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Groundwater atlas of the Milk River transboundary aquifer, Alberta, Canada and Montana, U.S.A.

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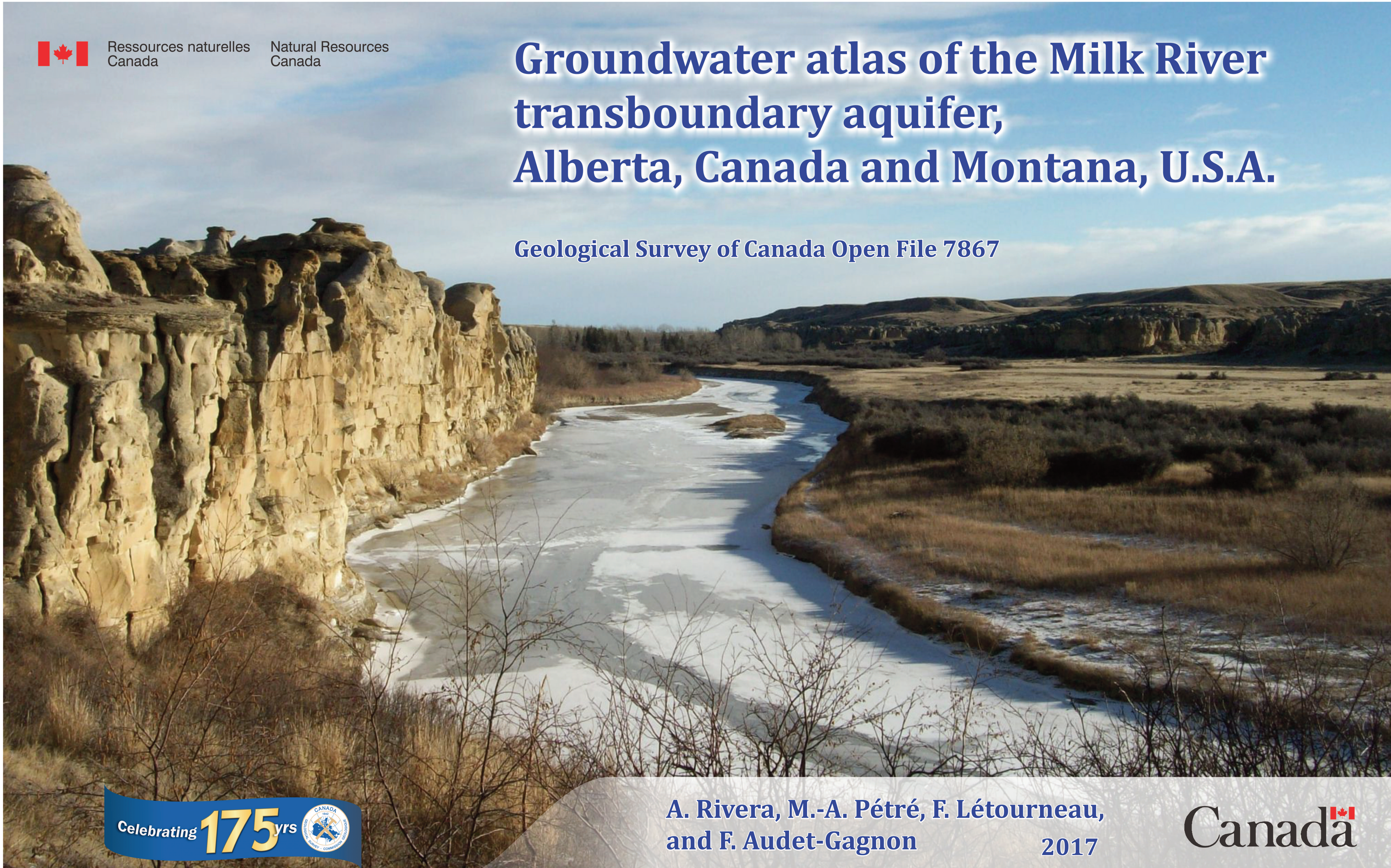

A. Rivera, M.-A. Pétré, F. Létourneau, and F. Audet-Gagnon

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Groundwater atlas of the Milk River transboundary aquifer, Alberta, Canada and Montana, U.S.A.

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Groundwater atlas of the Milk River Transboundary Aquifer, Alberta, Canada and Montana, U.S.A.

Project's Partners and Stakeholders

Natural Resources Canada, Geological Survey of Canada, Quebec Division (GSC-Q)
Milk River Watershed Council Canada (MRWCC)
Institut national de la recherche scientifique - Centre Eau Terre Environnement (INRS-ETE)
École Nationale des Mines de Paris, France
United States Geological Survey (USGS), Wyoming-Montana Water Science Center
Alberta Geological Survey (AGS), Alberta Energy Regulator (AER)
Alberta Environment and Parks
Montana Bureau of Mines and Geology (MBMG)
Department of Natural Resources and Conservation, Montana (DNRC)

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MRWCC: Sandi Riemersma and Tim Romanow
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Foreword

This atlas illustrates the characteristics of groundwater and aquifers in southern Alberta, Canada, and northern Montana, U.S.A. The atlas is a result of a research project carried out over the period of 2009 to 2015 within the framework of the Geological Survey of Canada's Groundwater Geoscience Program, in collaboration with the United States Geological Survey (USGS) Wyoming-Montana Water Science Center, Alberta Geological Survey, Alberta Environment and Sustainable Resource Development, Montana Bureau of Mines and Geology, Department of Natural Resources and Conservation, Montana, Milk River Watershed Council Canada, and the Institut national de la recherche scientifique - Centre Eau Terre Environnement (INRS-ETE). The core work of this project was conducted through a Ph.D. thesis program in partnership between the GSC-Quebec Division (GSC-Q), INRS-ETE and École des Mines de Paris (Mines ParisTech), France, by Marie-Amélie Pétré.

The delineation of the study area follows the natural hydrogeological boundaries of the Milk River Aquifer, which are thus continuous across the international border. The resulting products presented in this atlas are innovative because they integrate numerous previous works of researchers on both sides of the international border that have been carried out since the early 1900s, as well as new hydrogeological and geochemical data recently collected in the field. The atlas synthesizes and unifies those works to provide a transboundary portrayal of the Milk River Aquifer.

This atlas includes 43 maps, many of which were newly compiled, as well as significantly updated figures with new data acquired during this project. These include hydrogeological and geochemistry maps. The Groundwater Atlas of the Milk River Transboundary Aquifer is both a snapshot in time and an indicator of the progress made in understanding the groundwater dynamics of the aquifer including its transboundary nature.

This atlas is an important contribution to the understanding of a precious hidden water resource that can constitute an educational tool for citizens and a reference tool for water managers in southern Alberta and northern Montana.

Alfonso Rivera
Chief Hydrogeologist
Geological Survey of Canada

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Financial support for this project was provided by Natural Resources Canada through its Groundwater Geoscience Program. In addition, in-kind support was provided by the Alberta Geological Survey (Alberta Energy Regulator), Alberta Environment and Parks, the USGS, the Montana Department of Natural Resources and Conservation (DNRC), the Montana Bureau of Mines and Geology, and the Institut national de la recherche scientifique - Centre Eau Terre Environnement (INRS-ETE), Quebec, Canada.

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We would like to acknowledge the field and logistical support to this project provided by Sandi Riemersma, Mary Lupwayi and Tim Romanow (Milk River Watershed Council Canada), Clarisse Deschêne-Rancourt (INRS-ETE), Daryl Jacques (PFRA Agri-Food Canada), Jill Frankforter and Kyle Blasch (USGS, Helena). We would also like to acknowledge the collaboration of landowners who provided access to their properties during the three field campaigns.

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1 Introduction

1 Introduction

1.1 Milk River Transboundary Aquifer Project (MiRTAP)

This groundwater atlas is an important component of the Milk River Transboundary Aquifer Project (MiRTAP) initiated by the Geological Survey of Canada in 2009 (Rivera, 2011).

The Milk River Transboundary Aquifer straddles southern Alberta (Canada) and northern Montana (United States) in a semi-arid region with well-documented water shortages (Government of Alberta 2006; Figure 1.1). The Milk River Aquifer is a confined sandstone aquifer that is a source for municipal water supply and agricultural uses on the Canadian side. It is also used to enhance secondary oil recovery on the U.S.A. side and for domestic purposes.

The extensive use of this resource since the mid 1950's has led to a dramatic drop in the water level in some places and concerns about the sustainability of the resource have arisen. The Milk River Aquifer was the focus of many studies during the 20th century. However, no studies integrated both sides of the Canada/U.S.A. border, thus limiting the ability to develop a sound understanding of the overall aquifer dynamics.

In 2010, the Milk River Aquifer (MRA) was listed as "Transboundary Aquifer System TAS#20N" in the inventory of UNESCO ISARM-Americas initiative (Rivera, ed., 2015). This initiative encourages riparian states to work cooperatively towards mutually beneficial and sustainable aquifer development. In this context, stakeholders from the two countries (municipal, provincial, state, federal) have worked cooperatively with the GSC (MRWCC, 2010).

The transboundary extent of the aquifer has been defined and an integrated stratigraphic study has been carried out in order to correlate differently named, but chrono-stratigraphically and depositional equivalent formations and members on both sides of the international border. The transboundary integration and development of a unified stratigraphic model (Pétré et al., 2015) allow for a better understanding of the aquifer. This model has been used to generate a conceptual hydrogeological model in support of the development of a three-dimensional numerical hydrogeological model (Pétré et al., 2016).

The main objective of MiRTAP was to better understand the dynamics of the Milk River Aquifer, following its natural limits, in order to make recommendations for sustainable management and good governance by the two international jurisdictions, as recommended in the UNGA Resolutions on the Law of Transboundary Aquifers: 63/124 (December, 2008), 66/104 (December, 2011), and 68/118 (December, 2013). <http://www.un.org/ga/63/resolutions.shtml>.

1.2 Why an atlas? – Objectives

In view of both existing and acquired information on this aquifer, including its physical and chemical hydrogeological data, it was decided to produce an integrated and visual document, in the form of an atlas, to pay tribute and to support the transfer of knowledge to the regional, national and international participants with stakes in this aquifer.

The atlas provides an overview of the knowledge of the aquifer, as of 2015, depicting an area of approximately 25 000 km^2 based on the natural physical boundaries rather than the political jurisdictional boundaries.

Such an atlas may:

- Disseminate the main integrated information on the region with simplified graphics and colourful maps;
- Become a powerful pedagogic tool to underline the importance of the groundwater resources contained in the aquifer;
- Support informed decision-making processes to avoid potential conflicts in the shared management of this transboundary aquifer; and
- Present groundwater information in an easy-to-understand manner to allow integrated planning of land-use management and groundwater protection.

1.3 Previous hydrogeological studies

Stratigraphy and geology

The transboundary nature of the Milk River Aquifer (MRA), and the fact that geological mapping agencies focus on their respective provincial, state or national mandates, has resulted in different terminology in the political jurisdictions and even within different geological domains, as is the case in Montana. Consequently, geological units do not have the same name on both sides of the border. As the characterization of the Upper Cretaceous Milk River Formation (or Eagle Formation in Montana) progressed during the 20th century, the stratigraphic nomenclature evolved significantly (Pétré et al., 2015).

The Milk River Formation, extending from southern Alberta to northern Montana, has been the object of numerous studies performed from the early 1900s; the sequence and description of these studies are synthesized in Pétré et al., (2015). The stratigraphic correlation of the Milk River aquifer and associated strata includes works from, but not limited to, Weed (1899); Stanton et al. (1905); Dowling (1915, 1917); Stebinger (1917a); Williams and Dyer (1930); Evans, (1931); Russell and Landes (1940); Tovell (1956); Meyboom (1960); Russell (1970); Rice and Cobban (1977); Rice (1980); Meijer-Drees and Mhyr (1981); Tuck (1993); Payenberg 2002a, and Payenberg et al., (2002; 2003).

Hydrogeology

The most important elements of the hydrogeology of the Milk River Transboundary Aquifer are synthesized in Pétré and Rivera (2015). They include the groundwater levels and hydrogeological parameters of the aquifer, analyses of hydrographs from observation wells, surface water–groundwater interactions, and the presence of gas.

A summary of previous hydrogeological studies is also presented in Pétré and Rivera (2015). The piezometric surfaces and direction of groundwater movement of the Milk River Transboundary Aquifer integrate works from Meyboom (1960), Borneuf (1974), Toth and Corbet (1986) and AGRA (1998) on the Alberta side of the aquifer; and Levings (1982), Zimmerman (1967), and Tuck (1993) on the Montana side of the aquifer. However, none of these works studied the transboundary nature of the piezometry and groundwater flows.

When groundwater exploitation in the region started in 1916, nearly all the wells drilled in the MRA were artesian (flowing). The distribution of flowing wells has been mapped incrementally over time providing a piecemeal understanding of the extent and evolution of artesian conditions with time. Dowling (1917b) mapped the artesian areas of the Milk River sandstone in southern Alberta. Other works on artesian wells include Meyboom (1960), Persram (1992), Tuck (1993), AGRA (1998) and AITF (2010).

Hydrogeological parameters, essentially transmissivity, have been studied by Meyboom (1960), Persram (1992) and AGRA (1998) in Alberta, and by Tuck (1993) and Zimmerman (1967) in Montana. Only a few observation wells in the Milk River Aquifer exist on both sides of the international border. GOWN (Groundwater Observation Well Network) is the most complete network and database on observation wells in Alberta; while the GWIC network (Ground Water Information Center) is the main reference in Montana.

The surface water-groundwater (SW-GW) interactions in the area of the Milk River transboundary aquifer have been the object of some studies but clear conclusions are yet to emerge. The Milk River streamflow is not sustained through the year by natural flow. Since 1917, the St. Mary River streamflow is diverted into the Milk River basin through the St. Mary Canal from March to September. Based on inspections of the riverbank geology and measurements of streamflow and specific conductance, Thompson (1986) suggested that there is no major interaction between the regional Milk River Aquifer and streamflow. There is a seasonal recharge–discharge of water between the surficial unconfined aquifer and the Milk River during spring and summer when runoff occurs and the St. Mary Canal adds flow. But once the flow from the canal is stopped in late summer and early fall, water is discharged from the surficial aquifer (Thompson, 1986). Other efforts to establish a clear link of SW-GW interactions include Meyboom (1960) and, most recently, MacCulloch and Wagner-Watchel (2010, 2011). The results of current research, which are the basis of this atlas, have provided new insight on SW-GW interactions in the area of the Milk River Transboundary Aquifer with a unified conceptual model. It has been estimated that a segment of the Milk River located parallel to the international border intercepts a large proportion of groundwater flowing to the north from the recharge area in the MRA. Pétré et al. (2016) estimated that 96% of the incoming groundwater flux is intercepted by the Milk River and its tributaries after it crosses the international border.

Several gas fields are present within the study area and some studies have tried to establish the effects of gas on groundwater, and vice versa. These include Rice and Claypool (1981); Gautier and Rice (1982); Swanick (1982); Berkenpas (1991); Andrews et al. (1991a); Lies and Letourneau (1995); Payenberg et al. (2003); Anna (2011); and O'Connell (2014).

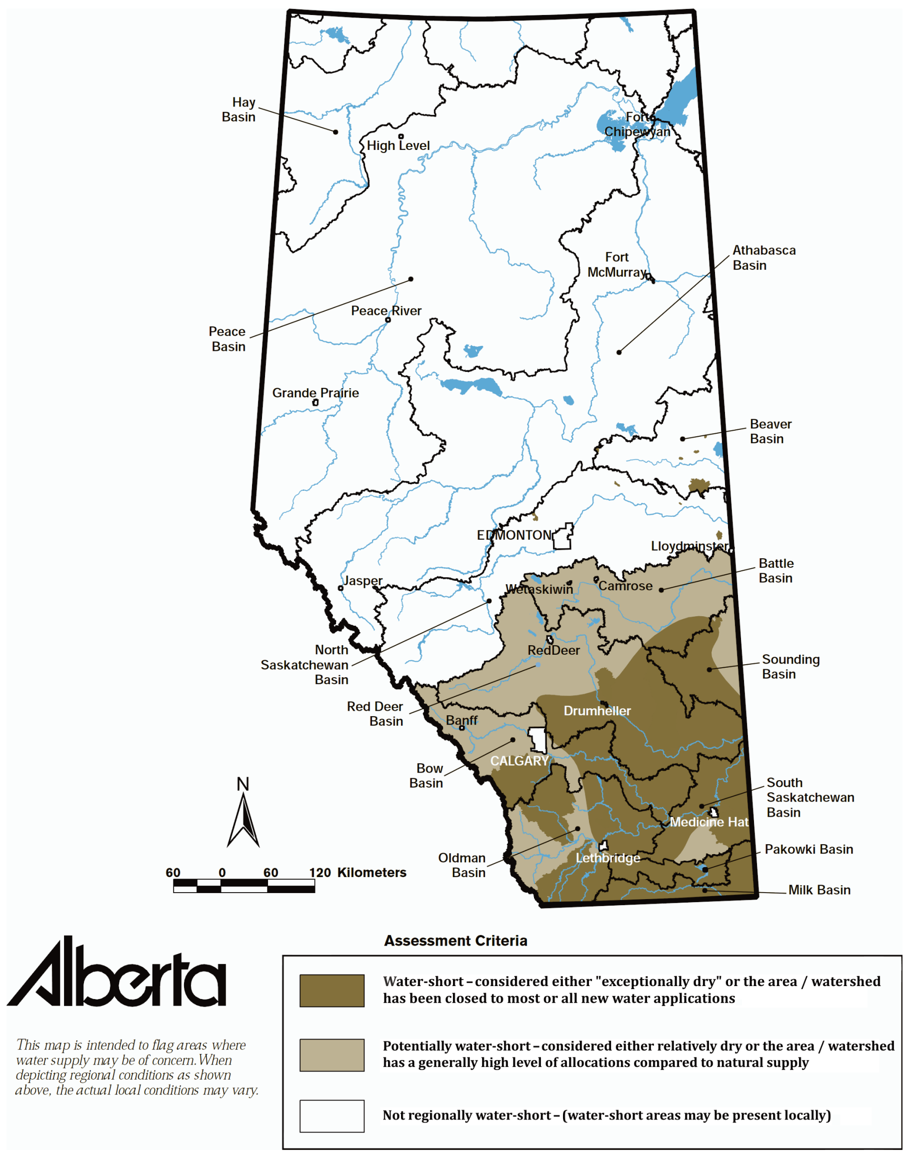

Figure 1.1 Map of the province of Alberta, Canada, showing different zones associated with their water shortages (Government of Alberta, 2006)

Geochemistry

There has been a multitude of studies focusing on groundwater chemistry in the Milk River Aquifer over the last 50 years. The most important elements of the geochemistry of the Milk River Transboundary Aquifer are synthesized in Pétré and Rivera (2015). They are: total dissolved solids (TDS), major and minor ions, groundwater types, the chemical evolution and isotopic patterns, as well as isotopic analyses and water dating.

Early studies focused on the chemical composition of the Milk River Aquifer, and the origin and age of groundwater in the aquifer. The chemical composition of the MRA in southern Alberta was first studied by Meyboom (1960), Borneuf (1976), Schwartz and Muelenbachs (1979) and Swanick (1982). In northern Montana, chemical analyses of groundwater from the Virgelle Sandstone are provided by Tuck (1993) in the Sweet Grass Hills area, and Zimmerman (1967) in the Cut Bank area. More recently, particularly in the late 1980s and early 1990s, studies focused on the origin of chemical and isotopic patterns of groundwater in the MRA (Hendry and Schwartz, 1988, 1990; Phillips et al., 1990). Other notable isotopic studies in the MRA include Nolte et al. (1990, 1991), Andrews et al. (1991b), Drimmie et al. (1991), Fabryka-Martin et al. (1991), Frölich et al. (1991), Lehmann et al. (1991), and Armstrong et al. (1998). Various aspects of this body of work are highlighted in Pétré and Rivera (2015).

Chapter 7 of this atlas presents the most important characteristics of the groundwater quality of the Milk River Aquifer, including new results obtained through the groundwater sampling performed under the MiRTAP project.

1.4 Groundwater in the hydrologic cycle: the World, Canada, Alberta and Montana

The water cycle (schematically represented in Figure 1.2 in the form of pools and fluxes) is driven by thermal energy provided by the Sun. Water evaporates from the surface of the oceans and continents and is transported through the atmosphere, where it remains no longer than eight days before it precipitates as rain on continents and oceans. The world's water resources include all the fresh and brackish water in the atmosphere, streams, lakes, estuaries, the unsaturated zone, and groundwater. Groundwater is a vital and essential part of the hydrologic cycle; it is widely recognized as a critical and vulnerable resource. Groundwater is water that infiltrates the ground, filling the voids, pores, cracks, and fractures of soils and rocks. Much of the precipitation that falls on the ground's surface is redirected back into the atmosphere as direct evaporation, or as transpiration from vegetation. The sum of both fluxes is called evapotranspiration and represents by far the most important flux of the cycle, some 63% of annual precipitation on average.

Once on the ground, precipitation fluxes are redistributed. During the summer, ground infiltration helps form the near-surface stock of water needed for evaporation and transpiration. In cooler seasons, however, water infiltrates deeper into the ground, recharging the groundwater contained in soils and rocks. This deeper infiltration represents, on average, 13% of annual precipitation.

Runoff, representing on average 24% of precipitation, is another important flux of the hydrologic cycle. Runoff occurs immediately after soil saturation, when the soil can no longer absorb more water. Runoff has high variability, depending on the type of soil and rain intensity. A large part of groundwater also discharges in rivers forming what is known as river "baseflow," i.e., natural flow in the absence of rain (these occurrences explain the differences between ocean fluxes and land fluxes in Figure 1.2).

The sum of evapotranspiration, approximately 496 000 km^3/a from oceans and land, equals the sum of precipitation at the global scale (Figure 1.2). Rainfall, on average, exceeds evaporation on the Earth's continents, whereas evaporation exceeds rainfall on the Earth's oceans. This difference is 40 000 km^3/a at the global scale. The equilibrium of the Earth's water cycle means that every year continents send 40 000 km^3 of water to the oceans (World Resources Institute [WRI], 1990).

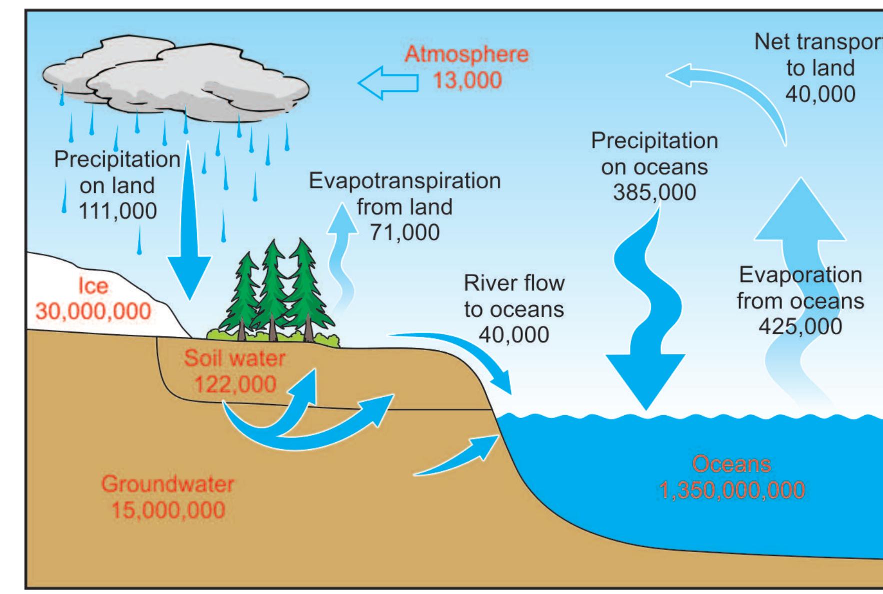

Figure 1.2 Global pools and fluxes of water on Earth, showing the magnitude of groundwater storage relative to other major water storage and fluxes. Pools (in red text) are in cubic kilometres; fluxes are in cubic kilometres per year (reproduced from Rivera, 2014).

How does Canada fit into the global water-balance picture? Figure 1.3 summarizes Canada's pools and water fluxes. 5 500 km^3 of precipitation (P) falls on Canada every year, mainly in the form of rain and snow. Evapotranspiration (ET) accounts for 40% of P with 2 200 km^3. River flow (RF), fed by runoff and groundwater (baseflow), accounts for 53% of P with 2 915 km^3 (WRI, 1990). The contribution of runoff to streamflow varies seasonally, mainly depending on precipitation, snowmelt, and in some locations, the summer melting of glaciers. Lastly, groundwater recharge (I) accounts for 7% of P with 385 km^3 (estimated from the sum of all baseflow of the rivers in Canada for which data exist; WRI, 2007).

The pools in Figure 1.3, ice and groundwater, are much larger than the yearly precipitation and all river flow combined. However, the ice pool cannot be used directly, although it does serve to maintain river flow and to recharge aquifers in some locations (e.g., the foothills of Alberta).

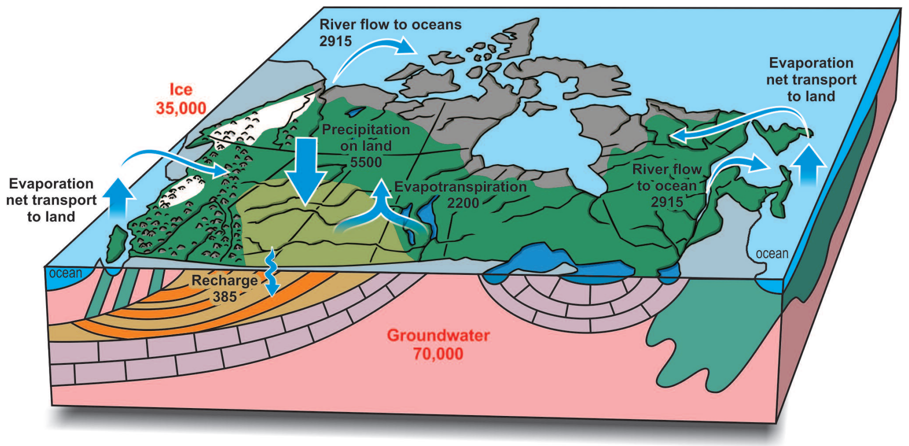

Figure 1.3 Pools and fluxes of water in Canada. Pools (in red text) are in cubic kilometres; fluxes are in cubic kilometres per year (reproduced from Rivera, ed., 2014).

Province of Alberta

In the Province of Alberta, there are five main major river drainage basins as shown in Figure 1.4. The components of the water balance in Alberta have been estimated (AGS, 2008) as:

- Average precipitation = 400–500 mm/a;
- Recharge = 3% to 15% of annual precipitation;
- Total annual outflow of rivers (1×10^{11} m^3 measured at gauging stations throughout the Province); and
- Baseflow in rivers estimated to be 5% to 30% of annual stream discharge.

The components of groundwater balance of five of the major drainage basins in Alberta are given in Table 1.1.

Table 1.1 Components of groundwater balance of five of the major drainage basins in Alberta (AGS, 2008).

River Basin	Annual Precipitation P (mm)	Recharge Rate (% of P)	Recharge (m^3)	Outflow (m^3)	Baseflow ratio (%) (recharge/outflow)
South Saskatchewan	400	5	2.4×10^9	9.30×10^9	26
North Saskatchewan	450	5	1.8×10^9	7.00×10^9	26
Beaver	450	3	0.2×10^9	7.00×10^9	30
Athabasca	500	4	2.7×10^9	20.9×10^9	13
Peace	500	5	7.3×10^9	68.2×10^9	11

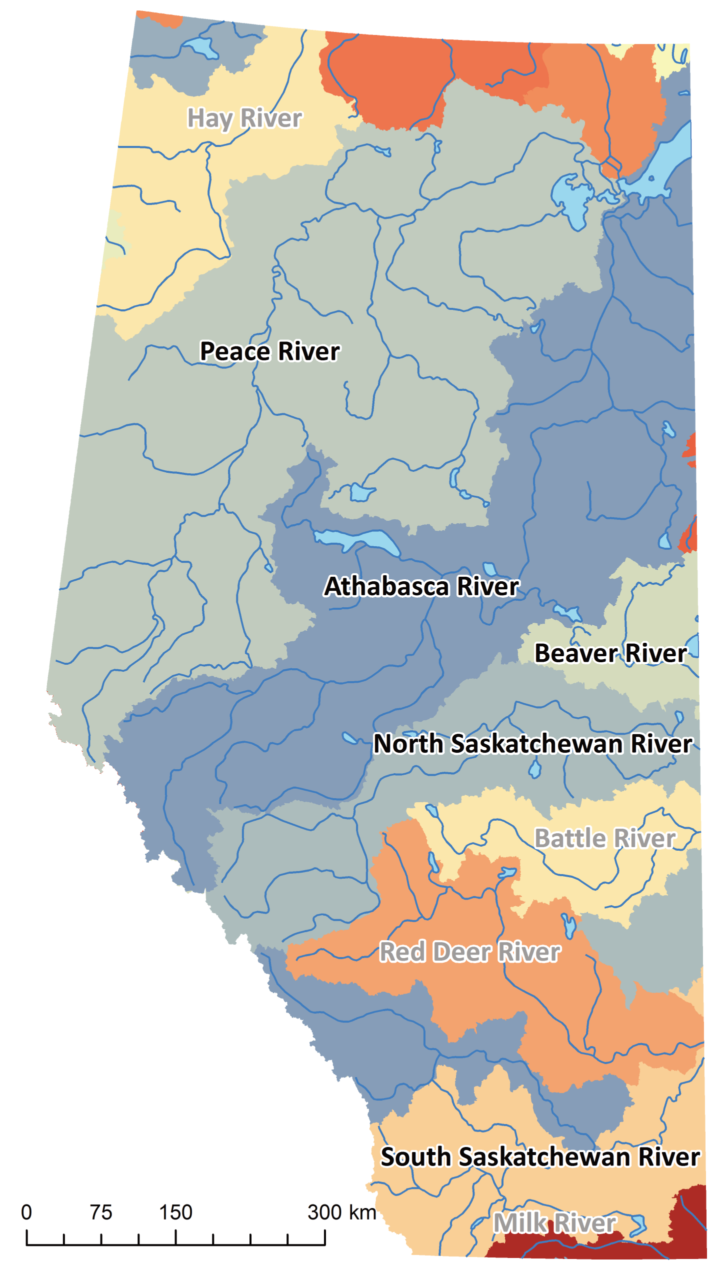

Figure 1.4 Major river drainage basins in Alberta

State of Montana

At the time of the preparation of this atlas, no statistics were found integrating the water balances (surface and ground waters) for the state of Montana. However, a comprehensive State Water Plan has been recently adopted by the State of Montana containing 68 recommendations intended to guide state water policy and management over the near, intermediate and long-term bases (DNRC, 2014).

The 2015 State Water Plan is a synthesis of the vision and efforts of regional Basin Advisory Councils (BACs) established in Montana's four main river basins: the Clark Fork/Kootenai, Upper Missouri, Lower Missouri, and the Yellowstone (Figure 1.5).

The Department of Natural Resources and Conservation (DNRC) has pulled together the work of members of the four BACs into a plan that addresses water management issues on a statewide basis.

Straddling the Continental Divide, Montana is headwaters to several major river systems of the northern Rockies, with both sides of the divide spawning rivers of national importance. The Milk River watershed is located in the most northern part of the state in the limits of the Upper and Lower Missouri basins (Figure 1.5). The headwaters of the Clark Fork and Missouri rivers originate in Montana, whereas the Kootenai and Yellowstone headwaters are in British Columbia and Wyoming respectively.

Statewide average annual river flow accumulations in Montana are (DNRC, 2014):

- Clark Fork River = 1.85×10^{10} m^3
- Kootenai River = 1.23×10^{10} m^3
- Missouri River = 8.63×10^9 m^3
- Yellowstone River = 1.1×10^{10} m^3

The Milk River watershed provides close to 6% of annual flow to the Missouri River, with 4.9×10^8 m^3/a. The annual precipitation for Montana is between 259 mm on the east to 639 mm on the northwest (DNRC, 2014).

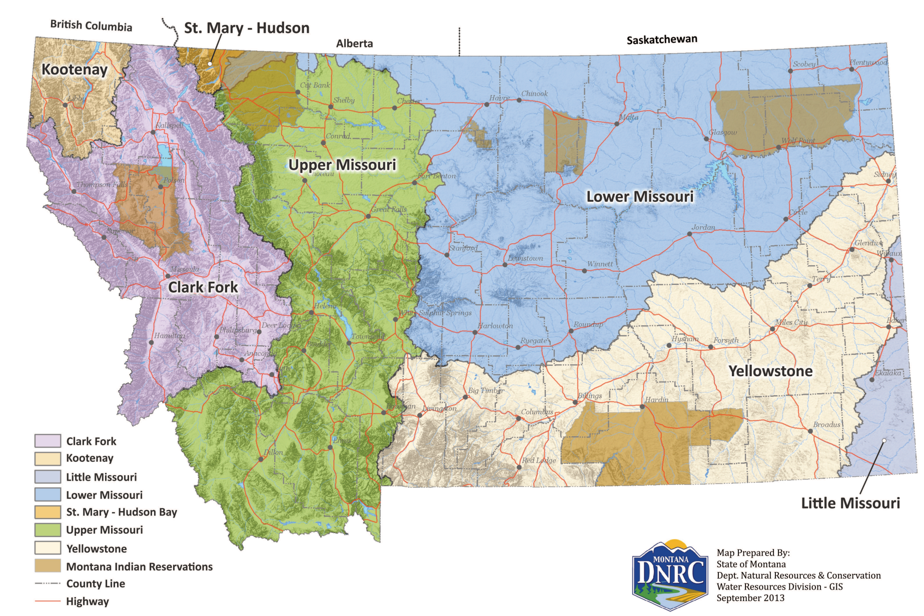

Figure 1.5 2015 Montana Water Supply Initiative Planning Basins.
<http://dnrc.mt.gov/divisions/water/management/state-water-plan>

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2 Description of the Study Area

2.1 Location

The Milk River Transboundary Aquifer region is located across Alberta (Canada) and Montana (United States) (Figure 2.1). The area covered by the maps in the atlas (study area and aquifer boundaries) represents a total area of 72 500 km² and includes southeastern Alberta, southern Saskatchewan (Canada) and north-central Montana (U.S.A.). It extends over 280 km from east to west and about 240 km from south to north.

The Milk River Aquifer (MRA), as delineated on Map 2.1, covers an area of 24 883 km². Located on the eastern flank of the Rocky Mountains, the region consists mostly of high plains entailed by numerous streams and rivers. Rising above the plains are five hills and mountains groups: Cypress Hills, Sweet Grass Hills, Milk River Ridge, Bears Paw Mountains and Montana Disturbed Belt. The aquifer is bounded by the edge of the Disturbed Belt on the west, by the Cypress Hills on the northeast and by the Bears Paw Mountains on the southeast. It ranges from longitude 109°40′ W to 112°30′ W and from latitude 48°10′ N to 49°55 N.

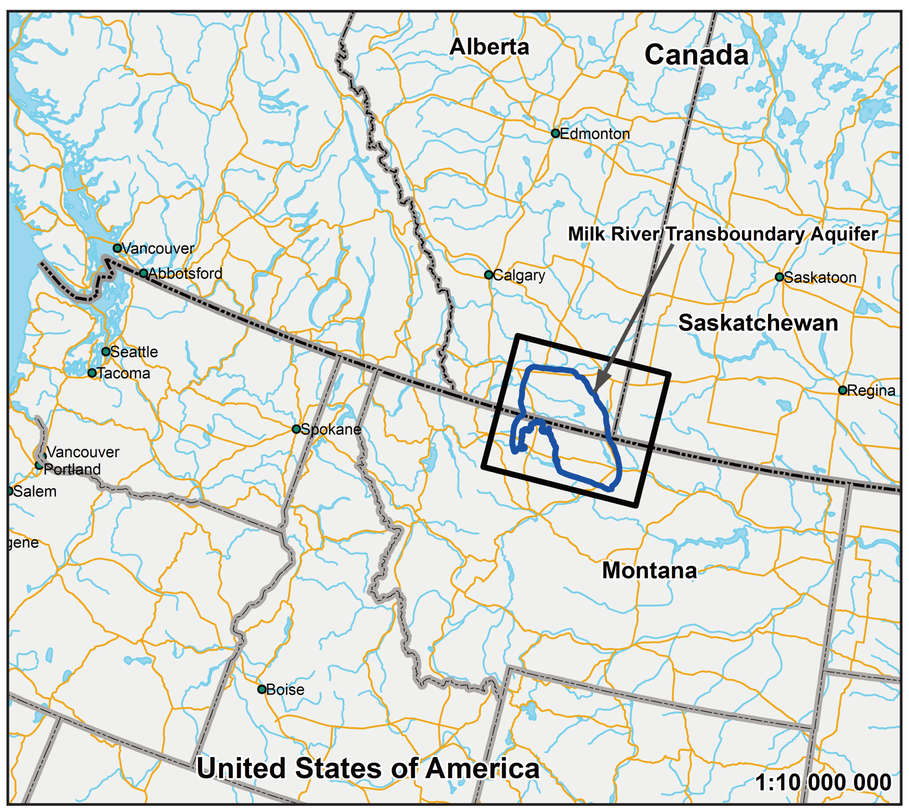


Figure 2.1 Location map of the Milk River Transboundary Aquifer region

The area represented on Map 2.1 covers 24 counties (in Alberta and Montana) or rural municipalities (in Saskatchewan). Table 2.1 shows the total area of each county or rural municipality labeled within the map. Map 2.1 shows the delimitation of each of these counties and rural municipalities (in black). The delineation of the MRA is shown in blue. The last two columns of Table 2.1 display the percentage of the total area of each county or municipality, and the percentage of the area covered by the MRA inside of each of these counties. The light-grey colour highlights the 12 counties in Alberta and Montana that are within the limits of the MRA (entirely or partially).

The study area is considered to be sparsely populated. Table 2.2 presents the most populated places (Statistics Canada, 2011; United States Census Bureau, 2010). It includes only two cities having more than 50 000 inhabitants: Lethbridge and Medicine Hat. Table 2.2 also covers towns, villages, and the Blackfeet Indian Reservation. The Alberta side is more populated than the Montana side of the study area.

Table 2.1 Counties and rural municipalities located within the bounds of Map 2.1

Province / State	County / Rural Municipality	Area (km²)	Area inside the map and covered by the MRA (km²)		Percentage inside the map and covered by the MRA (%)	
Alberta	Cardston	4 216	1 776	0.7	42	0.02
	Cypress	13 615	8 722	1 348	64	9.9
	Forty Mile No. 8	7 416	7 416	6 563	100	88.5
	Lethbridge	3 033	2 486	188	82	6.2
	Newell	5 848	541	0	9	0
	Taber	4 288	4 137	1 552	96	36.2
	Vulcan	5 752	477	0	8	0
	Warner No. 5	4 626	4 626	3 733	100	80.7
Montana	Blaine	8 222	4 160	0	51	0
	Chouteau	10 337	3 030	592	29	5.7
	Glacier	7 858	4 019	857	51	10.9
	Hill	7 550	7 550	5 641	100	74.7
	Liberty	3 745	3 745	2 948	100	78.7
	Pondera	4 248	3 715	73	87	1.7
	Teton	5 928	831	0	14	0
	Toole	5 032	5 032	1 383	100	27.5
Saskatchewan	Big Stick	855	672	0	79	0
	Reno	3 529	3 529	0	100	0
	Maple Creek	3 320	3 320	0	100	0

Natural Resources Canada (1997–2016)
United States Geological Survey (1997–2014)

Table 2.2 Population of the different administrative areas within the bounds of the Map 2.1

Province / State	Location	Population in 2010 (U.S.A.) and 2011 (Canada)
Alberta	Bow Island	2 025
	Foremost	526
	Lethbridge	83 679
	Magrath	2 217
	Medicine Hat	65 671
	Milk River	811
	Taber	8 199
	Warner No. 5	331
Montana	Blackfeet Indian Reservation	10 405
	Chester	847
	Cut Bank	2 919
	Havre	9 310
	Kevin	154
	Shelby	3 376
Saskatchewan	Maple Creek	2 176

Statistics Canada (2011) and United States Census Bureau (2010)

Sources:

Natural Resources Canada, 1997–2016. Canadian geographical names – all names. <http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/a5484da5-2b9e-4f8b-98ec-38d3fcb1e673.html>

Statistics Canada, 2011. Population and dwelling counts, for Canada, provinces and territories, and census subdivisions (municipalities), 2011 and 2006 censuses. <http://www12.statcan.gc.ca/census-recensement/2011/dp-pd/hlt-fst/pd-pl/Table-Tableau.cfm?LANG=Eng&T=302&SR=1&S=51&O=A&RPP=9999&PR=48&CMA=0>

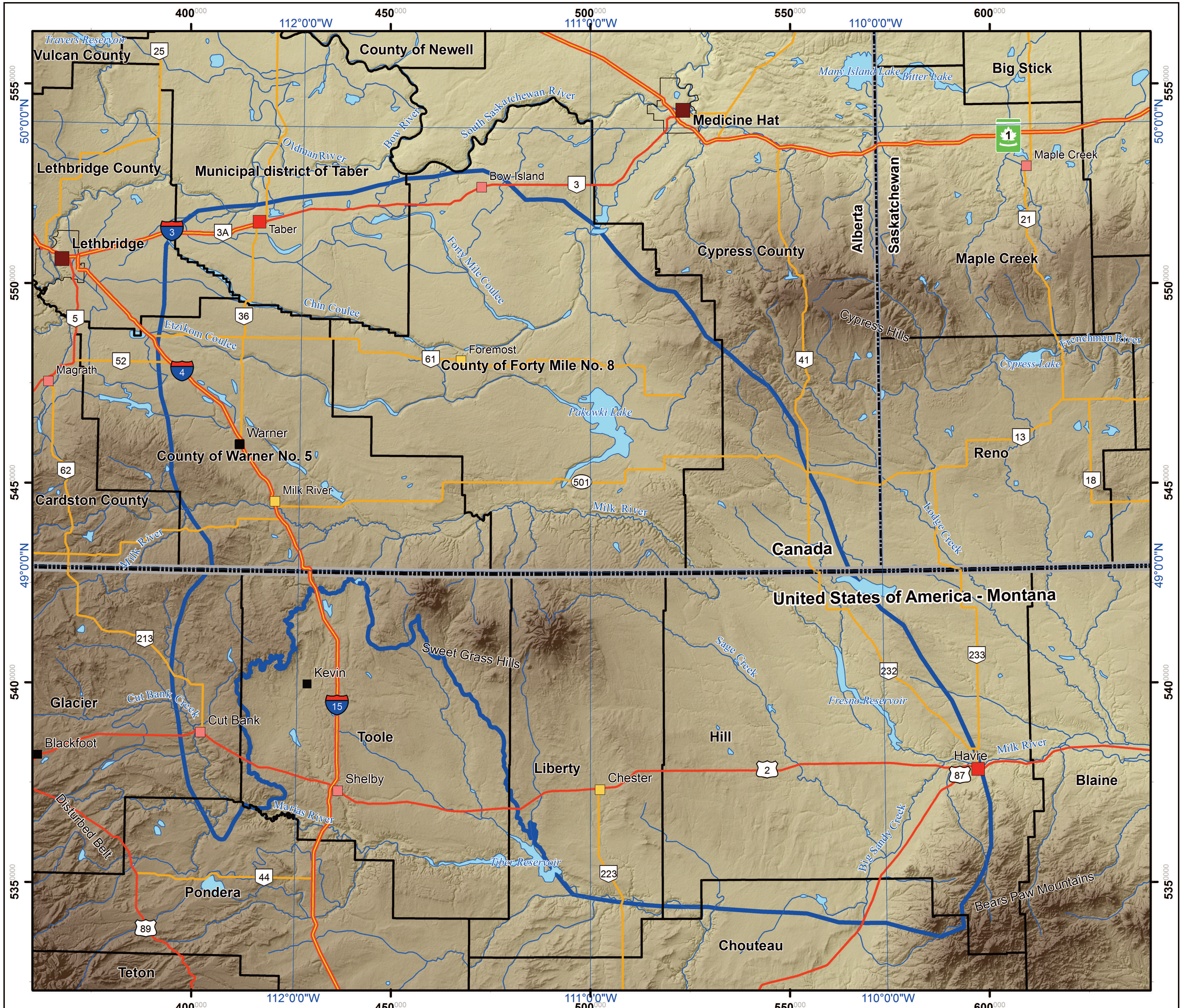
United States Census Bureau, 2010. Current population survey. <http://www.census.gov/cps>

United States Geological Survey, 1997–2014. The National Map Small-Scale Collection. <http://nationalmap.gov/small_scale>

MAP 2.1

Location of the Study Area

Projection UTM 12N 1:1 000 000



Legend

Population
- < 500
- 500 - 1 500
- 1 500 - 3 500
- 3 500 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Aquifer Extent
- Milk River

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m

2.2 Hydrography

The surface water system of the study area is characterized by geomorphological elements called *coulees*, *V valleys* (or ravines) with steep edges. The coulees were created either by glacial erosion, after the last ice age, or by the continuing erosion of water and wind (Dormaar 2010). The surface water system is well developed and shows many lakes and rivers. Among the major rivers are: Oldman River, Frenchman River, Etzikom Coulee, Marias River, and Milk River. Some of the rivers are transboundary, including Milk River, Sage Creek, Lodge Creek and Battle Creek.

Figure 2.2 Example of a coulee in Alberta. Photo taken from the web.

The Milk River flows over 1173 km from its source in the Blackfeet Indian Reservation in northwest Montana to the Missouri River. It flows northward into Alberta and loops eastward through the town of Milk River and then returns southward to Montana in the southeastern corner of Alberta. Many small tributaries, most of which flow northward from the Sweet Grass Hills of Montana, feed the Canadian section of the Milk River. Many of these streams are intermittent. Once the Milk River re-enters Montana, it is joined by numerous southward flowing tributaries from the Cypress Hills area of Alberta and Saskatchewan and northward flowing streams from the Bears Paw Mountains of Montana (Winhold and Quazi 1987).

The surface water system also includes many lakes. In total, the study area comprises about 159 lakes. The areas of the lakes are very heterogeneous in their size, ranging from 0.3 to 124.1 km^2. Some important lakes and reservoirs are Pakowki Lake, Tiber Reservoir and, Fresno Reservoir. Pakowki Lake is the largest lake of the study area and of all southern Alberta but it is very shallow, its average depth is 1.2 m. The lake is seasonally fed by water from the Etzikom Coulee and is included in a closed internal drainage lake (endorheic). This closed drainage basin retains water and allows no outflow to other external bodies of water; it equilibrates through evaporation.

Figure 2.3 Milk River at Writing-On-Stone Provincial Park (Alberta).
Photo credit: © Marie-Amélie Pétré

In addition to the Pakowki Lake watershed, the study area covers 29 other watersheds. Table 2.3 shows all the watersheds located in the study area, including the Milk River watersheds, which include Milk Headwaters, Upper Milk and Middle Milk. Together, those watersheds have a total surface of 17 406 km^2 and are located in parts of the provinces of Alberta, Saskatchewan and the state of Montana. The extents of the three Milk River watersheds and the Milk River Aquifer are not coincident and the global Milk River watershed has a smaller surface area than the Milk River Aquifer. Eight watersheds are Milk River tributaries: Wild Horse Lake, Lodge, Battle, Frenchman, Whitewater, Sage, Big Sandy and Peoples. Those watersheds cover 14 831 km^2 of the study area. Globally, the watershed of the Milk River and its tributaries cover 32 237 km^2, representing 45% of the study area.

Figure 2.4 Aerial view of Pakowki Lake, Alberta, Canada.
Photo credit: © Joe Mabel

Table 2.3 Watersheds included in the study area

Province / State	Watershed	Area (km²) Total	Area (km²) Study area	Percentage covered in the study area
Alberta	Central Oldman - Belly	5 214	1 027	20
	Little Bow	7 964	1 991	25
	Lower Bow - Mouth	5 555	1 668	30
	Lower Oldman	3 323	3 323	100
	Pakowki Lake	5 134	5 134	100
	Upper South Saskatchewan - Upper	2 529	2 529	100
Montana	Big Sandy	2 091	2 091	100
	Bullwhacker-Dog	5 010	1 028	21
	Cut Bank	3 109	2 439	78
	Fort Peck Reservoir	13 600	619	5
	Marias	9 564	9 014	94
	Middle Fork Flathead	2 939	39	1
	Middle Milk	9 096	3 641	40
	Peoples	1 840	321	17
	Teton	5 308	388	7
	Two Medicine	3 334	2 346	70
	Willow	2 572	2 572	100
Saskatchewan	Crane Lake	7 275	4 056	56
	Frenchman	6 183	1 347	22
	Swift Current	3 918	6	0
Alberta / Montana	Milk Headwaters	2 499	1 688	68
	Sage	2 564	2 564	100
	St. Mary	3 526	899	25
	Upper Milk	5 851	5 847	100
Alberta / Montana / Saskatchewan	Battle	4 451	4 251	96
	Lodge	2 826	2 826	100
	Wild Horse Lake	1 213	1 212	100
Alberta / Saskatchewan	Seven Persons	6 339	6 295	99
	Upper South Saskatchewan - Lower	5 331	1 144	21
Montana / Saskatchewan	Whitewater	5 404	219	4

Natural Resources Canada (2003) and United States Department of Agriculture (2013)

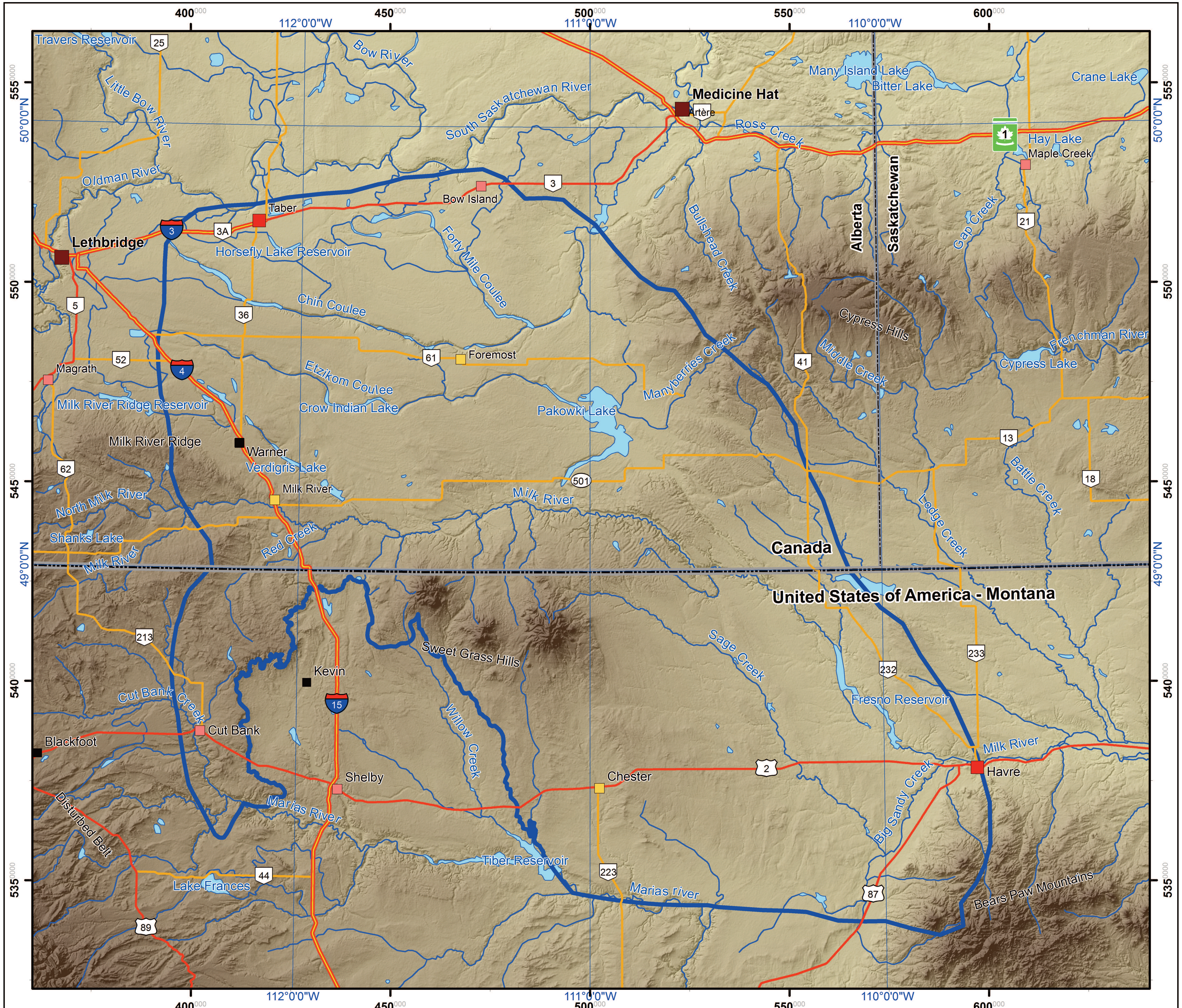
Sources:

Dormaar, J.F., 2010. The Alberta Stretch of the Milk River and the Mystique of Its Surrounding Landscape. Lethbridge Historical Society, 92 p.

Natural Resources Canada, 2003. Atlas of Canada 1,000,000 National Frameworks Data, Hydrology – Drainage Areas (WSC sub-sub drainage areas).
<http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/30b33615-6dda-51a5-a9dd-308802714a28.html>

United States Department of Agriculture, Natural Resources Conservation Service, National Geospatial Center of Excellence, 2013. Watershed Boundary Dataset 10 Digit Hydrologic Units For Montana.
<http://mslapps.mt.gov/Geographic_Information/Data/DataList/datalist_MetadataDetail.aspx?did={e390ec2a-991c-4fff-88d0-603db1166fdf}>

Winhold, T.H. and Quazi, M.E., 1987. Milk River Dam – Site 2: River Engineering Assessment, Alberta. Water Resources Management Services, Technical Services Division, 106 p.



MAP 2.2

Hydrographic Network

Projection UTM 12N 1:1 000 000

Legend

Population
- < 500
- 500 - 1 500
- 1 500 - 3 500
- 3 500 - 10 000
- 10 000 - 100 000

Border
- International
- Provincial

Hydrography
- Lake
- River

Road Network
- Highway
- Main Road
- Regional Road

Aquifer Extent
- Milk River

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m

2.3 Mean Annual Flow of Rivers

The hydrographs shown in this section (Figures 2.5a to 2.5h) represent the temporal variation of the flow of some rivers and creeks located within the study area (Map 2.3). The temporal length of the data varies from 35 to 120 years.

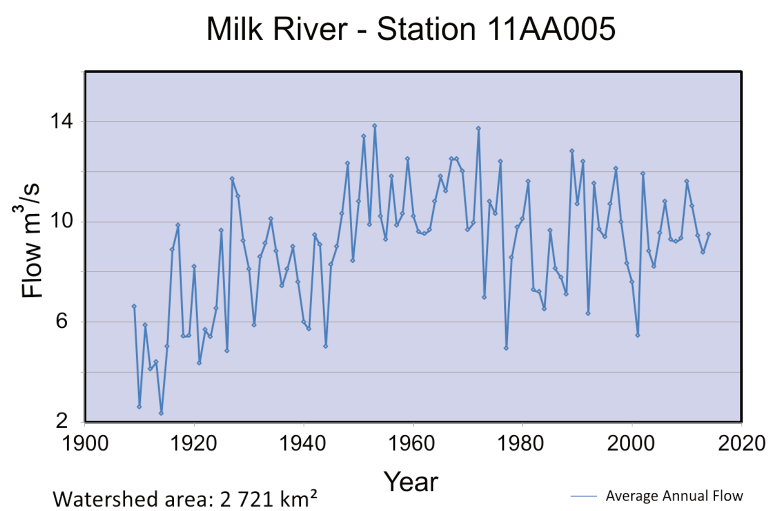


Figure 2.5a Hydrograph of the Station 11AA005, Milk River

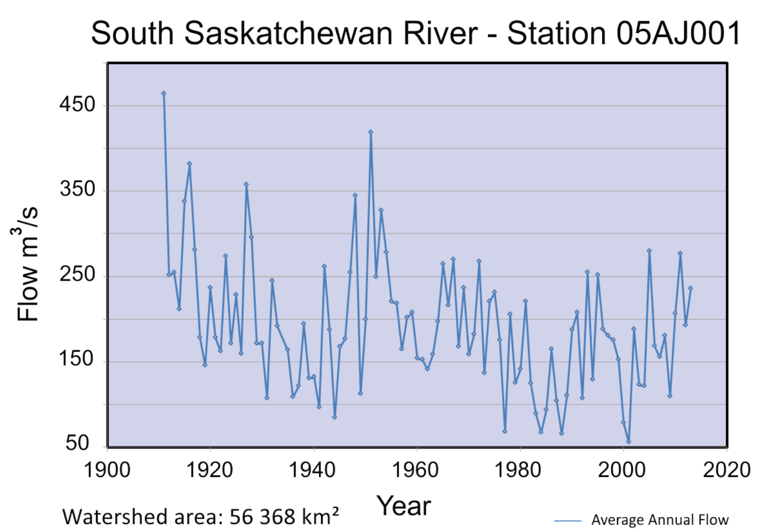


Figure 2.5b Hydrograph of the Station 05AJ001, South Saskatchewan River

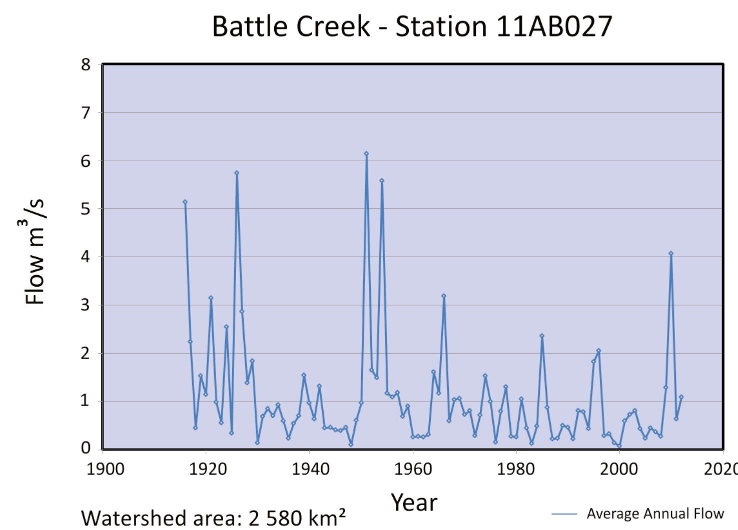


Figure 2.5c Hydrograph of the Station 11AB027, Battle Creek

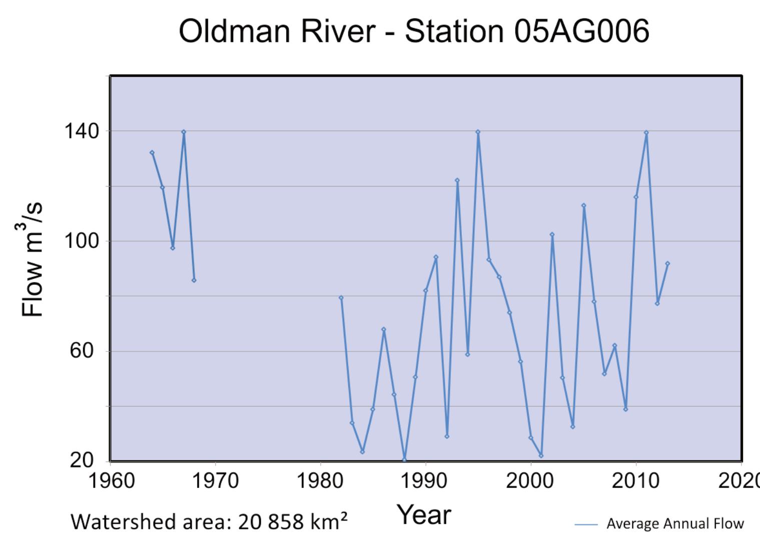


Figure 2.5d Hydrograph of the Station 05AG006, Oldman River

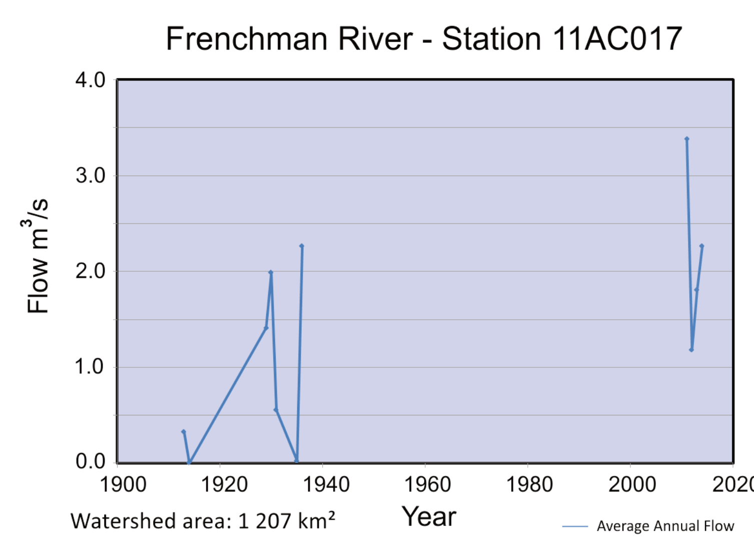


Figure 2.5e Hydrograph of the Station 11AC017, Frenchman River

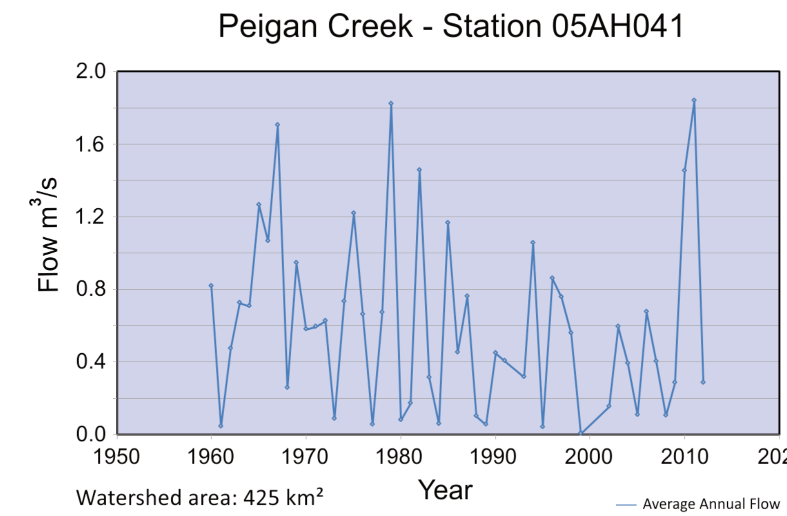


Figure 2.5f Hydrograph of the Station 05AH041, Peigan Creek

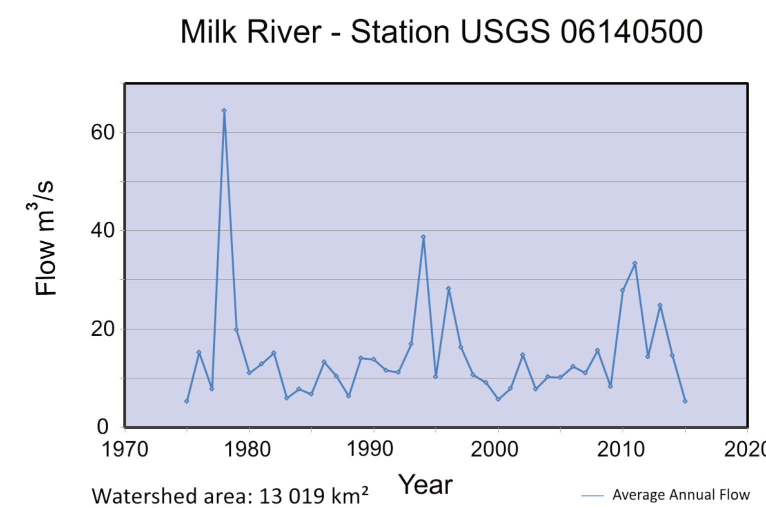


Figure 2.5g Hydrograph of the Station USGS 06140500, Milk River

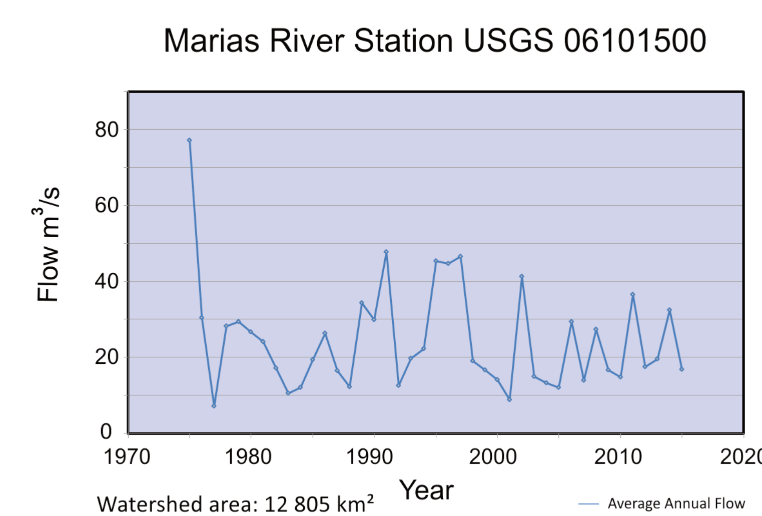


Figure 2.5h Hydrograph of the Station USGS 06101500, Marias River

Sources:

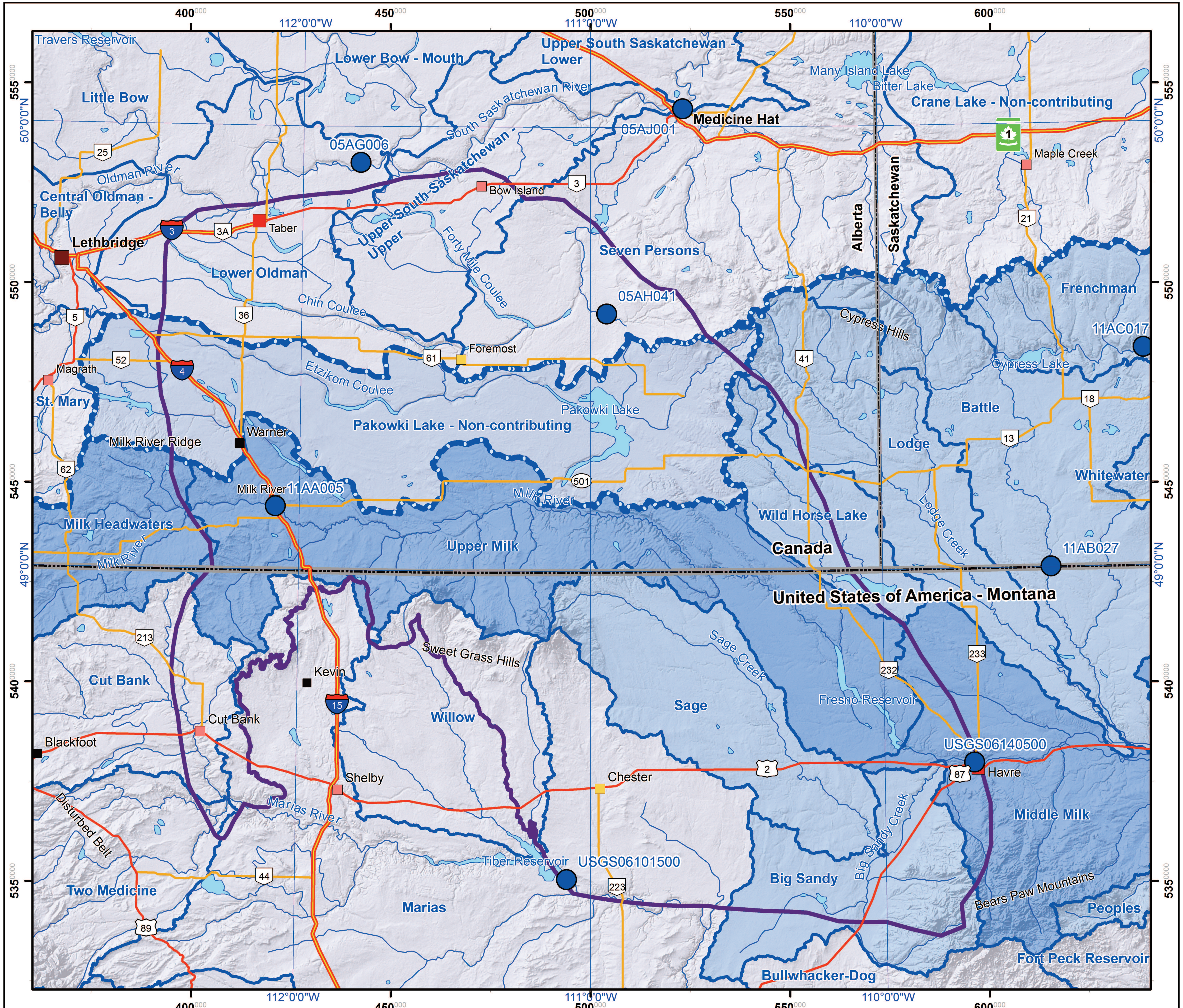
Environment Canada – Water Office, 2015. Historical Hydrometric Data Search. <http://wateroffice.ec.gc.ca/search/historical_e.html>

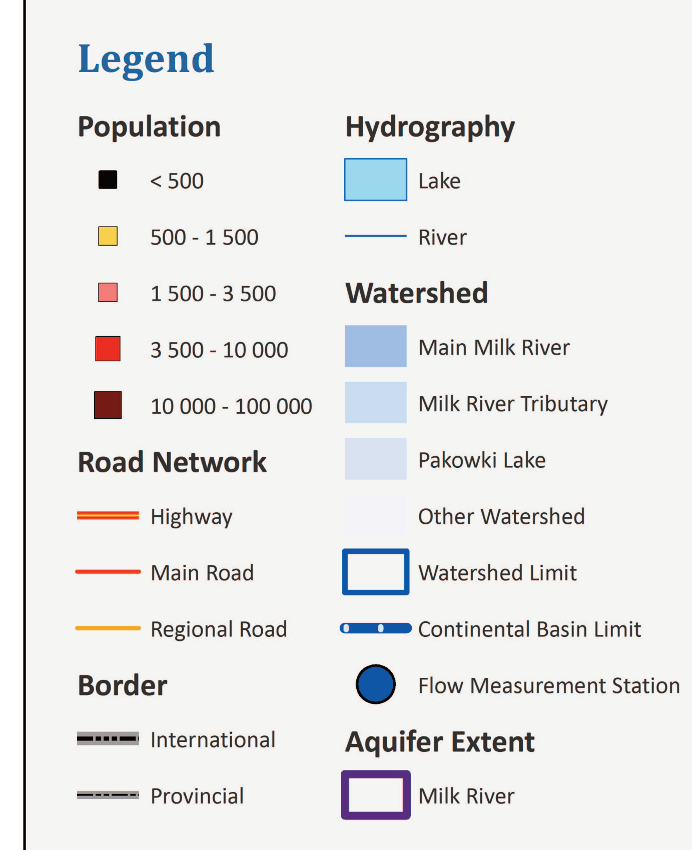
United States Geological Survey, 2015. National Water Information System – USGS Current Water Data for the Nation. <http://waterdata.usgs.gov/nwis/rt>

MAP 2.3

Watersheds and Hydrographs Location

Projection UTM 12N 1:1 000 000





2.4 Topography

The study area is located in the Western Prairies. The region is characterized by plains featuring an ondulating topography with some hills and mountains disseminated throughout the region. All the elevations are expressed as metres above sea level (m a.s.l.) or above mean seal level (m a.m.s.l.). The plains elevation ranges between 620 and 1100 m a.s.l. Low elevations (620–865 m a.s.l.) are observed in the vicinity of the rivers. In the mountains, the elevation rises to a maximum of 2595 m a.s.l.

Figure 2.6 Undulating topography of the plains.
Photo credit: © Marie-Amélie Pétré

There are five hills and mountain groups: Cypress Hills, Milk River Ridge, Sweet Grass Hills, Bears Paw Mountains and Montana Disturbed Belt. In Alberta and Saskatchewan, the Cypress Hills rise gently, climbing 600 metres above the surrounding prairies. The Cypress Hills plateau reaches a maximum elevation of 1468 m a.s.l. at its west end in Alberta (Alberta Parks). It represents Canada's highest point between the Canadian Rockies and the Labrador Peninsula. In Saskatchewan, the highest point is at 1392 m a.s.l., south of Maple Creek. The Cypress Hills were formed by millions of years of sedimentary deposition, followed by millions of years of erosion. They are known as an erosional plateau.

Figure 2.7 Cypress Hills. Photo credit: © Erik Lizee

In Montana, the Sweet Grass Hills (culminating around 2100 m a.s.l.) are a small group of three buttes in the northern counties of Toole and Liberty, at approximately 5 to 10 km south of the Canada-United States border. The Sweet Grass Hills were formed millions of years ago by molten rock coming up a volcanic neck and seeping along bedding planes (Figure 2.9). This mound of molten rock hardened below ground surface (Beaty, 1975; Smith, 1987). Through weathering, the surface was eroded, exposing the igneous rock. During the glaciations, the surrounding plains were eroded; however, the top of these hills was not as it consists of harder igneous rocks. The Sweet Grass Hills rise more than 900 m above the surrounding plains. The highest point in the hills is the West Butte at 2128 m a.s.l.

Figure 2.8 Sweet Grass Hills. Photo credit: ©2010 Wikipedia

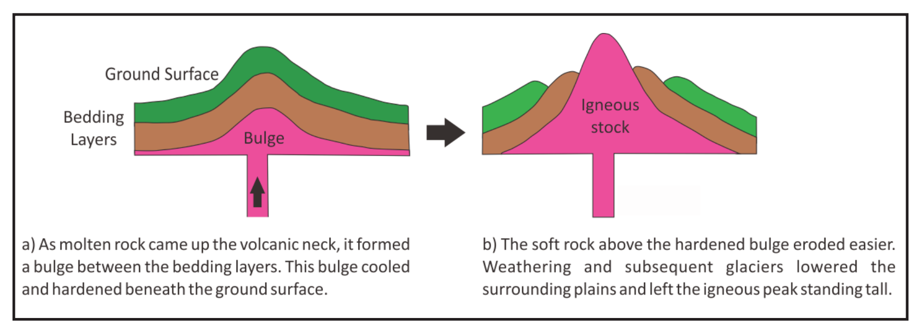


Figure 2.9 Sweet Grass Hills Formation
Image credit: © University of Lethbridge

Montana also has the Bears Paw Mountains, which extend in a 72 km arc south of Havre. The highest peak of those mountains is Baldy Mountain at 2108 m a.s.l. The Bears Paw Mountains are an insular-montane island range. The Bears Paw Mountains are divided in two distinct areas: east and west. The study area partly covers the Western half of the mountains and it is where the highest peaks are located. Other peaks in the western part of the mountains have elevations between 1525–1829 m a.s.l.

Figure 2.10 Bears Paw Mountains.
Photo credit: © www.bigskyfishing.com

Figure 2.11 View of the Montana Disturbed Belt from the Mount Wright summit. Photo credit: © J.Blend

The southwestern part of the study area is characterized by rugged landform, designating the Montana Disturbed Belt. This area shows the highest points of the study area, rising above 2550 m a.s.l. with a maximum elevation of 2 595 m a.s.l. The formation of these mountains is explained by the theory of vertical uplift that results in gravitational sliding (Mudge, 1969).

Sources:

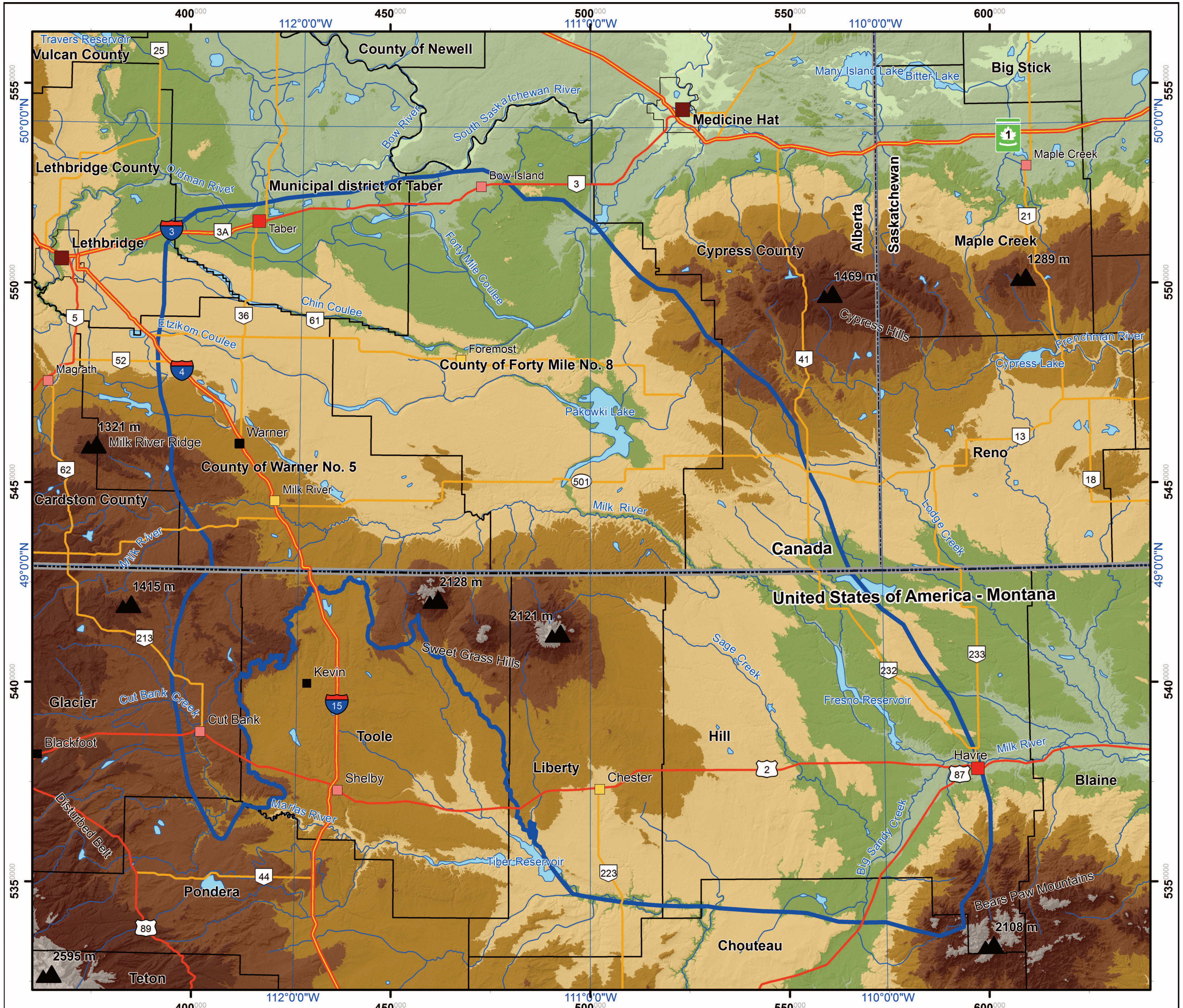
Alberta Parks. Geology Fact Sheet Cypress Hills Interprovincial Park, <http://www.albertaparks.ca/media/2850121/cypress_hills_-_geology_fact_sheet.pdf>

Beaty, C.B., 1975. The landscapes of southern Alberta: a regional geomorphology. Lethbridge: University of Lethbridge, Production Services, 95 p.

Doormaar, J.F., 2003. Sweet Grass Hills: A Natural and Cultural History. Lethbridge Historical Society, 84 p.

Mudge, M.R., 1969. Origin of the Disturbed Belt in northwestern Montana. The Geological Society of America Bulletin. v. 81, no. 2, p. 377–392.
doi: 10.1130/0016-7606(1970)81[377:OOTDBI]2.0.CO;2

Smith, D.G., 1987. Landforms of Alberta, interpreted from airphotos and satellite imagery. Canadian Society of Petroleum Geologists, 105 p.



MAP 2.4

Topography of the Study Area

Projection UTM 12N 1:1 000 000

Legend

Population
- < 500
- 500 - 1 500
- 1 500 - 3 500
- 3 500 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Aquifer Extent
- Milk River

Elevation (m a.m.s.l.)
- Elevation Point
- 620 - 650 m
- 650 - 725 m
- 725 - 800 m
- 800 - 865 m
- 865 - 975 m
- 975 - 1 100 m
- 1 100 - 1 250 m
- 1 250 - 1 500 m
- 1 500 - 1 850 m
- 1 850 - 2 595 m

2.5 Slope of the Land Surface

Slope is an important parameter to consider in hydrogeology, since it affects surface runoff and therefore infiltration and recharge. Water infiltration decreases with an increase of the slope's angle. Slopes of land surface often influence the gradient and direction of groundwater flow.

The study area is generally flat with some hills and mountains. Most parts of the study area have slopes gentler than 4° (Map 2.5, Figure 2.13). The slopes are a little steeper in the vicinity of the rivers and coulees where they range between 4° and 14° (Figure 2.12). This suggests an entrenchment of the rivers. The steepest slopes observed in the study area are located around the hills and mountains groups: Cypress Hills, Sweet Grass Hills, Bears Paw Mountains and Montana Disturbed Belt. The Cypress Hills are the group showing the gentlest slopes of the topographic highs, with only a few slopes between 14° and 24° (Figure 2.14). The Montana Distributed Belt also exhibits several gentle slopes; however, there is a concentration of steep slopes (14°–24° and 24°–59°) in the southwestern corner of the study area. Sweet Grass Hills and Bears Paw Mountains (Figure 2.15) both show a combination of moderate (8°–14°) and steep (14°–24° and 24°–59°) slopes.

Figure 2.12 Writing-On-Stone Provincial Park (Alberta).
Example of slopes in vicinity of the rivers. Photo credit: © Marie-Amélie Pétré

Figure 2.14 Cypress Hills – Examples of moderate slope class (14°–24°) for the study area.

Figure 2.13 Writing-On-Stone Provincial Park (Alberta).
Example of the gentlest slope class (< 4°). Photo credit: © Marie-Amélie Pétré

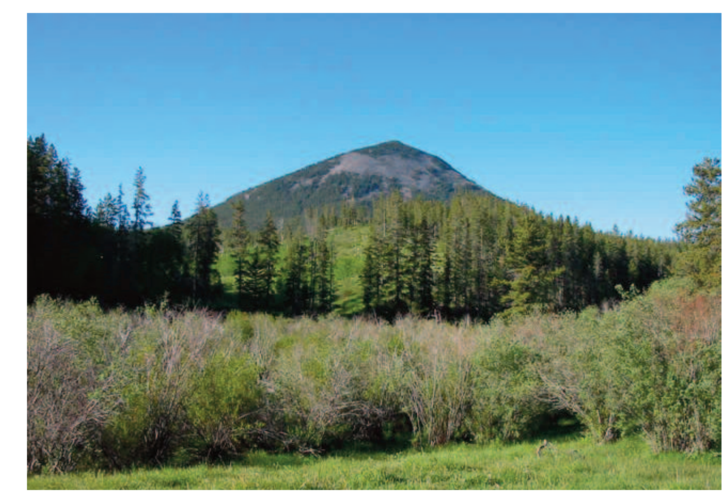


Figure 2.15 Baldy Mountain in Bears Paw Mountains – Example of the steepest slope class (24°–59°) for the study area.
Photo credit: © www.bigskyfishing.com

Methodology:

The slope was derived from the digital elevation model of the Shuttle Radar Topography Mission (SRTM), using ArcGis.

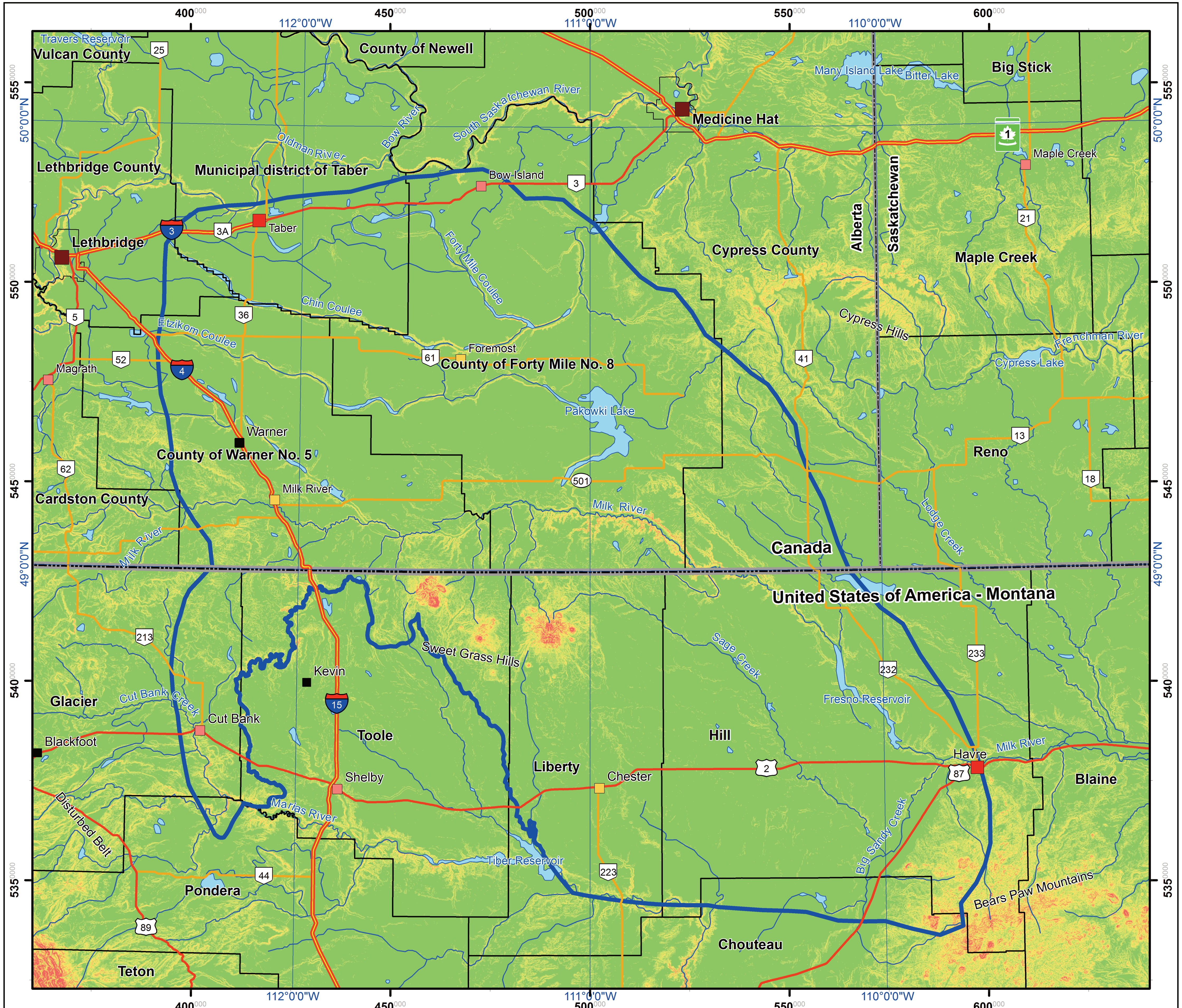
Sources:

NASA Shuttle Radar Topographic Mission (SRTM), 2007. SRTM 90m Digital Elevation Database v. 4.1. <http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1>

MAP 2.5

Slope of the Land Surface

Projection UTM 12N 1:1 000 000



Legend

Population
- < 500
- 500 - 1 500
- 1 500 - 3 500
- 3 500 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Aquifer Extent
- Milk River

Slope (degree)
- 0 - 2
- 2 - 4
- 4 - 8
- 8 - 14
- 14 - 24
- 24 - 59

2.6 Land Cover

The land cover of the study area has been divided into 10 classes defined by the North American Land Change Monitoring System (2010) (Table 2.4 and Map 2.6). The study area is dominated by two land cover classes: cropland and temperate or subpolar grassland. These classes are found everywhere and cover 95.4% of the study area.

The other land cover classes cover 0.2% to 1.6% of the study area. The water class designates the hydraulic network. The barren lands are concentrated in southwestern Saskatchewan and southeastern Alberta, around Lodge Creek and on the banks of some rivers, including Milk River. The urban and built-up class designates the cities and towns; there are two major urban sites that constitute the two biggest cities of the study area: Lethbridge and Medicine Hat. Wetlands represent very small areas located mainly in Alberta, between Etzikom Coulee and Oldman River.

The other classes are found mainly in the hills and mountains. The temperate or subpolar broadleaf forest is concentrated in the Saskatchewan part of the Cypress Hills. The Alberta part of the Cypress Hills is primarily covered by temperate or subpolar needleleaf forest and mixed forest. Hills and mountains in Montana are primarily covered with temperate or subpolar needleleaf forest and temperate or subpolar shrubland.

Table 2.4 North American Land Change Monitoring System (NALCMS) (2010)

Land cover class	Definition of land cover class	Area (km²)	Percentage within the study area
Cropland	Areas dominated by intensively managed crops. These areas typically require human activities for their maintenance. These include areas used for the production of annual crops, such as corn, soybeans, wheat, maize, vegetables, tobacco, cotton, etc.; perennial grasses for grazing; and woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class does not represent natural grasslands used for light to moderate grazing.	35 803	49.5
Temperate or subpolar grassland	Areas dominated by graminoid or herbaceous vegetation, generally accounting for greater than 80% of total vegetation cover. These areas are not subject to intensive management such as tilling but can be utilized for grazing.	33 200	45.9
Temperate or subpolar shrubland	Areas dominated by woody perennial plants with persistent woody stems less than three metres tall and typically accounting for greater than 20% of total vegetation.	1 187	1.6
Water	Areas of open water, generally with less than 25% cover of non-water cover types. This class refers to areas that are consistently covered by water.	754	1.0
Temperate or subpolar broadleaf deciduous forest	Forests generally taller than three metres and with more than 20% of total vegetation cover. These forests have greater than 75% of tree crown cover represented by deciduous species.	387	0.5
Barren land	Areas characterized by bare rock, gravel, sand, silt, clay, or other earthen material, with little or no "green" vegetation present regardless of its inherent ability to support life. Generally, vegetation accounts for less than 10% of total cover.	383	0.5
Temperate or subpolar needleleaf forest	Forests generally taller than three metres and accounting for more than 20% of total vegetation cover. The tree crown cover contains at least 75% of needleleaf species.	352	0.5
Mixed forest	Forests generally taller than three metres and accounting for more than 20% of total vegetation cover. Neither needleleaf nor broadleaf tree species occupy more than 75% of total tree cover, but the two are co-dominant.	115	0.2
Urban and built-up	Areas that contain at least 30% or greater urban constructed materials for human activities (cities, towns, transportation, etc.).	103	0.1
Wetland	Areas dominated by perennial herbaceous and woody wetland vegetation that is influenced by the water table at or near surface over extensive periods of time. These include marshes, swamps, bogs, mangroves, etc., either coastal or inland, where water is present for a substantial period annually.	20	< 0.1

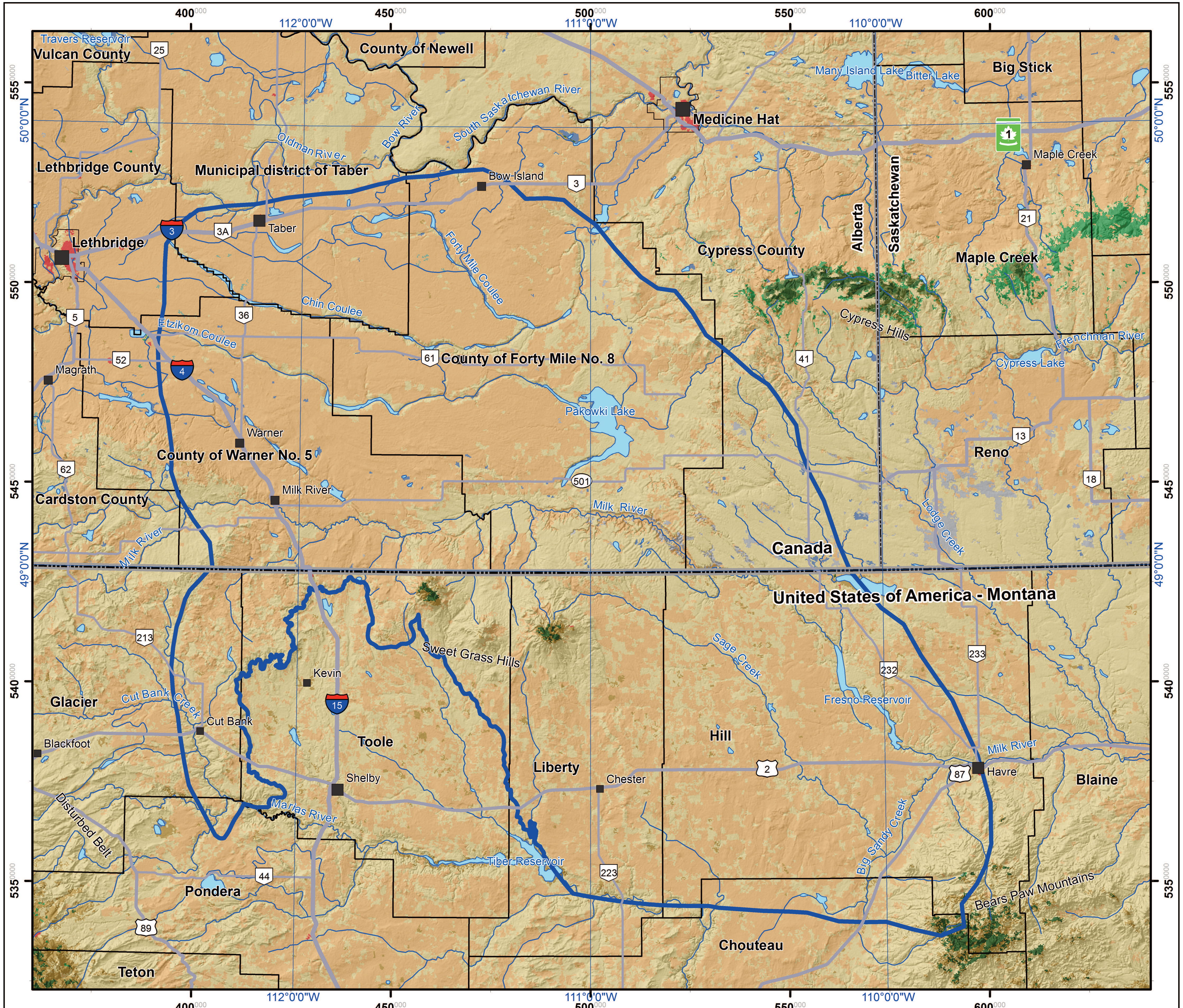
Sources:

North American Land Change Monitoring System, 2010. Commission for Environmental Cooperation.
<http://www.cec.org/Page.asp?PageID=924&ContentID=2819&AA_SiteLanguageID=1>

MAP 2.6

Land Cover

Projection UTM 12N 1:1 000 000



Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Aquifer Extent
- Milk River

Land Cover - Year 2010
- Temperate or subpolar needleleaf forest
- Temperate or subpolar broadleaf forest
- Mixed forest
- Temperate or subpolar shrubland
- Temperate or subpolar grassland
- Wetland
- Cropland
- Barren land
- Urban and built-up
- Water
- Snow and ice

2.7 Climate Stations

The climate maps (sections 2.8, 2.9, 2.10) and the potential evapotranspiration map (section 2.11) were produced with data from official climate stations in Canada and in the United States of America. These stations are located in the study area or in its vicinity. Considering that the climate data were interpolated to produce the maps, stations outside the study area have been used to ensure that the extent of the interpolation covers the entire study area. The spatial distribution of the climate stations is shown in Figure 2.16. Table 2.5 exhibits the climate data for every station.

Under the Köppen climate classification, the study area is characterized by a semi-arid climate, meaning that the region receives slightly less precipitation than potential evapotranspiration (Figure 2.17 in Section 2.8). A semi-arid climate designates an intermediate stage between desert climates and humid climates.

Table 2.5 Environment Canada (1981–2010) and National Oceanic and Atmospheric Administration (1981–2010)

Station	Elevation (m a.m.s.l.)	Mean Winter Temperature (°C)	Mean Summer Temperature (°C)	Mean Spring Temperature (°C)	Mean Fall Temperature (°C)	Mean Annual Temperature (°C)	Mean Annual Total Precipitation (mm)
Climate Stations in the study area							
Altawan	945	-11.6	17.2	3.5	2.9	3.0	290
Big Sandy	844	-5.2	19.7	7.4	7.6	7.4	341
Chester	955	-7.7	18.3	5.7	5.6	5.5	281
Chinook	738	-7.6	19.4	6.6	6.0	6.1	333
Claydon	975	-8.8	17.8	4.8	4.9	4.7	385
Conrad	1 082	-4.9	17.3	5.9	6.2	6.1	303
Cut Bank	1 170	-5.1	16.7	4.9	5.7	5.6	277
Cypress Hills	1 196	-8.1	14.6	3.1	3.4	3.3	601
Del Bonita	1 322	-5.8	15.6	4.1	5.1	4.8	336
Foremost	892	-6.0	17.8	6.0	5.8	5.9	396
Goldbutte 7 N	1 066	-4.6	16.9	5.8	6.3	6.2	360
Golden Prairie	746	-8.9	17.7	5.5	4.7	4.8	363
Havre	788	-6.8	19.2	6.5	6.5	6.4	285
Lethbridge A	929	-5.2	17.0	5.7	6.0	5.9	380
Maple Creek North	764	-7.1	18.4	6.0	5.9	5.8	388
Masinasin	953	-5.6	18.2	6.3	6.5	6.3	407
Medicine Hat A	717	-7.0	18.7	6.5	6.1	6.1	323
Shelby	1 014	-5.1	18.1	6.2	6.6	6.5	306
Sunburst 8 E	1 128	-5.2	17.6	5.9	6.5	6.3	352
Vauxhall North	760	-7.4	16.8	5.5	5.4	5.1	316
Warner West	1 109	-5.3	16.6	5.3	5.8	5.6	482
Climate Stations outside the study area							
Augusta	1 241	-2.6	17.4	6.3	7.3	7.1	350
Calgary Int	1 084	-6.4	15.3	4.2	4.6	4.4	419
Chinook 35	1 024	-4.7	17.7	6.0	6.7	6.5	324
Choteau	1 172	-3.5	16.9	5.8	6.7	6.5	269
Claresholm waterworks	1 008	-4.9	16.4	5.4	5.6	5.6	424
Creston	896	-3.8	16.7	6.2	6.1	6.3	503
Fairfield	1 214	-3.1	17.6	6.2	7.1	7.0	315
Fernie	1 001	-5.0	15.6	5.4	5.2	5.3	1 227
Fort Benton	807	-4.5	19.1	7.0	7.1	7.2	335
Gibson Dam	1 399	-3.7	14.9	4.2	5.7	5.3	409
Gleichen	905	-8.1	16.0	4.6	4.3	4.2	338
Great Falls	1 117	-3.5	18.1	6.1	7.2	7.0	375
Harlem 4 W	723	-6.1	19.9	7.6	7.6	7.3	295
Holter Dam	1 063	-1.3	19.1	7.7	9.0	8.7	334
Hungry Horse Dam	963	-3.6	17.9	6.3	6.4	6.8	837
Malta	690	-6.8	20.7	7.7	7.7	7.3	331
Oyen Cappon	793	-9.9	17.4	4.6	4.4	4.1	312
Polebridge	1 073	-6.3	14.2	4.3	4.2	4.2	494
Polson Kerr Dam	832	-1.9	18.9	8.1	8.1	8.3	395
Rosetown	586	-13	17.3	4.1	3.3	2.9	327
Saco 1 NNW	666	-8.8	19.4	6.4	6.0	5.8	299
Sand Creek	887	-5.8	19.6	6.7	6.7	6.8	374
Shaunavon 2	914	-8.3	17.4	4.8	4.7	4.7	395
Sparwood	1 138	-6.1	14.7	4.7	4.4	4.4	613
Swift Current CDA	825	-9.3	17.4	4.5	4.5	4.3	357
Vulcan	1 049	-7.4	16.3	5.0	5.0	4.7	415
West Glacier	961	-4.0	16.6	5.8	5.7	6.1	740
Zortman	1 230	-4.3	16.9	4.9	6.3	6.7	452

Sources:

Environment Canada, Canadian Climate Normals. 1981–2010 Climate Normals and Averages.
<http://climate.weather.gc.ca/climate_normals/index_e.html>

National Climatic Data Center of National Oceanic and Atmospheric Administration (NOAA). Data Tools: 1981–2010 Normals.
<http://www.ncdc.noaa.gov/cdo-web/datatools/normals>

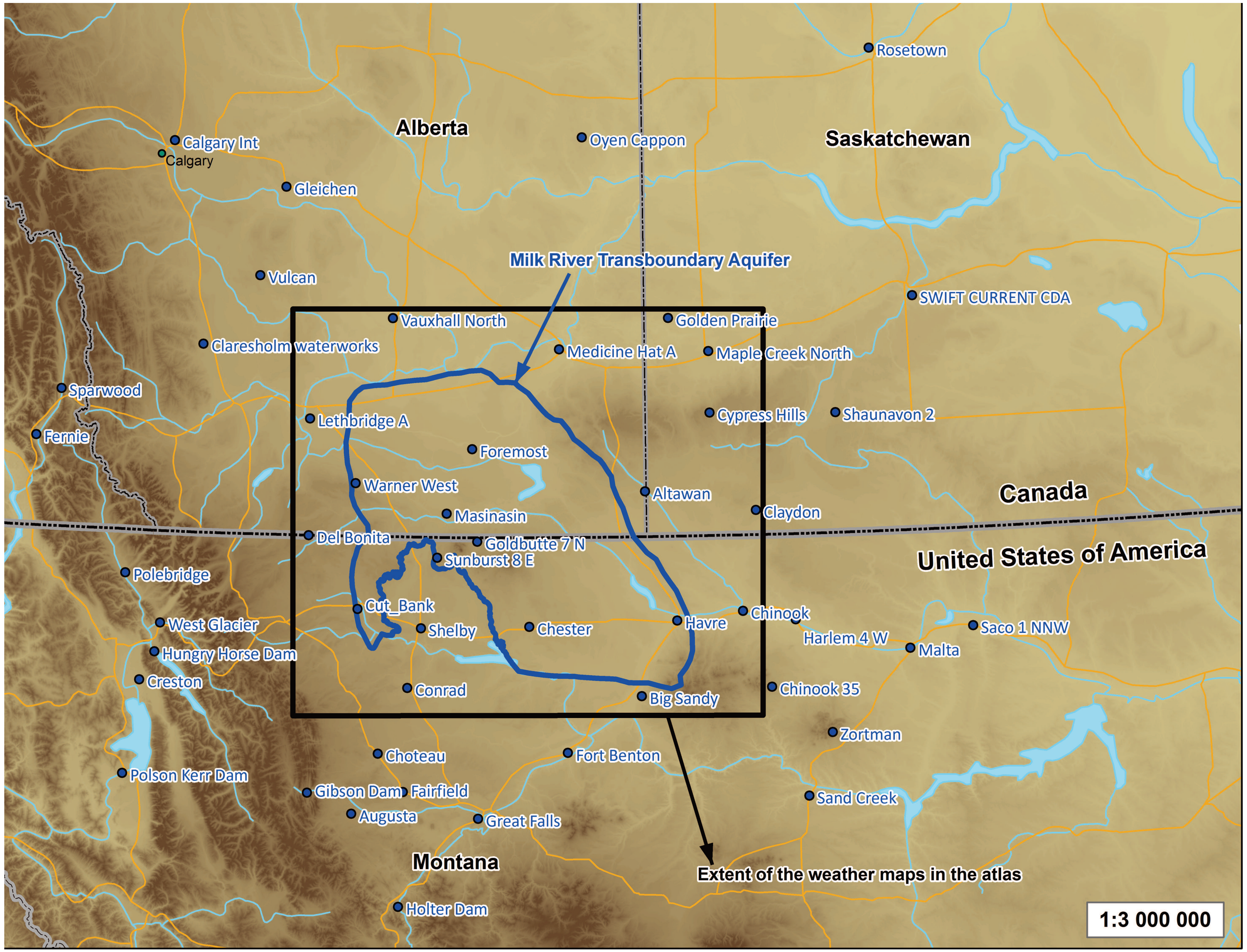


Figure 2.16 Spatial distribution of the climate stations

2.8 Annual Precipitation

Descriptions in this section are based on data from all the climate stations shown on Figure 2.16. The precipitation over the year can be divided into two periods: low and high precipitation. The high precipitation period extends from May to September inclusively. It accounts for more than 50% of the total annual precipitation. Within this period, May and June generally show more precipitation than the other months.

Figure 2.17 Köppen Climate Classification for North America.
Image credit: © 2014 Arizona Board of Regents

The low-precipitation season is from October to April. The precipitation levels are relatively constant over this period. The average total annual precipitation ranges from 277 mm to 700 mm with mean precipitation of 301 to 400 mm/a over a 30 years period. Precipitation in the form of rain generally constitutes 70% of the total precipitation. The highest average snowfall occurs in January; however, the greatest single snowstorm events often occur in March or April (Klohn Crippen Consultants Ltd., 2003).

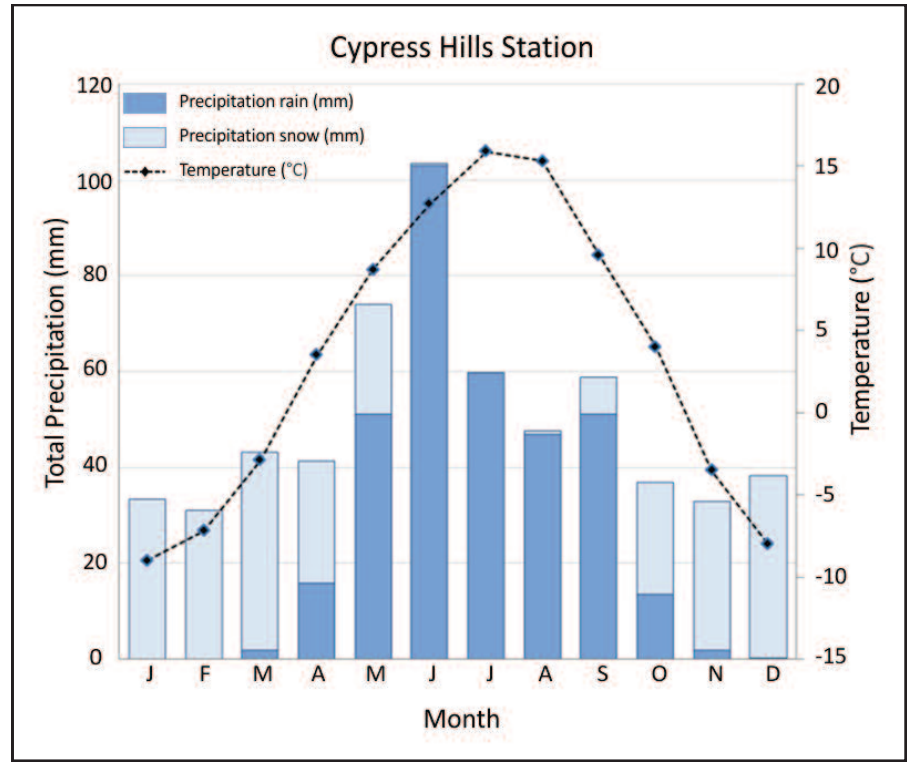


Figure 2.18 Monthly average total precipitation and temperature for Cypress Hills Station
Environment Canada (1981–2010)

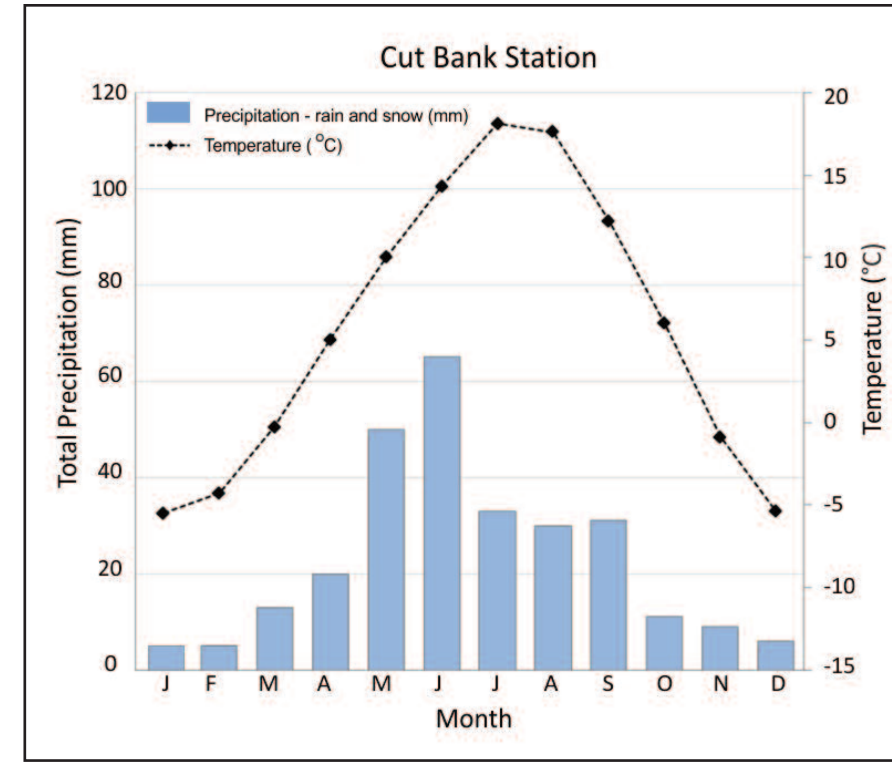


Figure 2.19 Monthly average total precipitation and temperature for Cut Bank Station
National Oceanic and Atmospheric Administration (1981–2010)

In the study area, Cypress Hills station, which has an elevation of 1196 m, receives the greatest amount of precipitation (Figure 2.18). This station also receives more snow than the surrounding stations. Snow represents 42% of the total precipitation in Cypress Hills. The highest part of the hills shows precipitation of 501 to 700 mm/a and the lowest part of 401 to 500 mm/a. There is another zone characterized by high precipitation (401–500 mm/a) that is located in central-southern Alberta; it extends to Magrath on the western side.

The driest sector is located in the Disturbed Belt, where the amount of precipitation varies between 269 and 300 mm/a (Figure 2.19). Cut Bank is the station that receives the least precipitation. The region extending between Tiber Reservoir, southern Havre and southern Cypress Hills is also characterized by low precipitation (269–300 mm/a). There is a high yearly variability and uneven distribution of rainfall within the study area (Kjearsgaard et al., 1986). The stations in Montana generally show less precipitation than the ones in Alberta.

Methodology:

Annual precipitation data were compiled in an Excel file with geographic coordinates, elevation and names of the climate stations. The Excel file was transformed to a point shapefile. Canadian data are the climate normals, measured and calculated by Environment Canada (2015). American data are the climate normals, measured and calculated by National Centers for Environmental Information of National Oceanic and Atmospheric Administration (NOAA).

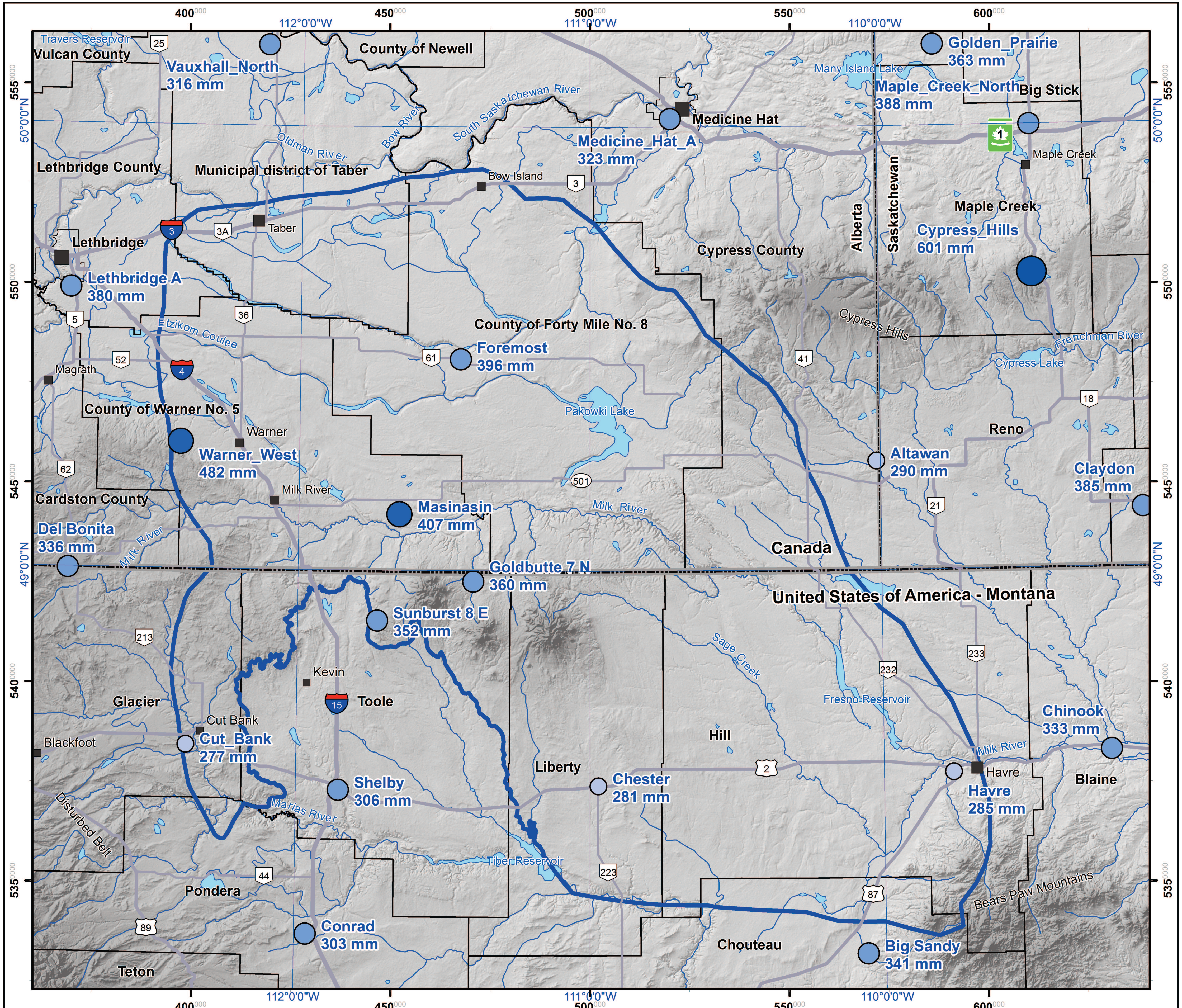
Sources:

Environment Canada, Canadian Climate Normals. 1981–2010 Climate Normals and Averages. <http://climate.weather.gc.ca/climate_normals/index_e.html>

National Centers for Environmental Information of National Oceanic and Atmospheric Administration (NOAA). Data Tools: 1981–2010 Normals. <http://www.ncdc.noaa.gov/cdo-web/datatools/normals>

Klohn Crippen Consultants Ltd., 2003. Milk River basin preliminary feasibility study report. Alberta Environment, Lethbridge, Alberta.

Kjearsgaard, A., Tajek J., Pettapiece, W.W., and McNeil, R.L., 1986. Soil survey of the County of Warner, Alberta. Alberta Institute of Pedology, report no. S-84-46. Agriculture Canada, Edmonton, Alberta.
<http://sis.agr.gc.ca/cansis/publications/surveys/ab/ab46/index.html>



MAP 2.7

Annual Average Total Precipitation 1981 - 2010

Projection UTM 12N 1:1 000 000

Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Climate Station - Annual Total Precipitation (mm)
- 269 - 300
- 301 - 400
- 401 - 500
- 501 - 700

Aquifer Extent
- Milk River

Elevation (m a.m.s.l.)
- High : 2595 m
- Low : 620 m

2.9 Annual Temperature

The study area is characterized by a semi-arid climate with short, warm summers and cold winters that include occasional to frequent mild periods. The climate of the region is influenced by the proximity of the Rocky Mountains and associated Chinook wind, and more locally by the hills and mountains. A Chinook is a warm, dry wind that moves down the eastern slopes of the Rockies and raises the temperatures. It moderates winters in southern Alberta, generating the warmest winters on the prairies. The local climate is further modified by the presence of the Milk River Upland, the Sweet Grass Hills and the Cypress Hills (Klohn Crippen Consultants Ltd., 2003).

Figure 2.20 Milk River at Writing-On-Stone Provincial Park (Alberta).
Photo credit: © Marie-Amélie Pétré

The frost-free period on the plains is generally greater than 120 days. The last spring frost occurs about mid-May and the first fall frost comes about mid-September. The warmest months are July and August. The coldest months are December and January.

The average annual temperature ranges from 3°C to 7.4°C. The warmest temperatures are found in Montana, while the coldest ones are generally observed in Saskatchewan or near the Alberta-Saskatchewan border. The coldest temperatures were recorded at the station of Altawan with annual average temperature of 3°C (Figure 2.21). The station is located near the Alberta-Saskatchewan border. The coldest zone (2.9 to 4°C) of the study area extends from south of the Alberta-Saskatchewan and Montana border to the north of the Cypress Hills in Saskatchewan.

Big Sandy is the warmest station with annual temperature of 7.4°C (Figure 2.21). Other warm temperatures were measured in central Montana. The warmest temperature (6.1 to 8°C) region of the study area extends from eastern Montana to south-western Montana including southern Alberta. This region does not include Cut Bank and Chester areas. Another warm area is found in northern Alberta in the Medicine Hat region. The spatial distribution of the annual temperature shows warmer temperatures in Montana and Alberta than in Saskatchewan (see Map 2.8). Areas higher in elevation are characterized by lower mean annual temperature.

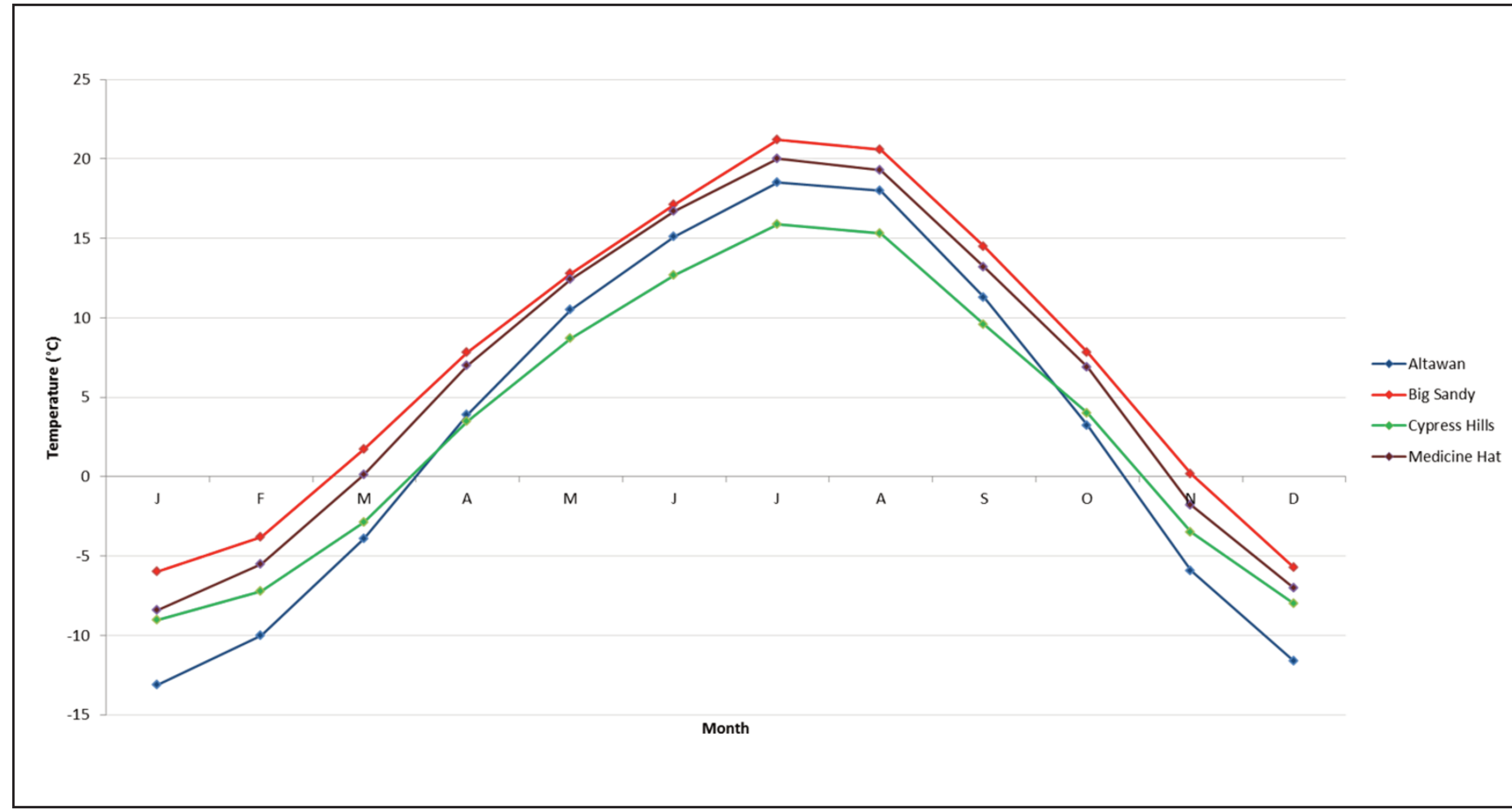


Figure 2.21 Monthly average temperature. Environment Canada (1981–2010) and National Oceanic and Atmospheric Administration (1981–2010)

Methodology:

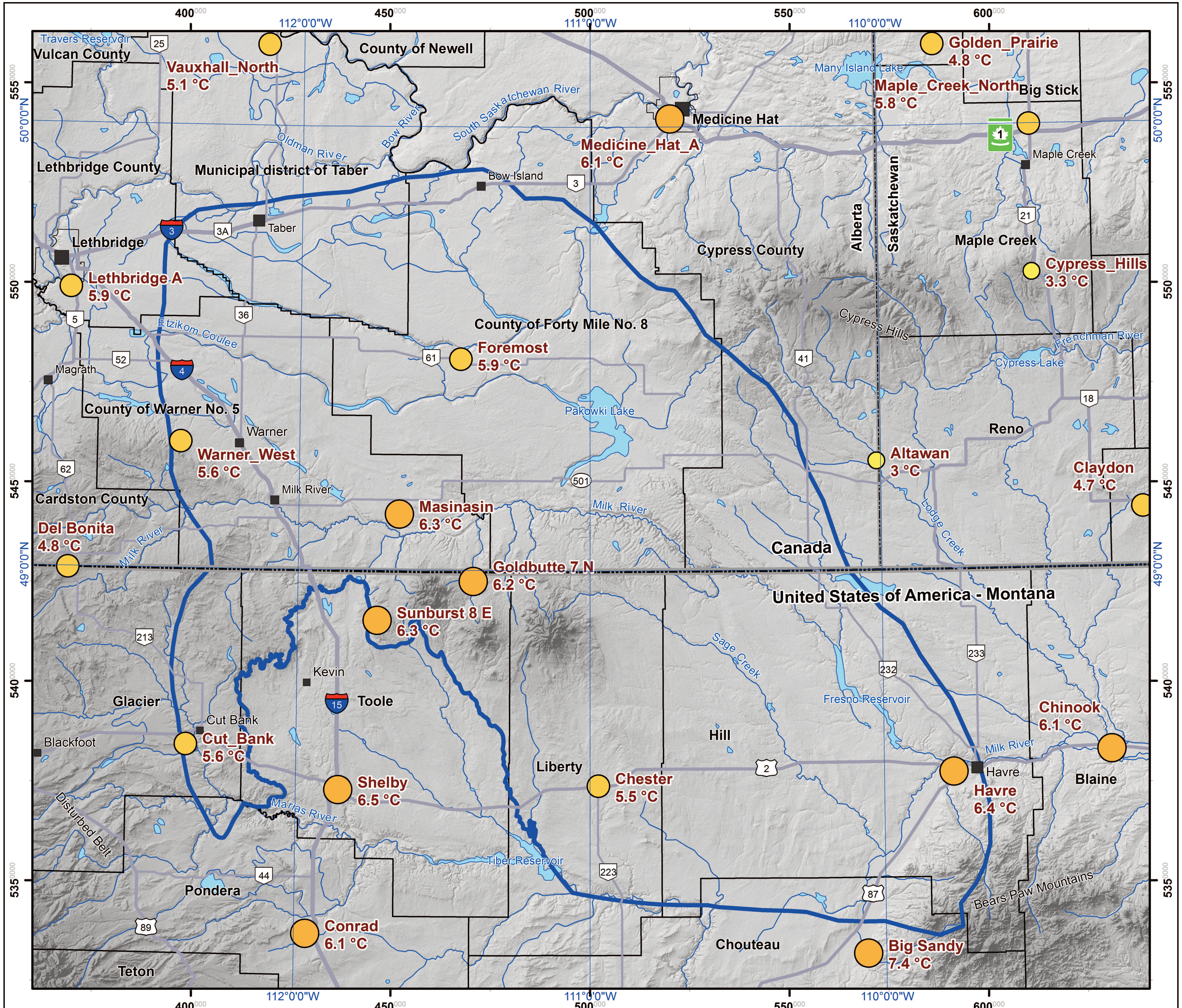
Annual temperature data were compiled in an Excel file with geographic coordinates, elevation and name of the climate stations. The Excel file was transformed to a point shapefile. Canadian data are the climate normals, measured and calculated by Environment Canada (2015). American data are the climate normals, measured and calculated by National Climatic Data Center of National Oceanic and Atmospheric Administration (NOAA).

Sources:

Environment Canada, Canadian Climate Normals. 1981–2010 Climate Normals and Averages. <http://climate.weather.gc.ca/climate_normals/index_e.html>

Klohn Crippen Consultants Ltd., 2003. Milk River basin preliminary feasibility study report. Alberta Environment, Lethbridge, Alberta.

National Centers for Environmental Information of National Oceanic and Atmospheric Administration (NOAA). Data Tools: 1981–2010 Normals.
<http://www.ncdc.noaa.gov/cdo-web/datatools/normals>



MAP 2.8

Annual Average Temperature 1981 - 2010

Projection UTM 12N 1:1 000 000

Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Climate Station - Annual Temperature (°C)
- 2.9 - 4.0
- 4.1 - 6.0
- 6.1 - 8.0

Aquifer Extent
- Milk River

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m

2.10 Seasonal Temperature

Summer

The summer season includes June, July and August. In the study area, the average summer temperature ranges between 14.6°C and 19.7°C (Figures 2.22 and 2.23). Summer monthly temperatures for July and August are comparable; however, June shows colder temperatures. July is the warmest month.

The lowest average summer temperatures are distributed in different parts of the study area. Cypress Hills is the coldest area with a temperature of 14.6°C. The western part of the study area, south of Magrath, also shows a low temperature (15.6°C). The three highest-temperatures stations are located around Bears Paw Mountains. The warmest temperatures are found at Big Sandy, the most southern station. High temperature (18.1°C to 20°C) is also found in three areas: Medicine Hat, Maple Creek, and south-central Alberta.

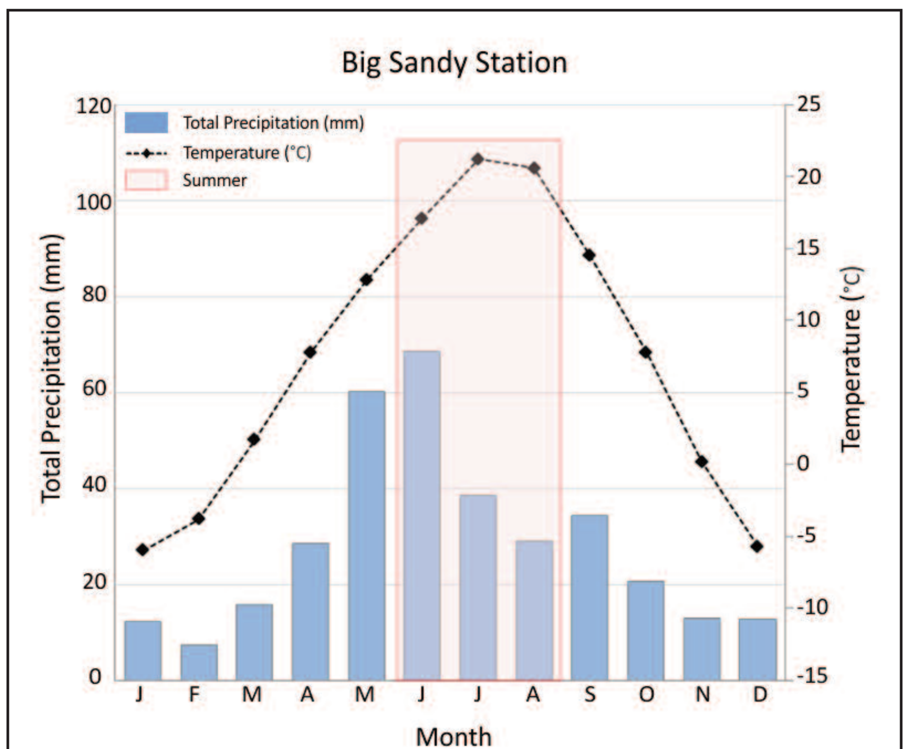


Figure 2.22 Big Sandy monthly precipitation and temperature.
National Oceanic and Atmospheric Administration (1981–2010)

Fall

The fall season includes September, October and November. In the study area, the average fall temperature ranges between 2.9°C and 7.6°C. Fall monthly temperatures are not comparable; there is a difference of more than 11°C between September and November (Figures 2.22 and 2.23). The coldest fall temperatures are mostly concentrated in Saskatchewan. Altawan and Cypress Hills stations show the coldest temperatures (2.9°C and 3.4°C, respectively). The coldest zone of the study area is characterized by temperatures of 2.9°C to 4.0°C. It extends from south of the Alberta-Saskatchewan-Montana border to the north of the Cypress Hills in Saskatchewan.

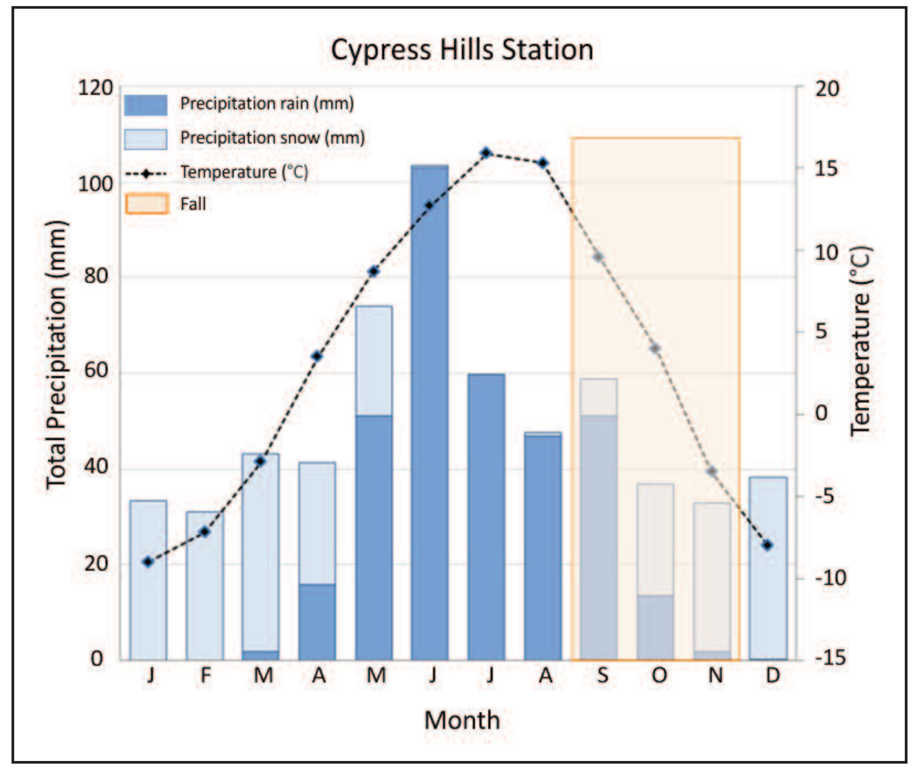


Figure 2.23 Cypress Hills monthly precipitation and temperature.
Environment Canada (1981–2010)

The highest temperatures are located heterogeneously in Montana and southern Alberta. The warmest fall temperature (7.6°C) is found at Big Sandy, the most southern station near Bears Paw Mountains. There are two zones of higher fall temperatures (6.1°C to 8°C) in the study area. The biggest one extends from eastern Montana to southwestern Montana including southern Alberta. The other one is located around Medicine Hat, in southeastern Alberta. The spatial distribution pattern of the lowest to highest average fall temperature is almost the same as the equivalent average annual temperature spatial distribution pattern. The only differences are in southwestern and northeastern Montana.

Winter

The winter season includes December, January and February. The temperatures are below the freezing point. In the study area, the average winter temperature ranges between -11.6°C and -4.6°C. Winter monthly temperatures are comparable; however, January is the coldest month except for Goldbutte station where December is colder (Figure 2.24).

The coldest temperatures are generally in the eastern part of the study area; however, the northern region also exhibits temperatures colder than the southernmost. The Altawan station, located near the Alberta-Saskatchewan border, shows the coldest temperature (-11.6°C). The zone around this station constitutes the coldest zone of the study area with temperatures of -13°C to -10°C. The second coldest region is next to the first one; it surrounds the Cypress Hills and extends to the north following the Alberta-Saskatchewan border. The temperatures in this zone vary between -9.9 and -8°C. The highest temperature is observed at Goldbutte station, near Sweet Grass Hills. The warmest area shows temperatures varying between -5.9°C and -4°C. It extends from the west to north of Chester and in the southeastern corner of the study area.

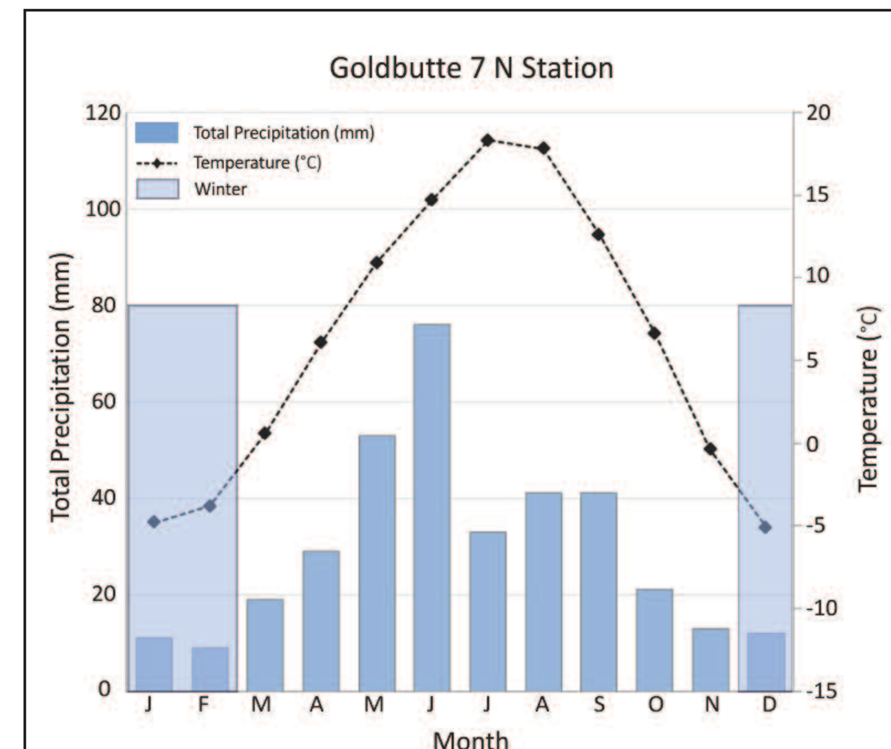


Figure 2.24 Goldbutte 7 N monthly precipitation and temperature.
National Oceanic and Atmospheric Administration (1981–2010)

Spring

The spring season includes March, April and May. In the study area, the average spring temperature ranges between 3.1°C and 7.4°C. Spring monthly temperatures are not comparable; there is a difference of more than 10°C between March and May.

The coldest spring temperatures are distributed in the eastern part of the study area. The Cypress Hills station shows the coldest temperature (3.1°C) (Figure 2..10). The Altawan station also exhibits a low spring temperature (3.5°C) (Figure 2.25). In spring, the coldest zone (2.9°C to 4°C) of the study area extends from south of the Alberta-Saskatchewan-Montana border to north of Cypress Hills in Saskatchewan.

The three highest spring temperatures are located around Bears Paw Mountains and northern Alberta. The warmest temperature (7.4°C) is found at Big Sandy, the most southern station. In spring, the Bears Paw Mountains become the warmest region of the study area. The two other warm areas (6.1°C to 8°C) in spring are a strip crossing Alberta north to south, from northern Medicine Hat to southern Masinasin, and the region around Shelby.

The spatial distribution of the temperature in spring is similar to the annual distribution. Central Montana has a colder temperature in the spring than the annual average; however, Alberta shows a warmer spring temperature than the average.

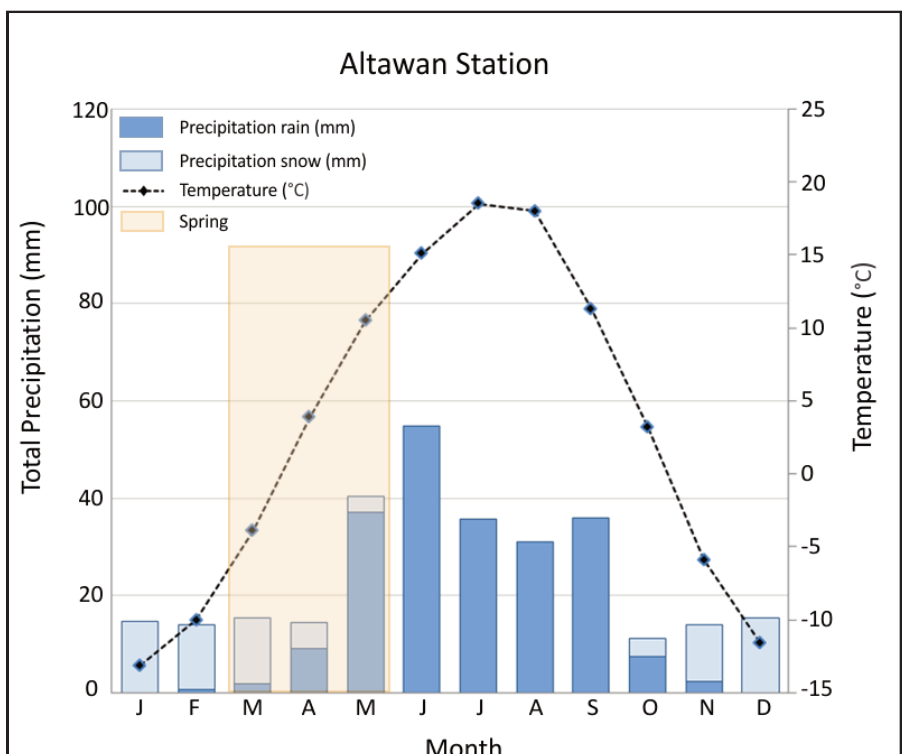


Figure 2.25 Altawan monthly precipitation and temperature.
Environment Canada (1981–2010)

Climate is an important parameter in hydrogeology. It has an impact on infiltration and consequently recharge. Indeed, the possibility of infiltration depends on many factors including precipitation and soil condition. In the study area, the ground is frozen during the winter, and precipitation falls mainly as snow (Figure 2.26). This situation continues until spring, when the ground thaws and melt water from the snow cover or spring rain are finally able to infiltrate the soil (Rivera, ed., 2014). During summer, temperatures are warm and evapotranspiration rates are high. These conditions produce a gradual decline in the water table that persists into the fall.

The climate of any region is variable over time, and these changes affect groundwater recharge. Moreover, local surface conditions within a region, including topography, vegetation, soil and aquifer permeability, also affect recharge (Rivera, ed., 2014). Recharge can thus vary also spatially even when the same climate conditions prevail throughout a region.

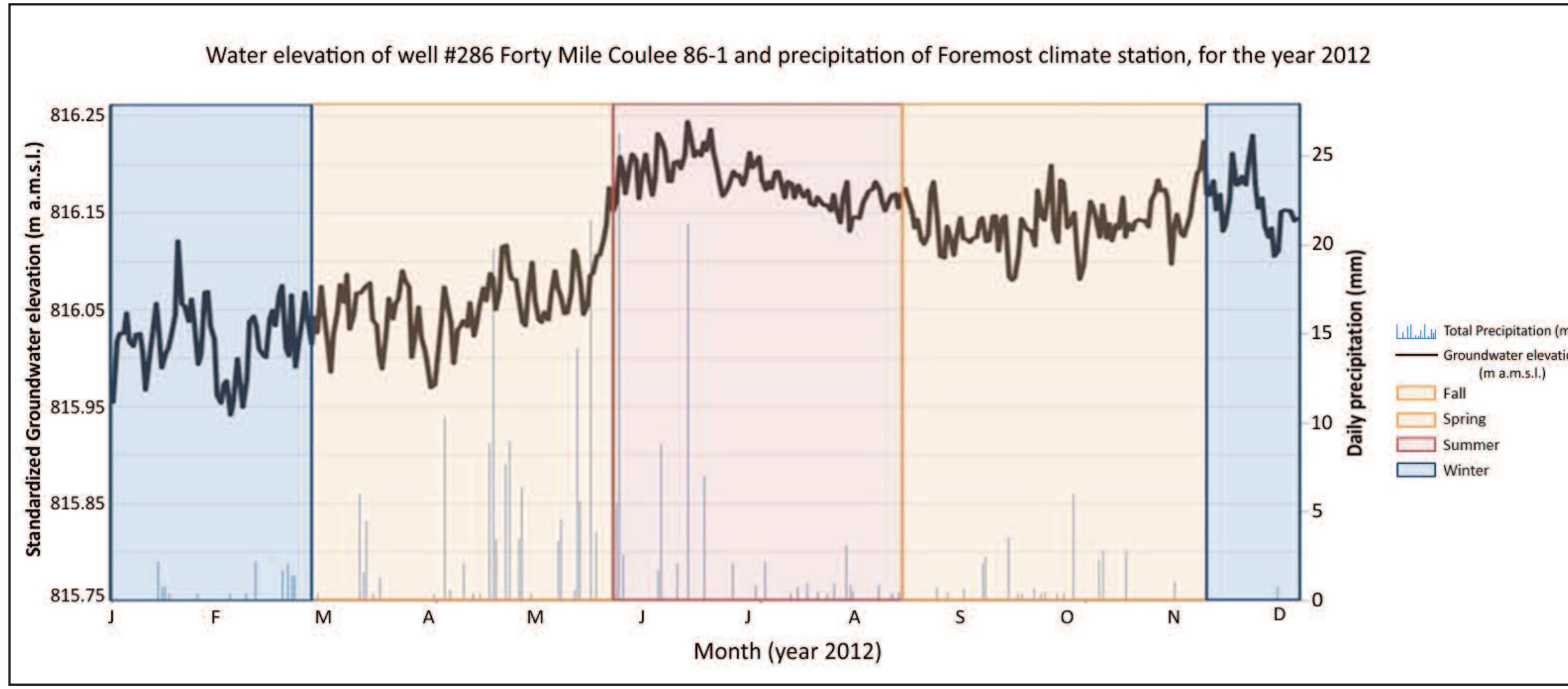


Figure 2.26 Seasonal variations of groundwater elevation and precipitation for the year 2012.
Alberta Environment and Parks, Groundwater Observation Well Network (GOWN) and Environment Canada (2012)

Methodology:

Monthly mean temperatures have been classified by season. Fall includes September, October and November. Spring includes March, April and May. Summer includes June, July and August. Fall includes September, October and November. Winter includes December, January and February. An average of these months' mean temperatures has been calculated. Seasonal temperature data were compiled in an Excel file with geographic coordinates, elevation and name of the climate stations. The Excel file was transformed to a point shapefile. Canadian data are the climate normals, measured and calculated by Environment Canada (2015). American data are the climate normals, measured and calculated by National Climatic Data Center of National Oceanic and Atmospheric Administration (NOAA). The values were classified in four classes for winter and three for the other seasons.

Sources:

Alberta Environment and Parks, Groundwater Observation Well Network <http://aep.alberta.ca/water/programs-and-services/groundwater/groundwater-observation-well-network/default.aspx>

Environment Canada, Canadian Climate Normals. 1981–2010 Climate Normals and Averages. <http://climate.weather.gc.ca/climate_normals/index_e.html>

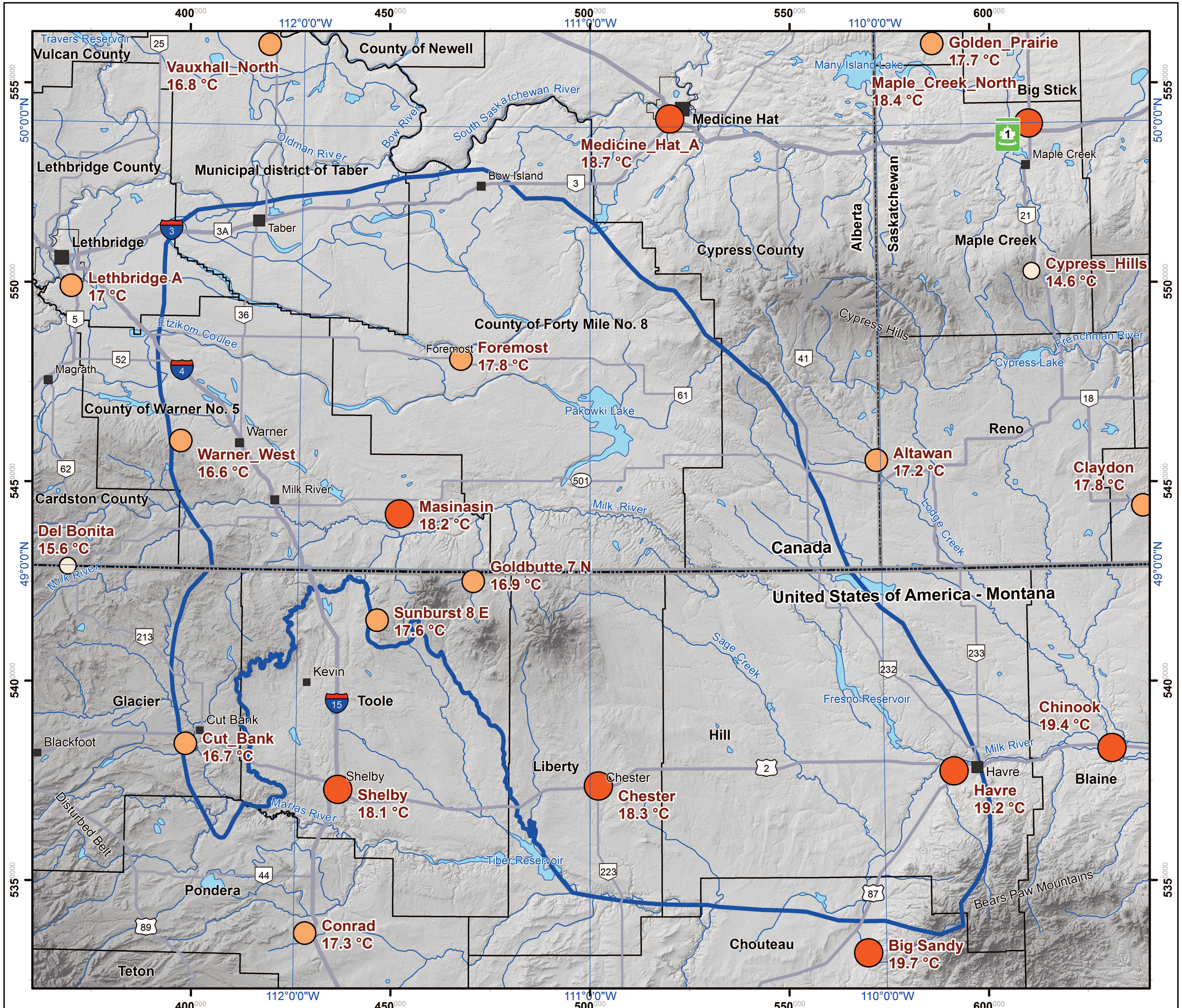
National Climatic Data Center of National Oceanic and Atmospheric Administration (NOAA). Data Tools: 1981–2010 Normals. <http://www.ncdc.noaa.gov/cdo-web/datatools/normals>

Rivera, A., (ed.), 2014. Book: Canada's Groundwater Resources. Markham, Ontario. Fitzhenry & Whiteside Limited, 824 p. ISBN 978-1-55455-292-4

MAP 2.9

Annual Average Summer Temperature 1981 - 2010

Projection UTM 12N 1:1 000 000



Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

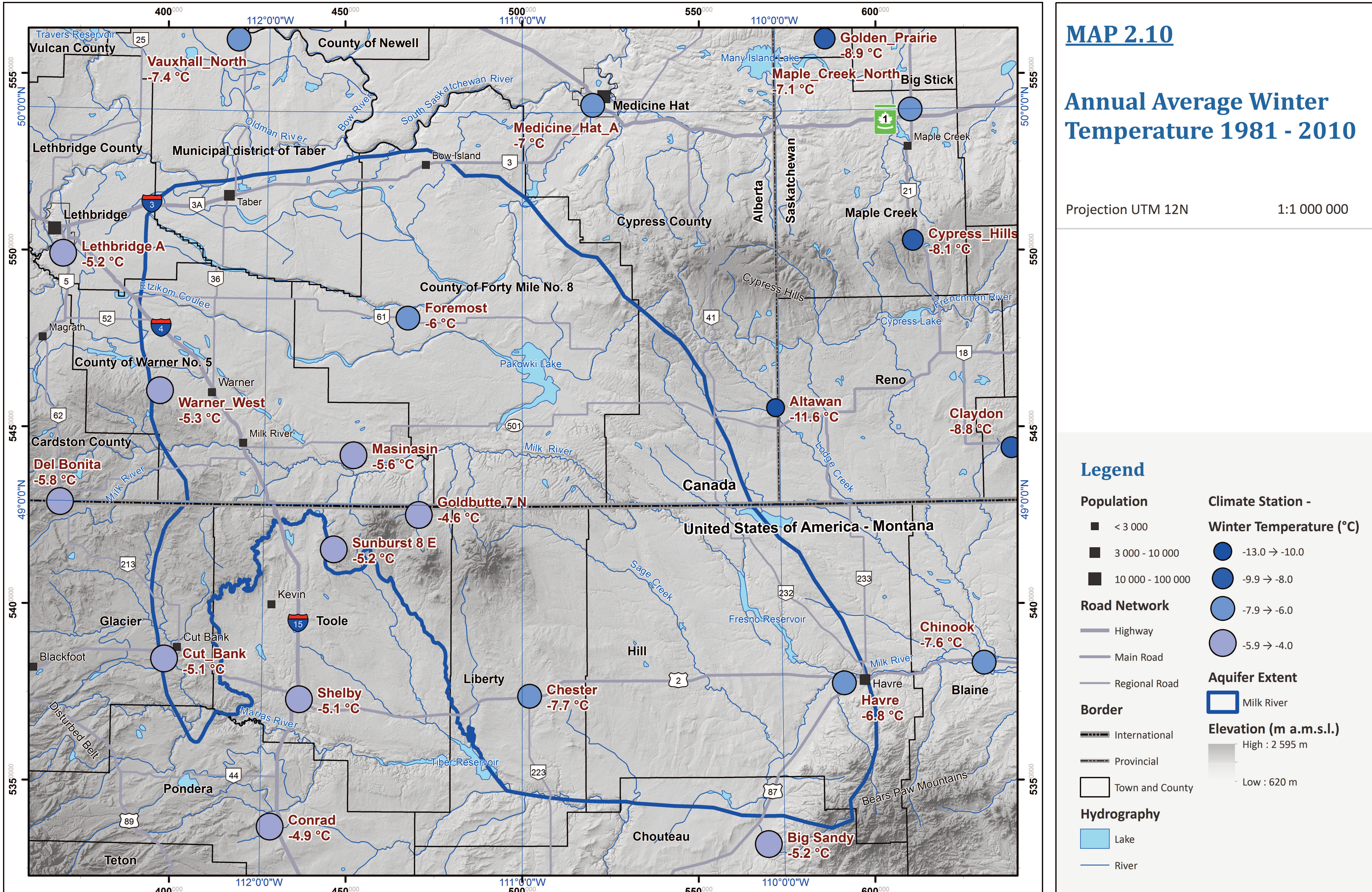
Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Climate Station - Summer Temperature (°C)
- 14.2 - 16.0
- 16.1 - 18.0
- 18.1 - 20.0

Aquifer Extent
- Milk River

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m



MAP 2.10

Annual Average Winter Temperature 1981 - 2010

Projection UTM 12N 1:1 000 000

2.11 Potential Evapotranspiration

Potential evapotranspiration is defined as “the maximum quantity of water capable of being evaporated in a given climate, by a continuous expanse of vegetation covering the whole ground and well supplied with water. It includes evaporation from the soil and transpiration from the vegetation from a specific region in a specific time interval, expressed as a depth of water.” (WMO, 1992). In the study area, potential evapotranspiration ranges between 502 and 621 mm/a with a mean value of 567 mm/a (Figure 2.27). Table 2.6 shows annual potential evapotranspiration values for the 49 stations used in the larger area defined on Figure 2.16.

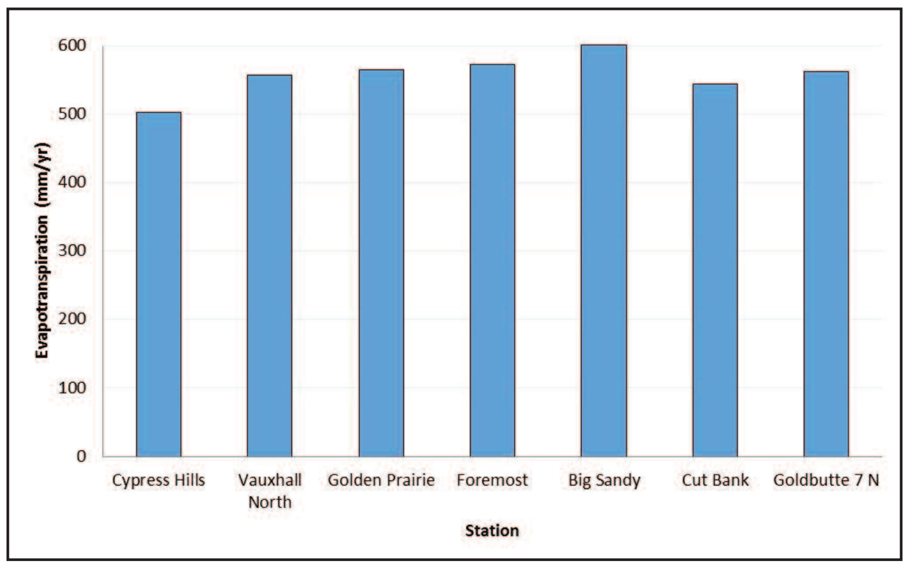


Figure 2.27 Potential evapotranspiration values throughout the study area. Based on climatic data from Environment Canada (1981–2010) and National Oceanic and Atmospheric Administration (1981–2010)

The actual evapotranspiration is defined as “the quantity of water vapour evaporated from the soil and the plants.” (WMO, 1992). The main difference between potential and actual evapotranspiration is that actual evapotranspiration considers that the water supply available for evaporation or transpiration is limited under natural climatic conditions. Estimating an exact value for evaporation over an area is very difficult due to the uncertainty of parameters that must be taken into account. Therefore, this parameter was not estimated for the Milk River Aquifer.

The station with the lowest potential evapotranspiration value (502 mm/a) is Cypress Hills. The area surrounding this station shows a low potential evapotranspiration values zone (502–540 mm/a). It extends from south of the Alberta-Saskatchewan border to the north of the Cypress Hills in Saskatchewan. There is another low potential evapotranspiration region in the western part of the study area, in Cardston County, which also shows a value of 525 mm/a.

Table 2.6 Potential evapotranspiration values for every climate station

Station	Elevation (m a.m.s.l.)	Precipitation (mm)	Potential Evapotranspiration (mm/a)
Climate Stations in the study area			
Altawan	945	290	536
Big Sandy	844	341	621
Chester	955	281	575
Chinook	738	333	601
Claydon	975	385	561
Conrad	1 082	303	567
Cut Bank	1 170	277	544
Cypress Hills	1 196	601	502
Del Bonita	1 322	336	525
Foremost	892	396	572
Goldbutte 7 N	1 066	360	562
Golden Prairie	746	363	565
Havre	788	285	598
Lethbridge A	929	380	560
Maple Creek North	764	388	581
Masinasin	953	407	584
Medicine Hat A	717	323	591
Shelby	1 014	306	581
Sunburst 8 E	1 128	352	571
Vauxhall North	760	316	557
Warner West	1 109	482	550
Climate Stations outside the study area			
Augusta	1 241	350	580
Calgary Int	1 084	419	524
Chinook 35	1 024	324	574
Choteau	1 172	269	565
Claresholm waterworks	1 008	424	547
Creston	896	503	561
Fairfield	1 214	315	580
Fernie	1 001	1 227	537
Fort Benton	807	335	611
Gibson Dam	1 399	409	515
Gleichen	905	338	536
Great Falls	1 117	375	584
Harlem 4 W	723	295	629
Holter Dam	1 063	334	627
Hungry Horse Dam	963	837	578
Malta	690	331	641
Oyen Cappon	793	312	557
Polebridge	1 073	494	505
Polson Kerr Dam	832	395	621
Rosetown	586	327	550
Saco 1 NNW	666	299	599
Sand Creek	887	374	605
Shaunavon 2	914	395	529
Sparwood	1 138	613	516
Swift Current CDA	825	357	553
Vulcan	1 049	415	543
West Glacier	961	740	518
Zortman	1 230	452	575

Based on climatic data from Environment Canada (1981–2010) and National Oceanic and Atmospheric Administration (1981–2010)

The stations with high potential evapotranspiration values are located around Bears Paw Mountains. The highest potential evapotranspiration value (620.8 mm/a) is found at Big Sandy, the southernmost station. The values in this area range from 581 to 640 mm/a. There are other high potential evapotranspiration zones in Medicine Hat, Shelby and eastern Milk River.

The spatial distribution pattern of the lowest to highest potential evapotranspiration values is comparable with the equivalent distribution pattern of summer temperature. The highest and lowest summer temperatures and potential evapotranspiration values correspond to the same areas.

Methodology:

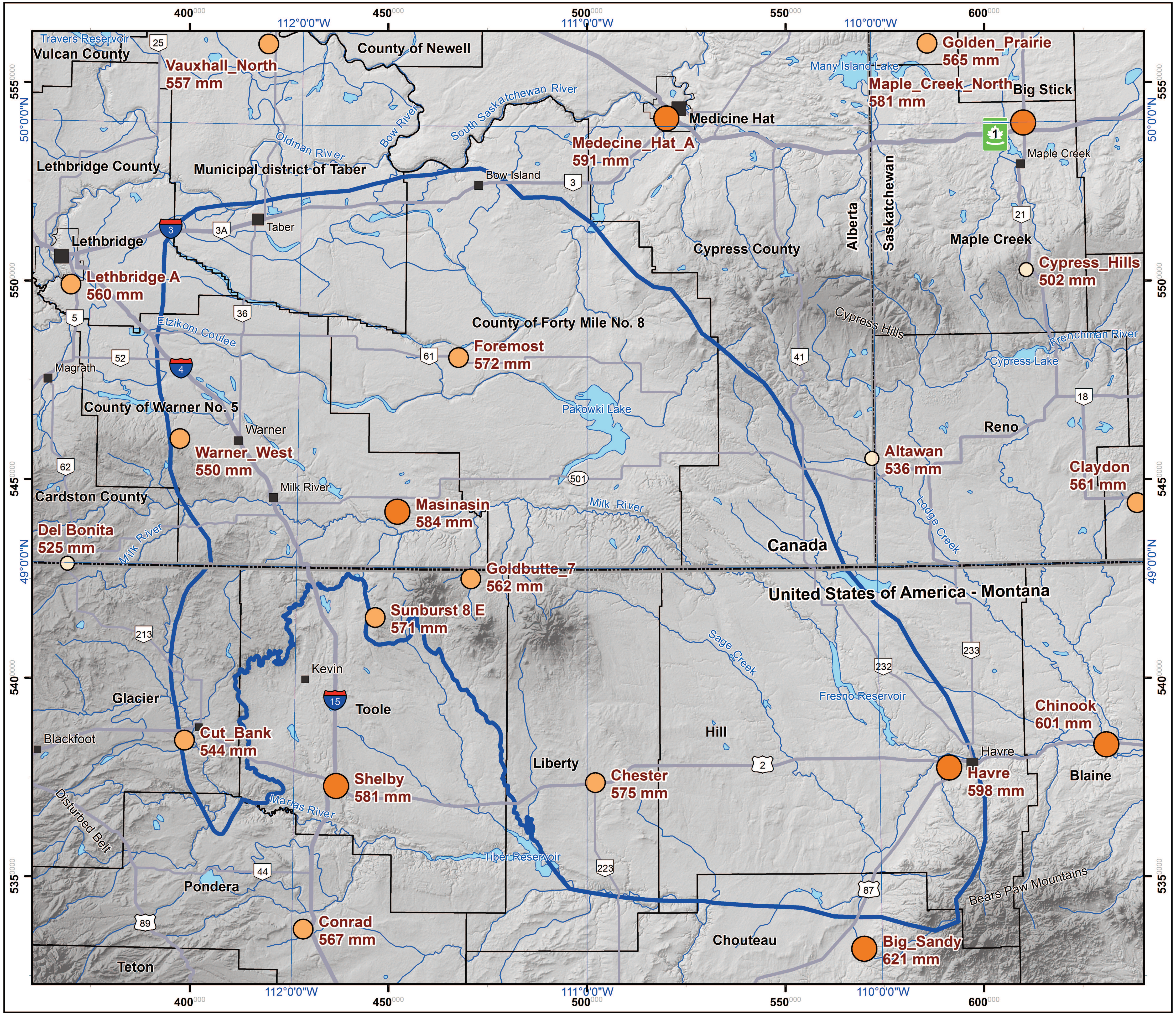
Potential evapotranspiration has been calculated with monthly mean temperature of the climate normals using the Thornthwaite method. Evapotranspiration data were compiled in an Excel file with geographic coordinates, elevation and name of the climate stations. The Excel file was converted into a point shapefile.

Sources:

Environment Canada, Canadian Climate Normals. 1981–2010 Climate Normals and Averages. <http://climate.weather.gc.ca/climate_normals/index_e.html>

National Centers for Environmental Information of National Oceanic and Atmospheric Administration (NOAA). Data Tools: 1981-2010 Normals. <http://www.ncdc.noaa.gov/cdo-web/datatools/normals>

World Meteorological Organization, 1992. International meteorological vocabulary, second edition. Geneva. ISBN 978-92-630-2182-3. Also available online through METEOTERM <http://www.wmo.int/pages/prog/lsp/meteoterm_wmo_en.html>



MAP 2.11

Annual Average Potential Evapotranspiration (PET) 1981 - 2010

Projection UTM 12N 1:1 000 000

Legend

Population

- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network

- Highway
- Main Road
- Regional Road

Border

- International
- Provincial
- Town and County

Hydrography

- Lake
- River

Climate Station - Potential Evapotranspiration PET (mm)

- 502 - 540
- 541 - 580
- 581 - 640

Aquifer Extent

- Milk River

Elevation (m a.m.s.l.)

High : 2 595 m

Low : 620 m

3 Fieldwork

3.1 Field Activities

Fieldwork was performed within the framework of the Milk River Transboundary Aquifer Project. The field campaigns took place in Winter 2012 (Alberta), Summer 2013 (Montana) and Winter 2013 (Alberta). The objectives of this fieldwork, as documented in Map 3.1, were to:

1. Measure the static water levels from private wells drilled in the MRA;
2. Collect groundwater samples for isotopic analysis (^{3}H, ^{13}C, ^{14}C and ^{36}Cl);
3. Measure the pressure of flowing artesian wells; and
4. Conduct a survey with landowners regarding the current groundwater use.

Fieldwork no. 1 (December 2012, southern Alberta)

This fieldwork was carried out by Marie-Amélie Pétré (GSC-Québec and INRS-ETE), Clarisse Deschêne-Rancourt (INRS-ETE) and Daryl Jacques (PFRA AgriFood Canada, Regina). Prior to the fieldwork, a flyer explaining the goals of the study and the field activities was sent to the stakeholders and landowners in southern Alberta.

Outcome: 24 wells visited, 17 groundwater samples collected (from 15 different wells+2 duplicates), and 13 static water levels measured. 17 samples were sent for ^{14}C analysis at the Environmental Isotopes Laboratory (EIL – U of Waterloo), 16 samples for ^{3}H analysis (EIL – U of Waterloo) and 10 samples for ^{36}Cl analysis (Prime Lab, Purdue University).

Fieldwork no. 2 (summer 2013, northern Montana)

The USGS (Helena Office) carried out summer fieldwork in northern Montana.

Outcome: 11 groundwater samples were collected; they were analyzed for ^{3}H, ^{14}C and ^{36}Cl. A survey on water use was conducted with the owners of the sampled wells.

Fieldwork no. 3 (December 2013, southern Alberta)

Davison Environmental Consulting was hired by the Geological Survey of Canada to carry out complementary fieldwork in southern Alberta.

Outcome: Four pressure measurements were collected from flowing wells, eight static water levels were measured and a groundwater usage survey was conducted with municipalities and communities both in southern Alberta and northern Montana.

Note: The physicochemical parameters were collected *in situ* for all the groundwater samples. However, the total alkalinity and inorganic chemistry analyses were performed only for the summer 2013 fieldwork no. 2 in northern Montana.

Table 3.1 shows the number of groundwater levels measured during each field campaign. The groundwater levels measured were all static, meaning that the elevation of the water table, or the piezometric surface, was not influenced by pumping or recharge.

Water levels were measured with a water level indicator. To do the measurement, the probe was lowered into the piezometer. When the probe touched the water table top, an acoustic signal sounded. The cable was then stretched. The water depth represents the distance between the water level and the top of the casing. The groundwater depth was converted to groundwater elevation using a digital elevation model.

Table 3.1 Groundwater levels measured during fieldwork

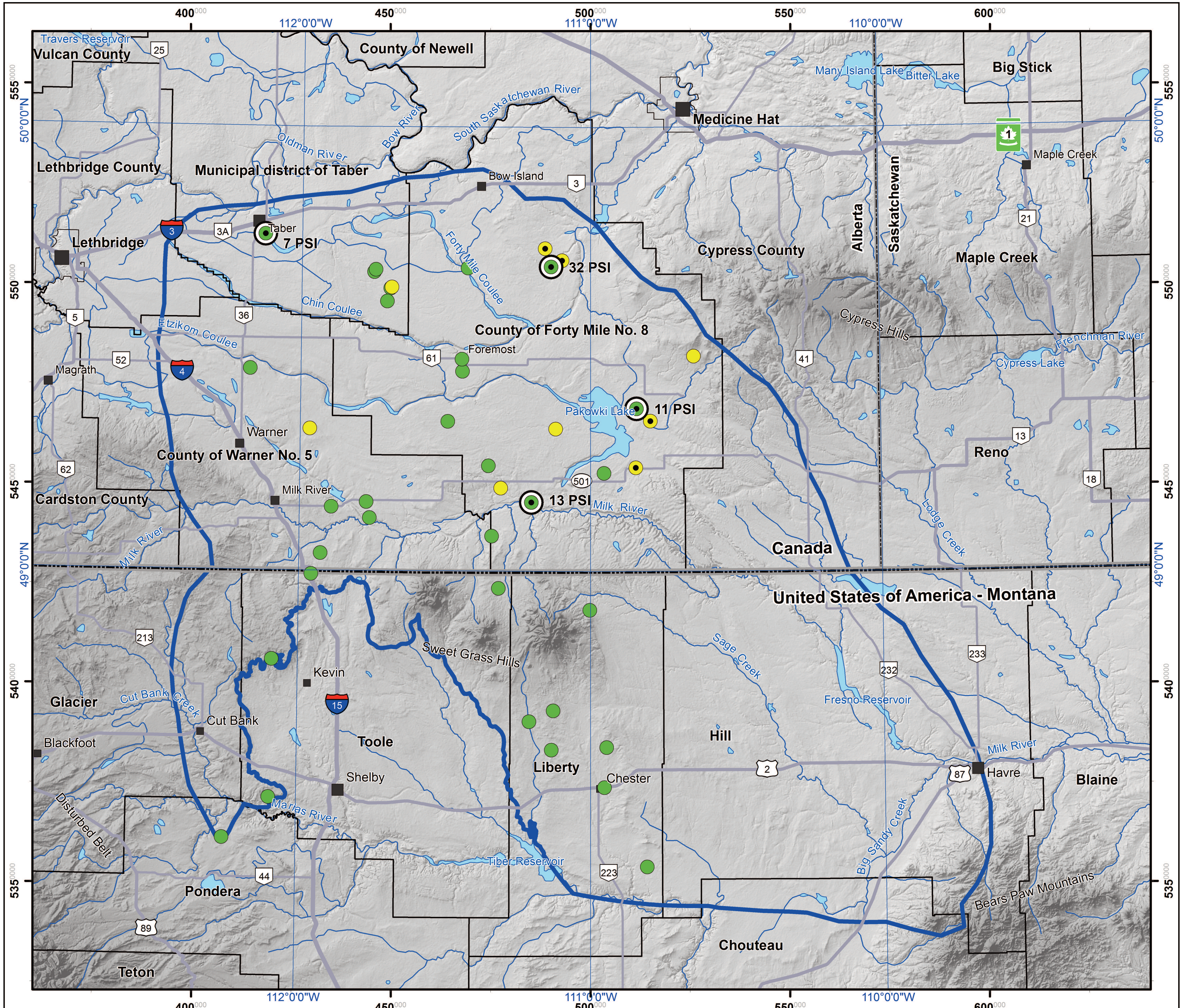
Fieldwork	Year	Location	Groundwater level measurements
1	2012	Southern Alberta	13
2	2013	Northern Montana	4
3	2013	Southern Alberta	10

Figure 3.1 Groundwater depth measurement – Example of a measurement taken with a water level indicator in a well with high casing.
Photo credit: © Alix Guillot

The casing height relative to the ground was measured with the cable of the water level indicator. This value was then subtracted from the groundwater elevation to obtain the water table elevation relative to the ground.

Figure 3.2 Water table depth measurement – Example of a measurement taken with a water level indicator in a well with low casing.
Photo credit: © Francesca Audet-Gagnon

Fieldwork



MAP 3.1

Field Activities – Groundwater Level Measurements

Projection UTM 12N 1:1 000 000

Fieldwork

3.2 Groundwater Sampling

To characterize the groundwater quality of the Milk River Aquifer, groundwater samples were collected during fieldwork. The physicochemical parameters were collected *in situ* for all the groundwater samples.

Twenty-eight groundwater samples were collected and analyzed for ^{3}H, ^{13}C and ^{14}C (17 in Alberta and 11 in Montana) by the EIL (University of Waterloo, Ontario). ^{36}Cl analyses were performed on 20 groundwater samples (9 in Alberta and 11 in Montana). The samples from Alberta were analyzed by the PRIME Lab (Purdue University, Indiana, U.S.A.) whereas those from Montana were analyzed by the Center for AMS (Livermore, California, U.S.A.). In addition, inorganic chemistry analyses were performed for the 11 Montana samples by the INRS-ETE laboratory (Québec City, Canada). All these samples are located on Map 3.2.

The groundwater samples are all representative of the Milk River Aquifer, except 3 groundwater samples that were collected from the Whisky Valley Aquifer, which is located near the town of Milk River, Alberta.

Table 3.2 Groundwater samples collected during fieldwork

Fieldwork	Year	Location	Number of groundwater samples
1	2012	Southern Alberta	17
2	2013	Northern Montana	11
3	2013	Southern Alberta	0

Figure 3.3 Multiparameter water quality probe
Photo credit: © 2008 Rice Rentals

Table 3.3 Groundwater sample analyses summary for MiRTAP (2012–2013)

Well ID (MiRTAP)	^{3}H	^{13}C	^{14}C	$^{36}Cl/Cl$	Inorganic chemistry	Total alkalinity	Physicochemical parameters in situ	Turbidity
A1	x	x	x					
A2	x	x	x	x			x	
A3	x	x	x				x	
A4	x	x	x				x	
A5	x	x	x	x			x	
A6	x	x	x	x			x	
A7	x	x	x	x			x	
A8	x	x	x	x			x	
A9	x	x	x	x			x	
A10	x	x	x	x			x	
A11	x	x	x	x			x	
A12	x	x	x	x			x	x
A13	x	x	x					
A14	x	x	x					
A15	x	x	x					
M1	x	x	x	x	x	x	x	x
M2	x	x	x	x	x	x	x	
M3	x	x	x	x	x	x	x	
M4	x	x	x	x	x	x	x	x
M5	x	x	x	x	x	x	x	x
M6	x	x	x	x	x	x	x	x
M7	x	x	x	x	x	x	x	
M8	x	x	x	x	x	x	x	
M9	x	x	x	x	x	x	x	x
M10	x	x	x	x	x	x	x	x
M11	x	x	x	x	x	x	x	x

Note: The total alkalinity and inorganic chemistry analyses were performed only for the summer 2013 fieldwork #2 in northern Montana.

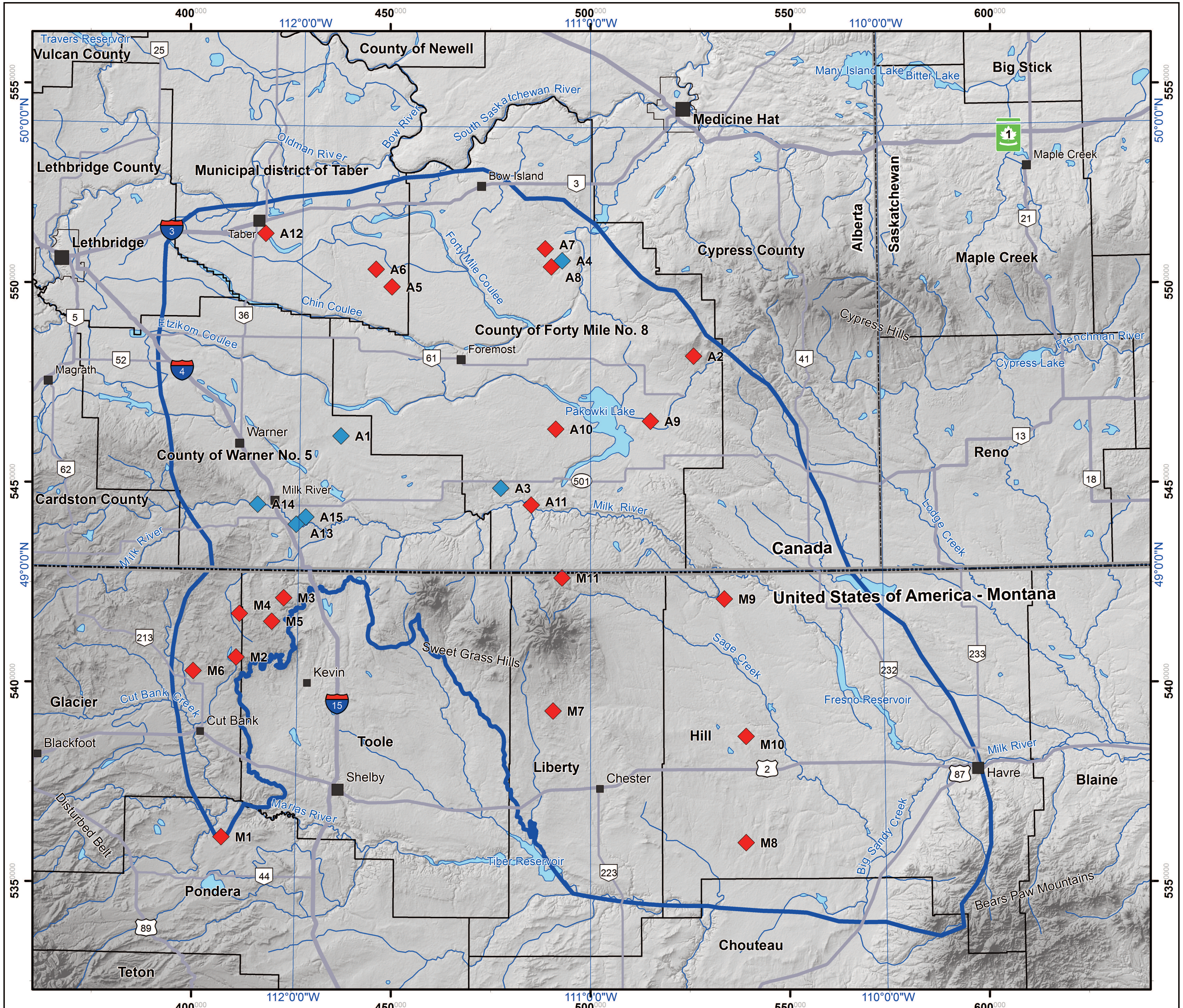
Table 3.2 shows the number of groundwater samples collected during each year. From the 17 samples collected in winter 2012, two were duplicates. Table 3.3 shows the parameters analyzed for every sample.

The physicochemical parameters were collected *in situ* for all the groundwater samples. These parameters are: total alkalinity, oxidation-reduction potential, conductivity, dissolved oxygen content, total dissolved solids, resistivity and salinity. These parameters were measured using a multiparameter water quality probe.

During the first field campaign (2012), 17 groundwater samples were collected: 15 samples from different wells and two duplicates. All the samples were sent for ^{14}C analysis (EIL – U. of Waterloo), 16 samples for ^{3}H analysis (EIL – U. of Waterloo) and 10 samples for ^{36}Cl analysis (Prime Lab, Purdue University).

The second year (2013), 11 groundwater samples were collected; they were analyzed for ^{3}H, ^{14}C and ^{36}Cl.

Figure 3.4 Water sampling – Example of water sampling from a flowing well in southern Alberta. Photo credit: © Marie-Amélie Pétré



MAP 3.2

Field Activities – Groundwater Sampling

Projection UTM 12N 1:1 000 000

Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

MiRTAP Sampling Wells

Analysed Isotopes
- ^{3}H, ^{13}C, ^{14}C
- ^{3}H, ^{13}C, ^{14}C, $^{36}Cl/Cl$

Aquifer Extent
- Milk River

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m

4 Geology

4.1 Bedrock Regional Geology

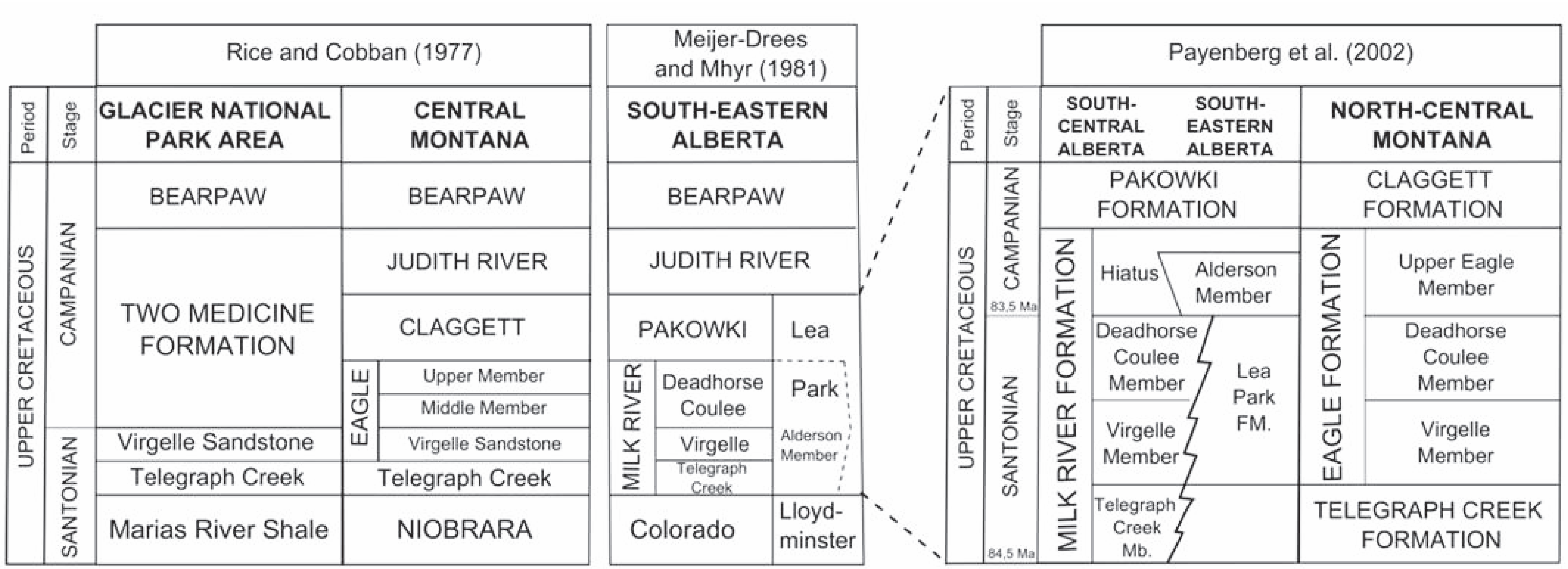
Introduction

The geologic and stratigraphic settings of the study area can be described as a succession of marine and continental sediments that were deposited as the Upper Cretaceous Interior Sea fluctuated (Russell, 1970). The Upper Cretaceous strata are briefly described below and represented on the bedrock geological map in Map 4.1. Their hydrostratigraphic role is indicated in Table 5.1 and briefly described in Section 5.2.

The following description of the bedrock regional geology in the study area is derived from Pétré et al. (2015; Map 4.1). The transboundary nature of the study area and the geological mapping delineated by provincial, state, and national boundaries has resulted in different terminology in the respective political jurisdictions and within different geological domains within, for example, Montana. Consequently, geological units do not have the same name on each side of the border. As the characterization of the Upper Cretaceous Milk River Formation (or Eagle Formation in Montana) progressed, the stratigraphic nomenclature evolved significantly during the 20th century (Table 4.1). The stratigraphic charts differ not only between southern Alberta and northern Montana but also within northern Montana (east and west of the Sweetgrass Arch).

The proposed nomenclature in the context of this study (Table 4.2) is based on the previous works of Payenberg et al. (2002) and Rice and Cobban (1977). The study area is divided into four zones, each with a distinct succession of geological units.

Table 4.1 Comparative stratigraphic nomenclatures, Pétré et al. (2015)



The locations of the four zones are defined by the geological disconformity surface, which separates the Milk River Formation in Zone 1 from the Alderson Member in Zone 2:

- Zone 1: Southwestern part of the study area in Alberta, before the facies change
- Zone 2: Southeastern Alberta, beyond the facies change.
- Zone 3: Northwestern Montana, west of the Sweetgrass Arch;
- Zone 4: Northern Montana, east of the Sweetgrass Arch.

Colorado Group

The Colorado Group underlies the whole study area. It consists mainly of dark grey to black bentonitic marine shale; however it also contains four thin sandstone units totalling less than 45 m in thickness. The Bow Island sandstone (25 m thick) is the most significant sandstone unit (Phillips et al., 1986). The Colorado Group ranges in thickness from 500 to 600 m in southern Alberta and from 450 to 500 m in north central Montana (Hendry et al., 1991; Stebinger, 1917). The upper boundary of the Colorado Group is commonly taken at the First White Speckled Shales (Meyboom, 1960). The Colorado Group is not exposed in southern Alberta (Williams and Dyer, 1930) but it outcrops widely in northern Montana, from the Sweet Grass Hills to Great Falls (Stebinger, 1917).

Milk River / Eagle Formation

The Milk River Formation (called Eagle Sandstone in Montana) has been traditionally subdivided into three members: the basal Telegraph Creek Member, the Virgelle Member and the Deadhorse Coulee Member. The Milk River Formation is 150 m thick in the southwest corner of the Canadian part of the study area and thins towards the northeast (O'Connell, 2014). It subcrops in southern Alberta near the border in circular rings around the Sweet Grass Hills, also following two "branches" on both sides of the Sweetgrass Arch.

Table 4.2 Nomenclature used in the present study, Pétré et al. (2015)

	Zone 1	Zone 2		Zone 3	Zone 4
	Southeastern AB (before facies change)	Southeastern AB (beyond facies change)		Northwestern MT (west of Sg. Arch)	Northern MT (east of Sg. Arch)
	Bearpaw	Bearpaw		Bearpaw	Bearpaw
	Belly River	Belly River		Two Medicine Formation	Judith River
	Pakowki	Pakowki			Claggett
Milk River Formation	DHC	Lea Park	Alderson Member		DHC
	Virgelle			Virgelle	Virgelle
	Telegraph Creek			Telegraph Creek	Telegraph Creek
	Colorado	Colorado		Colorado	Colorado

In southern Alberta, there is a disconformity surface towards the north, northeast and east separating the Milk River Formation from its sandy shale equivalent, the Alder- son Member of the Lea Park Formation. The Alderson Member can be included in the Milk River Formation as a fourth member. However, it is much younger than the other three members and is not present in Montana. The Alderson Member is gas-bearing; it contains the Milk River gas field (also called Medicine Hat gas field).

Telegraph Creek Member / Formation

The Telegraph Creek Member is a transitional unit between the shale of the Colorado Group and the massive sandstone of the Virgelle Member of the Milk River Formation. It consists of sandy shale, siltstone and fine-grained shaly sandstone. It is 36 to 52 m thick in the Cut Bank area and 30 to 52 m thick near the Sweet Grass Hills (Zimmerman, 1967; Tuck, 1993).

Virgelle Member

The Virgelle Member overlies the Telegraph Creek Member (Meijer-Drees and Mhyr, 1981). It consists of grey to buff massive sandstone with thinly bedded siltstone (Tuck, 1993). It is up to 69 m thick in southern Alberta and varies from 15 to 60 m thick on the west side of the Sweetgrass Arch (Lorenz, 1981; O'Connell, 2014). The Virgelle sandstone is not present in southwestern Saskatchewan or central Alberta due to the facies change of the Milk River Formation. The Virgelle sandstone outcrops along the Milk River in southern Alberta on approximately 25 km (Meyboom, 1960). It also outcrops on both sides of the Sweetgrass Arch in a continuous and narrow belt.

Geology

Deadhorse Coulee Member

The Deadhorse Coulee Member consists predominantly of shale, siltstone, and sandstone with coal seams (Payenberg, 2002). It has a maximum thickness of 60 m in southern Alberta and thins northeastwards to approximately 10 m east of the zero edge. The contact between the Deadhorse Coulee and the overlying Pakowki Formation / Claggett Shale is marked by a thin — but laterally continuous — bed of dark grey to black polished chert pebbles (Russell, 1970).

Lea Park – Milk River Formation: Alderson Member

The Alderson Member represents the lower member of the Lea Park Formation and is a stratigraphic equivalent to the Milk River Formation (Meijer-Drees and Mhyr, 1981). In southern Alberta, the Alderson Member is present just northeast of the depositional limit of the Virgelle Sandstone (Meijer-Drees and Mhyr, 1981). The lithology of the Alderson Member consists of very fine-grained sand, silt and mud (O'Connell, 2011). The sand content increases in the upper part (Meijer-Drees and Mhyr, 1981). The Alderson Member is 100 m thick in the northeast corner of the study area and about 85 m thick in southeastern Alberta (Meijer-Drees and Mhyr, 1981).

Pakowki Formation / Claggett Shale

The Milk River Formation is overlain by a thick unit of marine shales: the Pakowki Formation (Claggett Shale equivalent in Montana). The Pakowki Formation consists of thinly bedded, black marine shales, with few sandstone beds (Tovell, 1956, cited by Payenberg et al., 2003). A thin horizon of chert pebbles is present at the bottom of the unit. The Pakowki Formation is 98 m thick at Bow Island, 65 m at Lethbridge and up to 130 m in the Sweet Grass Hills area (Williams and Dyer, 1930); Tuck, 1993).

Two Medicine Formation

The Two Medicine Formation outcrops in northwestern Montana. This unit consists of mudstones and sandstones and is about 600 m thick (Lorenz, 1981). It overlies the well-defined Virgelle Member, which is mapped as a separate formation. It has a thickness of 152 m in the Cut Bank area (Zimmerman, 1967).

Belly River / Judith River Formation

The Belly River Group outcrops in a large part of the study area. It includes the Dinosaur Park Formation (upper part), Oldman Formation (middle part), and Foremost Formation (lower part) (Eberth and Hamblin, 1993; Hamblin, 1997). However, the upper part is present only in a limited portion of the study area in southern Alberta, Cypress County, and near the Saskatchewan border (Hamblin, 1997).

The dark shale, sandstone, and coal seams of Foremost Formation are overlain by massive yellow and grey sandstone of Oldman Formation and thick sandstones and siltstones of Dinosaur Park Formation. The Belly River Group / Judith River Formation is 320 m thick at Lethbridge and less than 182 m thick in northern Montana (Williams and Dyer, 1930; Pierce and Hunt, 1937).

Bearpaw Formation

The Bearpaw Formation is made up of dark grey shale (Russell, 1970). It is about 70 m thick in the northwestern part of the study. In the western part of the study area, the Bearpaw Formation outcrops along a narrow north-south directed band, and around the Cypress Hills in southeastern Alberta. It is lithologically similar to the Pakowki Formation: *i.e.*, composed of marine shales.

Sweetgrass Arch

The Sweetgrass Arch of northwestern Montana and southern Alberta is a major, ancient structural feature. Initial anticlinal development occurred in early Paleozoic times. Strong uplift followed by peneplanation occurred in the Late Jurassic and Early Cretaceous periods. During the Cretaceous and early Tertiary periods, the Sweetgrass Arch was quiescent but was rejuvenated in mid to late Tertiary, when it was upwarped by a basement flexure to its present structural configuration. The Sweetgrass Arch is a 322 km long, north-plunging anticline showing approximately 3 050 m of structural relief. Midway down its plunge, the anticline is offset 48 km by a right-lateral transcurrent fault. A seismic line exhibits the flexure. On the southwestern side of the Sweet Grass Hills, there is a large plain/plateau in Toole County that has the Colorado Group at the surface indicating the complete erosion of the Milk River Formation, that is the Sweetgrass Arch.

Methodology:

The bedrock geology map of Okulitch et al., 1996 was integrated in ArcGis. The extent of the area and the legend were adapted for the study area.

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Complete Legend of the Geological Map

PHANEROZOIC
CENOZOIC
NEOGENE AND QUARTAINARY
PLIOCENE AND PLEISTOCENE

NQE Empress Group
NQS Upland gravels and sands

NEOGENE
PLIOCENE

pNs Pre-glacial gravel terraces and fans

MIOCENE AND PLIOCENE

NS Gravel terraces and fans
NHH Hand Hills Formation
NF Flaxville Formation

MIOCENE

mNs Gravel, sand (redeposited unit P CH)

PALEOGENE
EOCENE AND OLIGOCENE

PK Kishenehn Formation
PCH Cypress Hills Formation
Ps Gravel terraces andfans

EOCENE

ePy Syenite, monzonite, shonkinite and latite sills, plugs, stocks and trachyte porphyry dykes
ePle minette and lamprophyre dykes

ePv Mafic and felsic flows, pyroclastics and tuff

ePw Wasatch Formation
ePSCC Swift Current Creek Beds

PALEOCENE

PPHU Porcupine Hills Formation (upper member)
PPU Paskapoo Formation (upper member)

PPHI Porcupine Hills Formation (lower member)
PPI Paskapoo Formation (lower member)
PR Ravenscrag Formation
PFU Fort Union Formation

pPy Syenite porphyry

MESOZOIC AND CENOZOIC
CRETACEOUS AND PALEOGENE
UPPER CRETACEOUS AND PALEOCENE

KPWC Willow Creek Formation
KPS Scollard Formation

MESOZOIC
CRETACEOUS
UPPER CRETACEOUS

KABR Alberta and Belly River Groups
UKM Montana Group (map unit includes all or some of the Telegraph Creek, Virgelle, Eagle, Claggett, Judith River, Bearpaw and Fox Hills Formations)

MAASTRICHTIAN
UPPER MAASTRICHTIAN

UMKF Frenchman Formation
UMKHC Hell Creek Formation

MAASTRICHTIAN

KFHC Fox Hills and Hell Creek Formations
KEWBF Eastend, Whitemud, Battle, and Frenchman Formations
Edmonton Group (MKHC, KWB)

KWB White Mud And Battle Formations
MKHC Horseshoe Canyon Formation
KEWB Eastend, Whitemud, and Battle Formations
KSMR St. Mary River Formation

MKE Eastend Formation
MKBR Blood Reserve Formation
KFH Fox Hills Formation
KH Horsethief Formation

MKS Bearpaw, Blood Reserve, Horsethief and St. Mary River Formations

MKB Bearpaw Formation

PHANEROZOIC
MESOZOIC
CRETACEOUS
UPPER CRETACEOUS
CAMPANIAN

CAKBR Belly River Group (includes Connelly Creek, Lundbreck and Drywood Creek Formations)
KJR Judith River Formation

KO Oldman Formation (connelly Creek Formation Equivalent)

KF Foremost Formation (Lundbreck and Drywood Creek Formations Equivalent)

KTM Two Medicine Formation (includes units KE, CAKC and KJR on the west flank of the Sweetgrass Arch)

Cakp Pakowki Formation
Cakc Claggett Formation
KLP Lea Park Formation

KTCE Telegraph Creek and Eagle Formations
KTVE Telegraph Creek, Virgelle and Eagle Formations
KTCV Telegraph Creek and Virgelle Formations

Milk River Group (KTC, KE, CAKV, KDC):
KDC Dead Horse Coulee Formation
KE Eagle Formation
CAKV Virgelle Formation
KTC Telegraph Creek Formation

TURONIAN TO CAMPANIAN

KA Alberta Group (includes Blackstone, Cardium, Wapiabi, Milk River and Pakowki Formations)

KMR Marias River Formation

LOWER AND UPPER CRETACEOUS
ALBIAN TO SANTONIAN

KC Colorado Group (includes Blackleaf and Marias River Formations)

LOWER CRETACEOUS

KKB Kootenai and Blackleaf Formations

ALBIAN

ALKB Blackleaf Formation

APTIAN

KK Kootenai Formation

BERRIASIAN TO ALBIAN

IKS Kootenai (Mist Mountain Formation) and Blairmore Groups and Crowsnest Formation

JURASSIC AND CRETACEOUS
MIDDLE JURASSIC TO LOWER CRETACEOUS

JKS Ellis Group, Morrison and Kootenai Formations (includes Mount Pablo and Blackleaf Formations in Foreland Belt)

JURASSIC
MIDDLE AND UPPER JURASSIC

JE Ellis Group

PALEOZOIC
CARBONIFEROUS
LOWER CARBONIFEROUS

CM Madison Group

DEVONIAN
MIDDLE AND UPPER DEVONIAN

DC Maywood, Jefferson and Three Forks Formations

CAMBRIAN TO CARBONIFEROUS
MIDDLE CAMBRIAN TO LOWER CARBONIFEROUS

PS Units Cs, DC and CM
PC Flathead, Emerson and Bighorn Formations, and Units Dc and Cm

CAMBRIAN
MIDDLE AND UPPER CAMBRIAN

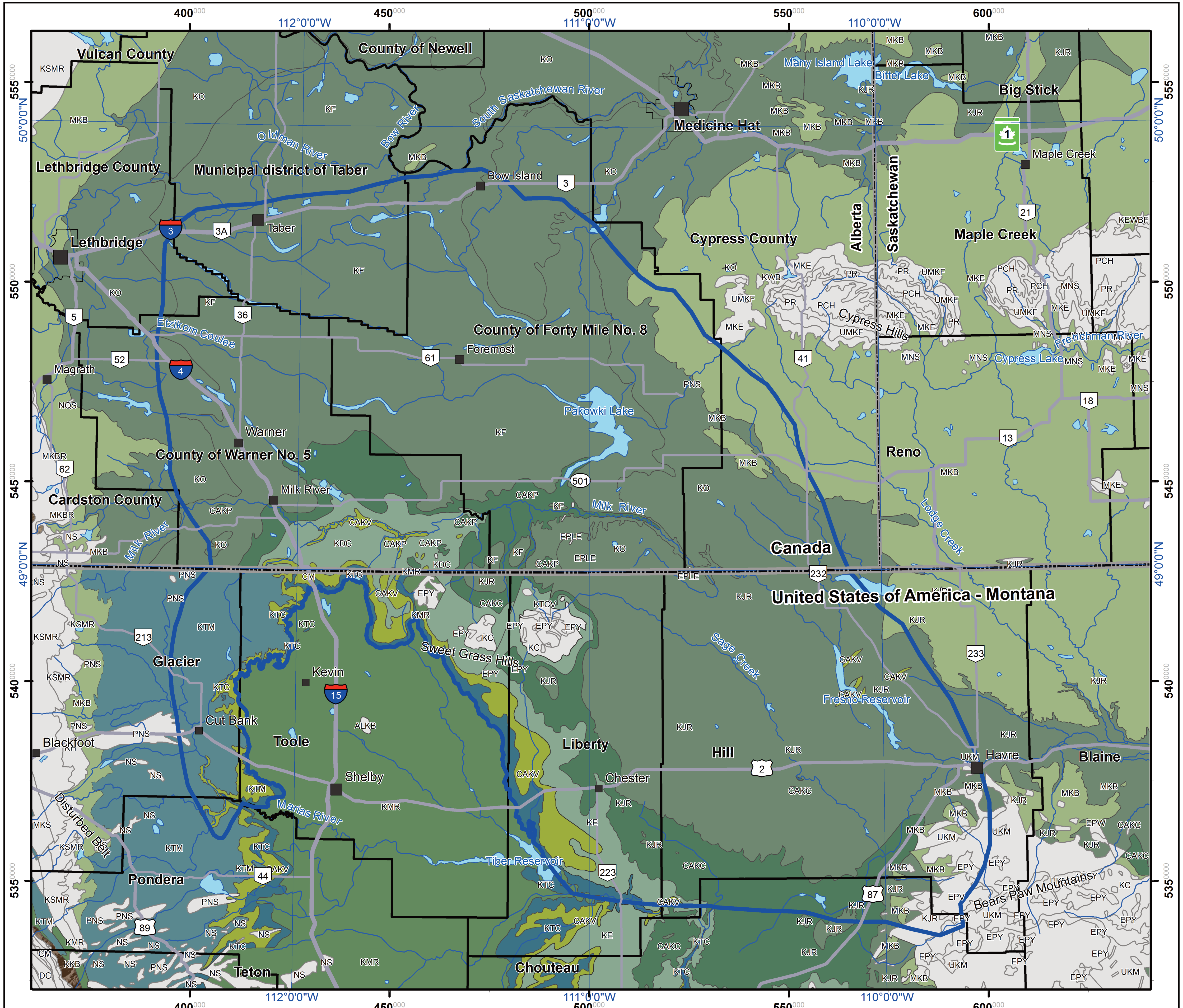
CS Flathead, Gordon, Damnation, Dear-born, Pagoda, Pentagon, Steamboat, Switchback and Devils Glen Formations

Figure 4.1 Complete legend for the Map 4.1

MAP 4.1

Bedrock Geology

Projection UTM 12N 1:1 000 000



Legend

Population

- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Border

- International
- Provincial
- Town and County

Road Network

- Highway
- Main Road
- Regional Road

Hydrography

- Lake
- River

Aquifer Extent

- Milk River

Simplified Bedrock Geology

Upper Cretaceous

MKB	Bearpaw Formation	
KO	Oldman Formation	Belly River Group
KF	Foremost Formation	Belly River Group
KJR	Judith River Formation	
KTM	Two Medicine Formation (includes KDC, CAKC and KJR)	
CAKC	Claggett Formation	
CAKP	Pakowki Formation	
KDC	Deadhorse Coulee Member	Milk River Group
KE	Eagle Formation	Milk River Group
CAKV	Virgelle Member	Milk River Group
KTC	Telegraph Creek Member	Milk River Group
KMR	Marias River Formation (from Colorado Group)	

4.2 Surficial Regional Geology

Surficial geology refers to those unconsolidated geologic materials lying on top of the bedrock. Common surficial materials include sand, gravel, till, clay, and silt. Table 4.3 shows the different surficial deposits and their proportion in the study area (Map 4.2).

Table 4.3 Surficial geology

Surficial geology	Area (km²)	Proportion of the study area (%)
Colluvial and mass-wasting deposits		
Undifferentiated deposits	1 200	1.7
Eolian sediments		
Dunes	386	0.6
Undifferentiated sediments	690	1,0
Alluvial sediments		
Floodplain	660	1.0
Undifferentiated sediments	1 779	2.6
Lacustrine sediments		
Undifferentiated sediments	132	0.2
Glaciolacustrine sediments		
Undifferentiated sediments	5 930	8.6
Glaciofluvial sediments		
Hummocky	477	0.7
Ice-contact	29	0.1
Outwash plain	3 055	4.4
Undifferentiated sediments	251	0.4
Glacial sediments		
Moraine complex	876	1.3
Ridged till, moraine	2 726	3.9
Hummocky till	15 718	22.7
Blanket sediments	27 994	40.4
Undifferentiated sediments	55	0.1
Bedrock outcrops		
Sedimentary, igneous, undifferentiated	5 544	8.0
No data		
No data area	1 854	2.7

Alberta Energy and Utilities Board and Alberta Geological Survey (2002), Saskatchewan Energy and Resources and Saskatchewan Research Council (2015), Colton, R.B et al. (1961)

Geology

Figure 4.2 Example of till – Alberta. Photo credit: © AGS <http://ags.aer.ca/document/Presentations/CON_ShallowGas_Pawlowicz.pdf>

The most common sediments are the glacial drift: blanket till and hummocky till. Till refers to an unstratified drift, deposited directly by a glacier without reworking by meltwater, and consisting of a mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape (Bates and Jackson, 1984).

The till blanket is found mainly in Montana, where it covers almost the entire plains. It is also largely present in Saskatchewan, except in the northern part of the province. In Alberta, the till blanket is deposited in smaller areas. It extends mostly in the western part of the province and at the Alberta-Saskatchewan border. Alberta is mainly covered with hummocky till, which extends across the plains of the province. There are also some hummocky till deposits found in northern Montana.

The northwestern part of the plains is covered with large glaciolacustrine deposits. This type of deposit is also found in smaller proportion elsewhere in the plains in Alberta, northern Saskatchewan, and western Montana.

The topographic highs of the study area were not glaciated, thus they are not covered with unconsolidated sediments. The four hills and mountains constitute bedrock outcrop areas, classified as igneous (Montana), sedimentary (Alberta and Saskatchewan), and undifferentiated (Montana) bedrock.

The riverbanks are characterized by alluvial and glaciofluvial sediments. These deposits follow the actual water system. In Montana, the deposits mostly are glaciofluvial sediments while Canadian fluvial deposits are classified as alluvial sediments. In Alberta, some river sections also show colluvial and mass-wasting deposits. These are found in the vicinity of Milk River, Etzikom Coulee, and Lodge Creek

Figure 4.3 Example of eolian deposit – Great Sand Hills, Saskatchewan
Photo credit: © 2015 www.canada-photos.com

(western Cypress Hills). The eolian deposits are sporadic and of limited extent. They are found in northern Saskatchewan, around Pakowki Lake, near Milk River and in northwestern Alberta.

Methodology:

The Montana surficial geology paper map was transformed into a digital map by using map tracing methods. The tracing was scanned and the noise was removed. The paper map and the tracing were georeferenced using ArcGis. A vectorization was then applied on the tracing and the polygons were generated into polylines, which were then transformed and exported to a polygon-based shapefile. The surficial geology was edited in the attribute table. The surficial geology classes of the three shapefiles were standardized using the Surficial Geology of Canada Legend of the Geological Survey of Canada (Deblonde et al., 2014). Efforts were made to harmonize the Alberta dataset with the Montana dataset in order to provide a unified map across the international border.

Sources:

Alberta Energy and Utilities Board and Alberta Geological Survey, 2002. Quaternary geology of southern Alberta – deposits. <http://www.ags.gov.ab.ca/publications/DIG/ZIP/DIG_2007_0012.zip>

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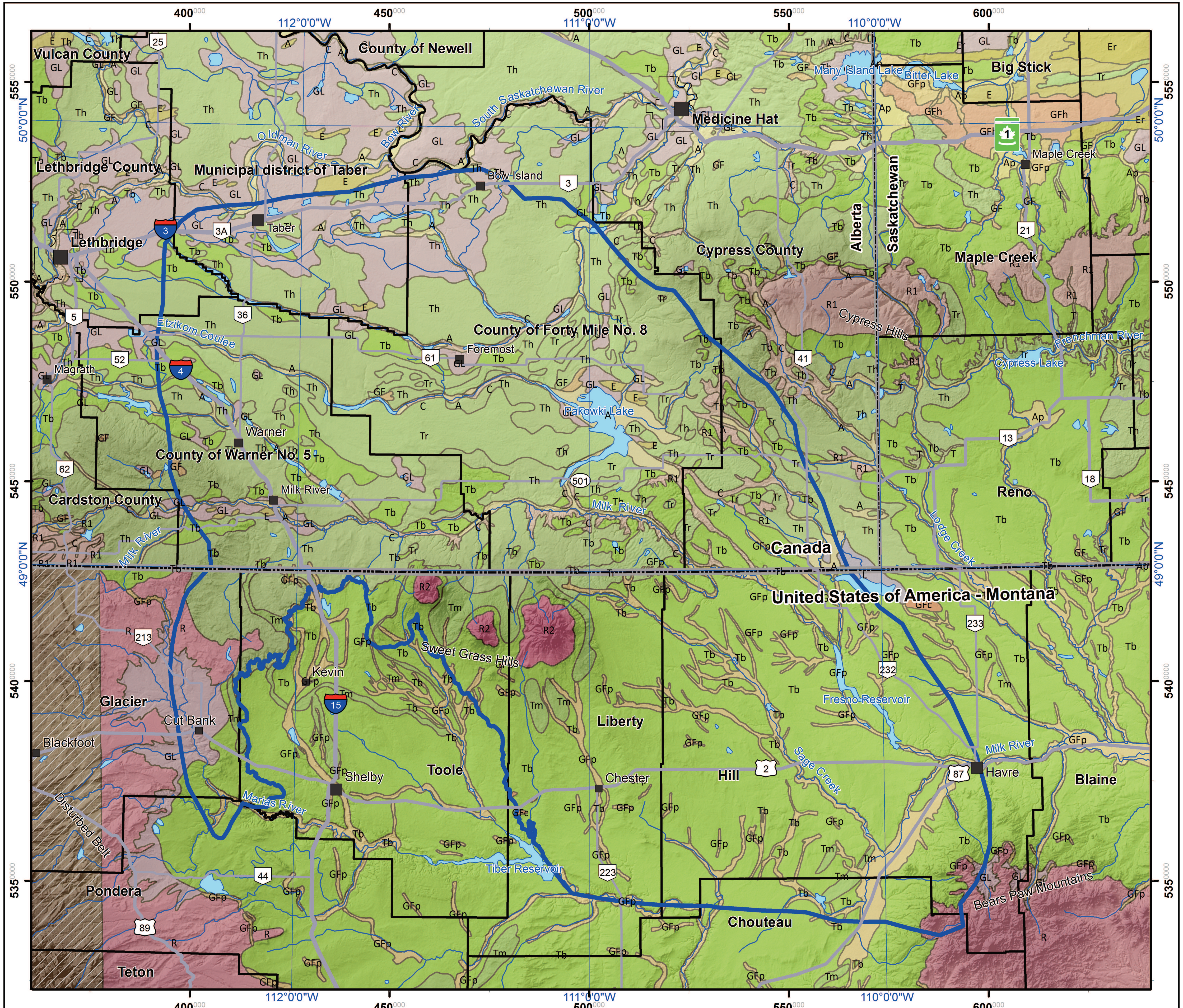
Fenton, M.M., Waters, E.J., Pawley, S.M., et al., 2013. Surficial geology of Alberta, Map 601, 1:1,000,000. Alberta Geological Survey, Edmonton, Alberta.

Saskatchewan Energy and Resources, 2015. Surficial geology of Saskatchewan. <http://www.infomaps.gov.sk.ca/website/sir_geological_atlas/viewer.htm>



MAP 4.2

Surficial Geology

Projection UTM 12N 1:1 000 000

Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Aquifer Extent
- Milk River

Surficial Geology

Colluvial deposits
- C Undifferentiated deposits

Eolian sediments
- Er Dunes
- E Undifferentiated sediments

Alluvial sediments
- Ap Floodplain
- A Undifferentiated sediments

Lacustrine sediments
- L Undifferentiated sediments

Glaciolacustrine sediments
- GL Undifferentiated sediments

Glaciofluvial sediments
- GFh Hummocky
- GFc Ice-contact
- GFp Outwash plain
- GF Undifferentiated sediments

Glacial sediments
- Tm Moraine complex
- Tr Ridged till, moraine
- Th Hummocky till
- Tb Blanket sediments
- T Undifferentiated sediments

Bedrock
- R Bedrock: undifferentiated
- R1 Sedimentary
- R2 Bedrock: igneous
- No Data Surficial Geology

4.3 3D Unified Geological Model and Cross-Sections

A three-dimensional, unified geological model was built from various sources of geological data on both sides of the international border. The Milk River Aquifer (Virgelle Member of the Milk River Formation) and the encasing units are all represented continuously through the border. Figure 4.4 presents the transboundary block diagram as well as the locations of the cross-sections. The general groundwater flow direction is indicated on the cross-sections, based on previous work (Meyboom, 1960; Zimmerman, 1967; Levings, 1982; Tuck, 1993; AGRA Earth and Environmental Limited, 1998). The area where the Alderson Member is no longer water-bearing but gas-bearing is indicated on cross-sections A-A', B-B' and D-D'. The bedrock geological map from Okulitch et al. (1996) is superimposed on the model (Figure 4.4).

Cross-section A-A' (Figure 4.4a) shows that the three members composing the Milk River Formation, especially the Milk River Aquifer (i.e., Virgelle Member), are continuously rep-resented from southern Alberta to north-central Montana. The Milk River Formation dips continuously from northern Montana to southern Alberta. It does not subcrop in this section. The regional unconformity between the traditional three members of the Milk River Formation and the Alderson Member is represented as an area of overlap. Groundwater flow is directed to the north, from northern Montana to Al- berta. The overlapping area of the Alderson Member corresponds to the Upper Alderson Sands. This part is still water-bearing. However, farther north, the Alderson Member is gas-bearing.

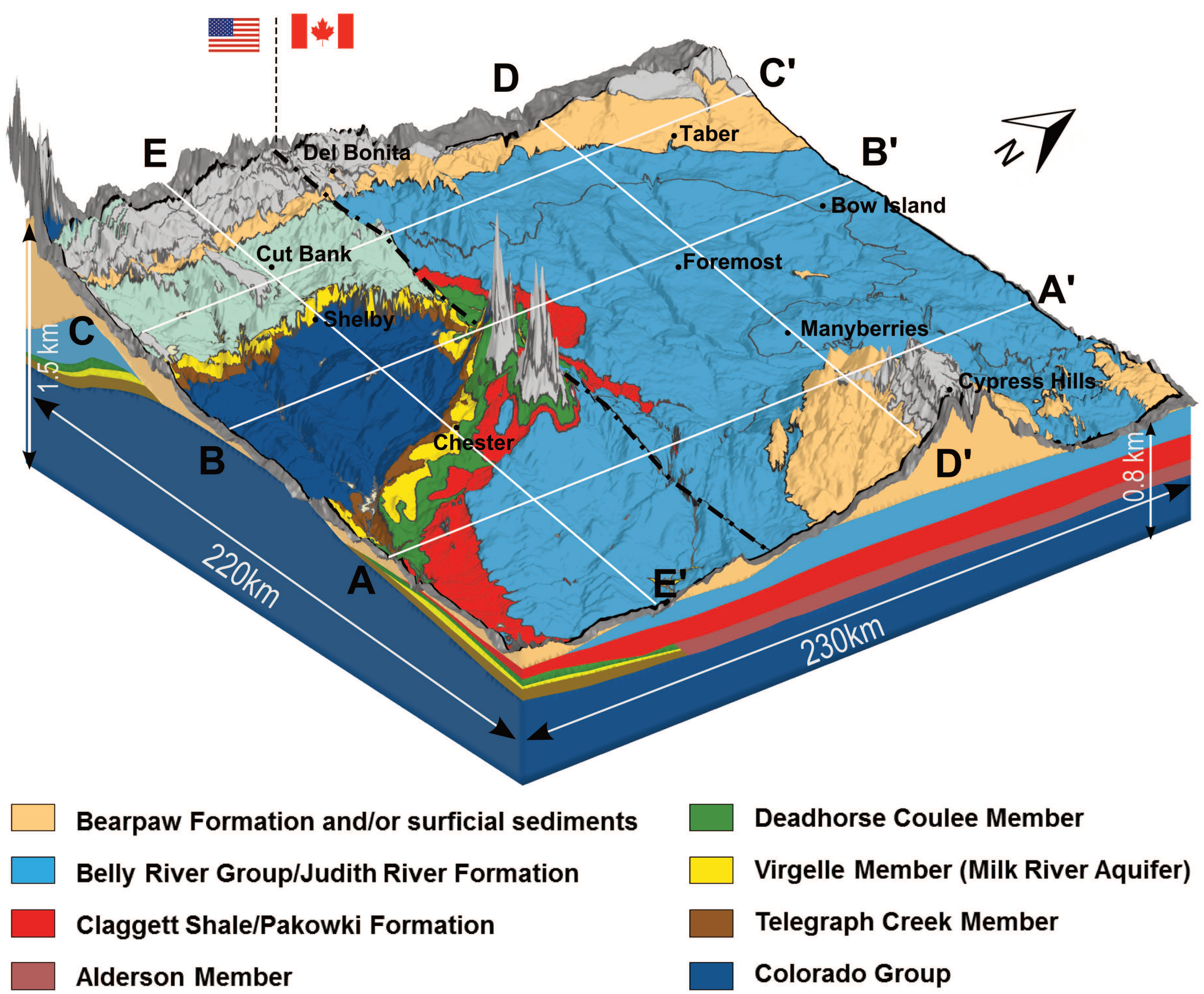


Figure 4.4 Three-dimensional unified geological model of the Milk River Aquifer and other geological units. Three-dimensional unified block showing the locations of cross-sections. Vertical exaggeration factor is 50. Cross-sections A-A', B-B', and C-C' are transboundary; cross-section D-D' is located in southern Alberta; and cross-section E-E' is located in northern Montana (Pétré et al., 2015).

Cross-section B-B' (Figure 4.4b) shows a steeper slope of the Milk River Formation from the international border to the north. The Colorado Group outcrops in northern Montana. A subcrop / outcrop area of the Milk River Formation at the border indicates unconfined conditions of the aquifer corresponding to a recharge area. From the international border, groundwater flows northwards.

West of the Sweetgrass Arch, cross-section C-C' (Figure 4.4c) shows that the Claggett (Pakowki) Formation pinches out in northwestern Montana. In Alberta, the Milk River Formation is overlain by the Pakowki (Claggett) Formation and the thick Belly River Group (Judith River Formation), whereas in Montana the Judith River Formation directly overlies the Milk River Formation equivalents. The Milk River Aquifer is confined and the general groundwater flow is from south to north, except in the vicinity of Cut Bank, where it is directed to the south.

Cross-section D-D' (Figure 4.4d) is located only in Alberta; it shows the gentle, antiformal geometry of the Milk River strata dipping eastward and westward as well as the overlap of the Alderson Member to the east. The Milk River Formation is overlain by 20 to 160 m of Claggett (Pakowki) Formation and 20 to 200 m of Belly River Group (Judith River Formation). Groundwater flows to the north, as well as to the east and west following the aquifer elevation.

Cross-section E-E' (Figure 4.4e) is located in northern Montana in the vicinity of the Sweetgrass Arch axis. The large outcrop of the Colorado Group is represented. The Milk River Formation equivalent dips to the east and to the west on both sides of the Sweet- grass Arch. The Claggett (Pakowki) Formation is not present west of the Sweetgrass Arch, but it overlies the Milk River Formation equivalent in the east. There are two subcrop areas of the Milk River Formation equivalent that correspond to the east and west outcrop bands described above in the bedrock geology section. Therefore, the Milk River Aquifer is under unconfined conditions in these areas, which represent recharge zones. Groundwater flow is directed to the south (perpendicular to the cross-section plan), as well as west and east from the subcrop areas.

Methodology:

The data used to create the three-dimensional geological model were in various formats. The first steps of the data processing were the conversion from feet to metres and from spatial reference NAD 27 to NAD 83; the transition from township / range system to latitude / longitude coordinates and the transition from depth to elevation data (the reference is the mean sea level). Then the two available DEM files were merged to obtain a unique DEM. The geological data were standardized on both sides of the international border. The 3D geological model was built using the software Leapfrog Hydro 2013. The approach used to build the model was to use location data (x, y, z) representing the top of the geological units. Contact surfaces were first created from these data. Volumes were obtained from the surfaces for which a chronology had been first determined. The model was adjusted with the help of cross-sections existing for the study area. The cross-sections served as a guide and allowed adjustments of the geological surfaces by manual editing within Leapfrog Hydro.

Sources:

Atkinson N. and Lyster S., 2010a. Bedrock Topography of Alberta, Canada. Energy Resources Conservation Board, ERCB/AGS Map, 550. <http://ags.aer.ca/publications/MAP_550.html>

Borneuf, D.M., 1976. Hydrogeology of the Foremost Area, Alberta. Alberta Research Council, Earth Sciences Report 1974-04. <http://ags.aer.ca/publications/ESR_1974_04.html>

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Tokarsky, O., 1974. Hydrogeology of the Lethbridge-Fernie area, Alberta. Earth Sciences Report 1974-01, Alberta Research, Edmonton, Alberta. <http://ags.aer.ca/publications/ESR_1974_01.html>

Geology

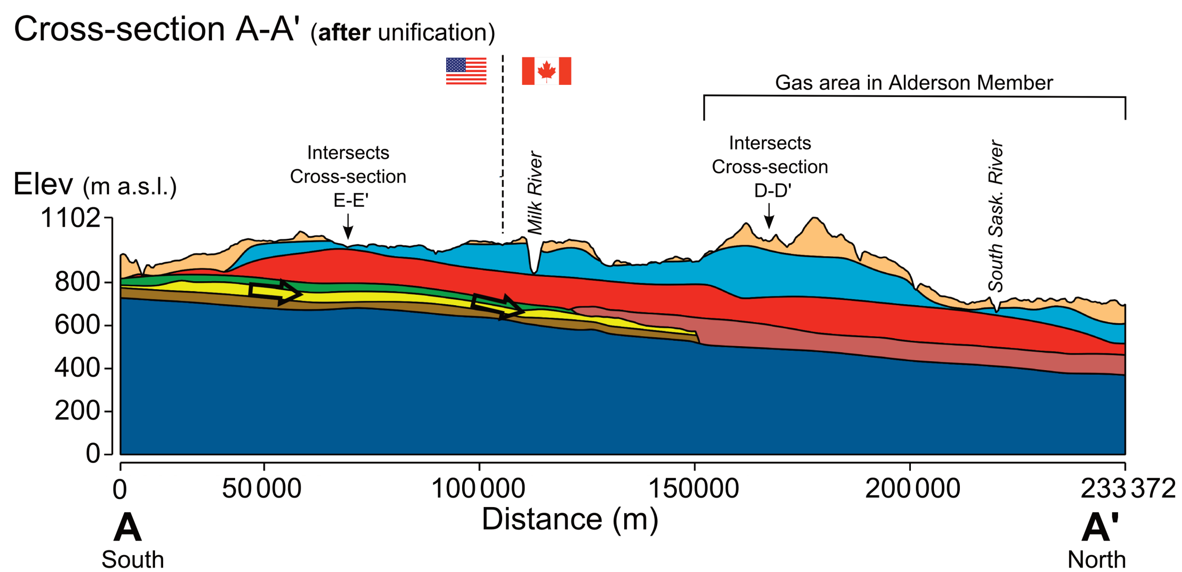

Figure 4.4a Cross-section A-A'

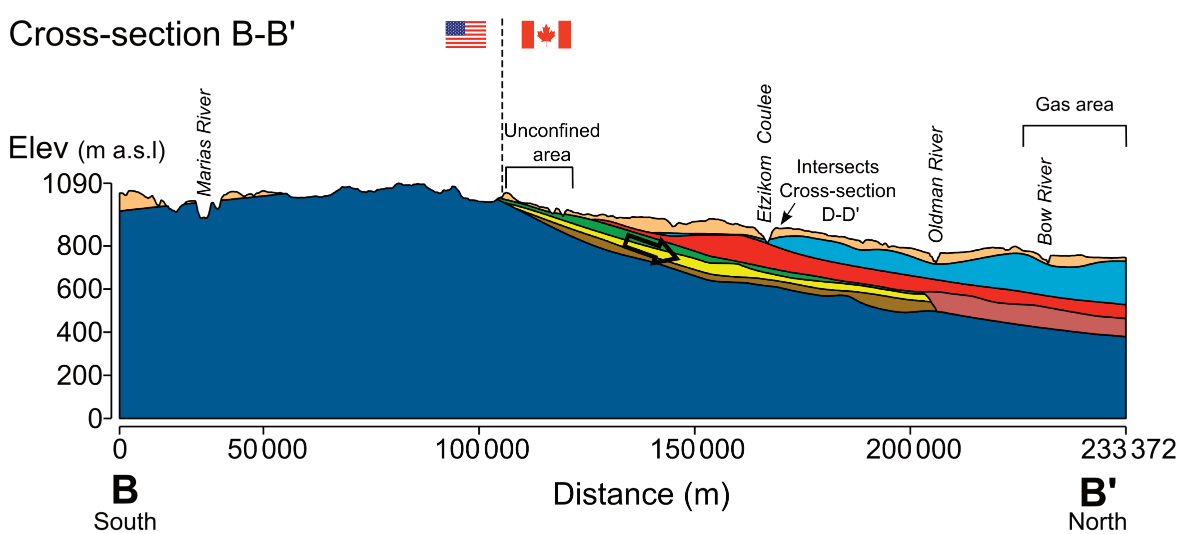

Figure 4.4b Cross-section B-B'

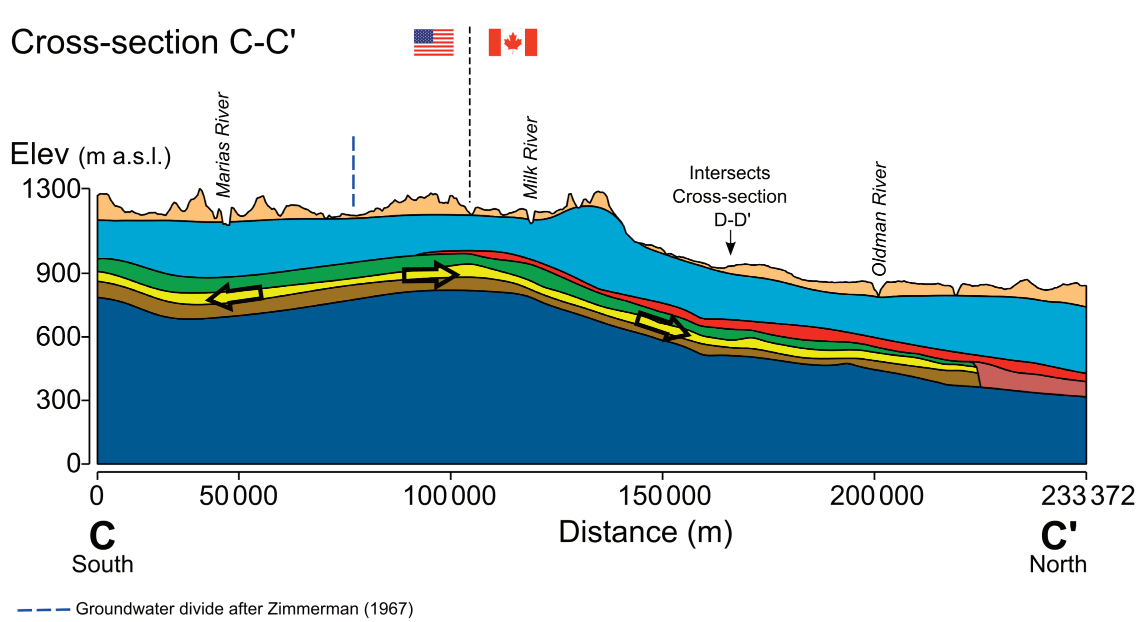

Figure 4.4c Cross-section C-C'

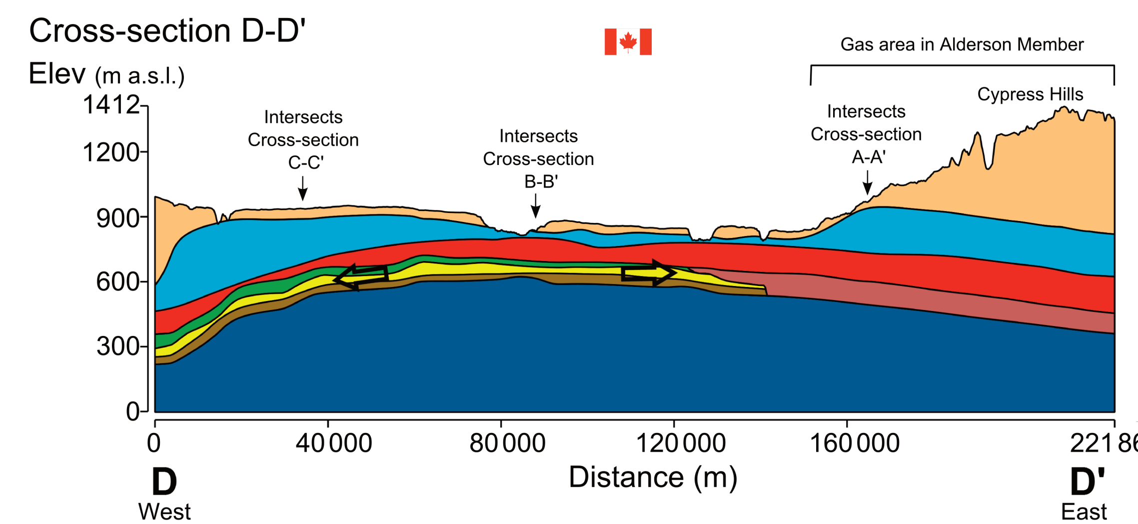

Figure 4.4d Cross-section D-D'

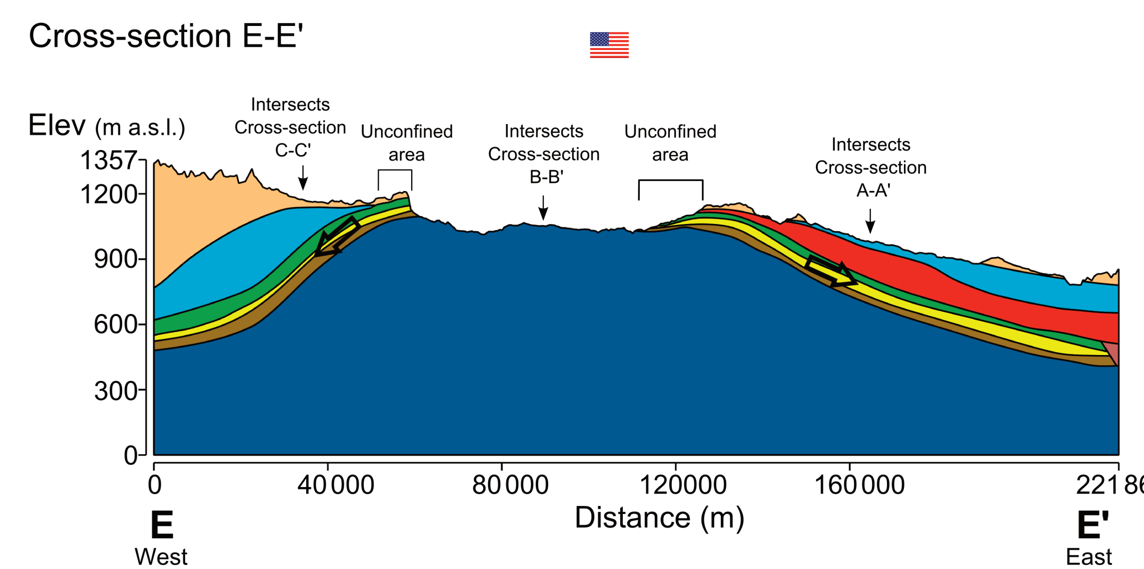

Figure 4.4e Cross-section E-E'

4.4 Bedrock Topography

The bedrock topography was derived from the three-dimensional geological model of the study area (Pétré et al., 2015). The bedrock topography corresponds more specifically to the top of the Belly River / Judith River Formation. As the geological data were sparse in the southwestern part of the study area, the elevation of the top of the Belly River / Judith River Formation is approximate (Map 4.3).

The bedrock topography is higher in the Sweet Grass Hills area and between the Milk River Ridge in Alberta and south of Cut Bank in Montana. It gradually decreases to the north, east and southeast.

The Sweet Grass Hills show bedrock elevation varying between 1100 m and 1771 m above mean sea level. They represent the highest bedrock elevation of the study area. They constitute an igneous intrusion. This uplift caused the upwarping of the older Cretaceous sediments (bedding layers, Figure 2.9 in Section 2.4). Only their flanks exhibit surficial material: lateral moraines. The bedrock topography in those hills is characterized by escarpments.

The plains are found in the central, northern, and southeastern parts of the study area. There is a gentle slope from the hills and mountains to the north and from the Sweet Grass Hills to the southeast.

Sources:

Dormaar, J.F., 2003. Sweet Grass Hills: A Natural and Cultural History. Lethbridge Historical Society, 84 p.

Furnival, G.M., 1946. Cypress Lake map area. Saskatchewan, Geological Survey of Canada, Memoir 242, 1946; pages (2 sheets), doi: 10.4095/101631

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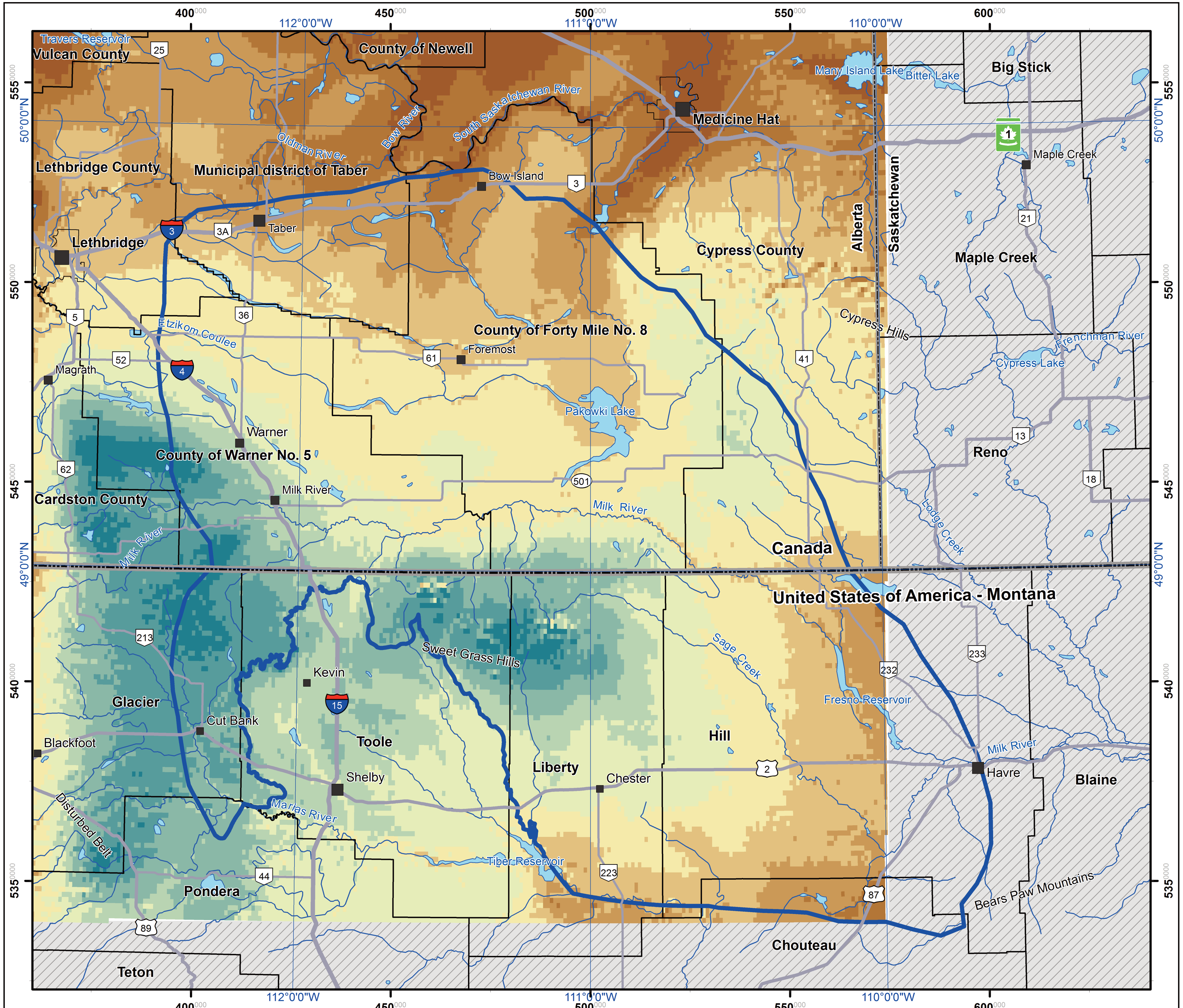
MAP 4.3

Bedrock Topography

Projection UTM 12N 1:1 000 000



4.5 Surficial Deposits and Bearpaw Formation Thickness

In hydrogeology, the thickness of the surficial sediments is an important geological layer to be considered since it affects the groundwater recharge. The surficial thickness was retrieved from the geological model of the Milk River Aquifer (Pétré et al., 2015). In this model, the surficial sediment layer corresponds to the interval between the top of the Belly River / Judith River Formation and the ground level. It includes the Bearpaw Formation where present. Indeed, this unit was not described individually in the geological model and was grouped with the surficial sediments.

Surficial sediment thickness roughly follows the surface topography. It shows the main landforms of the study area: the hills and mountains, and the plains. The Sweet Grass Hills and the plains show the thinnest surficial deposits. Two topographic highs exhibit the thickest surficial deposit values of the study area: Disturbed Belt and Cypress Hills (Map 4.4).

The Disturbed Belt is represented by a thin strip on the western part of the study area that mainly follows the surface topography with thicknesses increasing from 50 m to 600 m to the west. This strip extends from the southwest corner of the study area to 40 km north of the international border.

Sources:

Atkinson, N., and Lyster, S., 2010. Bedrock Topography of Alberta, Canada. Energy Resources Conservation Board, ERCB/AGS Map 550.

Borneuf, D.M., 1976. Hydrogeology of the Foremost Area, Alberta. Alberta Research Council, Earth Sciences Report 1974-04. <http://ags.aer.ca/publications/ESR_1974_04.html>

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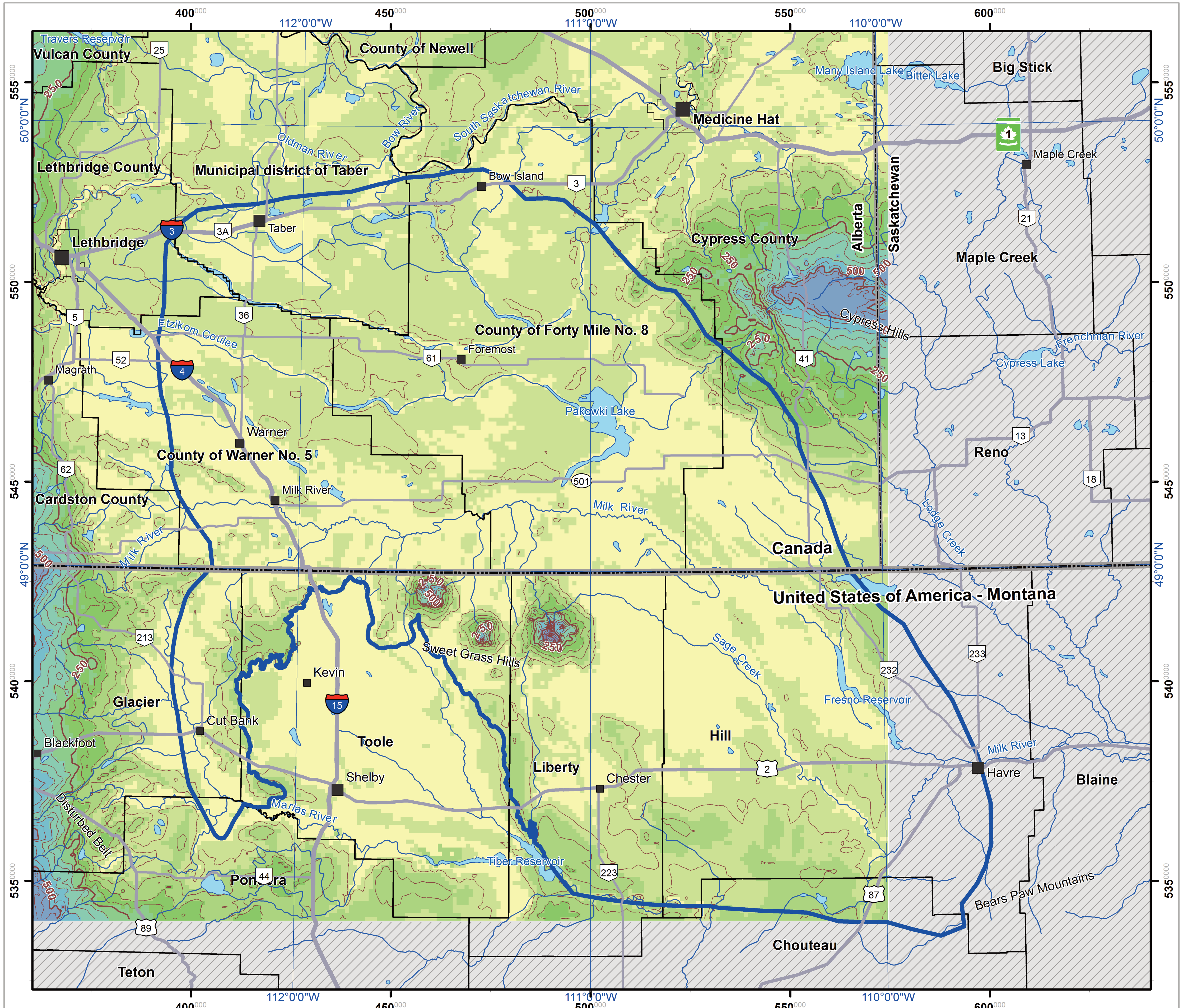

MAP 4.4

Surficial Deposits and Bearpaw Formation Thickness (m)

Projection UTM 12N 1:1 000 000

Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Aquifer Extent
- Milk River

Surficial Sediment Thickness (m)
- 0 - 25
- 26 - 75
- 76 - 150
- 151 - 225
- 226 - 300
- 301 - 400
- 401 - 500
- 501 - 650
- 651 - 900
- 901 - 1 157
- no data
- 250 m contour
- 50 m contour

5 Hydrogeology

5.1 Aquifer

The Milk River Transboundary Aquifer has been delineated following the aquifer description as “a layer, formation, or group of formations of permeable rocks, saturated with water and with a degree of permeability that allows economically profitable amounts of water to be withdrawn.” (De Marsily, 1986).

The proposed delineation of the Milk River Transboundary Aquifer covers 24 880 km^2 in the study area. It covers about 160 km from east to west and about 150 km from north to south (Map 5.1). This hydrogeological delineation corresponds to the extent of the Virgelle Member, which is the most permeable part of the Milk River Formation. It also includes the water-bearing Upper Alderson Sands, which overlaps the Virgelle Member along its depositional limit in the northeastern part of the study area.

The northern, northeastern and eastern limits of the Milk River Aquifer are defined by the gas field hosted by the Alderson Member in Alberta. Another gas field located near the city of Havre (near the Bears Paw Mountains) represents the southeastern boundary of the aquifer. In northern Montana, the Eagle Formation hosts the Bears Paw gas field. The Marias River constitutes the southern limit of the aquifer. Although the Milk River / Eagle Formation extends farther south in Montana, this physiographic limit was chosen with respect to the future hydrogeological model. The western limit of the aquifer corresponds to the westernmost area in which water wells have been completed in the Virgelle Member. The Virgelle Member extends farther west to approximately longitude -113°; however, no water wells have been completed in this unit due to its considerable depth in this area (>400 m; Stantec, 2002).

Figure 5.1 Example of a gas field in Alberta.
Photo credit: © 2005 Wikipedia – Economy of Alberta

Methodology:

The aquifer limit as shown on Map 5.1 was created in ArcGis, using the various geological and hydrogeological characteristics of the transboundary Virgelle Member and natural physiographic elements of the region, as exposed in the paragraphs of the section 5.1.

Sources:

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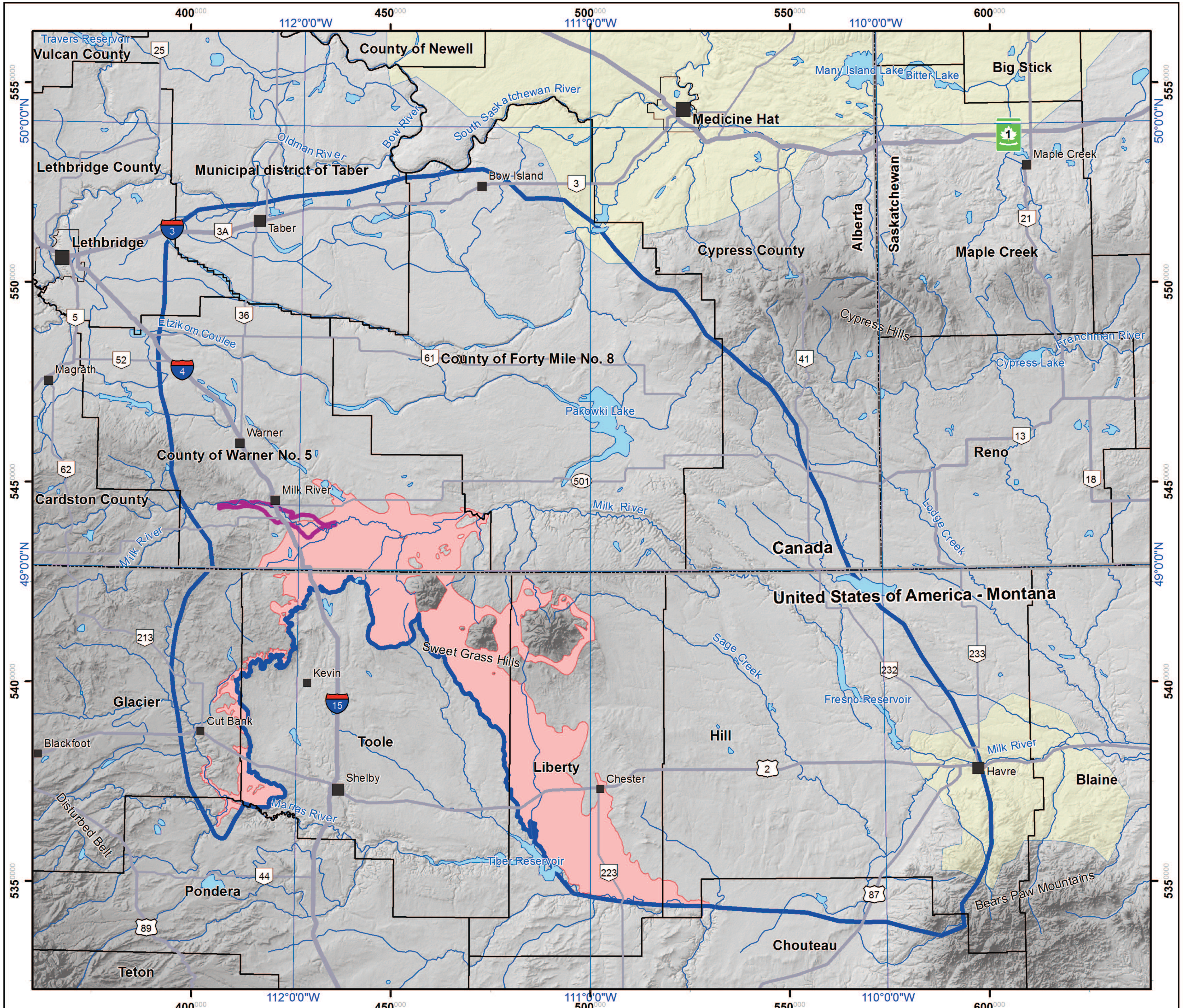
Stantec, 2002. Regional groundwater assessment of potable groundwater in County of Warner No. 5, Alberta.

MAP 5.1

Hydrogeological Extent of the Milk River Aquifer

Projection UTM 12N 1:1 000 000



Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Aquifer Extent
- Milk River
- Whiskey Valley
- Milk River Formation Outcrop

Gas Field
- Gas Field

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m

5.2 Hydrostratigraphy

Geological formations may be classified into hydrostratigraphic units according to their hydraulic properties, for example, hydraulic conductivity. Hydraulic conductivity commonly refers to the ease with which soil or rock allows groundwater to move through it. Hydrostratigraphic units can be classified as aquifers or aquitards depending on the amount of water that can be trapped. An aquifer may be defined as a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. An aquitard defines a bed of more or less impermeable material that cannot yield appreciable quantities of water. The following description of the hydrostratigraphic units in the study area is from Pétré et al. (2015). Table 5.1 shows the main hydrostratigraphic units found in the study area.

Table 5.1 Stratigraphy and hydrostratigraphy of the main geological units of the study area

Period	Stratigraphy		Hydrostratigraphy
Upper Cretaceous	Bearpaw Formation		Bearpaw Aquitard
	Belly River Group	Oldman Member	Belly River Aquifer
		Foremost Member	
	Pakowki Formation		Pakowki Aquitard
	Milk River Formation	Deadhorse Coulee Member	Milk River Aquifer
		Virgelle Member	
		Telegraph Creek Member	
	Colorado Shale		Colorado Aquitard

Colorado Group

The Colorado Shale constitutes a regional aquitard in the study area. The hydraulic conductivity of the Colorado Group ranges from 10^{-10} to 10^{-14} m/s (Hendry and Schwartz, 1988). This low hydraulic conductivity limits the quantities of water that can be exploited.

Milk River Formation / Eagle Formation

The Milk River Formation is confined above and below by the low-permeability shales of the Colorado and Pakowki Formation / Claggett Shale. The Milk River Aquifer is within the Milk River Formation. The Milk River Formation contains, from bottom to top, the Telegraph Creek Member, the Virgelle Member, and the Deadhorse Coulee Member. The middle member (Virgelle) is the most permeable part of the Formation. The Milk River Aquifer is a confined and inclined aquifer, which locally shows flowing artesian conditions.

Telegraph Creek Member / Formation

The Telegraph Creek Member / Formation is a transition zone, interpreted as deposits having a permeability lower than the Virgelle Member but higher than the Colorado Shale.

Virgelle Member

The Virgelle Member is the most important aquifer portion of the Milk River Formation and therefore constitutes the Milk River Aquifer. The average hydraulic conductivity of Virgelle Member is 1.81 x 10^{-7} m/s (Robertson, 1988).

Alderson Member

The upper part of the Alderson Member contains two distinct large sand bodies that form a regional aquifer in southern Alberta. According to O'Connell (2014), the Virgelle and Upper Alderson aquifers are separated by muddy sediments of the Alderson and Deadhorse Coulee members. The two members are locally in contact at the Virgelle erosional edge and water flow between the two aquifers is likely (O'Connell, 2014).

Pakowki Formation / Claggett Shale

The Pakowki Formation / Claggett Shale constitutes an aquitard; the hydraulic conductivity of the Pakowki Formation is 10^{-11} m/s (Toth and Corbet, 1987). In Montana, the hydraulic conductivity of the Claggett Shale has an estimated value of 3.5 x 10^{-11} m/s (Anna, 2011).

Belly River Group / Judith River Formation

The Belly River Group / Judith River Formation constitutes an aquifer and the hydraulic conductivity of the Judith River Aquifer in northern Montana ranges from 9 x 10^{-8} m/s to 8.8 x 10^{-7} m/s (Anna, 2011).

Bearpaw Formation

This marine strata is lithologically similar to that of the Pakowki Formation; therefore, it is a regional aquitard (Tokarsky, 1974).

Sources:

Anna, L.O., 2011. Effects of groundwater flow on the distribution of biogenic gas in parts of the northern Great Plains of Canada and United States. United States Geological Survey. <http://pubs.usgs.gov/sir/2010/5251>

Hendry, M.J. and Schwartz, F.W., 1988. An alternative view on the origin of chemical and isotopic patterns in groundwater from the Milk River Aquifer, Canada. Water Resources Research, v. 24, no. 10, p. 1 747–1 763. doi: 10.1029/WR024i010p01747

O'Connell, S., 2014. The Milk River transboundary aquifer in southern Alberta. Geological Survey of Canada, Open File 7751. doi: 10.4095/295603

Pétré, M.-A., Rivera, A., and Lefebvre, R., 2015. Three-dimensional unified geological model of the Milk River Transboundary Aquifer (Alberta, Canada – Montana, USA). Canadian Journal of Earth Sciences. doi: 10.1139/cjes-2014-0079. This paper is one in a series of three publications on this research on transboundary aquifers, following the United Nations Resolution on the Law of Transboundary Aquifers.

Robertson, C., 1988. Potential impact of subsurface irrigation return flow on a portion of the Milk River and Milk River Aquifer in southern Alberta. University of Alberta, Department of Geology, M. Sc. Thesis. <https://era.library.ualberta.ca/files/5t34sm86z#.Vs4bfOYve-M>

Tokarsky, O., 1974. Hydrogeology of the Lethbridge-Fernie area, Alberta. Earth Sciences Report 1974-01, Alberta Research, Edmonton, Alberta. <http://ags.aer.ca/publications/ESR_1974_01.html>

Toth, J. and Corbet, T., 1986. Post-Paleocene evolution of regional groundwater flow-systems and their relation to petroleum accumulations, Taber area, southern Alberta, Canada. Bulletin of Canadian Petroleum Geology, v. 34, no. 3, p. 339–363. doi: 10.1144/gsl.sp.1987.034.01.05

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5.3 Transmissivity

The transmissivity of an aquifer is the rate of flow under a unit hydraulic gradient through a cross-section of unit width over the whole aquifer thickness, expressed in m^2/s. The transmissivity is the product of the hydraulic conductivity (K, m/s) and the thickness (b) of the aquifer (m). In simple terms, transmissivity expresses the aquifer's capability to transmit water.

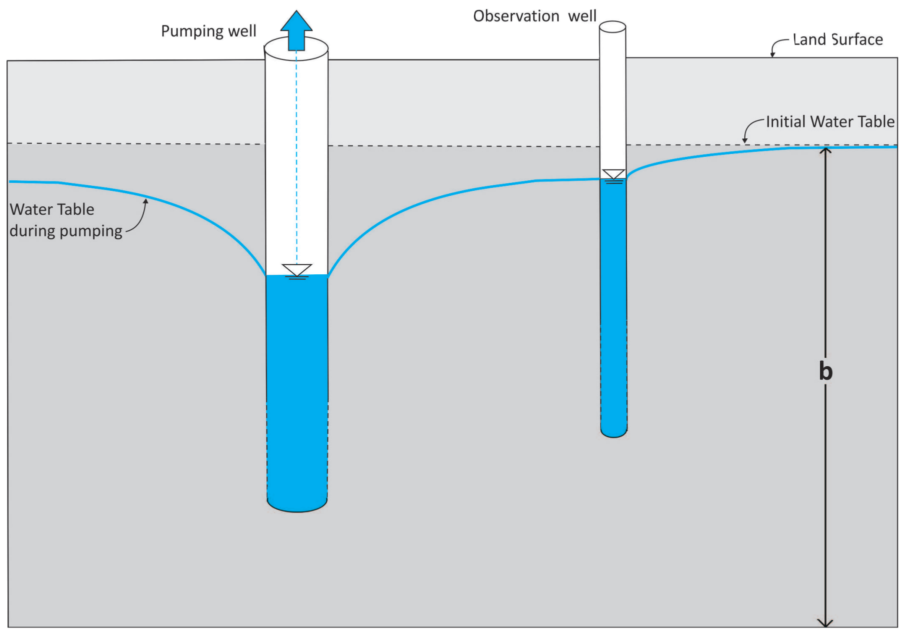


Figure 5.2 Pumping test.
Schema credit: © 2010-11 LANS, LLC

Transmissivity values have mainly been calculated from pumping tests (Figure 5.2). These tests consist of a controlled field experiment in which a well is pumped at a controlled rate and the water level response (drawdown) is measured in one or more surrounding observation wells and optionally in the pumped well itself. Response data from pumping tests are used to estimate the transmissivity. The transmissivity values of the Milk River Aquifer range between 1×10^{-6} and 2.9×10^{-2} m^2/s (Map 5.2). The highest transmissivities of the aquifer are found in the Cut Bank area, Montana. Other high values are observed in southern Alberta surrounding Pakowki Lake and north of it. The lowest transmissivities are located in central Alberta, near Foremost. Other low transmissivities are found in northern Alberta. These data are from various sources, four of which are described below.

In Alberta, Meyboom (1960) showed that there is an area of high transmissivity values from Pakowki Lake following a northwest trend. This zone corresponds to a thicker sandstone deposit in the aquifer. The transmissivity values were obtained from 32 shut-in pressure tests performed on flowing wells. The transmissivity of the aquifer in this area, estimated by Meyboom (1960), ranges from 1.4×10^{-6} to 5.2×10^{-4} m^2/s. Persram (1992, unpublished, cited by AGRA, 1998) calculated transmissivities from 42 pumping tests. The calculated transmissivities range from 1.2×10^{-6} to 1.3×10^{-6} m^2/s, which constitute lower values than in Meyboom's results. Persram (1992) showed a northeasterly trending zone of relatively high transmissivity, which is not in agreement with Meyboom's data. A subsequent study (AGRA, 1998) integrated data from Meyboom (1960) and Persram (1992), along with additional aquifer test results that resolved some of the apparent conflict. The highest transmissivities in both studies are centered on Lake Pakowki and south of it (AGRA, 1998). Low transmissivity values ($< 1.7 \times 10^{-5}$ m^2/s) are located in the northeast of the Milk River Aquifer, near the facies change into the Alderson Member over much of the western third portion of the study area (values $< 6.9 \times 10^{-6}$ m^2/s) (AGRA, 1998).

In Montana, Zimmerman (1967) obtained transmissivity values in the Cut Bank area from aquifer tests or estimates from specific capacity. The transmissivity of the Virgelle Member (Milk River Sandstone) ranges from 1×10^{-4} to 7.19×10^{-3} m^2/s, which represent higher values than those found in southern Alberta. Zimmerman (1967) indicated that the transmissivity could be locally affected by fracturing. In the Sweet Grass Hills area, Tuck (1993) found transmissivities ranging from 2.2×10^{-4} to 4×10^{-3} m^2/s in the Virgelle Member. These values are in agreement with Zimmerman's results.

Methodology:

Transmissivity data were compiled and converted to SI units.

Sources:

AGRA Earth and Environmental Limited, 1998. Evaluation of depletion of the Milk River aquifer. AGRA Earth & Environmental, Edmonton, Alberta.

Levings, G.W., 1981. Selected drill-stem-test data from the Northern Great Plains area of Montana. Open File Report 81-326, United States Geological Survey. <https://pubs.er.usgs.gov/publication/ofr81326>

Meyboom, P., 1960. Geology and groundwater resources of the Milk River sandstone in Southern Alberta. Research Council of Alberta. <http://ags.aer.ca/publications/MEM_02.html>

Norbeck, P.N., 2006, Sunburst water-supply renovation: April 2006 project report to the Montana Department of Natural Resources and Conservation: Montana Bureau of Mines and Geology Open File Report 548, 58 p. <http://www.mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=30021>

Persram, A., 1992. Hydrogeology of the Milk River Formation in southern Alberta. Alberta Environmental Protection, Hydrogeology Branch (unpublished data cited by AGRA, 1998 and AIFT, 2010).

Tuck, L.K., 1993. Reconnaissance of geology and water resources along the north flank of the Sweet Grass Hills, north-central Montana. United States Geological Survey, Water-Resources Investigations Report 93-4026. 68 p. <https://pubs.er.usgs.gov/publication/wri934026>

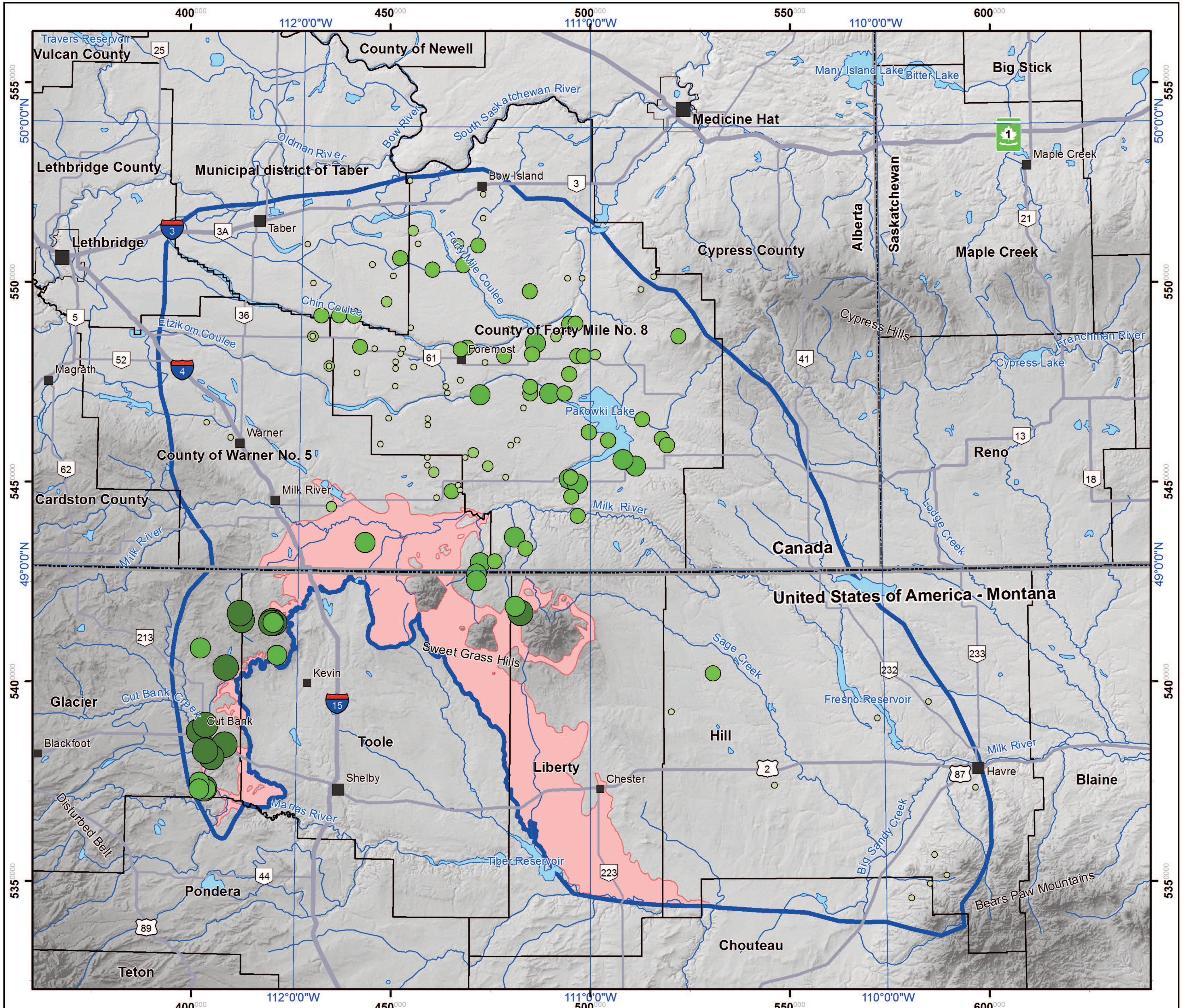
Water Right Solutions Inc., 2009. Cool Spring Colony — Application for beneficial water use hydrogeologic assessment, unpublished report submitted for Water Right Permit # 40G 30045714. 5 p.

Zimmerman, E.A., 1967. Water resources of the Cut Bank area, Glacier and Toole counties, Montana. Montana Bureau of Mines and Geology Bulletin 60, 37 p. <http://www.mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=10061>

MAP 5.2

Transmissivity Values

Projection UTM 12N 1:1 000 000



Legend

Population

- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network

- Highway
- Main Road
- Regional Road

Border

- International
- Provincial
- Town and County

Hydrography

- Lake
- River

Transmissivity (T) m^2/s

- 1.0×10^{-6} - 6.0×10^{-6}
- 6.0×10^{-6} - 1.0×10^{-5}
- 1.0×10^{-5} - 1.0×10^{-4}
- 1.0×10^{-4} - 1.0×10^{-3}
- 1.0×10^{-3} - 1.0×10^{-2}

Aquifer Extent

- Milk River
- Milk River Formation Outcrop

Elevation (m a.m.s.l.)

- High : 2 595 m
- Low : 620 m

5.4 Groundwater Level Elevation

Groundwater level fluctuations can result from a wide variety of hydrologic processes and anthropogenic activities. To ensure good management of the groundwater resource, information on the quantity of water stored underground as well as the water variations is necessary. This information is obtained by analyzing the periodic measurements of groundwater depth from some reference points over long periods of time.

The figures presented in this section (Figures 5.3a to 5.3i) show some of the hydrographs available for the study area (Map 5.3 for location). Both Well #221 and Well #211 (Figures 5.3d and 5.3a) appear to be impacted by pumping and show gradual long-term decline; these two wells are located in Foremost, Alberta. These observation wells are all completed into the Milk River Formation (in Alberta) or the Virgelle Member (in Montana).

Sources:

Alberta Environment and Parks, 2016. Groundwater Observation Well Network (GOWN), consulted online: <http://aep.alberta.ca/water/programs-and-services/groundwater/groundwater-observation-well-network/default.aspx>

Ground Water Information Center (GWIC database), Montana, (2015). Montana's Ground Water Information Center 2015, Consulted online: <http://mbmggwic.mtech.edu>

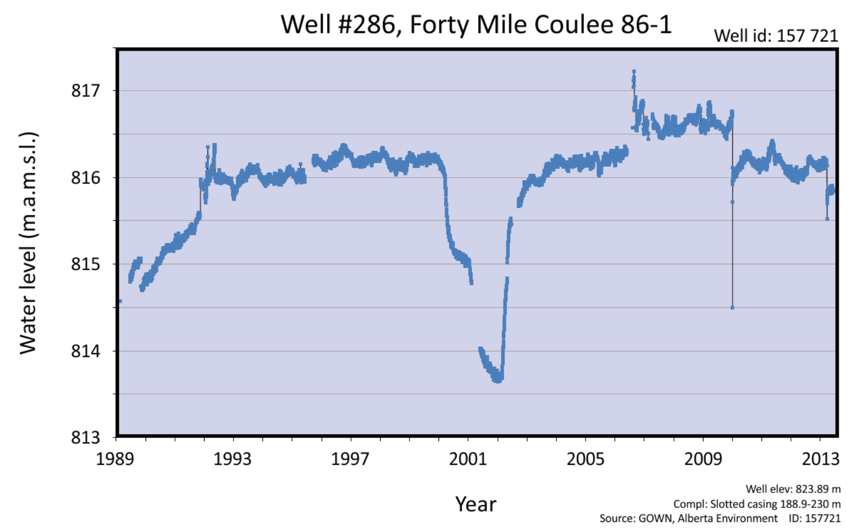


Figure 5.3b Water level, Well 286 (id 157 721)

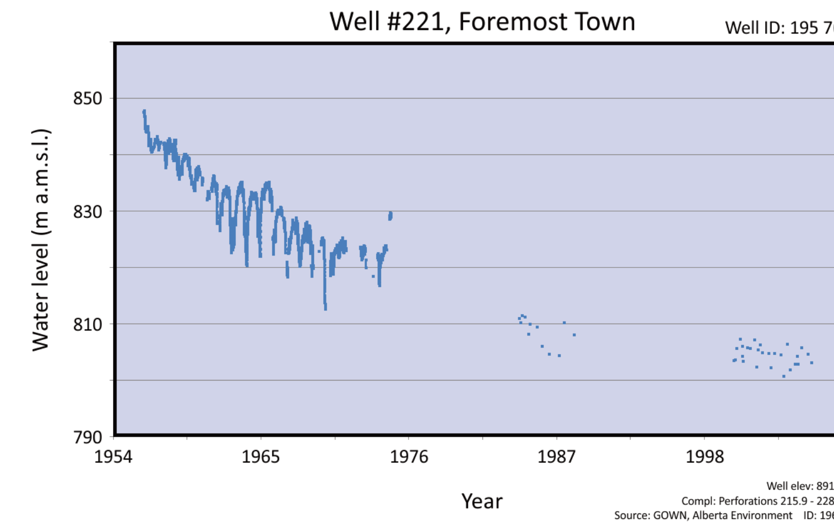


Figure 5.3d Water level, Well 221 (id 195 769)

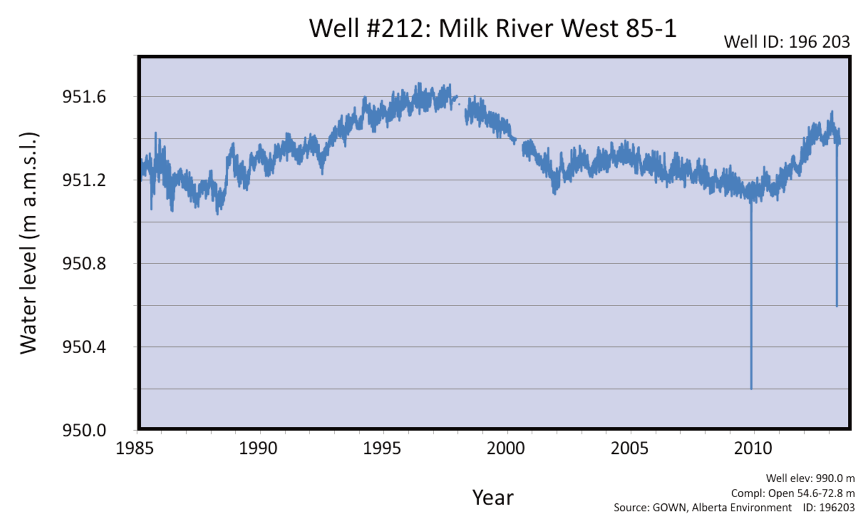


Figure 5.3c Water level, Well 212 (id 196 203)

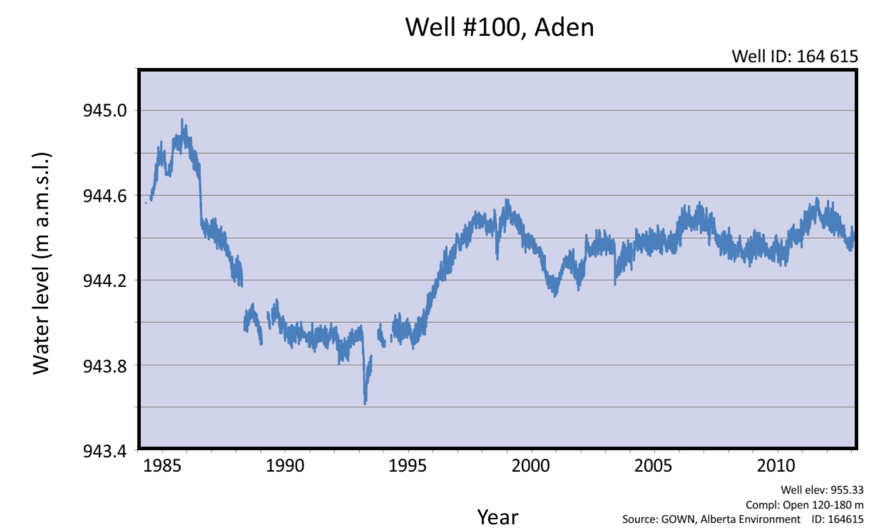


Figure 5.3e Water level, Well 100 (id 165 615)

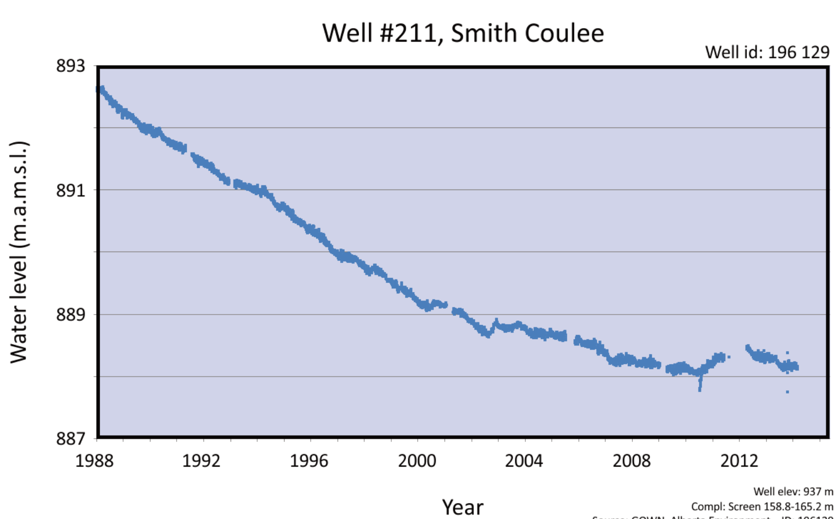


Figure 5.3a Water level, Well 211 (id 196 129)

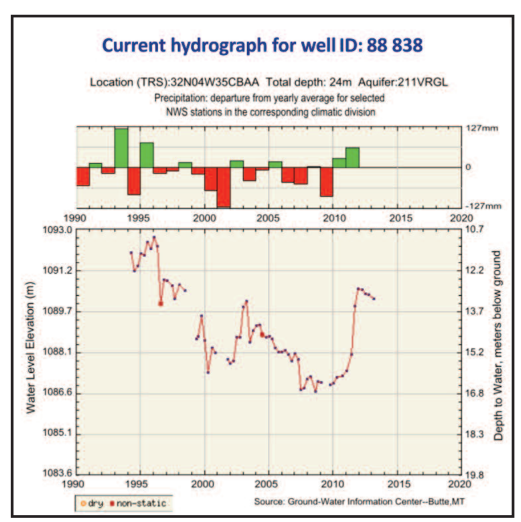


Figure 5.3f Water level, Well ID 88 838

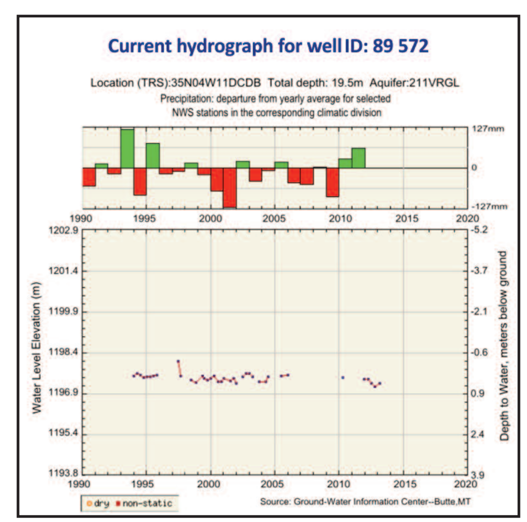


Figure 5.3g Water level, Well ID 89 572

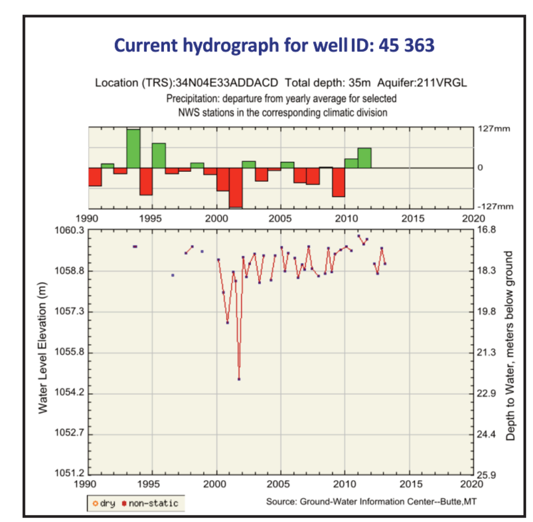


Figure 5.3h Water level, Well ID 45 363

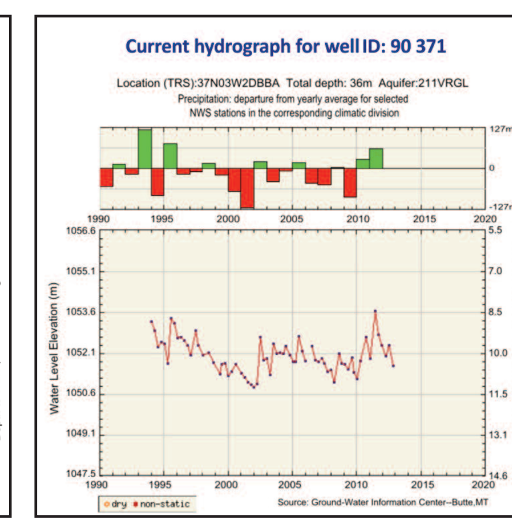
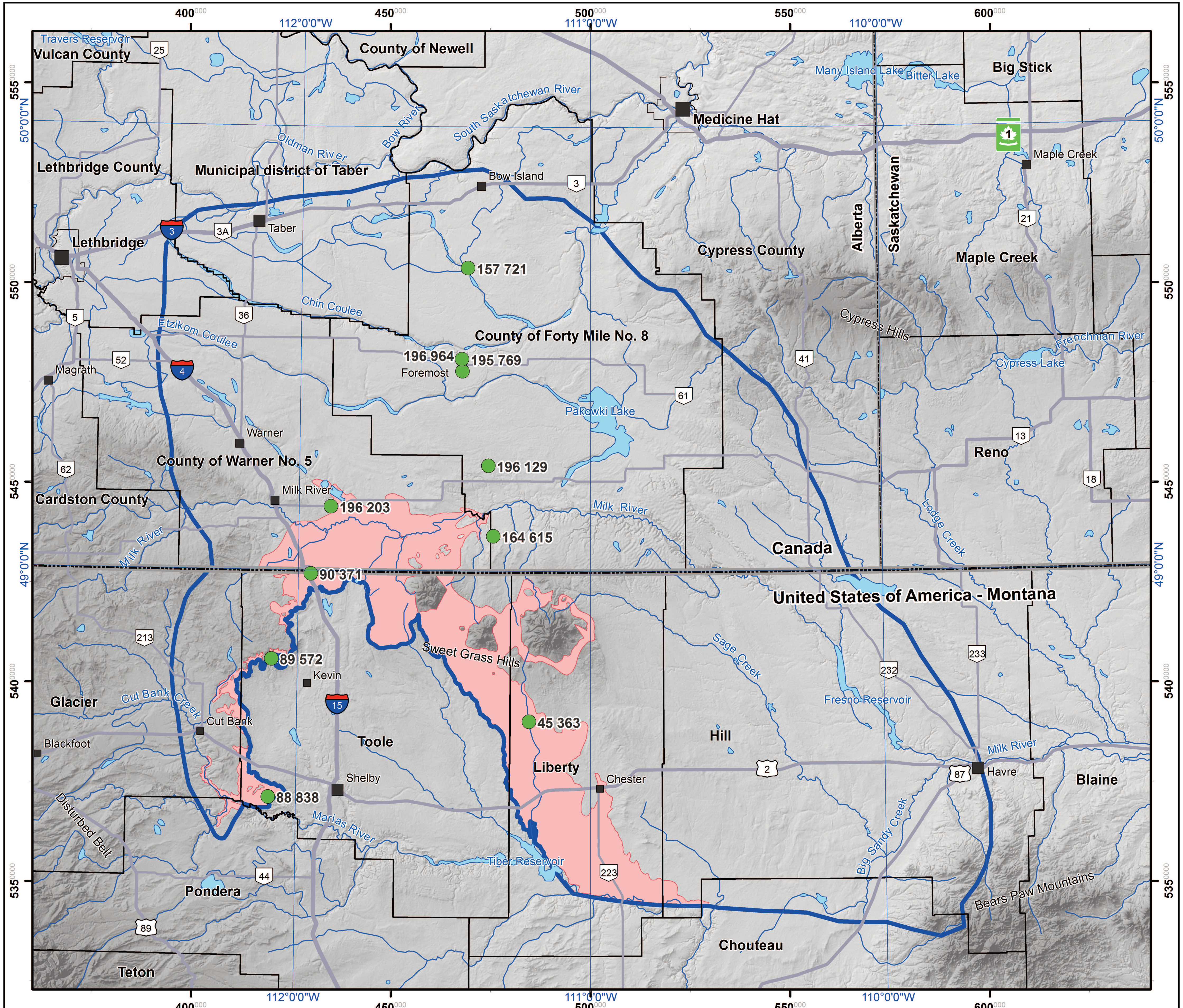


Figure 5.3i Water level, Well ID 90 371



MAP 5.3

Location of Observation Wells

Projection UTM 12N 1:1 000 000

Legend

Population

- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network

- Highway
- Main Road
- Regional Road

Border

- International
- Provincial
- Town and County

Hydrography

- Lake
- River

Groundwater Level

- Observation Well

Aquifer Extent

- Milk River
- Milk River Formation Outcrop

Elevation (m a.m.s.l.)

High : 2 595 m

Low : 620 m

5.5 Piezometric Surface and Groundwater Flow Path Direction

The piezometric surface designates a surface of equal hydraulic heads in an aquifer (Figure 5.4). It also indicates the level below which soil or rock is saturated with water in unconfined aquifers, corresponding to the water table. Groundwater flows from areas of high hydraulic heads to areas of low hydraulic heads; the highest and lowest piezometric contours correspond to the recharge and discharge areas, respectively.

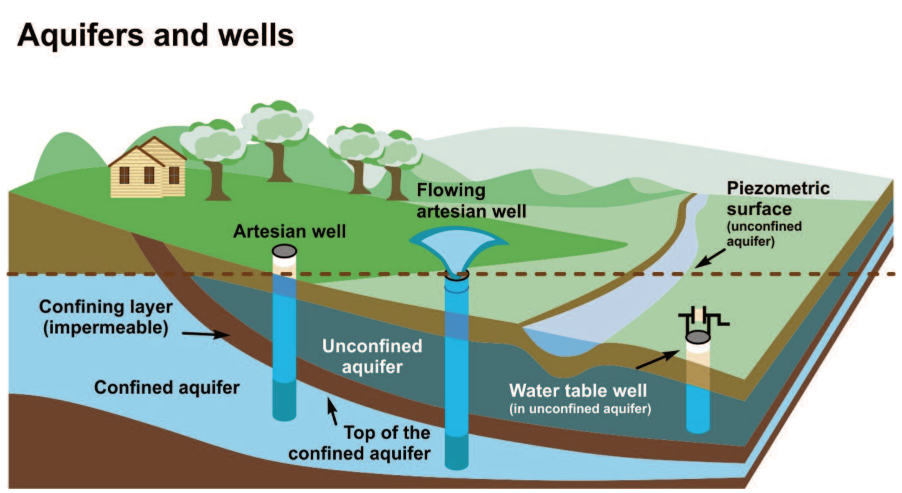


Figure 5.4 Examples of piezometric surfaces. Photo credit: © Environment Canada

In the Milk River Aquifer, the Sweet Grass Hills and Cut Bank areas show the highest piezometric contours with values of 1280 and 1220 m a.s.l. respectively. In the Cut Bank area, the values decrease to 1040 m in the south. The piezometric surface decreases from Cut Bank and Sweet Grass Hills to the north. In southern Bow Island, it is at 820 m. Other discharge areas are found in Foremost, southern Foremost and Pakowki Lake, where the piezometric surface is between 860 and 800 m. The lowest piezometric surface of the Milk River Aquifer (780 m) is found near Havre. The analysis of the piezometric map allows for understanding of the groundwater flow from the recharge to the discharge areas.

The main recharge of the Milk River Aquifer occurs at the circular outcrops around the Sweet Grass Hills. The recharge occurs through infiltration of precipitation on outcropping and in some sub-cropping areas, infiltration of streamflow across outcrops, and possible subsurface inflow from other geologic units (Tuck, 1993). Groundwater generally flows from the recharge areas on the flank of the Sweet Grass Hills and downdips in northerly directions to discharge areas (Tuck 1993). In Montana, groundwater flows from the Sweet Grass Hills to the north, but also to the south,

Figure 5.5 Example of a flowing well. Photo credit: © Marie-Amélie Pétré

southeast and east (Levings, 1982). There is a groundwater divide between West Butte and Gold Butte; and between Gold Butte and East Butte. The amount of natural discharge from the Milk River Aquifer (e.g. to the Milk River) is small and discharge also occurs through flow of springs and seeps, and subsurface outflow to other geologic units. (Meyboom, 1960; Tuck, 1993).

The Cut Bank area represents another recharge area of the Milk River Aquifer. In this area, the infiltration of precipitation along the outcrop and interformational leakage constitutes the major groundwater recharge in this zone. Groundwater in the Virgelle Member moves southwest and north from a groundwater divide north of Cut Bank. The discharge area of the Virgelle Member is located along Cut Bank Creek south of Cut Bank and north toward outcrops of the Milk River Sandstone near the confluence of Red Creek with the Milk River in Alberta (Zimmerman, 1967; Meyboom, 1960, Map 2.2 for reference).

The Bears Paw Mountains also constitute a recharge area. Groundwater flows northwards to the Milk River and southwards to the Missouri River. North of the Bears Paw Mountains, the piezometric contours indicate aquifer discharge to Big Sandy Creek and the Milk River. Levings (1982) doubted that vertical leakage occurred in this area because of the thick overlying Claggett Shale. He suggested that this decline in potentiometric surface could be caused by depressurization of the Eagle Sandstone from gas production.

The study of the piezometric maps reveals that there are two transboundary flow directions from northern Montana towards southern Alberta. The first one originates in the Sweet Grass Hills area and is directed to the north; the second one originates north of Cut Bank and is directed to the north as well.

Methodology:

Given the lack and scarcity of recent water level data, this map is an assemblage of historical maps from Zimmerman (1967), AGRA Earth and Environmental Limited (1998), Tuck (1993) and Levings (1982). A dataset of 40 recent water-level data measurements (2006–2014) collected during the MiR-TAP fieldwork, or obtained from public databases, was used to validate the transboundary map and confirm the trend in the regional groundwater flow pattern. The pressure gradients described by Berkenpas (1991) were also used to complete the map at the northern and eastern limits of the Milk River Aquifer in Alberta. Efforts were made to harmonize the various datasets, especially at the U.S.A.-Canada border, in order to give emphasis to the transboundary character of the aquifer.

Sources:

Berkenpas, P.G., 1991. The Milk River Shallow Gas Pool: Role of the Updip Water Trap and Connate Water in Gas Production From the Pool. *In*: SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers. doi: 10.2118/22922-MS

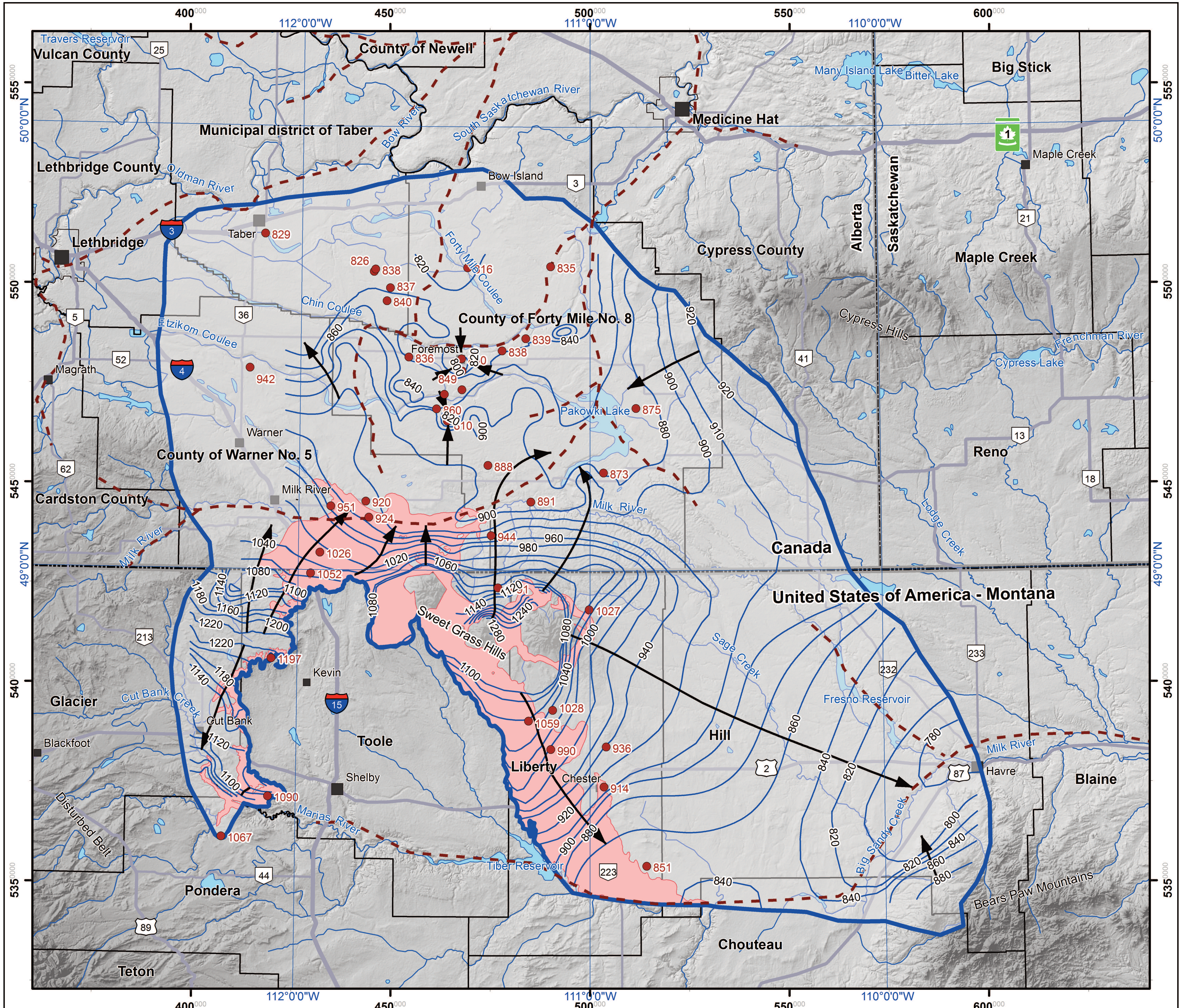
Levings, G.W., 1981. Selected drill-stem-test data from the Northern Great Plains area of Montana. Open File Report 81-326, United States Geological Survey. <https://pubs.er.usgs.gov/publication/ofr81326>

Meyboom, P., 1960. Geology and groundwater resources of the Milk River sandstone in southern Alberta. Research Council of Alberta. <http://ags.aer.ca/publications/MEM_02.html>

Milk River Transboundary Aquifer Project (MiRTAP), 2012–2013. Fieldwork Campaign 2012–2013.

Tuck, L.K., 1993. Reconnaissance of geology and water resources along the north flank of the Sweet Grass Hills, north-central Montana. United States Geological Survey, Water-Resources Investigations Report 93-4026. 68 p. <https://pubs.er.usgs.gov/publication/wri934026>

Zimmerman, E.A., 1967. Water resources of the Cut Bank area, Glacier and Toole counties, Montana. Montana Bureau of Mines and Geology Bulletin 60, 37 p. <http://www.mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=10061>



MAP 5.4

Piezometric Surface and Groundwater Flow Path Direction

Projection UTM 12N 1:1 000 000

Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Groundwater
- Recently Measured Hydraulic Head (m a.m.s.l.)
- Piezometric Contour (m a.m.s.l.)
- Groundwater Flow Path
- Bedrock Valley Thalweg

Aquifer Extent
- Milk River
- Milk River Formation Outcrop

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m

5.6 Aquifer Types

There are three types of aquifers: confined, unconfined, and semi-confined (Figure 5.6). A confined aquifer is bounded from above and below by impervious formations. An unconfined aquifer is under atmospheric pressure and has a water table that serves as its upper boundary. Semi-confined conditions occur when the overlying unit is not impervious and water is leaking through.

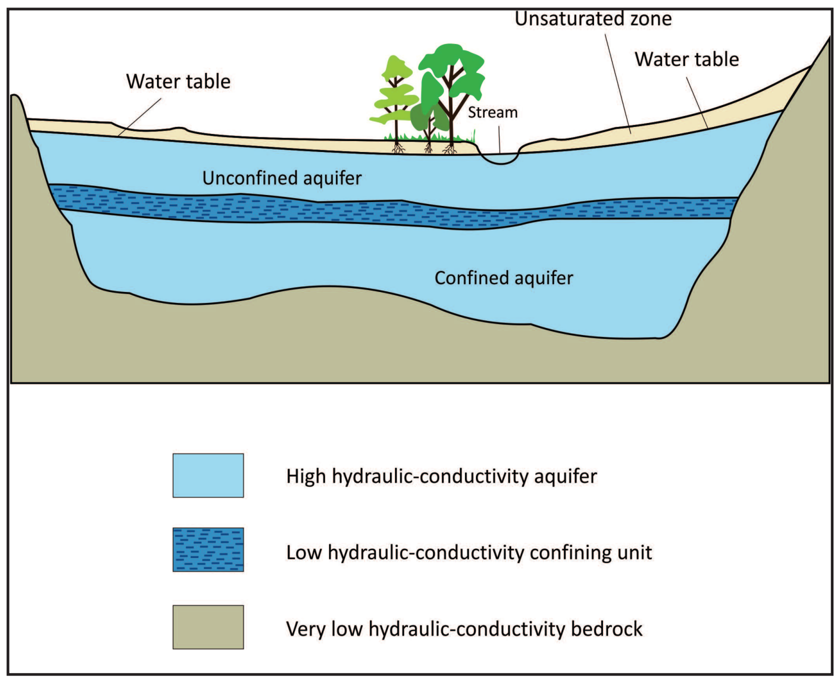


Figure 5.6 Example of confined and unconfined aquifers.
Schema credit: © USGS – North Dakota Water Science Center

The Milk River Aquifer is mainly confined (Table 5.2). The Milk River Formation dips to the north from the outcropping areas in the Sweet Grass Hills and near the border in southern Alberta. It dips to the south and east and to the south and west of the study area. The Milk River Aquifer is therefore confined by the overlying Pakowki Formation / Claggett Shale throughout 88% of its total extent.

Table 5.2 Types of aquifers

Aquifer type	Area (km²)	Proportion of the study area (%)
Confined	20 549	88
Semi-confined	2 218	9
Unconfined	631	3
Total	23 397	100

The Milk River Formation outcrops near the border in southern Alberta and around the Sweet Grass Hills in Montana (Figure 5.7). Most importantly, the Virgelle Member subcrops along both sides of the Sweetgrass Arch in Montana, which constitute the only locations where the Milk River Aquifer is not confined. In this area, the aquifer is mostly semi-confined. This type of aquifer represents 9% of the entire aquifer. Only 2% of the aquifer is under unconfined conditions. Because these conditions are found only in the vicinity of the Sweet Grass Hills and along the Milk River (Map 5.5), the Milk River Aquifer is not vulnerable to surface contamination.

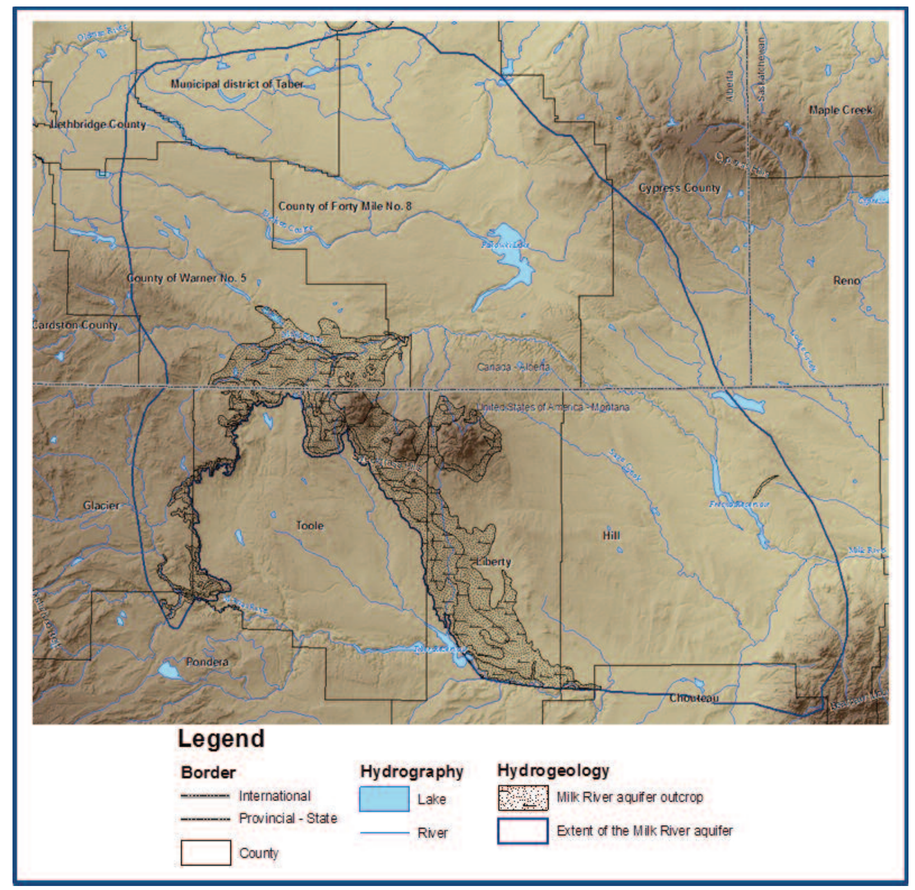


Figure 5.7 Milk River Formation outcrop

Methodology:

The aquifer was defined as confined except where the Milk River Aquifer outcrops and/or subcrops. In this area, the types of aquifers have been defined using the following rules:

Unconfined aquifer:
- Absence of clay and/or silt
- Till thickness is below 3 m

Semi-confined aquifer:
- Till and/or clay and/or silt thickness is below 5 m

Confined aquifer:
- Clay and/or silt thickness is equal to or above 5 m

The sediment thickness values are derived from the three-dimensional geological model of the aquifer (Pétré et al., 2015) (cf. Map 4.5 in section 4.5)

Sources:

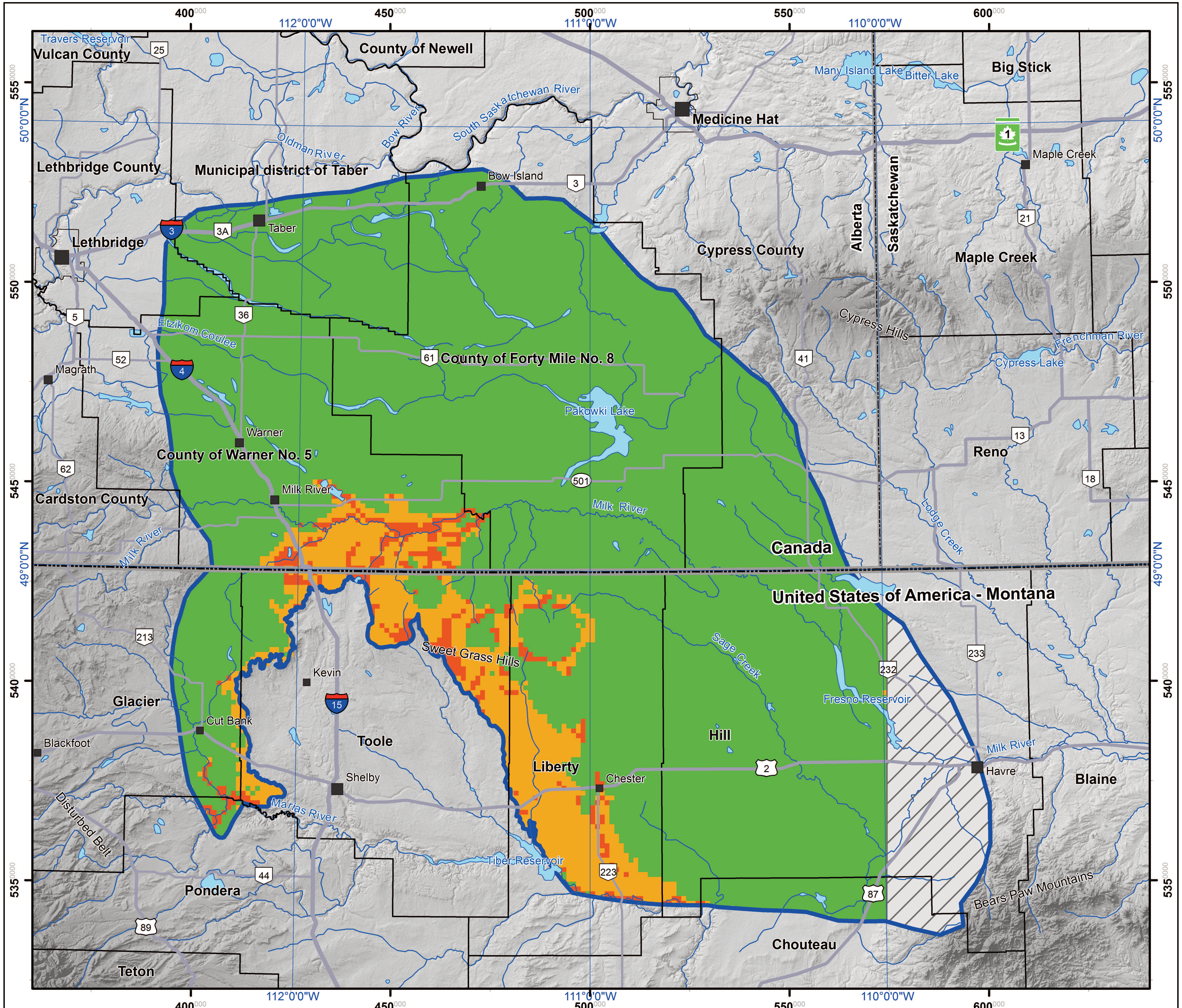
Colton, R.B., Lemke, R.W., and Lindvall, R.M., 1961. Glacial map of Montana east of the Rocky Mountains. United States Geological Survey, Miscellaneous Geologic Investigations Map I-327, <http://ngmdb.usgs.gov/Prodesc/proddesc_1391.htm>

Fenton, M.M., Waters, E.J., Pawley, S.M., et al., 2013. Surficial geology of Alberta, Map 601, 1:1,000,000. Alberta Geological Survey, Edmonton, Alberta.

Okulitch, A.V., Lopez, D.A., and Jerzykiewicz, T., 1996. Bedrock geology, Lethbridge, Alberta-Saskatchewan-Montana. Geological Survey of Canada, National Earth Science Series, Geological Atlas no. NM-12-G. doi: 10.4095/208987

Pétré M-A., Rivera, A., and Lefebvre, R., 2015. Three-dimensional unified geological model of the Milk River Transboundary Aquifer (Alberta, Canada – Montana, USA). Canadian Journal of Earth Sciences, v. 52, no. 2, p. 96–111. doi: 10.1139/cjes-2014-0079

Saskatchewan Energy and Resources, 2015. Surficial geology of Saskatchewan. <http://www.infomaps.gov.sk.ca/website/sir_geological_atlas/viewer.htm>



MAP 5.5

Aquifer Types

Projection UTM 12N   1:1 000 000

Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Aquifer Type
- Confined Aquifer
- Semi-Confined Aquifer
- Unconfined Aquifer
- No Data

Aquifer Extent
- Milk River

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m

5.7 Apparent Yields

The yield of water wells drilled in the Milk River Aquifer has been the subject of various studies over the past 50 years. The yield of water wells has been either measured in flowing wells or estimated as "apparent yield" from well logs, monitoring, and areas with known hydraulic conductivity. Data generally corresponded to estimates based on short development tests following well construction. Therefore, these data do not correspond to the maximum acceptable well yield, nor are they representative of the actual use (as stated in Rivard et al., 2005). Water well yields in Alberta range from 8.6 m^3/d to 864 m^3/d on individual wells; in Montana they vary between 5.2 m^3/d and 1 382 m^3/d.

In Alberta, the apparent yields were calculated for each county (Map 5.6). A generalization of the data is presented. The highest yield values (>300 m^3/d) are found in the southern County of Forty Mile No. 8. Other high values (100 to 300 m^3/d) are mainly found in Forty Mile No. 8 and Warner No. 5 counties. There are also some high yield values in the eastern part of Cypress and Taber counties. Table 5.3 shows the area covered by each apparent yield class.

Table 5.3 Apparent yield class area

Apparent yield class (m^3/d)	Area (km^2)	Proportion of Albertan Milk River Aquifer (%)	Proportion of Milk River Aquifer (%)
0-100	6 717	50	27
100-300	4 611	34	19
>300	1 720	13	7
No Data	11 441	3	47

Compiled from HCL Consultants (2007 and 2004) and Stantec (2002)

In the Municipal District of Taber, 156 bedrock water wells have been completed in the Milk River Aquifer (HCL consultants, 2007). The apparent yield for individual water wells completed throughout the Milk River Aquifer is greater than 30 m^3/d, and the median apparent yield value is 55 m^3/d. Of all the water wells completed in the upper bedrock aquifers (the whole sequence from drift to the top of Colorado Shale), 65% have apparent yield values of less than 50 m^3/d, with a median apparent yield equal to 35 m^3/d (HCL Consultants, 2007). Yields higher than 50 m^3/d are associated with wells drilled in the Milk River Aquifer in the vicinity of the buried bedrock valleys. It is assumed that these higher yield areas may identify areas of increased permeability resulting from weathering (HCL consultants, 2007).

In the County of Warner No. 5, yields for 115 out of 559 wells in the Milk River Aquifer are in the range from 5 to 75 m^3/d (Stantec, 2002). Local yields in areas with high transmissivities are between 230 and 830 m^3/d.

In the County of Forty Mile No. 8, of the 1213 upper bedrock water wells identified by HCL Consultants (2004), about 845 wells are completed in the Milk River Aquifer. The apparent yields for individual water wells drilled in the Milk River Aquifer range from less than 10 to more than 300 m^3/d (HCL Consultants, 2004). The southeastern part of the county shows the highest yields.

In Cypress County, only three water well records were available. An additional 160 apparent yields located in the County of Forty Mile No. 8 were used to calculate apparent yields. The area shows apparent yields between 10 and 100 m^3/d, except in the eastern part of the county, which has yields of 100 to 300 m^3/d.

In the Cut Bank area of Montana, Zimmerman (1967) indicated that wells drilled into the Virgelle Member produce as much as 1363 m^3/d. In the Sweet Grass Hills area, Tuck (1993) mentioned that sandstone of Virgelle Member yields from 5.2 m^3/d to 437 m^3/d of water to wells. In the Eagle Sandstone, the average reported or measured discharge from 115 wells is about 125 m^3/d (Levings, 1982). The discharge ranges from 2.6 to 1090 m^3/d, with 28 wells having discharges greater than 109 m^3/d (Levings, 1982).

Meyboom (1960) reported that the average flow of flowing wells near Pakowki Lake decreased from 82 m^3/d in 1937 to a range of 28 to 38 m^3/d in the 1960s. AITF (2010) compared well flow rates from the 1973 Nelson and Sidlinger study, the 1992 Persram study, and the 1998 AGRA survey. Most of the flowing wells experience a decrease flow over time (AITF, 2010).

Methodology:

The Milk River Aquifer apparent yield maps from HCL Consultants (2004 and 2007) and Stantec (2002) were integrated and georeferenced in ArcGis to produce Map 5.6. The well yield polygons were edited in a polygon shapefile. Considering that the yield classes from the different maps were not concordant, all the classes were merged to create four classes as shown in the table below.

Classes grouping (m^3/d)	Original classes (m^3/d) (from the consultants' reports)
0-100	0-10
	0-50
	10-100
100-300	100-300
	100 and more
300 and more	300 and more
Insufficient data	Insufficient data
	No data

Sources:

AGRA Earth and Environmental Limited, 1998. Evaluation of depletion of the Milk River Aquifer. AGRA Earth & Environmental, Edmonton, Alberta.

Alberta Innovates Technology Future (AITF), 2010. Milk River Aquifer hydrogeology report.

HCL Consultants, 2001. Cypress County part of the Missouri and South Saskatchewan river basins, Parts of Tp 001 to 021, R 01 to 13, W4M.

HCL Consultants, 2004. County of Forty Mile No. 8, Parts of the South Saskatchewan River and Missouri river basins. Regional groundwater assessment, Tp 001 to 013, R 05 to 14, W4M.

HCL Consultants, 2007. M.D. of Taber, Part of the South Saskatchewan river basin. Regional groundwater assessment, Parts of Tp 007 to 015, R 12 to 20, W4M.

Levings, G.W., 1982. Potentiometric-surface map of water in the Eagle Sandstone and equivalent units in the Northern Great Plains area of Montana. Open File Report 82-565. United States Geological Survey. <https://pubs.er.usgs.gov/publication/ofr82565>

Meyboom, P., 1960. Geology and groundwater resources of the Milk River sandstone in southern Alberta. Research Council of Alberta. <http://ags.aer.ca/publications/MEM_02.html>

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Persram, A., 1992. Hydrogeology of the Milk River Formation in southern Alberta. Alberta Environmental Protection, Hydrogeology Branch (unpublished data cited by AGRA, 1998 and AIFT, 2010).

Rivard, C., Deblonde, C., Michaud, Y., Boisvert, V., Carrier, C., Castonguay, S., and Lefebvre, R., 2005. Hydrogeological atlas of the south-central area of the Maritimes Carboniferous basin, Geological Survey of Canada, Open File 4884, 54 p., 1 CD-ROM. doi: 10.4095/216758

Stantec, 2002. Regional groundwater assessment of potable groundwater in County of Warner No. 5, Alberta.

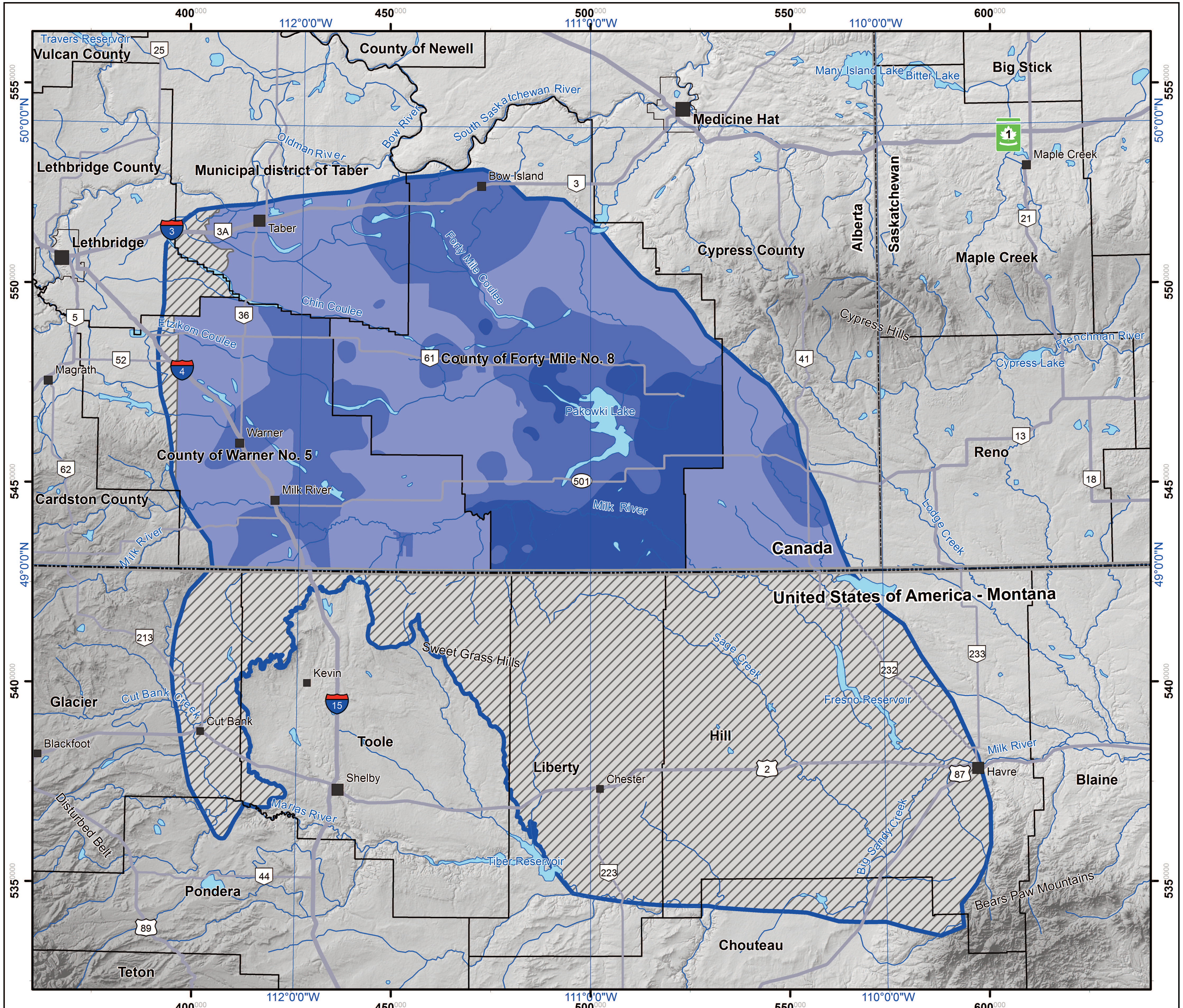
Tuck, L.K., 1993. Reconnaissance of geology and water resources along the north flank of the Sweet Grass Hills, north-central Montana. United States Geological Survey, Water-Resources Investigations Report 93-4026. 68 p. <https://pubs.er.usgs.gov/publication/wri934026>

Zimmerman, E.A., 1967. Water resources of the Cut Bank area, Glacier and Toole counties, Montana. Montana Bureau of Mines and Geology Bulletin 60, 37 p.
<http://www.mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=10061>

MAP 5.6

Apparent Yields

Projection UTM 12N 1:1 000 000



Legend

Population

- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network

- Highway
- Main Road
- Regional Road

Border

- International
- Provincial
- Town and County

Hydrography

- Lake
- River

Apparent Yield (m^3/d)

Integrated from 2002 to 2007

- 0 - 100
- 100 - 300
- > 300
- Insufficient data

Aquifer Extent

- Milk River

Elevation (m a.m.s.l.)

High : 2 595 m

Low : 620 m

5.8 Conceptual Model

The hydrogeological and geochemical evidence collected by Pétré et al. (2016) allowed the development of a comprehensive conceptual model of the MRA along its natural boundaries. On the basis of groundwater divides inferred from the piezometric map (Map 5.4), the MRA was divided into three natural subsystems in which groundwater flows in different directions and discharges into three distinct locations (Figure 5.8). Zones 1, 2 and 3 were delineated. Zone 1 corresponds to the area where groundwater flows from northern Montana to southern Alberta. A distinction is made between the portions located south (Zone 1a) and north of the Milk River (Zone 1b), the latter of which intersects a large part of the transboundary flux coming from northern Montana. Zone 1b also includes groundwater flow from the Cypress Hills. Zone 2 comprises the southeastern part of the study area in Montana, in which groundwater flows from the Sweet Grass Hills and Bears Paw Mountains to the Big Sandy Creek area. Zone 3 is located in the southwestern part of the study area.

The MRA is under unconfined or semi-confined conditions in the outcrop and subrop areas of the Virgelle Member as shown on the conceptual hydrogeological cross-section in Figure 5.9. The level of confinement of the aquifer is due to changes in surface topography, especially due to the presence of coulee and river valleys and the presence of buried valleys that have eroded part of the aquitards above the MRA. The MRA presents flowing artesian conditions in the northern part of the study area. The study of groundwater flow and the quantification of the fluxes up-gradient and down-gradient from the Milk River show that the main discharge mechanism of the MRA in southern Alberta is from interception of flow by the Milk River. Several studies established that the Milk River served as a point of discharge for the MRA rather than recharge (Meyboom, 1960; Robertson, 1988; Drimmie et al., 1991, Fröhlich, 2013).

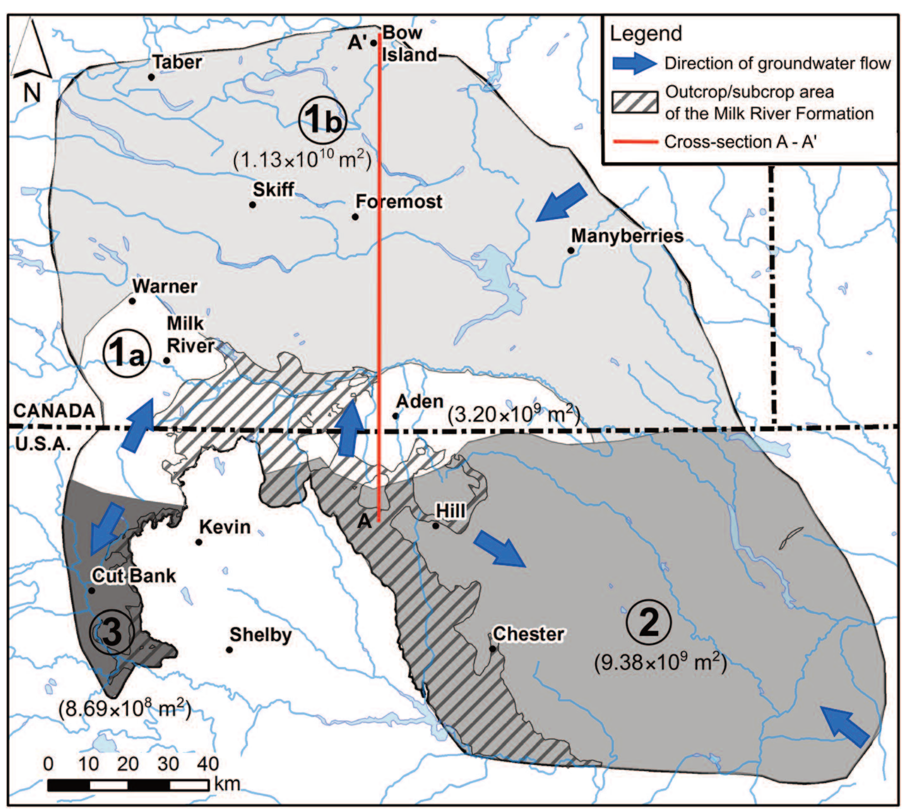


Figure 5.8 Delineation of three natural zones (Zone 1a/1b, Zone 2, and Zone 3) of the MRA and their surface areas (Pétré et al., 2016)

Previous estimates of the volume of the springs and seeps along the Milk River were about 5.8×10^{-2} m^3/s (Meyboom, 1960) or 9.0×10^{-3} m^3/s (Robertson, 1988). These values are lower than the current estimate of about 0.3 m^3/s because they were obtained considering that the discharge into the river takes place only along the 30 km outcrop of the Virgelle Member, where it is incised by the Milk River. The piezometric map (Map 5.4) and the isotopic data (Maps 7.14 to 7.17) rather indicate that groundwater flow is intercepted along the entire length of the Milk River in Alberta and part of the Verdigris Coulee even if the hydraulic connection is indirect. This mechanism could be supported by the buried valley located underneath the present-day Milk River.

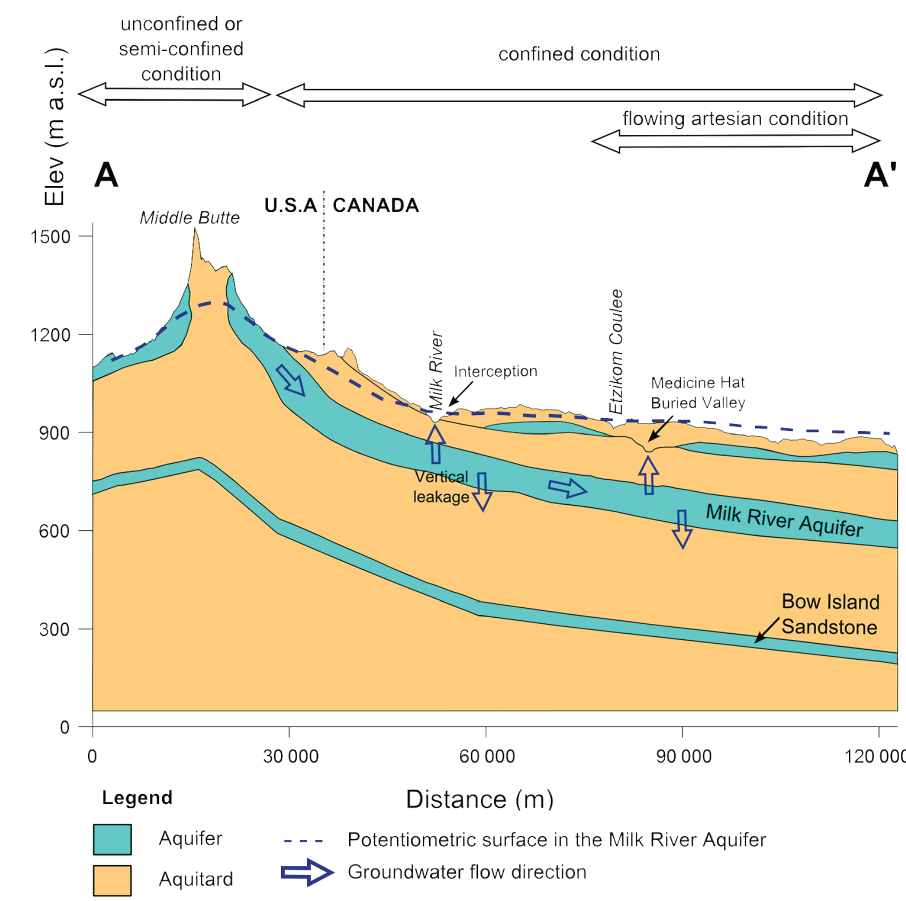


Figure 5.9 SW-NE hydrogeological cross-section of the MRA located along a flow line (Pétré et al., 2016)

Modern water (defined by high tritium concentrations, Map 7.14) is found not only in the outcrop areas near the border, but also west of the Sweetgrass Arch. This suggests that the entire outcrop belt around the Sweetgrass Arch could serve as a recharge area for the MRA. Furthermore, hydrographs of three monitoring wells of the MRA located in the outcrop branches in Montana (GWIC ID 88838, 45363 and 90371) show that water level fluctuations follow the meteorological changes, thus supporting the assumption that they are located in a recharge area. This assumption differs from previous work where the emphasis was generally placed on the Sweet Grass Hills as the main recharge area (Meyboom, 1960; Domenico and Robbins, 1985).

There is no ^{14}C in the waters of the MRA north of the Milk River. This strongly suggests that a major part of the groundwater flow is intercepted by the Milk River. Therefore, the remaining flux and the hydraulic gradient are low north of the river, resulting in low groundwater velocity and large groundwater residence time (> 50 000 years) as indicated by isotopic tracers. In Montana, the disappearance of ^{14}C is due simply to the decay along the flow path. Southwest of the Sweetgrass Arch in Montana, the decrease in ^{14}C values is less pronounced. This observation is consistent with the low chlorine concentration, the high transmissivity and the prevalence of little-evolved water types containing sulfates defining this area. These characteristics indicate that the groundwater flow is active in this part of the study area.

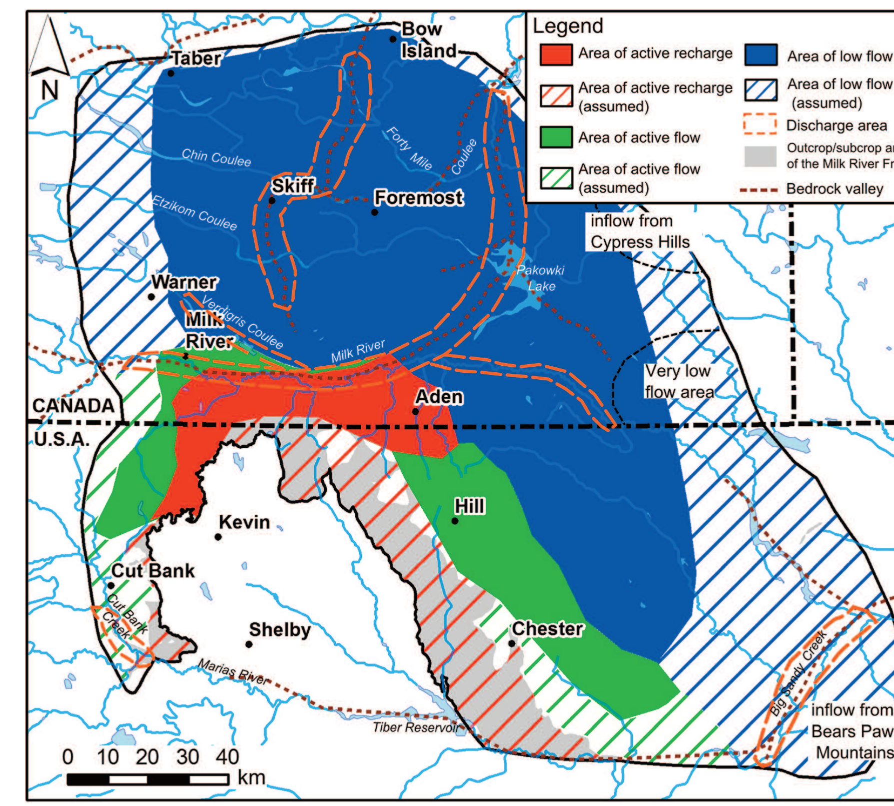


Figure 5.10 Plan view of the conceptual model of the MRA (Pétré et al., 2016)

North of the Milk River and in the southeastern part of the study area, old to very old waters up to two million years (Ma) are found, as shown by ^{36}Cl data. The groundwater flow is low and water types are more evolved. Berkenpas (1991) provided hydrogeological evidence southeast of Lake Pakowki and south of Manyberries indicating that a region with a no flow (hydrostatic conditions) or very low groundwater flow existed in the area. The evolved water type Na^{+}–HCO_3^{-} and the old water residence time found during the study are consistent with this statement. Figure 5.10 presents a plan view of the groundwater flow conceptual model of the MRA (Pétré et al., 2016) in which the areas of active recharge, active flow, low flow, and discharge are delineated within the natural extent of the MRA.

The area of active recharge is characterized by high levels of tritium in the MRA waters and is limited to the outcrop/subcrop areas of the MRA. Some groundwater may come from the topographic highs (Cypress Hills, Bears Paw Mountains). The area of active flow is characterized by the presence of ^{14}C and is located beyond the recharge area and upgradient of the Milk River. The area of low flow covers most of the study area and is defined by the absence of ^{14}C and thus, very old water with evolved water types. Except for the Milk River, there is no natural direct discharge zone, but discharge or outflow may occur through vertical leakage along the buried valleys and through the underlying aquitards of the Colorado Group. The vertical leakage could also be enhanced in the northwestern part of the study area due to the gradual thinning of the Pakowki Formation (Swanick, 1982; Pétré et al., 2015). In Montana, the piezometric map indicates that the same mechanism is likely to occur as an upward flow from the Eagle Formation towards the Claggett Shale and Judith River formations and into the surficial sediments of the Big Sandy Creek area. Besides, the presence of the Bears Paw Mountains in the southeast corner of the study area would prevent groundwater flow from progressing any farther east and therefore inciting the vertical leakage.

6 Groundwater Quantity

6.1 Groundwater Quantity

The quantity of freshwater resources is fast becoming a big issue in many parts of the world, including Canada. Although essentially a renewable resource, freshwater is being extracted from river basins at rates approaching those at which the supply is renewed, and from some aquifers at rates exceeding natural replacement (i.e., recharge). Many human activities have high water-use rates. As societies grow, so have withdrawals of water for agricultural, industrial and municipal use.

A new element of uncertainty is the potential change in the amount of precipitation, and hence freshwater resources, as a consequence of changes in climate caused by human activities.

How much groundwater is there? How much is available for use? And for how long? To answer those questions, groundwater should be quantified as a resource using terms such as quantity, availability, sustainability, supply, and use. Those terms can provide guidance for groundwater resources management for a single aquifer, for a series of aquifers, for a province, or for a whole country.

Quantity

Groundwater resources may be evaluated as fluxes (volume in time, for instance, annual recharge to aquifers) or as pools (volumes of groundwater stored in aquifers).

The main hydrogeological parameters, or variables, needed to assess groundwater quantity are water table elevation and depth, saturated thickness of the aquifer, transmissivity, and changes in the groundwater levels.

The water table is an undulating surface much like the land surface above it. It consists of highs, lows, and divides, and it intersects the land surface along the banks of streams and lakes. Using a large number of water table measurements, hydrogeologists can draw lines connecting points of equal elevation, giving an approximation of the water table of the aquifer. Groundwater moves from high elevation to low elevation in three dimensions (both horizontally and vertically) creating a hydraulic gradient. A map of the water table (or piezometric surface) is a two-dimensional representation of the horizontal hydraulic gradient that indicates the direction of flow, as depicted in Map 5.4 (Section 5.5).

Hydrogeologists can do a lot with and learn a lot from piezometric maps, such as direction of groundwater flow, estimation of groundwater fluxes, location of discharge zones, trends of increasing or decreasing groundwater recharge, interaction with surface water, and initial estimations of groundwater quantities.

Saturated thickness is the thickness of an aquifer material that is completely saturated with water. Given its geological and confined conditions, most of the Milk River Aquifer is completely saturated with water. In some localized areas, the Milk River is unconfined and its thickness is variable from the base of the aquifer to the water table (phreatic conditions), as shown with pink colours representing the outcrop of the aquifer in Map 5.1. The schema of Figure 5.6 and Table 5.2 in Section 5.6 shows the three confined, semi-confined, and unconfined conditions found in the Milk River Aquifer.

To estimate water in storage, the saturated thickness must be multiplied by the effective porosity, which is defined as the part of the pore volume where the water can circulate (i.e., where pores are connected). In a confined aquifer, the saturated thickness is the thickness of the aquifer between the two primary confining units; in the case of the Milk River Aquifer, these are for most part the Colorado Shale Group and the Pakowki unit (see Section 4 and 5). For unconfined aquifers, this volume also corresponds to the volume of water that could theoretically be available for pumping, although if pumping exceeds aquifer recharge, the water table will of course decrease. In confined aquifers, the theoretical amount of water available for pumping would have to be calculated using the storage coefficient, which is defined as the volume of water that an aquifer releases per unit area of aquifer given unit head change, and a representative drawdown that should not exceed the top of the aquifer.

Transmissivity can be used as an indication of how aquifers transmit water to wells. Though transmissivity is useful as a guide, one cannot directly predict well yield based on it alone. The yield, or pumping rate, of a well depends also on the type of construction and development of a well, the amount of drawdown during pumping, and whether the aquifer is confined or unconfined.

Effective porosity is generally defined as that portion of the media that contributes to flow under confined conditions; it is that part of the pore space where velocity is greater than the average fluid velocity.

Availability

Although the quantities of water in a hydrologic system (pools and/or fluxes) can be measured, computed, or estimated in a straightforward manner, water availability cannot. Like water sustainability, water availability is an elusive and multifaceted concept. Thus, the challenges of determining groundwater availability are many.

Groundwater availability is a function not only of the quantity and quality of the water in an aquifer system, but also the physical structures, laws, regulations, and socioeconomic factors that control its demand and use. Physical and chemical characteristics of an aquifer may be used as indicators of groundwater availability; however, at the local level where most decisions are taken, these characteristics must be considered jointly with societal factors that determine actual groundwater availability and society's tolerance of the consequences of its use. Societal perspectives and constraints change with time just as the groundwater resource does.

Groundwater availability may be defined as "renewable freshwater resources," i.e., yearly recharge. Availability could also include volumes of groundwater in storage, but that would be a management decision in cases of temporary water scarcity, e.g., in semi-arid regions.

Sustainability, supply and use

In simple terms, groundwater sustainability is the assurance of long-term groundwater availability for all uses. This long-term assurance can only be reached by a balance between the availability of groundwater and the benefits of its use by humans and ecosystems. Water availability and use are closely related to water sustainability, which can be thought of as an approach for managing water resources. Sustainability of groundwater resources cannot be defined as an absolute concept. It is a relative concept and it has many variations.

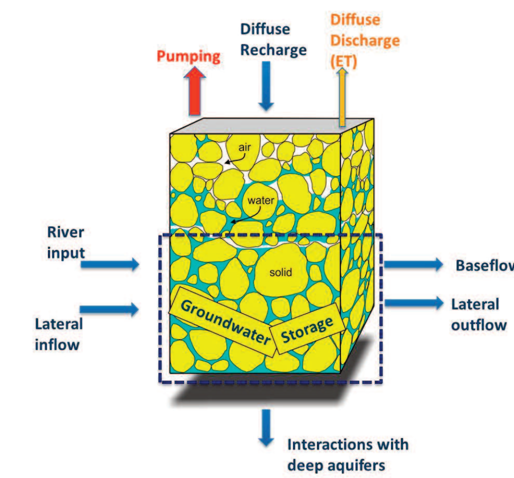


Figure 6.1 Fluxes that affect groundwater storage change (Rivera et al., 2016)

Sustainable use of groundwater resources demands knowledge of recharge and discharge, fluxes for which adequate measurement techniques are not available in many instances. The sustainability of groundwater resources requires a detailed knowledge of the components of the water balance of a given aquifer or any other management unit where groundwater is withdrawn by humans and/or ecosystems (Figure 6.1).

Groundwater budget in the MRA

To estimate groundwater quantity (or availability), a good management practice is the assessment of groundwater budgets as a function of space and time. In the course of the MRA studies, Pétré et al. (2016) calculated detailed groundwater budgets of the aquifer. As the concerns regarding aquifer depletion are mostly present in southern Alberta, a detailed groundwater budget in Zone 1 of the aquifer (see Figure 5.8 in Section 5.8 for location) was proposed by Pétré et al. (2016) (Figure 6.2).

The water balance equation states the following under steady-state condition: outflow - inflow = change in storage. The source of water to the aquifer system corresponds to the groundwater recharge from precipitation.

Outflows include the part of the flow intercepted by the Milk River, the vertical leakage through overlying and underlying aquitards, pumping wells, and flowing wells. The components of the groundwater budget were estimated on a cross-section representing the annual water budget in Zone 1 (Figure 6.2a). A distinction was made between Zone 1a and Zone 1b, areas south and north of the river, since the remaining flow out of Zone 1a (part of flow that is not intercepted by the Milk River) constitutes the inflow of Zone 1b. For consistency, components were expressed as a water thickness equivalent uniformly distributed on the total surface of the considered area (i.e., 1.45×10^{10} m^2).

The vertical leakage fluxes directed upwards and downwards were estimated from vertical hydraulic gradients. The magnitude of the vertical leakage through the aquitards and along the bedrock valleys depends on the vertical hydraulic conductivity of the units surrounding the MRA. These parameters are not well known over the regional study area, hence the large range of values.

The amount of groundwater stored in the MRA was obtained by multiplying the volume contained between the top of the aquifer and the piezometric surface by the storage coefficient (3×10^{-4}; Meyboom, 1960). This calculation was made only where the potentiometric surface was defined in Zone 1b, where the aquifer is contained (a surface of 7.43×10^9 m^2, see Figure 5.8). The mean distance between the piezometric surface and the top of the MRA is about 171 m. The total amount of water stored in the MRA is about 380×10^6 m^3. Figure 6.2b shows a comparison between the different parameters, and the effective recharge in zone 1a is taken as a reference. As shown in Figure 6.2a, most of the recharge is intercepted by the Milk River. The remaining flux transmitted beyond the Milk River is only about 0.4×10^6 m^3/a (0.03 mm/a), i.e., up to 10 times smaller than the sum of the outflows in Zone 1b (3.5×10^6 m^3/a or 0.24 mm/a using maximum values).

The human stress on the aquifer resource (through pumping and flowing wells) constitute the main outflows north of the Milk River. Indeed, the location of the main groundwater users in southern Alberta is precisely north of the Milk River (Zone 1b), explaining the water budget deficit in this area. It is clear that, given the very low inflow in zone 1b, the groundwater extracted from the aquifer mostly comes from storage, indicating a depletion of the MRA following the definition from Konikow and Kendy (2005). The situation can also be described as groundwater mining since exploitation of groundwater far exceeds groundwater renewal (Custodio, 2002). Moreover, previous studies (Meyboom, 1960; AGRA Earth and Environmental, 1998; HCL consultants, 2004) had estimated that the exploitable reserve of the MRA may last less than 200 years in southern Alberta. However, the full implications of the potential duration of exploitation of the resource are not discussed further; they are currently being explored (Pétré et al., 2017, in preparation) using a numerical model built within the transboundary study of the MRA.

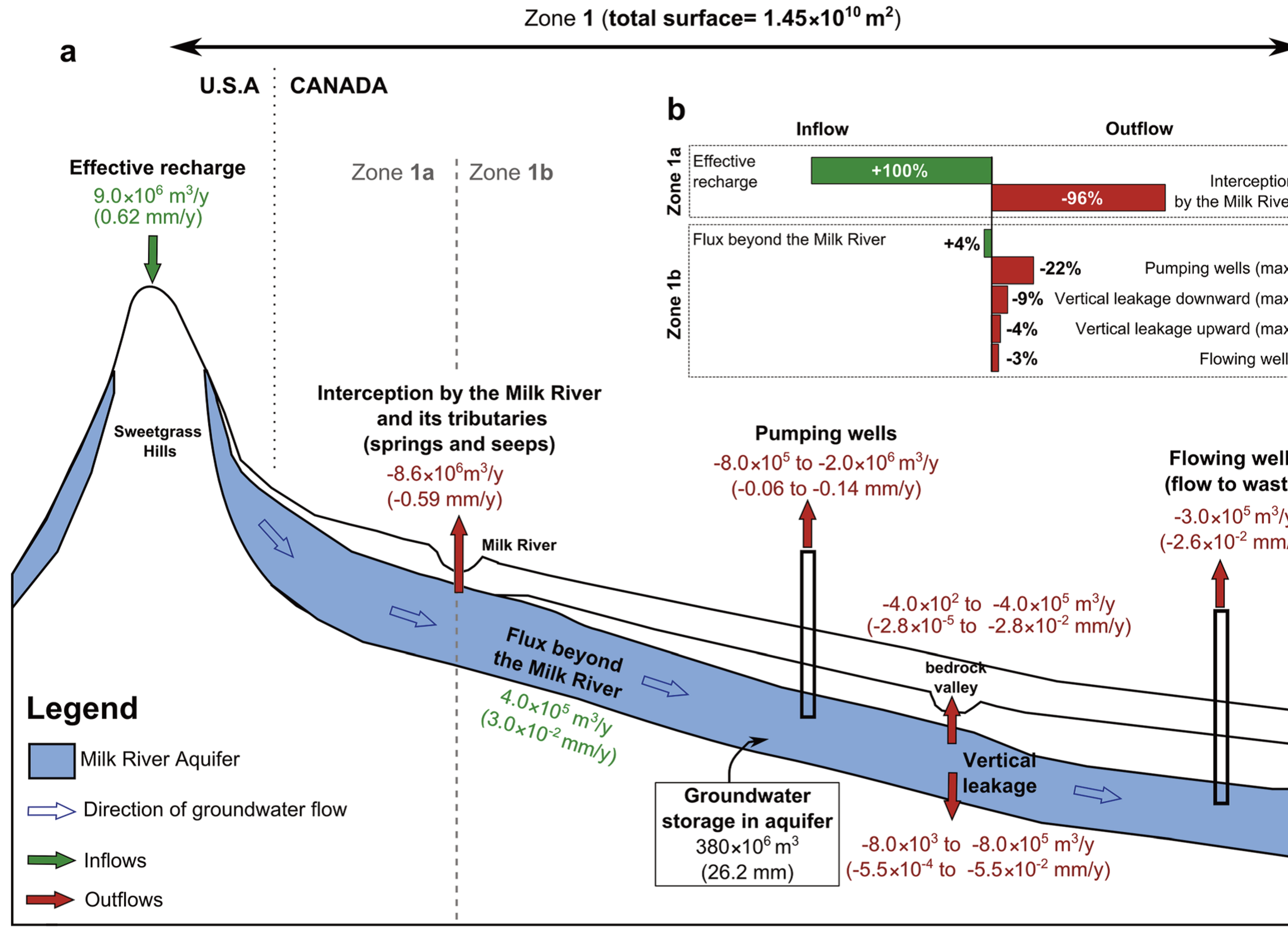


Figure 6.2
part a: Groundwater budget in southern Alberta. The recharge located south of the Milk River is mostly intercepted by the Milk River as the water flows downgradient. The remaining flux beyond the Milk River corresponds to the inflow towards the northern part of the MRA.

part b: Comparison of the components of the budget that are in deficit in the southern parts. The reference of the scaling is taken from the recharge (100%).
From Pétré et al. (2016).

7 Groundwater Quality

7.1 Major and Minor Ions, pH and Total Dissolved Solids

Groundwater geochemical characterization is a useful tool for groundwater management and to better understand groundwater flow. Since groundwater geochemistry depends locally on the geological context in which it flows, certain problems observed in one place may be present in other places where the geological context is similar. Identifying problems observed in an area and their causes allows anticipation of potential water quality problems. Moreover, the geochemical characterization allows the definition of the various background levels in the area, i.e., the natural concentrations of the different physicochemical parameters and the water types can also provide a better understanding of the groundwater flow dynamics.

Major ions

The major dissolved components of groundwater include the anions bicarbonate (HCO_3^-), chloride (Cl) and sulfates (SO_4^{2-}), and the cations sodium (Na), calcium (Ca), magnesium (Mg) and potassium (K). These constituents are usually present at concentrations in the range of a few mg/L to several hundred mg/L. Table 7.1 shows descriptive statistics for different constituents for which concentrations are presented in Maps 7.1 to 7.11. In the Milk River Aquifer, the major ions show three major trends: 1) calcium, magnesium and sulfate decrease to the north; 2) bicarbonate, sodium and chloride increase to the north; 3) potassium exhibits no well-defined trend. The guideline values are from the Summary Tables of Guidelines for Canadian Drinking Water Quality, posted October 2014 and published on Health Canada's website (see <http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/sum_guide-res_recom/index-eng.php>).

High calcium, magnesium and sulfate concentrations are observed in the subcropping area of the Milk River Aquifer. The concentrations found in Montana are 10 to 20 times higher than the ones observed in Alberta for the three components (Table 7.1). In Montana, the calcium and magnesium concentrations are higher than 50 mg/L for 40% and 23% of the samples, respectively. In Alberta, 84% of the calcium samples and 23% of the magnesium samples have concentrations lower than 5 mg/L. The water quality aesthetic objective for sulfates is ≤ 500 mg/L. This objective is exceeded in 36% of the samples in Montana. The samples exceeding this threshold are mainly found in the subcropping area. In Alberta, only 8% of the samples have sulfate concentrations higher than 500 mg/L.

Low bicarbonate, sodium and chloride concentrations are found mainly in the subcrop area and increase northwards to central-northern Alberta (Schwartz and Muelhenbach, 1979; Swanick, 1982; Hendry and Schwartz, 1988). In Montana, only 17% of the samples have bicarbonate concentration higher than 750 mg/L compared to 73% in Alberta.

About 25% of the samples show chloride concentration higher than the aesthetic objective, which is ≤250 mg/L (Table 7.1). The exceeding samples are mostly located in central and northern Alberta. In the municipality district of Taber, 85% of the chloride concentrations from the Milk River Aquifer are greater than 250 mg/L and the median value (502 mg/L) exceeds the guideline. In the Cut Bank area, chloride concentrations of groundwater from the Virgelle Sandstone rarely exceed 100 mg/L (Zimmerman, 1967). The chloride geochemistry of the Milk River Aquifer is complex; In Alberta, chloride concentration increases from the recharge area to the north. This areal distribution has been explained by flushing of connate waters (Domenico and Robbins, 1985); ion filtration (Swanick, 1982; Philips et al., 1986) and diffusion of chloride into the aquifer from the underlying shale unit (Hendry and Schwartz, 1988). Nolte et al. (1991) suggested that this increase in chloride from south to north matches the general groundwater flow tendency. In Montana, the chloride concentrations are lower than in Alberta; an increase in chloride is noticeable from the Sweet Grass Hills to the east and southeast, following the regional groundwater flow paths.

The aesthetic objective for sodium is ≤200 mg/L. A proportion of 93% of the samples exceed the objective with a median of 469 mg/L (Table 7.1). High sodium concentrations are observed almost everywhere in the aquifer, except in the area surrounding the Sweet Grass Hills. The dominance of sodium in the Milk River Aquifer is explained by the process of ion exchange of Na^+ on the rock matrix for Ca^+ and Mg^{2+} in solution (Meyboom, 1960; Schwartz and Muelhenbach, 1979).

The concentration of potassium exhibits no well-defined trends throughout the aquifer (Hendry and Schwartz 1990). The median value is 1.82 mg/L and 89% of the samples have potassium concentration lower than 4 mg/L.

Minor ions

Minor ions present in this area are: iron, manganese, fluoride, boron, nitrogen species, strontium, and carbonate. Fluoride, manganese and iron show samples exceeding the guideline. Fluoride has a maximum acceptable concentration of 1.5 mg/L (Table 7.1). In the Milk River Aquifer, 8% of the samples exceed the guideline. Samples exceeding this guideline are distributed almost everywhere in the study area. For manganese, the aesthetic objective is ≤ 0.05 mg/L. Only 18 samples exceed the guideline, representing 3% of all the analyzed samples. 6% of the iron samples exceed the guideline (Table 7.1).

pH

The maximum acceptable value for the pH in groundwater is between 6.5 and 8.5. Throughout the Milk River Aquifer, 55% of the pH measurements do not respect the maximum acceptable criteria (Table 7.1). Only 1% of the measurements are associated with lower pH. These values are distributed irregularly in the Milk River Aquifer. The pH values exceeding 8.5 constitute 54% of the measurements. They show no well-defined trend: they are located over most of the study area. They indicate that groundwater has evolved chemically through interaction with the surrounding rock. The increase in pH could be explained by the dissolution of calcite, which consumes carbon dioxide and produces increased amounts of sodium and bicarbonate and an increase in pH (Swanick, 1982).

Total dissolved solids

The total dissolved solids (TDS) constitute the sum of all dissolved solids (volatile and non-volatile) in water, expressed in mg/L. The principal constituents are usually the cations calcium magnesium, sodium, and potassium and the anions carbonate, bicarbonate, chloride, sulfate, and nitrate (Health Canada, 2014). The aesthetic objective for total dissolved solids is ≤500 mg/L. In the Milk River Aquifer, 97% of the samples exceed the objective (Table 7.1). Only some samples taken in the subcropping area have total dissolved solids concentration below 500 mg/L. The highest concentrations are found in western Montana near the Cut Bank area. The total dissolved solids concentrations in the Virgelle Sandstone range from 213 to 1360 mg/L with a median value of 620 mg/L in the Sweet Grass Hills area (Tuck, 1993). The high concentration of total dissolved solids is due to elevated concentrations of certain ions, including bicarbonate, carbonate, sodium, chloride, and sulfates.

Conclusion

Based on the characterization of the groundwater samples, whose statistics are summarised in Table 7.1, the water quality of the MRA may be considered from good to average, to poor in areas.

Table 7.1 Descriptive statistics for groundwater samples

Parameters	Descriptive statistics				Quality criteria value (mg/L) [1]	Number of exceedances	Proportion (%) of samples exceeding the criteria
	Number of Samples	Minimum (mg/L)	Median (mg/L)	Maximum (mg/L)			
Chloride (Cl^-)	565	0.9	78.6	3 220	≤ 250	143	25
Fluoride (F^-)	709	0	0	7.6	1.5	58	8
Iron (Fe^{2+})	709	0	0	54.52	≤ 0.3	45	6
Manganese (Mn^{2+})	709	0	0	1.34	≤ 0.05	18	3
Sodium (Na^+)	347	6.7	469	2 902	≤ 200	323	93
Sulfates (SO_4^{2-})	396	0.1	132	7 840	≤ 500	69	17
Total Dissolved Solids (TDS)	272	5	1102	11 728	≤ 500	264	97
Bicarbonate (HCO_3^-)	281	0	720	1 524			
Bicarbonate and Carbonate ($HCO_3^- + CO_3^{2-}$)	91	1 198	2 069	4 271			
Calcium (Ca^{2+})	379	0.01	2.1	428			
Carbonates (CO_3^{2+})	204	0	20	266			
Magnesium (Mg^{2+})	373	0	1	393			
Potassium (K^+)	226	0.4	1.82	26			
Sodium Adsorption Ratio (SAR) [2]	199	0.2	72.4	143			
pH [3]	272	6.2	8.6	11.2	6.5 to 8.5	150	55

[1] According to Health Canada (2014)
[2] Measure of the suitability of water for use in agricultural irrigation (consulted online: <https://en.wikipedia.org/wiki/Sodium_adsorption_ratio>)
[3] No units for pH

From:
Alberta Environment and Sustainable Resource Development (2015); Armstrong S.C., Sturchio N.C., Hendry M.J. (1998); County of Forty Mile No. 8 (2006); Domenico P.A., Robbins G.A. (1985); Drimmie R.J., Aravena R., Wassenaar L.I., et al. (1991); Fabryka-Martin J., Whittemore D.O., Davis S.N., et al. (1991); Groundwater Information Center (GWIC database), Montana (2015); HCL consultants (2004 and 2007); Health Canada (2014); Hendry J., Schwartz F.W., Robertson C. (1991); Hendry M.J., Schwartz F.W. (1988 and 1990); Life Water Drilling Ltd. (2007); Meyboom P. (1960); Milk River Transboundary Aquifer Project (MiRTAP) (2012–2013); Milk River Watershed Council Canada (2011); Nolte E., Krauthan P., Korschinek G., et al. (1991); Phillips F.M., Bentley H.W., Davis S.N. et al. (1986); Schwartz F.W., Muehlenbachs K. (1979); Stantec (2002); Swanick G.B. (1982); Tuck L.K. (1993); Zimmerman E. (1967).

Methodology:

Major ions concentrations data were extracted from multiple sources and integrated in a standardised dataset, except for the MiRTAP data, which were collected in the field.

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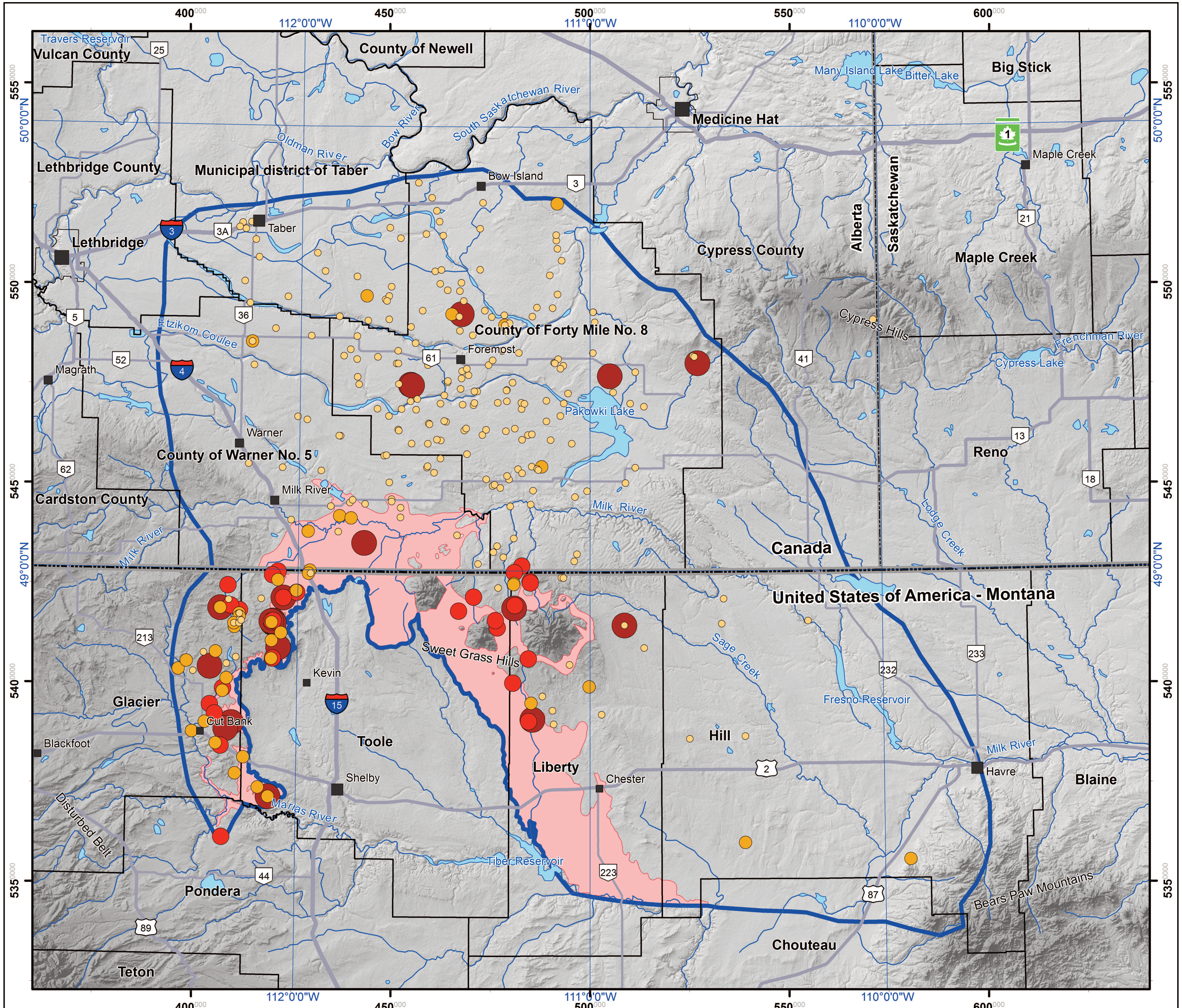


MAP 7.1

Calcium (Ca^{2+}) Concentration

Projection UTM 12N 1:1 000 000

Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

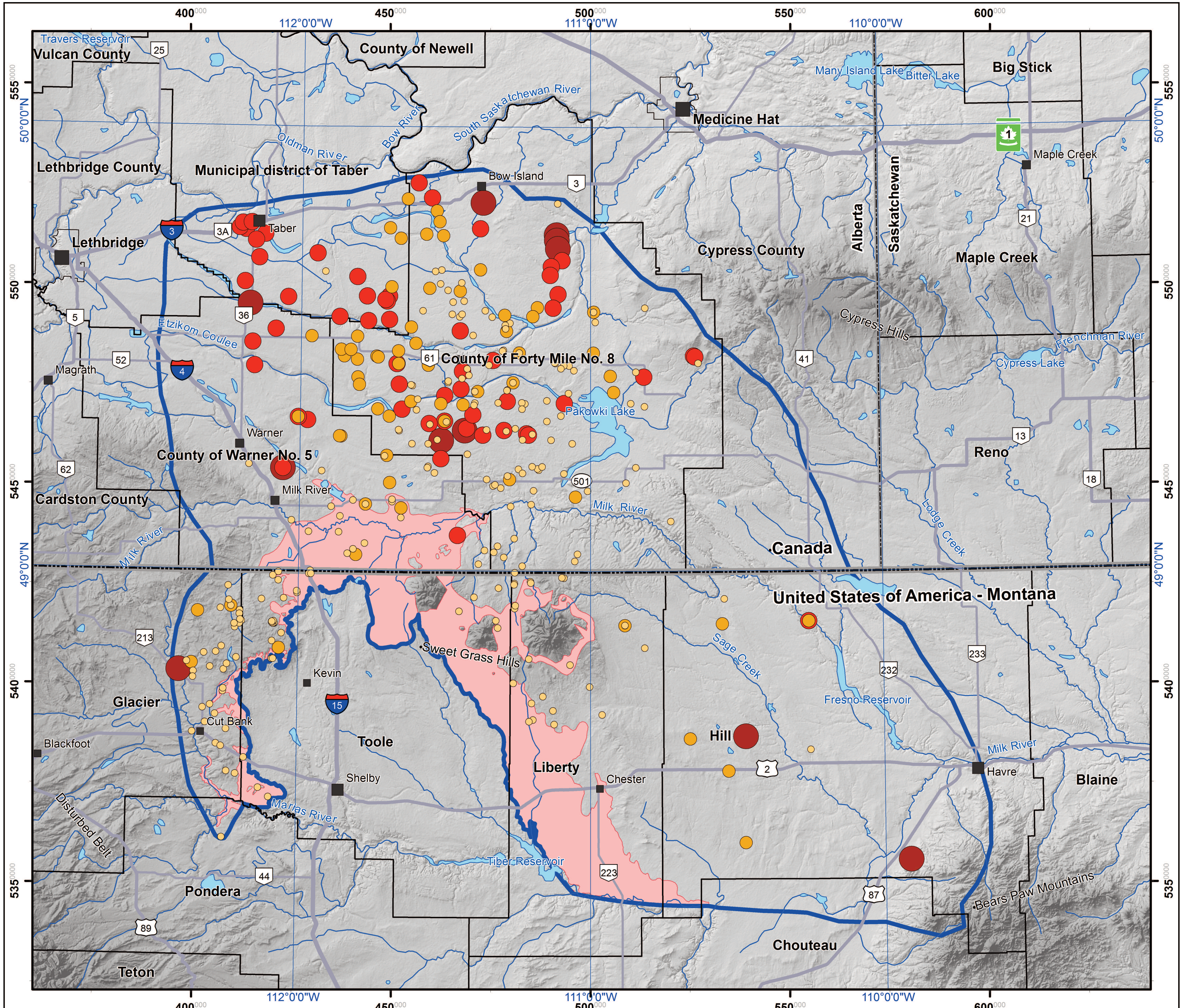
Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Calcium Ca^{2+} (mg/L)
- > 0 - 10
- > 10 - 50 — 50 mg/L limit
- > 50 - 100
- > 100 - 428

Aquifer Extent
- Milk River
- Milk River Formation Outcrop

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m



MAP 7.2

Chloride (Cl^-) Concentration

Projection UTM 12N 1:1 000 000

Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Chloride Cl^- (mg/L)
- 1 - 100
- > 100 - 250 250 mg/L limit
- > 250 - 1 000
- > 1 000 - 3 220

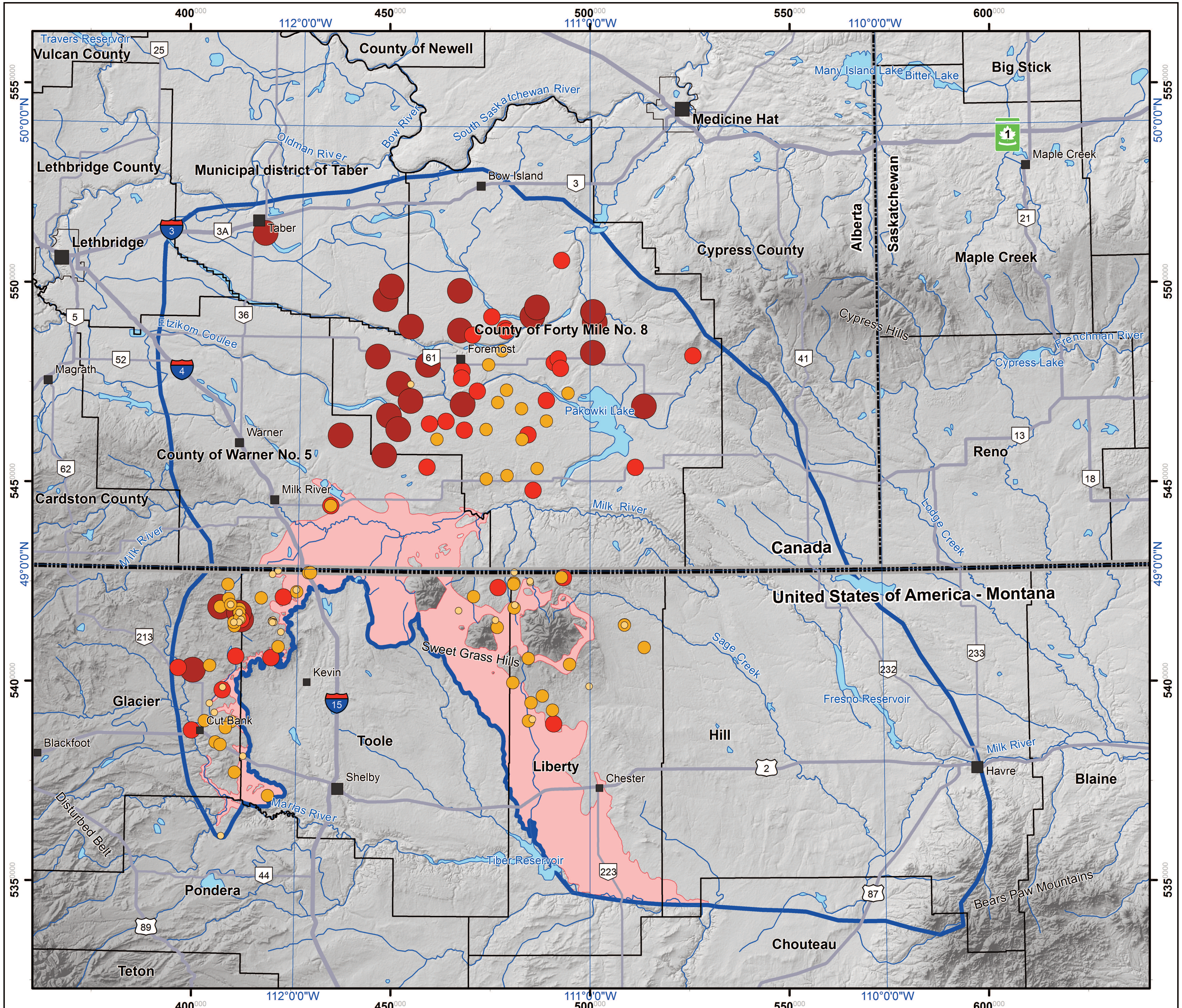
Aquifer Extent
- Milk River
- Milk River Formation Outcrop

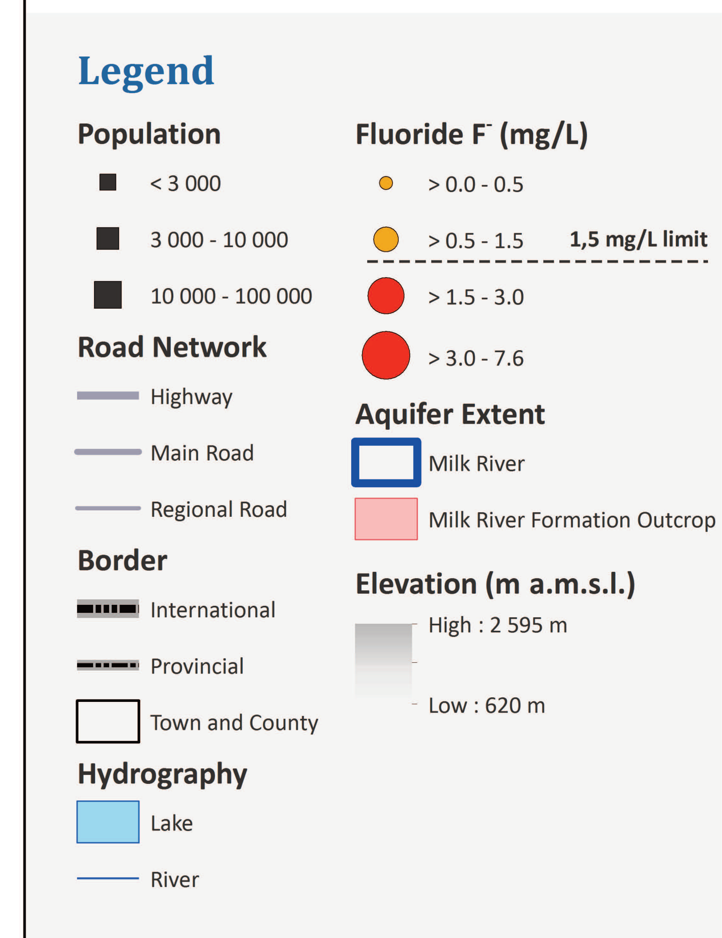
Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m

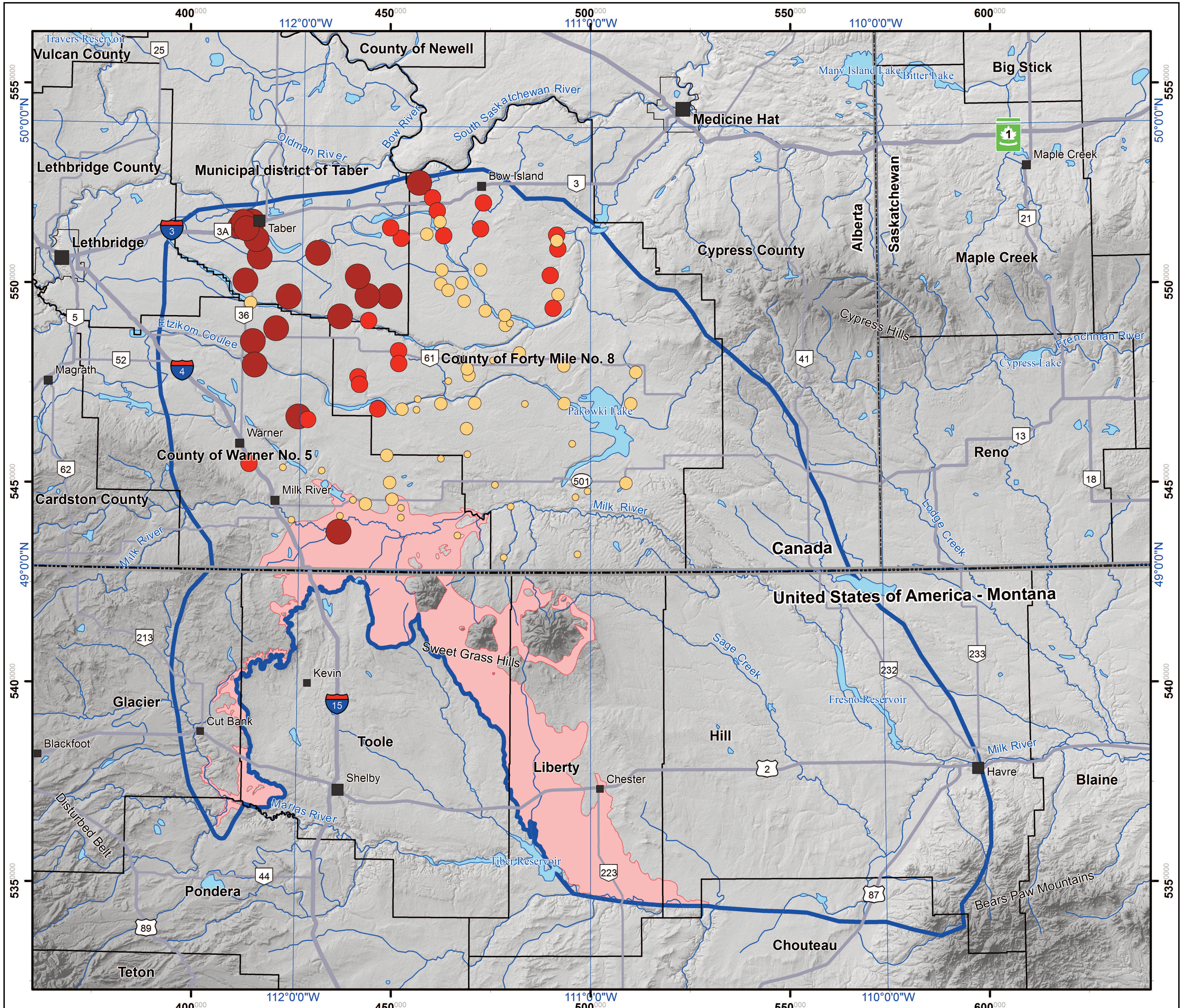
MAP 7.3

Fluoride (F⁻) Concentration

Projection UTM 12N 1:1 000 000







MAP 7.4

Bicarbonate and Carbonate (HCO_3^-, CO_3^{2-}) Concentration

Projection UTM 12N 1:1 000 000

Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

HCO_3^- + CO_3^{2-} (mg/L)
- 1 197 - 1 750
- > 1 750 - 2 150
- > 2 150 - 2 750
- > 2 750 - 4 271

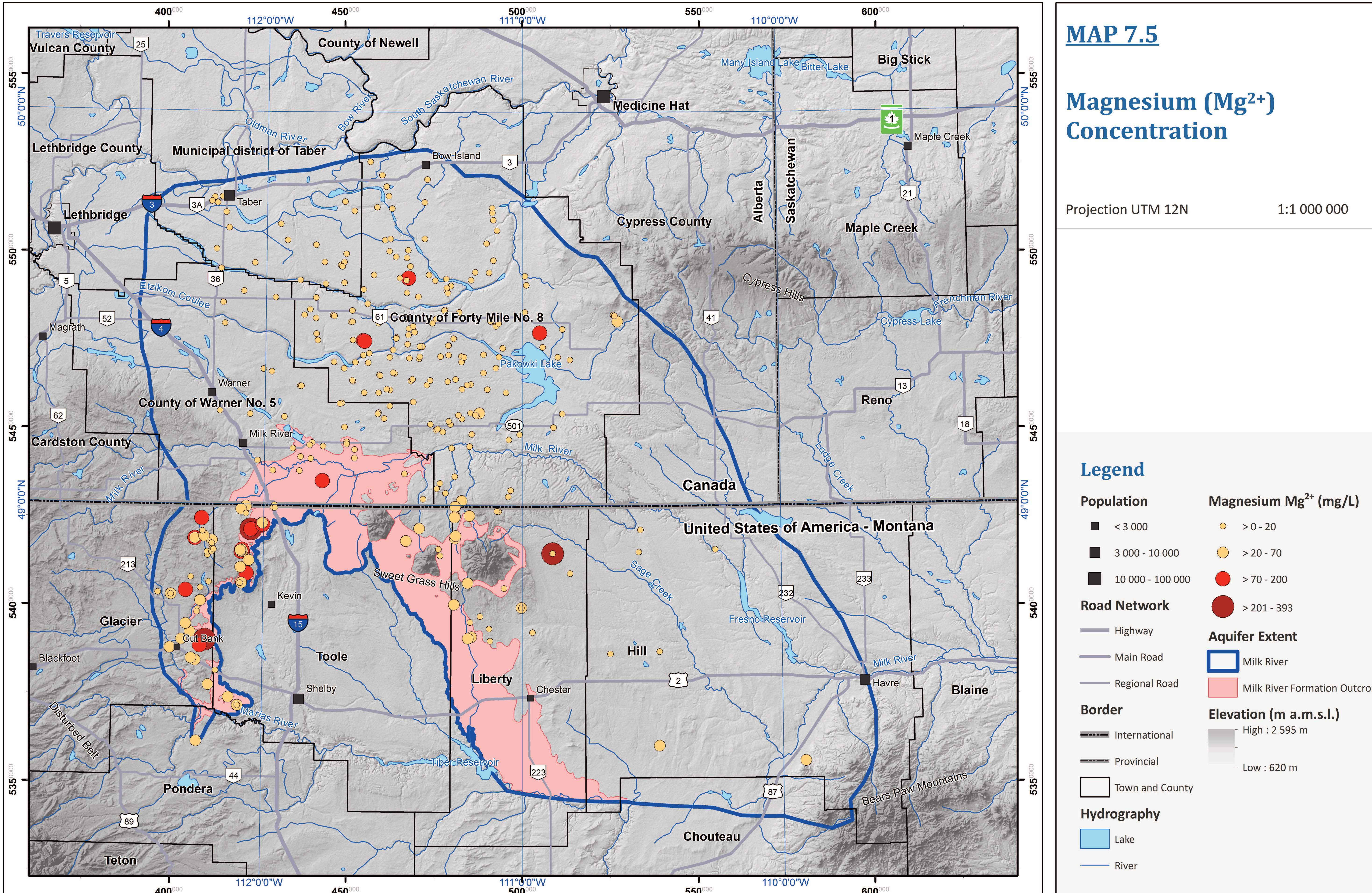
Aquifer Extent
- Milk River
- Milk River Formation Outcrop

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m

MAP 7.5

Magnesium (Mg^{2+}) Concentration

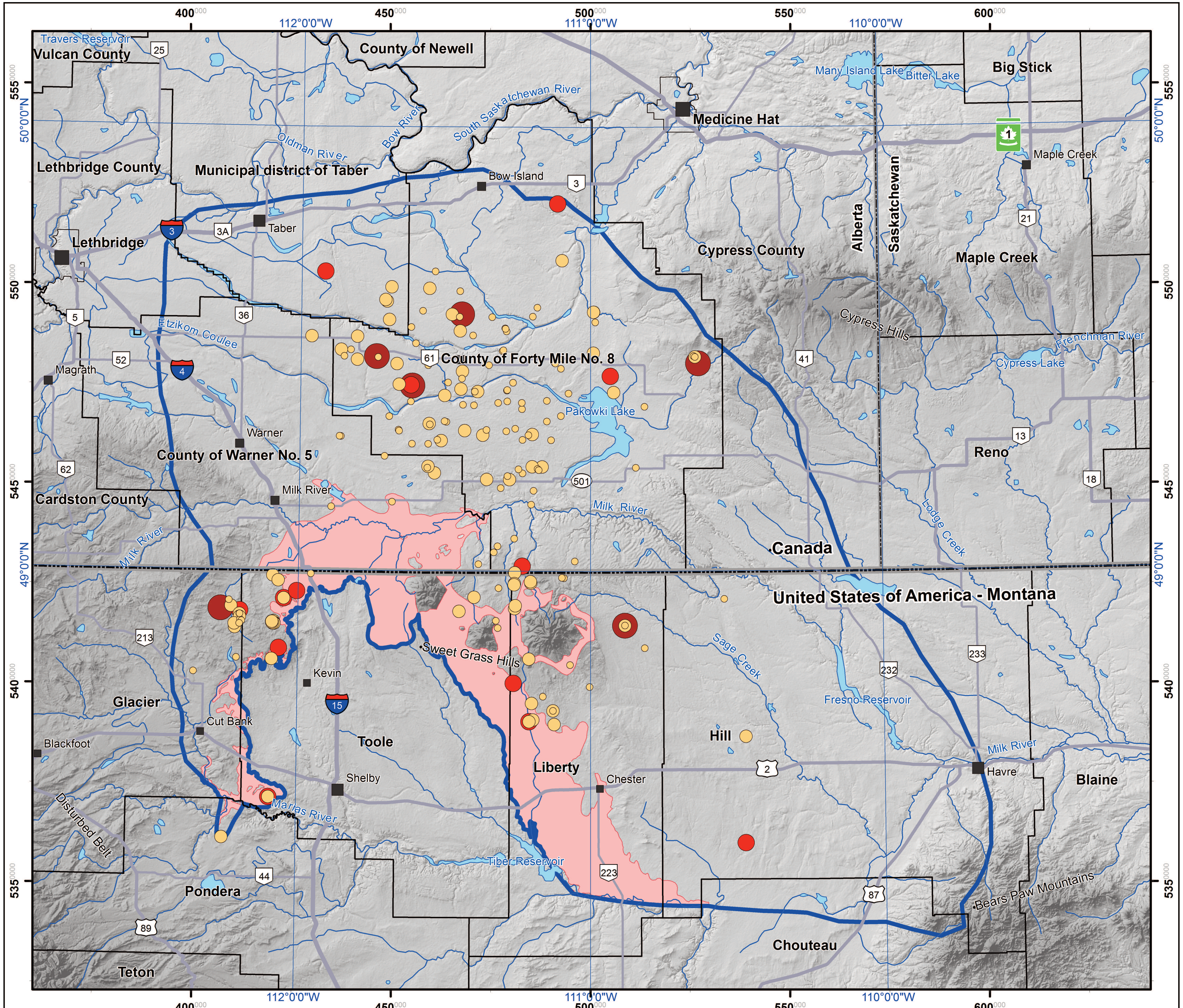
Projection UTM 12N 1:1 000 000



MAP 7.6

Potassium (K+) Concentration

Projection UTM 12N 1:1 000 000



Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

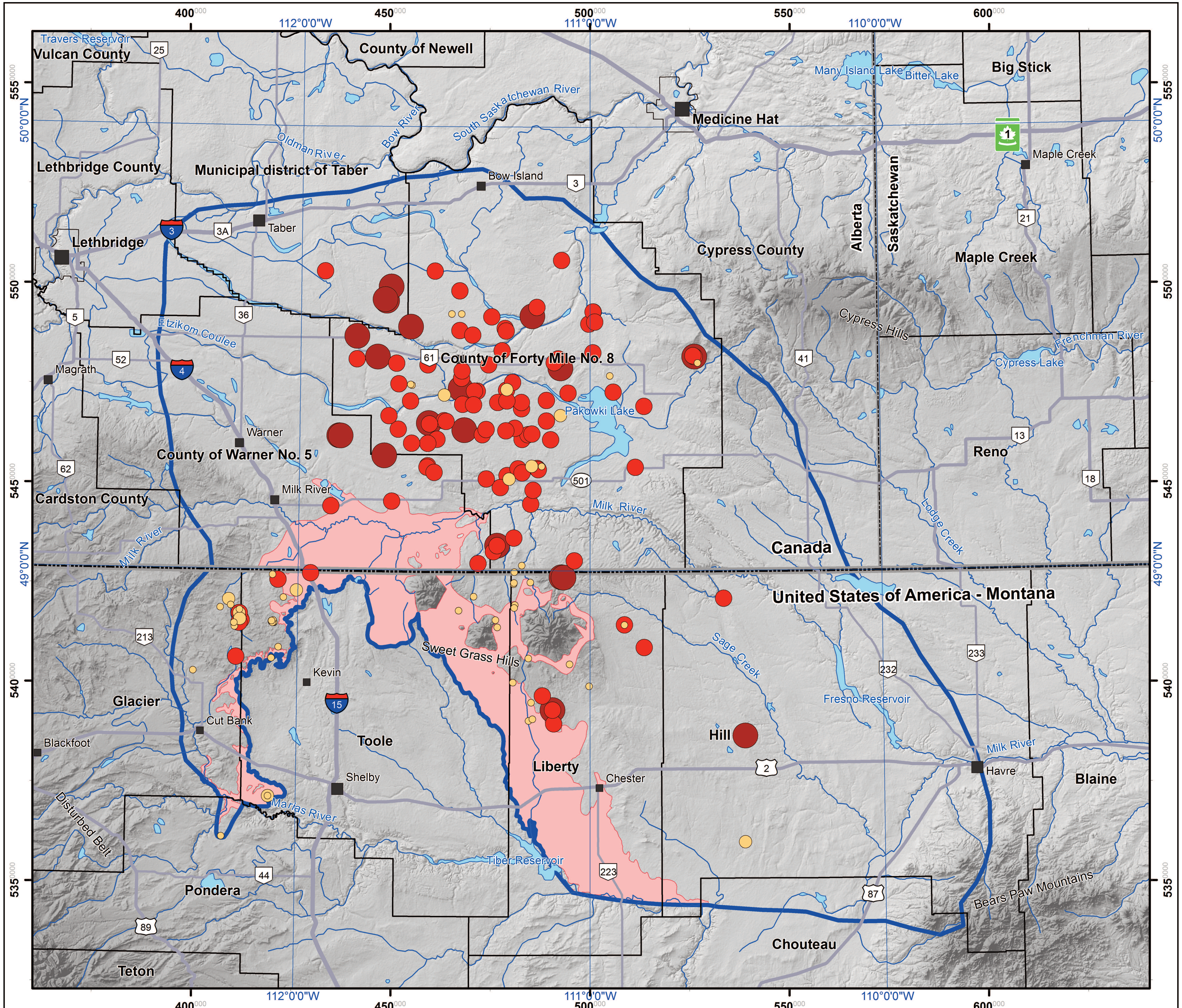
Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Potassium K+ (mg/L)
- 0,4 - 2
- > 2 - 5
- >5 - 10
- >10 - 26

Aquifer Extent
- Milk River
- Milk River Formation Outcrop

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m



MAP 7.7

Sodium Adsorption Ratio

Projection UTM 12N 1:1 000 000

Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Sodium Adsorption Ratio (SAR)
- > 0 - 30
- > 30 - 60
- > 60 - 90
- > 90 - 143

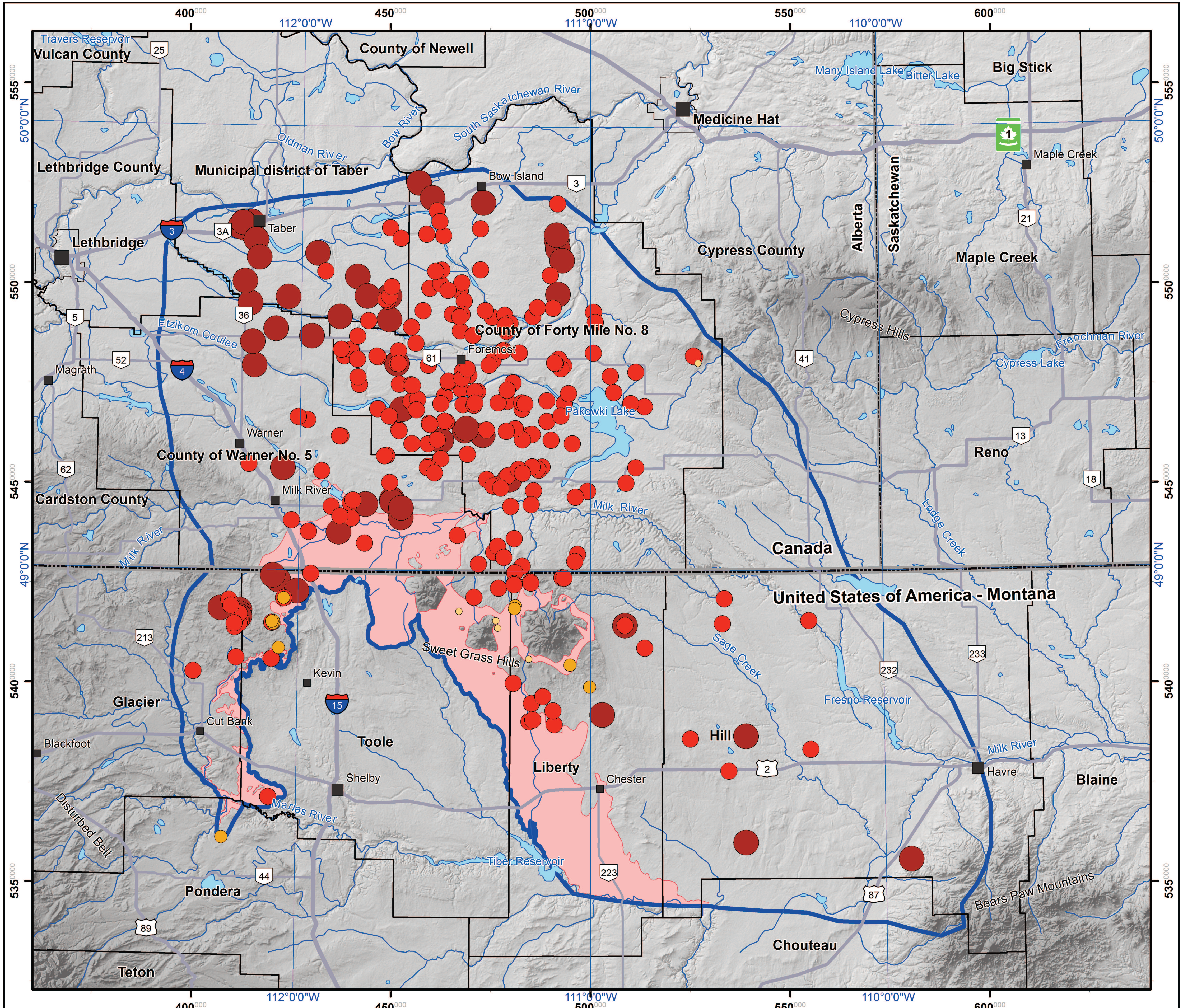
Aquifer Extent
- Milk River
- Milk River Formation Outcrop

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m

MAP 7.8

Sodium (Na^+) Concentration

Projection UTM 12N 1:1 000 000



Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and county

Hydrography
- Lake
- River

Sodium Na+ (mg/L)
- 7 - 50
- > 50 - 200
- 200 mg/L limit
- > 200 - 800
- > 800 - 2 902

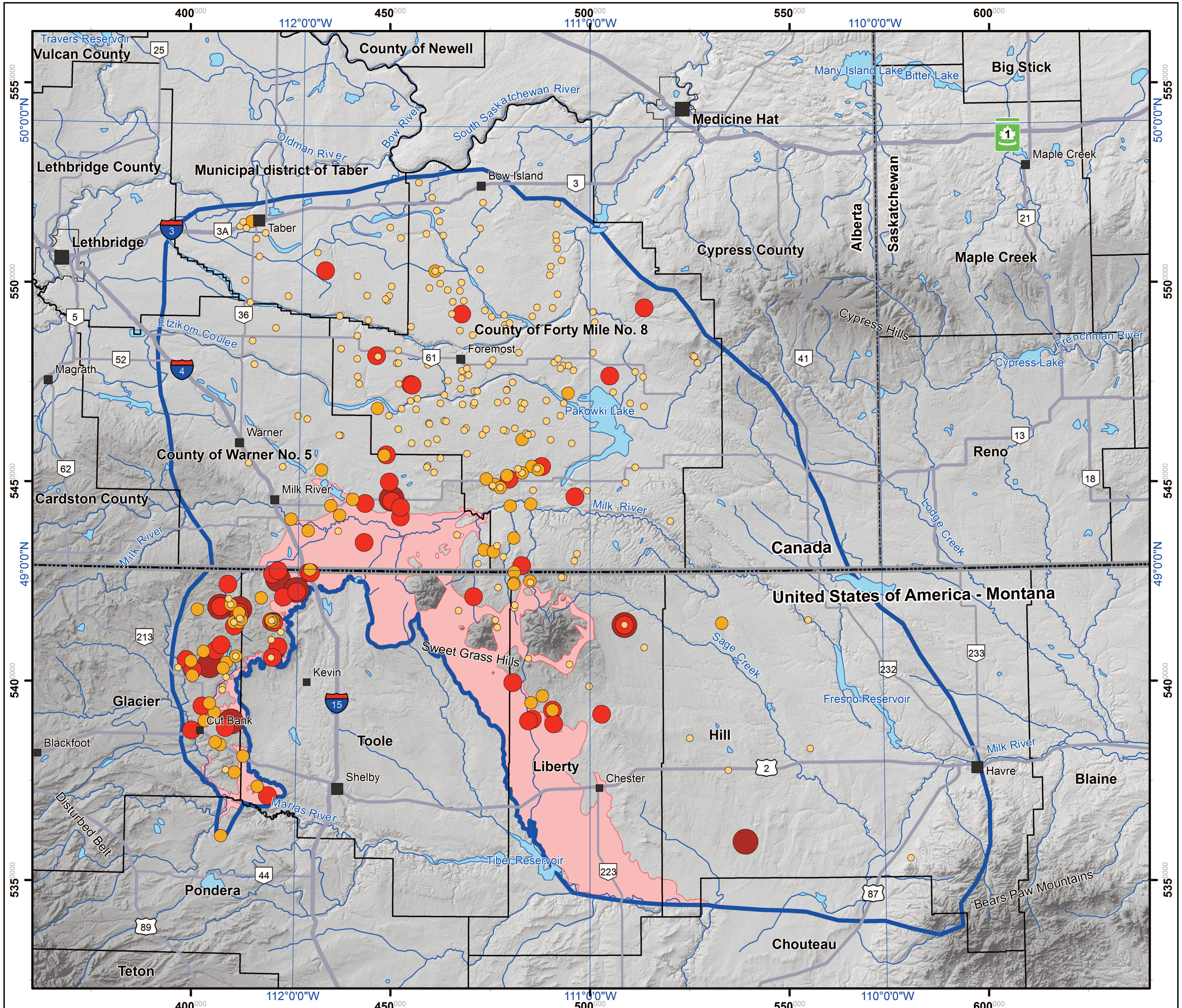
Aquifer Extent
- Milk River
- Milk River Formation Outcrop

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m

MAP 7.9

Sulfate (SO_4^{2-}) Concentration

Projection UTM 12N 1:1 000 000



Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

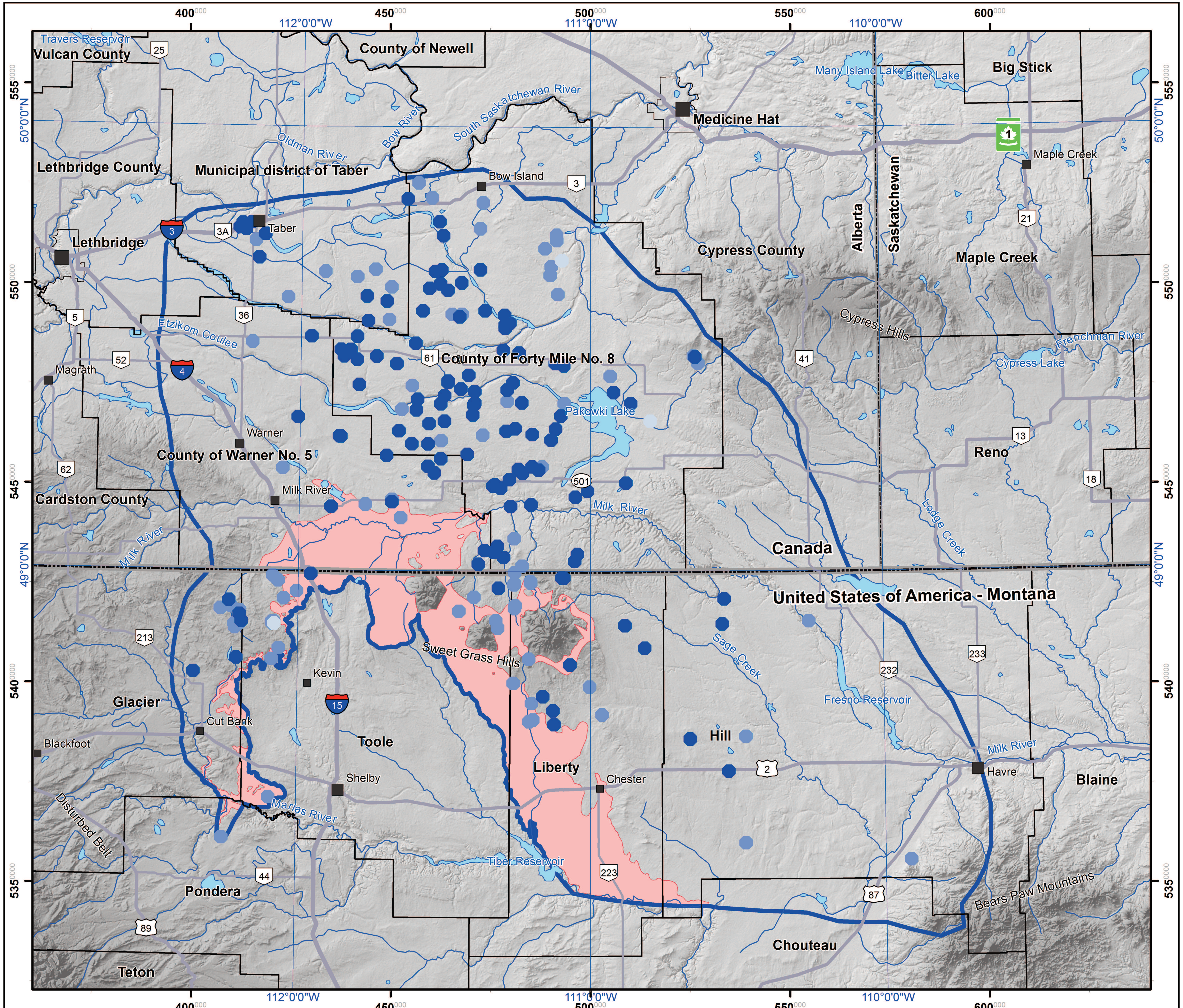
Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Sulfate SO_4^{2-} (mg/L)
- > 0 - 250
- > 250 - 500 **500 mg/L limit**
- > 500 - 2 000
- > 2 000 - 7 840

Aquifer Extent
- Milk River
- Milk River Formation Outcrop

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m



MAP 7.10

pH Measurements

Projection UTM 12N 1:1 000 000

Legend

Population

- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

pH

- < 6.5 (acidic pH)
- 6.5 - 8.5 (neutral pH)
- > 8.5 (basic pH)

Road Network

- Highway
- Main Road
- Regional Road

Aquifer Extent

- Milk River
- Milk River Formation Outcrop

Elevation (m a.m.s.l.)

High : 2 595 m

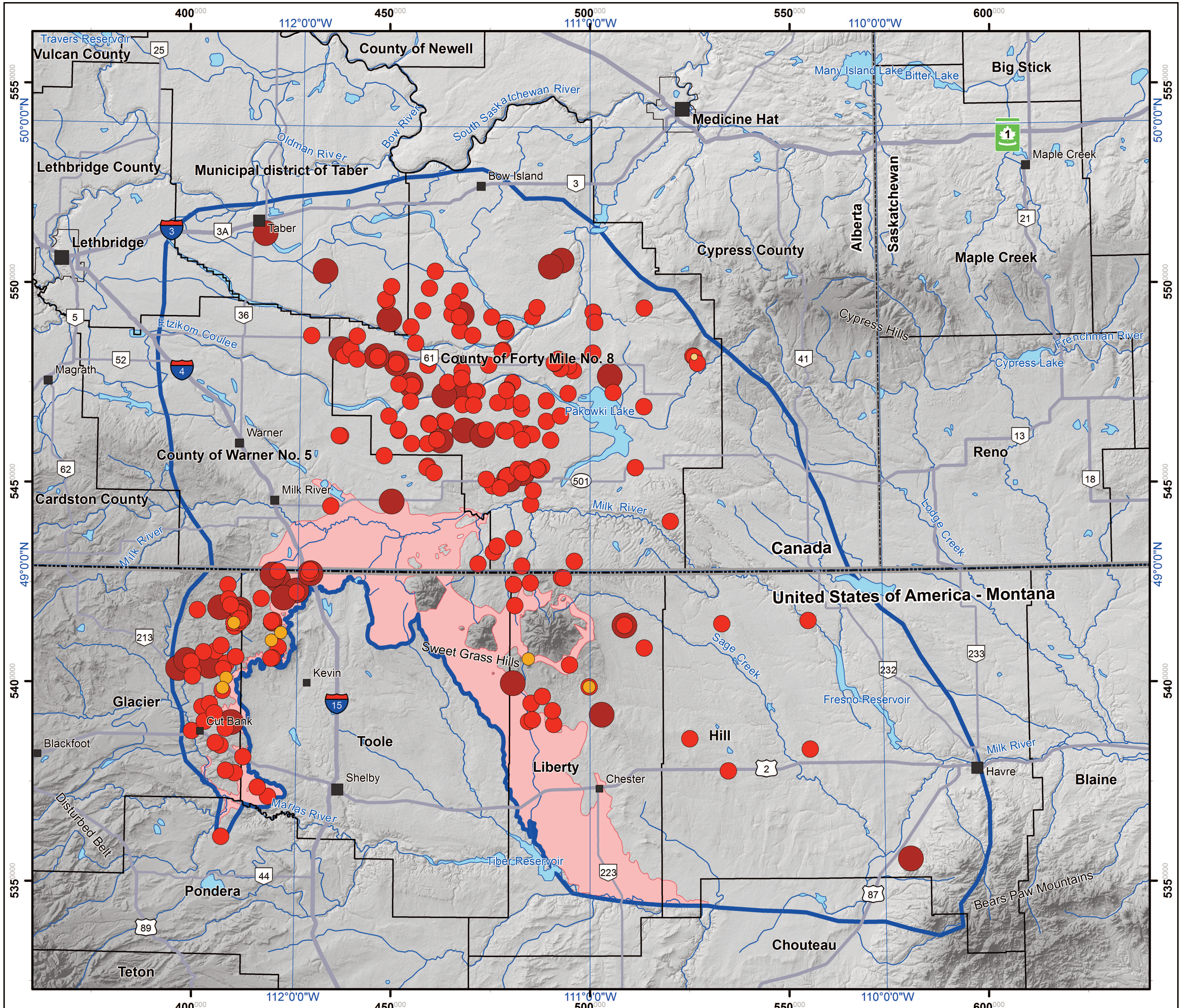
Low : 620 m

Border

- International
- Provincial
- Town and County

Hydrography

- Lake
- River



MAP 7.11

Total Dissolved Solid Concentration

Projection UTM 12N 1:1 000 000

Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

Total Dissolved Solid TDS (mg/L)
- 5 - 250
- > 250 - 500 **500 mg/L limit**
- > 500 - 2 000
- > 2 000 - 11 729

Aquifer Extent
- Milk River
- Milk River Formation Outcrop

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m

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Groundwater Quality

7.2 Isotopes

Isotopes are atoms of the same element that have the same number of protons and electrons but different numbers of neutrons. Isotopic analyses of water from the Milk River Aquifer were used for dating groundwater and understanding groundwater flow path directions.

Deuterium and oxygen-18 (δ^2H and δ^{18}O)

The distribution of deuterium (δ^2H) and oxygen-18 (δ^{18}O) in the water of the Milk River Aquifer shows a δ^{18}O and δ^2H enrichment from south to north (from -20‰ to -9‰ and from -157‰ to -88‰, respectively). Three zones of isotope values can be observed. The first zone shows the lightest waters. They correspond to unaltered surface or near-surface water from the recharge area of the aquifer (as illustrated by the green circles and diamonds points, Map 7.12 and Map 7.13) (Swanick, 1982). The second zone exhibits waters with higher ^{2}H and ^{18}O concentrations, corresponding to an older recharge (see yellow and orange circles and diamonds, Map 7.12 and Map 7.13). There is a third zone, where a mixing of groundwater and more saline formation water occurs (see red circles and diamonds, Map 7.12 and Map 7.13 (Drimmie et al., 1991).

Tritium (^{3}H)

Tritium (^{3}H) is below the detection limit (0.8 tritium units or TU) in most sampling sites, indicating that recharge occurred before 1952 (Map 7.14). Higher tritium values are located in the outcrop areas of the Milk River Formation both in southern Alberta and northern Montana. These values indicate that the entire outcrop belt around the Sweetgrass Arch likely serves as the recharge area of the Milk River Aquifer. The three groundwater samples from the wells completed in the Whisky Valley Aquifer also contained tritium with values ranging from 4.7 to 5.2 TU. These values correspond to recent water, up to 10 years old. These results indicate that the Whisky Valley Aquifer could constitute another recharge area for the Milk River Aquifer where a hydraulic link exists between these two geological units (as described by Golder, 2004).

Carbon-14 (^{14}C)

Radiocarbon (^{14}C) data of dissolved inorganic carbon (DIC) is reported in percent modern carbon (pMC), meaning that the higher the radiocarbon value is, the younger the groundwater is. Except in the southern part, Alberta shows the lowest carbon-14 values (ranging from 0 to 2), indicating that the groundwater is over 50 000 years. Higher carbon-14 values are found in the outcrop area of the Milk River Formation and in the entire southwest corner of the study area, in the recharge area and where the groundwater active flow zone is located (see Figure 5.10).

Carbon-13 (δ^{13}C)

Map 7.16 illustrates the spatial distribution of carbon-13 (δ^{13}C DIC) values for the MRA; the recent results (MiRTAP samples) are consistent with historical data (Philips et al., 1986; Drimmie et al., 1991). Some locations show enriched δ^{13}C values (higher values); other locations show depleted δ^{13}C values (lower values). In either case, there is no radiocarbon left at those locations. The enriched δ^{13}C values in the northern part of the study area may be due to calcite solution and methanogenic CO_2 (Phillips et al., 1986; Drimmie et al., 1991; Clark and Fritz, 1997). The lowest δ^{13}C values suggest methane oxidation or organic carbon reduction (Drimmie et al., 1991; Clark and Fritz, 1997).

Chlorine-36 (^{36}Cl)

In the Milk River Aquifer, chlorine-36 (^{36}Cl) measurements were used for dating groundwater (Phillips et al., 1986; Nolte et al., 1990). All studies showed that the chlorine-36 and chlorine ratio (^{36}Cl/Cl) decrease to the north from 1532 to 4×10^{-15} (Map 7.17). Groundwater age estimates range up to 2 Ma at the distal end in northern Alberta, if uncorrected for any dilution by subsurface sources of dead chloride, whereas a maximum age of 0.5 Ma was calculated using a hydrodynamic model (Phillips et al., 1986; Hendry and Schwartz, 1988 as cited by Fabryka-Martin et al., 1991), near the international border. The estimated groundwater ages are consistent with the ^{36}Cl/Cl ratio, the lowest the ratio the oldest the water. For instance, in the northern part of the study area, the ^{36}Cl/Cl ratio reaches a value of about 4 to 8×10^{-15}; corresponding to the secular equilibrium value in sandstone (i.e. production rate equals the decay rate (Bentley et al. 1986).

Conclusion

The analysis of the different water isotopes leads to these conclusions:

- Modern water (defined by high tritium concentrations) is not only found in the outcrop areas near the border, but also west of the Sweet Grass Arch. This suggests that the entire outcrop belt around the Sweet Grass Arch could act as a recharge area of the MRA.
- There is no ^{14}C in the waters of the MRA beyond the Milk River. This suggests that a major part of the groundwater flow is intercepted by the Milk River. Therefore, the remaining flux and the hydraulic gradient are low north of the river, resulting in low groundwater velocity and long groundwater residence time as indicated by isotopic tracers.
- North of the Milk River and in the south-eastern part of the study area, old to very old waters (up to 2 Ma) were found, as shown by ^{36}Cl data. The groundwater flow is low and water types are more evolved.

Methodology:

Isotopic data were compiled from historical sources and new data collected during MiRTAP (2012–2013). They were transformed and integrated in a standardized dataset.

Sources:

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Groundwater Information Center (GWIC database), Montana, 2015. <http://mbmggwic.mtech.edu>

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Phillips, F., Knowlton, R., and Bentley, H.W., 1990. Comment on “An alternative view on the origin of chemical and isotopic patterns in groundwater from the Milk River aquifer, Canada” by M. J. Hendry and F. W. Schwartz (WRR 1988, 24(10), 1747-1763). Water resources research, 1990, v. 26, no. 7, p. 1693–1698

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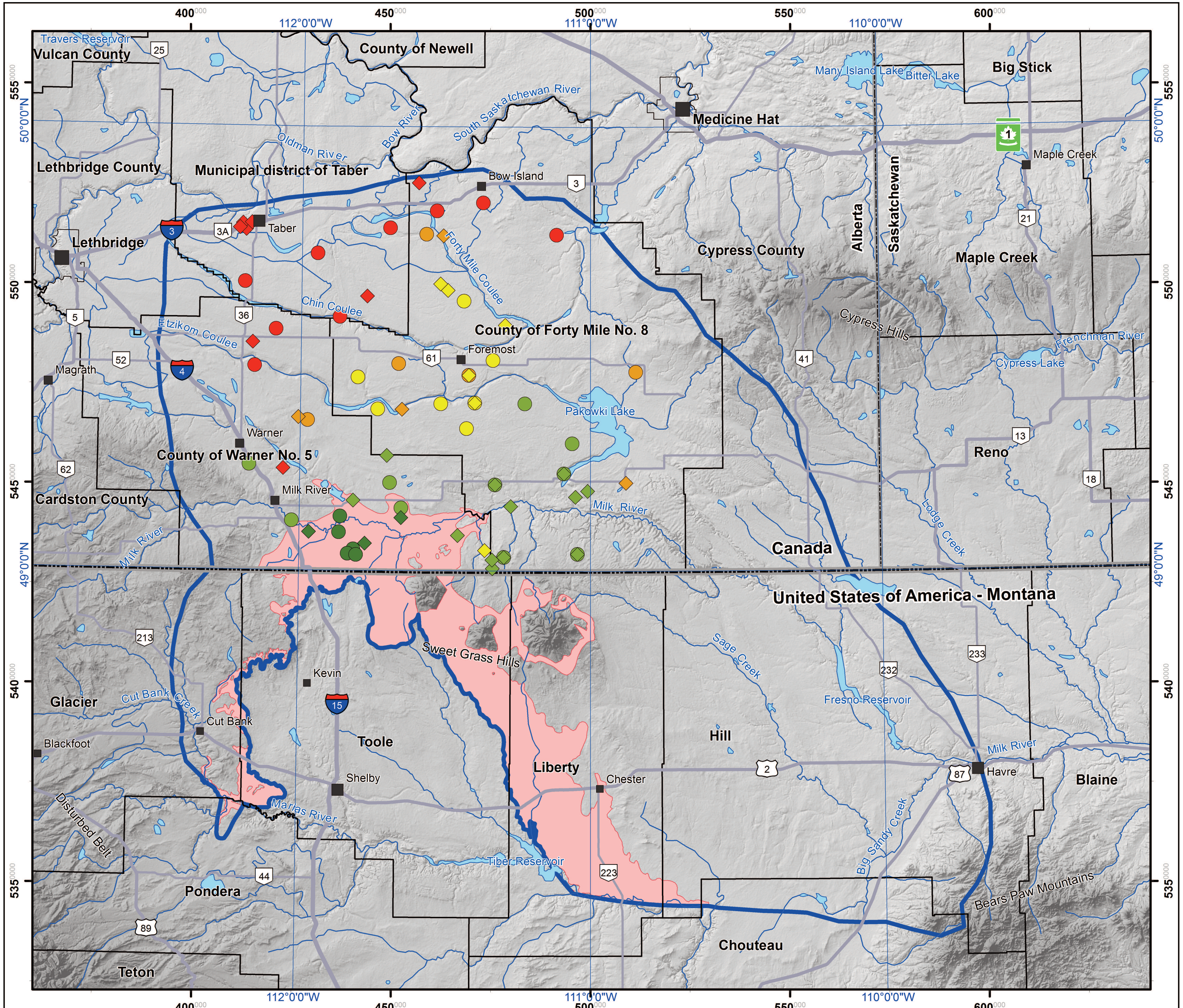


MAP 7.12

Deuterium (^2H) Concentration

Projection UTM 12N 1:1 000 000

Legend

Population

- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network

- Highway
- Main Road
- Regional Road

Border

- International
- Provincial
- Town and County

Hydrography

- Lake
- River

Aquifer Extent

- Milk River
- Milk River Formation Outcrop

Deuterium ^2H (‰)

(Hendry and Schwartz, 1988)

- -167 → -155
- -155 → -143
- -143 → -132
- -132 → -109
- -109 → -70

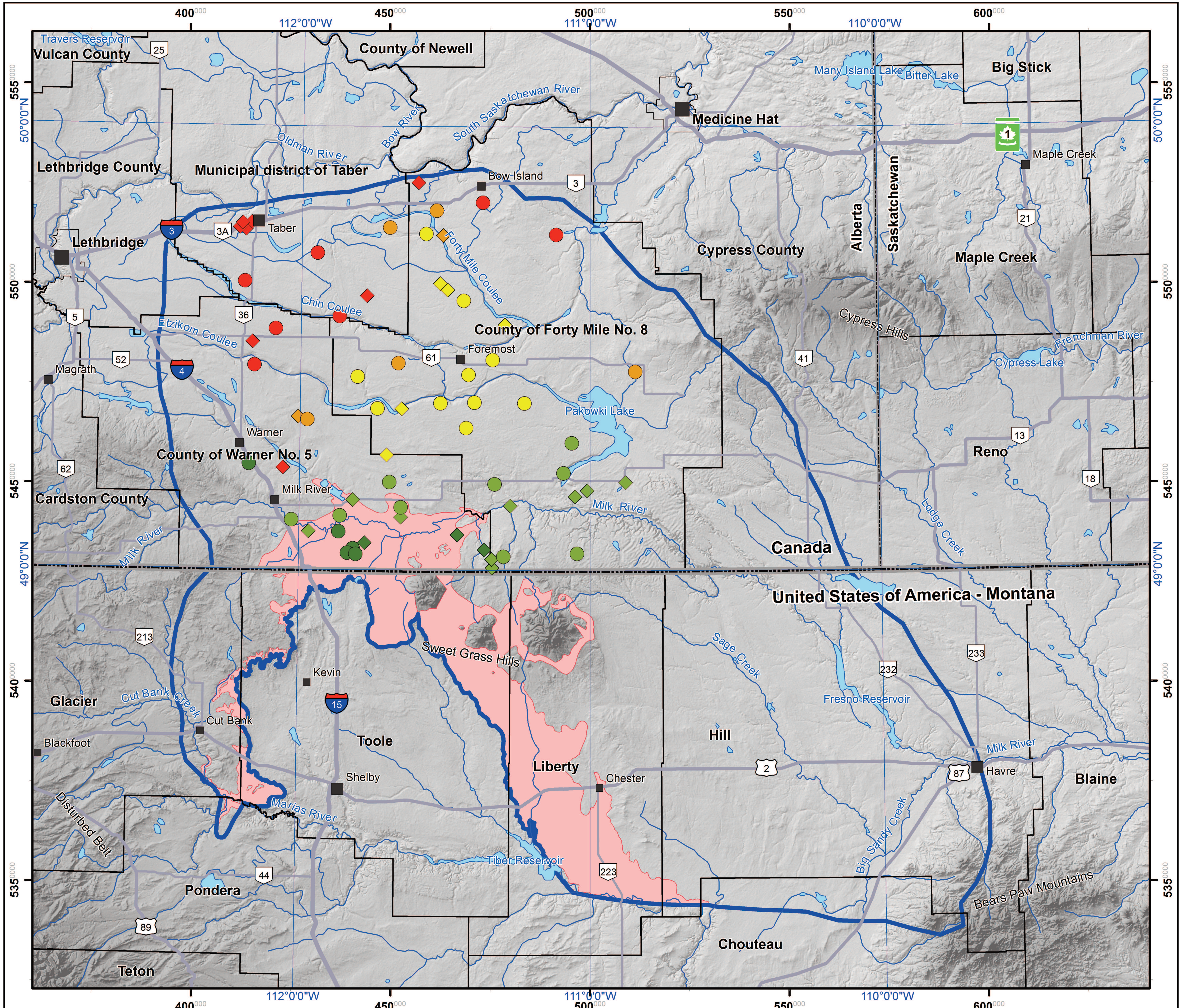
(Drimmie et al., 1991)

- -167 → -155
- -155 → -143
- -143 → -132
- -132 → -109
- -109 → -70

Elevation (m a.m.s.l.)

High : 2 595 m

Low : 620 m



MAP 7.13

Oxygen (^{18}O) Concentration

Projection UTM 12N 1:1 000 000

Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and County

Hydrography
- Lake
- River

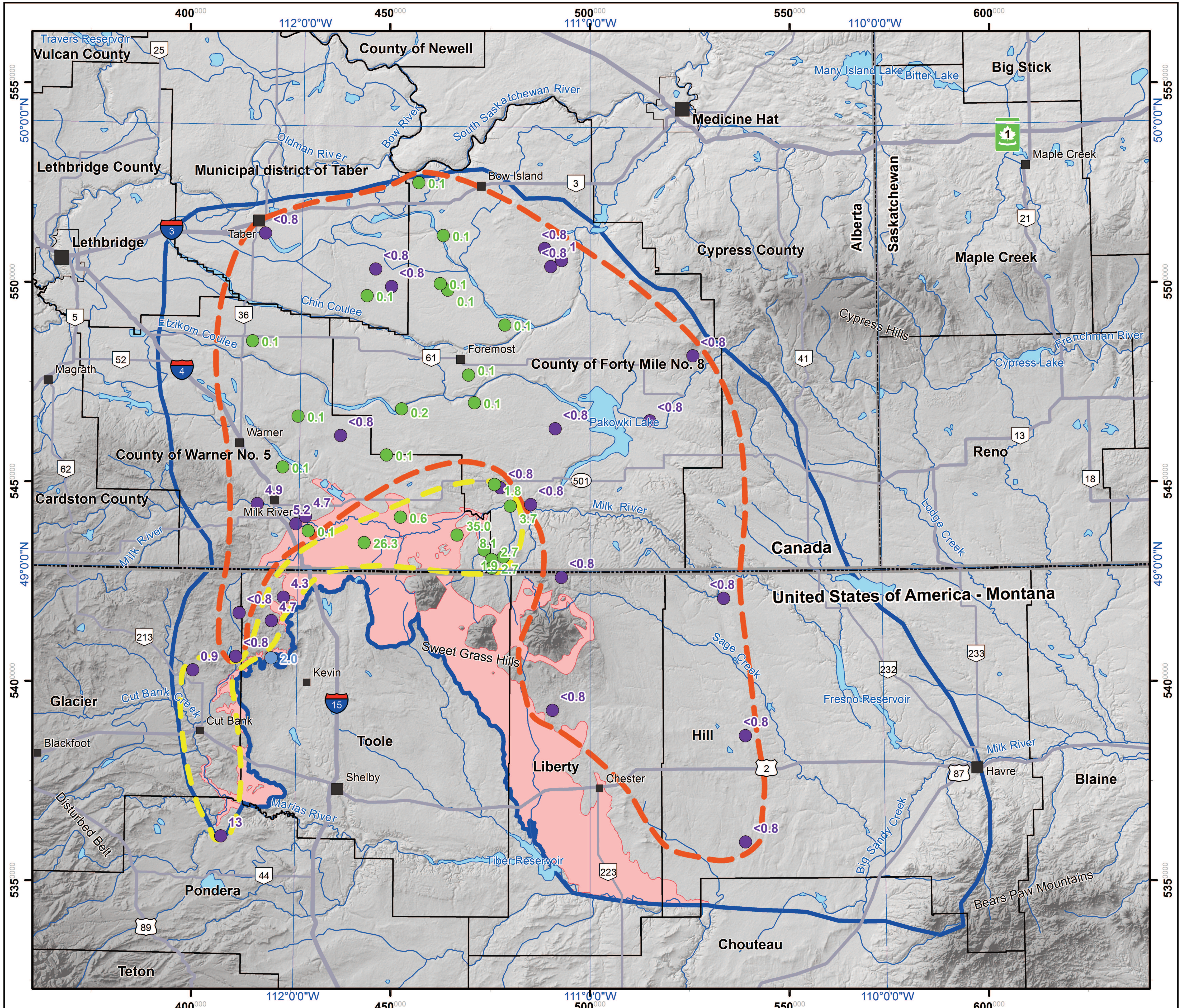
Aquifer Extent
- Milk River
- Milk River Formation Outcrop

Oxygen ^{18}O (‰)

(Hendry and Schwartz, 1988)
- -21.2 → -20.0
- -20.0 → -18.2
- -18.2 → -15.6
- -15.6 → -12.1
- -12.1 → -8.4

(Drimmie et al., 1991)
- -21.2 → -20.0
- -20.0 → -18.2
- -18.2 → -15.6
- -15.6 → -12.1
- -12.1 → -8.4

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m



MAP 7.14

Tritium (³H) Concentration

Projection UTM 12N 1:1 000 000

Legend

Population

- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network

- Highway
- Main Road
- Regional Road

Border

- International
- Provincial
- Town and County

Hydrography

- Lake
- River

Aquifer Extent

- Milk River
- Milk River Formation Outcrop

Tritium ^3H (TU)

- Drimmie et al. (1991)
- NWIS Database (2000)
- MiRTAP Groundwater Samples (2012 - 2013)
- Recharge Zone
- Sub-modern Water

Elevation (m a.m.s.l.)

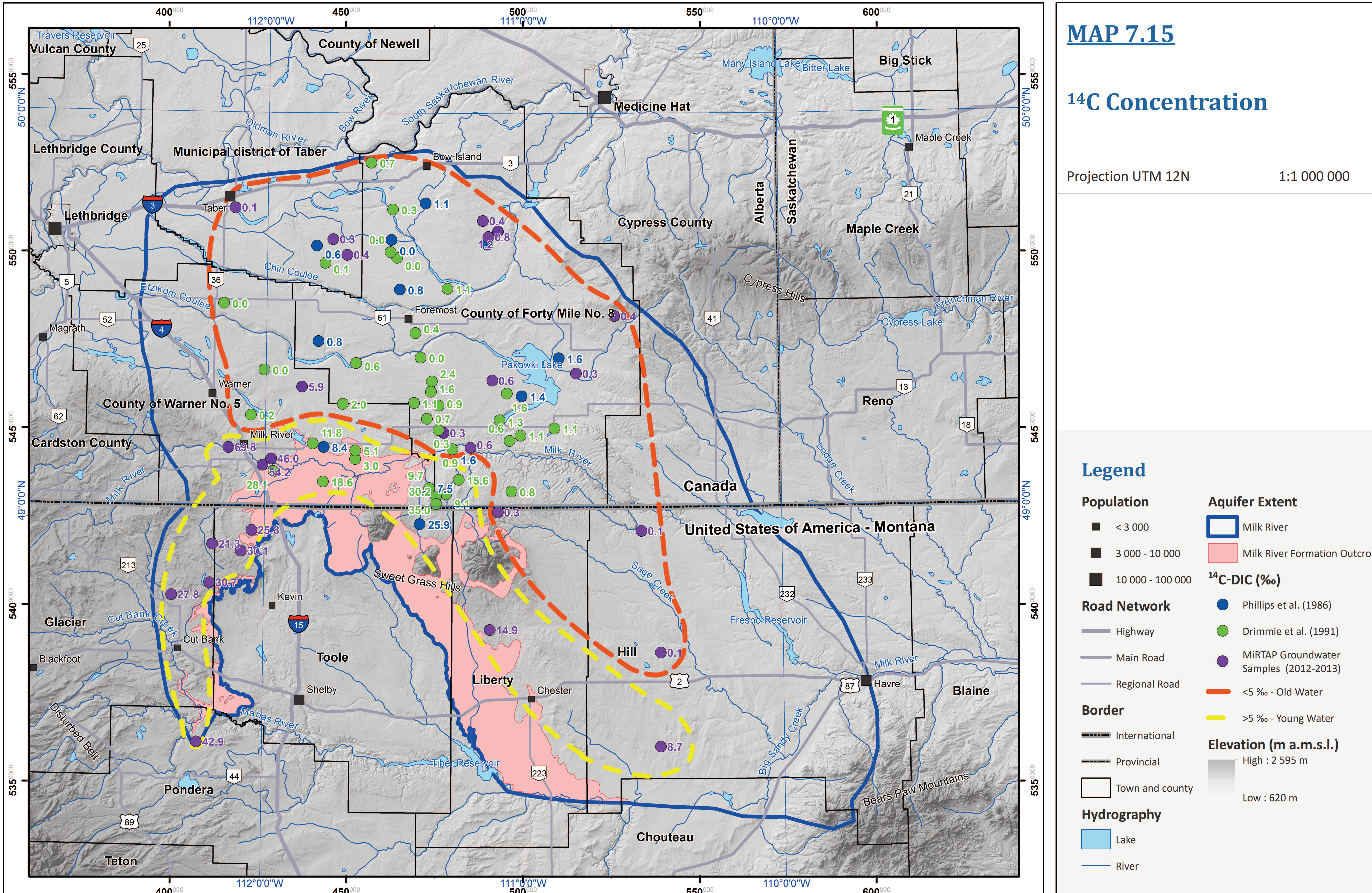
High : 2 595 m

Low : 620 m

MAP 7.15

^{14}C Concentration

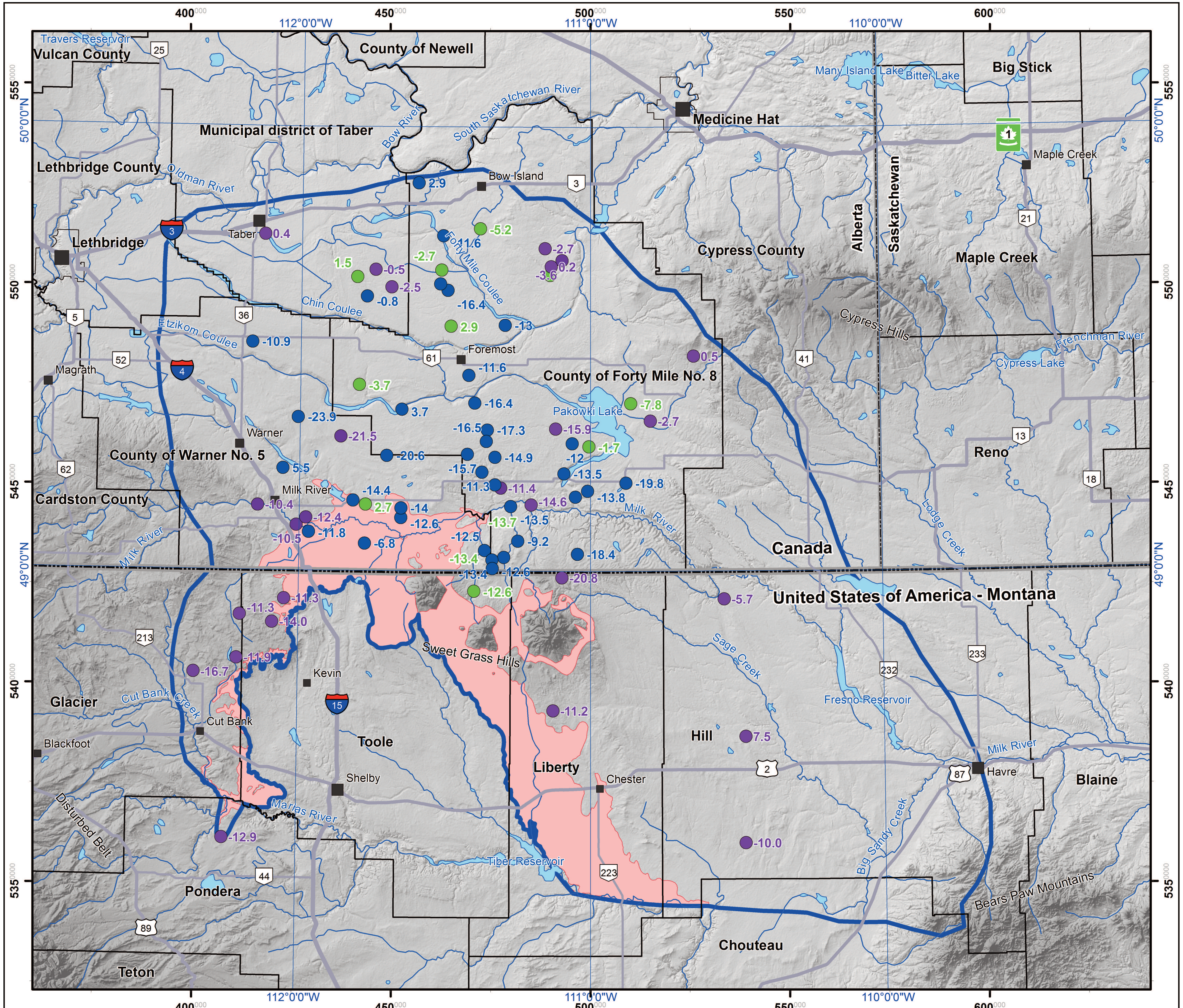
Projection UTM 12N 1:1 000 000



MAP 7.16

^{13}C Concentration

Projection UTM 12N 1:1 000 000



Legend

Population

- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network

- Highway
- Main Road
- Regional Road

Border

- International
- Provincial
- Town and county

Hydrography

- Lake
- River

Aquifer Extent

- Milk River
- Milk River Formation Outcrop

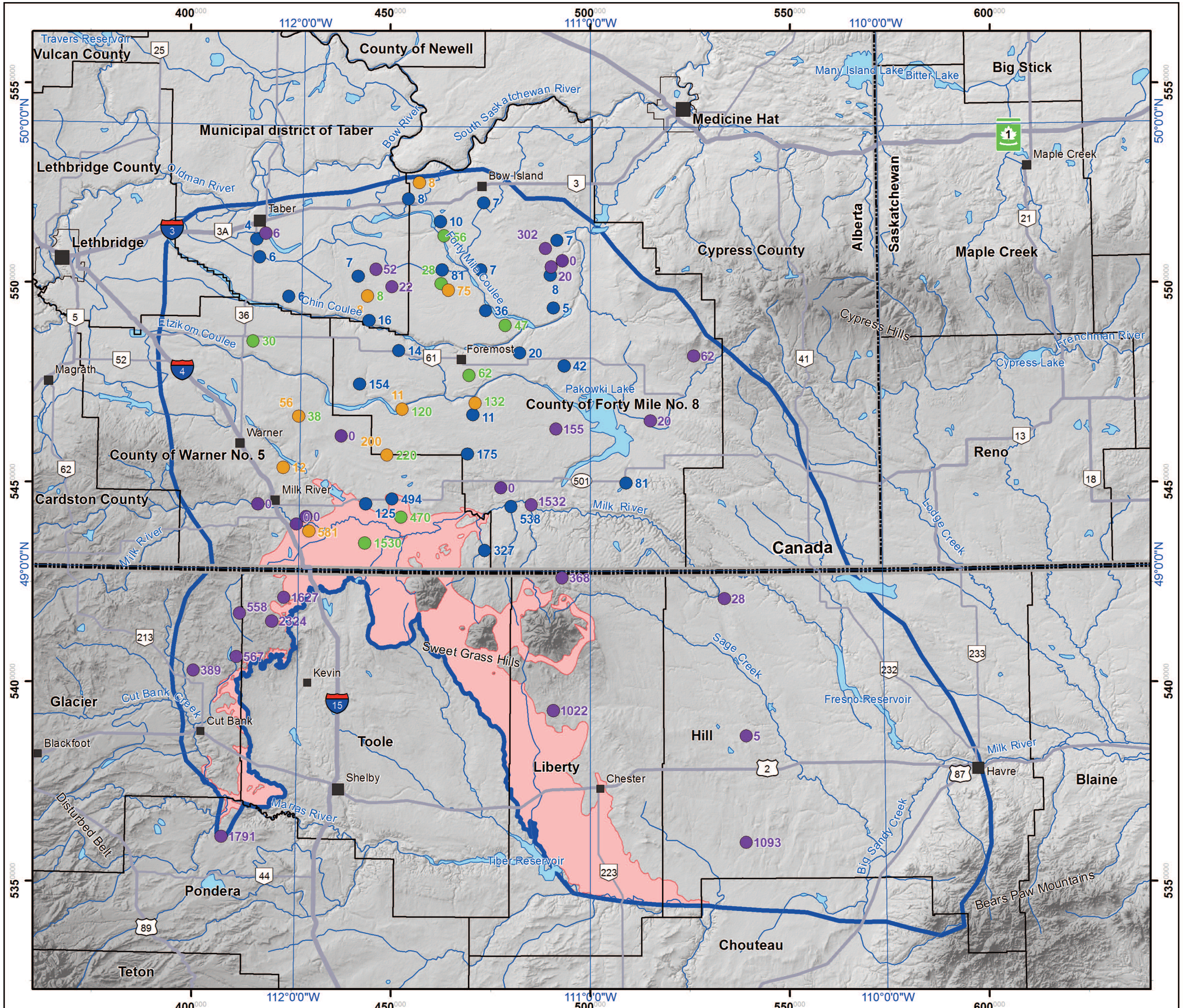
^{13}C-DIC (‰)

- Phillips et al. (1986)
- Drimmie et al. (1991)
- MiRTAP Groundwater Samples (2012 - 2013)

Elevation (m a.m.s.l.)

High : 2 595 m

Low : 620 m



MAP 7.17

^{36}Cl/Cl Ratio

Projection UTM 12N 1:1 000 000

Legend

Population
- < 3 000
- 3 000 - 10 000
- 10 000 - 100 000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial
- Town and county

Hydrography
- Lake
- River

Aquifer Extent
- Milk River
- Milk River Formation Outcrop

^{36}Cl/Cl ratio (x10^{-15})
- Phillips et al. (1986)
- Fabryka-Martin et al. (1991)
- Nolte et al. (1991)
- MiRTAP Groundwater Samples (2012–2013)

Elevation (m a.m.s.l.)
- High : 2 595 m
- Low : 620 m

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8 Groundwater Use

8.1 Groundwater Use

There are multiple users of groundwater in the Milk River Transboundary Aquifer region, but due to the lack of water meters, precise quantities of groundwater use are unknown. Nonetheless, it is possible to provide a close picture of the use of groundwater in the region by combining an inventory of wells and associated uses with water permits and knowledge of well yields.

There are many types of groundwater users in the region from which an estimation of the use of groundwater can be obtained. On the Alberta side, the main users are farmers (livestock use) and municipalities (domestic use); on the Montana side, the main users are municipalities, industries, and oil and gas industries for secondary oil recovery. A significant amount of groundwater use is the amount of water flowing to the surface from flowing wells; this naturally flowing unused water is known in the region as "water wastage". Estimations of groundwater use have been done over the years by different authors on different areas covering the Milk River Aquifer on both sides of the border.

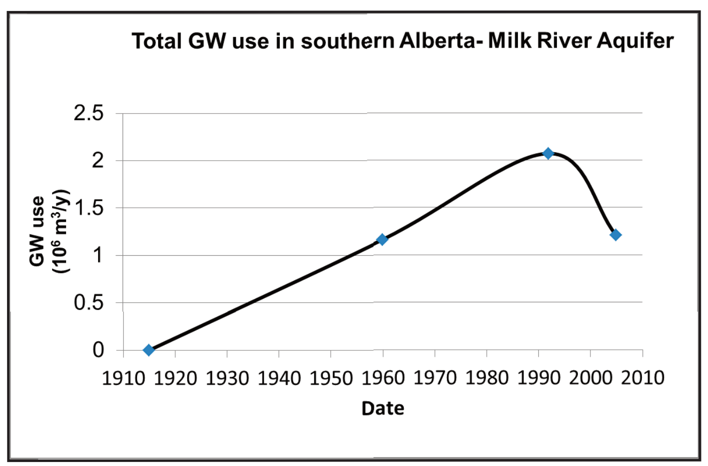


Figure 8.1 Evolution of groundwater use in the Milk River Aquifer in southern Alberta, (Pétré et al., 2016)

Southern Alberta

There was no groundwater use prior to 1915; it is estimated that groundwater use began in southern Alberta in the 1930s when 250 wells were inventoried by the Geological Survey of Canada during the 1930s in the form of well inventories (as cited in Geiger et al., 1966). However, it was not until the 1960s when a close inspection of the area provided the first quantitative estimate of groundwater use. In 1960, Meyboom (1960) identified 409 water wells and estimated the total production to be **1.16 × 10⁶ m³/a**. This value includes the water wastage. Two other studies were carried out in the 1990s and 2000s by Persram (1992) and HCL Consultants (2007). Persram (1992) estimated an increase in the total groundwater use by 1999 with a total of **2.07 × 10⁶ m³/a**, whereas HCL estimated a decrease in the total groundwater use with **1.21 × 10⁶ m³/a.**

The total water usage in southern Alberta almost doubled between 1960 and the early 1990s (Figure 8.1). It was estimated that the increase in groundwater use was attributed to the increase in the number of livestock (16 000 head estimated in 1960 and 100 000 head in 1992). By the 2000s, there had been a decrease of 58% in groundwater consumption, mainly in the counties of Forty Mile, Warner No. 5, and Taber. In general, groundwater use in the county of Forty Mile had been decreasing as a result of rural population decline and connection to the regional water pipeline. Figure 8.2 shows the location of the main groundwater users in the 1990s.

Northern Montana

Groundwater from the Milk River Aquifer is also a very valuable resource in northern Montana. However, the magnitude of the total consumption is much less than the one in southern Alberta. In the Cut Bank area west of the Sweetgrass Arch, groundwater from the Virgelle Sandstone and the Two Medicine Formation is the principal source of fresh water for domestic, stock, and industrial use (Zimmerman, 1967). Most of the rural residents of the Kevin, Sunburst, and Santa Rita areas, as well as the oil refineries, depend on groundwater supplies. The total groundwater use estimated by Zimmerman (1967) in the Cut Bank area was about **0.96 × 10⁶ m³/a**.

In the Sweet Grass Hills area, Tuck (1993) estimated that the Virgelle discharge from wells reached a total amount of **134 397** m³/a. About 70% of this amount was used for secondary oil recovery and about 21% corresponded to the flowing wells (water wastage). Recent groundwater use data from the Eagle Formation are sparse. A survey conducted in 2013 within the framework of the MiRTAP project indicated that the town of Sunburst uses about **110 000** m³/a of groundwater from the Virgelle Member. This amount is three times lower than in 1967. In addition, east of Sweetgrass Arch, the Galata County and the Eagle Creek Colony now use **91 000** m³/a and **40 750** m³/a respectively.

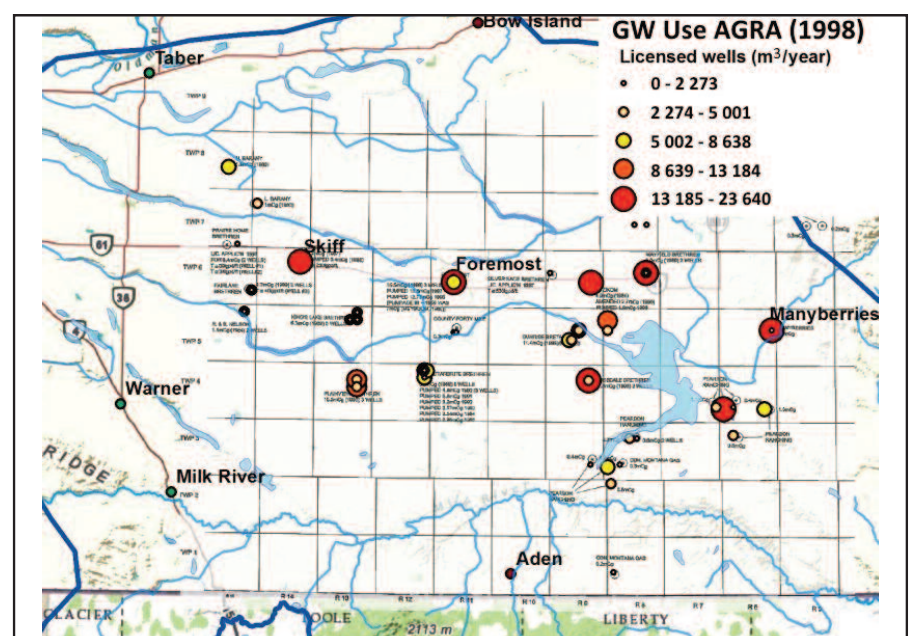


Figure 8.2 Main Milk River Aquifer groundwater users in southern Alberta (AGRA, 1998)

More recently, the Department of Natural Resources and conservation (DNRC), one of the stakeholders in the MiRTAP project, indicated that secondary oil recovery was still going on in the Sweet Grass Hills area, but that it did not have groundwater use records from the water users (cited by DNRC). In 1967, groundwater was discharged by hundreds of wells in the Cut Bank area; most of those wells provided domestic and stock water. The rate of discharge for stock and domestic wells was low; their aggregate discharge was about **500 000** gpd (0.7 × 10⁶ m³/a), as reported by Zimmerman (1967).

In 1967, the town of Kevin obtained its municipal water supply from the Virgelle Member and from the Telegraph Creek Member. The town of Sunburst, two miles east of the study area, obtained its water from the Virgelle. Kevin used about **86 000** gpd (0.12 x 10⁶ m³/a) and Sunburst about **229 000** gpd (0.32 x 10⁶ m³/a). Cut Bank had a standby well to supplement the surface-water supply. The well would yield more than 250 gpm (**360 000** gpd, 0.5 x 10⁶ m³/a) of water, but the amount of dissolved solids was so high that it was used only in emergencies. The Union Oil Company of California refinery east of Cut Bank and the Big West Oil Company refinery at Kevin were among the leading industrial users of water in the study area. The Big West refinery obtained its water from the Kevin public supply. The Union refinery used three wells tapping the Virgelle Sandstone. Two were pumped almost continuously and the third was a standby well. They used to produce about **288 000** gpd (0.4 x 10⁶ m³/a). Water injection for secondary oil recovery was another industrial use of water in the study area. The injection of this water was expected to extend the life of the oil fields by as much as 17 years and to nearly double the amount of oil recovered. At the end of 1965, 10 secondary recovery projects were operating in oil fields in the Cut Bank area. Seven of these used about **1 000 000** gpd (1.38 x 10⁶ m³/a) of water from Madison County and three used about **93 000 gpd** (0.13 x 10⁶ m³/a) of water from the Virgelle Member (Oil and Gas Conservation Commission of the State of Montana, 1965). Prior to May 1963 and June 1964, two of the water flood projects now using Madison County water were using Virgelle water. There are no current updates on these groundwater users. Table 8.1 summarizes the multiple groundwater uses on both sides of the international border in the Milk River transboundary region. Map 8.1 shows the percentages of the groundwater users and the main areas of groundwater extraction.

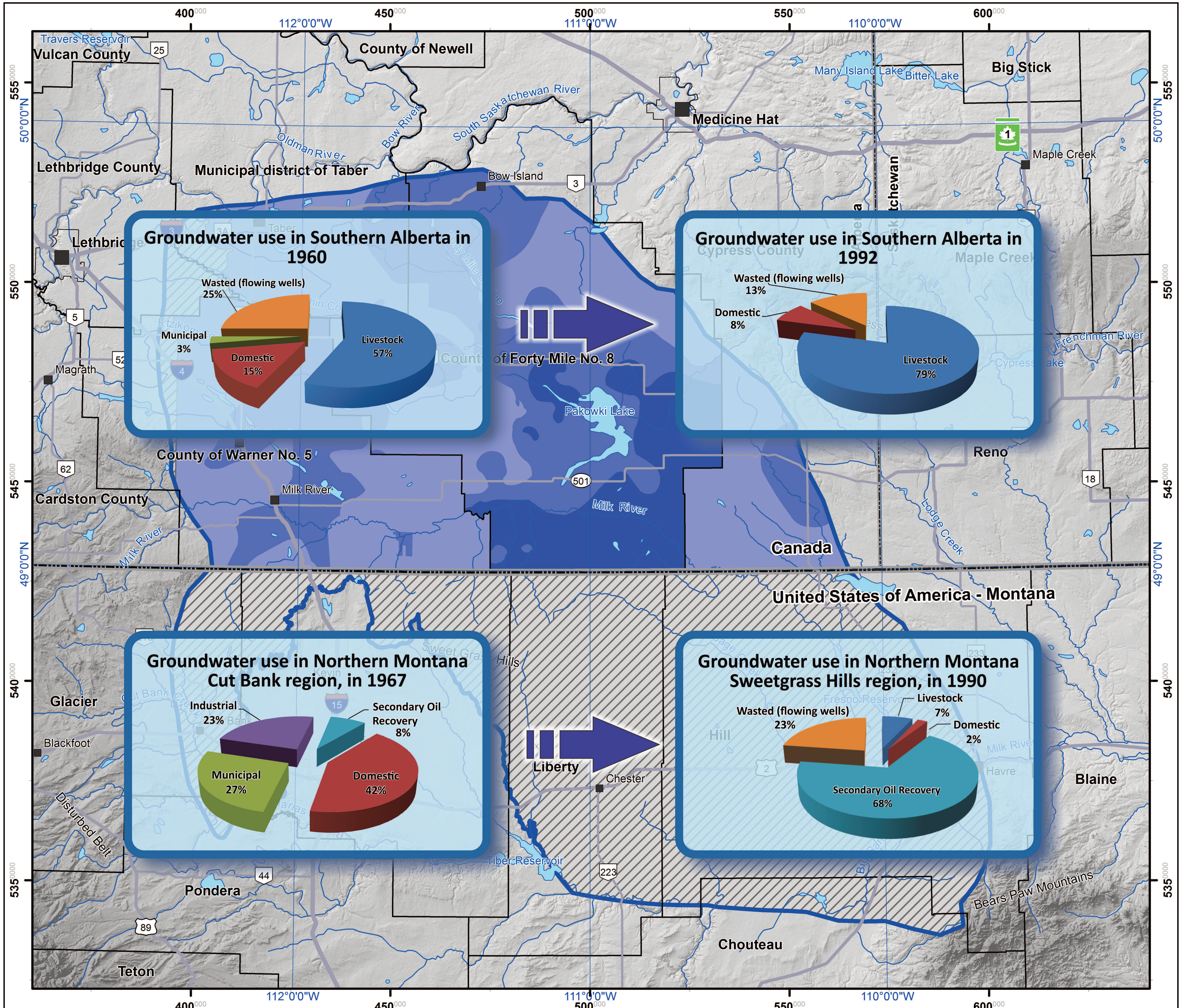
Table 8.1 Estimated groundwater uses in the Milk River transboundary region

	Alberta		Montana	
			Cut Bank	Sweetg. Hills
Year	1960	1992	1967	1993
	Meyboom (1960)	Persram (1992)	Zimmerman (1967)	Tuck (1990)
GW use volume	(10^6 m³/a)	(10^6 m³/a)	(10^6 m³/a)	(10^6 m³/a)
User				
Livestock	0.66	1.64	0.7	0.009
Domestic	0.18	0.16		0.003
Municipal	0.03	(in domestic)	0.44	
Industrial			0.39	
Secondary oil recovery			0.13	0.09
Water wastage (flowing wells)	0.29	0.27		0.03
Total use	**1.16**	**2.07**	**1.66**	**0.13**

MAP 8.1

Groundwater Use

Projection UTM 12N 1:1 000 000



Legend

Population
- < 3000
- 3001 - 10000
- 10001 - 100000

Road Network
- Highway
- Main Road
- Regional Road

Border
- International
- Provincial - State
- Town and County

Hydrography
- Lake
- River

Groundwater Estimated Use (m^3/d)

For 2002 - 2007 time period
- 0-100
- 100-300
- 300 and more
- Insufficient data

Aquifer Extent
- Milk River

Elevation (m a.m.s.l.)
- High : 2595 m
- Low : 620 m

9 Conclusion

9.1 Conclusion

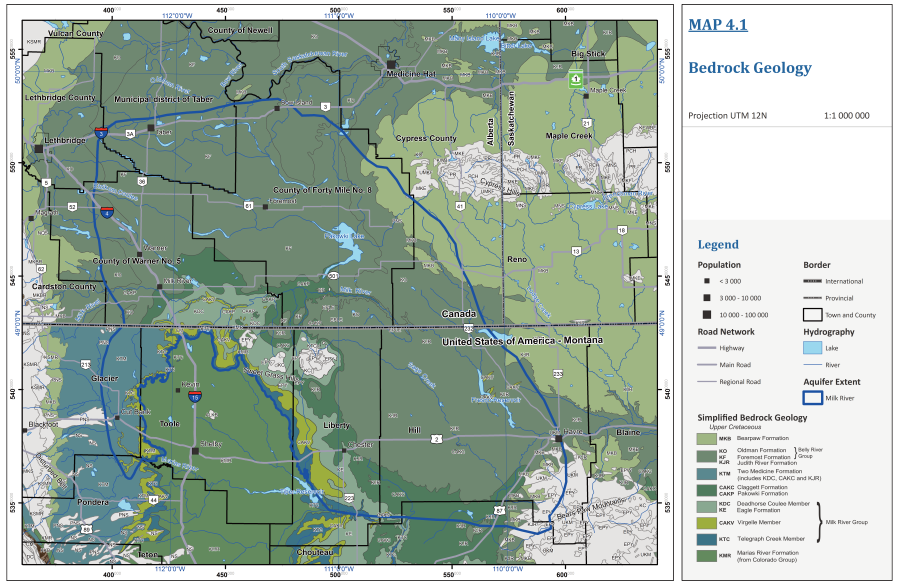
This atlas synthesizes and integrates numerous works to provide a unified portray of the Milk River Transboundary Aquifer. It includes previous works of researchers on both sides of the Canada–U.S.A. border since the early 1900s, as well as new hydrogeological and geochemical data recently collected in the field. The aquifer delineation was based on natural physical boundaries rather than the political and jurisdictional boundaries.

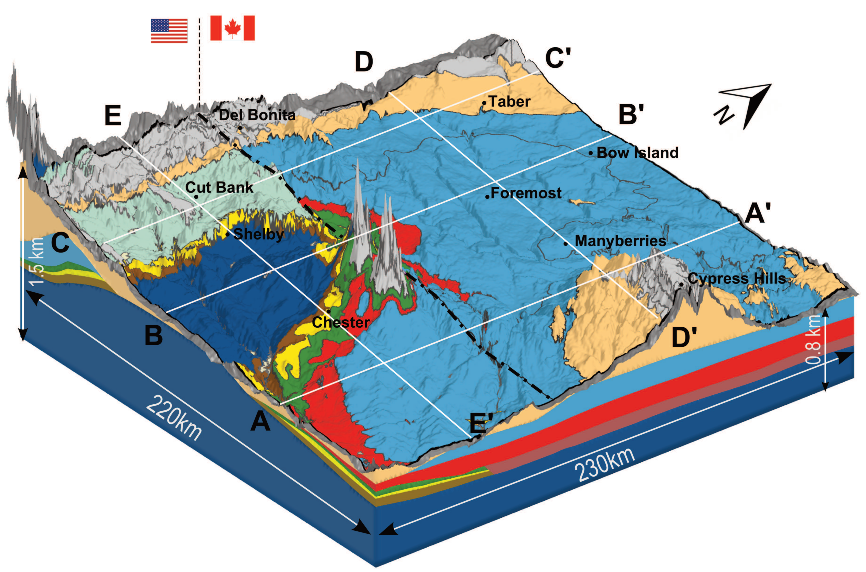
The very rich and historical data collection; the existing information on this aquifer; the transfer of knowledge on the physical and chemical hydrogeology of the Milk River Aquifer to the regional, national, and international participants with stakes in this aquifer provide a clear and visual document for the lay person in the form of an atlas. It is a comprehensive geographical view of the Milk River Aquifer on both sides of the Canada–U.S.A. border, providing a unified picture of our knowledge of the aquifer as of 2016.

This is accomplished through the integration of data and information on the region with very visual, colourful basic mapping tools. This approach represents a powerful pedagogic tool that underlines the importance of the groundwater resources contained in the aquifer to support informed decision-making processes. Production of such a transboundary groundwater atlas will hopefully help foster collaboration and integrated management of the shared resource. This atlas may be useful as an easy-to-understand tool in order to be integrated into the planning of land-use management and groundwater protection.

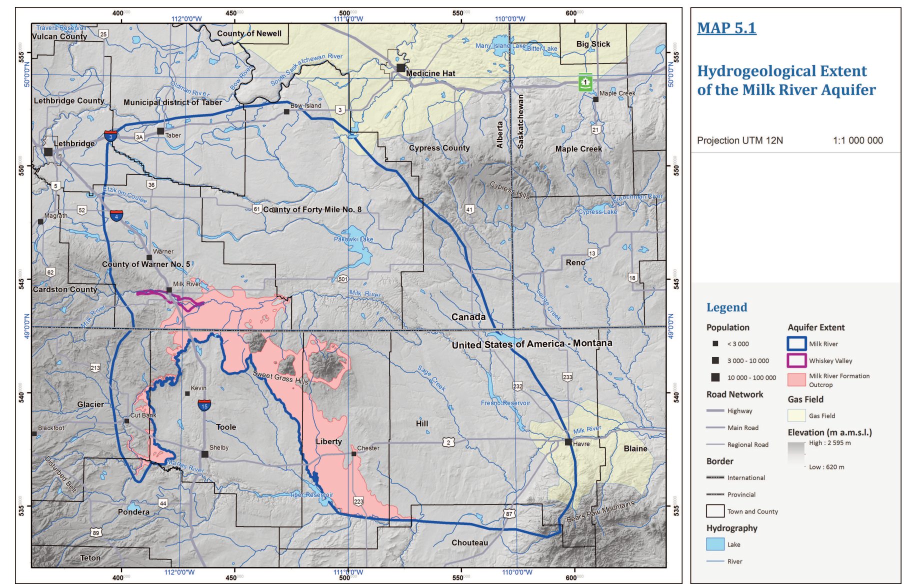
Land-use planning must consider all available information, including the needs of townships and counties; water uses and users, constraints on managing natural and anthropogenic issues; regulation and application of standards and natural characteristics of the land etc. In that context, regrouping several layers of information on the same map constitutes an excellent tool in the decision-making process for land-use management.

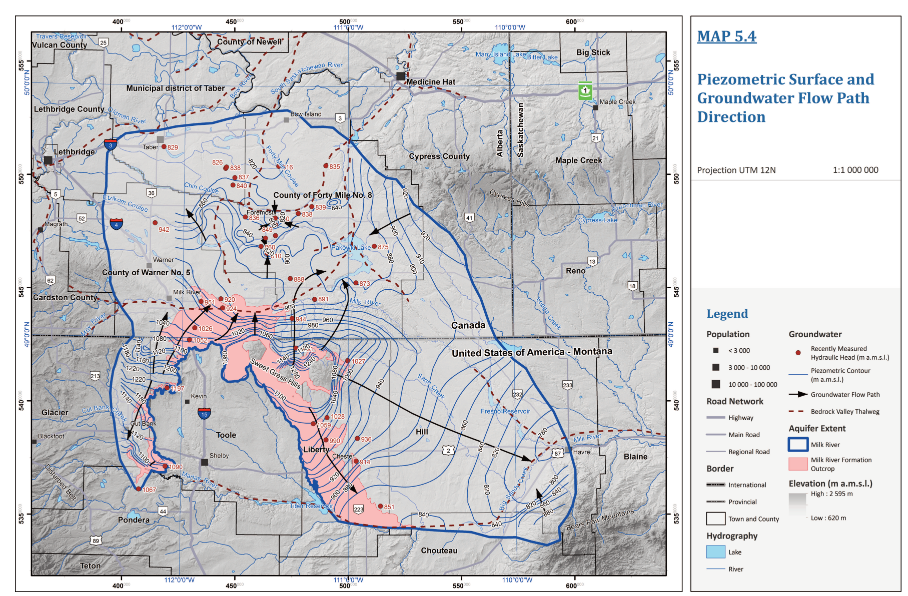
This is the first atlas of the Milk River Transboundary Aquifer. It is both a snapshot in time (2016) and an indicator of the progress made in understanding the groundwater dynamics of the aquifer, including its transboundary nature on the Alberta and Montana sides of the border. This is an important contribution to the understanding of the precious hidden resource of groundwater and an educational tool for citizens and water managers in southern Alberta and northern Montana.

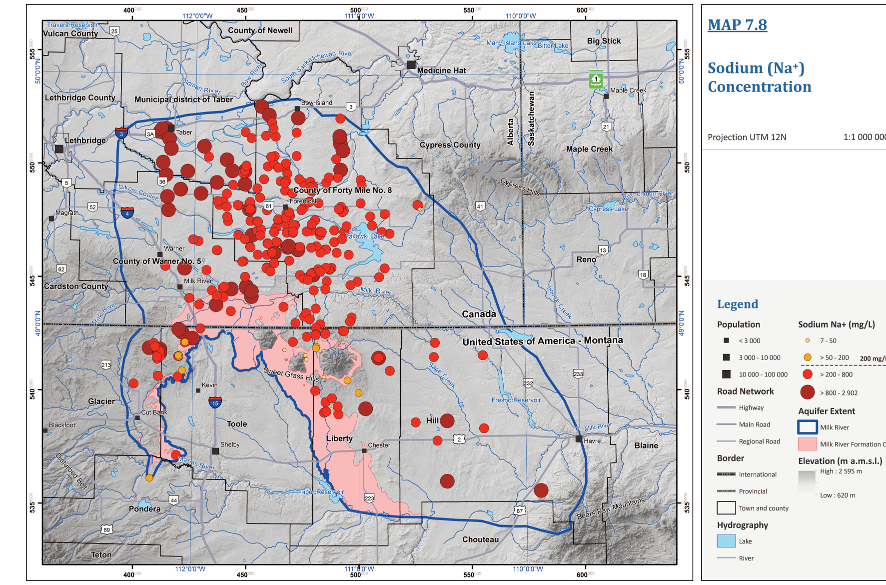


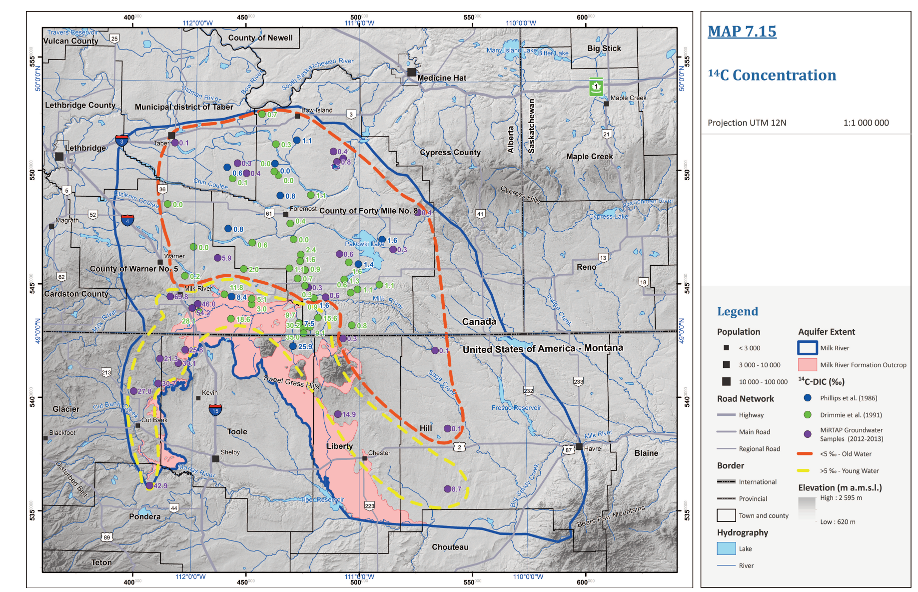


Bearpaw Formation and/or surficial sediments
Belly River Group/Judith River Formation
Claggett Shale/Pakowki Formation
Alderson Member
Deadhorse Coulee Member
Virgelle Member (Milk River Aquifer)
Telegraph Creek Member
Colorado Group









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<http://www.mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=10061>

Glossary

Apparent yield: Quantity of water which can be collected for a given use from groundwater sources in a basin in a given time interval.

UNESCO/WMO International Glossary of Hydrology, second edition, 1992. Van den Berghe, W., 1995. Achieving Quality in Training. European guide for collaborative training projects. Tilkon, Wetteren., 308 p., ISBN 90-75427-01-8

Aquifer: It is a layer, formation, or group of formations of permeable rocks, saturated with water and with a degree of permeability that allows economically profitable amounts of water to be withdrawn.

De Marsily, G., 1986. Quantitative hydrogeology: groundwater hydrology for engineers. Academic Press, Inc. 440 p.

Aquitard: A confining bed that retards but does not prevent the flow of water to or from an adjacent aquifer; a leaky confining bed.

United States Geological Survey (USGS), 2015. Water Science Glossary of Terms. <http://water.usgs.gov/edu/dictionary.html#A>

Casing: A special steel tubing welded or screwed together and lowered into a borehole to prevent [the] entry of loose rock, gas, or liquid into the borehole or to prevent loss of circulation liquid into porous, cavernous, or crevassed ground.

Thrush, P.W., 1968. A dictionary of Mining, Mineral and Related Terms. Maclean Hunter Publishing Company, 1275 p.

Coal seam: A bed of coal usually thick enough to be mined with profit.

Babcock Fove, P., 1976. Webster's Third New International Dictionary, G. & C. Merriam Co., 2782 p.

Conductivity: Conductivity (or specific conductance) of an electrolyte solution is a measure of its ability to conduct electricity.

Conductivity (electrolytic), Wikipedia. <https://en.wikipedia.org/wiki/Conductivity_(electrolytic)>

Confined aquifer: An aquifer that is bounded from above and below by low permeability formations.

Jackson, J.A., 2003. Glossary of Geology. Springer; 4th edition, 769 pages.

Confining unit: A geological unit which retards groundwater flow, a synonym of aquitard or aquiclude.

Conners, J.A., 2016. Groundwater for the 21st Century: A Primer for Citizens of Planet Earth, by. McDonald & Woodward Publishing Co., USA, 2013.

Coulee: A small stream, usually intermittent, flowing in a comparatively steep-sided valley or ravine. Generally found in the Prairies.

Glossary of generic terms in Canada's geographical names. Public Works and Government Services Canada. Translation Bureau. <http://publications.gc.ca/pub?id=9.588135&sl=0>

Discharge area: An area in which groundwater is discharged to the land surface, surface water, or atmosphere (WRC, 1980).

United States Geological Survey (USGS), 2015. Water Science Glossary of Terms. <http://water.usgs.gov/edu/dictionary.html#P>

Drawdown: The vertical distance the water elevation is lowered or the reduction of the pressure head due to the removal of water (after ASCE, 1985).

United States Geological Survey (USGS), 2015. Water Science Glossary of Terms. <http://water.usgs.gov/edu/dictionary.html#P>

Endorheic lake: Lake without surface or subsurface outflow where the inflow water is lost by evaporation.

UNESCO/WMO International Glossary of Hydrology, second edition, 1992. Van den Berghe, W., 1995. Achieving Quality in Training. European guide for collaborative training projects. Tilkon, Wetteren., 308 p., ISBN 90-75427-01-8

Effective porosity: A term used to refer to interconnected pore space; it is a measure of how effective the pores are in allowing water migration through the material, usually an aquifer. In unconsolidated sediments, effective porosity will be close to total porosity.

Conners, J.A., 2016. Groundwater for the 21st Century: A Primer for Citizens of Planet Earth, by. McDonald & Woodward Publishing Co., USA, 2013.

Facies: The aspect, appearance, and characteristics of a rock unit, usually reflecting the conditions of its origin; esp. as differentiating the unit from adjacent or associated units.

D. G. A., Whitten with J. R. V. Brooks, 1972. The Penguin Dictionary of Geology. 495 p., 161 figures, tables. Penguin Books Ltd., Harmondsworth, Middx. p. 515–516.

Glacial drift: All rock material in transport by glacier ice, all deposits made by glacier ice, and all deposits predominantly of glacial origin made in the sea or in bodies of glacial meltwater whether rafted in icebergs or transported in the water itself.

Canadian Quaternary vocabulary. Public Works and Government Services Canada. Translation Bureau. <http://publications.gc.ca/pub?id=9.590511&sl=0>

Hydraulic conductivity: A proportionality constant relating hydraulic gradient to specific discharge, which, for an isotropic medium and homogeneous fluid, equals the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow (after ASCE, 1985).

United States Geological Survey (USGS), 2015. Water Science Glossary of Terms. <http://water.usgs.gov/edu/dictionary.html#P>

Hydraulic gradient: Change in elevation of the water table, or water pressure, from one point to another.

Conners, J.A., 2013. Groundwater for the 21st Century: A Primer for Citizens of Planet Earth, by. McDonald & Woodward Publishing Co., USA.

Hydrogeology: The science that relates geology, fluid movement (i.e., groundwater) and geochemistry to gain an understanding of water residing under the Earth's surface.

Rivera, A., 2014. Canada's groundwater resources. Geological Survey of Canada. Fitzhenry & Whiteside, Markham, Ontario, 804 p. ISBN 978-1-55455-292-4

Hydrostratigraphic unit: Any soil or rock unit or zone which by virtue of its hydraulic properties has a distinct influence on the storage or movement of groundwater (after ANS, 1980).

United States Geological Survey (USGS), 2015. Water Science Glossary of Terms. <http://water.usgs.gov/edu/dictionary.html#P>

Intrusion: The process of emplacement of magma in pre-existing rock.

Jackson, J.A., 2003. Glossary of Geology. Springer; 4th edition, 769 p.

Montane: Of, pertaining to, or inhabiting cool upland slopes below the timber line, characterized by the dominance of evergreen trees.

Gary M., McAfee R. Jr., and Wolf C. L., 1972. Glossary of geology. American Geological Institute, 805 p.

Moraine: A mound, ridge, or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited chiefly by direct action of glacier ice, in a variety of topographic landforms that are independent of control by the surface on which the drift lies.

Jackson, J.A., 2003. Glossary of Geology. Springer; fouth edition, 769 p.

Oxidation-reduction: An oxidizing chemical change, where an element's positive valence is increased (electron loss), accompanied by a simultaneous reduction of an associated element (electron gain).

Lapedes, D. N., 1976. Dictionary of the Life Sciences. McGraw-Hill, 992 p.

Piezometric surface: A piezometric surface map is a representation in two dimensions of lines of equal head in the groundwater body, called equipotential lines. For unconfined groundwater, the piezometric surface map is basically a water table map.

Conners, J.A., 2013. Groundwater for the 21st Century: A Primer for Citizens of Planet Earth, by. McDonald & Woodward Publishing Co., USA.

Piezometry: The measurement of groundwater pressure, which expresses the elevation of groundwater.

Costello, E. and Costello, R.B., 1998. The Random House dictionary of English language, Random House Websters, 630 p.

Plateau: An extensive, elevated region, with either level terrain, or nearly uniform summit levels.

Glossary of generic terms in Canada's geographical names. Public Works and Government Services Canada. Translation Bureau. <http://publications.gc.ca/pub?id=9.588135&sl=0>

Pumping test: Evaluation of an aquifer by "stimulation" through controlled pumping and observing the aquifer's "response" (drawdown) in the production and observation wells.

New York State Department of Environmental Conservation, 2015. Groundwater Definitions. <http://www.dec.ny.gov/lands/76322.html>

Recharge: In the hydrogeological unit, quantity of water that replenishes groundwater beneath the water table, expressed in mm/a.

New York State Department of Environmental Conservation, 2015. Groundwater Definitions. <http://www.dec.ny.gov/lands/76322.html>

Resistivity: The tendency of water to oppose the flow of an electric current.

Daintith, J. and Clark, J., 1999. The Facts On File Dictionary of Physics, third edition., 256 p.

Shut-in pressure test: The surface force per unit area exerted at the top of a wellbore when it is closed at the large valve at the top of a well (BOP).

Schlumberger Limited, 2015. Oilfield Glossary. <http://www.glossary.oilfield.slb.com/en/.aspx>

Saturated thickness: It refers to that part of the subsurface water-bearing formation in which all interstices (voids), large and small are filled with water.

Margat, J. and Van der Gun, J., 2013. Groundwater around the World: A Geographical Synopsis. Taylor & Francis Group.

Stratigraphy: A branch of geology concerned with the study of the origin, composition, distribution, and succession of rock strata.

University of Texas, 1976. A dictionary of petroleum terms. Pretoleum Extension Service and Texas Education Agency.

Surface runoff: Flow of rainwater on the ground, expressed in L^3T^{-1}.

United States Geological Survey (USGS), 2015. Water Science Glossary of Terms. <http://water.usgs.gov/edu/dictionary.html#P>

Total alkalinity: Total alkalinity is measured by measuring the amount of acid (e.g., sulfuric acid) needed to bring the sample to a pH of 4.2. At this pH all the alkaline compounds in the sample are "used up." The result is reported as milligrams per liter of calcium carbonate (mg/L $CaCO_3$).

Water: Monitoring & Assessment. 5.10 Total Alkalinity, What is total alkalinity and why is it important? Environmental Protection Agency (EPA) Web Archive <https://archive.epa.gov/water/archive/web/html/vms510.html>

Transmissivity: The rate at which water is transmitted through a unit length, usually the depth or thickness, of an aquifer or related water-bearing geologic formation under a hydraulic gradient of one.

Conners, J.A., 2016. Groundwater for the 21st Century: A Primer for Citizens of Planet Earth, by. McDonald & Woodward Publishing Co., USA, 2013.

Unconfined aquifer: An aquifer in which the water table is at or near atmosphere pressure and is the upper boundary of the aquifer. Because the aquifer is not under pressure the water level in a well is the same as the water table outside the well.

New York State Department of Environmental Conservation, 2015. Groundwater Definitions. <http://www.dec.ny.gov/lands/76322.html>

Vertical leakage: The fluxes exchanged between a confined aquifer and its confining beds are called vertical leakage fluxes.

De Marsily, G., 1986. Quantitative Hydrogeology. Groundwater Hydrology for Engineers. Academic Press. Inc. (London) LTD.

Volcanic neck: The nearly circular vertical feed channel of a volcano which has been filled with solidified lava and/or pyroclastic material, and has subsequently been exposed by erosion of the volcanic cone.

D. G. A. Whitten with J. R. V. Brooks, 1972. The Penguin Dictionary of Geology. 495 p., 161 figures, tables. Penguin Books Ltd., Harmondsworth, Middx. p. 515–516.

Water table: The surface separating the upper layer of non-saturated soil and the lower layer of saturated soil.

World Meteorological Organization, 1992. International meteorological vocabulary, Secretariat of the World Meteorological Organization, 784 p.

Watershed: The territory draining naturally to a given point, a water course or to a sea.

United States Geological Survey (USGS), 2015. Water Science Glossary of Terms. <http://water.usgs.gov/edu/dictionary.html#W>

Weathering: The destructive processes by which rocks are changed on exposure to atmospheric agents at or near the Earth's surface, with little or no transport of the loosened or altered material.

Jackson, J.A., 2003. Glossary of Geology. Springer; fourth edition, 769 p.

A view of the Sweet Grass Hills