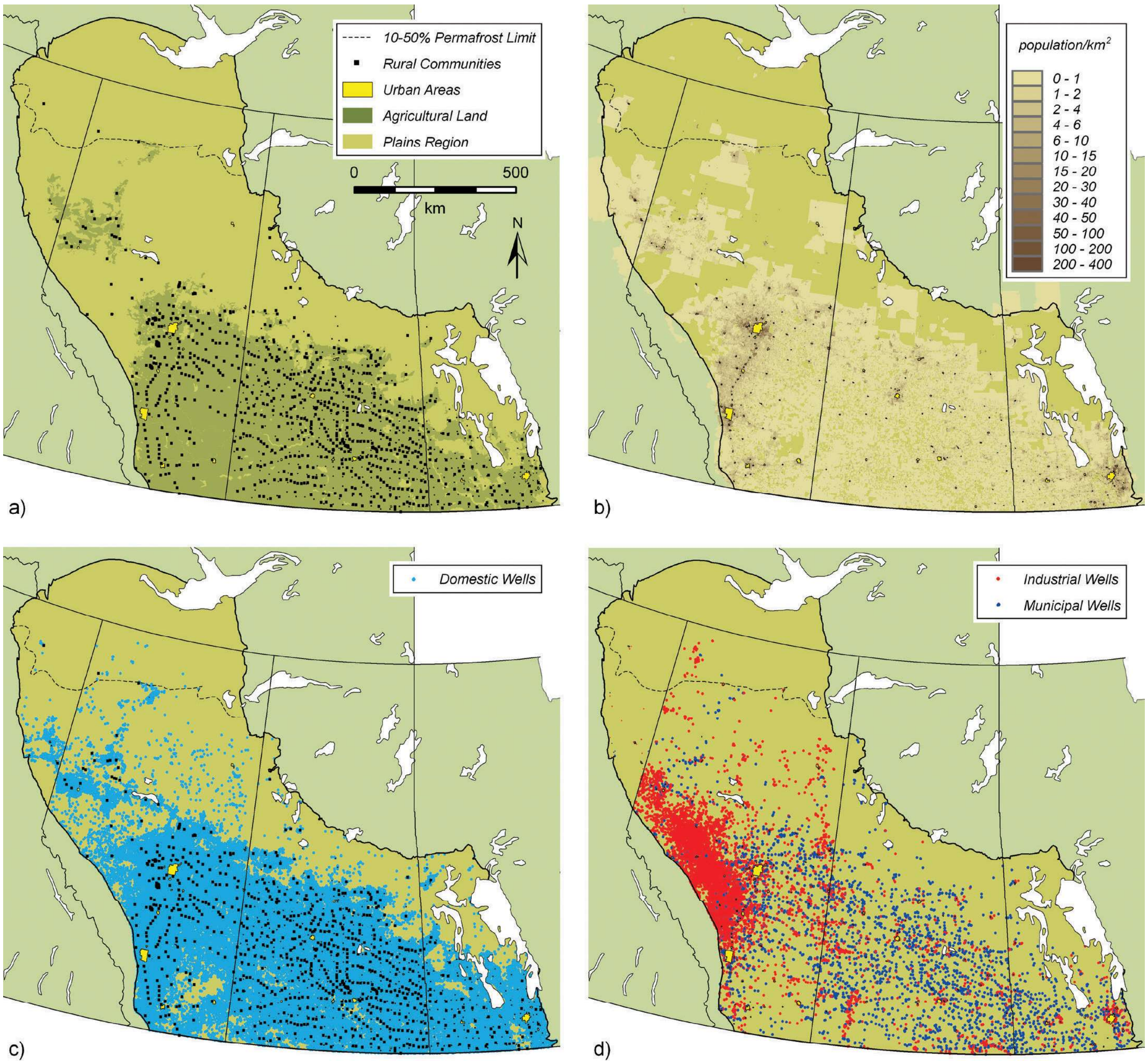


Figure 10.11 (a) Primary land use in the Plains Region, **(b)** Rural population density, **(c)** Domestic wells, and **(d)** Municipal and industrial wells showing close spatial coincidence, with the exception of industrial wells in Alberta that are located outside agricultural lands and areas of lower population density. Sources: Statistics Canada, Hydrogeo NR, J5707 (Government of Canada, 2007); AVHRR Land Cover Data, Canada (Government of Canada, 2009); Permafrost Map of Canada, Atlas of Canada, MCR 4177 (Government of Canada, 1995); Atlas of Canada 1,000,000 National Frameworks Data, Administrative Boundaries (Government of Canada, 2009); British Columbia Ministry of Environment, 2008; Alberta Environment, 2007; Saskatchewan Watershed Authority, 2007; and Manitoba Water Stewardship, 2007.

not preclude the possibility of deeper aquifers. Consequently, bedrock aquifers are dominant in Alberta and Manitoba where glacial drift is relatively thin, while Quaternary aquifers are the dominant groundwater supply source in the thick glacial drift regions of Saskatchewan.

Information in the form of lithology from drilling logs and well construction reports as well as designated aquifers in provincial databases provide an idea of whether groundwater is produced from unconsolidated Quaternary deposits or from bedrock. The data is recorded differently in each jurisdiction.

In the Plains portion of British Columbia, 32% of groundwater wells are installed in bedrock and 61% in unconsolidated deposits (British Columbia Ministry of Environment, 2008).

In Alberta, 84% of the wells draw water from bedrock aquifers and 16% from unconsolidated deposits (Alberta Environment, 2007).

Data for Saskatchewan water well drilling (Saskatchewan Watershed Authority, 2007) does not allow a distinction to be readily made. However, only 19% of well records include lithology data that can be classified as bedrock. In addition, the average top of bedrock lithology occurs at about 45 m (Saskatchewan Watershed Authority, 2007), while the average total well depth based on all available well drilling records is 37 m (Saskatchewan Watershed Authority, 2007). This information suggests that the majority of wells in Saskatchewan are installed in unconsolidated deposits.

In Manitoba, 90% of the well records provide a known aquifer type, with 61% of those wells in bedrock (78% in limestone or dolomite) and the remaining 39% in unconsolidated deposits (94% in sand and gravel) (Manitoba Water Stewardship, 2007).

Below we provide an overview of the major bedrock aquifers and then the overlying Quaternary aquifer systems within the Plains Region.

10.3.1 Bedrock aquifers

As discussed above, the prevalence of groundwater extraction from bedrock aquifers is related mostly to the thickness of overlying glacial drift. Bedrock aquifer usage is most significant where drift cover is thinnest, in southern Manitoba and Alberta. Bedrock aquifers in the plains can be divided into two large groups, carbonate and sandstone, each of which has distinct properties, groundwater production, and protection issues.

10.3.1.1 Carbonate Aquifers

Although Paleozoic rocks underlie the entire Prairie Region, they form freshwater aquifers only where they extend to the east and north of overlying Mesozoic and Cenozoic bedrock sediments (Figure 10.8). Paleozoic-age sediments are dominated by dolostone and limestone, with carbonate units separated by extensive shale, evaporitic or argillaceous beds. Gypsum or anhydrite beds are found locally, in the freshwater portion of these sediments, generally near the transition to saline groundwater, but in most areas, these units have been removed by erosion or dissolution. Groundwater quality in the Paleozoics is generally saline within the deeper parts of the basin, and fresh groundwater is found only in parts of Manitoba, a portion of east-central Saskatchewan, and northeastern Alberta. In Manitoba, these rocks are referred to as the Carbonate Aquifer System, while in Saskatchewan, they are called the Cumberland Aquifer. In this discussion, we will focus on the most extensively used carbonate aquifer that occurs in south-central Manitoba.

10.3.1.1.1 Carbonate Aquifer System of Manitoba

The Carbonate Aquifer System in Manitoba is formed by the erosional remnants of Paleozoic formations overlying the sandstone and shale of the Winnipeg Formation and extending east and north of overlying Jurassic and Cretaceous terriginous and evaporitic materials (Figure 10.12). The basal unit is the Middle Ordovician Red River

Formation, while the uppermost unit is the Middle Devonian Souris River Formation. Several widespread argillaceous units or beds have been identified in this sequence, and these form important aquitards, although the influence of these units is thought to decline to the north as they become less argillaceous.

Grasby and Betcher (2002) and Betcher et al. (1995) have provided an overview of regional groundwater flow systems throughout the Carbonate Aquifer in Manitoba. The areas lying generally to the east of the Red River, north of the Assiniboine River, east of Lakes Manitoba and Winnipegosis, then north of the Little Saskatchewan River contain fresh groundwater that encompasses an area of approximately 75,000 square kilometres. Areas to the west and south contain saline groundwater. A distinct water quality boundary appears to be controlled by lakes and rivers which form major physiographical lows (Figure 10.13) (Grasby and Betcher, 2002). By contrast, the deeper groundwater system of the Winnipeg Formation has a saline/fresh water boundary that appears less influenced by surface features (Ferguson et al., 2007).

The regional saline water system is believed to be driven by recharge occurring in upland areas of Montana, Wyoming and South Dakota (Downey, 1984), with discharge occurring as a series of spectacular saltwater springs and generalized seepage along the southern shore of Dawson Bay, along the Red Deer River and within Dawson Bay and Lake Winnipegosis (Cole, 1915; van Everdingen, 1971; Grasby and Londry, 2007; Grasby et al., 2010). This regional flow system, however, is largely a transient response to deglaciation and does not likely represent a long-term (millions of years) flow condition (Grasby et al., 2000; Grasby and Chen, 2005).

Two main intermediate to regional fresh water flow systems have been identified within the Carbonate Aquifer. In southeastern Manitoba, the piezometric surface of the aquifer system is elevated in the area of the Sandilands glacial upland (Figure 10.13). The erosional edge of the aquifer system lies just to the west of the upland area and may extend locally beneath the western part of the upland. Groundwater flow is west to north-westerly, away from the upland, with the aquifer system overlain by lacustrine clays of Lake Agassiz and glacial tills in this area. It would appear that the primary recharge zone for the freshwater portion of the aquifer system occurs near the Sandilands Upland. However, test drilling has shown that the sand/gravel aquifers in the Sandilands Upland and areas to the west are generally separated from the underlying Carbonate Aquifer System by glacial tills. It has been speculated that "recharge windows" may occur where the tills are absent. More recently, mass balance calculations and groundwater modelling indicate that generalized seepage through these relatively low-permeability tills may account for most of the recharge.

Groundwater discharge from this part of the Carbonate Aquifer System is less well understood than the recharge system. West of the Sandilands complex, the aquifer system is overlain by glacial tills and lacustrine clays that inhibit discharge. Prior to significant groundwater development from the aquifer system, groundwater levels through much of the area were above ground and only declined in response to the installation of large numbers of wells beginning in the late 1800s. Charron (1965) documented the progressive decline in flowing well conditions throughout the early- to mid-1900s. The pre-development flowing artesian conditions can perhaps be viewed more as a consequence of

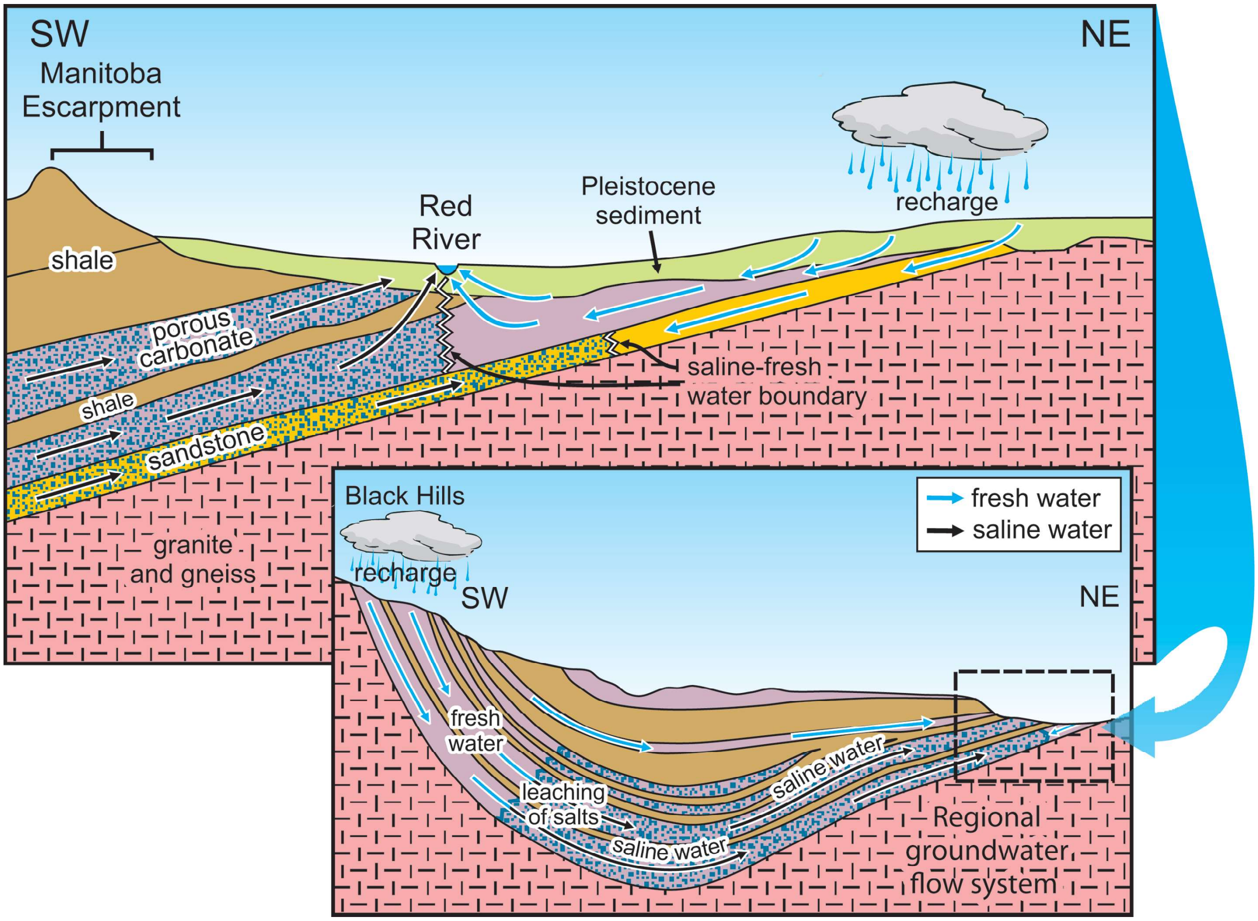


Figure 10.12 Schematic cross section showing fresh water-saline water boundaries in the Carbonate and underlying Winnipeg (Sandstone) Aquifers.

the lack of direct discharge points from this very permeable aquifer, rather than as an abundance of recharge, which may in fact be relatively low.

Grasby and Betcher (2002) observed that the Red River forms a major lateral flow and water quality boundary for the west- to northwest-directed groundwater flow system, indicating that the river is a groundwater discharge area. Bedrock outcrops occur along and perhaps directly beneath parts of the river between Winnipeg and Selkirk where direct discharge may take place; however, the hydraulic role of the river elsewhere is debated. The Red River Floodway, a large canal constructed around the east side of Winnipeg to divert floodwaters away from the city, has been an area of significant groundwater discharge since breakthroughs developed during construction in the early 1960s. Groundwater losses to the Floodway have been approximately 8,640 m^3/day to 17,280 m^3/day since the late 1960s.

A second intermediate to regional flow system has been identified in the Interlake area lying between Lakes Manitoba and Winnipegosis on the west and Lake Winnipeg on the east (Figure 10.13). A large groundwater mound has developed in the upland areas of the central Interlake with groundwater movement to the east, west and south of the mound. It is generally believed that recharge to this system occurs primarily in areas where overlying tills and clays are thin to absent;

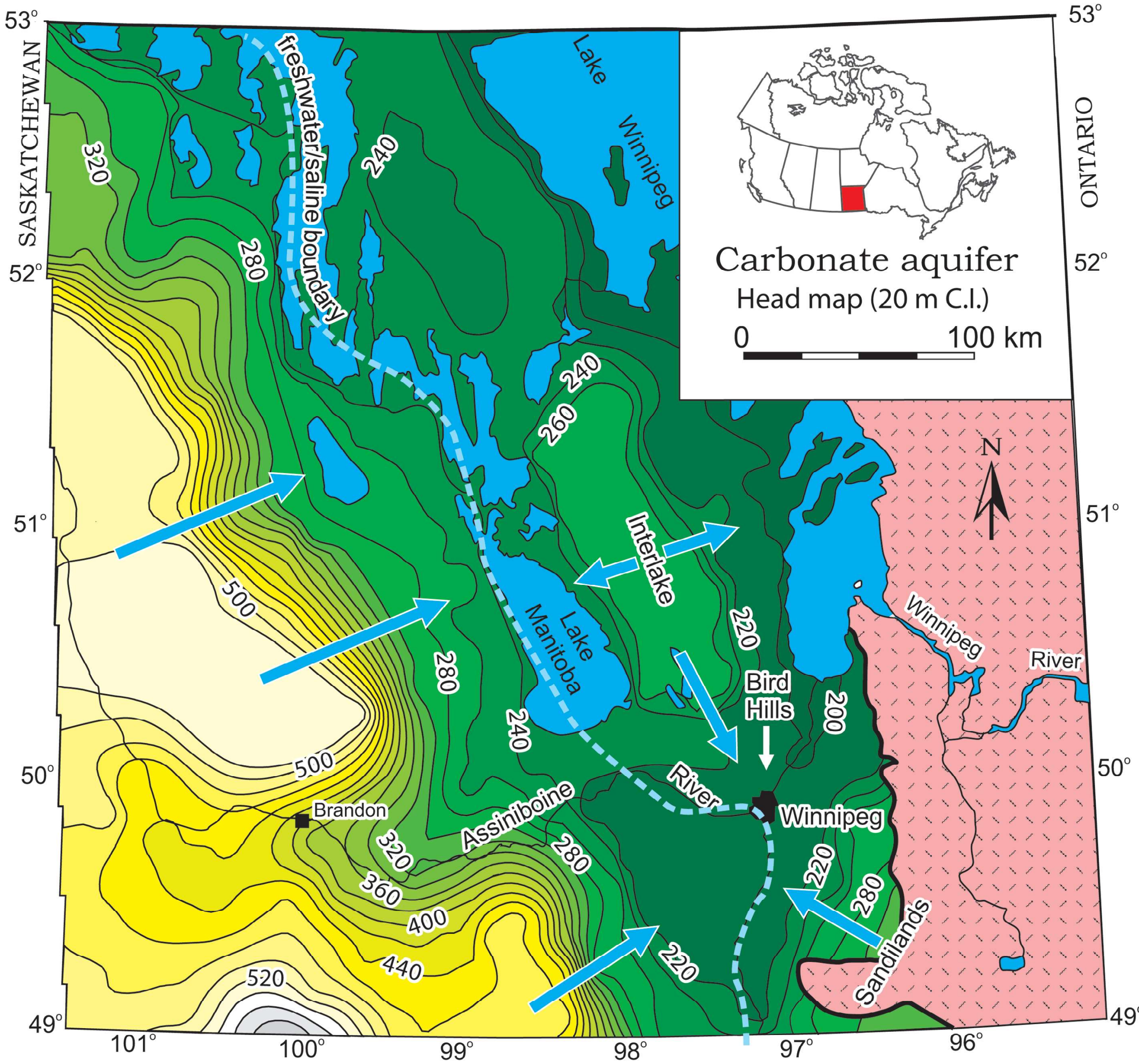


Figure 10.13 Regional hydraulic head in the Carbonate Aquifer of southern Manitoba.

however, the role of generalized seepage through large areas where the aquifer is overlain by relatively permeable glacial tills has not yet been evaluated in a quantitative fashion. Discharge occurs as springs and seepage along a number of rivers and perhaps into marshes, bogs and other wetlands, although many of these features may owe their presence more to underlying clays which restrict downward seepage. Flowing artesian areas are found along the western shore of Lake Winnipeg and the eastern shore of Lake Manitoba, indicating that these topographic lows are the terminal points of the regional system. The overburden, however, is quite thick in much of these areas and discharge must occur as very slow seepage.

More locally, a number of north-south trending glacial uplands east of Winnipeg also form focused recharge areas to the Carbonate Aquifer System, of which the Birds Hill upland, located just northeast of Winnipeg, is the most prominent. Groundwater

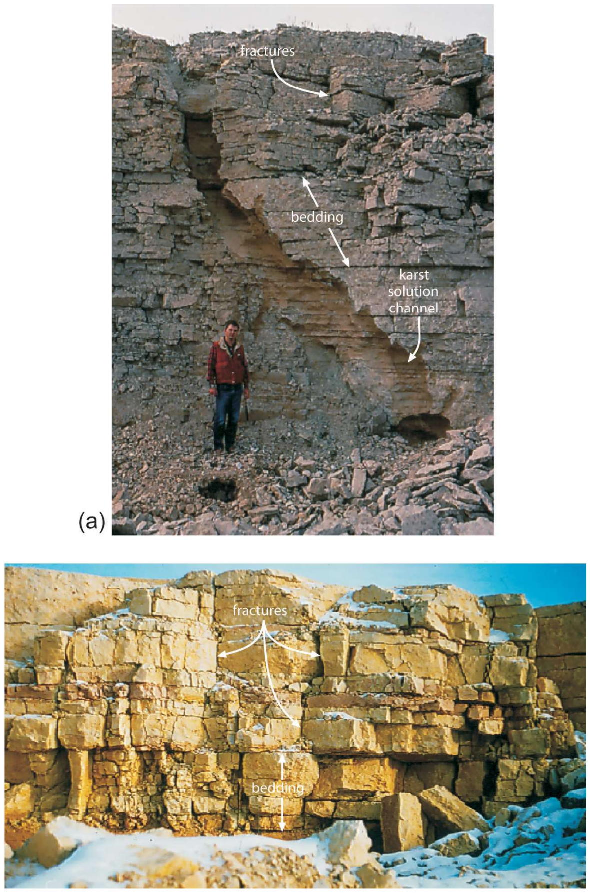


Figure 10.14 Field photographs of a quarry in the Carbonate Aquifer showing (a) bedding and well-developed karst features and (b) fracture sets.

in the Carbonate Aquifer, beneath and down-gradient from this upland, has anomalously low dissolved solids content, a sign of recharge to the aquifer through sand/gravel "windows".

No published estimate of groundwater recharge rates has been made for any significant part of the aquifer system, although work is currently underway in southeastern Manitoba to develop a digital model that may provide some answers. The lack of long-term streamflow monitoring of most of the smaller rivers has been a significant impediment to evaluating groundwater recharge rates.

Porosity in the carbonates and argillaceous carbonates is formed by void pore spaces, sub-vertical joints and fractures, sub-horizontal bedding planes, and features developed through solution processes that have altered existing primary and secondary porosities and formed discrete porous features. Intergranular porosity averages 7% to 9% (Ferguson, 2004). The hydraulic interconnection of these pore spaces is uncertain, although these features may be significant in transmitting water over intermediate to long time scales.

Joints and fractures related to the regional stress regime (Bell and Grasby, 2012) are ubiquitous in the aquifer (Figure 10.14). Mapping of fracture orientations in bedrock exposures in the Interlake area by McRitchie (1996) has consistently identified three subvertical joint sets with orientations along east, north-east and north-west trends. Dissolution processes have enlarged some joints, fractures and bedding planes, while mineral precipitation processes have infilled or lined the sidewalls of existing fractures to a minor degree. A more significant impact of fracture lining or partial infilling is that it reduces the potential for exchange of fluids and dissolved species between fractures and the adjacent intergranular pore spaces over various time scales.

Glacial stresses are also believed to have caused significant modifications to the fracture network of the upper part of the carbonate rock (which has often been observed to be highly permeable), leading to the designation of the upper 10 m or so of bedrock as the Upper Carbonate Aquifer (Render, 1970). In some areas, particularly in the vicinity of Winnipeg and Selkirk, the upper, middle and lower portions of the local aquifer system have been identified (Render, 1970; Render, 1986) based on the intersection of permeable features in widely spaced boreholes at relatively common depth, and, in some cases, differences in groundwater quality and head.

Dissolution processes have also formed karst

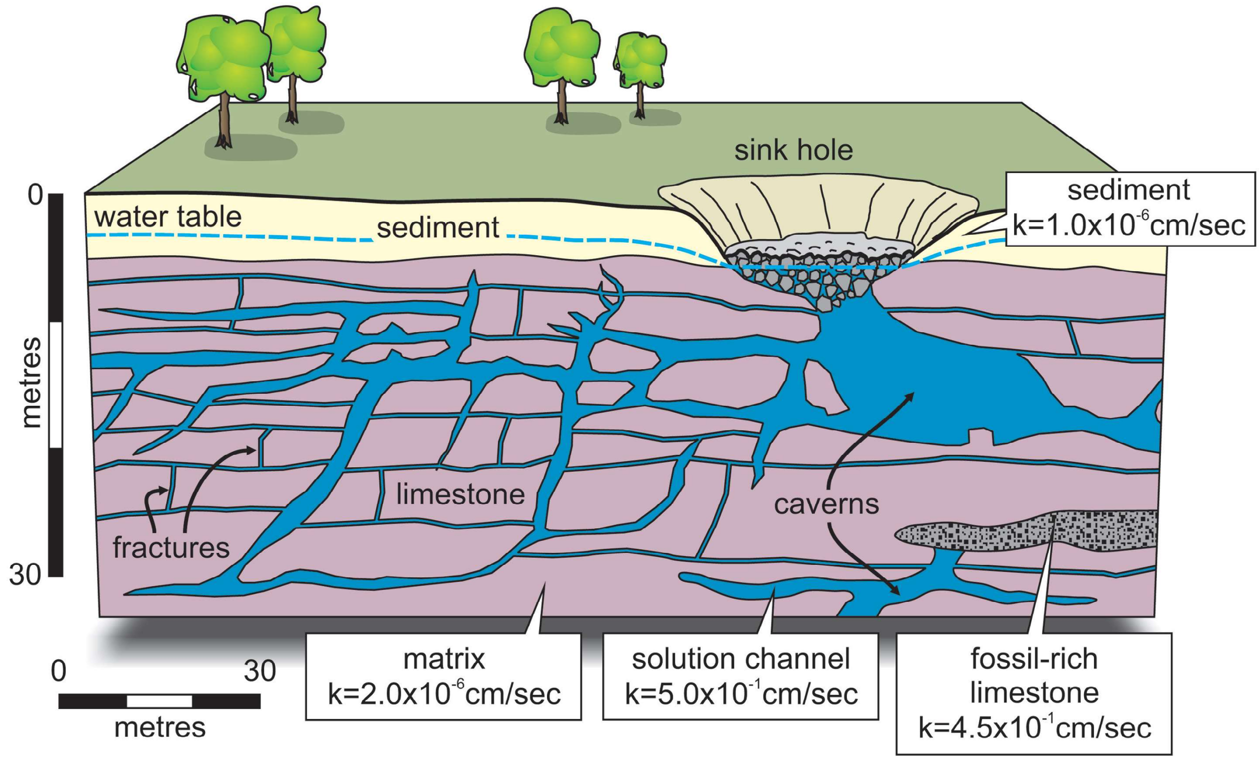


Figure 10.15 Diagram illustrating the hydraulics of the Carbonate Aquifer System.

features, such as sinkholes, tunnels and caves, while glacial loading/unloading and erosion have significantly modified near-surface fractures and pre-existing dissolution openings (Figure 10.15). Simpson et al. (1987) refer to three periods of intense karst development beneath the sub-Mesozoic, sub-Cretaceous and sub-Quaternary unconformities. Pre-Jurassic dissolution and infill features are quite pronounced in parts of southern Manitoba.

A number of water wells have also intersected thick karst infill sediments consisting of inter-bedded silica sands, silt and clay, often in association with lignite, which, in one case, was reported to be more than 100 m thick. Sediment-infilled karst features have been intersected in many parts of the Carbonate Aquifer at depths of 50 m to 100 m below the bedrock surface.

Not all karst features, however, have been infilled with younger sediments. Many boreholes have intersected large openings at depth within otherwise competent bedrock and large springs have been observed to discharge from circular bedrock openings up to several metres in diameter (Figure 10.15).

Reported yields from wells completed in the Carbonate Aquifer System show a broad range of aquifer properties. While wells have been drilled with yields of less than 6 m^3/day, most wells will produce at least 115 m^3/day, and yields in excess of 11,500 m^3/day have been reported. In some areas, drillers consistently report intersecting water-producing fractures at approximately the same stratigraphic interval, while in other areas, fracture intersects are much less predictable and nearby wells may be drilled to considerably different depths to produce sufficient water for household use. A fairly consistent feature is that if water-producing fractures are not encountered in the upper 30 m or so of bedrock (within the upper few metres of bedrock in some areas), extending the well depth will normally result in additional fractures being encountered, but yields from these deeper fractures may be only a few tens of cubic metres per day or less.

Kennedy (2002) compiled transmissivity data for the Carbonate Aquifer System in southern Manitoba using results from single-well and multiple-well pumping tests and estimates of transmissivity from specific capacity values supplied in water well drillers logs. She concluded that the natural logarithm of transmissivity follows a normal distribution with a mean of -7.2 corresponding to a transmissivity of approximately 62 m^2/day. The maximum transmissivity estimate was 34,700 m^2/day. Transmissivity values range over 12 orders of magnitude. Storativity values indicate the aquifer to be "semi-confined." Where pumping tests have been conducted with observation wells, the aquifer has responded in a classically confined fashion with little indication of leakage or dual porosity responses (over periods of 8 to 72 hours). Chen et al. (2011) examined the spatial trends in Kennedy's data set and concluded that highly transmissive zones in some areas appeared to have orientations similar to the overall trends in mapped bedrock joints and fractures. They concluded that dominant fracture systems influence the regional transmissivity patterns.

The hydraulics of the Carbonate Aquifer therefore consist of a complex and heterogeneous interconnected primary and secondary porosity. Groundwater flux is primarily through secondary joints and bedding planes which, in those areas where karst features have developed, serve to move water to dissolution channels through which large fluxes of groundwater may be transmitted. This can lead to localized high-vulnerability areas in the Carbonate Aquifer due to rapid contaminant transport (Figure 10.16). However, the rate of groundwater movement in these features will only be rapid where these channels are able to freely discharge to the surface. In large parts of southern and central Manitoba, discharge is severely restricted by glacial and lacustrine sediments that overlie the aquifer system's discharge areas. This is particularly apparent within the major lakes of Manitoba, which, although they occupy regional topographic lows, contain thick glacial and lacustrine sediments and likely do not form major volumetric discharge areas (Teller and Last, 1981; Forbes et al., 2000). Consequently, groundwater velocities within the aquifer system are likely quite slow through much of southern Manitoba. Transport rates estimated from the extent of contaminant plumes have indicated flow velocities in the order of a few tens of metres per year. In the central and northern Interlake area, velocities may be much higher because the overburden cover is generally much less and karst dissolution features are very prominent in some areas (e.g., the Grand Rapids area, Grice, 1964).

The role of intergranular porosity remains somewhat uncertain because the interconnection of primary pores is poorly understood and may vary based on the lithology of the various carbonate units. A slug test conducted in a "dry" hole with an open interval of 70 m in the Red River Formation just east of Winnipeg indicated a hydraulic conductivity of ~10^{-8} m/s, some of which may be attributed to unrecognized fractures intersecting the borehole. Nonetheless, if some of the intergranular pores are interconnected throughout the rock mass as a whole, they may contribute significantly to

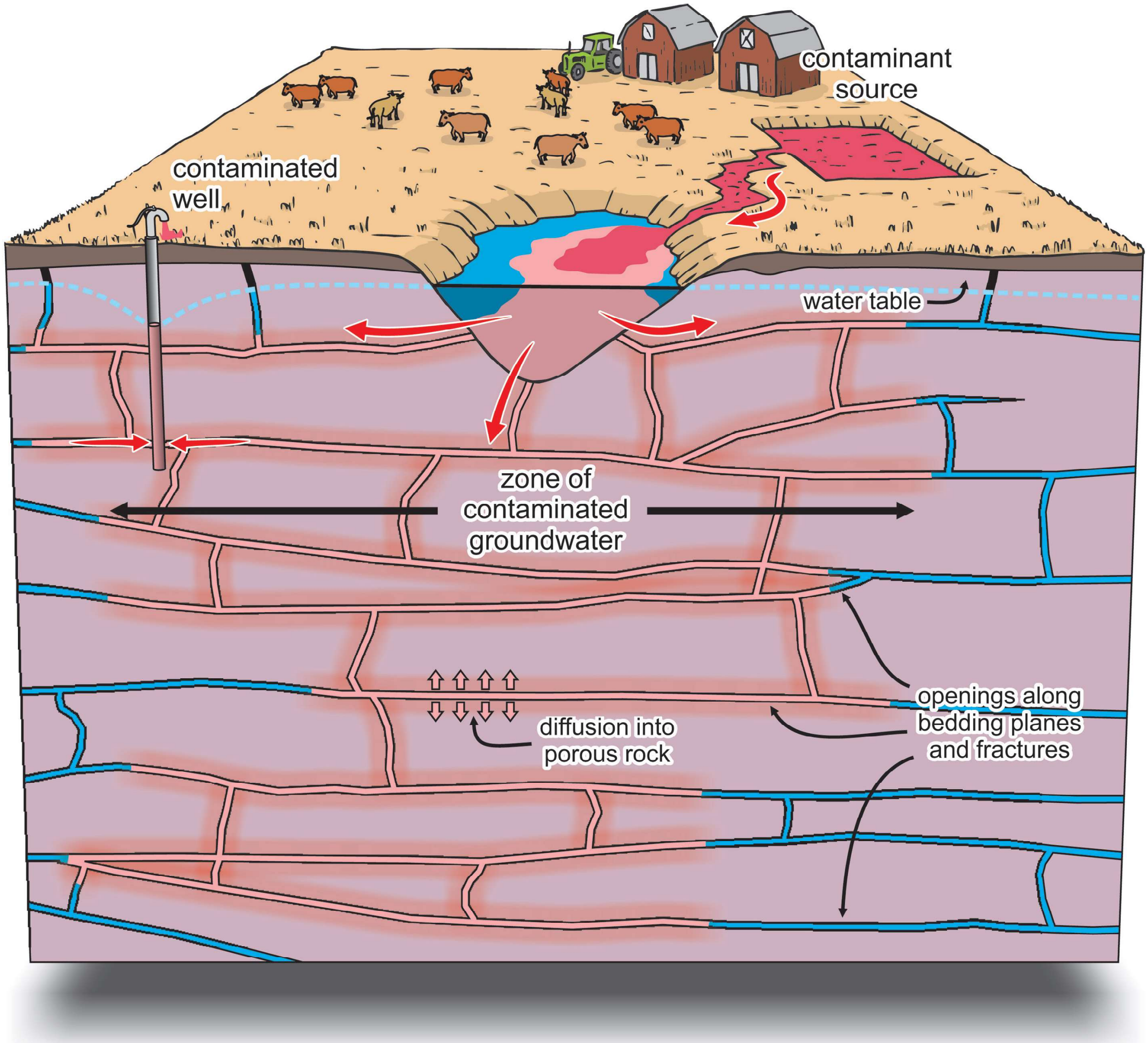


Figure 10.16 Schematic diagram illustrating the significant influence of fracture systems on contaminant transport within the Carbonate Aquifer.

the overall flux of groundwater through the aquifer system and may provide a dual porosity leakage to fractures during long-term pumping tests or groundwater withdrawal developments within the system.

The geochemistry of fresh groundwater in the Carbonate Aquifer is characterized as calcium-magnesium-bicarbonate type with a TDS (total dissolved solids) of 400 mg/L to 800 mg/L, typical of geochemical development in carbonate-rich terrains (Grasby and Betcher, 2002). The lower-TDS groundwater is associated with recharge areas in the Interlake and the Sandilands Upland, while elevated TDS contents and a transition to more sodium- and chloride-dominated groundwater occurs near the fresh water–saline water boundary. Localized regions of elevated-TDS, sulphate-rich groundwater are also found along the western edge of the Red River between Winnipeg and Selkirk, to the east of Winnipeg and in the Interlake area. These appear to be areas where leakage of water from the overlying clays provides

Figure 10.17 Outcrop of the silica sandstones of the Winnipeg Formation on Black Island, between the north and south basins of Lake Winnipeg. Note the variable cementing of the sandstones and the fracture-controlled discharge of groundwater from the well-cemented sandstones in the centre of the section.

a significant component of local recharge. Fresh groundwater in the Carbonate Aquifer is isotopically modern, with $\delta^{18}O$ values ranging from about –13‰ to –15‰, indicating that the active flow systems in the freshwater portion of the aquifer have removed residual Pleistocene water that would have been present at the end of the last glaciation.

10.3.1.2 Sandstone aquifers

There are a number of freshwater-bearing sandstone aquifers, ranging in age from Ordovician through Tertiary, found locally or regionally across the Prairie Provinces. Regional and provincial summaries of many of these aquifers have been provided by Brown (1967), Lennox et al. (1988), Betcher et al. (1995), Pupp et al. (1989) and Pupp et al. (1991). In this discussion, we deal with the major sandstone aquifers in the Plains Region, while recognizing that local freshwater-bearing aquifers do exist in other strata, such as Jurassic sandstones in Manitoba.

10.3.1.2.1 Winnipeg Aquifer

The oldest freshwater-bearing sandstone aquifer in the Prairie Region is within the Winnipeg Formation (Lower Ordovician) in southeastern and central Manitoba. The aquifer has a variety of names, such as the Upper Sandstone and Lower Sandstone aquifers (Render, 1970), the Winnipeg Formation aquifer (Betcher et al., 1995; Ferguson et al., 2007) and the Sandstone aquifer (Kennedy, 2002). In this discussion we use the term Winnipeg

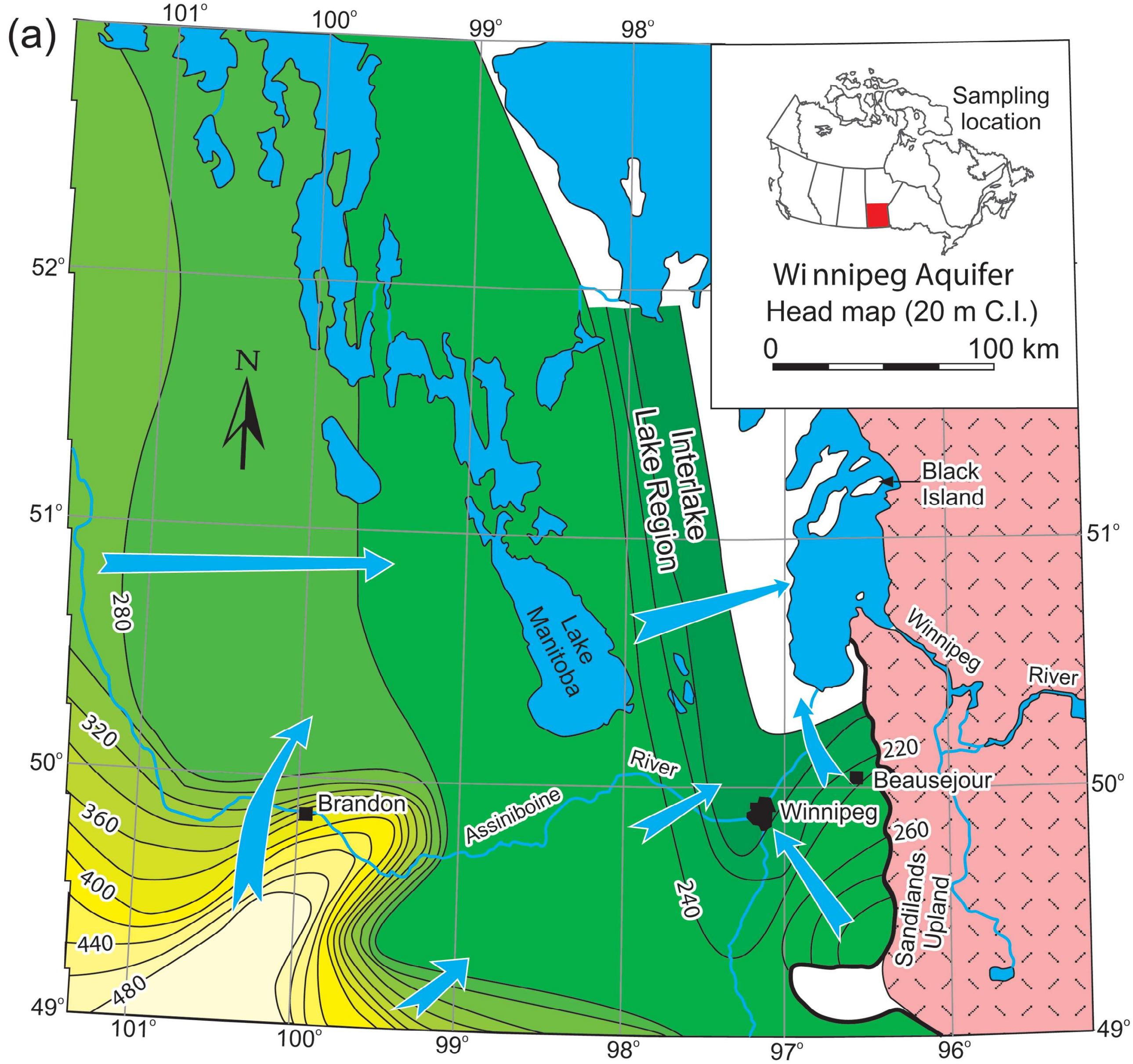


Figure 10.18 Hydraulic head for the Winnipeg Aquifer at 20 m contour intervals (after Fergusson et al., 2007).

Aquifer. This formation thins to the north and is not recognized as a significant freshwater-bearing unit in either Saskatchewan or Alberta. The geology has been discussed by many authors (Andrichuk, 1959; McCabe, 1978) and a recent summary of the hydrogeology of the formation in Manitoba has been provided by Ferguson et al. (2007). Outcrops of the aquifer are rare and confined to portions of a number of islands in the south basin of Lake Winnipeg (Figure 10.17).

The freshwater-bearing portion of the Winnipeg Aquifer in Manitoba sits directly on weathered Precambrian igneous and metamorphic rocks and is hydraulically separated from the overlying Carbonate Aquifer System by a shale aquitard in southern and central Manitoba (Figure 10.12). North of Lakes Winnipeg and Winnipegosis, geological test holes indicate that the upper shale is absent and that the sandstones are likely interconnected with the Carbonate Aquifer System. Based on the location of the fresh water–saline water boundary provided by Betcher (1986), the freshwater portion of the aquifer underlies an area of approximately 7,550 km^2 from the Canada/USA border to the northern Interlake (Figure 10.18).

Within this area, the dominant lithology is a grey-to-white, fine, variably cemented silica sandstone. Shale beds in the lower portions of the formation have been observed to confine basal sandstones to the extent that water level and water quality differences have been observed between the upper and lower sandstones. Visual observation and the responses of several pumping tests indicate that portions of the sandstones are fractured. Spring discharge can be observed from individual fractures in a well-cemented portion of the sandstone on Black Island (Figure 10.17). Betcher (1986) summarized the results from 20 single-well pumping tests carried out on wells and test holes completed in the aquifer. The hydraulic conductivity varied from 1.1×10^{-3} m/s to 3.2×10^{-6} m/s, reflecting the influence of local cementing and fracturing in the sandstones. The highest hydraulic conductivity was measured in a test hole where it is believed that the fractures were intersected in a cemented layer of sandstone.

Betcher (1986), Betcher et al. (1995) and Ferguson et al. (2007) have described two separate intermediate to regional groundwater flow systems within the freshwater portion of the Winnipeg Aquifer (Figure 10.18). In southeastern Manitoba, the Winnipeg Formation subcrops near the Sandilands Upland and a series of smaller upland areas near the southeastern tip of Lake Winnipeg. Hydraulic head and groundwater quality information indicate that these areas form the dominant recharge zones for the aquifer, with groundwater movement occurring westward to northwest (Figure 10.18).

Interestingly, these two freshwater recharge areas are separated by a "tongue" of saline groundwater stretching from Winnipeg to the subcrop area east of Beausejour. Betcher (1986) speculated that prior to emplacement of the Sandilands and other uplands near the end of the last glaciation, saline groundwater extended to the subcrop area throughout much of southeastern Manitoba. With the establishment of these glacial uplands, and the higher heads they imposed on the subcrop area, fresh groundwater influx occurred beneath or near these areas, driving the saline water to the north and west by the advancing "modern" freshwater fronts. East of Beausejour, where there is no upland area over the subcrop of the Winnipeg Formation, saline groundwater continues to extend to the subcrop area.

A second regional flow system is found in the Interlake area. Saline groundwater occurs in the western Interlake and advances to the east, driving fresh water out of the system. Isotopic evidence suggests that subglacial meltwater was injected into the system during glacial periods, advancing several tens of kilometres to the west (Ferguson et al., 2007). With the removal of subglacial excess heads, the natural system of west-to-east flow has been re-established (Grasby and Chen, 2005).

Little work has been done to examine how discharge occurs from the Winnipeg Formation. In southeastern Manitoba, a number of erosional channels have been mapped where scouring has penetrated through the Carbonate Aquifer and the upper shale of the Winnipeg Formation. These features may form limited pathways for discharge of groundwater from the system. However, piezometric surface maps for both southeastern

Manitoba and the Interlake region indicate that Lake Winnipeg forms the dominant regional discharge area for groundwater flow systems within these areas. This is somewhat puzzling because geophysical studies have shown thick clay sediments overlying bedrock within Lake Winnipeg, excluding areas such as Hecla, Black and Deer Islands. It may be that the observed slow rates in advancement of the water quality fronts reflect a very diffuse seepage of discharging groundwater through these clays. This situation has changed, at least in the southeastern part of the system, with the construction of deep bedrock water wells beginning in the late 1800s. Betcher and Ferguson (2003) estimate discharge of about 1,500 m^3/day from the Winnipeg Formation into the overlying Carbonate Aquifer through interconnecting boreholes. This appears to have led to significant head reductions in this part of the aquifer and may account for the loss of a significant percentage of recharge to the aquifer.

The quality of fresh groundwater in the Winnipeg Aquifer shows considerable variation.

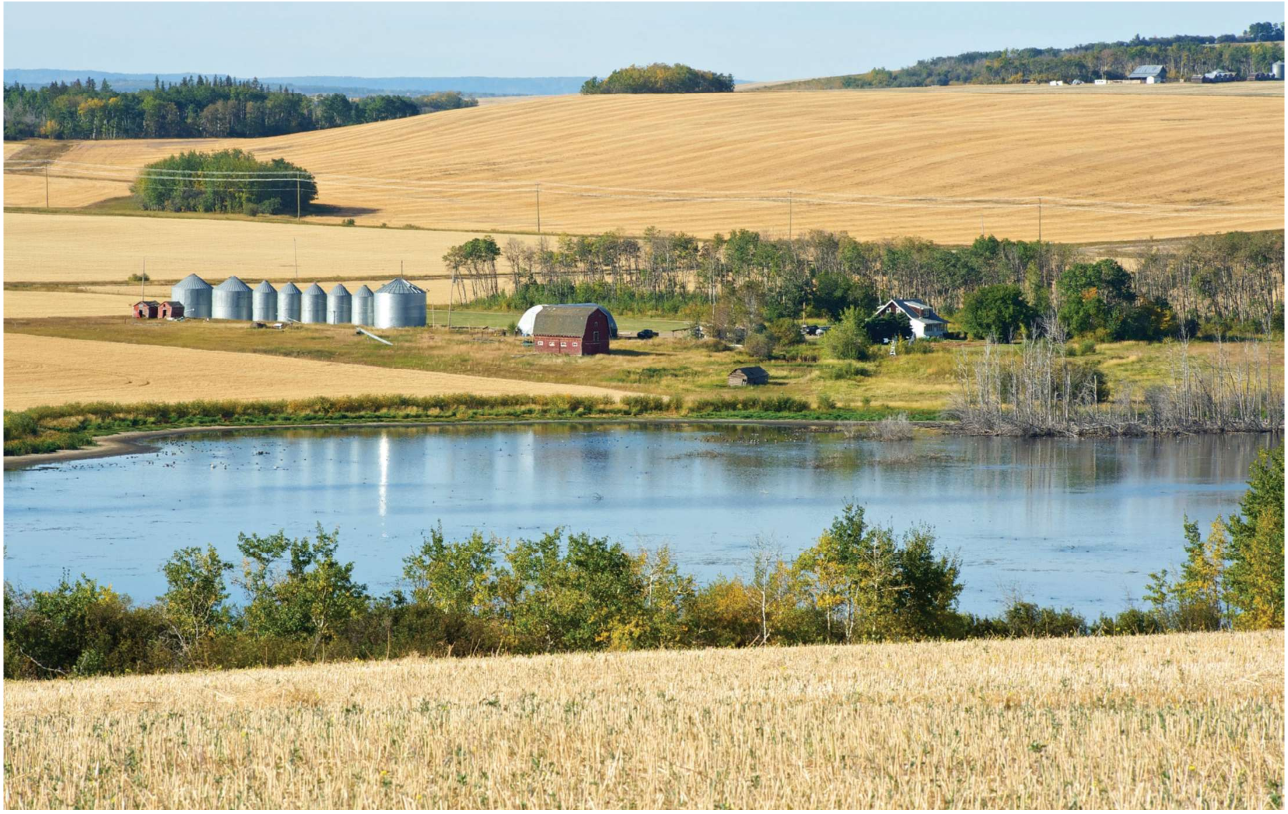
In the eastern Interlake, where residual Pleistocene water has not been flushed from the aquifer, the groundwater is sodium-mixed anion type with a TDS of 1,000 mg/L to 1,300 mg/L. Chloride concentrations range from 300 mg/L to 500 mg/L and sulphate from 200 mg/L to 300 mg/L. This reflects mixing of very fresh Pleistocene water with residual saline groundwater likely held in lower-permeability portions of the aquifer.

In southeastern Manitoba, isotopically modern groundwater extends westward from the Sandilands Upland before transitioning to sodium chloride type water along the fresh water–saline water boundaries to the west and north. Near the eastern recharge area, the groundwater is Na-Ca-Mg-HCO_3 type with TDS concentrations ranging from 200 mg/L to 300 mg/L, but gradually increasing down the flowpath to 300 mg/L to 400 mg/L. Calcium and magnesium concentrations initially rise as the TDS increases, but then decline dramatically to very low concentrations east and south of the saltwater boundaries. In these areas, the groundwater is Na-HCO_3 type with very low hardness, reflecting cation exchange processes in the parts of the aquifer where saline groundwater has been flushed more recently by recharging fresh modern water (Ferguson et al., 2007). This naturally soft water has been a drilling target for more than a century, allowing water users to escape the problems of hard water from the overlying Carbonate Aquifer. Water analyses reveal elevated fluoride and boron concentrations in these soft water zones.

10.3.1.2.2 Mannville Aquifer

The Mannville Aquifer is formed by sandstone beds within the Lower Cretaceous Mannville Formation (equivalent to the Inyan Kara Formation in North Dakota and the Swan River Formation in Manitoba) which forms the basal Cretaceous sedimentary unit of western Canada. The Mannville was deposited unconformably on an eroded Jurassic or Paleozoic surface in a fluvio-deltaic environment. Sediments consist of variably cemented sandstone, siltstone, shale and coal, with individual beds apparently having little lateral continuity.

In much of the Plains Region the Mannville aquifer is either too deep for water supply development or yields saline water. Only in a fringe along the boundary with the Precambrian Shield, where the Mannville Group forms the bedrock surface and is overlain by Quaternary deposits, may it yield potable water (Pupp et al., 1989; Christopher, 1984).



Sandstone beds within the Mannville Formation also form freshwater-bearing aquifers in parts of west-central Manitoba (Rutulis, 1984).

Studies in Manitoba and Saskatchewan, where the formation may be as much as 150 m thick, have shown the upper part of the aquifer to contain relatively fresh water, although water quality generally declines with depth in an irregular fashion (Betcher, 1991). Well yields are highly variable, consistent with the lithologic heterogeneity. Betcher (1991) summarized reported well yields in the Swan River area of Manitoba as ranging from 7 m^3/day to 650 m^3/day, for an average of 130 m^3/day.

In Manitoba, freshwater recharge to the Mannville Formation occurs along the eastern and northern edges of the Manitoba Escarpment (Rutulis, 1984) through leakage from overlying Quaternary sediments with regional groundwater movement toward the east to northeast. Discharge occurs to rivers and creeks in the Swan River area where outcrops of the formation have been mapped. In most areas, however, the sandstone beds are overlain by low-permeability materials, and interaction with the surface environment is inhibited.

Groundwater quality in the Mannville Aquifer in Manitoba is characterized by extreme changes, both spatially and vertically. Betcher (1991) reports TDS values varying between 316 mg/L and 15,000 mg/L, with rapid variations found over short lateral or vertical distances. This is believed to reflect the limited extent of individual sandstone units and their separation by low-permeability, clay-rich materials. Shallow sandstone units have generally been flushed of residual saline groundwater, while in the deeper units, flushing is severely impeded. Fresh groundwater consists of two major types: (1) Ca-Mg-HCO_3 in those areas where flushing of saline groundwater and replacement by "modern" water has occurred, and (2) Na-mixed anion groundwater typically with low hardness in those sandstone units where much of the saline water has been flushed, but cation exchange sites remain charged with Na. In Saskatchewan, there is little groundwater quality information available. In northwest Saskatchewan, the aquifer yields Na-Cl or $Na\text{-}HCO_3$-type waters with TDS in the 650 mg/L–7,750 mg/L range (Maathuis, 2008).

Water from the Mannville Group is used in some oil-producing areas for enhanced oil recovery. Well yields range from 5 m^3/day to 3,200 m^3/day, but are typically in the 86 m^3/day to 430 m^3/day range. Data on the hydraulic conductivity of the Mannville Group aquifer is scarce. Lissey (1962) reports an in situ hydraulic conductivity of 1.6×10^{-6} m/s at a site near Regina. Meneley et al. (1979) report a value of 2×10^{-4} m/s for a Mannville Group sand in northeastern Saskatchewan.

10.3.1.2.3 Milk River Aquifer

The Milk River Aquifer is an important groundwater source for southern Alberta (Figure 10.19). The aquifer has been the subject of a number of hydrogeological studies, including Meyboom (1960), Schwartz and Muehlenback (1979), Domenico and Robbins (1985), Phillips et al. (1986), Hendry and Schwartz (1990), as well as an international study on the use of isotope tracers in groundwater studies (Fröhlich et al., 1991).

This is a transboundary aquifer covering over 10,000 km^2 and extending 100 km northward from the recharge zone in exposed outcrop belts around the Sweetgrass Hills. The aquifer is characterized by 30 m to 75 m thick sandstone dipping northward from the recharge zone and overlain by up to 120 m of confining marine shales of the Pakowki Formation. The massive marine sandstones of the Milk River Aquifer diminish northward and transition into shale, limiting the northern extent of the aquifer. Previous work has suggested that the water of the Milk River Aquifer has a complex history of original marine water being displaced by freshwater recharge after the formation was exposed to surface ~ 50 Ma ago due to erosional unroofing (Hendry and Schwartz, 1990). This initial freshwater influx was later altered by deposition of glacial drift over the recharge belt, imparting a new, more sulphate-rich water chemistry onto the more modern-day recharge water, creating distinct compositional zones along the flow gradient within the aquifer. Meyboom (1960) determined transmissivity values, based on shut-in tests on 45 wells, ranging from 0.15 m^2/day to 30 m^2/day.

The Milk River Aquifer has been used as a water source since the early 1900s. Over time, numerous wells were drilled and, later, a significant number of them abandoned. Meyboom (1960) identified 409 wells installed in the aquifer, of which 192 had flowing water. A recent survey identified 1,027 wells, of which 442 were inactive (43%), and 41 of the inactive wells were flowing. A reclamation and conservation plan was recently implemented to protect water quantity and water quality. A total of 101 wells, 22 of which were flowing, were sealed by cementing (Printz, 2004). Monitoring data are being collected, but the impact of well decommissioning on the aquifer has not yet been assessed.

10.3.1.2.4 Judith River Aquifer

The Late Cretaceous Judith River Formation extends from southern Alberta into southwestern Saskatchewan and the United States. The formation crops out in Montana and locally in Alberta and Saskatchewan. However, over most of its extent, it is overlain by the Bearpaw Formation, Tertiary sediments, and Quaternary deposits (Figure 10.8). In Alberta, in areas where the Bearpaw Formation is absent, the Judith River Formation may be overlain by the Horseshoe Canyon Formation.

Descriptions of the geology of the Judith River Formation and its subdivisions can be found in McLean (1971), Eberth and Hamblin (1993), Dawson et al. (1994), and Hamblin and Abrahamson (1996). The Judith River Formation is an eastward-thinning sedimentary wedge composed of non-marine and marine, multi-coloured sandstones (very fine to medium-grained), silts and clays with carbonaceous and concretionary zones deposited in a deltaic environment (McLean, 1971), including alluvial, lacustrine, aeolian, lagoonal, swamp, beach and marine sediments. The lower part of the Judith River Formation was deposited in a more marine environment, whereas the upper portion represents a more continental depositional environment (Dawson et al., 1994). The depth at which the Judith River Formation is encountered may range from zero at the outcrop edge to 635 m in southwestern Saskatchewan. Its thickness ranges from zero at its erosional or depositional edges to 125 metres. Individual sand units within the formation are less than 15 m thick, and commonly only a few metres thick. It is difficult to trace individual sand layers and silt and clay beds over more than a few kilometres (McLean, 1971).

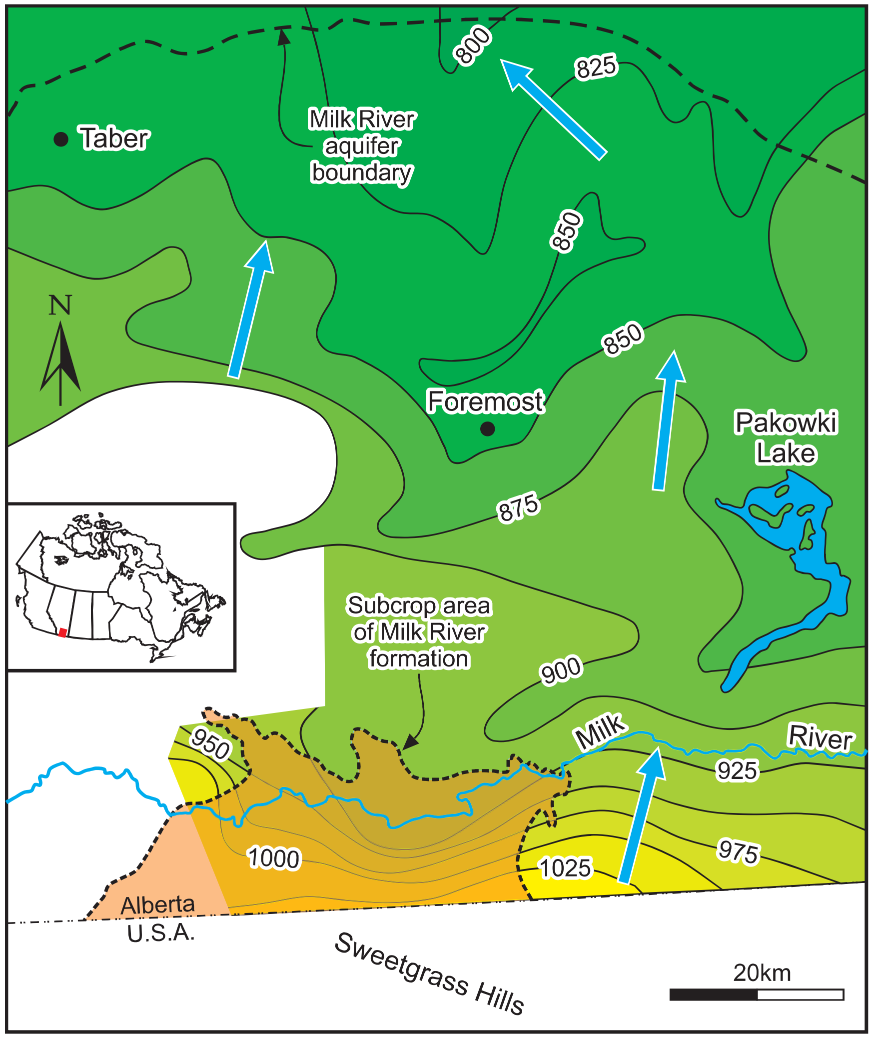


Figure 10.19 Location and extent of the Milk River Aquifer along with contoured head values (shown at 25 m contour interval).

The regional hydrogeology of the Judith River Aquifer has been described by Kewen and Schneider (1979), Whitaker (1982a, b), Maathuis and Simpson (2007a, b, c, d) and Pupp et al. (1989). The Judith River Aquifer is recharged directly by infiltrating precipitation and surface water in those areas where the aquifer crops out in Montana. Over much of its extent, however, the aquifer is overlain by aquitards formed by the silts and clay units of the Bearpaw Formation, as well as Quaternary unconsolidated sediments. Consequently, downward flow through these overlying aquitards limits vertical recharge to no more than a few millimetres per year.

Whitaker (1982a) suggests that the maximum hydraulic conductivity of Judith River Aquifer sand beds could be 15 m/day (≈ 1.7×10^{-4} m/s), but that the average hydraulic conductivity for the fine to medium-grained sands would likely be no more than 5 m/day (≈ 5.8×10^{-5} m/s). Hydraulic conductivity in the 0.1 m/day-to-5 m/day (≈ 1.2×10^{-6} to 5.8×10^{-5} m/s) range can be taken as a general characteristic for the Judith River Aquifer sands.

Pupp et al. (1989) indicate that in Alberta, this aquifer unit generally yields sufficient water for domestic supplies, and that some zones yield enough water for municipal and industrial purposes. In Saskatchewan, the aquifer is also used as a source of domestic/farm, municipal and industrial water. In southwestern Saskatchewan, water from the aquifer is used for enhanced oil recovery. Wells for this purpose may yield up to 600 m^3/day (Maathuis and Simpson, 2007a). Although this aquifer is a highly complex formation, under pumping conditions the entire structure will, in complex ways, act as a single aquifer unit because of interaction between sand units.

The quality of water in the Judith River Aquifer in Saskatchewan has been described by Maathuis (2008). Both the quality of the water and the water type are highly variable. The TDS may range from 725 mg/L to 12,250 mg/L, median 2,000 mg/L. Locally, the aquifer yields small amounts of natural gas and is known to yield brownish-coloured water. Pupp et al. (1989) provided some water quality data for the aquifer in Alberta.

10.3.1.2.5 Eastend to Ravenscrag Formations

During the Late Cretaceous to Miocene, non-marine sands and silts were deposited in an advancing delta and alluvial deltaic plain across the Plains Region (Whitaker et al., 1978), including the Late Cretaceous Eastend, Whitemud, Battle and Frenchman Formations, the Tertiary Ravenscrag, Turtle Mountain and Paskapoo Formations, the Oligocene Cypress Hills Formation and the Miocene Wood Mountain Formation. Locally, these units can all form large aquifer systems.

The Eastend Formation is composed of greyish and greenish sandstone, siltstone, and mudstone, with thin coal seams in the upper part. The Whitemud is composed of kaolinitized, white sandstone and mudstone, separated by a carbonaceous zone and overlain by purplish shale of the Battle Formation. The Frenchman Formation is composed of sandstone and mudstone. The Ravenscrag Formation is comprised of sandstone, siltstone, mudstone, and coal. Christiansen (1983) states that the bottom portion of the Eastend Formation consists of blanket sands. The Frenchman, Ravenscrag and Paskapoo Formations were deposited by rivers meandering over swampy floodplains and are characterized by fine to medium-grained channel sands. The Tertiary Cypress Hills Formation is composed of conglomerate, gravel, sand and silt (Vonhof, 1965a, b; Vonhof, 1969). Leckie and Cheel (1989) interpreted the formation as a braidplain deposit. It unconformably overlies the Ravenscrag Formation (or Eastend to Ravenscrag Formations) or directly overlies the Bearpaw Formation. The Wood Mountain Formation has been described by Whitaker (1965, 1967), Vonhof (1969) and Leckie et al. (2004). The present occurrences of the Miocene Wood Mountain Formation in the Wood Mountain area are erosional remnants of an originally much more extensive deposit. The formation consists of gravel and sand up to 30 m thick deposited in a braided river system environment.

The Eastend-Ravenscrag Aquifer is formed by the sediments of the Eastend, Whitemud, Battle, Frenchman and Ravenscrag Formations. In southwestern Saskatchewan, it also includes the aquifers formed by the Cypress Hills and Wood Mountain Formations, where these formations overlie the Eastend-Ravenscrag Aquifer. The thickness of the aquifer ranges from zero (0) metres at its erosional edges to 290 metres beneath the Cypress Hills in southwestern Saskatchewan. This transboundary aquifer extends into the United States.

Regional hydrogeology of the Eastend-Ravenscrag Aquifer has been described by Meneley (1983), and Maathuis and Simpson (2003, 2007a, b, c, d). West of 103°W, large portions of the aquifer are exposed at the ground surface or covered by a thin layer of glacial drift. In this area, the aquifer can be considered a tabular mass overlying an impermeable base formed by thick siltstones and mudstones of the Bearpaw Formation. The aquifer is unconfined and recharge occurs over virtually the aquifer's entire extent. The area is characterized by significant topographic relief. In a general sense, groundwater flow will be from the central parts of the aquifer toward its erosional edges. However, because of the topographic relief, flow will also discharge into river and creek valleys dissecting the landscape. In the southeastern part of Saskatchewan (east of the 103°W), there is less topographic relief and the aquifer is generally covered by several tens of metres of glacial drift, mainly till. The aquifer in this part of Saskatchewan is semi-confined.

Using analyses of specific capacities, Meneley (1983) derived hydraulic conductivity values in the 1 $\times 10^{-5}$ to 7 $\times$ 10^{-5} m/s range for sandstones in the Frenchman and Ravenscrag Formations. Based on reported values, the hydraulic conductivities of the Eastend-Ravenscrag sandstones are probably 1.1 $\times$ 10^{-5}–1.1 $\times$ 10^{-4} m/s, typical for the fine to medium-grained sandstones of the aquifer. Coal within the Ravenscrag Formation may be fractured, making coal layers a potential target for well completion. However, there is no actual data on the hydraulic conductivity or transmissivity of fractured coal layers. There is also no information on the transmissivity or hydraulic conductivity of the gravels within the Cypress Hills and Wood Mountain Formations, although the literature suggests that the hydraulic conductivity of gravels can range from hundreds to thousands of metres per day (e.g., Freeze and Cherry, 1979).

Meneley (1983) estimated that the yield of individual wells may be in the order of 50 m^3/day to 500 m^3/day. Wells screened across multiple zones within the aquifer may yield higher volumes. Because of the complex lithological settings of the aquifer, pumping-induced drawdowns will not show radial flow patterns. The presence of the more permeable channel sands causes drawdowns along the axes of these channels (i.e., elongated drawdowns).

Water quality data for the Eastend-Ravenscrag Aquifer and the Cypress Hills Aquifer have been discussed by Dyck (1980) and Maathuis (2008). Water in the Cypress Hills Formation is commonly either Ca/Mg-SO_4 or Ca/Mg-HCO_3 type. The sum of ions ranges from 125 mg/L to 4,500 mg/L, but typically is less than 1,000 mg/L.

Within the Eastend-Ravenscrag Aquifer, the water quality changes from west to east. The highest-quality water is found in the western part, where the aquifer is unconfined. In this area, the sum of ions is typically less than 1,500 mg/L. In the eastern part, the sum of ions in the water is typically in the 1,500 mg/L to 3,000 mg/L range. The type of water is variable, but in the southeastern region, sodium is typically the dominant cation.

In Manitoba, erosional remnants of the Eastend-Ravenscrag are recorded as sandstones within the Upper Cretaceous and Tertiary Boissevain and Turtle Mountain Formations within and immediately adjacent to the Turtle Mountain upland of southwestern Manitoba: These sandstones encompass an area of approximately 1,100 km2 (Figure 10.8) in Manitoba and extend south into the United States, as another transboundary aquifer. These units are equivalent to the Eastend-Ravenscrag Aquifer of southeastern and south-central Saskatchewan and the Fox Hills and Hell Creek aquifer systems of North Dakota.

The Boissevain Formation overlies grey, non-calcareous shale of the Coulter Member of the Pierre Shale and consists of sandstone with minor amounts of mudstone and siltstone, averaging about 30 m in thickness where it has not been eroded (Bamburak, 1978). In North Dakota, Randich and Kuzniar (1984) report that sandstone comprises approximately 18% of the total formation thickness, with individual sandstone beds ranging in thickness from 0.6 m to 25 m. The Boissevain Formation is overlain by up to 158 m of non-marine siltstone, sandstone, and mudstone, grading upward to silty mudstone with minor thin fine-grained sandstone forming the Turtle Mountain Formation (Bamburak, 1978). Lignite beds are common in the lower part of the formation and were mined sporadically from 1883 to 1943 (Bannatyne, 1978). It is interesting to note

that groundwater seepage from sandstone aquifers was a serious problem for some mining attempts. Bedrock units have been deeply incised in places and are unconformably overlain by up to 120 m of Quaternary deposits.

In most areas, sandstone aquifers of the Boissevain and Turtle Mountain Formations are confined by overlying low-permeability materials. However, outcrops occur locally along the flanks of Turtle Mountain, providing unconfined conditions. Recharge to the bedrock units occurs primarily as a result of seepage through overlying Quaternary deposits, but direct recharge is also found in local areas of outcrop, particularly in the Turtle Mountain Formation (Halstead, 1959). Springs have been reported around the base of Turtle Mountain (Johnston, 1934; Kohut, 1972) and in a ravine where outcrops of the Boissevaine Formation occur (Elson and Halstead, 1949).

Rutulis (1978) suggested that groundwater flow would generally be from south to north in Canada with discharge along the flanks of Turtle Mountain. However, Western Ground-Water Consultants (1982) suggested a regional north-to-south movement of groundwater. This observation is consistent with studies in North Dakota indicating regional groundwater movement toward the Souris River valley (Randich and Kuzniar, 1984). It is likely that local to intermediate groundwater systems have developed along the flanks of Turtle Mountain in response to topographic changes, and that groundwater movement in these areas would be from higher elevations to discharge areas in topographic lows.

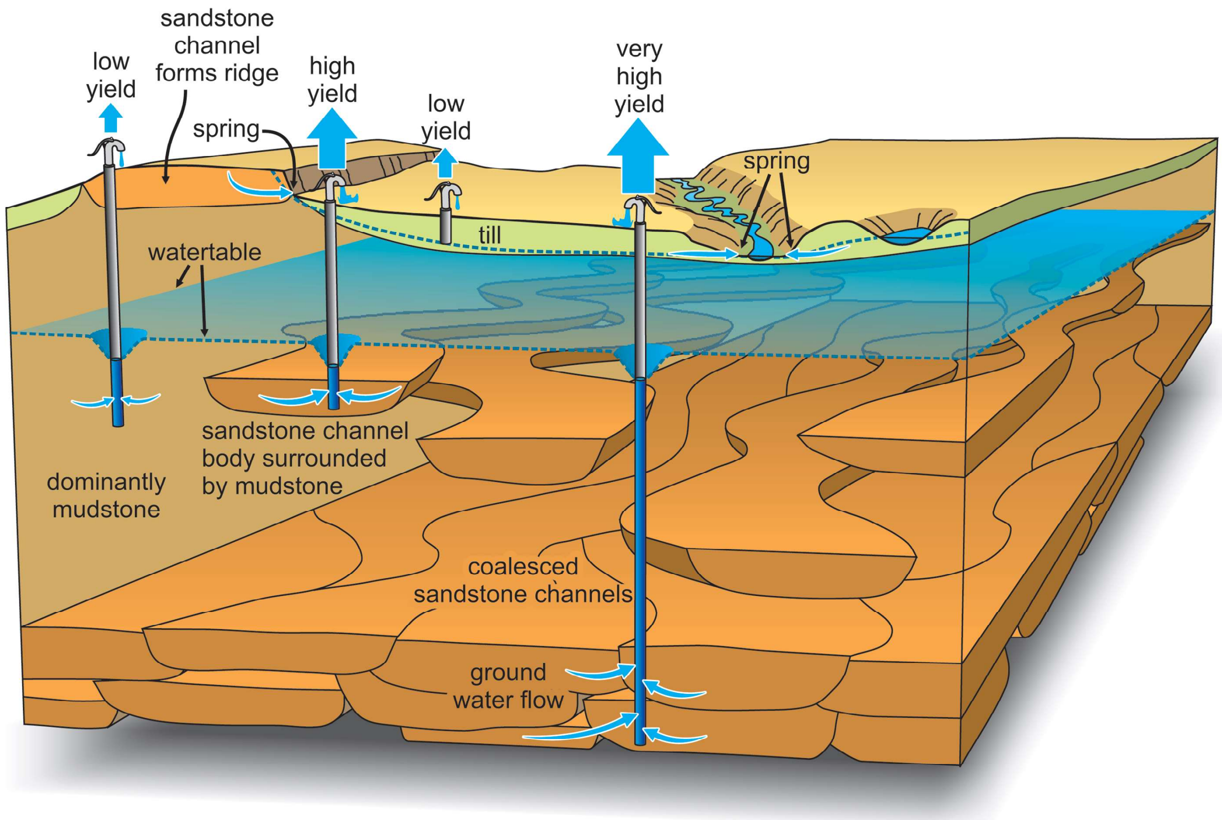


Figure 10.20 Conceptual hydrogeological model for the Paskapoo Aquifer, illustrating isolated sand channels encased in mudstones.

Yields from wells completed in the Boissevain and Turtle Mountain Formations are quite variable, with excellent supplies sufficient for most rural residential or small agricultural operations obtained whenever thicker sand beds are intersected, and poor yields where finer-grained sediments are found (Elson and Halstead, 1949). Well yields from equivalent formations in North Dakota are about 9 m3/day to 260 m^3/day from the Fox Hills aquifer system and less than 86 m^3/day from the Hell Creek aquifer system (Randich and Kuzniar, 1984). Western Ground-Water Consultants (1982) conducted a test drilling program in the Canadian portion of Turtle Mountain in 1981 and suggest that well yields from the formations decline with a fining of grain size from north to south. Their studies indicate that yields up to 475 m^3/day may be possible along the northern flank of Turtle Mountain, although the sustainability of the resource was not evaluated.

Groundwater quality analyses for samples from the Boissevain and Turtle Mountain Formations have been presented by Elson and Halstead (1949), Halstead (1959) and Western Ground-Water Consultants (1982). The groundwater is Ca-Mg-(Na)-HCO_3-(SO_4) type with TDS ranging from about 850 mg/L to 2,500 mg/L. Sodium concentrations are variable, but typically range from 150 mg/L to 500 mg/L, while sulphate concentrations generally exceed 200 mg/L and are more than 1,000 mg/L in some areas. Chloride concentrations in groundwater are generally less than 50 mg/L, although Na-Cl-type groundwater is reported in equivalent units in the North Dakota portion of Turtle Mountain.

10.3.1.2.6 Paskapoo Aquifer System

The Paskapoo Formation of southern Alberta is an extensive Tertiary fluvial mudstone and sandstone complex covering ~65,000 km2 (Figure 10.20). It forms the westernmost and most extensive erosional remnant of Tertiary deposits equivalent to those in Saskatchewan and Manitoba. Roughly one third of wells in Alberta are located within the Paskapoo outcrop belt and 96% of these penetrate bedrock. The number of wells completed in the Paskapoo (~64,000) makes this Formation the most significant groundwater supply in the Plains Region. Many previous studies have examined localized areas of the Paskapoo (Farvolden, 1961; Meyboom, 1961, 1967; Tóth, 1962, 1966; and Ozoray & Barnes, 1978) and included research into nested flow systems by Tóth (1962, 1963). A recent study of the Paskapoo Aquifer System was conducted by Grasby et al. (2008, 2010).

The Paskapoo Formation ranges in thickness from zero up to 800 m and is comprised of light grey, thick-bedded sandstone, with greenish sandy siltstone and mudstone, deposited in non-marine environments. In the Plains, the strata dip westward at <1º. Although commonly referred to as sandstone because of the tendency of sand channels to form outcrops, the Paskapoo is greater than 50% siltstone and mudstone. Background literature and detailed measured sections of Paskapoo rocks in cores and outcrops within the Calgary to Red Deer region are provided in Hamblin (2004, 2007a, b, c).

The Paskapoo Formation sits on top of the coal-bearing upper Scollard Formation. This surface is overlain successively by the Haynes Member and the Lacombe Member (described below), which together make up the bulk of the Paskapoo Formation. In some northern and western locations, there is some evidence that an additional (later) sequence is present (Dalehurst Member), but these deposits have not been studied in detail.

The basal Haynes Member (Demchuk and Hills, 1991) is characterized primarily by vertically stacked, multi-storey, medium-grained channel sandstone bodies, which form a distinctive, regionally extensive, laterally continuous unit up to 150 m thick. It includes only minor and discontinuous mudstone layers (10%–30%) and sandstones (70%–90%), although it appears that the thick sandstones do not extend southward to the vicinity of Calgary. The overlying Lacombe Member (Demchuk and Hills, 1991) is very widespread and characterized by thinly inter-bedded channel and splay sandstone, overbank siltstone and mudstone and minor coal, and is up to 300 m thick. This unit represents the bulk of the near-surface Paskapoo rocks for much of its area plus some isolated, thick channel sandstone aquifer units and many thinner isolated, splay sandstone aquifer units (30%–50%), all encased in the dominant aquitard overbank deposits (50%–70%). The uppermost Dalehurst Member (Demchuk and Hills, 1991) is characterized by inter-bedded, fine-grained sandstones, grey mudstones and at least five thick coal seams. The geometry of the sand channels within a mudstone matrix ensure complex groundwater movement through the Paskapoo Formation (Burns et al., 2010a, b).

Paskapoo sandstones are predominantly litharenites with major framework grains including quartz, feldspar and rock fragments (mainly chert, volcanic, metamorphic and sedimentary) (Grasby et al., 2007) (Figure 10.21). Diagenetic production of clays through alteration of feldspars and rock fragments is a significant process reducing sandstone permeability. Calcite cement is also

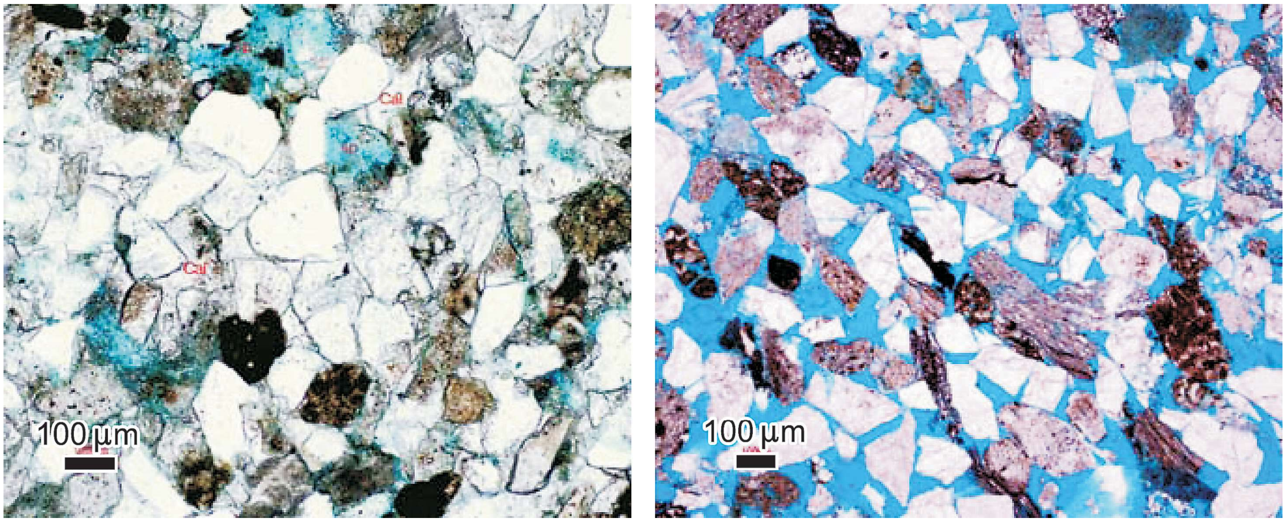


Figure 10.21 Thin section of Paskapoo sandstones illustrating (on left) well-cemented sands with little porosity (in blue) and (on right) poorly cemented sands with high porosity.

observed to occlude intergranular pore spaces, particularly near redox boundaries between the upper weathered and lower unweathered portions of the aquifer, where calcite cement can be pervasive (Grasby et al., 2009).

Both porosity and permeability of sandstones in the Paskapoo Formation show significant variation. Measured helium porosity values show a broad range from 4.2% to 32.5%, with an average of 19.2% ± 7.3. Porosity is generally highest in coarser-grained sandstones. Estimated porosity from petroleum well sonic logs (4%–28%) (Chen et al., 2007b) is consistent with the range measured from core samples.

Hydraulic conductivity is generally low (average 1×10^{-5} m/s for 159 measurements). Diagenesis of rock fragments appears to reduce hydraulic conductivity by generating clay minerals that occlude pore necks (Grasby et al., 2007). A bimodal distribution is observed, representing higher-permeability, coarse-grained sandstones and lower-permeability, fine-grained sandstones and mudstones. Permeability values are generally highest in association with thick coarse channel sands. Fractures are thought to significantly enhance permeability in some sandstones (Farvolden, 1961; Tóth, 1966) and probably mudstone units as well.

The piezometric surface in the Paskapoo mimics regional topography. Indications are that there are no confined regional-scale flow systems here, and groundwater is dominated by local-scale flow systems. This theory is consistent with observations suggesting that recharge occurs over most of the Paskapoo outcrop area as a result of downward infiltration through overlying glacial drift. The aquifer system is characterized by a general downward directed flow system (Grasby et al., 2008, 2010).

Although there are few long-term monitoring wells not affected by nearby pumping, an examination of historical trends for this aquifer shows that reported water levels have increased over the last 40 years (Figure 10.22). This fact may suggest a general lowering of the regional water table. Some high-volume-production wells providing municipal water supplies have recently been abandoned because of local reductions (Wozniak et al., 2008). These observations suggest that more work is needed to effectively quantify sustainable production from this important aquifer system.

10.3.1.3 Fractured shale aquifers

Shale is generally considered an aquitard. In parts of southwestern Manitoba and southeastern Saskatchewan, (Figure 10.8), however, the Odanah Member of the Pierre Shale is highly siliceous and fractured, such that it forms a large-scale aquifer. In outcrops, layers of hard, brittle, heavily fractured shale are found inter-bedded with layers of soft, less fractured shale and thin but continuous layers of yellow bentonite. Seepage faces have been observed at the point of contact between the fractured siliceous layers and underlying bentonite beds. Drillers' descriptions of the unit are similar to what is seen in outcrops, i.e., generally described as "layers of soft and hard shale." The Odanah Member is as much as 240 m thick (Bannatyne, 1978; Figure 10.23) in southwestern Manitoba, but becomes increasingly less siliceous and more bentonitic with depth. The Odanah is underlain by the Millwood Member, which is a soft bentonitic shale with little reported groundwater production potential. The contact between the two members is often reported as being very abrupt.

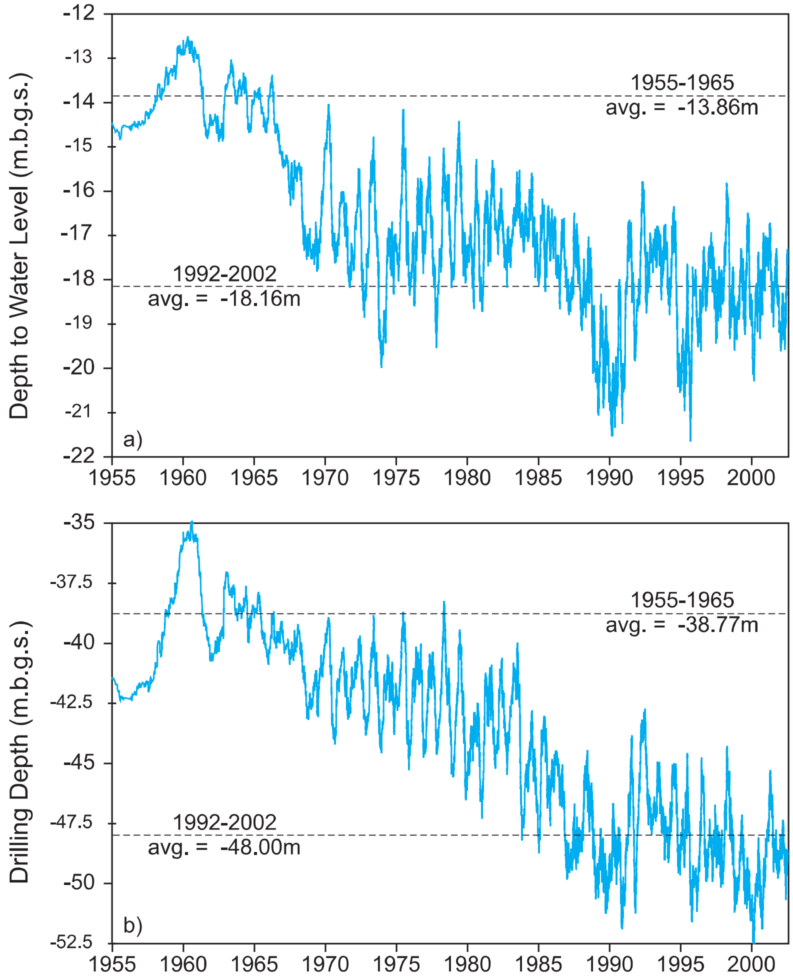


Figure 10.22 Plot showing historical changes in average drilling depth and water levels.

Through much of its outcrop area, the Odanah Member occurs as a series of rounded hills known as the Pembina and Tiger Hills in southern Manitoba. In some parts, the hills appear to be large blocks of bedrock that have been scoured and transported significant distances by glacial ice sheets. To some degree, these physiographic features may divide the aquifer or parts of the aquifer into a series of non-interconnected units. Given these lateral boundaries, the occurrence of groundwater primarily in fracture porosity, and the vertical separation of the aquifer by bentonite layers, it would be expected that any attempts to withdraw substantial amounts of groundwater would lead to dewatering of the local portion of the aquifer. Unfortunately, long-term monitoring information is not available for any of the larger water supply developments, but dewatering would certainly be a concern.

Well yields from the Odanah Aquifer are

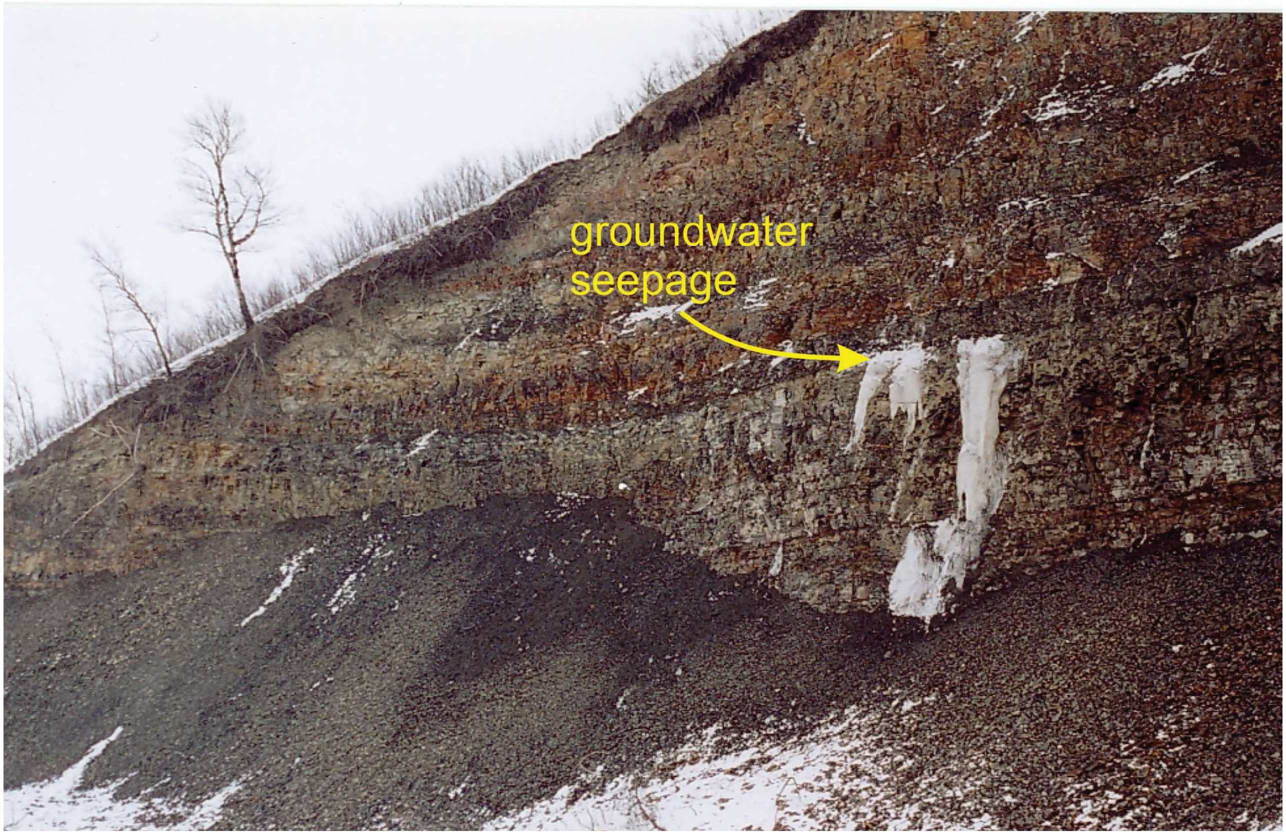


Figure 10.23 Photograph showing the Odanah Aquifer in Southwestern Manitoba. Note the seepage occurring at the top of thin bentonite beds forming icings. The extent of the Odanah Member in Saskatchewan is limited (see Figure 10.8). Wells are known to have been completed in this unit for domestic/farm water supplies, but there is no information on hydraulic properties, yields and water quality.

generally less than 43 m^3/day, but in exceptional cases, yields of 860 m^3/day or more have been reported. The aquifer has been developed as a source of municipal water supply in a few locations, but the lack of predictability in well yield and generally poor water quality have hindered additional development.

Betcher (1997) provided a summary of water quality in the aquifer in Manitoba based on regional sampling of private wells. TDS varied from less than 500 mg/L to more than 6,000 mg/L, averaging 1,770 mg/L. TDS values tended to increase with well depth, although there was considerable scatter. Groundwater in shallow wells (<15 m) was typically Ca-Mg-HCO_3-(SO_4) type trending toward increased NaCl and SO_4 and a decline in Ca and Mg with depth. Sodium concentrations exceeded 300 mg/L in many of the deeper wells.

10.3.2 Quaternary aquifers

Quaternary aquifers are unconfined to highly confined sand or sand and gravel units that occur in the sediments between the bedrock surface and the present ground surface. Quaternary aquifers (Figure 10.24) in ascending order include aquifers between bedrock and the first till, inter- and intra-till aquifers, and surficial aquifers. Aquifers between bedrock and the first till are often referred to as Empress Group aquifers and include the preglacial buried-valley aquifers. Inter-till aquifers can be buried-valley or sheet/blanket. Surficial aquifers

TABLE 10.2 HYDRAULIC CONDUCTIVITIES OF TILLS IN THE PRAIRIES

SITE	FORMATION	HYDRAULIC CONDUCTIVITY (M/S)	REFERENCES
Warman	Sutherland till, unfractured	$10^{-10} – 10^{-11}$	Keller (1987), Keller et al. (1988, 1991), Fortin et al. (1991), Remenda et al. (1996)
Dalmeny	Floral till, fractured	5×10^{-9}	
	Floral till, bulk	3.2×10^{-10}	
Birsay	Battleford till, Unfractured	5.4×10^{-11} - 2.7×10^{-11}	Shaw and Hendry (1998)

include those formed as inwash (deltaic sediments deposited in icebound glacial lakes by extra-glacial rivers) or outwash (silt, sand and gravel washed out from a glacier by meltwater sediments) during the final deglaciation of the Prairies and alluvial deposits. Quaternary aquifers do not necessarily represent a single hydrostratigraphic unit, but they can be comprised of stratified sediments of different ages.

Throughout the Plains, Quaternary aquifers are a major source of domestic, municipal and industrial water supplies. Tills (an unsorted and unstratified mixture of clay, silt, sand, gravel and boulders directly deposited by glaciers) and silts and clays form aquitards. Table 10.2 provides a summary of reported hydraulic conductivities of tills in the Prairies.

10.3.2.1 Confined Quaternary aquifers

Inter-till, intra-till and buried-valley aquifers are major sources of groundwater within the Prairie

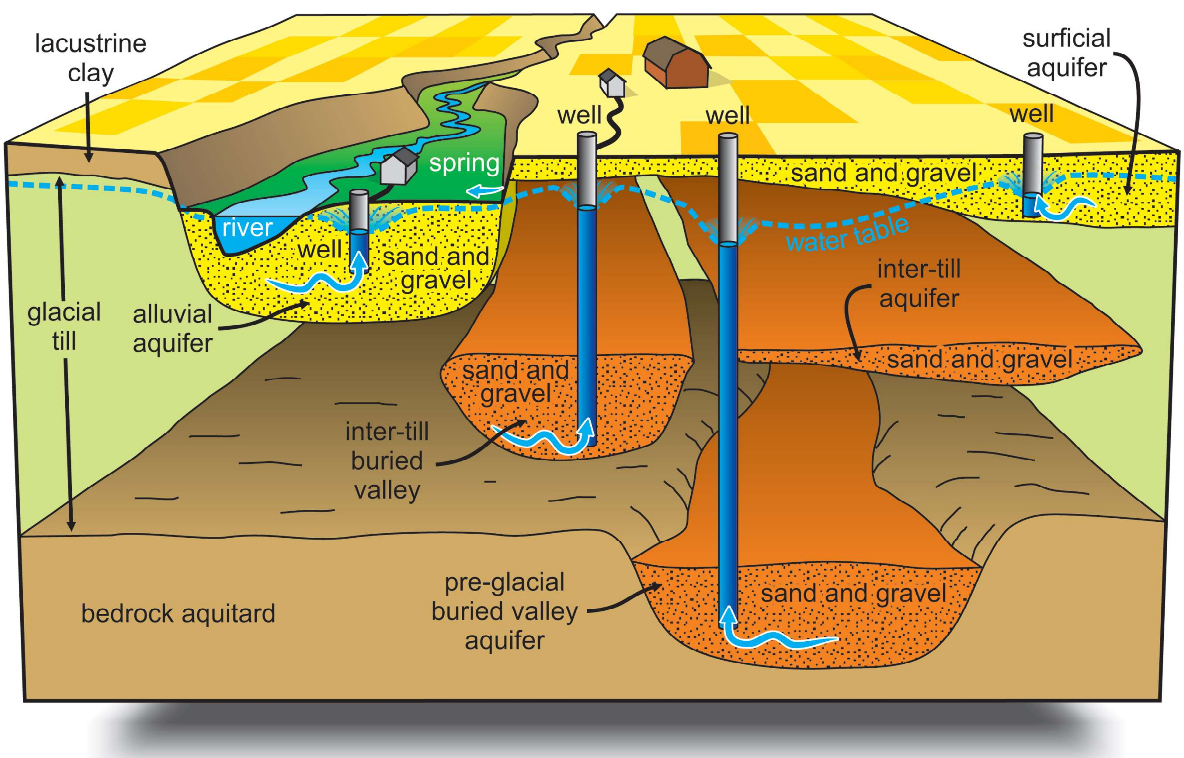


Figure 10.24 Block diagram of Quaternary aquifers.

Region. Considerable effort has been devoted to mapping major buried-valley aquifers, particularly in Saskatchewan where these aquifers can provide significant rates of supply. Less effort has been devoted to mapping the occurrence and extent of inter-till and intra-till aquifers, which are locally important.

10.3.2.1.1 Buried-valley aquifers

Buried-valley aquifers are common in the glaciated terrain of North America (e.g., Betcher et al., 2005; Russel et al., 2004; Maathuis and Thorleifson, 2000; Shaver and Pusc, 1992; van der Kamp, 1986). In the Prairies, the term "buried-valley aquifer" commonly refers to aquifers occupying preglacial valleys, although the term is also used in Manitoba to refer to aquifers occupying valleys scoured by glacial meltwater. At the end of the Tertiary, an extensive network of river systems was present in the bedrock surface of the Prairie landscape. Prior to the onset of glaciation, Tertiary sediments (quartzite and chert gravel) were deposited in many of these valleys, forming the lower portion of the fill. The upper, and generally thicker, portion of the fill consists of preglacial sands and gravels which contain igneous, carbonate and metamorphic clasts (e.g., Christiansen, 1992). Significant silt and clay beds can be found locally. In Saskatchewan and Alberta, these stratified deposits are referred to as the Empress Group (Whitaker and Christiansen, 1972; Christiansen, 1992). There is no specific stratigraphical name for the fill deposits in Manitoba, although Empress Group sediments are less common. During the first and subsequent glaciations, these stratified sediments, several tens of metres thick, were covered by glacial drift, mainly till. The thickness of the glacial drift overlying these preglacial buried-valley aquifers is commonly in the 60-metre to 90-metre range. These aquifers are typically semi-confined to highly confined.

Current knowledge of the extent of buried valley aquifers varies across the Plains Region, as shown in Figure 10.25. In Saskatchewan, the preglacial buried valleys have been mapped in detail. In Alberta, the main buried valleys are known, but only parts of them have been mapped in detail (for example, the buried-valley aquifers in the Cold Lake area, e.g., Parks et al., 2005). Several buried-valley aquifers have been identified in Manitoba (Betcher et al., 2005).

The largest of these buried-valley aquifers in the Prairie Provinces is the Hatfield Valley Aquifer in Saskatchewan. In contrast to the older preglacial valleys, this valley was cut into bedrock by fluvial erosion during the advance of the first continental glacier. It was filled with stratified sediments (Empress Group) before it was covered by drift of the first and subsequent glaciations (Christiansen et al., 1977). The aquifer traverses Saskatchewan from the northwest Alberta border to the southeast Manitoba border and continues into both provinces. It is approximately 550 km long and up to 30 km wide and is typically between 30 m and 50 m thick. The thickness of the overlying confining layer, mainly consisting of tills, averages about 90 m (e.g., Maathuis and Schreiner, 1982a, b; Schreiner and Maathuis, 1982).

Typically, there are no surface expressions of preglacial buried valleys: with the exception of a few areas, their location does not coincide with that of present-day major rivers. Preglacial buried-valley aquifers are longitudinally extensive, but there is increasing evidence that they are not continuous, and that continuity is interrupted by transverse low-transmissivity barriers (Maathuis, 2005; van der Kamp and Maathuis, 2002; Shaver and Pusc,

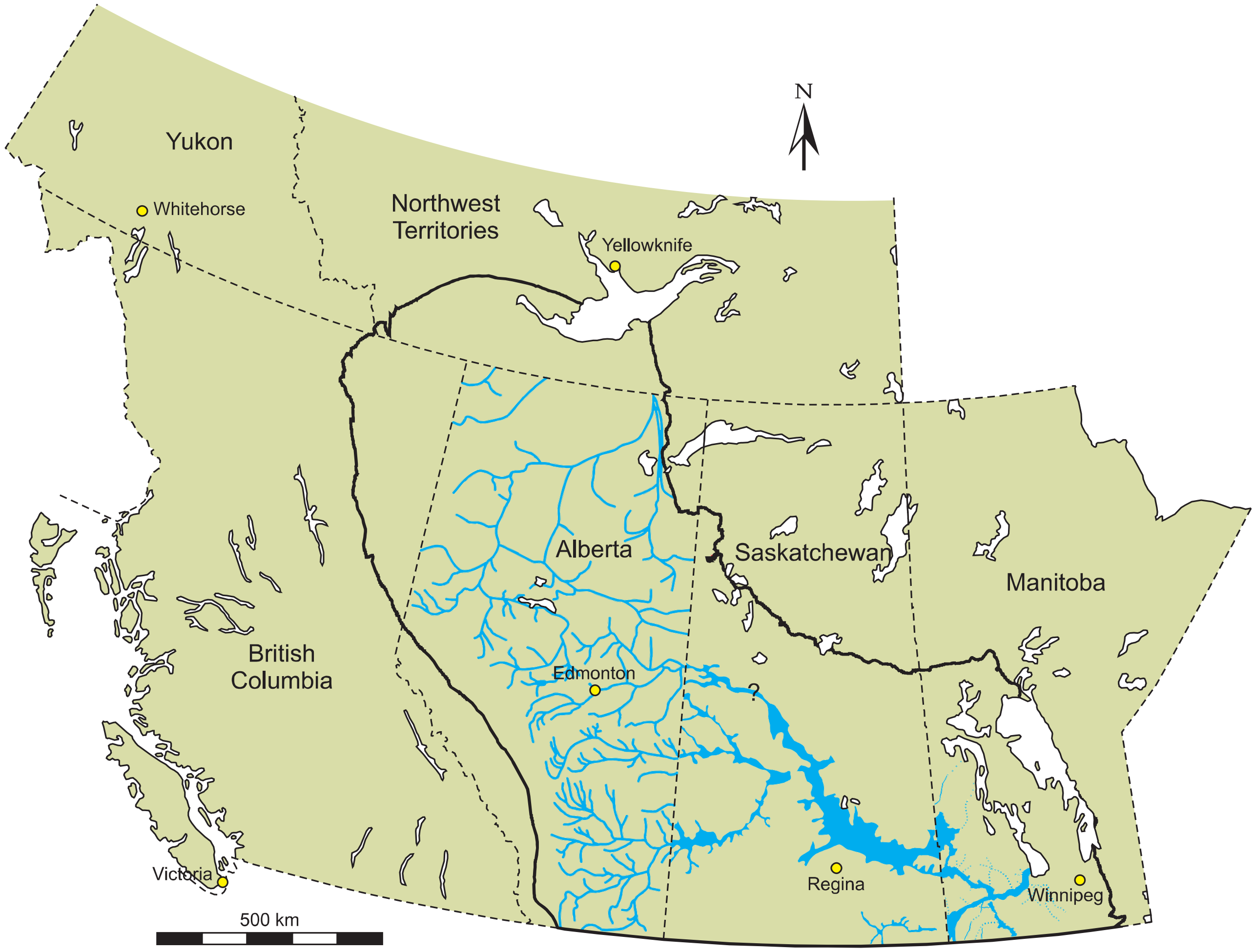


Figure 10.25 Locations of (preglacial) buried valley aquifers in the southern part of the Plains; no data on BC and NWT (after Maathuis and Thorleifson, 2000; and Toop and Betcher, unpublished data).

1992; Meneley, 1970). It remains a matter of speculation as to what causes these transverse barriers, which can be identified if monitor wells have been installed throughout the aquifer. When not stressed by pumping, large hydraulic head differences between wells indicate the existence of these transmissivity barriers. In other cases, presence of a barrier and/or barriers becomes apparent only when there are significant withdrawals from such aquifers (e.g., Maathuis, 2005). It has been noted that barriers are rarely found during exploratory drilling.

Buried-valley aquifers in the Prairies are not limited to aquifers formed by the preglacial valleys. They may also occur throughout the sequence of Pleistocene sediments, formed as subglacial or as proglacial meltwater valleys. These valleys were filled with stratified sediments and subsequently covered by tills or, in a few cases, outcrop at the ground surface. Compared to the preglacial buried-valley aquifers, these aquifers tend to be of limited longitudinal extent; nevertheless, they are an important source of local water supply.

Recharge to the deep buried-valley aquifers depends on their geological setting. When incised into Cretaceous/Tertiary siltstones and mudstones recharge occurs by vertical seepage through the overlying aquitard, formed predominantly by till units, or by lateral seepage from the surrounding bedrock. Given the thick aquitard (more than 30 m) and the low vertical hydraulic conductivity of the tills, recharge to these preglacial buried-valley aquifers is typically only a few millimetres per year. Deep buried-valley aquifers incised into low-permeability bedrock aquifers are also recharged by lateral flow from these sediments and can act as a drain for the adjacent bedrock aquifer.

The preglacial buried-valley aquifers often discharge into present-day valleys. For example, the Hatfield Valley Aquifer discharges into the North Saskatchewan River and the Qu'Appelle and the Assiniboine River Valley near the Manitoba border (Meneley, 1972). The main discharge for the Battleford and Tyner Valley aquifers is the North Saskatchewan River just north of Saskatoon (Meneley, 1970). Discharge from the shallower Pleistocene buried-valley aquifers is poorly documented. These aquifers may discharge into present-day valleys as generalized seepage or as springs.

The water quality in preglacial buried-valley aquifers is highly variable and depends on the aquifer's setting. If buried-valley aquifers are recharged solely by vertical flow through the overlying tills, then the water quality is controlled by till water geochemistry. If the recharge is from bedrock, the quality of the water in the buried-valley aquifer will be a mixture of till water and bedrock aquifer water.

The water quality in Saskatchewan's preglacial buried-valley aquifers has been described by Maathuis (2008) as highly variable, both in terms of concentration and composition. The water is often Ca/Mg-SO_4 type or Na-SO_4 type with a TDS in the 1,000 mg/L to 3,000 mg/L range. Betcher et al. (2005) noted that water quality in Manitoba's buried-valley aquifers is also highly variable.

Recent significant groundwater withdrawals from two of the preglacial buried valleys in Saskatchewan provided invaluable information on the unique behaviour of these aquifers (Maathuis, 2005; Maathuis and van der Kamp, 2003; van der Kamp and Maathuis, 2002). Key discoveries in this work include recognition that buried-valley aquifers are of finite extent and bounded on all sides by low-permeability units. They can be considered "bucket"-type aquifers. Because of their hydrogeological setting (long, narrow, highly transmissive and bounded on all sides), pumping-induced drawdowns in buried-valley aquifers may extend over tens of kilometres on each side of a production well or well field. The drawdown cone in a bucket-type aquifer is created initially within the well field area, but as pumping continues, the water levels will drop throughout the entire area by about the same amount. Additional recharge to the aquifer is induced by the drawdown of the water levels within the aquifer. This drawdown will continue until pumping balances the lateral and vertical recharge. When the pumping rate exceeds the maximum possible recharge, the water levels will continue to drop indefinitely until pumping becomes impractical. Once pumping has ceased, there is a rapid infilling of the drawdown cone in the well field area by lateral flow toward the pumping centre. A general flattening of the water levels occurs and, throughout the aquifer, there are similar amounts of residual drawdown. The rate of recovery decreases with time, as with any type of semi-confined aquifer. Depending on the hydrogeological setting, complete recovery may take up to several decades. Reliable estimates of the maximum sustainable pumping rate can only be made if long-term pumping and water level data are available.

These observations show that, while significant volumes of water can potentially be obtained from preglacial buried-valley aquifers, these aquifers must be managed carefully because of their peculiar behaviour. Such characteristics not only are valid for the preglacial buried-valley aquifers, but also apply to Pleistocene buried-valley aquifers.

10.3.2.1.2 Confined Quaternary aquifers

Inter-till and intra-till aquifers are major sources of groundwater within the Prairie Region. Intra-till aquifers are formed by aqueous sorting of glacial deposits, and are often associated with eskers or moraines. Individual aquifers generally have a limited extent, although the glacial feature itself may be quite impressive. Inter-till aquifers are formed by similar processes, but are found in sediments between till sheets or at the till-bedrock point of contact. Again, while individual aquifers may have limited extent, the overall extent of the inter-till deposits can be considerable and is often a target for test drilling or water wells.

While considerable effort has been devoted to mapping major buried-valley aquifers, less effort has been devoted to mapping the occurrence and extent of locally important inter-till or intra-till aquifers. In many cases, the presence of these aquifers is only known through water well logs, but in places where development has occurred, there may be more extensive information, such as test drilling and pumping test results and data resulting from monitoring of development impact. A number of municipal well fields have been established in intra-till sand and gravel aquifers in parts of southern and central Manitoba.

In most instances, these aquifers are highly confined by overlying and underlying glacial tills, but some of them, or portions of them may extend to the surface or nearly to the surface, providing an unconfined or partially confined area where more direct interaction with the surface or shallow subsurface can occur (see discussion of the Winkler Aquifer in Box 10-1). Typically, these are areas where most of the recharge water enters the aquifer. When the aquifer is highly confined, however, limited isotopic analysis and age dating reveal that the groundwater is very old, probably dating back to the time of deposition, indicating very, very slow groundwater movement through the surrounding low-permeability tills.

10.3.2.2 Unconfined sand and gravel aquifers

Unconfined sand and gravel aquifers are composed of glaciofluvial, glaciolacustrine, fluvial and alluvial materials deposited after the retreat of the Wisconsinan Ice Sheet. Major aquifers are formed by inwash or outwash (Christiansen, 1979, 2005). Some of these deposits may have been modified by later aeolian action (e.g., Great Sand Hills in southwestern Saskatchewan). The extent of major deposits of unconfined sand and gravels in the Prairies is illustrated in Figure 10.26 , which is based on published surficial geology maps. Although many of these deposits do form aquifers, others may not have sufficiently saturated thicknesses to provide water for household needs.

Major unconfined sand and gravel aquifers in the Plains Region are located in the Great Sand Hills in southwestern Saskatchewan, in the deltas along the Saskatchewan River (e.g., Prince Albert and Nipawin) and in Manitoba's Oak Lake and Assiniboine deltas.

Unconfined sand and gravel aquifers are bounded at the bottom by an aquitard and at the top by the water table. They receive recharge directly from precipitation. Discharge from these types of aquifers

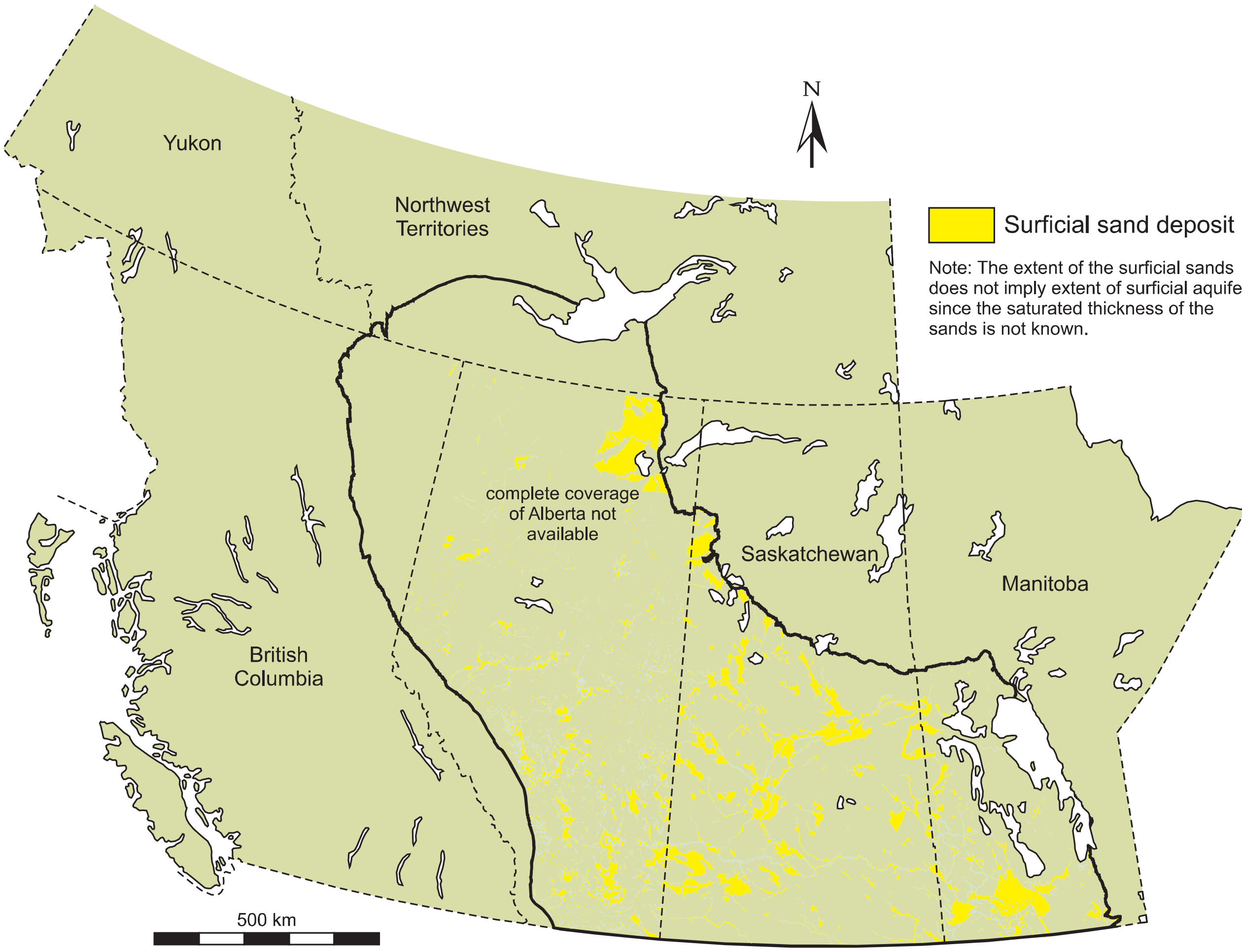


Figure 10.26 Extent of surficial sands and gravels in the southern part of the Plains; no data on BC and NWT (after Maathuis and Thorleifson, 2000).

is by evapotranspiration and through springs and seeps. A hydrograph showing typical water level response in a surficial aquifer is shown in Figure 10.27. Recharge occurs primarily in the spring or during the early summer by infiltration of snowmelt and seasonal rains, with a smaller rise also occurring in the fall in those years where precipitation is sufficient. Summer recharge events are relatively uncommon on the Plains, but may occur in response to significant storm events or after a series of storms. Annual recharge rates have been estimated for a number of surficial aquifers. Render (1997) estimated an annual average recharge rate for the Assiniboine Delta Aquifer in Manitoba to be ~52 mm based on an analysis of streamflow records in a small sub-basin within the aquifer.

Most shallow aquifers in southern Manitoba experienced a gradual decline in groundwater levels through the 1970s and 1980s, followed by a gradual but consistent rise in groundwater levels starting in about 1991.

Surficial and alluvial aquifers provide water supplies for domestic/farm use and locally for towns, villages, irrigation and acreages. The yield of these aquifers varies, but in some circumstances, may exceed several hundreds of m^3/day and be suitable for irrigation and other high-production uses (see discussion of the Assiniboine Delta Aquifer below). Surficial sand and gravel aquifers that are connected hydraulically to surface water bodies (e.g., wells installed in alluvial aquifers) may potentially yield significant volumes of water. However, in these cases, the yield is largely derived from induced recharge from surface water and the aquifer merely performs a transfer function. The quality of the water in sand and gravel aquifers is normally excellent. Water is typically Ca/Mg-HCO_3 type with a TDS of less than 1,000 mg/L.

Across the Plains Region, there is a significant percentage of shallow, wide-diameter bored wells. Typically, these wells, commonly less than 30 metres deep, are completed in fractured tills or in thin sand and gravels seams that have a very limited extent within the till. Many of these wells are water table wells, although in areas with a significant downward or upward vertical gradient, the "static" water in these wells may be below or above the water table. The yield of these types of wells is typically low, but often sufficient for domestic use. The quality of the water is variable, but often poor because it is usually till water (i.e., high content of Ca, Mg and SO_4). These wells are susceptible to contamination from the ground surface and a significant percentage of them have high concentrations of nitrates.

10.3.2.2.1 Assiniboine Delta Aquifer

We are discussing the Assiniboine Delta Aquifer (ADA) in greater detail because it is the largest and most representative aquifer of its type within the region. The ADA is a 4,000 km^2 sand and gravel deposit laid down where the ancestral Assiniboine River flowed eastward into glacial Lake Agassiz (Render, 1988, Figure 10.28). The sands and

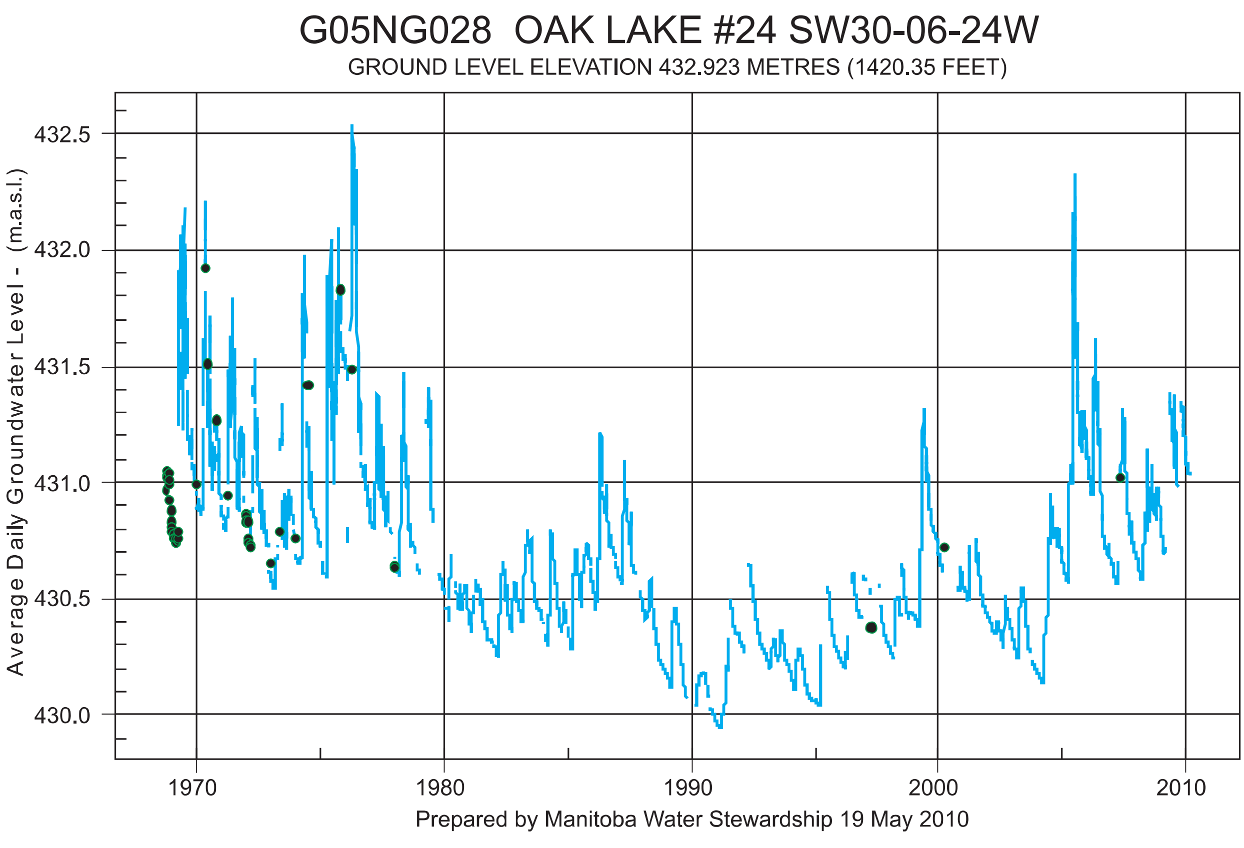


Figure 10.27 Hydrograph for a monitoring well unaffected by pumping in the shallow unconfined Oak Lake Aquifer of Southwestern Manitoba.

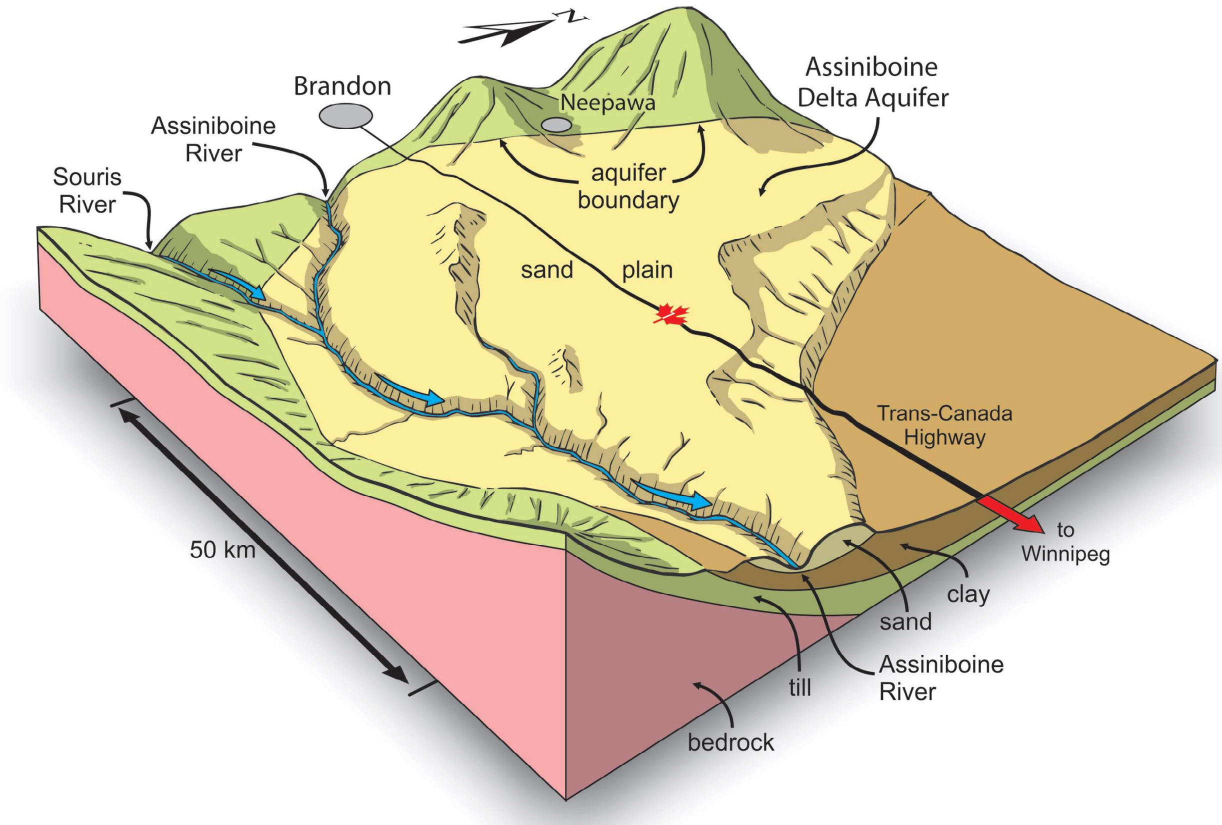


Figure 10.28 Block diagram of the Assiniboine Delta Aquifer.

gravels forming the aquifer are exposed at surface through most of its extent, but some parts are overlain by relatively thin clay deposits. The ADA averages about 18 m in thickness, but sometimes exceeds 30 m. Grain size varies from very fine sand to coarse gravel, with the coarser deposits generally found in the western part of the aquifer. In the Brandon area, there are very coarse gravel and boulder deposits which were left along the spillway of the ancestral Assiniboine River as it flowed toward Lake Agassiz. The aquifer is underlain by thick deposits of silt, clay and till. Regional-scale groundwater flow is generally directed toward the Assiniboine River, although smaller-scale flow systems discharge to a number of smaller creeks. Depth to the water table is quite variable and may be as much as 20 m or more beneath some areas of dune development.

Render (1988) summarized the available information on aquifer transmissivity. The transmissivity is greatest in the coarser deposits of the western parts of the aquifer, where values may exceed 1.43×10^{-2} m^2/s, it then declines toward the east and the aquifer's boundaries. These high transmissivities have allowed the development of high-capacity wells for irrigation use in parts of the aquifer. Storage coefficient values range from 0.0006 to 0.001, and specific yield values from 0.11 to 0.39.

Until the mid-1970s, the aquifer was used primarily for small towns, domestic and farm water supplies. Over the past few decades, however, there has been increased demand for groundwater withdrawals specifically for irrigation purposes. The aquifer is a major source of irrigation water supply for Manitoba's potato industry as well as a vital source of baseflow for the Assiniboine River. There are future plans for significant development to support the expansion of irrigation systems based on the aquifer and the extension of municipal water supplies to surrounding water-shortage areas.

In 1993, a well drilling program was implemented to allow further aquifer definition and instrumentation to a level suitable for detailed groundwater potentiometric surface mapping and measurement of hydrologic properties. Based on this work, the aquifer was divided into 13 subbasins in order to enable segmental assessment of groundwater and surface water hydrology: a detailed hydrologic budget was prepared. An extensive monitoring network has been developed within the ADA (rain gauges, snow accumulation, soil moisture, groundwater levels and creek flows). To date, management of the aquifer has provided sustainable development for domestic, municipal, agricultural, industrial and irrigation uses. The annual sustainable yield of the aquifer is estimated to be 1.34×10^8 m^3 of water. Slightly less than one-half of this amount (6.27×10^7 m^3) has been made available for non-domestic purposes. Of this latter amount, about 3.32×10^7 m^3 is currently licensed, mostly to persons using the water for irrigation purposes. About 7.13×10^7 m^3 has been reserved for domestic and environmental protection purposes.

Chemical water quality within the aquifer is generally good to excellent. TDS range typically between 200 mg/L and 500 mg/L, and are of a calcium-magnesium-bicarbonate type. Nitrate concentrations in the aquifer are variable and can be high. Nitrate-N findings in excess of the Canadian Drinking Water Quality (CDWQ) guideline of 10 mg/L are not uncommon, especially in shallower groundwater.

10.4 GROUNDWATER QUALITY

10.4.1 Major ion chemistry

Groundwater in the Plains Regions has significant variations in geochemistry. This is well demonstrated by springs in the region, which range from those with nearly pure fresh water to those with over 300,000 mg/L of total dissolved solids (TDS). Salinity within the sedimentary basin underlying the Plains Region increases progressively with depth, and in some of the deepest parts are in excess of 600,000 mg/L TDS. The amount of dissolved salts in groundwater is largely a function of the history of that water. The highly saline waters in the deep portions of the sedimentary basin are remnants of evaporating oceans (Connolly et al., 1990) 100s of millions of years old. Saline water has also formed where fresh water entering the basin through regional recharge systems encountered buried salt deposits at depth (Grasby et al., 2003; Grasby and Chen, 2005). This water is seen returning to the surface as brine springs in west-central Manitoba and Northern Alberta. Most potable groundwater within the region overlies these deeper brines, occurring at the near surface (<400 m).

Potable water across the Plains Region exhibits a broad range of chemistry and quality, as a function of the geology of the aquifers and their local environments. In south-central Manitoba, for example, groundwater in the carbonate aquifer is generally of excellent quality. However, dissolution of carbonate minerals within the aquifer through dedolimitization reactions generates Ca-Mg-rich hard water. Water within the underlying Winnipeg Formation sandstones, not in contact with carbonate minerals, is Na-HCO_3-dominated as a result of ion exchange processes (Ferguson et al., 2007).

Surficial sand aquifers are composed mainly of quartz with minor amounts of limestones, dolomites, and igneous and metamorphic rock fragments. Dominant geochemical processes in such aquifers are the generation of carbonic acid (H_2CO_3) within the soil zone, and the dissolution of limestones and dolomites. The result is calcium-, magnesium- or bicarbonate-dominated water with minor sodium and sulphate. The TDS in such water is low, often less than 1,000 mg/L.

The chemical evolution of the major ion chemistry of groundwater in tills has been the subject of many studies. In Saskatchewan, studies were carried out by Rutherford (1967), Rozkowski (1967), Davison and Vonhof (1978), Keller (1987), Keller et al. (1988, 1991), Mermut and Arshad (1987) and van Stempvoort et al. (1994). Relevant studies conducted elsewhere in glaciated prairie environments include those by Grisak et al. (1976), Wallick (1981), Groenewold et al. (1983), Hendry et al. (1986, 1989) and Grasby et al. (2010). These studies have determined that the chemical characteristics of water in fractured tills in the near subsurface, and thus the characteristics of the water quality in shallow confined aquifers, are formed in the unsaturated zone as a result of chemical processes active since the final deglaciation. Within the unsaturated zone, and to some extent at greater depth, chemical evolution occurs through (1) generation of organic and carbonic acids (H_2CO_3); (2) dissolution of carbonates, generating calcium, magnesium, and bicarbonate; (3) oxidation of reduced sulphur, generating hydrogen (H) and sulphate (SO_4); (4) dissolution of gypsum which produces calcium and sulphate; and (5) cation exchange, resulting in the loss of dissolved calcium and magnesium and the gain of dissolved sodium.

Keller's (1987) study of hydrochemical evolution within an 18 m thick fractured till at the Dalmeny site near Saskatoon revealed large differences in chemical evolution over lateral distances of tens of metres. Virtually all of the reduced sulphur in the first few metres of till beneath a slough in a depression at this site had been oxidized to sulphate. This sulphate was removed downward into the aquifer because of the concentrated downward flow beneath the slough. The water quality in the till beneath the slough was characterized by calcium-bicarbonate-type water with relatively low sulphate concentrations. In the non-depression areas, where the water table was relatively deep, all of the reduced sulphur had been oxidized, but because of the small vertical flow rate, the oxidized sulphur remained in the unsaturated zone as gypsum. Downward movement of sulphate-rich water and dissolution of gypsum will occur only after extreme infiltration events and perhaps under irrigation conditions. In such settings, water is calcium/magnesium-sulphate type and has high TDS (up to 5,000 mg/L). Keller (1987) attributes these lateral differences in chemical evolution to the high bulk hydraulic conductivity of the till at the Dalmeny site and the resulting groundwater flow regimes.

In settings where a thin fractured till overlies a thick-till aquitard with low bulk hydraulic conductivity, the main geochemical processes taking place in the thin fractured till are the same as listed above. However, since there is little downward flow, water in the thin till is characterized by high TDS (up to 15,000 mg/L) and high sulphate concentration (up to 10,000 mg/L).

Thick (> 25 m) unweathered and unfractured, near-surface tills contain pore water introduced during or shortly after glaciations. Hydrochemical processes within such till units are diffusion-dominated with negligible advection (e.g., Remenda et al., 1996; Shaw and Hendry, 1998; Hendry and

Wassenaar, 2000). These geochemical processes have been active since the Holocene, and were probably also active during interglacial periods between Pleistocene glaciations, as evidenced by buried weathering zones containing gypsum at the top of older till units.

In coal/lignite-bearing formations, such as the Judith River and the Ravenscrag Formations, sulphate reduction can also be an important process. Van Stempvoort et al. (2005) showed that bacterial sulphate reduction may play a role in bio-attenuation of fugitive natural gas in groundwater within the Plains Region. The reduction of nitrate by oxidation of organic matter (denitrification) within aquifers can also be important (e.g., Trudell et al., 1986).

Groundwater recharges through Laurentide till imparts SO_4-rich water chemistry to underlying bedrock aquifers (e.g., the Milk River Aquifer; Hendry and Schwartz, 1990). Similarly, the abrupt east-to-west transition from high- to low-sulphate groundwater in the Paskapoo Aquifer is coincident with the boundary of the overlying till, between igneous/metamorphic-dominated till derived from the east and the carbonate-dominated till derived from the Cordillera to the west (Grasby et al., 2010). This suggests that recharge through till plays a dominant role in setting the initial geochemical conditions of underlying bedrock aquifers.

10.4.2 Trace element concentrations

Locally, groundwater in the Plains contains naturally occurring concentrations of trace elements that exceed drinking water guidelines. Of particular concern are arsenic, boron, barium, fluoride, selenium and uranium because exceedances of these elements are more widely distributed than other trace elements. The following discussion is based primarily on recent compilations carried out in Manitoba (Betcher et al., 2003, and subsequent unpublished updates) and Saskatchewan (Maathuis, 2008). No similar regional presentations are known for Alberta.

Arsenic concentrations in excess of the current drinking water guideline (0.01 mg/L) are widely reported across both Saskatchewan and Manitoba. In Manitoba, elevated arsenic concentrations are commonly found in groundwater from confined inter- or intra-till sand/gravel aquifers where the confining tills developed from glacial movement over Cretaceous shale. Erickson (2005) reported a similar relationship between elevated arsenic concentrations in groundwater and the footprint of "Northwest Provenance" tills in the upper Midwest of the United States. Northwest Provenance tills are considered to have the Riding Mountain and Winnipeg areas as their provenance and have been found to contain "significant fractions of both carbonate and shale, and a large fraction of fine-grained material" coupled with organics entrained from periglacial forests.

In the Winkler aquifer, a sand and gravel body deposited along the eastern flank of the Manitoba Escarpment and overlain by lacustrine clay for most of its extent, elevated arsenic is found in groundwater from many municipal and private wells. Recent sampling has also identified elevated arsenic in the deeper (anoxic) groundwater of some unconfined sand aquifers in south-central and southwestern Manitoba. Arsenic speciation analysis has not been done. Arsenic concentrations greater than 0.01 mg/L are rarely found in samples from bedrock aquifers within the province. A number of municipalities have recently installed treatment facilities in order to facilitate arsenic removal to concentrations below the drinking water guideline.

In Saskatchewan, Maathuis (2008) has examined arsenic results reported from more than 4,300 wells. The average arsenic concentration was approximately 0.006 mg/L, with arsenic concentrations exceeding the current Canadian guideline of 0.010 mg/L in 14.9% of the samples. No correlation was reported between arsenic concentration and either well depth or aquifer type.

Boron is rarely found at concentrations above the current drinking water guideline (5 mg/L) in Manitoba, but elevated groundwater concentrations (>2.5 mg/L) are found in in parts of the Winnipeg and Swan River sandstones and in groundwater from some wells completed into the Odanah Shale aquifer. Higher boron concentrations are generally found in groundwater with elevated salinity. Boron concentrations also exceed 5 mg/L in groundwater from a number of wells in the Gypsumville area (Desbarats, 2009). The geology of this area is very unusual, with uplifted Precambrian basement, gypsum and red beds resulting from a meteorite impact (McCabe and Bannatyne, 1970) and from subsequent Jurassic deposition.

Maathuis (2008) reports an average boron concentration in groundwater samples from Saskatchewan to be 0.41 mg/L, with very few samples containing more than 5 mg/L.

Elevated barium concentrations are found in two distinct areas of Manitoba. In the southeastern part of the province, elevated barium concentrations are found in groundwater from the Winnipeg Aquifer along a distinct NW-SE trend about 15 km wide and running for about 30 km northwest of the subcrop area (Underwood et al., 2009). To the south of this zone, anomalously high barium concentrations are found in groundwater from wells installed in the Carbonate aquifer or wells installed as open hole-type across both the Carbonate and the Winnipeg Aquifers. Barium concentrations in excess of 10 mg/L have been found in these areas (the current Canadian drinking water guideline for barium is 1 mg/L). Barium solubility may be elevated as a result of very low sulphate concentrations in recharge waters or due to bacterial sulphate reduction (Underwood et al., 2009). Barium has also been found to exceed the drinking water guideline in some wells installed in the unconfined Assiniboine Delta Aquifer. Sulphate concentrations are typically very low in this aquifer, but localized zones of detrital coal within the aquifer matrix may also cause the development of both strongly reducing conditions, and further declines in sulphate concentrations.

In Saskatchewan, about 0.5% of the wells produce water with a barium concentration in excess of 1 mg/L with a maximum reported value of 1.9 mg/L. No relationship has been reported between barium concentration and aquifer type or geochemical controls that may result in lower sulphate concentrations.

Fluoride concentrations have been found to exceed the drinking water guideline value of 1.5 mg/L in groundwater from a number of bedrock aquifers in Manitoba, particularly the Winnipeg Aquifer in southeastern Manitoba and along the western shore of Lake Winnipeg, and the Swan River Aquifer near Porcupine Mountain. Elevated fluoride concentrations are associated with cation exchange reactions near fresh water–saline water boundaries or with mixed fresh and saline groundwater as found in the Interlake. Fluoride concentrations are also above drinking water guidelines in some wells within the Carbonate aquifer, particularly near the fresh water–saline water boundary on the eastern side of the south basin of Lake

Manitoba and to the west of Lake Winnipeg, and near Dauphin, where water quality in the aquifer is brackish. Fluoride concentrations exceeding 15 mg/L have been found locally in groundwater from granitic rocks of the Lac du Bonnet batholith in southeastern Manitoba (locally, concentrations may exceed 15 mg/L) and from the disturbed bedrock units found in the Gypsumville area, although the reason for this is disputed (Leybourne et al., 2008; Desbarats, 2009).

In Saskatchewan, elevated fluoride concentrations are found in groundwater from the Judith River Aquifer in the southwestern part of the province and also from Bearpaw sands in the Riverhurst area from the Gravelbourg Valley Aquifer. As in Manitoba, elevated fluoride concentrations are found in the Mannville Aquifer in northeastern Saskatchewan.

Uranium concentrations greater than the drinking water guideline of 0.02 mg/L are found locally in southern Manitoba. A study carried out by Betcher et al. (1988) examined the uranium content of groundwater in a portion of southeastern Manitoba east of Beausejour. An average uranium concentration of 115.6 µg/L was found in samples from wells completed into Precambrian rock aquifers (primarily the Lac du Bonnet batholith) with concentrations as high as 2,020 µg/L. Groundwater in a number of sand and gravel aquifers in the area were also found to contain elevated uranium concentrations where leaching of uraniferous water from overlying lacustrine clays was occurring. Uranium concentrations over the drinking water guideline have also been found in groundwater from the Winkler Aquifer (confined sand and gravel), the Odanah shale aquifer and in a few wells completed into the Carbonate aquifer.

Uranium concentrations in Saskatchewan average 0.011 mg/L with about 14.5% of samples containing more than the current Canadian guideline (0.020 mg/L). Maathuis reports that most elevated uranium is found in samples from wells completed to relatively shallow depth (<25 m), but he does not discuss which aquifers these represent.

Although elevated selenium concentrations have been reported in Saskatchewan, limited sampling in Manitoba has not revealed significant issues. In Saskatchewan, concentrations up to 0.58 mg/L have been reported with samples from 7.9% of wells exceeding current Canadian guidelines (0.01 mg/L). As with uranium, the higher selenium concentrations appear to be found primarily in shallow wells.

BOX 10-1 SALINE INTRUSION

Intrusion of saline water into freshwater-bearing aquifers is a common concern along coastal regions. Saltwater intrusion occurs naturally because of the higher density of saline water and it may become a serious issue in coastal regions where there are substantial freshwater withdrawals. Climate change can also introduce increasing intrusion problems because of rising sea levels and potential declines in fresh groundwater head.

Saltwater intrusion may also be a serious issue in aquifers lying far from the ocean where saline groundwater or brines occur within many aquifers adjacent to freshwater zones. An interesting example is found in south-central Manitoba's Winkler Aquifer. This sand and gravel aquifer lies adjacent to the Manitoba Escarpment and is highly confined by overlying lacustrine clays, except at its northern extent where the aquifer outcrops within an area of about 500 hectares. This outcrop area and adjacent regions of thin clay cover form the principle recharge areas for the aquifer. Render (1987) estimated the annual recharge rate to be approximately 416×10^3 m^3/year, although it is interesting to note that this recharge estimate was made at the end of a long period of groundwater decline.

Fresh groundwater is found in the upper part of the northern extent of the aquifer and is underlain by saline water. Test drilling has revealed that the aquifer may locally be in hydraulic connection with sandstones of the Swan River Formation, which, in this area, are occupied by saline groundwater containing total dissolved solids (TDS) of approximately 20,000 mg/L. The fresh water–saline water system is thus in a dynamic equilibrium between the volume of the aquifer occupied by fresh water and intrusion/extrusion of saline water with the Swan River sandstones.

Although the aquifer was developed as a source of freshwater, beginning in the late1800s, there was little intensive pumping, other than a cannery well in the City of Winkler, until the early 1960s, when the city began to develop the aquifer as a source of municipal water supply. Through the 1980s and early 1990s, the City installed 10 production wells, while additional production wells were installed by adjacent municipalities. By the mid-1990s, the estimated rate of fresh groundwater withdrawal was about $1070–1340\times10^3$ m^3/year, perhaps three times the average freshwater recharge rate (Phipps and Betcher, 2007). Groundwater levels in the aquifer were also observed to have declined through the mid-1970s into the early 1990s (Figure 10.29). Monitoring wells in the vicinity of pumping centres began to record increases in the salinity of deeper groundwater within the aquifer (Figure 10.30), raising concerns of salinization to the extent that the water quality would no longer be potable. Responses to this concern have included reducing the pumping rates in some of the higher-capacity wells, cycling of pumping among the various production wells serving the City of Winkler, and reduction or withdrawal of the amount of water allocated by water rights licences issued by the province. Current groundwater withdrawals (2007) are estimated to be less than 800×10^3 m^3/year, which is still about twice the estimated recharge rate to the aquifer.

Since the early 1990s, groundwater levels in the aquifer have risen and stabilized at an elevation near the levels observed during the early 1960s (prior to significant development). The trend of rising water levels is similar to what has been seen in confined aquifers in many other parts of Manitoba and reflects a return to a wetter climate than what

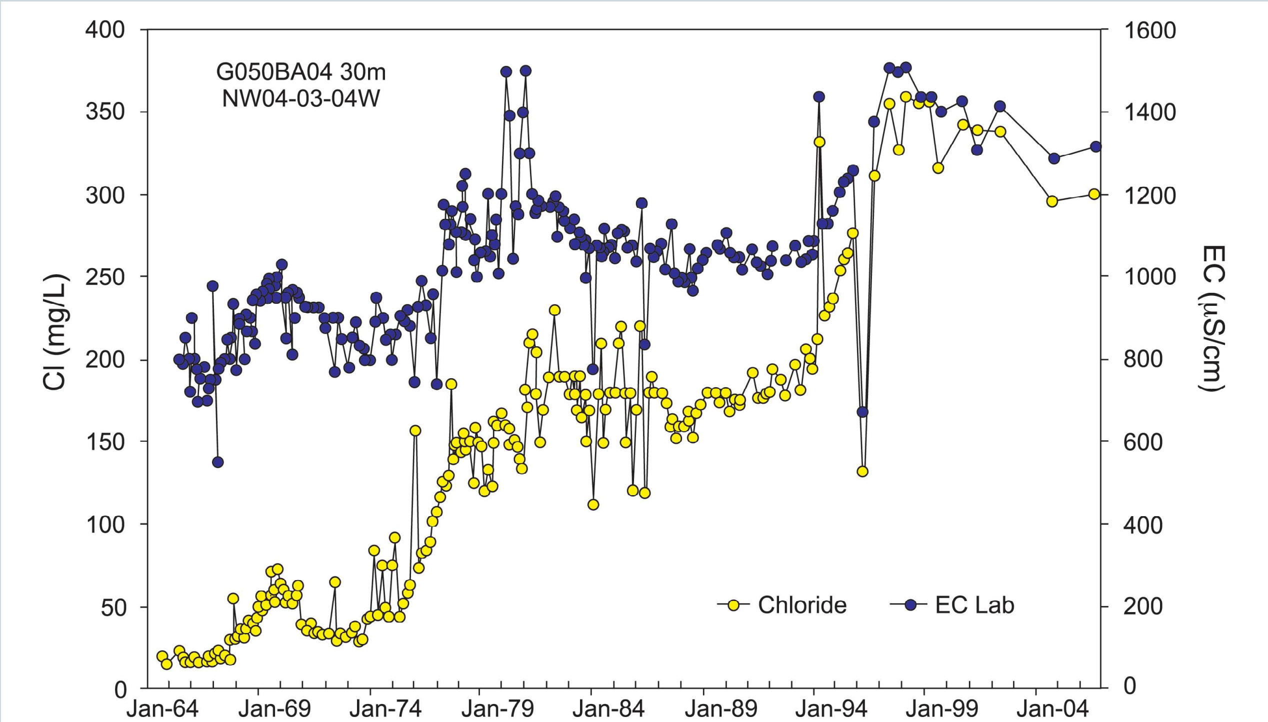


Figure 10.29 Chloride and conductivity for observation well G05OB004, 30 m depth, in the central portion of the Winkler Aquifer.

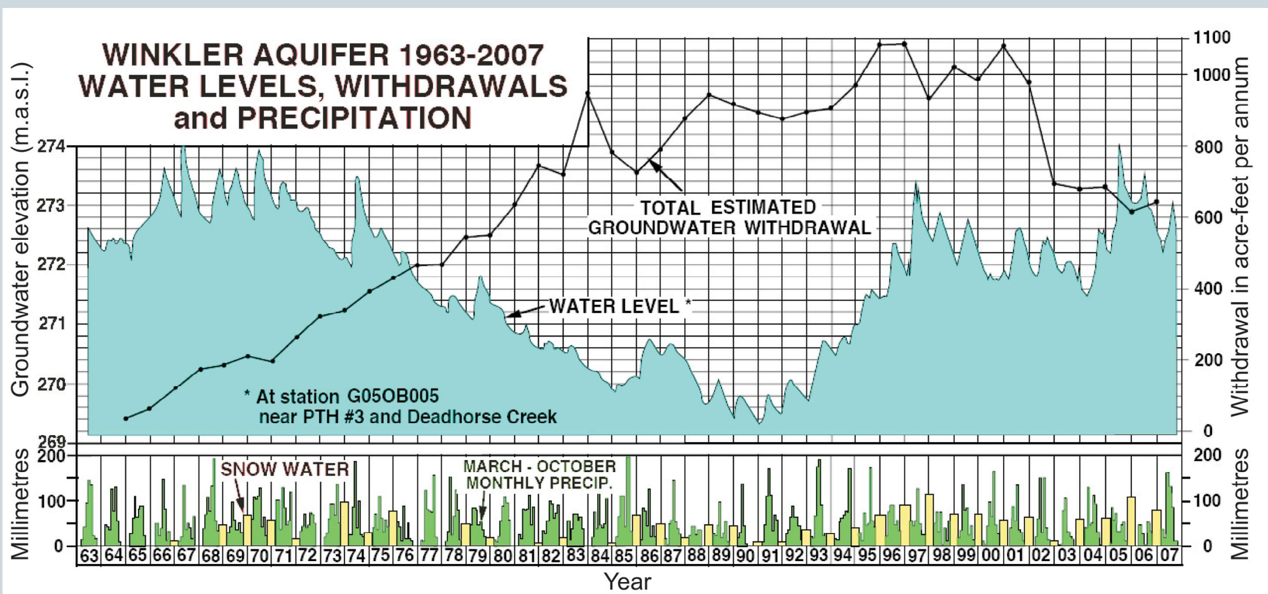


Figure 10.30 Groundwater levels in the Winkler Aquifer for the period 1963 to 2007. Estimates of withdrawal rates from the aquifer and precipitation are also shown.

was experienced during the 1980s. While groundwater withdrawals have been reduced and aquifer levels have risen, the salinity increases observed over the past 35 years have only stabilized, indicating the need for intensive management of the aquifer in order to minimize further salinization.

BOX 10-2 THE ESTEVAN VALLEY AQUIFER SYSTEM—A LONG-TERM CASE STUDY OF THE BEHAVIOUR OF BURIED-VALLEY AQUIFERS

The Estevan Valley Aquifer System is unique in that it has been the subject of groundwater resource evaluations for over four decades. It is a major preglacial buried-valley aquifer in southeastern Saskatchewan (Figure 10.31). The system consists of the preglacial Yellowstone, Missouri and “Northwest” channels. In the vicinity of the City of Weyburn, the Northwest Channel is referred to as the Weyburn Valley channel. The extension of the preglacial Missouri and Yellowstone River valleys into Saskatchewan was speculated on as early as the 1910s (Beekly, 1912; Bauer, 1915). Meneley et al. (1957), using oil, coal and water well information, prepared a bedrock topography map for the Weyburn-Estevan area. This map defined the location of the preglacial Missouri, Yellowstone and Estevan River valleys in southeastern Saskatchewan.

The preglacial valleys were incised into low-permeability bedrock siltstones and sandstones formed by the Eastend to Ravenscrag Formations, and locally into the siltstones and mudstones of the Pierre Shale. They were filled with predominantly coarse-grained sediments of the Empress Group, up to 80 m thick. Over most of its extent, the aquifer consists of a lower and upper unit, separated by a clay and silt layer. It is overlain by a 60 m–80 m thick aquitard composed mainly of clay-rich

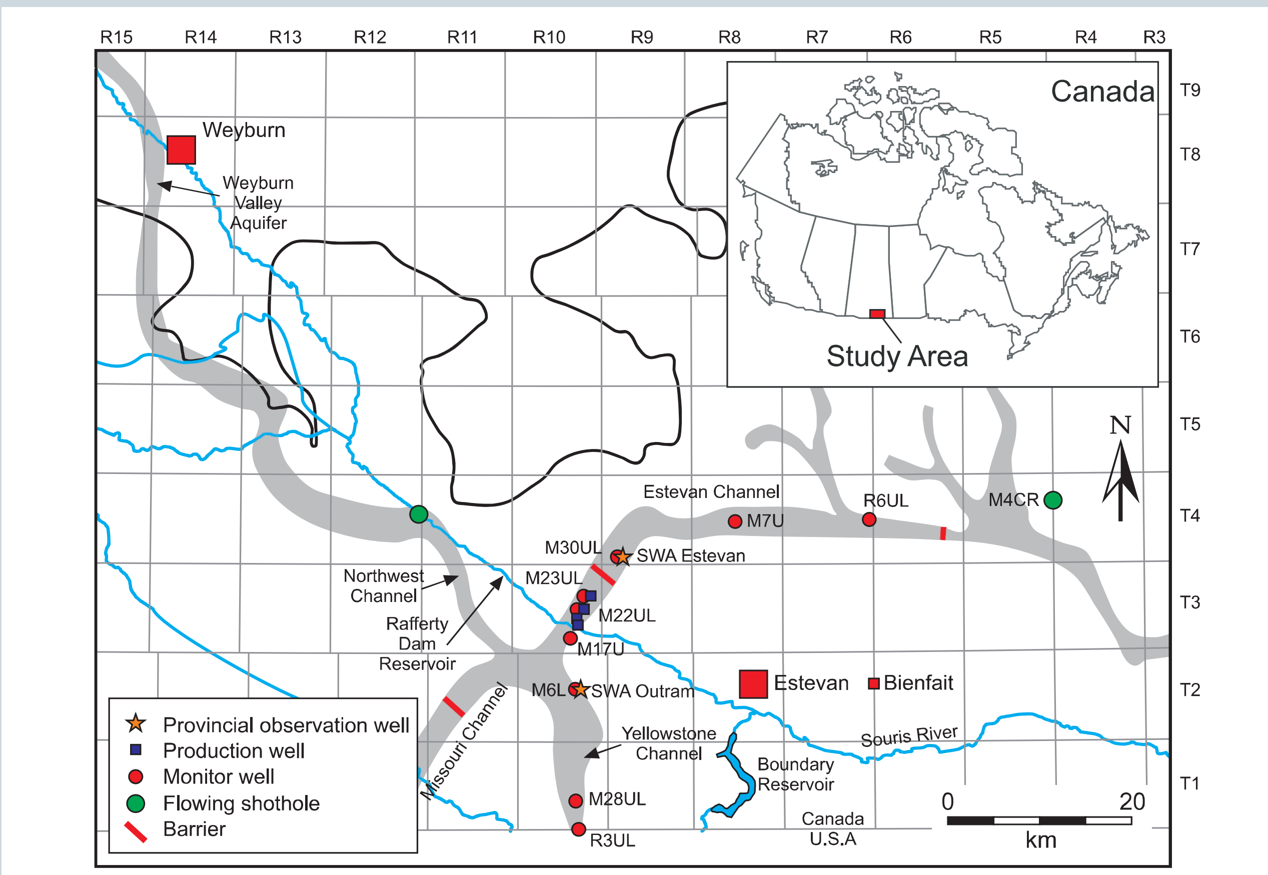


Figure 10.31 The Estevan Valley Aquifer System in southeastern Saskatchewan.

till. Within Saskatchewan, the aquifer is at least 70 km long and up to 4 km wide. It extends well into northwestern North Dakota and northeastern Montana, making it a transboundary aquifer.

The first major study was done in the mid-1960s as part of the search for a groundwater supply source for a proposed heavy water plant in the Estevan area. This study involved the drilling of a production well and observation wells, the conducting of a seven-day pumping test and the construction of an electrical analog model. Walton (1970) documented the study in his book.

The Midale flowing shothole (NE16-24-4-12-W2) was a significant hydrogeological event documented by Meneley and Whitaker (1970). This shothole was drilled into the Estevan Valley Aquifer System on November 20, 1965, and water flowed until May 20, 1966, when the hole was plugged. The drawdown caused by the flow and the subsequent slow recovery affected water levels over large distances and provided the first indication of the peculiar behaviour of water levels in stressed buried-valley aquifers.

In 1959, the Boundary Dam power plant, located about 6.5 km south of the City of Estevan, was commissioned. The cooling water supply for the plant comes from the Boundary Dam reservoir. It became evident during the early 1980s that consumption demands on the Boundary Dam Reservoir were such that only short periods of below-normal water flow could be tolerated. Lacking an alternative source of surface water (water from the Rafferty Dam and other reservoirs was not available at the time), a groundwater source had to be found. A large number of studies, including testhole drilling and pump tests, led to the development of a well field and the establishment of a large network of observation wells. The well field consisting of four production wells installed in the Estevan Valley Aquifer is located in the area between observation wells M22UL and M23UL (see Figure 10.31).

From September 16, 1988, until May 24, 1994, a total of 21,338 dam^3 (1 dam^3 = 1,000 m^3) was pumped, corresponding to an average annual pumping rate of 3,750 dam^3/year (about 118 L/s). Near the end of pumping, the observed drawdowns in the well field were in the 45 m to 50 m range and were very close to the top of the aquifer. If pumping had continued, the water level in the aquifer would have dropped below the top of the aquifer and the pumping rate of 3,750 dam^3/year would have been unsustainable. At the Canada-USA border, 23 km away from the centre of the well field, the drawdown was 20 m.

The development of the drawdown cone is shown in Figure 10.32 in the form of a longitudinal profile through the Yellowstone and Estevan channels (R3UL, M28UL, M17UL, M22UL, M23UL, M30UL, M7U and R6UL; see Figure 10.31 for locations).

Figure 10.32 shows the development of large drawdowns (up to 45 m) in the centre of the well field (M22UL). The development of a large hydraulic gradient between M22/23UL and M30UL, because of the presence of a blockage, can be observed, as well as the development of a strong lateral gradient in the Yellowstone channel from the border to the centre of the well field. A systematic and virtually equal amount of additional drawdown along the entire length of the aquifer during the May 1990–September 1992 period occurred, followed by a partial recovery of water levels in the centre of the well field in October 1993, owing to a decreasing pumping rate, coupled with a continuation of drawdowns at distances further from the pumping centre.

The recovery of water levels, depicted in Figure

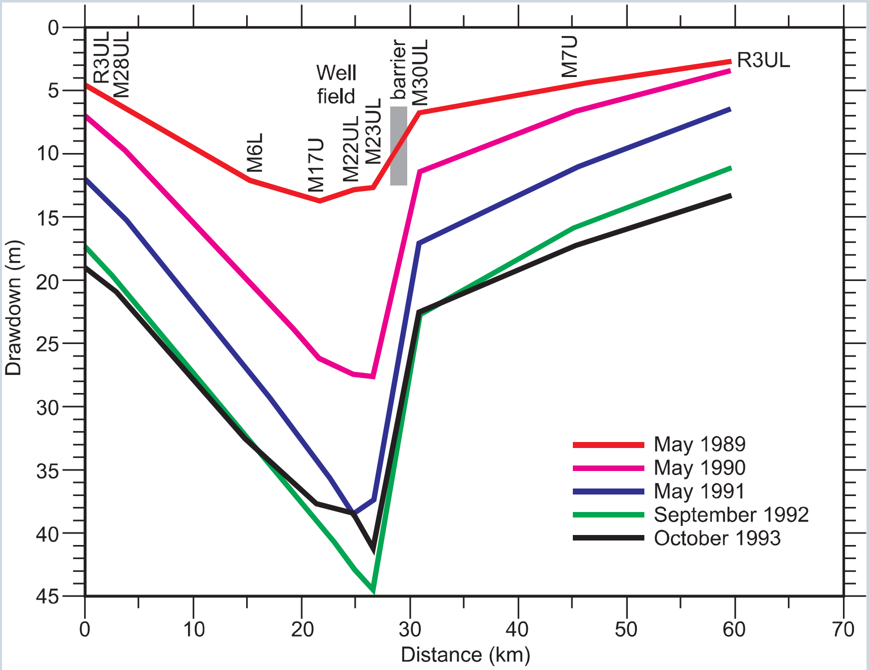


Figure 10.32 Development of the drawdown cone in the Estevan Valley Aquifer.

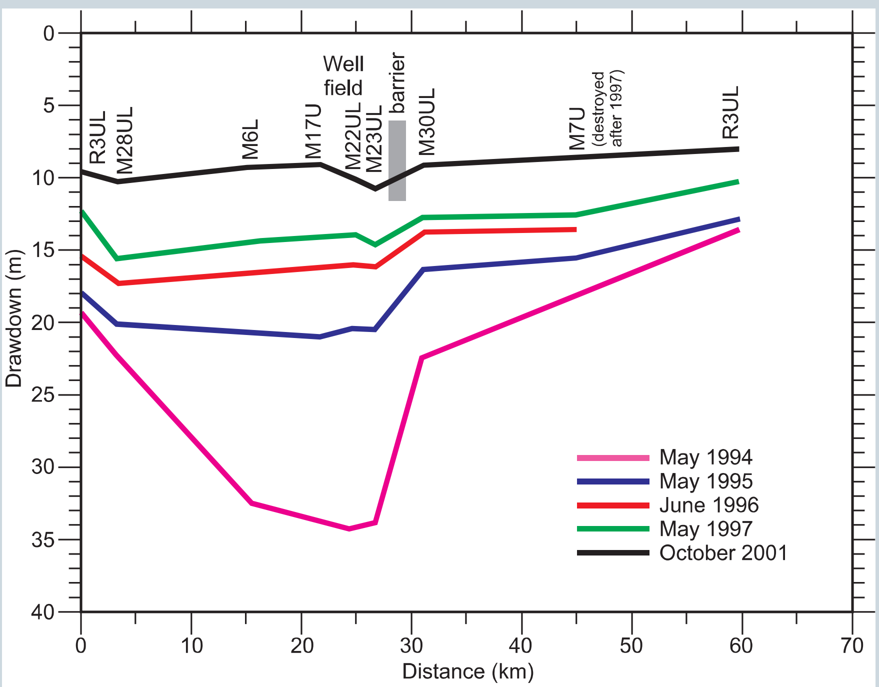


Figure 10.33 Residual drawdowns in the Estevan Valley Aquifer after pumping stopped.

10.33 as residual drawdowns, shows a rapid infilling of the drawdown cone in the well field during the first few years after pumping ceased: this was caused by lateral flow toward the centre. Subsequently, there was a general flattening-out of the water levels with similar amounts of residual drawdowns throughout the entire aquifer.

In 2007, 13 years after pumping stopped, the residual drawdown in the aquifer is still in the 6 m–8 m range, as illustrated in Figure 10.34 (which shows the long-term hydrographs for provincial observation wells SWA Estevan and Outram).

The slow recovery of the water levels merely indicates that recharge to the Estevan Valley Aquifer is small, only a few millimetres per year. As the rate of recovery decreases over time, complete recovery cannot be expected to occur for some considerable time to come.

Over the decades, various estimates have been made of the safe or sustainable yield of these aquifers (Maathuis and van der Kamp, 2003). These estimates were based on the results of an analog model (Walton, 1965, 1970), on image well theory (Meneley 1972; Puodziunas, 1977), on numerical modelling (van der Kamp, 1985) and on analyses of actual performance (Van Stempvoort and Simpson, 1994; Maathuis and van der Kamp, 1989 and 1998). Sustainable yield estimates ranged from 20,000 dam^3/year during the 1970s to 2,400–2,800 dam^3/year in 1998. The estimates decreased as more actual performance data became available.

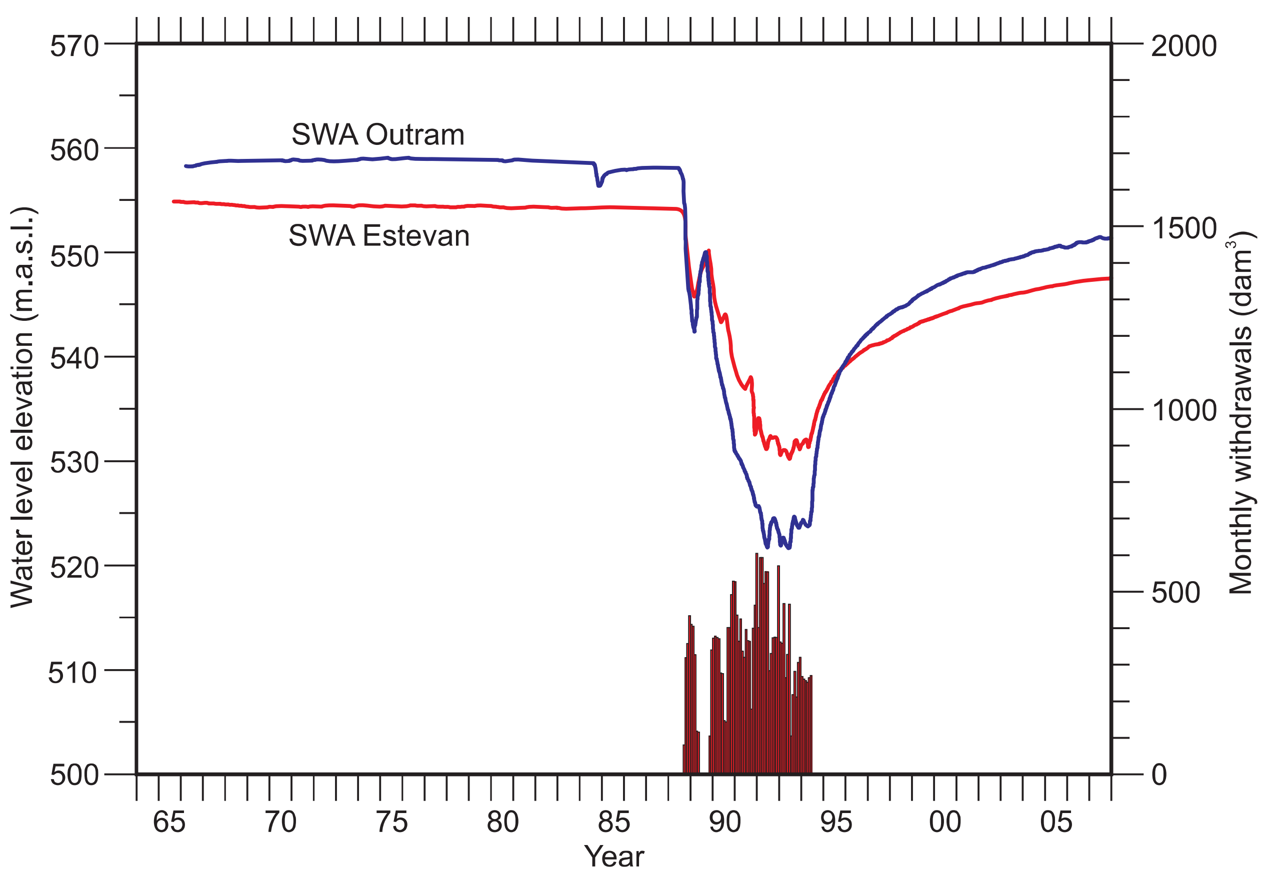


Figure 10.34 Hydrographs for SWA Estevan and Outram observation wells and pumping history from the Estevan Valley Aquifer.

The lessons learned from the Estevan Valley Aquifer case show that buried-valley aquifers have limited safe yields and can only be pumped at high rates for short periods of time. Furthermore, drawdown will extend over tens of kilometres and recovery will take a very long time (up to decades). This case has also demonstrated that realistic sustainable yields can only be determined when long-term water level and pumping records are available, a fact which applies to all types of aquifers.

CANADA'S GROUNDWATER RESOURCES

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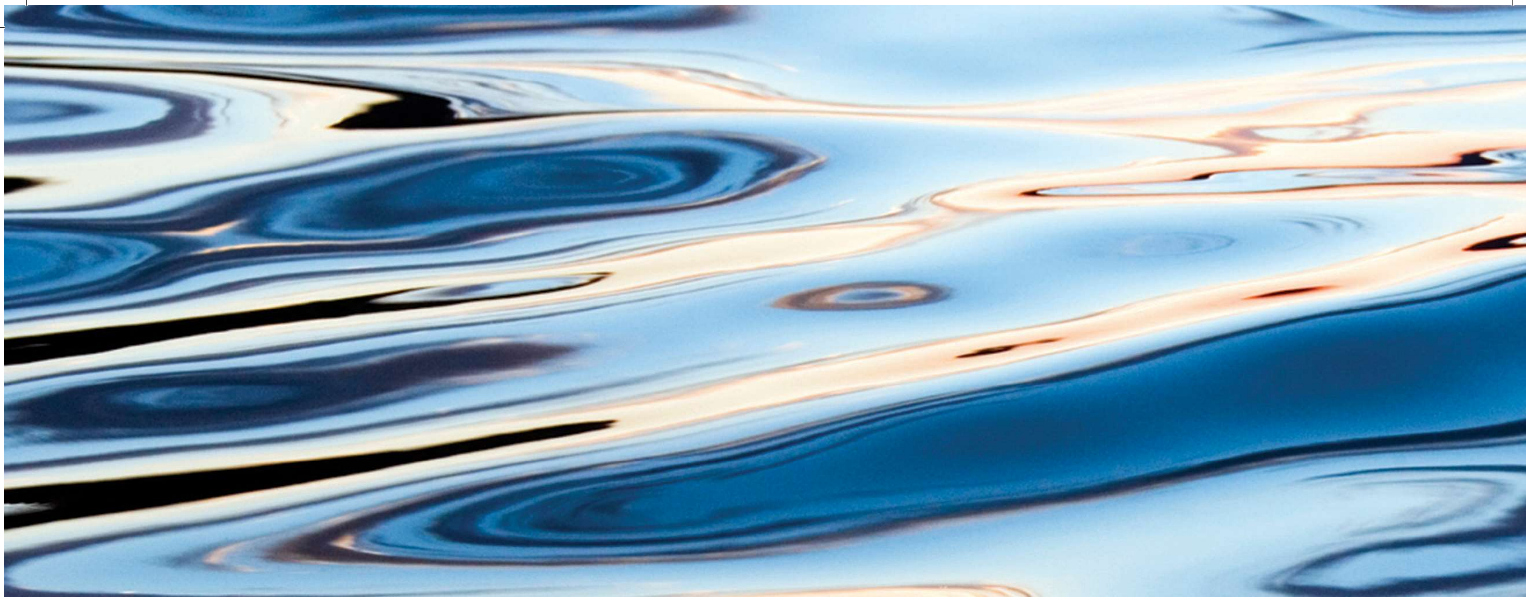

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