Natural Resources Canada | Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7654

A synthesis of knowledge of the Milk River Transboundary Aquifer (Alberta, Canada–Montana, U.S.A.)

M.-A. Pétré and A. Rivera

2015

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7654

A synthesis of knowledge of the Milk River Transboundary Aquifer (Alberta, Canada–Montana, U.S.A.)

M.-A. Pétré[1] **and A. Rivera**[2]

[1] Institut national de la recherche scientifique (ETE), 490 de la Couronne, Québec, Quebec
[2] Geological Survey of Canada, 490 de la Couronne, Québec, Quebec

2015

doi:10.4095/295754

This publication is available for free download through GEOSCAN (http://geoscan.nrcan.gc.ca/).

Recommended citation
Pétré, M.-A. and Rivera, A., 2015. A Synthesis of knowledge of the Milk River Transboundary Aquifer (Alberta, Canada–Montana, U.S.A.); Geological Survey of Canada, Open File 7654, 109 p. doi:10.4095/295754

Publications in this series have not been edited; they are released as submitted by the author.

Summary

This report is part of the Milk River Transboundary Aquifer Project (MiRTAP) initiated by the Geological Survey of Canada in 2009.

The objective of this report is to integrate information from previous geological, hydrogeological and geochemical studies of the Milk River Aquifer with data from the current study in order to develop an integrated dataset for study of the aquifer. The present report constitutes a comprehensive review of previous and current studies of the Milk River aquifer on both sides of the Canada/US border. It is a synthesis of knowledge on the aquifer as per 2015.

A 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 depositionally equivalent Formations and members on both sides of the international border.

The transboundary integration and development of unified stratigraphic model allows a better understanding of the aquifer. It will be used to generating a conceptual hydrogeological model to support development of a three-dimensional numeric hydrogeological model. It is anticipated that the transboundary numeric groundwater model will aid in improved water management and contribute to improved understanding of the sustainability of the groundwater resource.

Acknowledgments

Financial support for this project was provided by Natural Resources Canada through its Groundwater Geoscience Program (project AM02, Aquifer Inventories, *MiRTAP*: Milk River Transboundary Aquifer Project). In addition, in-kind support was provided by the Alberta Geological Survey, Montana Bureau of Mines and Geology, the U.S. Geological Survey and INRS-ETE, Quebec, Canada.

We are thankful to Joanna Thamke and Lori Tuck from the USGS office in Helena (Montana, USA), and Luke Buckley from the Montana Bureau of Mines and Geology. Thanks are due to Dan Palombi from the Groundwater Section and the bedrock geologists of the Alberta Geological Survey (Alberta Energy Regulator) and Tony Hamblin (GSC-Calgary Division).

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 Blash (USGS Helena). We are much grateful to Shaun O'Connell who contributed to this project through a contract for the digitalization of hydro-stratigraphic layers.

The production of this report greatly benefitted from the scientific review of Hazen Russell.

TABLE OF CONTENTS

1. INTRODUCTION 6

1.1 Study Context 6
1.2 Partnerships 8
1.3 Project objectives 8
1.4 Methodology 10
1.5 Field activities 10

2. CHARACTERISTICS OF THE STUDY AREA 11

2.1 Location of the study area 11
2.2 Climatological data 12
2.3 Topography and land slopes 16
2.4 Hydrology 16

3. STRATIGRAPHY AND GEOLOGY...20

3.1 Stratigraphic correlation of the Milk River and associated strata....... 20
3.2 Geology and hydrostratigraphy 23
3.3 Extent of the Milk River aquifer 34
3.4 3D unified geological model 35

4. HYDROGEOLOGY...37

4.1 Piezometric surface and direction of groundwater movement 37
4. 2 Artesian Well Flows 45
4.3 Hydrogeological parameters.. 46
4.4 Observation wells 50
4.5 Groundwater interactions with others units 54
4.6 Surface Water-Groundwater interactions.. 55
4.7 Presence of gas 57

5. GEOCHEMISTRY...61

5.1 Milk River Aquifer groundwater types.. 61
5.2 TDS, major and minor ions 62
5.3 Chemical evolution and isotopic pattern.. 63
5.4 Isotopic analysis and water dating 64

6. GROUNDWATER YIELD AND DEMAND.......................................73

6.1 Water Yield.. 73
6.3 Sustainability and management of the groundwater resources 81

CONCLUSIONS...86

REFERENCES 86

ANNEX A 94

ANNEX B 102

1. Introduction

1.1 Study Context

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; Fig. 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 also is used for water supply to enhance secondary oil recovery on the US-side of the border.

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 risen. The Milk River aquifer was the focus of many studies during the 20th century. Unfortunately few if any studies were completed on both sides of the Canada/US border, thus limiting the ability to develop a sound understanding of the global aquifer dynamics.

The Milk River Aquifer is exploited on both sides of the international border, and in the absence of an international agreement or convention between the USA and the Canada on the sharing of this resource is susceptible to over exploitation. In 2009, the Geological Survey of Canada (GSC) launched *MiRTAP* (Milk River Transboundary Aquifer Project) as part of its Groundwater Geoscience Program (Rivera, 2011).

In 2010, the Milk River Transboundary Aquifer was listed as transboundary aquifer system TAS 20N in the inventory of UNESCO ISARM-Americas initiative (Rivera, 2014). 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).

MiRTAP aims 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). The latest adopted resolution is reproduced in Annex A.

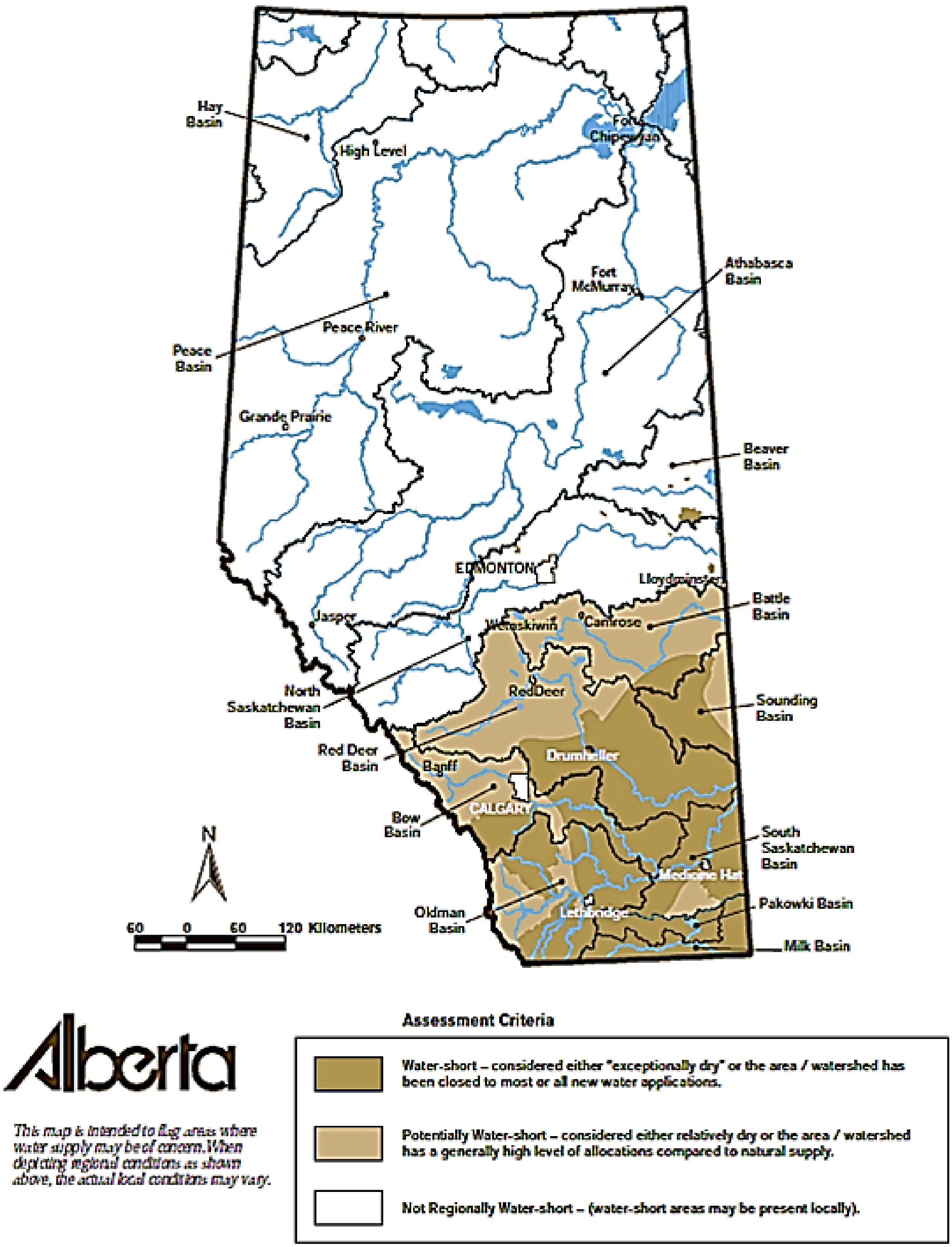


Figure 1: Map of the province of Alberta, Canada with Water short areas highlighted (Government of Alberta, 2006).

1.2 Partnerships

The Milk River Transboundary Aquifer Project involves stakeholders on both sides of the Canada/US border in six levels of jurisdiction (three in each country; Fig. 2).

Various coordination meetings were held since 2009; in Calgary, November 2009; in Milk River (Alberta) in April 2010, April 2012 and December 2012; in Medicine Hat in March 2010; and in Helena (Montana) in August 2013.

On February 2013, a data-sharing agreement was signed between the Alberta Geological Survey (AGS) and the Geological Survey of Canada (GSC). This agreement dealt with some missing geological data in the Milk River region, especially the elevation of the top of the Lea Park Formation (AGS, unpublished data).

1.3 Project objectives

The objectives of MiRTAP are to provide a unified portrait of the Milk River Aquifer across the Canada/US border by integrating existing data and studies, collecting new data, generating a conceptual model of the aquifer, creating a 3D unified hydrogeological model, and providing recommendation for a shared management of the aquifer. The term "unified" is used to signify that the aquifer study is based on the natural physical boundaries and not the political jurisdictional boundaries.

The approach used in this study is presented in Figure 3. The first stage of the study is the unified conceptual hydrogeological model (Pétré et al., 2012, Pétré et al., 2014; Pétré and Rivera, 2013). It consists of several components including the geological model of the aquifer, the groundwater flow system, and groundwater quality and isotopic dating; with an effort to address both the USA and Canada portions of the aquifer equally.

The unified conceptual hydrogeological model is then converted into a 3D hydrogeological numerical model of the aquifer (using FEFLOW). This model will permit a number of scenarios to be explored regarding water extraction from the aquifer, and will contribute to recommendations for the sustainable use of this shared resource.

It is anticipated that upon completion of the study the results will be documented in three peer reviewed journal papers documenting the geological model (Pétré et al., 2015), the unified conceptual model, and the 3D hydrogeological numerical model using FEFLOW.

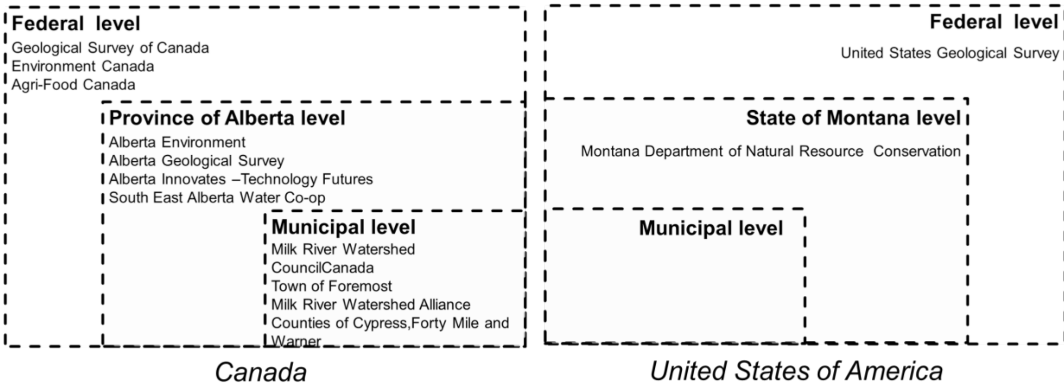


Figure 2: MiRTAP's stakeholders are composed of 6 jurisdictional levels.

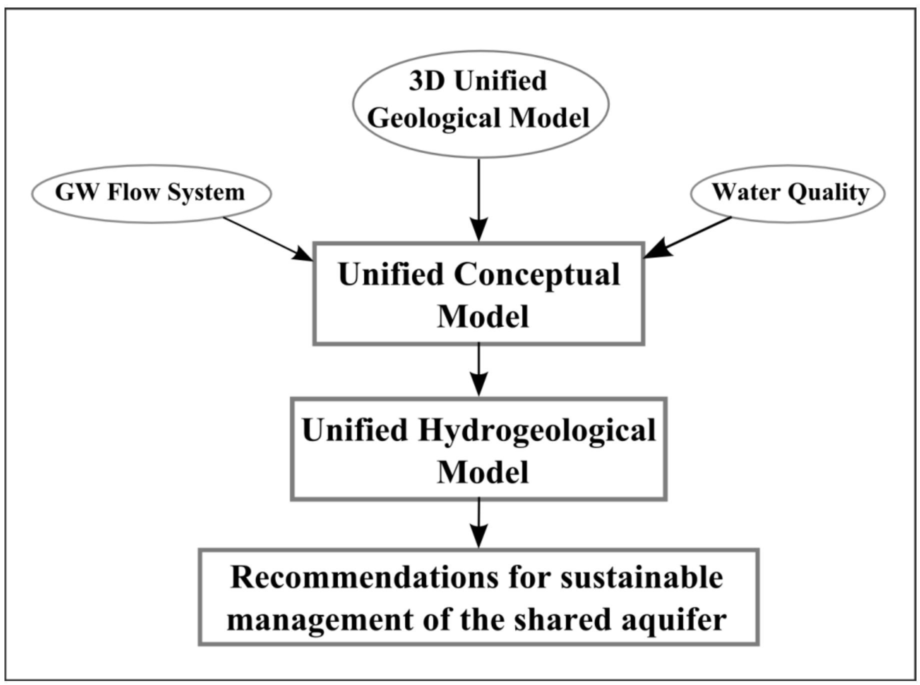


Figure 3: Study approach (Pétré et al., 2015).

1.4 Methodology

The approach adopted in the study included the following stages:

- Review: Completion of a comprehensive review of previous work on the Milk River aquifer, on both sides of the Canada/US border.
- Data Assembly: Collection and unification of available data (geological, hydrogeological, geochemical) for the Milk River aquifer.
- Geological Correlation: Carry out a correlation study based on previous works and collection of new geological data in order to unify the stratigraphic framework of the Milk River aquifer in the study area.
- Fieldwork: Carry out fieldwork on both sides of the international border, especially in the less-documented areas, in order to measure water levels and to sample groundwater for isotopic analysis. Conduct a groundwater usage survey with the landowners during the field activities.
- Conceptual Model: Integration and analysis of data to propose a 3D unified conceptual model of the transboundary aquifer.

1.5 Field activities

The Milk River Transboundary Aquifer Project had 3 fieldwork campaigns in the Canadian-side of the aquifer study area during the winter of 2012, summer of 2013 and winter of 2013. Additional fieldwork was carried out in collaboration with the USGS-Montana under a MoC Project Annex #26 (USGS/ESS Project Annex 26, 2013).

The objectives of the field work were to 1) measure the static water levels from wells drilled in the Milk River aquifer; 2) collect groundwater sampling for isotopic analysis (Tritium, Carbon 14 and Chlorine 36); 3) Measure the pressure of flowing artesian wells; and 4) Conduct a survey with landowners (status of the well, groundwater usage etc.).

Fieldwork #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 field work, a flyer explaining the goals of the study and the field activities was sent to the stakeholders and landowners in southern Alberta. The outcome was: 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 (Eilab-Waterloo), 16 samples for ^{3}H analysis (Eilab-Waterloo) and 10 samples for ^{36}Cl analysis (Prime Lab, Purdue University).

Fieldwork #2 (summer 2013, northern Montana)
The USGS (Helena Office) carried out a summer field work in northern Montana.
Outcome: 11 groundwater samples were collected; they were analyzed for ^{3}H, ^{14}C and ^{36}Cl. A survey was conducted with the owners of the sampled wells.

Fieldwork #3 (December 2013, southern Alberta)
Davison Environmental Consulting was hired by the Geological Survey of Canada to carry out a complementary fieldwork in southern Alberta. Outcome: 4 pressure measurements were collected from flowing wells, 8 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 analysis were only performed for the summer 2013 field work #2 in northern Montana.

2. Characteristics of the study area

2.1 Location of the study area

The study area is located in southern Alberta (Canada) and northern Montana (USA) in the central grassland ecoprovince of the Prairies ecozone (National Ecological Framework for Canada; Fig. 4). In Alberta, the study area covers 330 township areas in the counties of Warner, Taber and Forty Mile (from T1N to T15N and from R1W4 to R22W4). In Montana, the study area spans 184 township areas in Glacier, Toole, Liberty and Toole counties (from T37N to T29 N and from R13E to R10W).

The study area is within the Western Canadian Sedimentary Basin and the main geological structural feature in the study area is the Sweet Grass arch, composed of the Kevin-Sunburst Dome, the Bow Island Arch and the Sweet Grass Hills. The structure map of the Sweet Grass Arch in Montana is described by Collier (1930). The Sweet Grass Hills are an ensemble of three Buttes (2100 m altitude) near the Canada-US border. The rise of the Sweet Grass Hills (between 65 and 50 million years ago) and the erosion that followed (about 600 m) caused the exposure of certain geological units (Fig. 5).
The geology of the Sweet Grass Hills has been mapped by Kemp and Billingsley (1921) and more recently by Lopez (Lopez, 2002).

2.2 Climatological data

The study area has a semi-arid climate with short, warm summers and cold winters. The climate of the region is influenced by the proximity of the Rocky Mountains and associated Chinook winds, and more locally by the Sweet Grass Hills and Cypress Hills (AITF 2010). The average annual rainfall ranges from 300 mm to 450 mm (Fig. 6). The topographic highs (Cypress and Sweet Grass Hills) receive the highest precipitation rates. The potential evapotranspiration (PET) greatly exceeds the amount of precipitation throughout the region. For example, the County of Forty Mile (Alberta) receives about 345 mm of rain per year, based on data from 1971 to 2000 (AITF 2010). The calculated annual evapotranspiration is 625 mm (HCL Consultants, 2004).

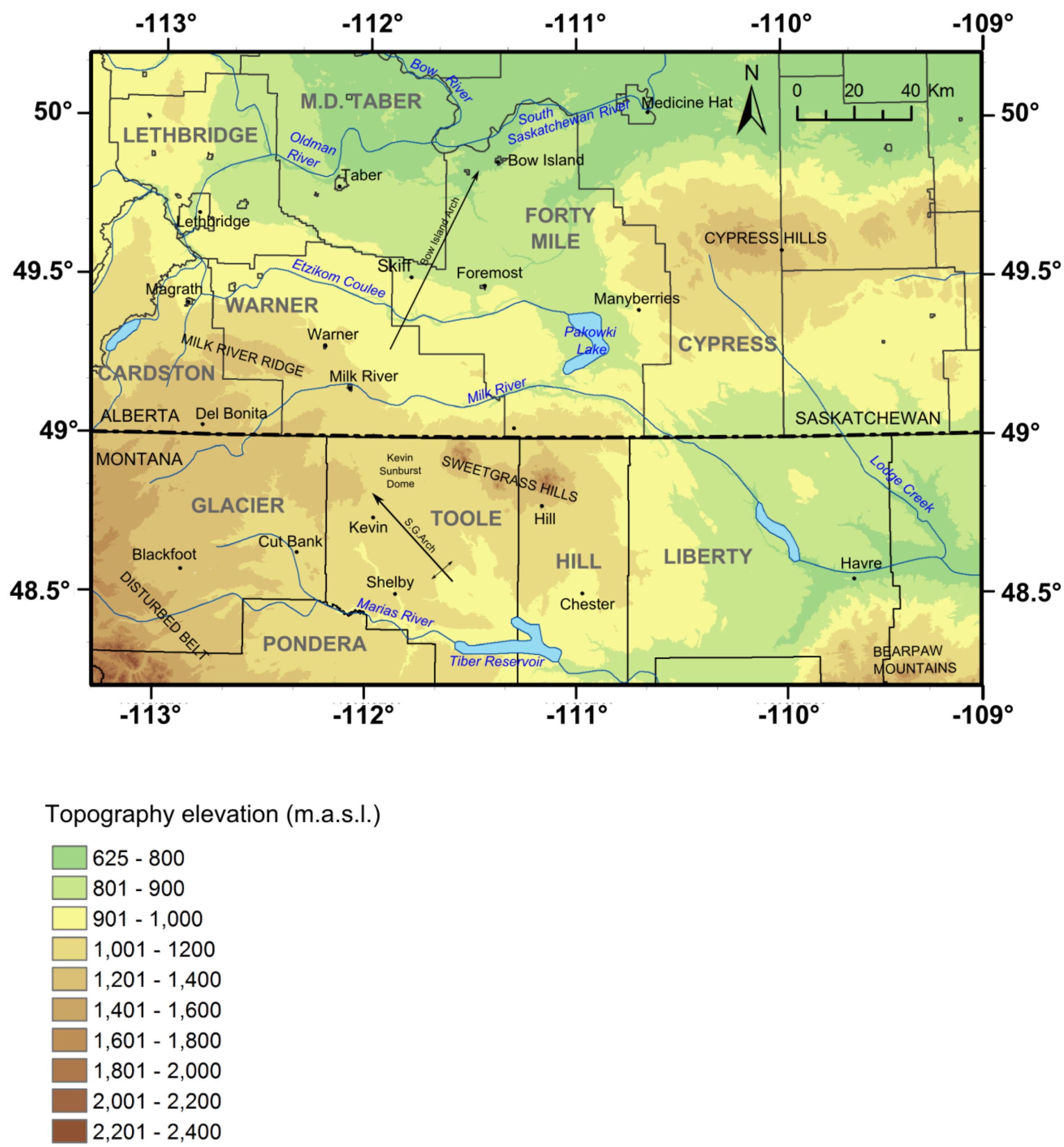


Figure 4: Location of the study area and county limits.

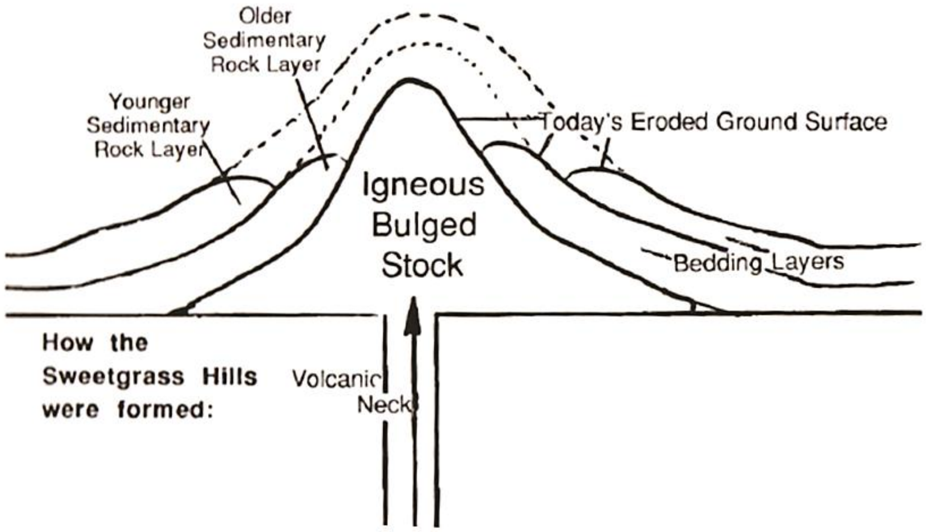


Figure 5: Formations of the Sweet Grass Hills (Doormar, 2003).

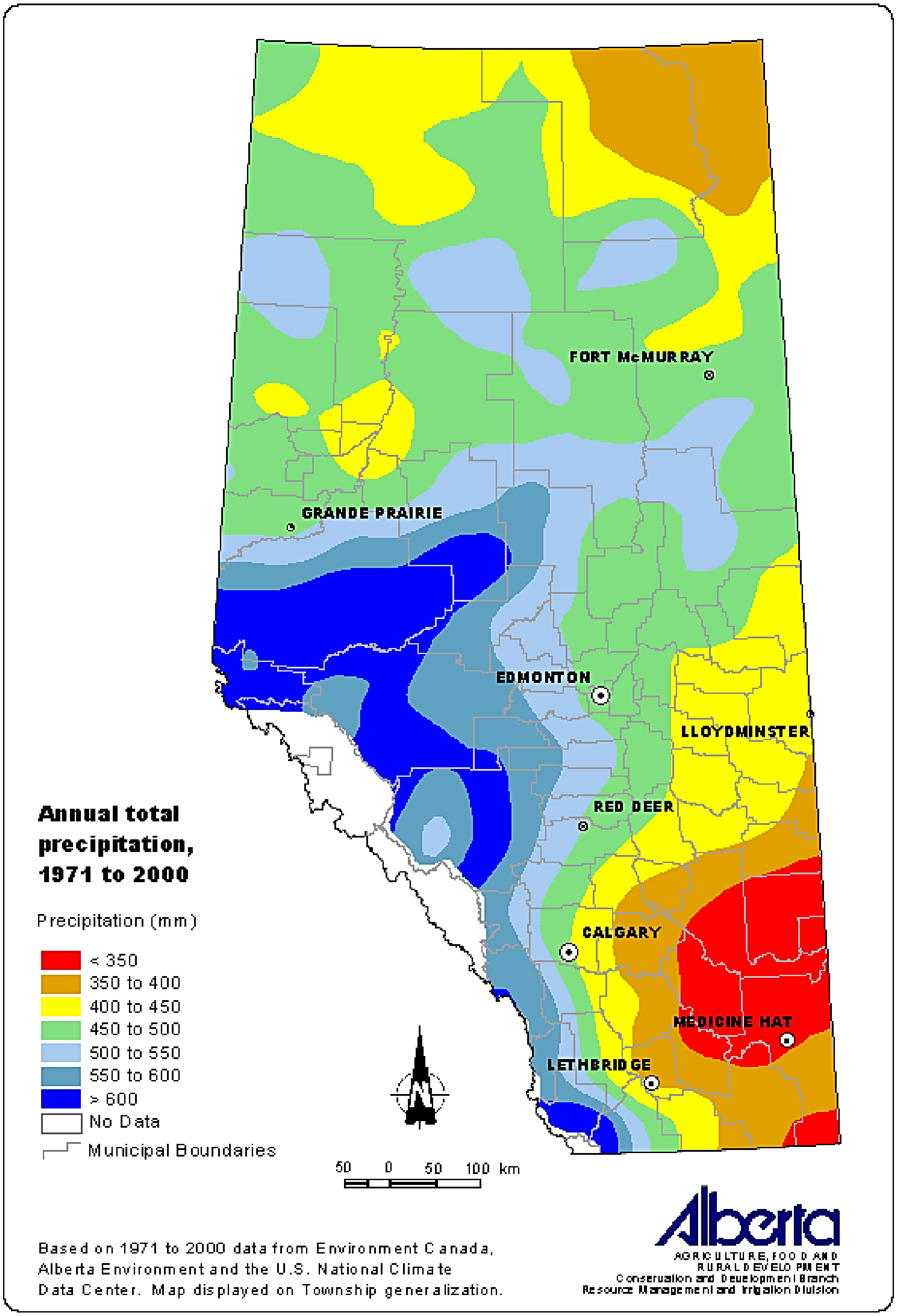


Figure 6: Annual total precipitation in Alberta 1971-2000 (Data provided by Alberta Agriculture and Rural Development, AgroClimatic Information Service (ACIS) http://agriculture.alberta.ca/acis/ (April, 2014).

2.3 Topography and land slopes

The topography of the region is undulating (Fig. 4). The altitude in the outcrop area of the Milk River aquifer ranges from 1050 m (above sea level) to approximately 800 masl at the north end of the aquifer.

The Cypress Hills in Alberta have an altitude of about 1400 masl west of the study area, the Milk River Ridge in the western part of the study area rises to 1219 masl altitude. The Milk River Canyon, one of the deepest on the Canadian prairies was formed due to glacial processes (AITF 2010). It is up to 1500 meters wide and 150 meters deep.

In Montana, the Sweet Grass Hills (2100 m altitude) are a set of three buttes and smaller hills in the northern counties of Toole and Liberty, at approximately 5 to 10 km south of the Canada-US border (Fig. 7). They were formed due to the intrusion of igneous rocks during the Paleocene.

Most parts of the study area have a surface slope of < 1% (Fig. 7). The surface slope is steeper in the vicinity of the rivers and coulees where it ranges between 1 to 10%. The surface slope is > 10% locally around the Sweet Grass Hills in Montana.

2.4 Hydrology

The Milk River flows over 1173 km from its source in the Blackfeet 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.
However the surficial drainage network above the aquifer extends beyond the Milk River watershed to the North, as part of the much larger South Saskatchewan River watershed.

The Milk River watershed has a surface of 6664 km^2 and occurs in parts of the provinces of Alberta, Saskatchewan and the State of Montana (Fig. 9). It is the smallest watershed of the Province of Alberta (Fig. 8).
The extents of the Milk River watershed and Milk River aquifer are not coincident and the watershed has a smaller surface area than the Milk River aquifer which extends up to 100 km north of the Canada-US border and 380 km south in Montana for a total area of 22,000 km^2.

Key geomorphological elements in the area are "coulees ", "V" valleys (or ravines) with steep edges. The coulees were either created by glacial erosion, after the last ice age, or by the continuing erosion of water and wind. (Doormaar 2010).

The study area also includes a closed internal drainage basin (endorheic) containing the Pakowki Lake (average depth 1.2 m; Fig. 10). This closed drainage basin retains water and allows no outflow to other external bodies of water, it equilibrates through evaporation. This intermittent lake covers a maximum area of 123 km^2 and is seasonally fed by water from the Etzikom Coulee.

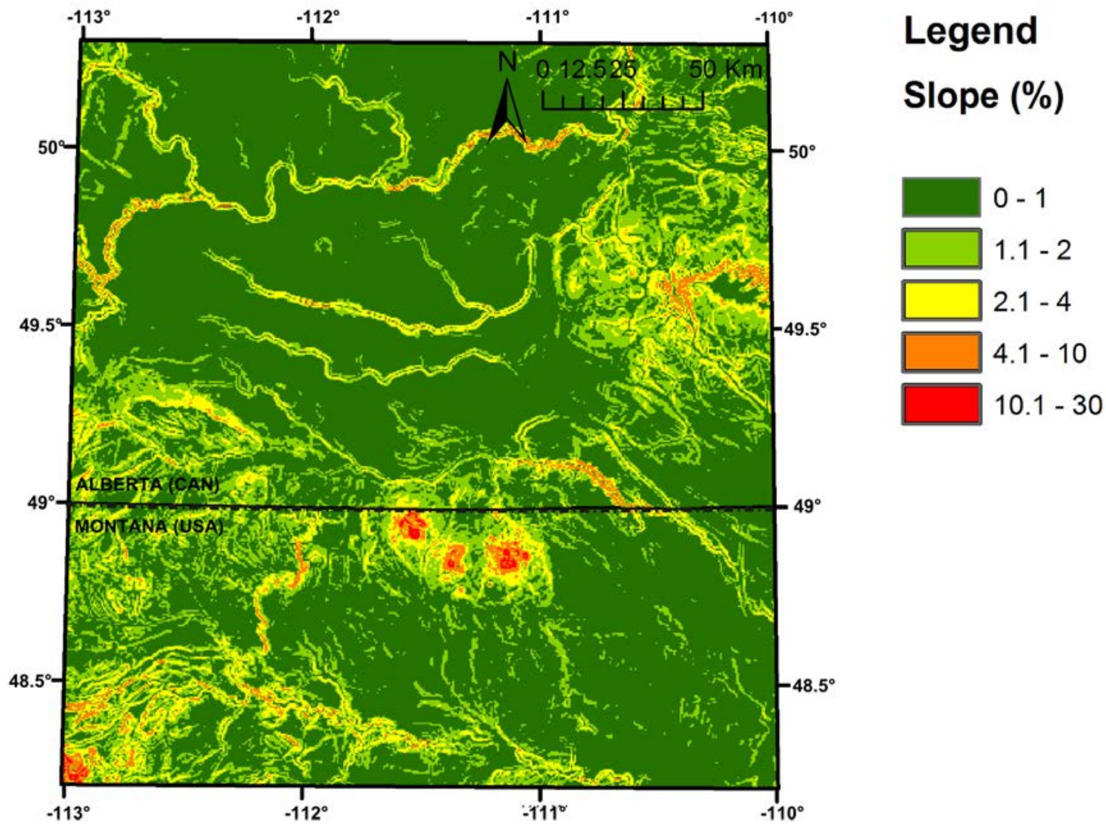


Figure 7: Slope of land surface in the study area.

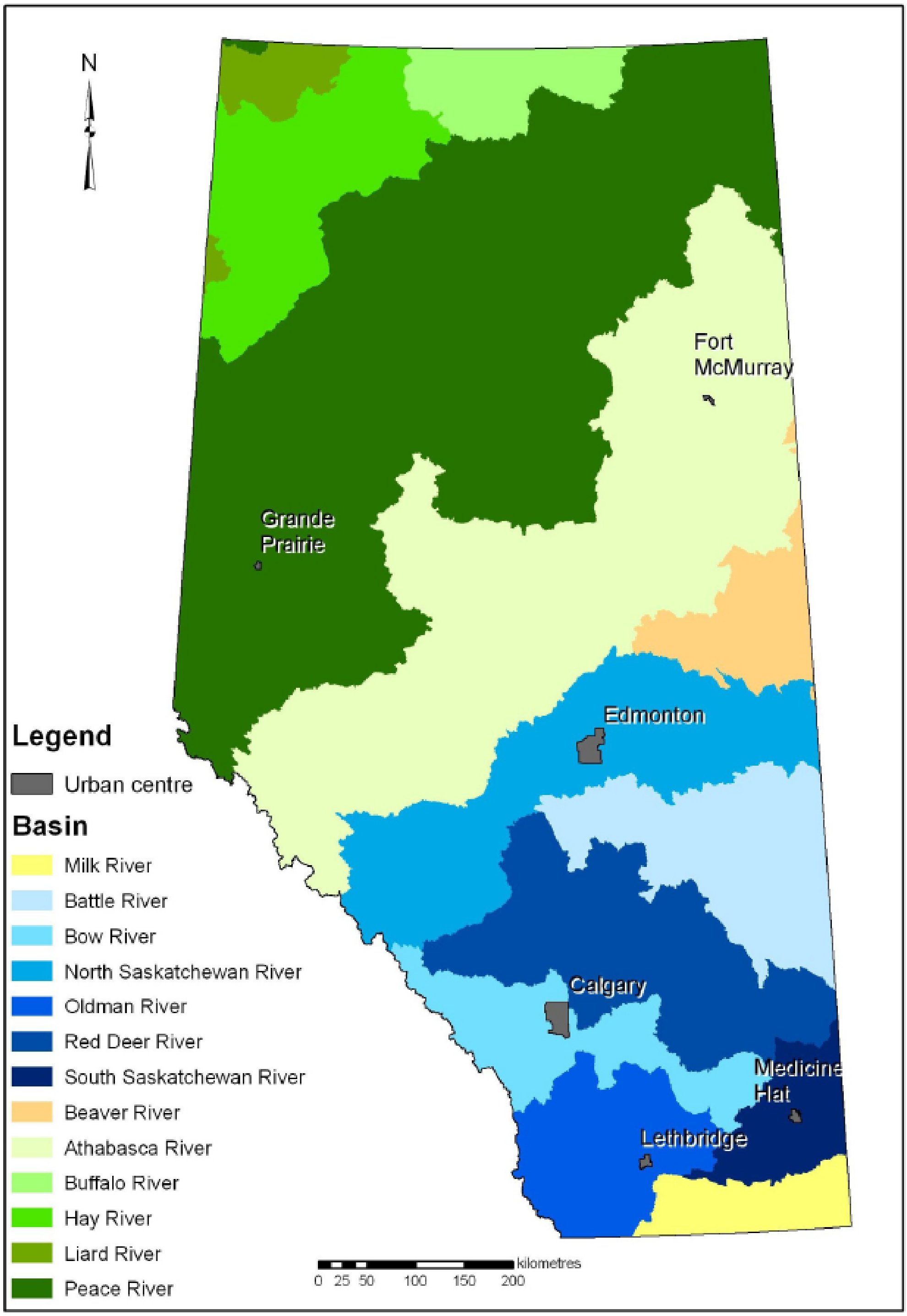


Figure 8: Alberta river basins (Lemay and Guha, 2009).

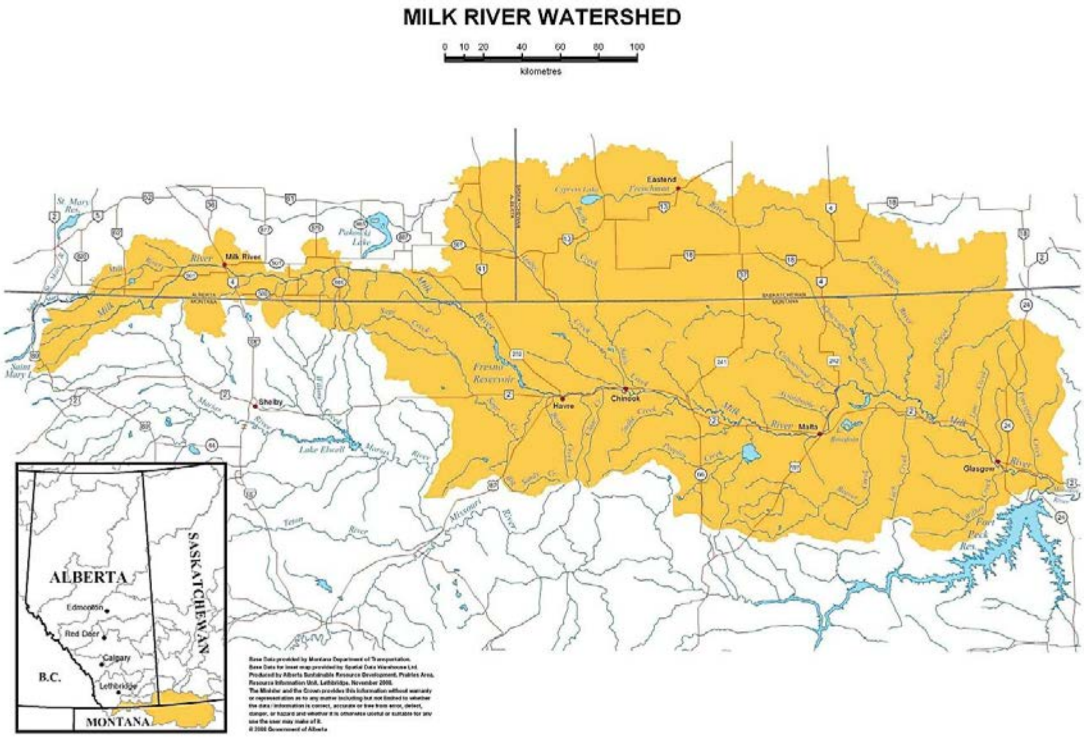


Figure 9: Milk River Watershed (Milk River Watershed Council Canada, 2008).

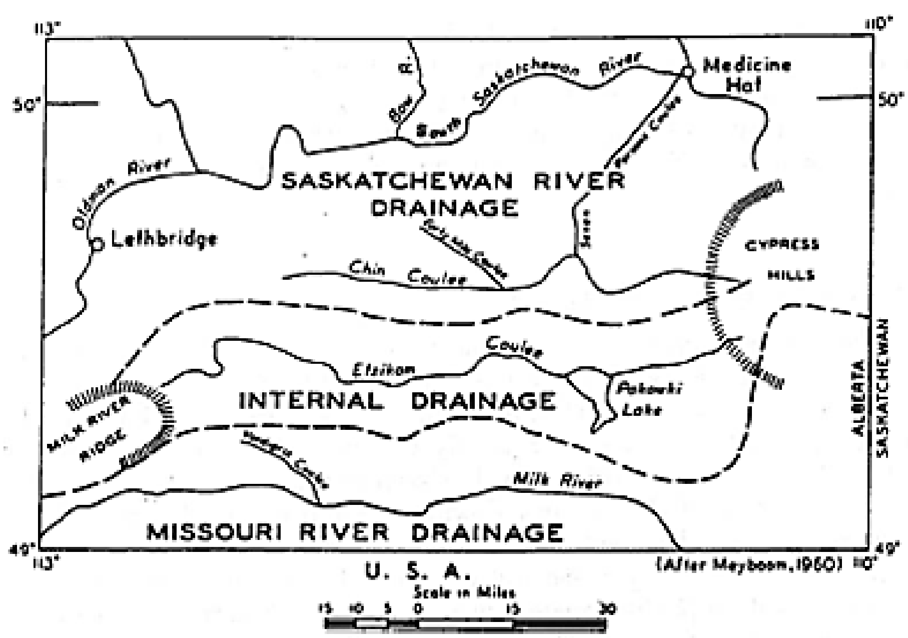


Figure 10: Drainage systems in southern Alberta (From Meyboom, 1960).

3. Stratigraphy and geology

3.1 Stratigraphic correlation of the Milk River and associated strata

The transboundary nature of the study area and focus of respective geological mapping agencies to focus on their respective provincial, state and national mandates 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 twentieth century (Table 1). The stratigraphic charts not only differ between southern Alberta and northern Montana but also within northern Montana (east and west of the Sweet Grass arch). In 1917, Stebinger (1917) described the differences between the geologic sections east and west of the 112th meridian in Montana.

The Milk River Formation of southern Alberta was first identified by Dowling (1915, 1917) as the “Milk River Sandstone” in his study of the Southern Plains of Alberta. Other authors divided The Milk River Sandstone in two parts (lower and upper) bearing successive terminologies (Evans, 1931; Russell and Landes, 1940). A three-part subdivision of the Milk River Formation was introduced by Tovell (1956), with the Transition beds, Virgelle and Deadhorse Coulee (Tovell, 1956, cited by Meijer Drees and Mhyr, 1981). In Montana, the upper and lower parts of the Milk River Sandstone were referred to as Upper Eagle and Virgelle by Williams and Dyer (1930). Meyboom (1960) also equated the lower part of the Milk River Formation to the Virgelle member of Eagle sandstone in Montana.

In Montana, Stanton et al. (1905) first described the stratigraphy of Upper Cretaceous rocks in northern and central Montana and adjacent areas in Canada. They defined the Eagle Formation (named by Weed 1899 from Eagle Creek) as massive white sandstone overlain by softer beds consisting of alternating sandstones, shale, and many beds and seams of lignite. They also noticed that small black pebbles occurred at the top. Rice (1980) divided the Eagle formation in three members: the basal Virgelle member, and the unnamed middle and upper member.

Stanton et al. (1905) studied the overlying strata and found that the Belly River beds in Alberta were identical to the Judith River beds in Montana.They also correlated the Pakowki shales in Alberta with the Claggett Formation in Montana. Payenberg et al., (2002) confirmed that Claggett and Pakowki are of the same age.

In the northeastern part of the study area, the stratigraphic equivalent of the Pakowki Formation is the Lea Park Formation (Williams and Dyer, 1930).

Meijer-Drees and Mhyr (1981) proposed a stratigraphic nomenclature for southeastern Alberta that defined the Milk River Formation as the stratigraphic equivalent of the Telegraph Creek Formation and Eagle Sandstone defined by Rice and Cobban (1977). They also defined the Deadhorse Coulee Member in Southeastern Alberta as occupying the same interval as the upper and middle members of Eagle Sandstone.

In the Sweet Grass Hills area, Tuck (1993) named the interval between Virgelle and Claggett the “upper part” of Eagle sandstone. This upper part consisted in inter-bedded shale, siltstone sandstone and coal, which is very similar with the Deadhorse Coulee Member.

Until recently, a clear regional correlation of the Milk River Formation and the Eagle Formation was not possible, due to differences in lithology and time-range (Russell, 1970). Another reason is the limited and remote exposure of the Eagle Formation within northern Montana (Payenberg et al., 2003). Russell (1970) revealed misunderstandings relative to previous correlation works.

Thirty years after Russell’s (1970) attempt for a correlation between the Milk River and Eagle formation, Payenberg et al. (2002) reevaluated the lithostratigraphic and chronostratigraphic relationships of Alberta and Montana Upper Cretaceous rocks. He used recent advances in geochronology, magneto-stratigraphy and paleontological data. Payenberg’s work provided a clearer litho- and chrono-stratigraphic framework of the study area; he identified that the Telegraph Creek, Virgelle and Deadhorse Coulee members were continuous and correlative across the international border (Payenberg 2002). He also introduced the Alderson Member of the Lea Park Formation to the southern Alberta nomenclature (Table 1).

The proposed nomenclature in the present study (Table 2) is based on the previous works of Payenberg et al. (2002) and Rice and Cobban (1977). The study area is divided in four zones, each with a distinct succession of geological units. The location of the four zones are shown on Figure 13a and defined by the geological disconformity surface, which separates the Milk River Formation in zone 1 from the Alderson Member in zone 2:

Zone 1: South-western part of the study area in Alberta, before the facies change

Zone 2: South-eastern Alberta, beyond the facies change.

Zone 3: North-western Montana, west of the Sweet Grass Arch;

Zone 4: Northern Montana, east of the Sweet Grass Arch.

Rice and Cobban (1977)

Period	Stage	GLACIER NATIONAL PARK AREA	CENTRAL MONTANA
UPPER CRETACEOUS	CAMPANIAN	BEARPAW	BEARPAW
		TWO MEDICINE FORMATION	JUDITH RIVER
			CLAGGETT
			EAGLE: Upper Member
			EAGLE: Middle Member
	SANTONIAN	Virgelle Sandstone	EAGLE: Virgelle Sandstone
		Telegraph Creek	Telegraph Creek
		Marias River Shale	NIOBRARA

Meijer-Drees and Mhyr (1981)

SOUTH-EASTERN ALBERTA	
BEARPAW	
JUDITH RIVER	
PAKOWKI	Lea
MILK RIVER: Deadhorse Coulee	Park
MILK RIVER: Virgelle	Alderson Member
MILK RIVER: Telegraph Creek	
Colorado	Lloyd-minster

Payenberg et al. (2002)

Period	Stage	SOUTH-CENTRAL ALBERTA	SOUTH-EASTERN ALBERTA	NORTH-CENTRAL MONTANA
UPPER CRETACEOUS	CAMPANIAN	PAKOWKI FORMATION		CLAGGETT FORMATION
	83,5 Ma	MILK RIVER FORMATION: Hiatus	Alderson Member	EAGLE FORMATION: Upper Eagle Member
	SANTONIAN	Deadhorse Coulee Member	Lea Park FM.	Deadhorse Coulee Member
		Virgelle Member		Virgelle Member
	84,5 Ma	Telegraph Creek Mb.		TELEGRAPH CREEK FORMATION

Table 1: Comparative stratigraphic nomenclatures modified from Rice and Cobban (1977); Meijer-Drees and Mhyr (1981) and Payenberg et al. (2002.) (Pétré et al., 2015).

<table>
<tr><th></th><th>Zone 1</th><th colspan="2">Zone 2</th><th>Zone 3</th><th>Zone 4</th></tr>
<tr><th></th><th>South-Eastern AB (southwest of the Virgelle depositional limit)</th><th colspan="2">South-Eastern AB (northeast of the Virgelle depositional limit)</th><th>North-Western MT (west of SG. arch)</th><th>Northern MT (East of SG Arch)</th></tr>
<tr><td></td><td>Bearpaw</td><td colspan="2">Bearpaw</td><td>Bearpaw</td><td>Bearpaw</td></tr>
<tr><td></td><td>Belly River</td><td colspan="2">Belly River</td><td rowspan="3">Two Medicine Formation</td><td>Judith River</td></tr>
<tr><td></td><td>Pakowki</td><td colspan="2">Pakowki</td><td>Claggett</td></tr>
<tr><td rowspan="3">Milk River Formation</td><td>DHC</td><td rowspan="3">Lea Park</td><td rowspan="3">Alderson Member</td><td>DHC</td></tr>
<tr><td>Virgelle</td><td>Virgelle</td><td>Virgelle</td></tr>
<tr><td>Telegraph Creek</td><td>Telegraph Creek</td><td>Telegraph Creek</td></tr>
<tr><td></td><td>Colorado</td><td colspan="2">Colorado</td><td>Colorado</td><td>Colorado</td></tr>
</table>

Table 2: Nomenclature used in the present study (from Pétré et al., 2015).

3.2 Geology and hydrostratigraphy

The geology of the study area can be described as a succession of shallow marine and continental sediments deposited as the extent of Upper Cretaceous Interior Sea fluctuated (Russell, 1970). Tertiary deposits have been removed by erosion across the region except at the Cypress Hills.

The area is almost entirely covered by glacial and pre-glacial deposits < 50 m thick (Fig. 11); however, the thickness can be up to 149 m (Atkinson and Lyster, 2010b). The thickest surficial sediments are where bedrock valleys have been infilled and buried in Municipal District (M.D.) of Taber (Hydrogeological Consultant, HCL, 2007). The surficial geology map in southern Alberta is shown in Figure 12.

The Upper Cretaceous strata are described below (Figure 13). The hydrostratigraphic role are briefly described in the present section (Fig. 14).

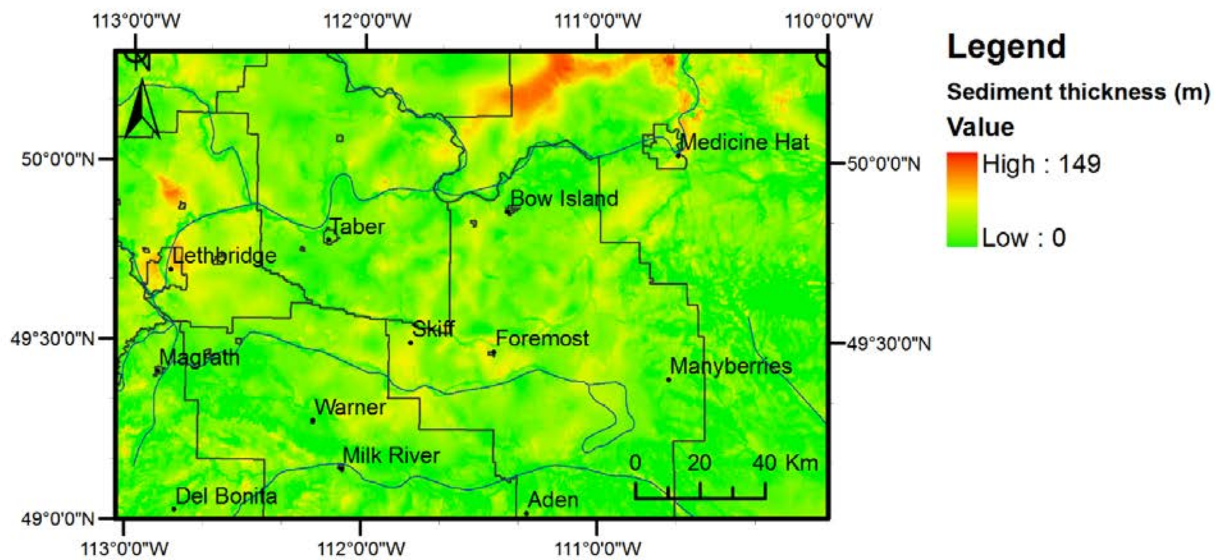


Figure 11: Sediment thicknesses in southern Alberta (from Atkinson and Lyster, 2010b).

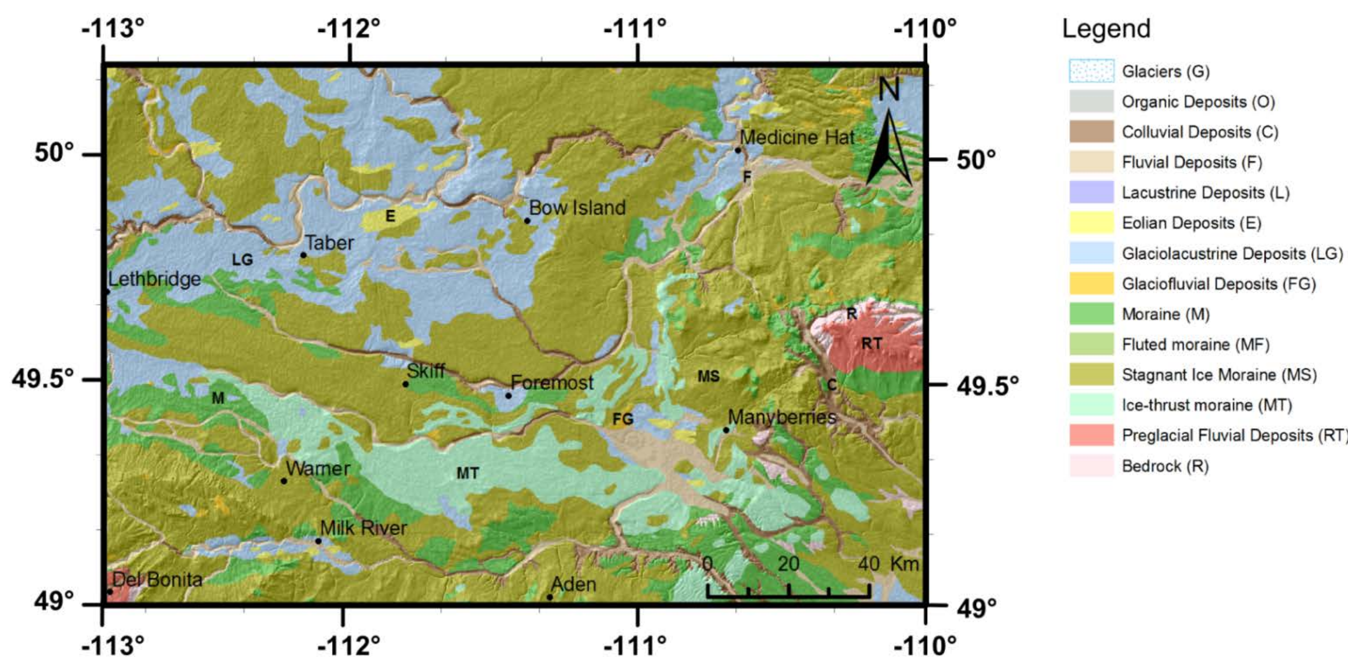


Figure 12: Surficial geology in southern Alberta (from Fenton et al., 2013).

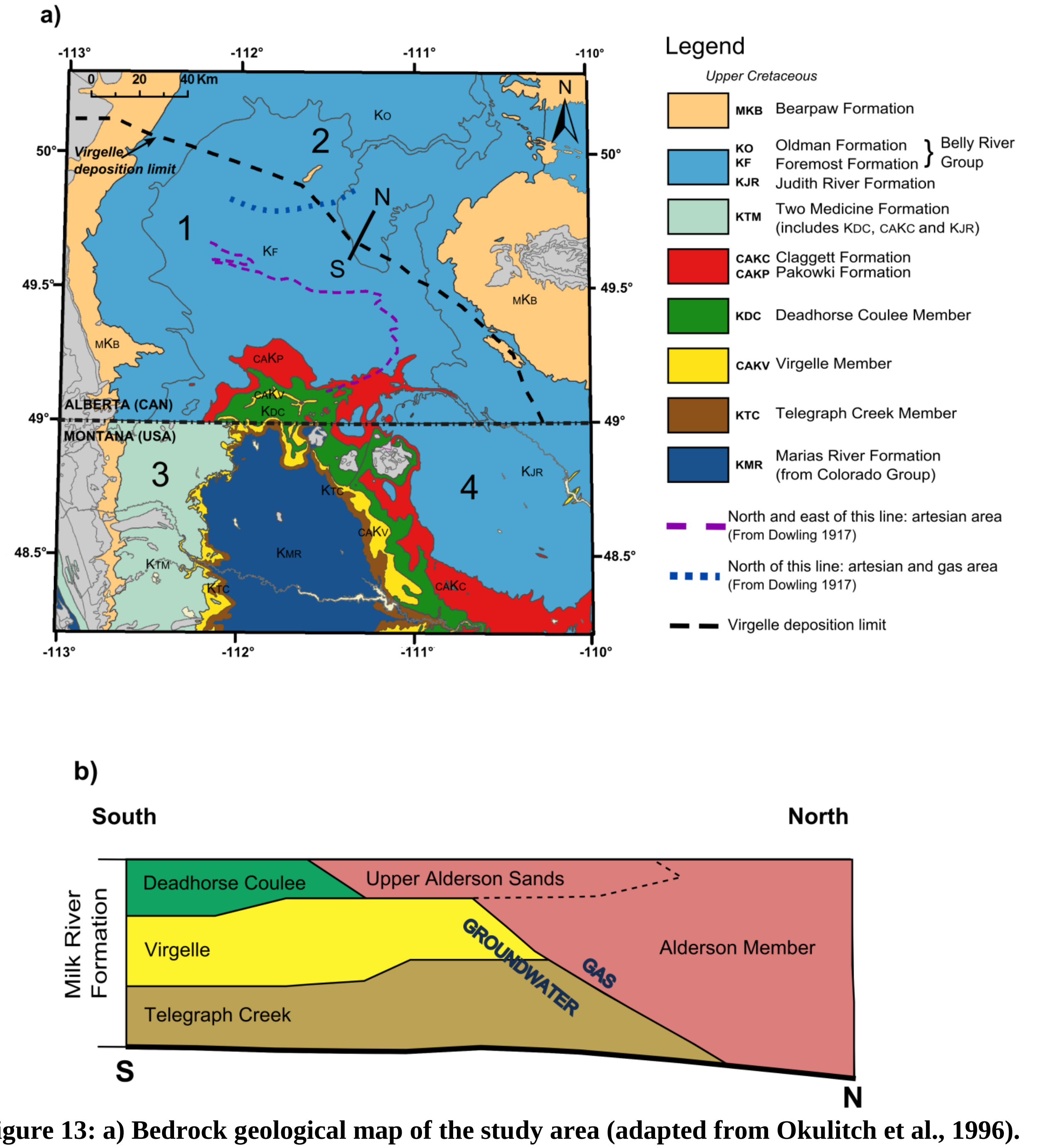


Figure 13: a) Bedrock geological map of the study area (adapted from Okulitch et al., 1996). b) Cross-section (indicated by "S-N" in Fig. 13a) showing the unconformity surface separating the Alderson Member from the three other members of the Milk River Formation. The encasing units are not represented on this cross section (modified from O'Connell 2014; Pétré et al., 2015).

Period	STRATIGRAPHY		HYDROSTRATIGRAPHY
UPPER CRETACEOUS	BEARPAW		BEARPAW AQUITARD
	BELLY RIVER	OLDMAN	BELLY RIVER AQUIFER
		FOREMOST	
	PAKOWKI		PAKOWKI AQUITARD
	MILK RIVER FORMATION		MILK RIVER AQUIFER
	COLORADO SHALE		COLORADO AQUITARD

Figure 14: Stratigraphy and hydrostratigraphy of the main geological units of the study area (Pétré et al., 2015).

Colorado Group

The Colorado Group (middle Albian to Santonian) underlies the whole study area. The Colorado Group consists mainly of dark grey to black bentonitic marine shale. It 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 over 5 counties in northern Montana, from the Sweet Grass Hills to Great Falls (Stebinger, 1917). It was deposited during marine conditions in deep sea environment.

It constitutes a regional aquitard in the study area (Fig. 14). The hydraulic conductivity of the Colorado Group ranges from 10^{-10} to 10^{-14} m/s (Hendry and Schwartz, 1988). However, the Colorado Group contains four thin sandstone units totaling less than 45 m in thickness. The Bow Island sandstone (25 m thick) is the most significant sandstone unit of the Colorado Group and is located about 400 m below the contact with the Milk River Sandstone (Phillips et al., 1986).

Milk River/Eagle Formation

The Milk River Formation (called Eagle Sandstone in Montana) is a regressive clastic wedge deposited during the Upper Cretaceous (Rice, 1980; Payenberg et al., 2001). The Milk River Formation 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 an area of 14 townships in southern Alberta near the border, in circular rings around the Sweet Grass Hills and also following two "branches" on both sides of the Sweet Grass Arch.

According to Russell (1970): "There is little difference between the western and eastern developments." The Milk River Formation dips gently to the north, east and west, from the subcrop areas following a radial or "fan-like" pattern (Meyboom 1960; Schwartz and Muehlenbachs 1979; Toth and Corbet 1987; O'Connell 2014; Fig.15). The Milk River Formation is confined above and below by the low-permeability shales of the Colorado and Pakowki/Claggett Formation.

The Milk River Aquifer is within the Milk River Formation. 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. About 200 flowing artesian wells were inventoried in the 1960s in southern Alberta (Meyboom, 1960). In Montana, flowing artesian water occurs in much of the area of Cut Bank due to the westward dip of the Formation (Zimmerman 1967). Tuck (1993) also highlighted some flowing artesian wells in the Sweet Grass Hills area. However, many wells have lost their flowing artesian characteristics because of the intensive use of this resource. Nowadays, the flowing artesian areas are located in the vicinity of Pakowki Lake and north of the study area, which is still consistent with the flowing artesian limit drawn by Dowling (1917) (Fig. 13a).

Meyboom (1960) showed that the recharge areas of the aquifer were located mainly in the concentric outcrops around the Sweet Grass Hills and, in a lesser extent, at the subcrop area near the international border. The main discharge areas are located at the pumping or flowing wells of the study area, the amount of natural discharge being small (Meyboom 1960).

Groundwater flow in the Milk River Aquifer follows the regional dip of the Milk River/Eagle Formation. In Alberta the general flow is semi-radial from the topographic highs of the Sweet Grass Hills to the north, west and east (Hendry and Schwartz, 1990). In Montana, groundwater flows from the Sweet Grass Hills to the east and south-east. There is also groundwater flow from the subcrop areas west of the Sweet Grass arch to the west and south (Zimmerman 1967; Levings 1982). Thus, two transboundary flow paths are identified in the study area: 1) from the Sweet Grass Hills to the north, and 2) from the north of Cut Bank area to the north as well (Zimmerman 1967; Tuck 1993).

In southern Alberta, there is a disconformity surface towards the north, northeast and east separating the Milk River Formation to its sandy shale equivalent, the Alderson Member of the Lea Park Formation (Fig. 13b). 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 (Payenberg et al., 2003; O'Connell, 2014). The Alderson Member is gas-bearing; it contains the Milk River gas field (or Medicine Hat gas field, Fig. 16). Therefore it represents a natural limit of the Milk River Aquifer. There is another limit imposed by a gas field in Montana as the Eagle Sandstone hosts the Tiger Ridge gas field in the Bearpaw Mountains area (Fig. 16) (Gautier and Rice, 1982).

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. The Telegraph Creek Member consists of sandy shale, siltstone and fine-grained shaly sandstone. Cobban (1950) gave a name and a formational status to this transition zone in north-central Montana. The Telegraph Creek Formation 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). The Telegraph Creek Member of southern Alberta has formational status in Montana (Payenberg et al., 2001). This transition zone was first included in the Virgelle Sandstone in north-central and northwestern Montana by Stebinger (1914, 1916). It is interpreted as deposits of an offshore to shore-face transition (Payenberg, 2002), having a lower permeability than the Virgelle formation but higher than the Colorado Shale..

Virgelle Member

The Virgelle Member overlies the Telegraph Creek Member with a gradational contact (Meijer Drees and Mhyr, 1981). It consists in gray 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 Sweet Grass 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 in Township 1 and 2, Ranges 12 to 15 (Meyboom, 1960). It also outcrops on both sides of the Sweet Grass arch, in a continuous and narrow belt (Fig. 13 a). The Virgelle Member was deposited during a regression sequence and is interpreted as a shore-face to foreshore sandstone (Rice, 1980).

This massive sandstone unit is the most important aquifer portion of the Milk River Formation and therefore constitutes the Milk River Aquifer. The hydraulic conductivity of Virgelle member is 1.81 x 10^{-7} m/s (Robertson, 1988). The limits of the Milk River Aquifer are shown on Figure 16. They correspond to the area in which Virgelle exists and is exploited. However the Virgelle Member still exists farther west, until the longitude -113° but is too deep (depth > 400m) to be exploited (Stantec, 2002).

Deadhorse Coulee Member

The Deadhorse Coulee Member represents the upper part of the Milk River Formation, named by Tovell (1956). This well-defined unit consists predominantly of shale, siltstone and sandstone with coal seams (Payenberg, 2002). The Deadhorse Coulee has a maximum thickness of 60 m in southern Alberta and thins northeastwards to approximately 10 m east of the zero edge. The zero edge extends northwards from T1 R5 W4 to T13 R22 W4 (O'Connell, 2014). In northern Montana, the Deadhorse Coulee equivalent is the unnamed middle member of Eagle Formation (Payenberg et al., 2001). The contact between Deadhorse Coulee and the overlying Pakowki /Claggett Formation is marked by a thin - but laterally continuous- bed of dark grey to black polished chert pebbles, which is interpreted as a transgressive lag (Russell, 1970). It is a non-marine unit deposited in the coastal plain environments landward of the Virgelle shore faces (O'Connell, 2014).

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 2014). The sand content increases in the upper part (Meijer-Drees and Mhyr, 1981). O'Connell (2014) includes the Alderson Member in the Milk River Formation, as its youngest member, which 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) The Alderson Member is younger than the Telegraph Creek, Virgelle and Deadhorse Coulee member of the Milk River Formation and is separated from them by a large time-gap (O'Connell, 2014; Payenberg et al., 2003). This entirely marine stratum has been deposited in proximal to distal offshore marine environments (O'Connell, 2014).

The Alderson Member hosts the Medicine Hat gas field and is therefore a natural boundary of the aquifer in the geological model developed in the present study. However, the upper part of the Alderson Member contains two distinct large sand bodies which form a regional aquifer in southern Alberta. This unit is named the Upper Alderson Sands by O'Connell (2014). It covers an area of 74 townships and has a NW-SE trend. The Upper Alderson Sands forms small lobate sand bodies. 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 Milk River Formation is overlain by a thick unit of marine shales, the Pakowki Formation (Claggett shale equivalent in Montana). The Pakowki and Claggett Formations consist of thinly bedded, black marine shales, with few sandstone beds (Tovell, 1956 cited by Payenberg et al., 2003). A thin horizon of chert pebble 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). The formation was deposited during the first transgression episode of the Montana time; however, the marine incursion did not reach the western part of the Sweet Grass arch (Stebinger, 1917). Therefore, the tongue of marine shale progressively thins to zero westwards. Where the Claggett/Pakowki formation pinches out, the Milk River Formation is directly overlain by the Judith/Belly River Formation. The Pakowki/ Claggett Formation does not constitute an aquifer (Fig. 14); 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 10^{-11} m/s (Anna, 2011).

Two Medicine Formation

The non-marine Two Medicine Formation of Upper Cretaceous age outcrops in northwestern Montana. This unit consists of mudstones and sandstones and is about 600 m thick (Lorenz, 1981). West of the Sweet Grass Arch, the Two Medicine Formation includes the equivalent upper part of Eagle Formation (i.e. Deadhorse Coulee Member), the Claggett Shale (which is not easily recognizable) and the Judith River Formation (Stebinger, 1914; Pierce and Hunt, 1937; Zimmerman, 1967). The Two Medicine Formation 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 (or equivalent Judith River Formation in Montana) outcrops in a large part of the study area (Fig. 5a). It represents the sequence of continental beds above the Pakowki Formation and below the Bearpaw Formation. The Belly River includes the Dinosaur Park Formation (upper part), the Oldman Formation (middle part) and Foremost Formation (lower part) (Eberth and Hamblin, 1993; Hamblin, 1997). However, the upper part is only present in a limited portion of the study area, about 12 townships in Southern Alberta in the Cypress County, near the Saskatchewan border (Hamblin, 1997).

The dark shale, sandstone and coal seams of the Foremost are overlain by massive yellow and grey sandstone of the Oldman and thick sandstones and siltstones of the Dinosaur Park Formation. The Belly River Group/Judith River Formation is 320 m thick at Lethbridge, and is less than 182 m in northern Montana (Williams and Dyer, 1930; Pierce and Hunt, 1937). The Belly River Group/Judith River Formation constitutes an aquifer and the hydraulic conductivity of the Judith River Aquifer in northern Montana ranges from 9×10^{-8} m/s to 8.8×10^{-7} m/s (Anna, 2011).

Bearpaw Formation

The Bearpaw Formation overlies the Belly/Judith River Formation (or the Two Medicine Formation, west of the Sweet Grass Arch) and is made up of dark gray shale (Russell, 1970). The Bearpaw Formation 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 south-eastern Alberta

This marine strata was deposited during the second transgression episode of the Montana time, it is therefore lithologically similar to the Pakowki Formation. It is a a regional aquitard (Tokarsky, 1974).

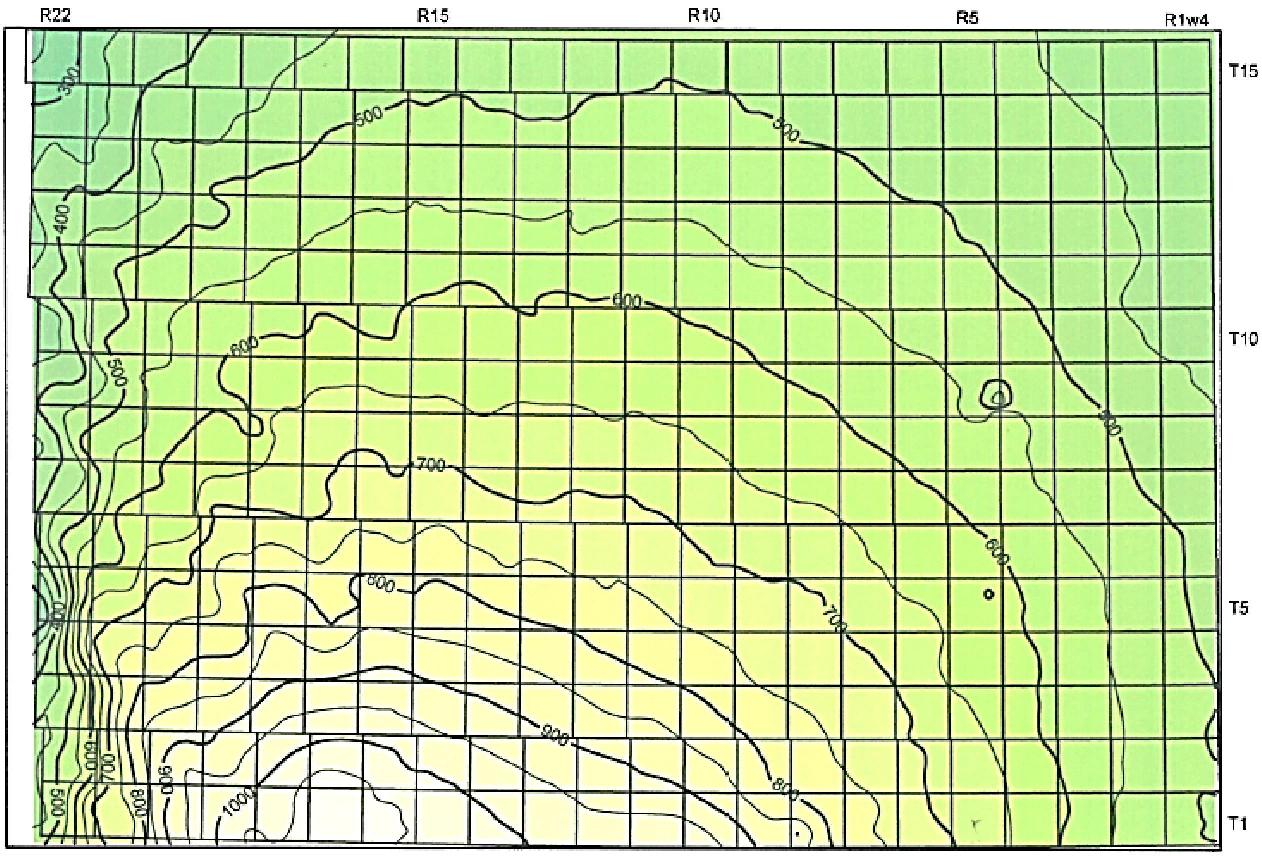


Figure 15: Structure at the top of the Milk River Formation. Elevation in meters (O'Connell, 2014).

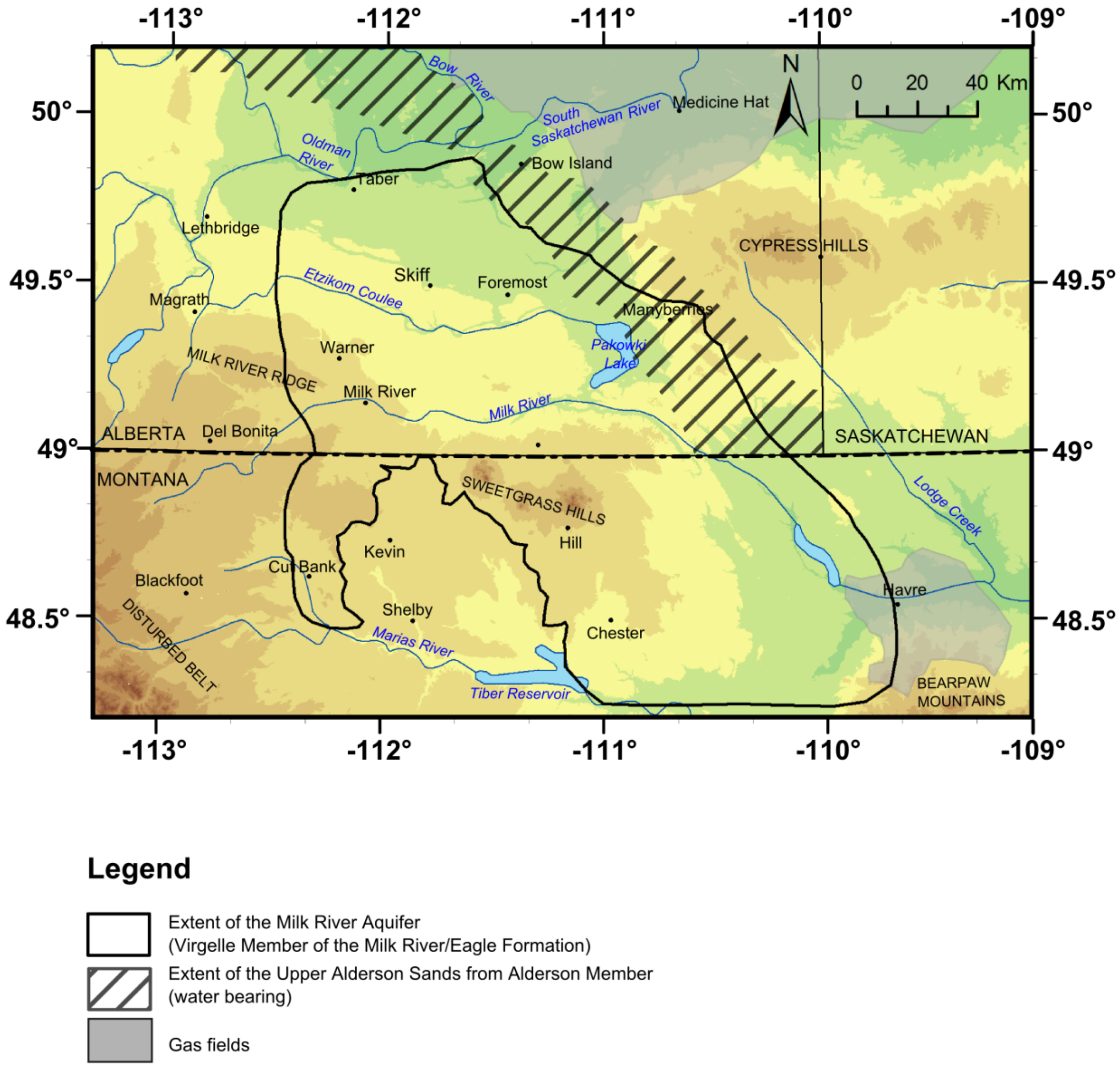


Figure 16: Extents of the Milk River Aquifer and Upper Alderson Sands. The shaded shapes represent the extent of gas fields. The extent of the Upper Alderson Sands is from O'Connell (2014).

3.3 Extent of the Milk River aquifer

A transboundary delineation of the Milk River transboundary aquifer has been proposed, (Figure 16). The Milk River transboundary aquifer covers about 22,000 km^2 in the study area. This delineation corresponds to the extent of the Virgelle Member which is the most permeable part of the Milk River Formation. Since Alderson Member is included in the Milk River Formation (O'Connell 2014, Payenberg et al., 2003) and its upper part (Upper Alderson Sand) is water-bearing, it has been included in the delineation of the Milk River Aquifer in Southern Alberta by Printz (2004). However, Printz (2004) did not mention the presence of the Alderson Member and the geological change in the Milk River Formation With no recognition of the geological changes (i.e., facies).

O'Connell (2014) considered that the Milk River Aquifer consists of two regional sand units within the Milk River Formation: the Virgelle Sand and the Upper Alderson Sands. However, Alderson Member is much younger than the three other members of the Milk River Formation (Payenberg et al., 2002). Unlike the Virgelle Member which is continuous across the international border, the Alderson member is not present in Montana where it does have a chronostratigraphic equivalent, but it is located south of the study area (Payenberg et al., 2003).

These differences lead us to consider the Alderson Member as distinct from the Milk River Formation. Thus, in the present study the Milk River transboundary aquifer is constituted of the transboundary Virgelle Member only. The limits of the Milk River Aquifer are defined by the gas field hosted by the Alderson member, north, north-east and east of the study area in Alberta. Another gas field located near the city of Havre (near the Bearpaw Mountains in Montana) represents the south-eastern boundary of the aquifer. The Milk River Formation is separated from the Alderson Member by a discontinuity surface. In northern Montana, the Eagle Formation hosts the Bearpaw gas field in Montana. The Marias River constitutes the southern limit of the Aquifer. Although the Milk River /Eagle Formation extends farther south in Montana, this physiographic limit has been 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 around the longitude -113°; however, no water wells are completed in this unit because of the depth to the aquifer (>400 m; Stantec, 2002).

3.4 3D unified geological model

The 3D geological model of the aquifer is a crucial component of the unified conceptual model of the Milk River Aquifer (Fig. 3). Before moving to the hydrogeological part of the study, it is essential to have a sound understanding of the stratigraphic framework of the aquifer and the geometry of the geological units in the study area.

Based on the correlations described in part 3.1, a three-dimensional geological model of the Milk River Transboundary Aquifer was developed (Fig. 17). It integrates geological data from both sides of the Canada/US border (Feltis et al., 1981; O'Connell, 2014; Atkinson and Lyster, 2010a; Montana Geological Society, 2013). In addition about 15 cross sections from previous hydrogeological studies in southern Alberta (Borneuf, 1974; Tokarsky, 1974) were georeferenced as shown on Figure 18.

This allowed the unification of the stratigraphic framework across the Canada/US border through data processing and adopted hypotheses. The unified 3D geological model represents the 3 members of the Milk River Formation (especially the middle Virgelle Member-Milk River Aquifer) continuously through the Canada/US border. The facies-change transition separating the gas-bearing Alderson Member from the three members of the Milk River Formation in southern Alberta is also represented in the model. The model was developed using the three dimensional interpolation and visualization software Leapfrog Hydro®. This recent software has been chosen mostly for its interoperability with FEFLOW® (Diersch 2014).

The methodology applied in the building of the 3D geological model, as well as the resulting unified geological model, are described in more detail in Pétré et al. (2015).

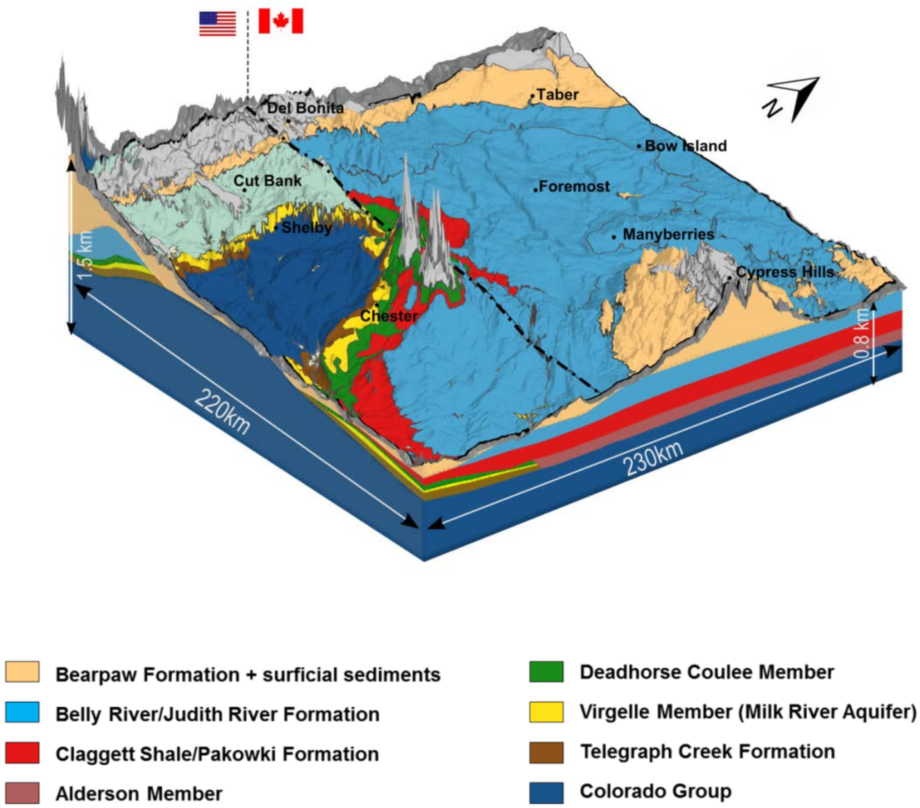


Figure 17: 3D unified geological model of the Milk River Transboundary Aquifer (Pétré et al., 2015).

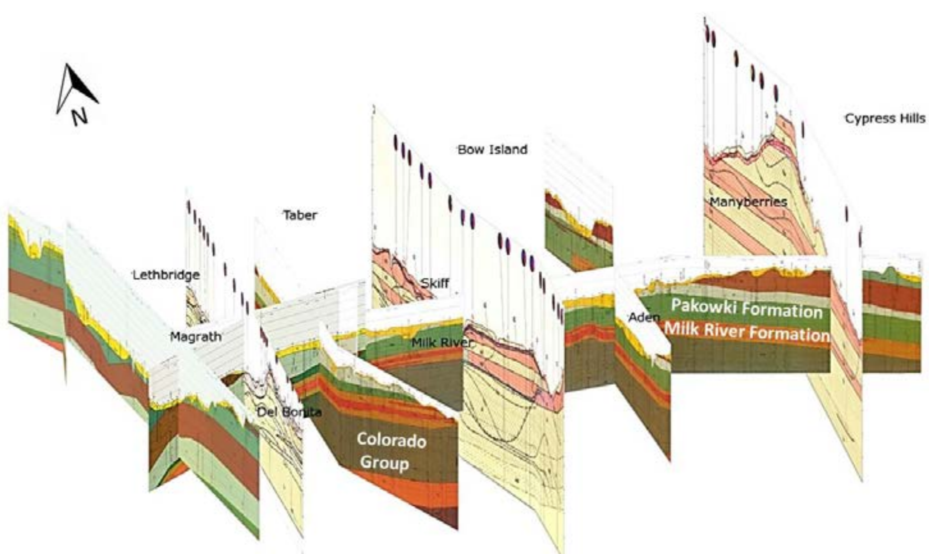


Figure 18: Fence diagram of the Milk River Formation and others units in southern Alberta (cross-sections from Borneuf, 1974 and Tokarsky, 1974).

4. Hydrogeology

4.1 Piezometric surface and direction of groundwater movement

Meyboom (1960) mapped the piezometric surface of the Milk River Sandstone (i.e. Virgelle Member) in southern Alberta, based on water levels measured during 1958 and 1959 (Fig. 19).

According to Meyboom (1960), the recharge of the aquifer occurs at the circular outcrops around the Sweet Grass Hills; the outcrop area near the border would provide only a limited source of recharge. He mentioned that prior to pumping; the overall gradient was to the north, east and west. The development of the aquifer caused a steepening of the gradient to the north and the reversal of the gradients to the east and west. The water moves from all directions to cones of depression caused by heavy pumping.

Meyboom (1960) indicated that the areas of discharge were at the town of Foremost, the Pakowki Lake area and the Chin, Etzikom, Seven Pearson and Forty Mile Coulees. These are all artificial discharge areas, caused by pumping or flowing wells. The amount of natural discharge of the Milk River Aquifer is small and is constituted by springs and seeps along the southern bank of the Milk River (ranges 12 to 15, townships 1 and 2) (Meyboom, 1960).

Toth and Corbet (1987) reinterpreted Meyboom's data. The potentiometric surface they mapped (Fig. 20) mimics the topography. They concluded that water enters and leaves the Milk River Formation through overlying and underlying shale beds. They also suggested that recharge not only occurs at the Sweet Grass Hills but also include the Cypress Hills, the west Milk River Ridge, the Lucky Strike Upland and the Etzikom Coulee. They hypothesized that the Lethbridge, Medicine Hat and Skiff valleys constituted the discharge areas. However, in building this 3D geological model, we found that the Milk River Aquifer does not outcrop in these areas and is overlain by 100 to 500 m of sandstone (Belly River aquifer) and shale (Pakowki aquitard) formations.

AGRA (1998) proposed a piezometric map of the Milk River Aquifer in southern Alberta for the period of 1985-1998 (Fig. 21).

In Montana, Levings (1982) draw a regional piezometric map of water in the Eagle sandstone (Fig. 22). This map shows that the groundwater flows from the Sweet Grass Hills to the north, but also to the south, south-east and east. There is a groundwater divide between West Butte and middle Butte; and between middle Butte and East Butte. The Bearpaw Mountains constitute a recharge area. The groundwater flow is northwards to the Milk River and southwards to the Missouri River. In northwestern Montana, the groundwater flow is from East to west. North of the Bearpaw 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.

In the Sweet Grass Hills area, Tuck (1993) provided a piezometric surface map of the water in the Virgelle sandstone (Fig. 22). Water in Virgelle Sandstone is unconfined in and near the outcrop areas. (Tuck 1993). The groundwater generally flows from the recharge areas on the flank of the Sweet Grass Hills downdip in northerly directions to discharge areas (Tuck 1993). The recharge to the Virgelle sandstone Member is through infiltration of precipitation on outcrops and in some sub-cropping areas, infiltration of streamflow across outcrops, and possible subsurface inflow from others geologic units. (Tuck 1993).The discharge from the Virgelle sandstone is through withdrawals from wells, flow of springs and seeps, and subsurface outflow to other geologic units. (Tuck 1993). Tuck provided an estimated hydrologic budget of the Virgelle sandstone Member in the Sweet Grass Hills area, values of the budget components are given in Table 3.

In the Cut Bank area, Zimmerman (1967) studied the groundwater movement of the Virgelle sandstone (Fig. 23). He mentioned that the infiltration of precipitation along the outcrop and inter-formational leakage constituted the major means of groundwater recharge in this area. The groundwater in Virgelle moves southwest and north from a groundwater divide in Township 36, Range 4 and 5 West. In the Cut Bank area, the discharge area of Virgelle is located along the Cut Bank Creek south of Cut Bank and north toward outcrops of the Milk River Sandstone near the confluence of Red River with the Milk River in Alberta (Zimmerman, 1967; Meyboom, 1960).

Zimmerman (1967) noticed springs along the Virgelle escarpment, especially where coulees cut back into the Virgelle member. Natural discharge also occurs at many seeps flowing less than 1gpm (0.06 l/s) each and “alkali” patches caused by evaporation of slowly discharging waters along Cut Bank Creek (Zimmerman 1967). The artificial discharge of the aquifer is caused by hundreds of wells in the Cut Bank area (Zimmerman, 1967).

The study of the Piezometric maps reveals that there are two transboundary flow directions from northern Montana toward 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.

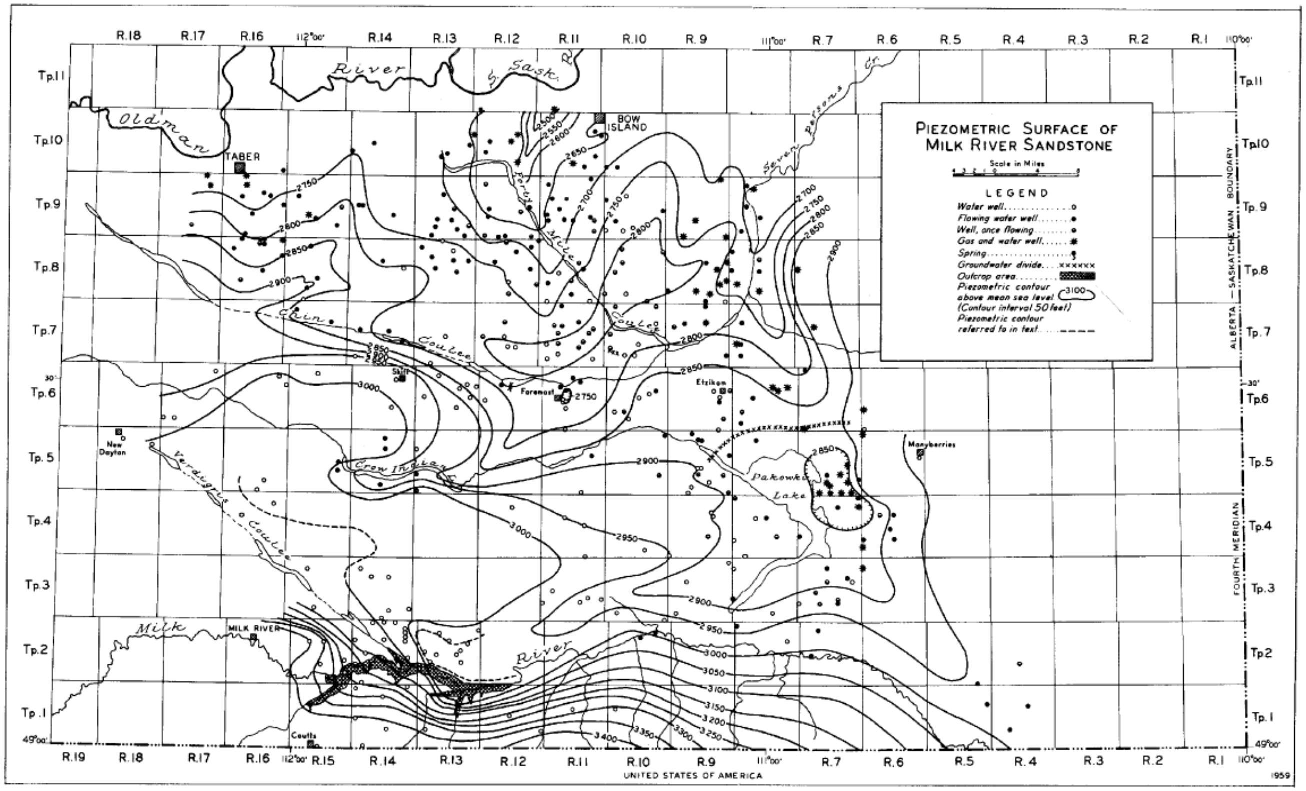


Figure 19: Piezometric map of the Milk River Sandstone (Virgelle Member) in feet (Meyboom, 1960).

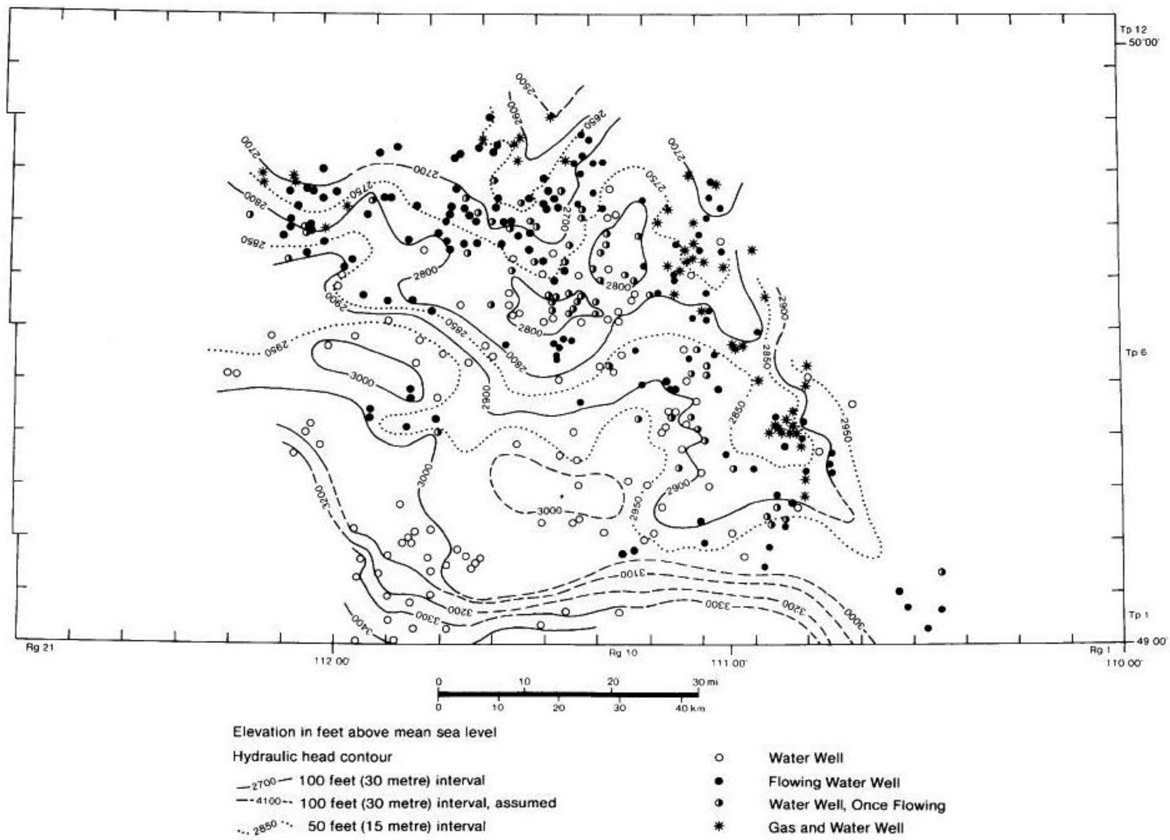


Figure 20. Piezometric map (Toth and Corbet, 1987).

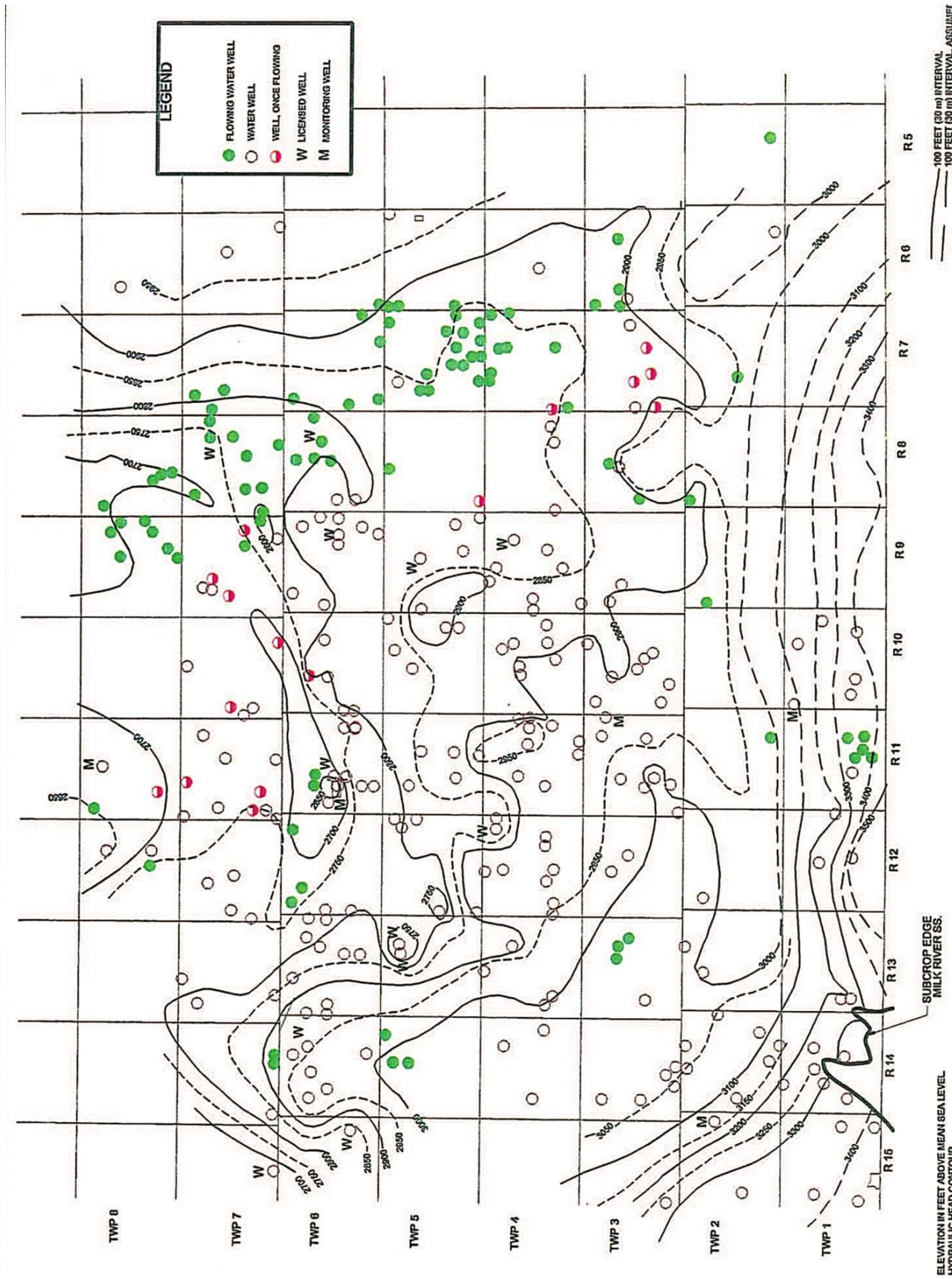


Figure 21 Piezometric surface of Milk River aquifer 1985-1998 (AGRA, 1998).

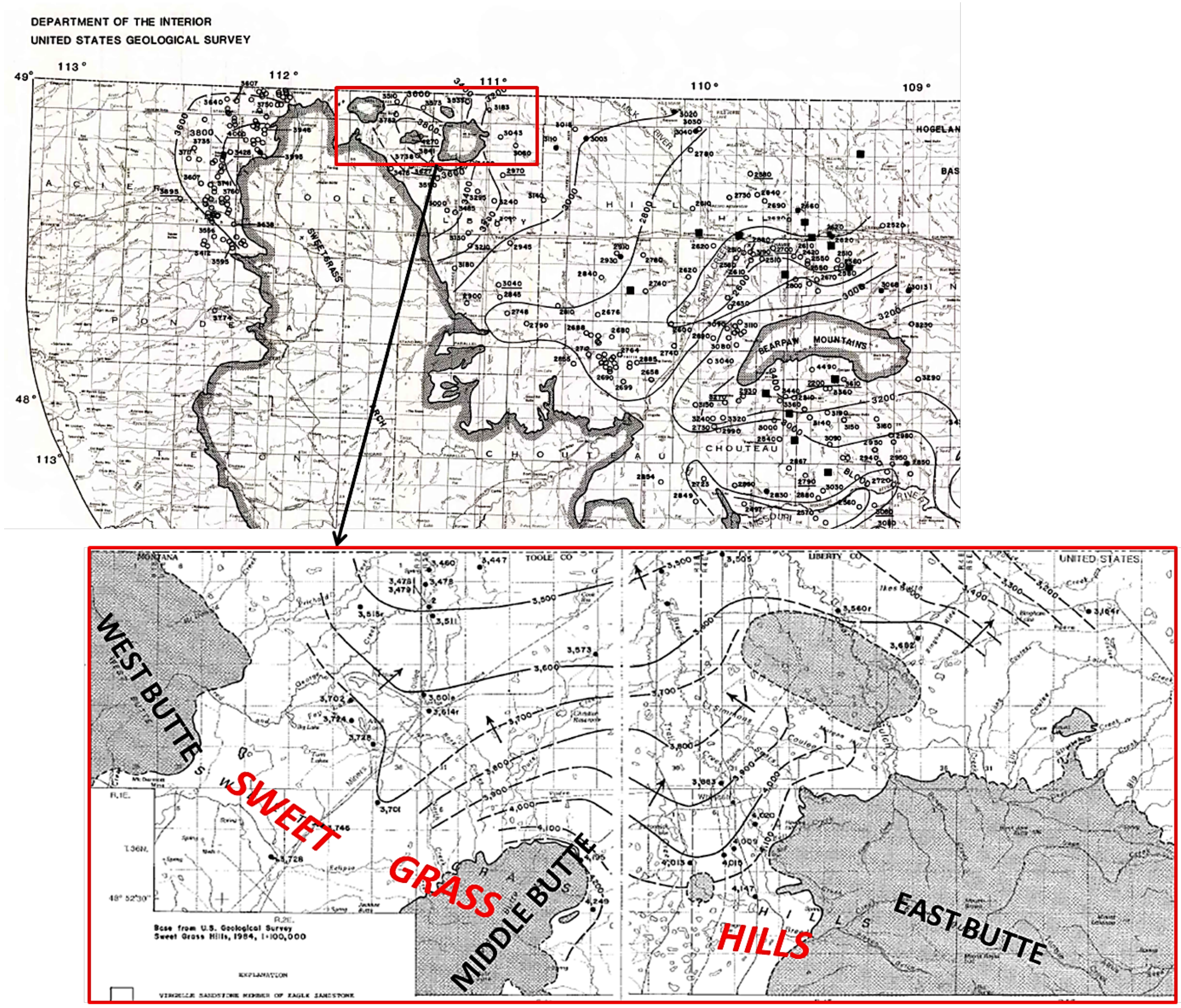


Figure 22: Piezometric maps of Eagle sandstone (Levings, 1982) (top) and Virgelle Sandstone Member of Eagle Sandstone (modified from Tuck, 1993) (bottom).

Budget component	Acre-ft /y	m^3 /y
Recharge		
Infiltration of precipitation on outcrops (est.)	1,610	1.99 10^6
Infiltration of precipitation in subcrops areas (est.)	18-2,530	2.22 10^4 - 3.12 10^6
Infiltration of streamflow across outcrops (est.)	1,650	2.03 10^6
Subsurface inflow from other geologic units	?	?
Total additions (rounded)	3,280- 5,790	4.05 10^6- 7.14 10^6
Discharge		
Withdrawals from wells:		
For the secondary recovery of oil	76	9.37 10^4
For domestic use (est.)	2.6	3.31 10^3
For livestock watering (est.)	7.8	9.62 10^3
From continuous flowing wells (est.)	23	2.84 10^4
Springs and seeps	48	5.92 10^4
Subsurface outflow to other geologic units	?	?
Flow across study-area boundary	4,490	5.54 10^6
Total subtractions (rounded)	4,650	5.74 10^6

Table 3: Estimated hydrologic budgets for the Virgelle sandstone member of Eagle Sandstone, 1989-90, in the Sweet Grass Hills Area (modified from Tuck, 1993).

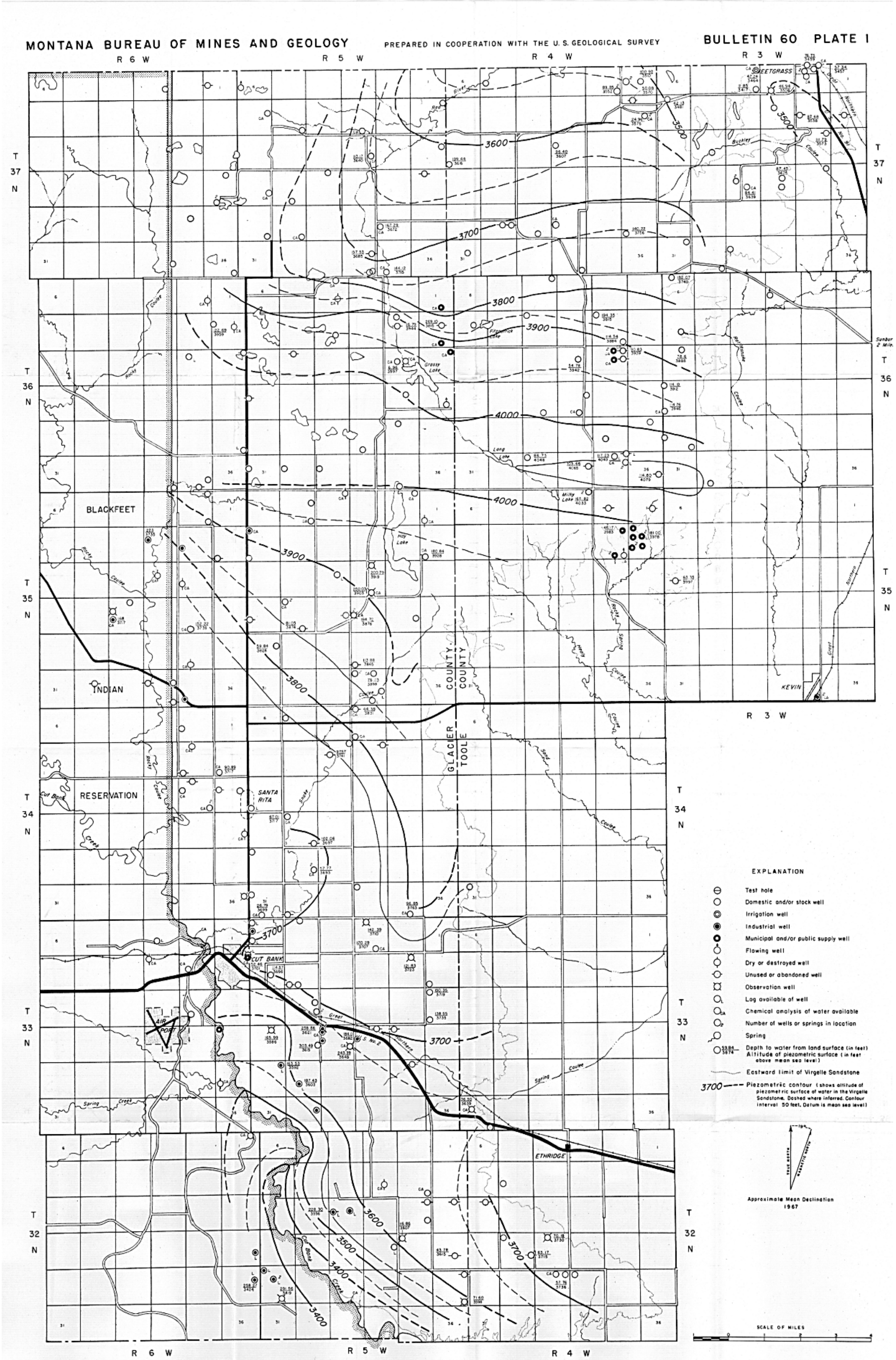


Figure 23 Piezometric surface of the Virgelle Sandstone in the Cut Bank area in Montana for year 1965 (Zimmerman, 1967).

4. 2 Artesian Well Flows

When groundwater exploitation started in 1916, nearly all the wells drilled in the Milk River aquifer were flowing (Phillips et al. 1986). 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 (1917) mapped the artesian areas of the Milk River sandstone in southern Alberta.

These areas were located north of the study area and east of the Pakowki Lake (Fig 13a and Fig. 24).Some of the artesian wells located beyond the depositional limit of the Virgelle Member may actually be completed in the Upper Alderson Sands rather than in the Milk River Formation. Meyboom (1960) identified 409 wells completed in the Milk River aquifer in the area of townships 1 to 11, ranges 4 to 18W4M, of which 192 were flowing wells (AGRA, 1998). The Persram survey (1992, unpublished) identified 502 Milk River aquifer wells over the area of townships 1 to 11, ranges 1 to 19W4, of which 201 were flowing (AGRA, 1998). Today the flowing wells are confined mainly to the major valleys and coulees, and are still common around Pakowki Lake. Flow rates, however, have diminished (AGRA, 1998). In the Sweet Grass Hills area, many wells completed in the Virgelle formation flow upwards, indicating a vertical gradient (Tuck, 1993).

Artesian wells have also been mapped near Mannyberries and Pakowki Lake and appear to be associated with the Medicine Hat Valley, the Skiff Valley and Forty Mile and Chin Coulees (AITF, 2010).

During the MiRTAP field works, 8 wells were identified as artesian. Water pressure was measured from 4 artesian flowing wells in southern Alberta. The pressure ranges between 7 and 32 psi (49.6 and 220.6 kPa) (Fig. 24).

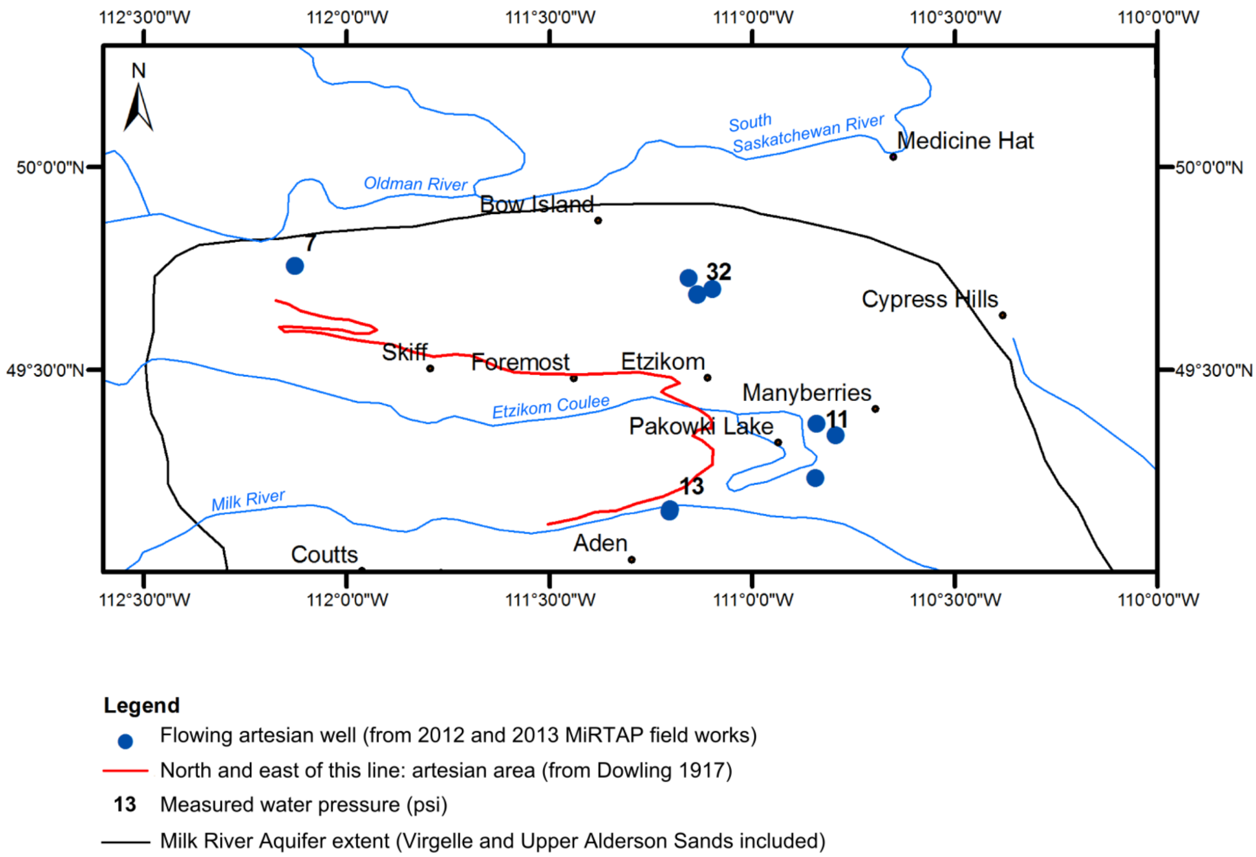


Figure 24: Location of flowing artesian wells and pressure measurement from the 2012 and 2013 MiRTAP field works in southern Alberta.

4.3 Hydrogeological parameters

In Alberta, Meyboom (1960) showed that there is an area of high transmissivity values, following a northwest trend (Fig. 25). This zone corresponds to a thicker sandstone deposit in the aquifer. The transmissivity values were obtained from about 32 shut-in tests performed on flowing well. The transmissivity of the aquifer ranges between 8 and 3000 igpd/ft (1.38×10^{-6} and 5.17×10^{-4} m^2/s).

Persram (1992, unpublished, cited by AGRA, 1998) calculated transmissivity from about 42 pumping tests. The calculated transmissivity ranges from 7 to 730 igpd/ft (1.21×10^{-6} to 1.26×10^{-4} m^2/s) which are lower values than in Meyboom's results. Persram showed a northeasterly trending zone of relatively high transmissivity, which is not in agreement with Meyboom's data. Subsequent study (AGRA, 1998) integrated data from Meyboom and Persram data, along with the additional aquifer test results that resolved some of the apparent conflict. The highest transmissivity in both studies are centered around the Lake Pakowki and south of it (AGRA, 1998). Low transmissivity values (< 100 igpd/ft or < 1.72×10^{-5} m^2/s) are located in the northeast of the study area, near the facies change into the Alderson Member of and over much of the western third of the area (values < 40 igpd/ft or < 6.90×10^{-6} m^2/s) (AGRA, 1998). A map including the 3 sources of transmissivity results mentioned above is shown in Figure 26 (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 700 gpd/ft to 50 000 gpd/ft (1×10^{-4} and 7.19×10^{-3} m^2/s) which are higher values than in southern Alberta. Zimmerman (1967) indicated that the transmissivity could be locally affected by fracturing. In the Sweet Grass Hills area, Tuck (1993) indicated transmissivities of 200 to 3700 ft^2/d (2.15×10^{-4} to 3.98×10^{-3} m^2/s) in the Virgelle member. These values are in agreement with Zimmerman's results and higher than those in southern Alberta.

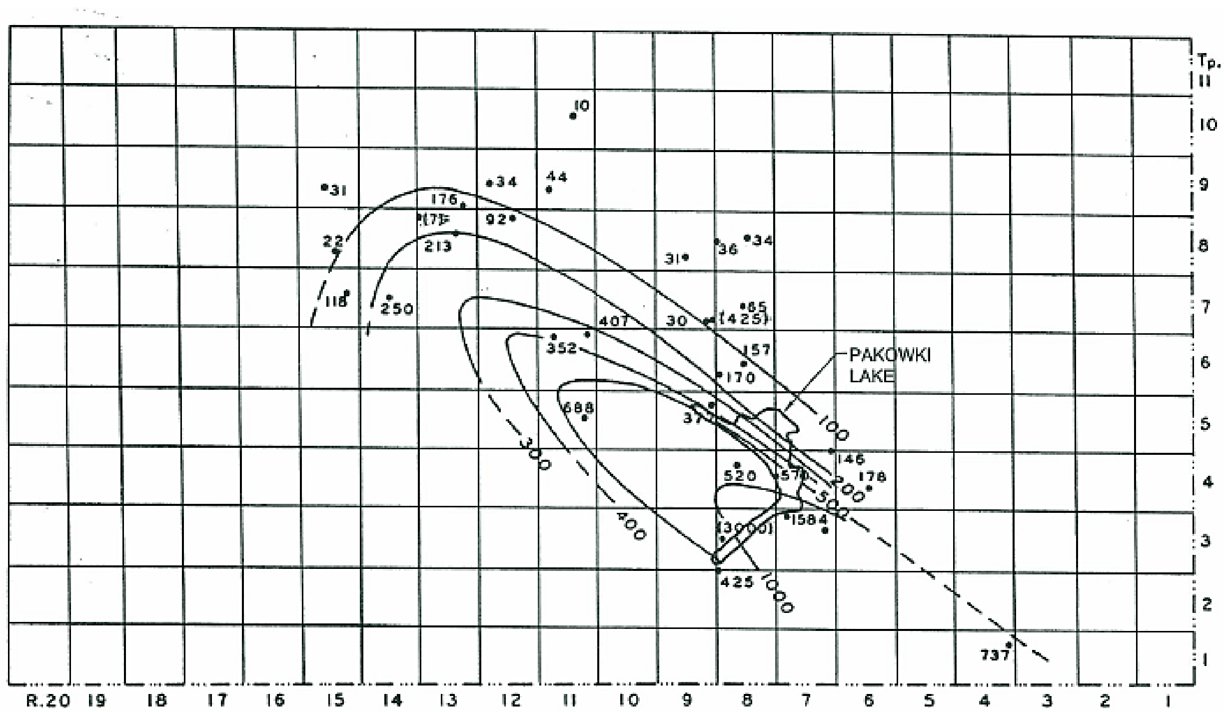


Figure 25: Transmissivity of the Virgelle Sandstone in southern Alberta (igpd/ft) (Meyboom, 1960).

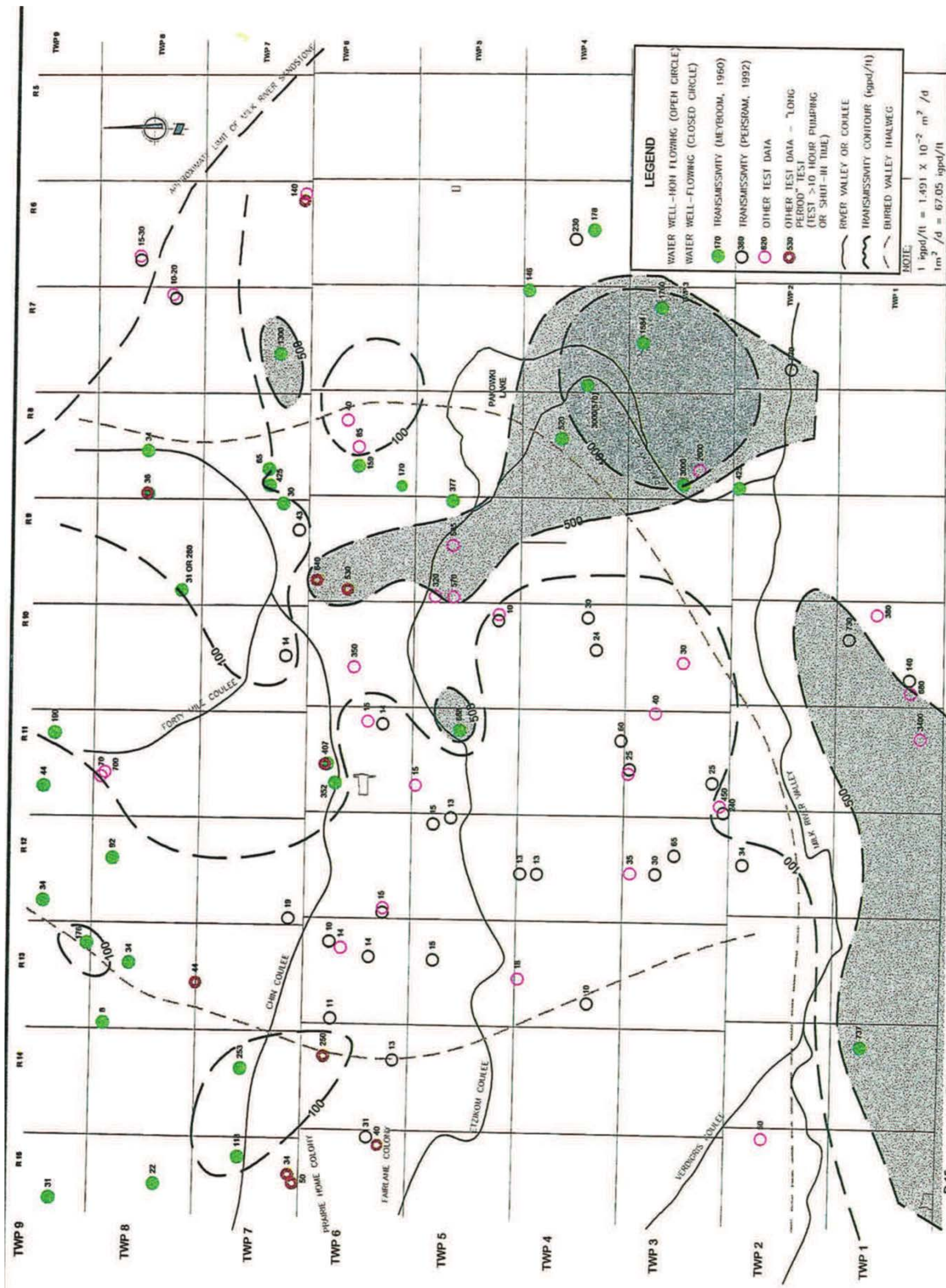


Figure 26: Transmissivity of the Milk River Sandstone (AGRA, 1998).

4.4 Observation wells

The GOWN network (Groundwater Observation Well Network, Alberta Environment) has 5 active observations wells in the Milk River Aquifer (Fig. 27). A sixth observation well (Foremost Town) was abandoned in 2006. This well has been replaced by a well located south of the Town of Foremost (Foremost Farm #954) (Table 4).

In Montana, the GWIC (Groundwater Information Center) database contains 4 wells completed in the Virgelle Member (Fig. 27) of the Milk River Aquifer that have regular water level records (Table 5). Their depths range from 19.5 to 36 m.

The hydrographs are provided in Annex B. The hydrographs from the GOWN network have been produced from the raw data file which was provided by Alberta Environment. The hydrographs in Montana have been retrieved from the GWIC database and converted from feet into meters.

The pumping at the town of Foremost is from 3 water wells located along a coulee on the east side of the town (AGRA, 1998). Dowling (1923) reported that the original pumping well at Foremost was flowing at a small rate in 1923 (AGRA, 1998). The original Foremost Town well (#221) has a drop in the water level of about 44 m between 1958 and 2006 (the elevation of the water level is 843 m in 1958 and 799 m in 2006). There would have been an approximate water decline of 43 m between 1923 (assuming that the well stopped flowing after Dowling's observation) and 1957. The total drop in the water level would be about 87 m over the period 1923-2013. The amount of lowering is higher between 1957 and 1987 than in the succeeding period 1987-2006. (See Annex B well #221).

The Foremost town monitoring well was reclaimed in 2006 and replaced by the Foremost Farm well (#954). For the 7 years since installation the new well does not have a clear record of falling water level, with a water level range between 825 and 824.2 masl.

The Aden (#100) hydrograph indicates that the water level dropped about 1 meter between 1986 and 1989. It then remained stable until 1996, and rose about 0.5 m from 1997 to 2013. AGRA (1998) explains the leveling-off and subsequent rise to the closing of a nearby flowing well. Since 1998, the water level has oscillated in the range of 0.3 m. The total change of the water level during the 27 years of recording is only 1.3 m.

The monitoring well record of Forty Mile Coulee (well#286) has a net rise in the water level between 1990 and 2000, then an abrupt drop of the water level between 2000 and 2002. The water level has a rise between the end of 2002 and 2009 then decreases until 2013; attaining the same elevation as in the 90s.The reason for the drop and subsequent rise between 2000 and 2009 is not clear.

The monitoring well of Milk River West (#212) is the only well located in the sub-cropping area of the aquifer. It has a depth of only 72.8 m, the other observation wells having depths between 130 and 230 m. The hydrograph of this well has a fluctuation in water level of about 0.6 m over the period 1986-2013. During this period the water level rose between 1986 and 1998, and then it dropped between 1999 and 2010. From 2010 to 2013 the water level rose again of about 0.3 m. It is worth noting that although this well is located in the sub-cropping area of the Milk River Formation; its completion interval is between 54.6-72.8 m. The drilling report of this well indicates that the sandstone is overlain by more than 50 m of alternating beds of shale and bentonitic sandstone. Thus, the aquifer is confined at this location.

There is a well completed in the gravels (Milk River 85-2, well #213) at the same location as the Milk River West well. The production interval is 8.5-9.75 m depth. The hydraulic head in the gravel is higher than in the Milk River Aquifer sandstone. Thus, there is a downward vertical flux.

In Montana the monitoring record is not continuous, with only a couple of measurements each year. The hydrograph of well **88838** shows that the water level fluctuates with an amplitude of about 6 m over the 19 year period of 1994-2013.

The hydrograph of well **89572** has a total change in the water level that is < 1 m over the period 1994-2013. The hydraulic head is highest in the area west of the Sweet Grass Arch, which indicates that this well would be located in a recharge zone.

The water level of well **90371** fluctuates in a range of about 2.7 m over the period 1995-2013. The well is located in the sub-cropping area of the Eagle Sandstone, and the drilling report indicates that the aquifer is overlain by 3 m of clay and 8 m of shale.

The record of well **45363** was discontinued between 1993 and 2000. The water level dropped more than 4 m between 1999 and 2002, which correspond to a period of precipitation deficit. Over the period 2002-2013, the water level rose and fluctuated with an amplitude of 1 m.

Station name	Status Details	LSD	Sec	TWP	Rng	Aquifer	In Use Since (WL)	End of Available Data	Elevation Top of Casing masl	GIC Well ID	Drill Date	Depth (m)	Production (m)	Completion	Aquifer Type
Aden_0100	**Active**	4	31	1	10	Milk River	26-Apr-85	WL Recent / WQ Oct 1993	955.33	164615	1-Jan-85	180	120 - 180	Open	Confined
Milk River 85-1 West_0212	**Active**	14	24	2	15	Milk River	1-Mar-86	WL Recent / WQ Oct 2009	990.84	196203	25-Oct-85	73	54.6 - 72.8	Open	Confined
Smith Coulee 2469E_0211	**Active**	8	25	3	11	Milk River	14-Mar-88	WL Recent / WQ Oct 1992	937	196129	12-Nov-87	165.2	158.5 - 165.2	Screen	Confined
Foremost Town_0221	**Reclaimed**	16	17	6	11	Milk River	2-Jan-57	WL Jun 20 2006	888	195769	1-Nov-87	228.6	215.91 - 228.6	Slotted	
Forty Mile Coulee 86-1_0286	**Active**	13	27	8	11	Milk River	19-Dec-89	WL Recent / WQ Dec 2009	823	157721	9-Mar-86	231.04	188.98 - 230.12	Slotted	Confined
Foremost Farm	**Active**	1	8	6	11	Milk River				196964	15-Apr-66	220.98	182.88- 219.46		Confined

Table 4: Observation wells in the Milk River Aquifer, southern Alberta (GOWN, Alberta Environment).

Gwic Id	Twn	Rng	Sec	Q Sec	Td	Comp Date	Aquifer	First Date	Last Date	Avg Swl Ground	Readings
88838	32N	04W	35	CBAA	78	08/10/1979	211VRGL	04/04/1994	2/22/2013	46.99123	65
89572	35N	04W	11	DCDB	64	8/25/1957	211VRGL	01/10/1994	2/22/2013	1.14421	38
90371	37N	03W	2	DBAA	118	1/30/1987	211VRGL	01/04/1994	10/31/2012	33.384714	70
45363	34N	04E	33	ADDAC	115	09/12/1980	211VRGL	7/21/1993	1/30/2013	59.212727	44

Table 5: Observation wells in the Virgelle Member of Eagle formation, northern Montana (GWIC).

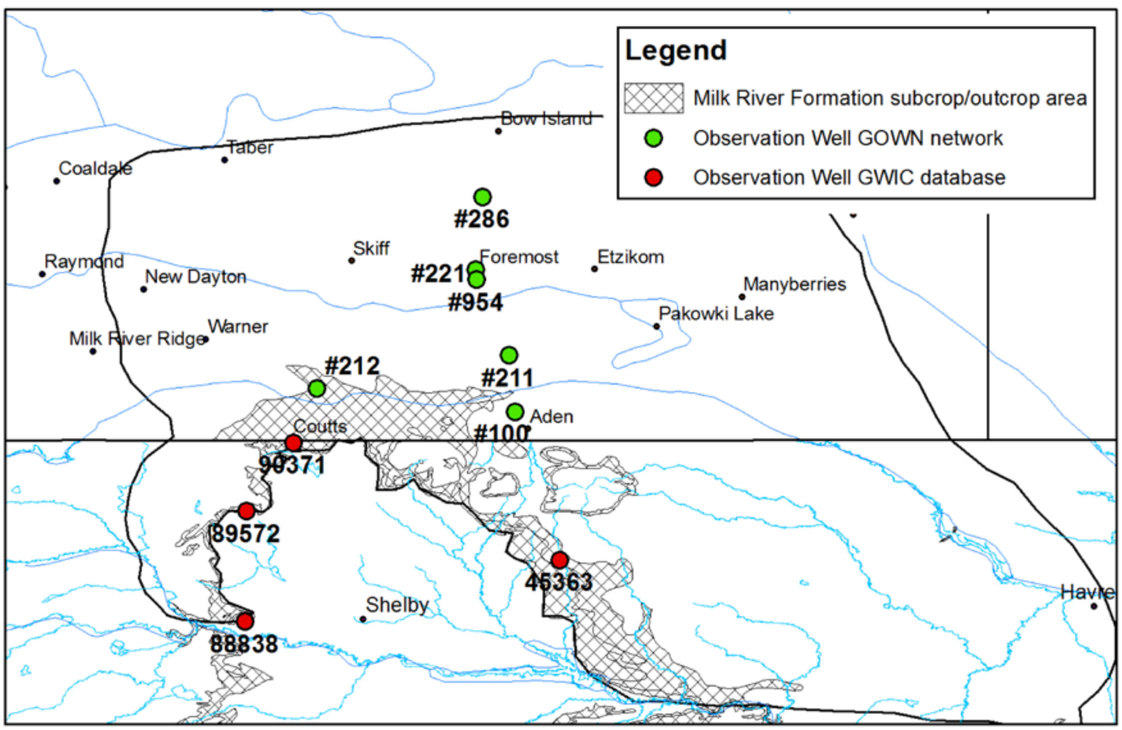


Figure 27: Locations of the Milk River Aquifer observation wells in the study area.

4.5 Groundwater interactions with others units

The Whisky Valley Aquifer is in the surficial fill of the Whisky Valley buried valley, a pre-glacial bedrock valley that is situated below much of the present-day Milk River. The aquifer lies south of the Town of Milk River and is composed of sand and gravel that is 10 to 30 m thick (AITF 2010). The Whisky Valley aquifer has been found to be connected to the Milk River in some locations (Golder Associates, 2004) (Fig. 28).

There are two main sources of recharge to the Whisky Valley Aquifer. The first is vertical recharge from precipitation; the second source of recharge is located in the eastern part of the Study Area where groundwater flows upward from sub-cropping sandstone aquifers in the Milk River Formation. There is an additional smaller source of recharge to the Whisky Valley Aquifer at a more local level directly from the Milk River (Golder Associates, 2004).

Lies and Letourneau (1995) estimated the significance of cross-formational flow by using a hydrogeological model. They indicated that the Milk River Aquifer has a strong vertically upward flow component and that a downward flow component to the Bow island aquifer, beneath the underlying confining Colorado Group also exists. Hydraulic head values within the Milk River Aquifer are up to 200 m higher than those in the Bow Island Formation (Lies and Letourneau, 1995). They noted that, although the permeability of the confining aquitards is low, they are greater than zero (Lies and Letourneau, 1995).

In the Sweet Grass Hills area, Tuck (1993) mentioned that many wells completed in the Virgelle Member flowed, indicating a probable upward vertical gradient. Tuck (1993) showed evidence that the Interstratified Sand and Gravel aquifer (in glacial deposits) and Virgelle might be connected along Bear Gulch.

In the Cut Bank area, the Two Medicine Formation is hydraulically connected with the Virgelle in many places (Zimmerman, 1967). Zimmerman (1967) reported that the water levels in the two formations differ only slightly and reacted similarly to pumping from a nearby well during an aquifer test.

In southern Alberta, the Virgelle and Upper Alderson aquifers are separated by muddy sediments of the Alderson and Deadhorse Coulee members but they are locally in contact at the Virgelle erosional edge and water flow between the two aquifers is likely (O’Connell, 2014).

The configuration of the water levels in surficial sediment in the vicinity and north of Pakowki Lake suggests that groundwater crosses the northern divide of this closed basin, and enters the Medicine Hat bedrock valley that passes under Pakowki Lake and trends toward the northern part of the map area (Borneuf, 1976).

The gravel existent in the bedrock valley, under Pakowki Lake and north of it, could act as a drain for groundwater, and could explain the absence of discharge features in the area (Borneuf, 1976).

4.6 Surface Water-Groundwater interactions

The Milk River discharge is not sustained all 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 (Thompson, 1986). The river discharge is also affected by withdrawals along the reach for irrigation and municipal uses (Thompson 1986). The mean natural streamflow of the Milk River from September to March is about 1 m^3/s and reaches 16 m^3/s during the irrigation season when the St. Mary Canal is adding flow (Fig. 29).

Normally, the surface water-ground water interaction can be assessed by using the hydrograph separation method. However, this technique cannot be applied in the case of the Milk River which is not a natural channel.

Thompson (1986) suggested that there is no major interaction between the regional aquifer (Milk River Aquifer) and streamflow, based on inspections of riverbank geology and measurements of streamflow and specific conductance. 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, with some streamflow likely moves into the alluvium. Once the flow from the canal is stopped in late summer and early fall, water is discharged from the alluvium (Thompson, 1986).

In 2007 a field study was conducted in southern Alberta (MacCulloch and Wagner-Watchel, 2010 and 2011) to assess the Milk River main channel losses and gains through August and October of that year. This study showed a trend with flows decreasing along the river reach in August 2007 (from 16.6 m^3/s to 13.2 m^3/s), and flows increasing along the river reach in October 2007 (from 0.3 m^3/s to 0.99 m^3/s). Recommendations are made to include factors such as consumptive use, evaporation/evapotranspiration and precipitation for attaining a complete understanding of the losses and gains along the Milk River.

During post-glacial time, the Milk River eroded its present valley and intersected the Virgelle Member in township 1 and 2, ranges 12 to 15 (Meyboom, 1960). The natural discharge of the Milk River Aquifer was from springs and seeps along the southern bank of the Milk River. Meyboom (1960) indicated that this post-glacial disturbance led to a lowering of the piezometric surface over a large area, resulting in a change from artesian to water-table conditions in the aquifer on a short distance north of the river.

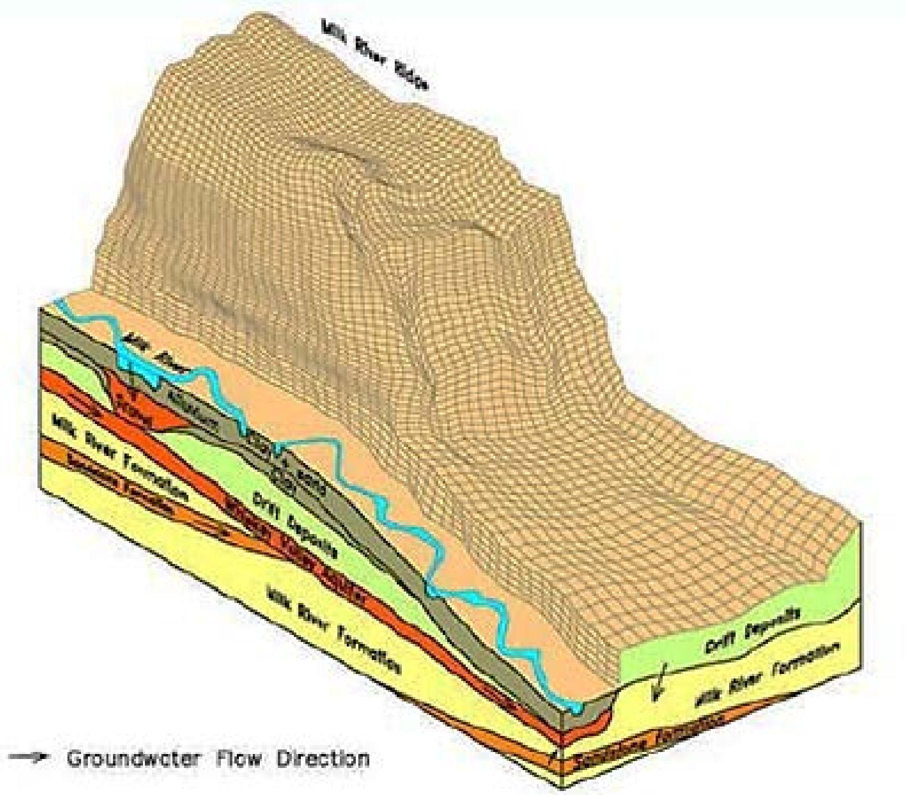


Figure 28: The conceptual model of the Whisky Valley Aquifer (Golder Associates, 2004).

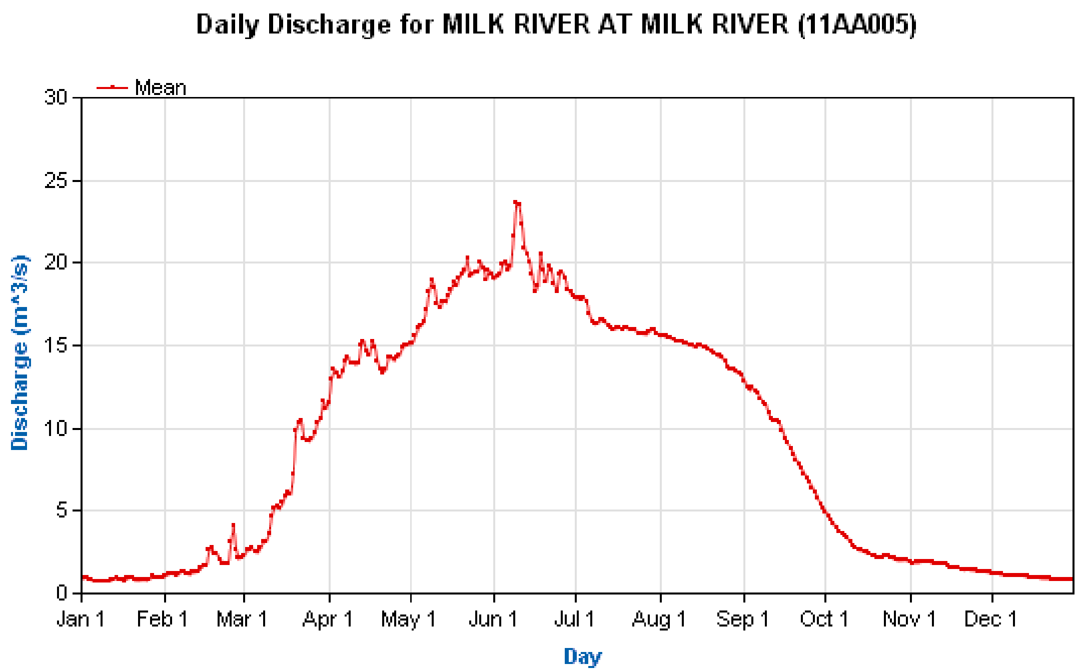


Figure 29: Milk River Hydrogram. Mean daily discharge at Milk River Station for the period 1909-2011 (Environment Canada).

4.7 Presence of gas

Several gas fields are present within the study area (Fig. 16). In southern Alberta, the Alderson Member hosts the Milk River Gas Field (O'Connell, 2014). It is the largest single gas accumulation in the Western Canadian Sedimentary Basin, with recoverable reserves estimated at 14 x 10^{10} m^3 (Lies and Letourneau, 1995). A hydrodynamic trapping mechanism was proposed by Berkenpas (1991, Fig. 30). In Montana, the Eagle Formation hosts the Tiger Ridge gas field near the city of Havre (see well log in Fig. 31). They both constitute natural boundaries of the Milk River Aquifer.

In the Bearpaw Mountains area, the Eagle sandstone is a major source of shallow gas, with estimated reserve of more than 2.1 x 10^{10} m^3 (Gautier and Rice, 1982). Gas production from conventional reservoirs around the Bearpaw Mountains comes mainly from the Upper Member of Eagle Formation (Payenberg et al., 2003). The underlying Virgelle member typically tested wet and does not appear to host significant gas reserves (Payenberg et al., 2003).

These gas reserves are of biogenic origin and consist predominantly of methane. The generation and accumulation of biogenic gas in the study area has been described by Rice and Claypool (1981).

Swanick (1982) noted many wells produce methane gas with groundwater, particularly in the northern part of the study area (Fig. 32). Andrews et al. (1991a) studied the dissolved gases in the Milk River Aquifer in southern Alberta. They collected groundwater samples for gas and isotopic analysis. The presence of dissolved gas at some sites caused degassing of the water as it ascended the well. The more saline waters generally contain considerable amounts of dissolved methane (CH_4). The highest area of CH_4 in the Milk River aquifer occurs in the area of well 16 (Fig. 33).

A numerical model of the Milk River gas field was carried out by Lies and Letourneau (1995). They showed that the Milk River Gas field is hydrodynamically trapped. They also had to consider gas interference effects in the model in order to match the existing Milk River aquifer water isopotential distribution. O'Connell (2014) has proposed a different view, considering unlikely that water production from the Virgelle Member or Upper Alderson aquifer sands would affect Milk River gas production.

O'Connell (2014) stated that Virgelle and Upper Alderson sands are separated from the Milk River gas field by muddy sediment of the Alderson Member, which acts as a barrier to water flow.

Anna (2011) studied the effects of groundwater flow on the distribution of biogenic gas in southern Alberta and northern Montana. He showed that hydraulic heads in high permeability aquifers in structural updip areas could negate buoyancy forces of gas in structural downdip low permeability rocks.

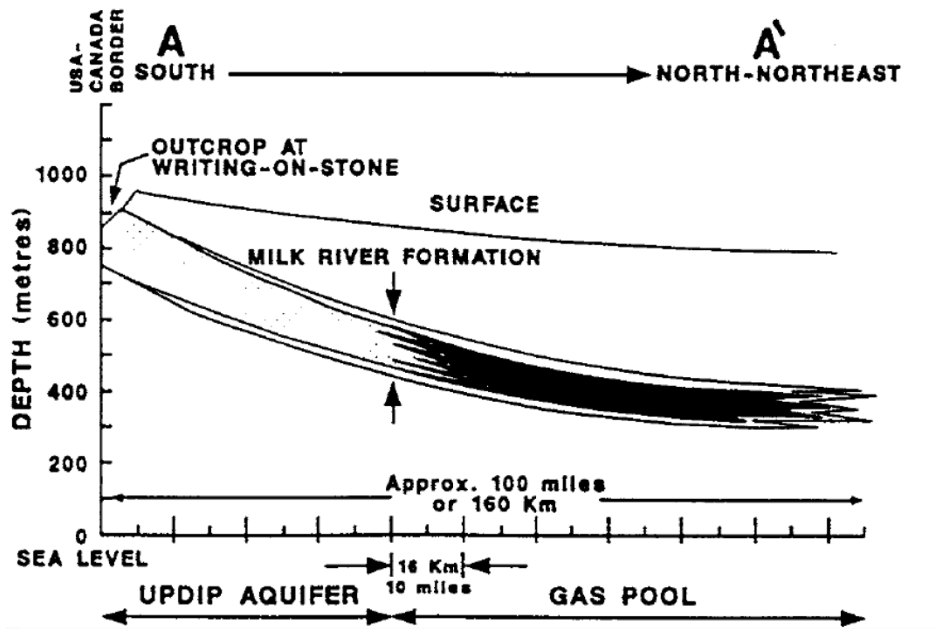


Figure 30: Relationship between the Milk River Aquifer and the Milk River gas field (Berkenpas, 1991).

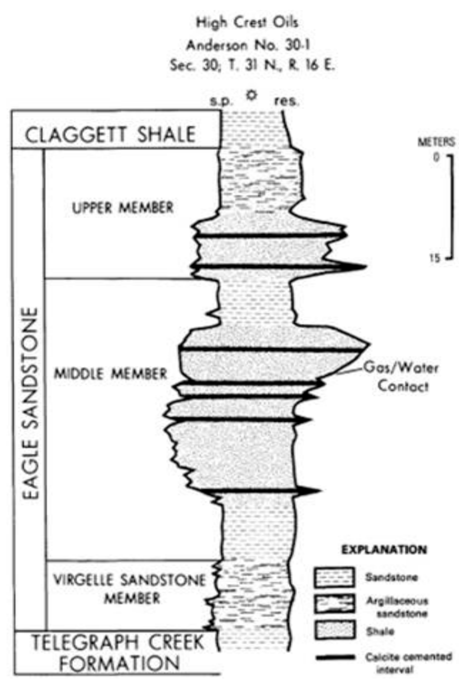


Figure 31: Well log located in the Tiger Ridge gas field, in the vicinity of the Bearpaw Mountains, Montana (Gautier and Rice, 1982).

.

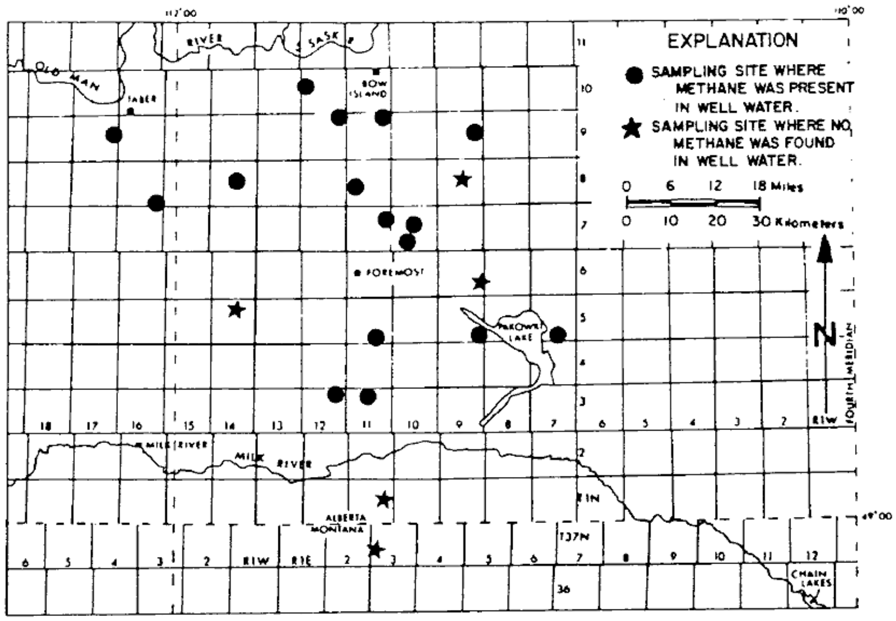


Figure 32: Presence of methane in water wells (Swanick 1982).

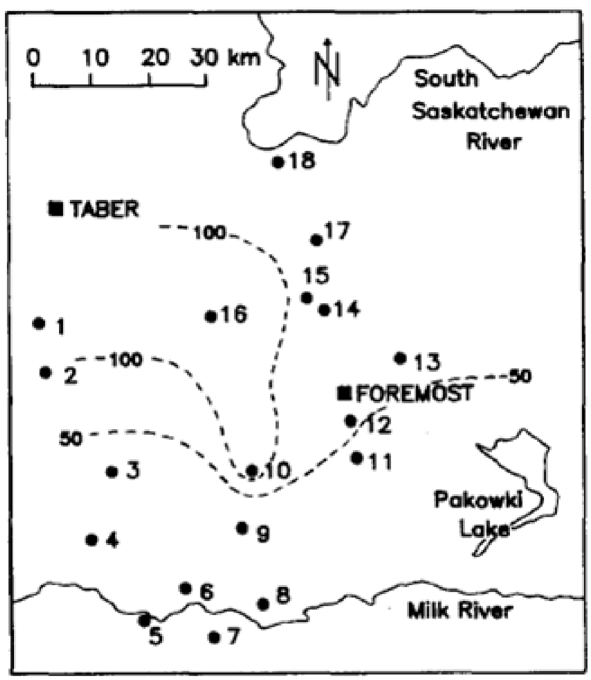


Figure 33: Distribution of CH_4 in groundwater in the Milk River Aquifer. Isopleths at 50 and 100 cm^3/L are represented (Andrews et al., 1991a). Well numbers are the author's own numbering system.

5. Geochemistry

There has been fifty years of groundwater chemistry studies in the Milk River Aquifer. 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 Milk River Aquifer 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 in groundwater from the Milk River Aquifer (Hendry and Schwartz, 1988, 1990; Phillips et al., 1990). Other notable isotopic studies in the Milk River Aquifer include Nolte et al. (1990, 1991), Andrews et al. (1991b), Drimmie et al. (1991), Fabryka-Martin et al. (1991), Frölich et al. (1991), Lehman et al. (1991), and Armstrong et al. (1998). Various aspects of this work are highlighted in the respective subsections below.

5.1 Milk River Aquifer groundwater types

Groundwater from the Milk River Sandstone is mainly sodium-bicarbonate or sodium-chloride type in southern Alberta. In Montana in the Sweet Grass Hills area, water from the Virgelle sandstone is a calcium bicarbonate type near the recharge area and a sodium bicarbonate type with distance from the recharge area (Tuck, 1993). In the Cut bank area (west of the Sweet Grass Arch) groundwater from the Virgelle sandstone is sodium bicarbonate or sodium sulfate type (Zimmerman, 1967).

Meyboom (1960) distinguished four types of water in the Milk River Aquifer (type A to D) with distinct distributions (Fig. 34). Type A is moderately mineralized (TDS up to 1000 ppm) sodium bicarbonate water. Type B water has higher sulfates concentration, which may reach 500 ppm in township 1 (near the international border). Type C water is transitional between Type A and the more highly mineralized water of Type D with alkalinity between 1000 to 1300 mg\L and are predominantly in the north-eastern part of the aquifer. Type D are highly mineralized, sodium-chloride type waters, believed to be unaltered connate water in the northwestern part of the aquifer. Hendry and Swartz (1988) suggest that the high chloride content in the Type D water is caused by diffusion of Cl^- from the confining marine shale into the Milk River Aquifer, with an increasing Na+ concentration developed as a counter ion to Cl^-.

5.2 TDS, major and minor ions

Total Dissolved Solid

In the county of Warner, approximately 50% of the groundwater samples have TDS concentration in the range of 1,420 to 2,806 mg\L (Stantec, 2002). However, 12.4% of the groundwater samples have TDS concentration greater than 4,000 mg\L, including 3 samples exceeding 14,000 mg\l. These TDS concentration are above the Guidelines for Canadian Drinking Water Quality (GCDWQ) of 500 mg\L. In the county of Forty Mile, the TDS concentration of the Milk River Aquifer ranges from 500 to 3,000 mg\L. Higher TDS concentrations are located in the northern portion of the County (HCL consultants, 2004). In the MD of Taber, the TDS concentration ranges from 1,000 to 3,000 mg\L (HCL Consultants, 2007). In the Sweet Grass Hills area, TDS concentrations in the Virgelle Sandstone range from 213 to 1,360 mg\L with a median value of 620 mg\L (Tuck, 1993).

Sulphate concentrations

In the county of Warner, sulphate concentrations are lower than the Guideline of 500 mg\L in 58% of the samples. Elevated sulphate concentrations are mainly located in the southern part of the County (Stantec, 2002), which is consistent with Meyboom's observation. In the county of Taber, 90% of the sulphate concentration in the Milk River Aquifer are less than 100 mg\L (HCL Consultants, 2007). In the county of Forty Mile, nearly 80% of the sulfate concentrations in groundwater from the Milk River Aquifer are less than 100 mg\L (HCL consultants, 2004). In the Sweet Grass Hills area, the sulfate concentration in groundwater from Virgelle sandstone ranges from 13.7 mg\L to 545 mg\L with a median value of 183 mg\L (Tuck, 1993).

Hardness

Groundwater from the Milk River Aquifer is softer than groundwater from the other aquifer units of the study area (Stantec, 2002). In the county of Warner, 58% of the samples have a total hardness less than 60 mg\L, characterizing the water as soft. Some very hard water (hardness >180 mg\L) is present in the southern part of the county (Stantec, 2002).

Chloride concentrations

The water quality guidelines for Chloride is of 250 mg\L. In the southeast and northern parts County of Warner, chloride concentrations were higher than the guideline in 26% of the samples (Stantec, 2002). In the county of Forty Mile, 60% of the chloride concentrations from the Milk River Aquifer are greater than 100 mg\L (HCL consultants, 2004). In the MD of Taber, more than 90% of the chloride concentrations from the Milk River Aquifer are greater than 100 mg\L and the median value (523 mg\L) exceeds the guideline of 250 mg\L (HCL Consultants, 2007). In the Cut Bank area, chloride concentrations of groundwater from the Virgelle sandstone rarely exceed 100mg\L (Zimmerman, 1967).

Fluoride concentrations

The guideline for Fluoride concentrations in water is 1.5 mg\L. In the county of Warner 60% of the samples conformed to the guidelines. Fluoride concentrations increase from the southern portion of the county toward the north (Stantec, 2002). In the MD of Taber, 87% of the fluoride concentration in the Milk River Aquifer are > 1.5 mg\L and the median value (3.1 mg\L) exceed the guideline (HCL Consultants, 2007). In the County of Forty Mile, fluoride concentration ranges from < 0.5 mg\L to > 5 mg\L in the western part of the County. The median fluoride concentration in the Milk River Aquifer of 2.54 mg\L exceed the guideline (HCL, 2004).

5.3 Chemical evolution and isotopic pattern

The geochemical and isotopic analyses of water from the Milk River Aquifer are summarized in Table 6. Meyboom (1960) showed that the water of the Milk River aquifer becomes more mineralized to the north, east and west from the recharge area (Fig. 35). One reason for the increase in mineralization is the slow movement of groundwater which allows a large contact time between groundwater and the surrounding bedrock matrix (Stantec, 2002). Meyboom (1960) suggested that this increase in mineralization was due to a slow process of freshening and dilution of connate water chemistry by meteoric water.

The chemical pattern of the Milk River aquifer has an increase in ion concentration from the recharge area to the northern edge of the aquifer. An interesting feature of the Milk River aquifer is the consistent pattern in the distribution of major ions and ^{18}O and ^{2}H concentrations. Concentrations of Na^{+}, Cl^{-} , I^{-} , Br^{-} and HCO^{3-} increase to the north (Schwartz and Muelhenbach, 1979; Swanick, 1982; Hendry and Schwartz, 1988; Fig. 36).

The dominance of Na^{+} 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 chemical composition of the groundwater near the recharge area (near the Canada/US border) is different from the one down gradient. This difference is due to the percolation of water recharging the aquifer in the sub-cropping area through the glacial till that was deposited about 30 000 to 40 000 years ago (Swanick, 1982; Hendry and

Schwartz, 1990). Concentrations of Mg^{2+} and SO_4^{2-} are relatively high in the recharge area and decrease to north (Schwartz and Muelhenbach, 1979).

The distribution of ^{2}H and ^{18}O in the water of the Milk River Aquifer has been described by Schwartz and Muelhenbachs (1979), Swanick (1982); Hendry and Schwartz (1988), and Drimmie et al. (1991). There is a $\delta^{18}O$ and $\delta\ ^{2}H$ enrichment from south to north (from -20‰ to -9‰ and from -157‰ to -88‰ respectively; Fig. 37). Most negative values of $\delta^{18}O$ and $\delta\ ^{2}H$ concentrations fall very close to the meteoric line (Fig. 38). The lightest waters correspond to unaltered surface or near-surface water from the recharge area of the aquifer (Swanick, 1982). Drimmie et al (1991) recognized three segments in pointing the isotopic composition along groundwater flowlines (indicated by three zones of isotope values in Fig. 38): one with constant isotope values found in the extended recharge zone (zone A); a second with higher 2H and 18O concentration, which correspond to an older recharge (Zone B); and a third zone where a mixing with more saline formational water occur (Zone C). The uniform values in zone A suggest relatively constant recharge conditions; this would signify a minimum flow velocity of 1-1.5 m/year in this portion of the aquifer. Based on ^{18}O and deuterium concentration distributions, Schwartz and Muelhenbachs (1979) assumed that dispersion caused the observed isotopic patterns.

The chloride geochemistry of the Milk River aquifer is complex; Cl^{-} concentration increases from the recharge area to the north as shown in Figure 36 (Meyboom, 1960), Schwartz and Muelhenbachs (1979), and Swanick (1982). This areal distribution has been explained by flushing of connate waters (Domenico and Robbins, 1985); ion filtration (Swanick, 1982; Philips, 1986) and diffusion of Cl^{-} into the aquifer from the underlying shale unit (Hendry and Schwartz, 1988). Nolte et al. (1991) suggested that this increase in Cl^{-} from south to north matches the general groundwater flow tendency.

5.4 Isotopic analysis and water dating

Groundwater from the Milk River aquifer ranges from recent to >1Ma. The old age of water in the Milk River aquifer has made it a study site for evaluating various dating techniques for old groundwater (e.g. Fröhlich et al., 1991). The isotopic studies in the Milk River aquifer are summarized in Table 6.

Swanick (1982) used a steady-state flow model to calculate hydrodynamic ages of the groundwater prior to the incision of the Milk River into the Milk River sandstone. He compared the calculated ages with ^{14}C concentrations in the water. The model indicated groundwater ages up to 500 000 years in the vicinity of Taber, about 100 km north of the recharge area.

Later, Phillips et al. (1986) and Nolte et al. (1990) used ^{36}Cl measurements for dating groundwater from the Milk River aquifer. They both showed that the $^{36}Cl/Cl$ ratio decreases with distance to the north (Fig. 39). Groundwater ages estimates range up to 2 Ma at the distal end, if uncorrected for any dilution by subsurface sources of dead Cl, whereas a maximum age of 0.5 Ma is calculated using a hydrodynamic model (Phillips et al., 1986; Hendry and Schwartz, 1988 as cited by Fabryka-Martin 1991).

In 1991, a special issue of *Applied Geochemistry* published eight isotopic studies of the Milk River aquifer (Fröhlich et al., 1991). These studies were sponsored by the International Atomic Energy Agency and aimed at testing various isotopic and geochemical techniques for dating very old groundwater. The Milk River aquifer was chosen because its groundwater becomes “old” (beyond the ^{14}C dating range) within a short distance downstream from the recharge area (Fröhlich et al., 1991).

Lehmann et al. (1991) used measurement of ^{37}Ar, ^{39}Ar, ^{81}Kr and ^{85} Kr concentrations to determine the age of groundwater from the Milk River aquifer. They obtained an approximate groundwater “age” of 140 000 years in the northern part of the study area. Lehman et al. (1991) added that “the ^{81}Kr method is potentially the only method for absolute dating of groundwater older than 50 000 years”.

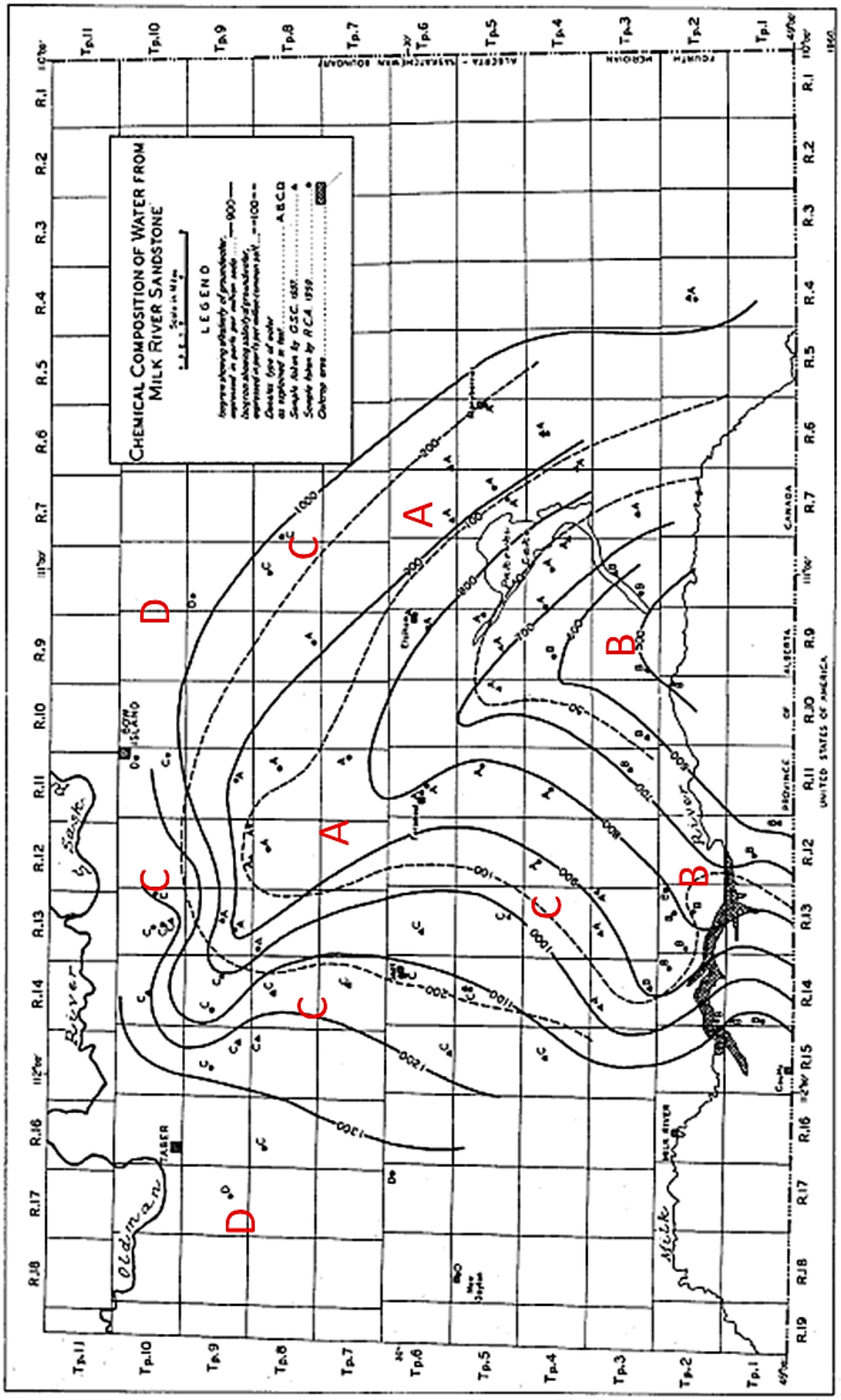


Figure 34: Milk River Aquifer groundwater types (modified from Meyboom, 1960).

Source	Location	Geochemical data	Number of wells sampled
Meyboom (1960)	Alberta	inorganic chemistry	
Schwartz and Muehlenbachs (1979)	Alberta	^{2}H, ^{18}O, inorganic chemistry	40
Swanick (1982)	Alberta	inorganic chemistry, ^{2}H, ^{18}O, ^{13}C, ^{14}C	45
Phillips et al. (1986)	Alberta	Cl^{-}, ^{36}Cl, $^{36}Cl/Cl$, temperature, pH, ^{13}C, ^{14}C	31
Hendry and Schwartz (1988)	Alberta	Cl^{-}, I^{-}, ^{18}O, ^{2}H	99
Andrews et al. (1991)	Alberta	$^{40}Ar/^{36}Ar$, $N_2/^{40}Ar$, N_2/Ar, N_2, CH_4/Ar, CH_4, ^{222}Rn, ^{4}He, Ne, Ar, Kr, Xe, EA, temperature, pressure	16
Drimmie et al. (1991)	Alberta	^{18}O, ^{2}H, ^{3}H, ^{18}O-SO_4, ^{34}S-SO_4, SO_4^{2-}, ^{14}C, ^{13}C, ^{13}C-CH_4, ^{2}H-CH_4, CH_4	45
Fabryka-Martin (1991)	Alberta	$^{36}Cl/Cl$, ^{36}Cl, $^{129}I/I$, ^{129}I, I^{-}, Cl^{-}, Br^{-}	46
Nolte et al. (1990) and (1991)	Alberta	$^{36}Cl/Cl$, Cl^{-}, ^{36}Cl, ^{3}H	12
Ivanovich et al. (1991)	Alberta	U content, ^{234}U, ^{238}U	22
Hendry et al. (1991)	Alberta	Inorganic chemistry	91
Lehman et al (1991)	Alberta	^{81}Kr, ^{85}Kr	1
Frohlich et al. (1991)	Alberta	synthesis of 1991 isotopic studies	16
Armstrong et al. (1998)	Alberta	$^{87}Sr/^{86}Sr$, Ca, Mg, Na, Sr	22
Groundwater Observation Network (GOWN)	Alberta	Inorganic chemistry	
PFRA (2006)	Alberta	Inorganic chemistry	4
Groundwater Information Center (NWIS)	Montana	Inorganic chemistry, isotopes ^{222}Rn, ^{3}H	119
Tuck (1993)	Montana	Inorganic chemistry	10
MIRTAP (2014), this report	Alberta & Montana	Inorganic chemistry, physicochemical parameters, isotopes ^{3}H, ^{13}C, ^{14}C, $^{36}Cl/Cl$	26

Table 6: Geochemical and isotopic analysis of water from the Milk River aquifer.

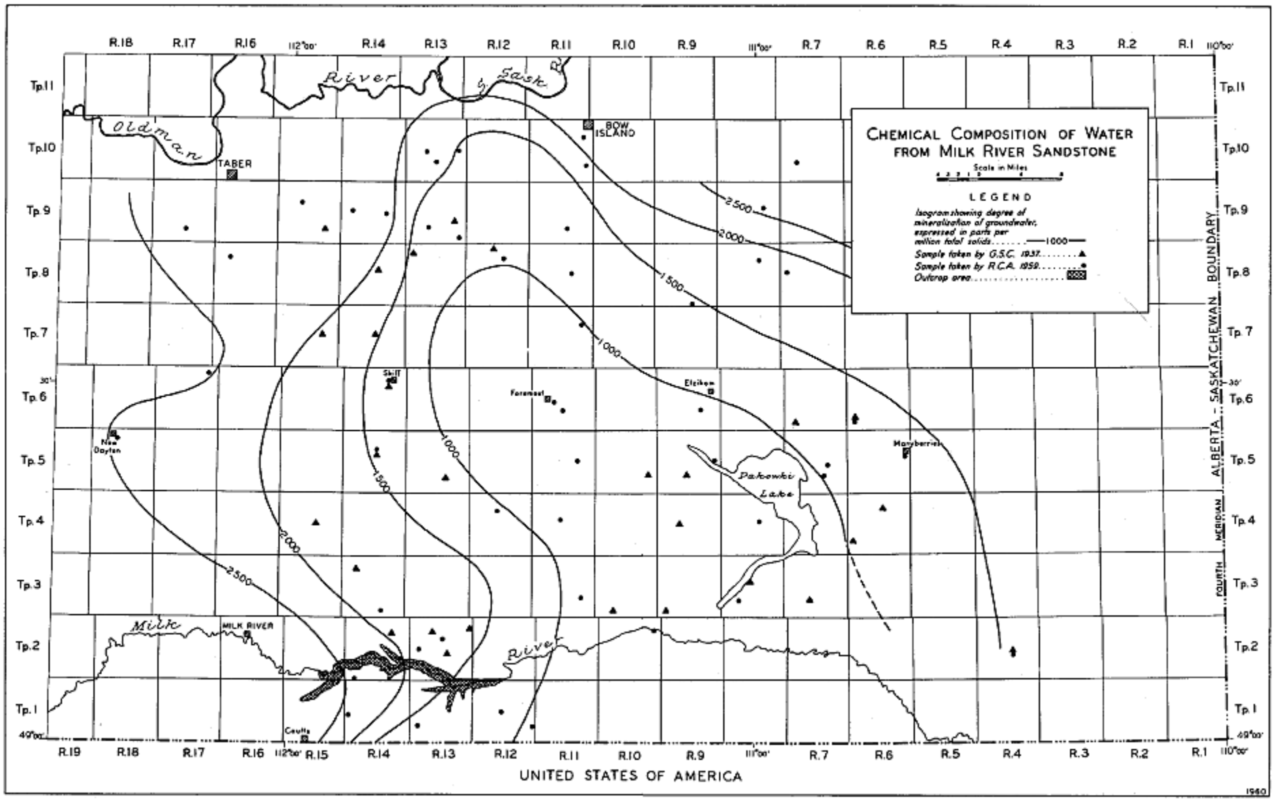


Figure 35: Degree of mineralization of groundwater from the Milk River aquifer (parts per million total dissolved solids; Meyboom, 1960).

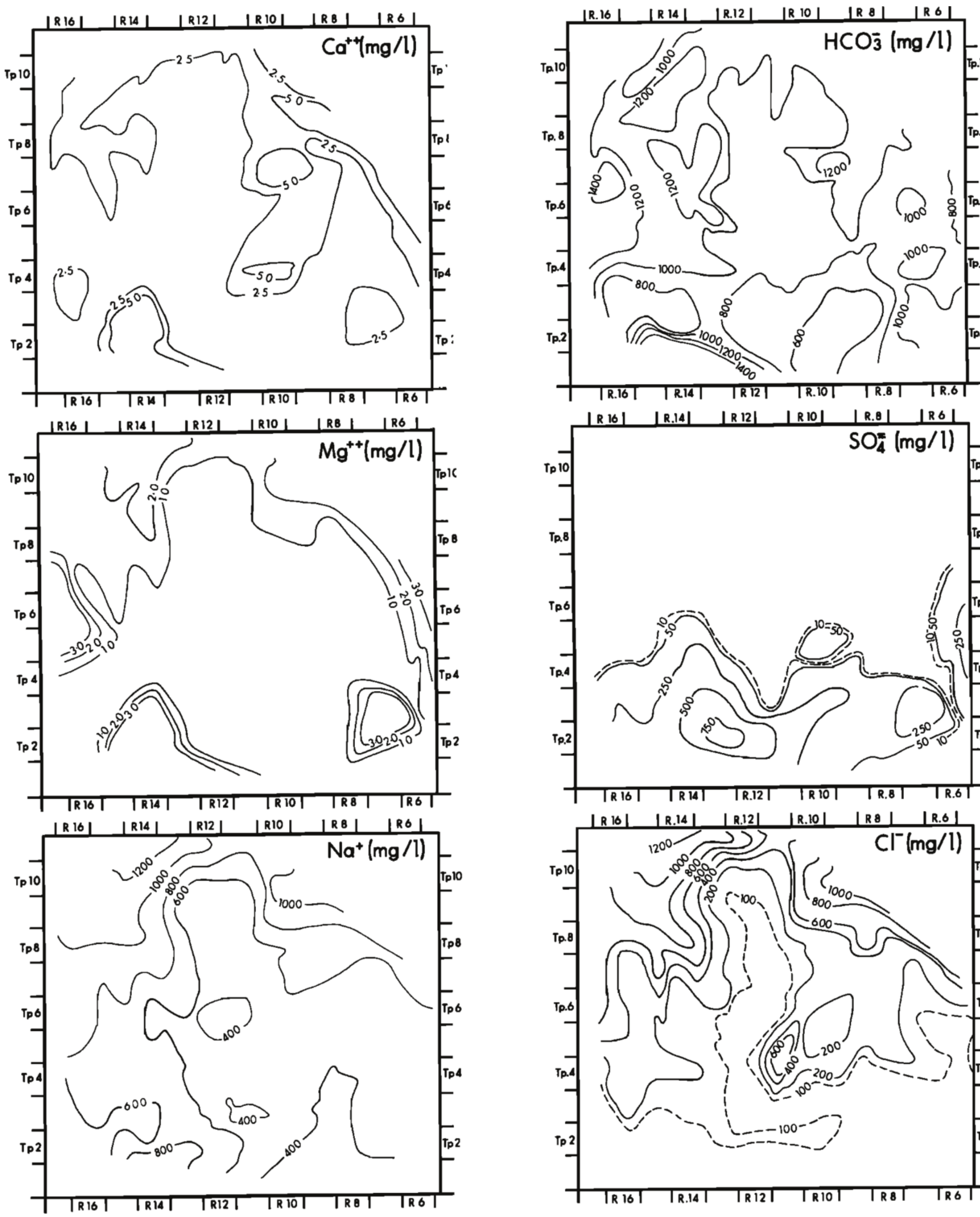


Figure 36: Spatial concentration distributions of the major ions in groundwater in the Milk River aquifer (Schwartz and Muelhenbachs, 1979).

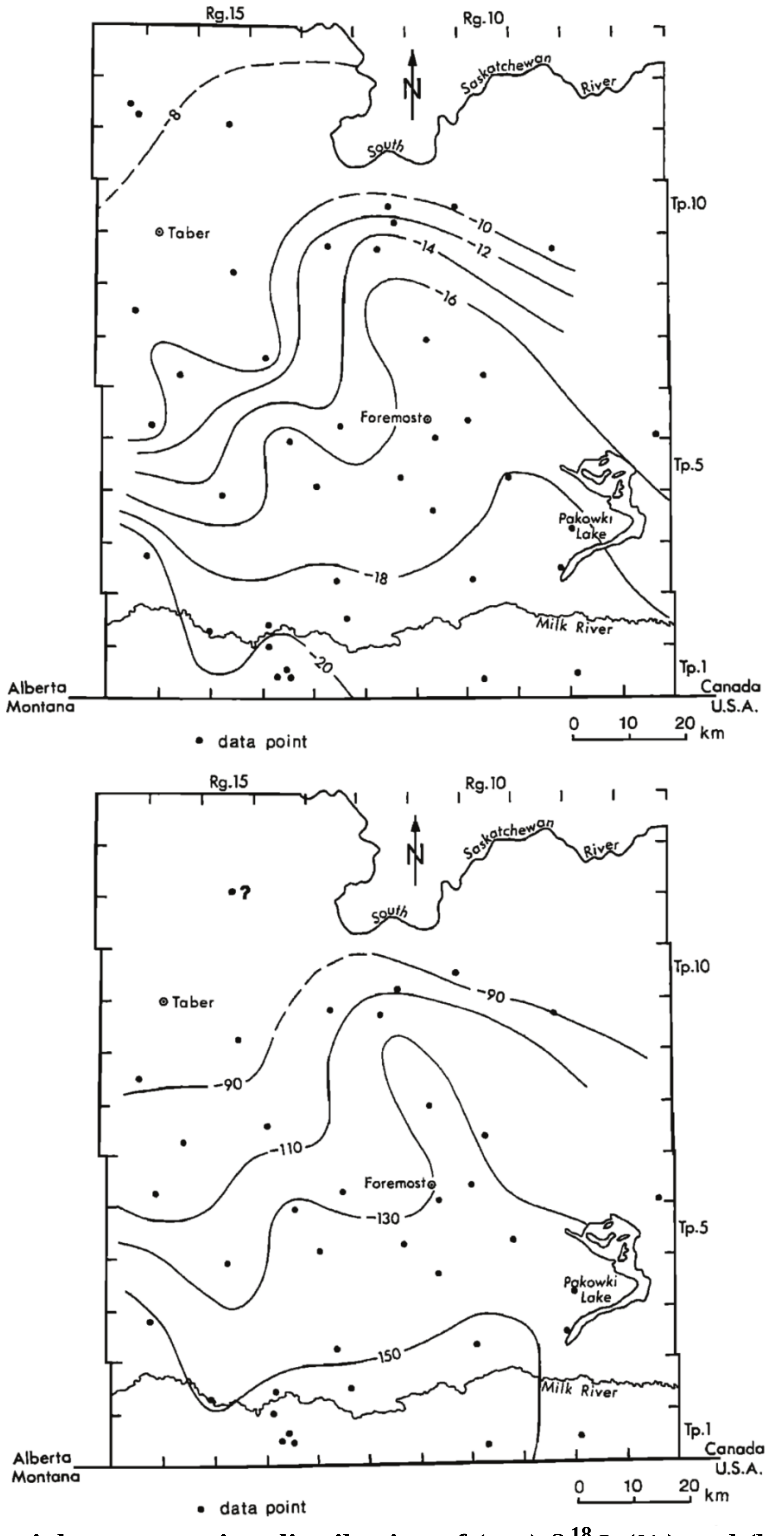


Figure 37: Spatial concentration distribution of (top) $\delta^{18}O$ (‰) and (bottom) $\delta^{2}H$ (‰) in the Milk River aquifer (Hendry and Schwartz, 1988).

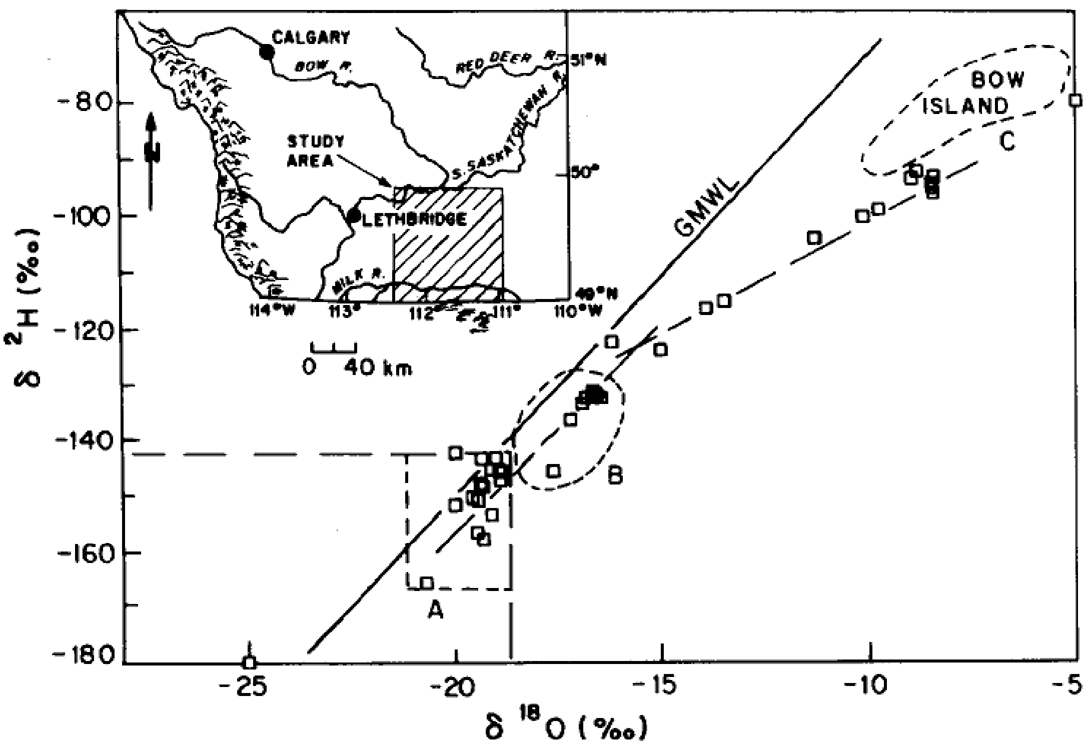


Figure 38: Oxygen vs Deuterium plot including the global meteoric water line (GMWL) showing three zones of isotope values. Zone A: recent recharge; zone B: older recharge; and zone C: mixing of older recharge and Bow Island Formation water. The location map is inset (Drimmie et al., 1991).

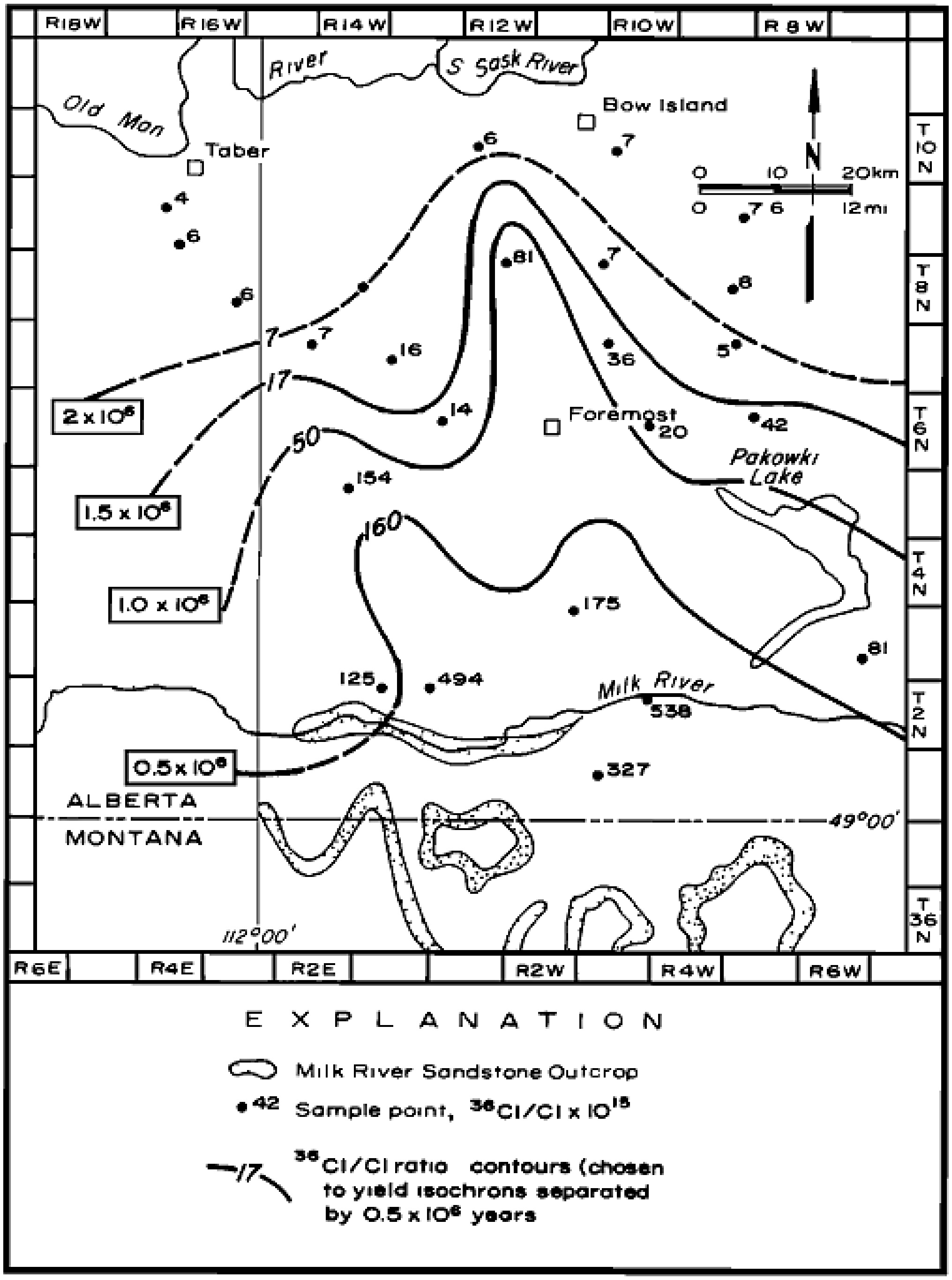


Figure 39: The ^{36}Cl/Cl ratios in the Milk River Aquifer; ^{36}Cl/Cl contours have been converted to equivalent isochrones (Phillips, 1986).

6. Groundwater yield and demand

6.1 Water Yield

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 permeability. Water well yields in Alberta range from 0.1 l/s to 10 l/s on individual wells; in Montana the ranges are from 0.06 l/s to 16 l/s.

In the Municipal District of Taber (southern Alberta), about 156 bedrock water wells are completed in the Milk River aquifer (HCL consultants 2007). The apparent yield for individual water wells completed throughout the Milk River aquifer are mainly greater than 30 m^3/day, and have a median apparent yield value of 55 m^3/day (Fig. 40). Of water wells completed in the Upper Bedrock aquifer(s) (the whole sequence from drift to the top of Colorado Shales), 65% have apparent yield values of less than 50 m^3/day, with a median apparent yield of 35 m^3/day (HCL consultants 2007). Yields greater than 50 m^3/day are associated with wells drilled in the Milk River aquifer, in the vicinity of the buried bedrock valleys. It is assumed these higher yield areas may identify areas of increased permeability resulting from weathering (HCL consultants, 2007).

In Forty Mile County, of the 1,213 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 (Fig. 41) (HCL consultants, 2004).The southeastern part of the County shows the highest yields.

In the County of Warner, yields for 115 out of 559 wells in the Milk River aquifer are in the range of 5 to 75 m^3/day (0.75 to 11.3 igpm) (Stantec, 2002).. Local yields in areas with high transmissivities could be in the range of 230 to 830 m^3/day (35 to 125 igmp) (Fig. 42).

In the Cut Bank area (Montana), Zimmerman (1967) indicated that wells drilled into the Virgelle Member produce as much as 250 gal/min. In the Sweet Grass Hills area, Tuck (1993) mentioned that sandstone of Virgelle member yields from 1 to 80 gal/min of water to wells. Levings (1982) indicated water yields to wells in the Eagle Sandstone. The average reported or measured discharge from 115 wells is about 23 gal/min. The discharge ranges from 0.5 to 200 gal/min, with 28 wells having discharges greater than 20 gal/min.

Meyboom (1960) indicates that the average flow of flowing wells near the Pakowki Lake decreased from 15 gpm in 1937 to 5-7 gal/min in the 1960's. AITF (2010) compared well flow rates from the 1973 Nelson and Sidlinger study, the 1992 study of Persram and the 1998 survey by AGRA. Most of the flowing wells have decreased flows over time (AITF, 2010).

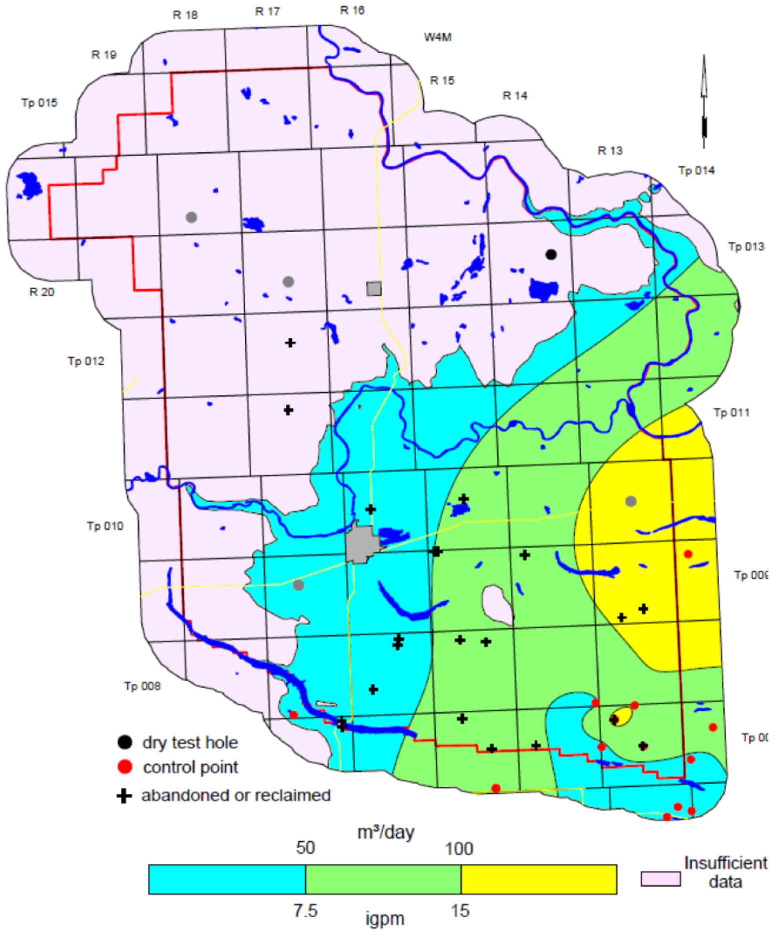


Figure 40: Apparent yield for water wells completed through the Milk River aquifer in the M.D. of Taber (HCL Consultants, 2007). See figure 4 for location of the municipal District of Taber.

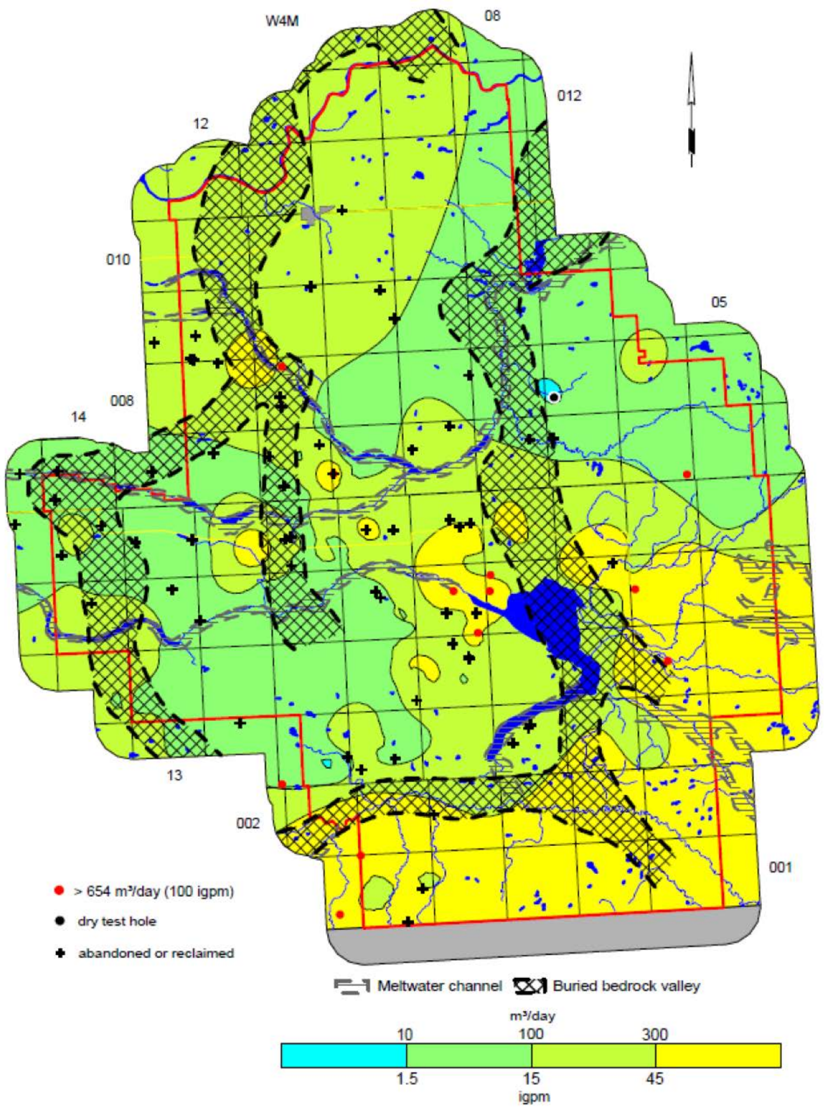


Figure 41: Apparent yield for water wells completed through the Milk River aquifer in Forty Mile County (HCL Consultants, 2004). See figure 4 for location of the county of Forty Mile.

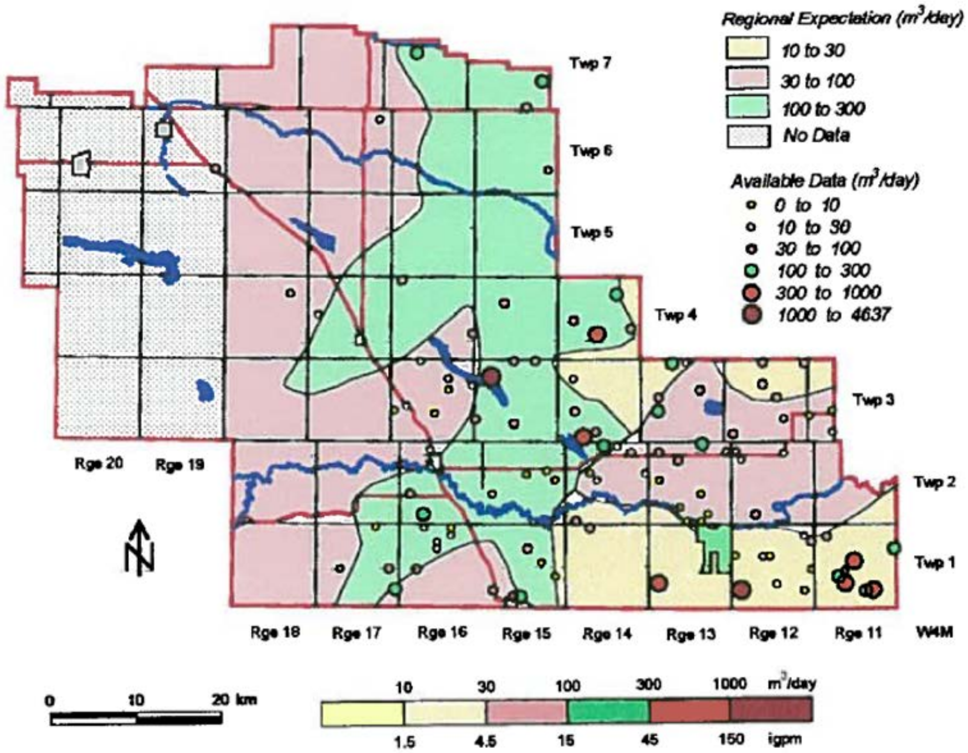


Figure 42: Apparent yield for water wells completed through the Milk River aquifer in the county of Warner (Stantec, 2002). See figure 4 for location of the county of Warner.

6.2 Groundwater use

The use of groundwater in southern Alberta is neither measured, nor monitored. Most of the existing data on groundwater use has been “estimated” based on permits and domestic and stock diversions.

Meyboom (1960) and Persram (1992, unpublished) have estimated the total groundwater use in southern Alberta (Table 7). Total water usage almost doubled between the late 1950s and the early 1990s. Meyboom (1960) estimated 16,000 head of cattle whereas Persram (1992) estimated 100,000 head. The term “water wastage” represents the unused water flowing to waste from flowing wells (AGRA 1998). There is an approximately 10% decrease in total water wastage between 1960 and 1992.

The Milk River aquifer is still solicited for domestic, agricultural, stock watering and municipal use. HCL consultants (2004 and 2007) provided groundwater use estimates in the county of Forty Mile (Table 8) and the M.D. of Taber (Table 9). Recent information collected during the 2012 and 2013 field work in southern Alberta seem to indicate that the global groundwater use from the Milk River aquifer may have diminished since the 2000s. This impression is based on the visited wells and surveys that were conducted during the field work. Additionally, an informal discussion with a driller from southern Alberta indicated that many wells drilled in the Milk River aquifer have been abandoned in the past 5 years. Further research, data collection and surveys are required in order to assess the current groundwater demand in the study area.

Use	Meyboom (1960)		Persram (1992, unpublished)	
	10^6 Cgal/year	10^6 m^3/year	10^6 Cgal/year	10^6 m^3/year
Livestock	**146**	**0.66**	**361**	**1.64**
Domestic	**40**	**0.18**	**36**	**0.16**
Municipal	**7 (Foremost)**	**0.03**	**Included in domestic**	
Total Usage	**193**	**0.87**	**397**	**1.8**
Total Consumption including flow to waste	**256**	**1.16**	**456**	**2.07**
Total wastage	**65 (25%)**	**0.29**	**59 (13%)**	**0.27**

Table 7: Comparison of water use in 1960 and in 1992 (modified from AGRA, 1998). The apparent decrease in domestic water use from 1960 to 1992 may be related in part to a general movement off the land between 1960 and 1992, and in part to slightly different boundaries of the areas surveyed in 1960 and 1992 (AGRA, 1998) (Cgal/year means Canadian gallons per year).

Aquifer Designation	Groundwater Diversions from Water Wells With or Without Licences and/or Registrations: Number of Domestic	Daily Use (0.5 m³/day)	Number of Stock	Daily Use (2.5 m³/day)	Number of Domestic and Stock	Daily Use (3.0 m³/day)	Totals m³/day	Groundwater Diversions With Licences and/or Registrations: Totals (m³/day)	Groundwater Diversions Without Licences and/or Registrations: Totals m³/day
Multiple Surficial Completions	1	0	0	0	0	0	0	0	0
Upper Sand and Gravel	292	140	187	471	481	1,442	2,052	38	2,014
Lower Sand and Gravel	9	4	7	18	10	30	52	0	52
Mulitple Bedrock Completion	23	11	19	48	49	147	206	4	202
Oldman	1	0	2	5	2	6	12	0	12
Foremost	51	24	46	116	75	225	365	10	355
Lea Park (Pakowki)	6	3	2	5	10	30	38	0	38
Milk River	168	80	121	305	416	1,247	1,632	888	744
Colorado Shale	1	0	0	0	1	3	3	2	1
Viking	0	0	1	3	1	3	6	0	6
Unknown	40	19	17	43	17	51	113	196	0
	592	281	402	1,014	1,062	3,184	4,479	1,138	3,424

(1) The values given in the table have been rounded and, therefore, the columns and rows may not add up equally

Table 8: Total groundwater diversions by aquifer in the County of Forty Mile, Alberta (HCL Consultants, 2004).

Aquifer Designation	Domestic and Domestic/Stock Diversions					Licensed and/or Registered Groundwater Diversions	Total Groundwater Diversions
	Number of Domestic	Daily Use (2.6 m^3/day)	Number of Domestic and Stock	Daily Use (2.6 m^3/day)	Totals m^3/day	Totals (m^3/day)	Totals (m^3/day)
Upper Sand and Gravel	149	387	164	426	814	628	1442
Lower Sand and Gravel	7	18	3	8	26	7	33
Mulitple Bedrock Completion	3	8	18	47	55	35	90
Bearpaw	0	0	1	3	3	2	5
Oldman	17	44	9	23	68	0	68
Foremost	22	57	20	52	109	35	145
Lea Park	0	0	0	0	0	0	0
Milk River	31	81	53	138	218	116	335
Saline	0	0	2	5	5	297	303
Unknown	28	73	8	21	94	55	149
Totals (1)	257	668	278	723	1391	1,177	2,568

(1) The values given in the table have been rounded and, therefore, the columns and rows may not add up equally

Table 9: Total groundwater diversions by aquifer in the M.D. of Taber, Alberta (HCL Consultants, 2007).

6.3 Sustainability and management of the groundwater resources

The Alberta Research Council (ARC) started investigations of the Milk River aquifer in the middle and late 1950's. The monitoring of water levels in an observation well at Foremost began in 1957 (AGRA, 1998).

In 1960, Meyboom published a comprehensive report on the geology and groundwater resources of the Milk River sandstone in which he pointed out that there had been depletion of the Milk River aquifer since development started. He mentioned that on the average, the piezometric surface had been lowered 20 feet since 1937 and, in some areas of heavy withdrawal (Pakowki Lake, Foremost); this value could reach 100 feet. Meyboom (1960) estimated that "At the present rate of withdrawal from storage and with very careful development, this reserve should last 200 years. In local cases, depletion will be reached sooner." He recommended carrying out an extensive conservation program in order to assure a continuing water supply from the Milk River sandstone.

Following Meyboom's study, the Alberta Research Council began a program of hydrogeological investigations in order to map the hydrogeology of Alberta on a scale of 1:250,000 by National Topographic Survey (NTS) (AGRA, 1998). Areas of the Milk River Aquifer studied by this program are documented by Tokarsky (1974) in the Lethbridge area, and Borneuf (1976) in the Foremost area.

Borneuf (1976) deplored the "gross mismanagement" of the water in the Milk River sandstone, as many wells completed in the Milk River sandstone have been allowed to flow freely. He indicated that some wells have been flowing for over 60 years and regretted this "unnecessary waste." For example, the well in the vicinity of the Pakowki Lake, which discharged freely for 25 years at 50 gpm (3.8 l/s), would result in 660 000 000 gallons (2,545,000 m^3) of water being wasted (Borneuf, 1976).

In 1992, the County Task Force was created by well owners concerned by the chronic water shortages in some areas of the County of Forty Mile. The Task Force recognized the importance of the Milk River aquifer as a regional water supply source, and the need for orderly water development planning. Since 1997, the Task Force was assisted financially by PFRA which had a program to help owners in properly abandoning unused wells.

In 1998, the County task Force hired a consultant (AGRA Earth and Environmental Limited) to assess the current hydrogeological state of the Milk River aquifer.
The 1998 AGRA's depletion study showed the areas of most severe water level decline between the late 1950's and the 1980's-1990's period. The change in Milk River aquifer

water levels is shown on a map in Figure 43. The map shows that the most recent water levels (1998) were considerably lower over most of the central and northern parts of the area. The aquifer depletion is most prominent in the central and northern parts of the study area than near the Pakowki Lake and in areas to the south. This study also pointed out that the Town of Foremost is the highest known water user in the area. They estimated that the Milk River aquifer could supply town needs (assuming no increase from current usage) for at least another 70 years. The total water usage from 1960 to 1992 approximately doubled. The total water wastage, represented by unused water flowing to waste from flowing wells was estimated to be about 288 million liters per year (112 igpm or 508 l/min) in 1992. This volume is estimated to be about 10% less than that being wasted in the early 1960's.

AGRA (1998) recommended several mitigation options, or strategies, in order to reduce or halt the Milk River Aquifer depletion:

1) Form a groundwater Management Committee.
2) Public Education and Awareness Program through the Groundwater Management Committee.
3) Change and enforce existing water well regulations and water well licensing to control flows from all actively used flowing wells drilled in the Milk River Aquifer.
4) Identify and decommission all unused wells, following the water well regulations.
5) Establish a long term monitoring program which would address both changes in aquifer water levels and water quality.

Following AGRA's recommendations, the Milk River Aquifer Reclamation and Conservation program was launched from 1999 to 2004. This 5 year program was established by Alberta Environment, Agriculture & Agri-Food Canada and the County of Forty Mile. This program included four components as following: education and awareness; a field survey of over 1,000 water wells to determine risks posed to the aquifer; proper sealing of unused wells; and monitoring of changes in water levels and water quality to evaluate the impact of the program (Printz, 2004).

Open houses have been held in several places to inform rural resident on the Milk River aquifer and raise awareness of the benefits of sealing unused wells. A well identification field survey was conducted to locate over 1000 water wells and to conduct a detailed questionnaire with landowners. Water samples were taken for about 10% of the wells for water quality analysis.

With the participation of local drilling companies, a total of 101 unused Milk River aquifer wells were cemented during the program. Of the 101 wells, 22 were flowing to the surface, wasting approximately 13 million gallons (59,735 m^3) of water per year (Printz, 2004).

About 79 unused, non-flowing wells have been decommissioned, reducing the risk of local contamination of the aquifer.

Concerning the monitoring component, water level measurements were obtained for 69 of the wells and another 218 wells were observed to be flowing to ground surface (Printz, 2004).

A summary report of the conservation program was published by PFRA (Printz, 2004). However, no detailed report interpreting the collected data has ever been finalized. The Geological Survey of Canada obtained some of the raw data from the Conservation program (estimated and measured values of water levels, location of the decommissioned wells). The location of the 101 decommissioned wells during the 1999-2004 reclamation and conservation program is represented on Figure 44.

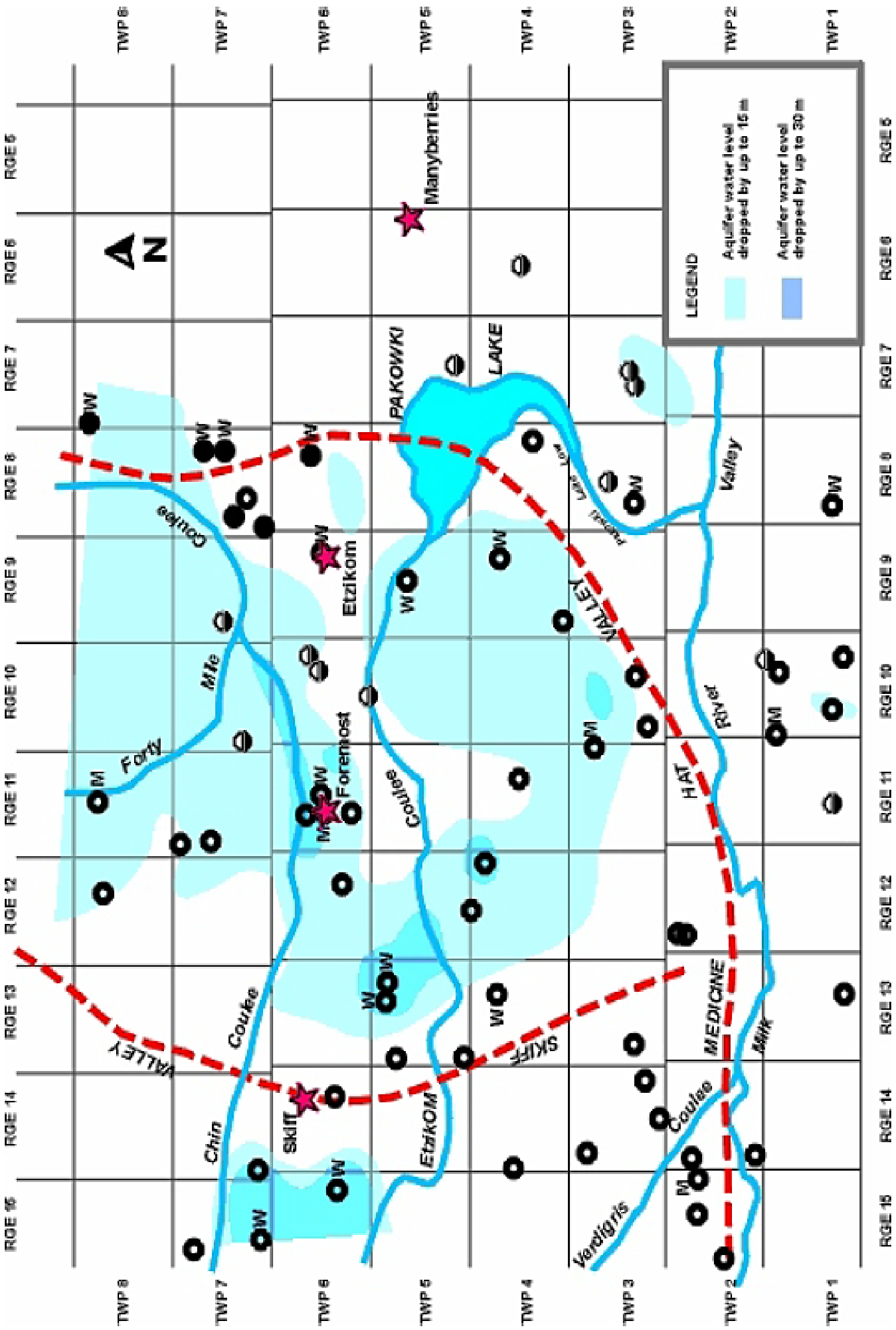


Figure 43: Depletion areas in southern Alberta (AGRA, 1998).

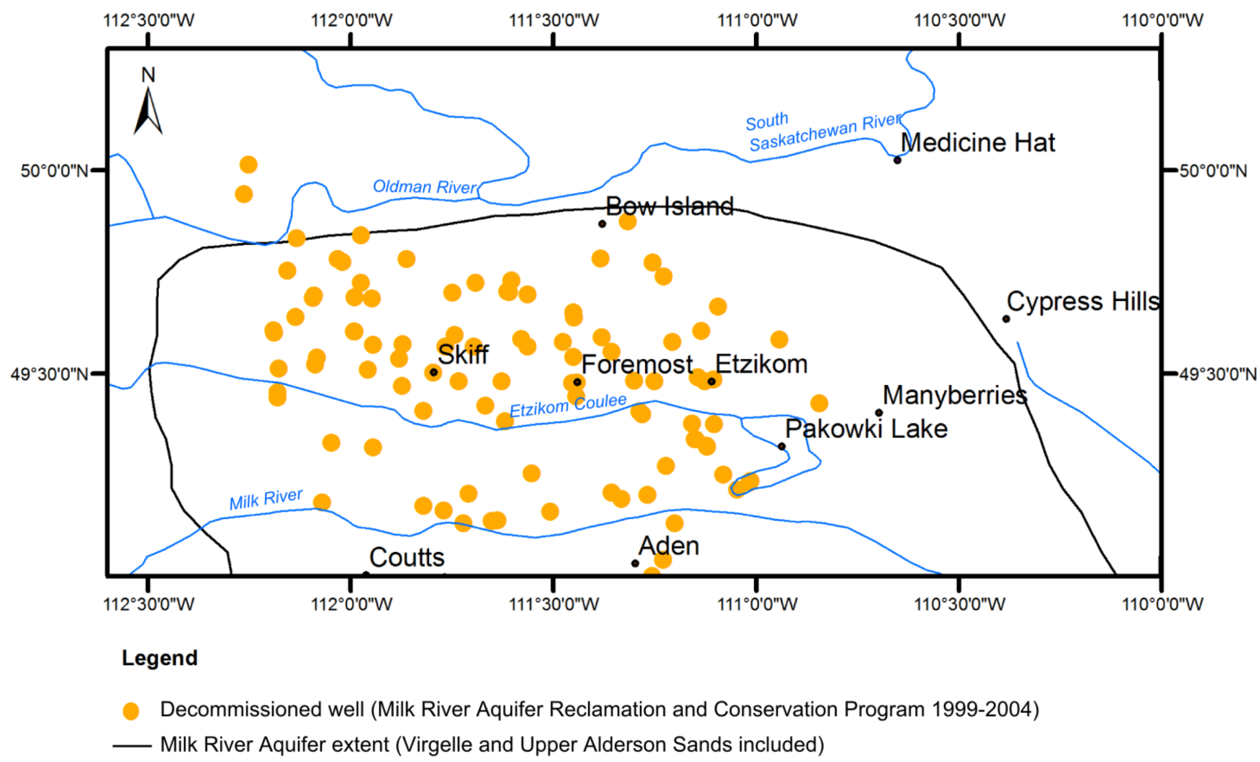


Figure 44: Location of the 101 decommissioned wells during the 1999-2004 Milk River Aquifer Reclamation and Conservation Program.

Conclusions

The Milk River transboundary aquifer has been the subject of many studies since the early 20th century. All the studies were completed on only one side or the other of the international border. This report presents a first synthesis of the groundwater knowledge of the aquifer on both sides of the border. The objective of this synthesis is to integrate published geological, hydrogeological and geochemical studies of the Milk River transboundary aquifer in order to present a unified portrait of the aquifer.

The integration and analysis of the many sources of data and existing information presented in this synthesis has revealed discrepancies in the understanding of some concepts related to the recharge and discharge mechanisms, the age of groundwater, the hydro-stratigraphic nature and continuity of the sandstone aquifer, the hydraulic connections with other geological layers, and the sustainable use of groundwater.

The Milk River Transboundary Aquifer Project proposes an extension of the aquifer through the international border to evaluate its transboundary nature. This work proposes a specific stratigraphic correlation based on more recent works, carried out to identify the equivalent geological layers on both sides of the international border.

The integration of previous data allows a better understanding of the transboundary aspects of the aquifer and will be used as basis to generating a conceptual model; the ultimate goal being the evaluation of the availability and sustainability of groundwater with a three-dimensional hydrogeological model. The current study will try to resolve some of the discrepancies found in previous works using the unified geological model, a proposed conceptual model, and a 3D numerical model.

References

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

Alberta Innovates Technology Future, 2010. Milk River Aquifer Hydrogeology Report.

Andrews JN, Drimmie RJ, Loosli HH, Hendry MJ, 1991a. Dissolved gases in the Milk River aquifer, Alberta, Canada. Applied Geochemistry 6:393–403. doi: 10.1016/0883-2927(91)90039-R.

Andrews JN, Florkowski T, Lehmann BE, Loosli HH, 1991b. Underground production of radionuclides in the Milk River aquifer, Alberta, Canada. Applied Geochemistry 6:425–434. doi: 10.1016/0883-2927(91)90042-N.

Anna LO, 2011. Effects of groundwater flow on the distribution of biogenic gas in parts of the northern Great Plains of Canada and United States. U.S. Geological Survey.

Armstrong SC, Sturchio NC, Hendry MJ, 1998. Strontium isotopic evidence on the chemical evolution of pore waters in the Milk River Aquifer, Alberta, Canada. Applied Geochemistry 13:463–475. doi: 10.1016/S0883-2927(97)00080-2.

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

Atkinson N, Lyster S, 2010b. Thickness and Distribution of Quaternary and Neogene Sediment in Alberta, Canada (Gridded data, ASCII format). Digital Data 2010-0036. Alberta Geological Survey.

Berkenpas PG (1991). The Milk River Shallow Gas Pool: Role of the Updip Water Trap and Connate Water in Gas Production From the Pool. doi: 10.2118/22922-MS.

Borneuf DM, 1974. Hydrogeological map Foremost, Alberta : NTS mapsheets 72E.

Borneuf DM, 1976. Hydrogeology of the Foremost Area. Alberta, Alberta Research Council, Edmonton, Alberta.

Cobban WA, 1950. Telegraph Creek Formation of Sweet Grass Arch, North-Central Montana: GEOLOGICAL NOTES. AAPG Bulletin 34:1899–1900.

Collier AJ, 1930. Contributions to economic geology (short papers and preliminary reports), 1929, Part II, Mineral fuels. The Kevin-Sunburst oil field and other possibilities of oil and gas in the Sweet Grass arch, Montana. United States Geological Survey.

Diersch H-JG, 2014. FEFLOW: finite element modeling of flow, mass and heat transport in porous and fractured media. Springer, 996 p

Domenico PA, Robbins GA, 1985. The displacement of connate water from aquifers. Geological Society of America Bulletin - GEOL SOC AMER BULL. DOI: 10.1130/0016-7606(1985)962.0.CO;2.

Dormaar JF, 2010. The Alberta Stretch of the Milk River and the Mystique of Its Surrounding Landscape. Lethbridge Historical Society

Doormaar JF, 2003. Sweet Grass Hills: A Natural and Cultural History. Lethbridge Historical Society.

Dowling DB, 1915. Water supply, southeastern Alberta. Summary Report 1915; Geological Survey of Canada, Summary Report (1915), 1916; p. 102-110.

Dowling DB, 1917. Southern plains of Alberta. Geological Survey of Canada, “A” Series Map 187A, 1917; 1 sheet, doi:10.4095/106740.

Dowling DB, 1923. Investigation of artesian water,coal,petroleum,and natural gas in Alberta. Geological Survey of Canada, Summary Report 1922, Part B.

Drimmie RJ, Aravena R, Wassenaar LI, et al., 1991, Radiocarbon and stable isotopes in water and dissolved constituents, Milk River aquifer, Alberta, Canada. Applied Geochemistry 6:381–392. doi: 10.1016/0883-2927(91)90038-Q,

Eberth DA, Hamblin AP, 1993. Tectonic, stratigraphic, and sedimentologic significance of a regional discontinuity in the upper Judith River Group (Belly River wedge) of southern Alberta, Saskatchewan, and northern Montana. Can J Earth Sci 30:174–200. doi: 10.1139/e93-016,

Environment Canada. Water Survey Canada. Water level and streamflow statistics
http://www.wsc.ec.gc.ca/staflo/index_e.cfm?cname=flow_monthly.cfm&first=1909&last=2011,

Evans, C. S., 1931. Milk River area and the Red Coulee Oil Field, Alberta. p. 1–30.

Fabryka-Martin J, Whittemore DO, Davis SN, et al., 1991. Geochemistry of halogens in the Milk River aquifer, Alberta, Canada. Applied Geochemistry 6:447–464. doi: 10.1016/0883-2927(91)90044-P,

Feltis RD, Lewis BD, Frasure RL, et al., 1981. Selected geologic data from the Northern Great Plains area of Montana. U.S. Geological Survey,

Fenton MM, Waters EJ, Pawley SM, et al., 2013. Surficial Geology of Alberta, 1:1,000,000 scale (GIS data, polygon features). Digital Data 2013-0002.

Fröhlich K, Ivanovich M, Hendry MJ, et al., 1991. Application of isotopic methods to dating of very old groundwaters: Milk River aquifer, Alberta, Canada. Applied Geochemistry 6:465–472. doi: 10.1016/0883-2927(91)90045-Q,

Gautier D, Rice D., 1982. Conventional and Low-Permeability Reservoirs of Shallow Gas in the Northern Great Plains. Journal of Petroleum Technology. doi: 10.2118/9846-PA,

Golder Associates L., 2004. Development of a Management/Protection plan for the Whisky Valley Aquifer, County of Warner, Alberta.

Government of Alberta, Alberta water for life, 2006. Water conservation and allocation guideline for oil field injection.

Hamblin AP, 1997. Regional Distribution and Dispersal of the Dinosaur Park Formation, Belly River Group, Surface and Subsurface of Southern Alberta. Bulletin of Canadian Petroleum Geology 45:377–399.

HCL consultants, 2003. Cardston County, Part of the South Saskatchewan and Missouri River Basins Regional Groundwater Assessment, Tp 001 to 007, R 19 to 29, 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.

Hendry J, Schwartz FW, Robertson C., 1991. Hydrogeology and hydrochemistry of the Milk River aquifer system, Alberta, Canada: a review. Applied Geochemistry 6:369–380. doi: 10.1016/0883-2927(91)90037-P.

Hendry MJ, Schwartz FW, 1988. An alternative view on the origin of chemical and isotopic patterns in groundwater from the Milk River Aquifer, Canada. Water Resour Res 24:1747–1763. doi: 10.1029/WR024i010p01747.

Hendry MJ, Schwartz FW, 1990. The Chemical Evolution of Ground Water in the Milk River Aquifer, Canada. Ground Water 28:253–261. doi: 10.1111/j.1745-6584.1990.tb02253.x.

Kemp JF, Billingsley P, 1921. Sweet Grass Hills, Montana. Geological Society of America Bulletin 32:437–478.

Lehmann BE, Loosli HH, Rauber D, et al., 1991. 81Kr and 85Kr in groundwater, Milk River aquifer, Alberta, Canada. Applied Geochemistry 6:419–423. doi: 10.1016/0883-2927(91)90041-M.

Lemay TG, Guha S., 2009. Compilation of Alberta groundwater information from existing maps and data sources; Energy Resources Conservation Board, ERCB/AGS Open File Report 2009-02, 43 p.

Levings GW, 1982. Potentiometric-surface map of water in the Eagle Sandstone and equivalent units in the Northern Great Plains area of Montana. United States Geological Survey.

Lies H, Letourneau J, 1995. Numerical Modelling of the Hydrodynamically Trapped Milk River Gas Field, Western Canada. Journal of Canadian Petroleum Technology 34.

Lopez, D. A., 2002. Geologic map of the Lonesome Lake 30’ x 60’ quadrangle, north-central Montana. Open-File Report 446. Montana Bureau of Mines and Geology, 2002.

Lorenz JC, 1981. Sedimentary and Tectonic History of the Two Medicine Formation, Late Cretaceous (Campanian), Northwestern Montana. Princeton University.

MacCulloch G, Wagner-Watchel J., 2010. Milk River Main Channel. Channel losses and gains assessment, Field study 2007. Preliminary Report. Environment Canada, Meteorological Service of Canada. Water Survey Division, Calgary, Alberta.

MacCulloch G, Wagner-Watchel J., 2011. Milk River Main Channel. Channel losses and gains assessment, Field study 2007. Supplementary Report. Environment Canada, Meteorological Service of Canada. Water Survey Division, Calgary, Alberta.

Meijer-Drees NC, Mhyr DW, 1981. The Upper Cretaceous Milk River and Lea Park Formations in Southeastern Alberta. Bulletin of Canadian Petroleum Geology 29:42–74.

Meyboom P, 1960. Geology and groundwater resources of the Milk River sandstone in southern Alberta. Research Council of Alberta.

MiRTAP, 2014. Geochemical data collected during fieldwork in this study (Milk River Transboundary Aquifer project), as presented in this open file.

Milk River Watershed Council Canada, 2008. Milk River State of the Watershed Report 2008.Milk River Watershed Council Canada. Milk River, Alberta. 155p.

Montana Geological Society, 2013. Northwest Geologic Service Sample Logs. Northern Rockies Geological Data Center.

MRWCC, 2010. Milk River Transboundary Aquifer Project. http://www.mrwcc.ca/index.php/projects/mirtap-milk-river-transboundary-aquifer-project/

Nelson MH, Sindlinger, 1973. Milk River sandstone water well survey, Alberta Dept. Of Environment report.

Nolte E, Krauthan P, Heim U, Korschinek G, 1990. 36Cl measurements and dating of groundwater samples from the Milk River aquifer. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 52:477–482. doi: 10.1016/0168-583X(90)90461-3.

Nolte E, Krauthan P, Korschinek G, et al., 1991. Measurements and interpretations of36Cl in groundwater, Milk River aquifer, Alberta, Canada. Applied Geochemistry 6:435–445. doi: 10.1016/0883-2927(91)90043-O.

O'Connell, S., 2014. The Milk River Transboundary Aquifer in Southern Alberta; Geological Survey of Canada, Open File 7751, 1 .zip file. doi:10.4095/295603

Okulitch AV, Lopez DA, Jerzykiewicz T., 1996. Bedrock geology, Lethbridge, Alberta-Saskatchewan-Montana.

Payenberg THD, 2002. Integration of the Alderson Member in southwestern Saskatchewan into a litho- and chronostratigraphic framework for the Milk River/Eagle coastline in southern Alberta and north-central Montana. In: Summary of Investigations 2002,Volume 1, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 2002-4.1.1.

Payenberg THD, Braman DR, Davis DW, Miall AD, 2002. Litho-and chronostratigraphic relationships of the Santonian-Campanian Milk River Formation in southern Alberta and Eagle Formation in Montana utilising stratigraphy, U-Pb geochronology, and palynology. Canadian Journal of Earth Sciences 39:1553–1577.

Payenberg THD, Braman DR, Miall AD, 2003. Depositional environments and stratigraphic architecture of the Late Cretaceous Milk River and Eagle formations, southern Alberta and north-central Montana: relationships to shallow biogenic gas. Bulletin of Canadian Petroleum Geology 51:155–176.

Payenberg THD, Miall AD, Braman DR, 2001. Sequence stratigraphy of the Milk River Formation in southern Alberta and Eagle Formation in northern Montana.

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).

Pétré, M-A., Rivera, A., and Lefebvre, R., 2012. A 3D unified geological conceptual model of the Milk River Transboundary Aquifer (Alberta-Montana). IAH 2012 World Congress. Niagara Falls, Canada. Special session on Transboundary Aquifers.

Pétré, M-A and Rivera, A., 2013. Science for informed decision: A 3D unified conceptual model of the Milk River Transboundary Aquifer (Alberta-Montana)**.** *AGU Fall Meeting*, San Francisco, 9-13 December 2013. American Geophysical Union poste**r** Session H097**.**

Pétré, M-A., Rivera, A. Lefebvre, R., and Ledoux, E., 2014. The 3D Geological Modeling of the Milk River Transboundary Aquifer: Challenges and Solutions. *NGWA Groundwater Summit* 2014, Denver, CO.

Pétré M-A, Rivera A, Lefebvre, R. 2015. 3D unified geological model of the Milk River Transboundary Aquifer (Alberta, Canada-Montana, USA). Canadian Journal of Earth Sciences. doi: 10.1139/cjes-2014-0079. [Just-IN version; Published online on January, 6th 2015].

Phillips F, Knowlton R, Bentley HW, 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 26:1693–1698.

Phillips FM, Bentley HW, Davis SN, et al., 1986. Chlorine 36 dating of very old groundwater: 2. Milk River Aquifer, Alberta, Canada. Water Resour Res 22:2003–2016. doi: 10.1029/WR022i013p02003.

Pierce WG, Hunt CB, 1937. Contributions to economic geology (short papers and preliminary reports), 1934-36. Geology and mineral resources of north-central Chouteau, western Hill, and eastern Liberty counties, Montana. United States Geological Survey.

Printz J., 2004. Milk River Aquifer Reclamation & Conservation Program 1999-2004 Summary Report.

Rice DD, 1980. Coastal and deltaic sedimentation of Upper Cretaceous Eagle Sandstone; relation to shallow gas accumulations, North-central Montana. AAPG Bulletin 64:316–338.

Rice DD, Claypool GE, 1981. Generation, accumulation, andresource potential of biogenic gas. AAPG Bulletin.

Rice DD, Cobban WA, 1977. Cretaceous stratigraphy of the Glacier National Park area, northwestern Montana. Bulletin of Canadian Petroleum Geology 25:828–841.

Rivera, A. (ed.), 2011. Groundwater Program Newsletter vol. 5, no. 1, 2011; 10 pages, doi:10.4095/290226. http://ftp2.cits.rncan.gc.ca/pub/geott/ess_pubs/290/290226/gwpn_v5.1_e.pdf

Rivera, A. (ed.), 2014. Regional Strategy for the Assessment and Management of Transboundary Aquifer Systems (TAS) in the Americas. A *UNESCO publication.* PHI-VIII/Serie ISARM Américas, N^{o} 4. 201pp. ISBN 978-92-9089-196-3.

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 Dept Of Geology.

Russell LS, 1970. Correlation of the Upper Cretaceous Montana Group between southern Alberta and Montana. Canadian Journal of Earth Sciences 7:1099.

Russell LS, Landes RW, 1940. Geology of the southern Alberta Plains. 219 pages.

Schwartz FW, Muehlenbachs K., 1979. Isotope and ion geochemistry of groundwaters in the Milk River Aquifer, Alberta. Water Resources Research 15:259–268. doi:10.1029/WR015i002p00259.

Stantec, 2002. Regional groundwater assessment of potable groundwater in county of Warner No5, Alberta. County of Warner No5.

Stanton TW, Hatcher JB, Knowlton FH, 1905. Geology and paleontology of the Judith River beds. United States Geological Survey.

Stebinger E., 1916. Anticlines in the Blackfeet Indian Reservation, Montana.

Stebinger E., 1914. The Montana group of northwestern Montana. Washington : Gov. Printing. Office.

Stebinger E., 1917. Possibilities of Oil and Gas in North-central Montana. U.S. Government Printing Office.

Swanick GB, 1982. The hydrochemistry and age of the water in the Milk River aquifer, Alberta, Canada.

Thompson RE, 1986. Natural flow and Water consumption in the Milk River Basin, Montana and Alberta, Canada. US Geological Survey water-resources investigation Report 86-4006.

Tokarsky O., 1974. Hydrogeology of the Lethbridge-Fernie area, Alberta. Alberta Research.

Toth J., and Corbet T., 1987. Post-Palaeocene evolution of regional groundwater flow systems and their relation to petroleum accumulations, Taber Area, southern Alberta, Canada. Special publication - Geological Society of London 34:45–77.

Tovell WM, 1956. Some Aspects of the Geology of the Milk River and Pakowki Formations (Southern Alberta). Thesis, University of Toronto.

Tuck LK, 1993. Reconnaissance of geology and water resources along the north flank of the Sweet Grass Hills, north-central Montana. U.S. Geological Survey.

USGS/ESS Project Annex 26, 2013. Groundwater monitoring and water quality sampling within the Milk River watershed, Montana, United States. This is a project annex to the Memorandum of Cooperation signed on April 9, 1999, and the Letter of Exchange signed February 13th and March 10th, 2004, between the Earth Sciences Sector (Natural Resources Canada) and the USGS. This project annex was approved in accordance with Article VI of the Memorandum of Cooperation.

Weed WH, 1899. Fort Benton folio, Montana. 7 pages.

Williams MY, Dyer WS, 1930. Geology of southern Alberta and southwestern Saskatchewan Memoir 163 Geological Survey of Canada.

Zimmerman E., 1967. Water resources of the Cut Bank area, Glacier and Toole Counties, Montana. Montana Bureau of Mines and Geology.

Annex A

United Nations A/RES/68/118 **General Assembly** Distr.: General 19 December 2013 **Sixty-eighth session** Agenda item 87

68/118. The law of Transboundary Aquifers

Resolution adopted by the General Assembly on 16 December 2013

[On the report of the Sixth Committee (A/68/470)]

The General Assembly,

Recalling its resolutions 63/124 of 11 December 2008 and 66/104 of 9 December 2011,

Noting the major importance of the subject of the law of transboundary aquifers in the relations of States and the need for reasonable and proper management of transboundary aquifers, a vitally important natural resource, through international cooperation for present and future generations,

Noting also that the provisions of the draft articles on the law of transboundary aquifers have been taken into account in relevant instruments such as the Guarani Aquifer Agreement signed by Argentina, Brazil, Paraguay and Uruguay on 2 August 2010, and the Model Provisions on Transboundary Groundwaters adopted by the sixth Meeting of the Parties to the Convention on the Protection and Use of Transboundary Watercourses and International Lakes on 29 November 2012,

Emphasizing the continuing importance of the codification and progressive development of international law, as referred to in Article 13, paragraph 1 (*a*), of the Charter of the United Nations,

Noting the comments of Governments and the discussion held in the Sixth Committee at the sixty-third, sixty-sixth and sixty-eighth sessions of the General Assembly on this topic,

1. *Commends* to the attention of Governments the draft articles on the law of transboundary aquifers annexed to the present resolution as guidance for bilateral or regional agreements and arrangements for the proper management of transboundary aquifers;

2. *Encourages* the International Hydrological Programme of the United Nations Educational, Scientific and Cultural Organization to continue its contribution by offering further scientific and technical assistance to the States concerned;

3. *Decides* to include in the provisional agenda of its seventy-first session the item entitled “The law of transboundary aquifers”.

68th plenary meeting 16 December 2013

Annex

The law of transboundary aquifers

…

Conscious of the importance for humankind of life-supporting groundwater resources in all regions of the world,

Bearing in mind Article 13, paragraph 1 (*a*), of the Charter of the United Nations, which provides that the General Assembly shall initiate studies and make recommendations for the purpose of encouraging the progressive development of international law and its codification,

Recalling General Assembly resolution 1803 (XVII) of 14 December 1962 on permanent sovereignty over natural resources,

Reaffirming the principles and recommendations adopted by the United Nations Conference on Environment and Development of 1992 in the Rio Declaration on Environment and Development1 and Agenda 21,[2]

Taking into account increasing demands for freshwater and the need to protect groundwater resources,

Mindful of the particular problems posed by the vulnerability of aquifers to pollution,

Convinced of the need to ensure the development, utilization, conservation, management and protection of groundwater resources in the context of the promotion of the optimal and sustainable development of water resources for present and future generations,

Affirming the importance of international cooperation and good-neighbourliness in this field,

Emphasizing the need to take into account the special situation of developing countries,

Recognizing the necessity to promote international cooperation, …

[1] *Report of the United Nations Conference on Environment and Development, Rio de Janeiro, 3–14 June 1992*, vol. I, *Resolutions Adopted by the Conference* (United Nations publication, Sales No. E.93.I.8 and corrigendum), resolution 1, annex I.

[2] Ibid., annex II.

Part one
Introduction

Article 1
Scope

The present articles apply to:
(*a*) Utilization of transboundary aquifers or aquifer systems;
(*b*) Other activities that have or are likely to have an impact upon such aquifers or aquifer systems; and
(*c*) Measures for the protection, preservation and management of such aquifers or aquifer systems.

Article 2
Use of terms

For the purposes of the present articles:

(*a*) "aquifer" means a permeable water-bearing geological formation underlain by a less permeable layer and the water contained in the saturated zone of the formation;

(*b*) "aquifer system" means a series of two or more aquifers that are hydraulically connected;

(*c*) "transboundary aquifer" or "transboundary aquifer system" means, respectively, an aquifer or aquifer system, parts of which are situated in different States;

(*d*) "aquifer State" means a State in whose territory any part of a transboundary aquifer or aquifer system is situated;

(*e*) "utilization of transboundary aquifers or aquifer systems" includes extraction of water, heat and minerals, and storage and disposal of any substance;

(*f*) "recharging aquifer" means an aquifer that receives a non-negligible amount of contemporary water recharge;

(*g*) "recharge zone" means the zone which contributes water to an aquifer, consisting of the catchment area of rainfall water and the area where such water flows to an aquifer by run-off on the ground and infiltration through soil;

(*h*) "discharge zone" means the zone where water originating from an aquifer flows to its outlets, such as a watercourse, a lake, an oasis, a wetland or an ocean.

Part two
General principles

Article 3
Sovereignty of aquifer States

Each aquifer State has sovereignty over the portion of a transboundary aquifer or aquifer system located within its territory. It shall exercise its sovereignty in accordance with international law and the present articles.

Article 4
Equitable and reasonable utilization

Aquifer States shall utilize transboundary aquifers or aquifer systems according to the principle of equitable and reasonable utilization, as follows:

(*a*) They shall utilize transboundary aquifers or aquifer systems in a manner that is consistent with the equitable and reasonable accrual of benefits therefrom to the aquifer States concerned;
(*b*) They shall aim at maximizing the long-term benefits derived from the use of water contained therein;
(*c*) They shall establish individually or jointly a comprehensive utilization plan, taking into account present and future needs of, and alternative water sources for, the aquifer States; and
(*d*) They shall not utilize a recharging transboundary aquifer or aquifer system at a level that would prevent continuance of its effective functioning.

Article 5
Factors relevant to equitable and reasonable utilization

1. Utilization of a transboundary aquifer or aquifer system in an equitable and reasonable manner within the meaning of article 4 requires taking into account all relevant factors, including:

(*a*) The population dependent on the aquifer or aquifer system in each aquifer State;
(*b*) The social, economic and other needs, present and future, of the aquifer States concerned;
(*c*) The natural characteristics of the aquifer or aquifer system;
(*d*) The contribution to the formation and recharge of the aquifer or aquifer system;
(*e*) The existing and potential utilization of the aquifer or aquifer system;
(*f*) The actual and potential effects of the utilization of the aquifer or aquifer system in one aquifer State on other aquifer States concerned;
(*g*) The availability of alternatives to a particular existing and planned utilization of the aquifer or aquifer system;
(*h*) The development, protection and conservation of the aquifer or aquifer system and the costs of measures to be taken to that effect;
(*i*) The role of the aquifer or aquifer system in the related ecosystem.

2. The weight to be given to each factor is to be determined by its importance with regard to a specific transboundary aquifer or aquifer system in comparison with that of other relevant factors. In determining what is equitable and reasonable utilization, all relevant factors are to be considered together and a conclusion reached on the basis of all the factors. However, in weighing different kinds of utilization of a transboundary aquifer or aquifer system, special regard shall be given to vital human needs.

Article 6
Obligation not to cause significant harm

1. Aquifer States shall, in utilizing transboundary aquifers or aquifer systems in their territories, take all appropriate measures to prevent the causing of significant harm to other aquifer States or other States in whose territory a discharge zone is located.

2. Aquifer States shall, in undertaking activities other than utilization of a transboundary aquifer or aquifer system that have, or are likely to have, an impact upon that transboundary aquifer or aquifer system, take all appropriate measures to prevent the causing of significant harm through that aquifer or aquifer system to other aquifer States or other States in whose territory a discharge zone is located.

3. Where significant harm nevertheless is caused to another aquifer State or a State in whose territory a discharge zone is located, the aquifer State whose activities cause such

harm shall take, in consultation with the affected State, all appropriate response measures to eliminate or mitigate such harm, having due regard for the provisions of articles 4 and 5.

Article 7
General obligation to cooperate

1. Aquifer States shall cooperate on the basis of sovereign equality, territorial integrity, sustainable development, mutual benefit and good faith in order to attain equitable and reasonable utilization and appropriate protection of their transboundary aquifers or aquifer systems.

2. For the purpose of paragraph 1, aquifer States should establish joint mechanisms of cooperation.

Article 8
Regular exchange of data and information

1. Pursuant to article 7, aquifer States shall, on a regular basis, exchange readily available data and information on the condition of their transboundary aquifers or aquifer systems, in particular of a geological, hydrogeological, hydrological, meteorological and ecological nature and related to the hydrochemistry of the aquifers or aquifer systems, as well as related forecasts.

2. Where knowledge about the nature and extent of a transboundary aquifer or aquifer system is inadequate, aquifer States concerned shall employ their best efforts to collect and generate more complete data and information relating to such aquifer or aquifer system, taking into account current practices and standards. They shall take such action individually or jointly and, where appropriate, together with or through international organizations.

3. If an aquifer State is requested by another aquifer State to provide data and information relating to an aquifer or aquifer system that are not readily available, it shall employ its best efforts to comply with the request. The requested State may condition its compliance upon payment by the requesting State of the reasonable costs of collecting and, where appropriate, processing such data or information.

4. Aquifer States shall, where appropriate, employ their best efforts to collect and process data and information in a manner that facilitates their utilization by the other aquifer States to which such data and information are communicated.

Article 9
Bilateral and regional agreements and arrangements

For the purpose of managing a particular transboundary aquifer or aquifer system, aquifer States are encouraged to enter into bilateral or regional agreements or arrangements among themselves. Such agreements or arrangements may be entered into with respect to an entire aquifer or aquifer system or any part thereof or a particular project, programme or utilization except insofar as an agreement or arrangement adversely affects, to a significant extent, the utilization by one or more other aquifer States of the water in that aquifer or aquifer system, without their express consent.

Part three
Protection, preservation and management

Article 10
Protection and preservation of ecosystems

Aquifer States shall take all appropriate measures to protect and preserve ecosystems within, or dependent upon, their transboundary aquifers or aquifer systems, including measures to ensure that the quality and quantity of water retained in an aquifer or aquifer system, as well as that released through its discharge zones, are sufficient to protect and preserve such ecosystems.

Article 11
Recharge and discharge zones

1. Aquifer States shall identify the recharge and discharge zones of transboundary aquifers or aquifer systems that exist within their territory. They shall take appropriate measures to prevent and minimize detrimental impacts on the recharge and discharge processes.
2. All States in whose territory a recharge or discharge zone is located, in whole or in part, and which are not aquifer States with regard to that aquifer or aquifer system, shall cooperate with the aquifer States to protect the aquifer or aquifer system and related ecosystems.

Article 12
Prevention, reduction and control of pollution

Aquifer States shall, individually and, where appropriate, jointly, prevent, reduce and control pollution of their transboundary aquifers or aquifer systems, including through the recharge process, that may cause significant harm to other aquifer States. Aquifer States shall take a precautionary approach in view of uncertainty about the nature and extent of a transboundary aquifer or aquifer system and of its vulnerability to pollution.

Article 13
Monitoring

1. Aquifer States shall monitor their transboundary aquifers or aquifer systems. They shall, wherever possible, carry out these monitoring activities jointly with other aquifer States concerned and, where appropriate, in collaboration with competent international organizations. Where monitoring activities cannot be carried out jointly, the aquifer States shall exchange the monitored data among themselves.

2. Aquifer States shall use agreed or harmonized standards and methodology for monitoring their transboundary aquifers or aquifer systems. They should identify key parameters that they will monitor based on an agreed conceptual model of the aquifers or aquifer systems. These parameters should include parameters on the condition of the aquifer or aquifer system as listed in article 8, paragraph 1, and also on the utilization of the aquifers or aquifer systems.

Article 14
Management

Aquifer States shall establish and implement plans for the proper management of their transboundary aquifers or aquifer systems. They shall, at the request of any of them, enter into consultations concerning the management of a transboundary aquifer or aquifer system. A joint management mechanism shall be established, wherever appropriate.

Article 15
Planned activities

1. When a State has reasonable grounds for believing that a particular planned activity in its territory may affect a transboundary aquifer or aquifer system and thereby may have a significant adverse effect upon another State, it shall, as far as practicable, assess the possible effects of such activity.

2. Before a State implements or permits the implementation of planned activities which may affect a transboundary aquifer or aquifer system and thereby may have a significant adverse effect upon another State, it shall provide that State with timely notification thereof. Such notification shall be accompanied by available technical data and information, including any environmental impact assessment, in order to enable the notified State to evaluate the possible effects of the planned activities.

3. If the notifying and the notified States disagree on the possible effect of the planned activities, they shall enter into consultations and, if necessary, negotiations with a view to arriving at an equitable resolution of the situation. They may utilize an independent fact-finding body to make an impartial assessment of the effect of the planned activities.

Part four
Miscellaneous provisions

Article 16
Technical cooperation with developing States

States shall, directly or through competent international organizations, promote scientific, educational, technical, legal and other cooperation with developing States for the protection and management of transboundary aquifers or aquifer systems, including, inter alia:

(*a*) Strengthening their capacity-building in scientific, technical and legal fields;
(*b*) Facilitating their participation in relevant international programmes;
(*c*) Supplying them with necessary equipment and facilities;
(*d*) Enhancing their capacity to manufacture such equipment;
(*e*) Providing advice on and developing facilities for research, monitoring educational and other programmes;
(*f*) Providing advice on and developing facilities for minimizing the detrimental effects of major activities affecting their transboundary aquifer or aquifer system;
(*g*) Providing advice in the preparation of environmental impact assessments;
(*h*) Supporting the exchange of technical knowledge and experience among developing States with a view to strengthening cooperation among them in managing the transboundary aquifer or aquifer system.

Article 17
Emergency situations

1 For the purpose of the present article, “emergency” means a situation, resulting suddenly from natural causes or from human conduct, that affects a transboundary aquifer or aquifer system and poses an imminent threat of causing serious harm to aquifer States or other States.

2. The State within whose territory the emergency originates shall:

(*a*) Without delay and by the most expeditious means available, notify other potentially affected States and competent international organizations of the emergency;

(*b*) In cooperation with potentially affected States and, where appropriate, competent international organizations, immediately take all practicable measures necessitated by the circumstances to prevent, mitigate and eliminate any harmful effect of the emergency.

3. Where an emergency poses a threat to vital human needs, aquifer States, notwithstanding articles 4 and 6, may take measures that are strictly necessary to meet such needs.

4. States shall provide scientific, technical, logistical and other cooperation to other States experiencing an emergency. Cooperation may include coordination of international emergency actions and communications, making available emergency response personnel, emergency response equipment and supplies, scientific and technical expertise and humanitarian assistance.

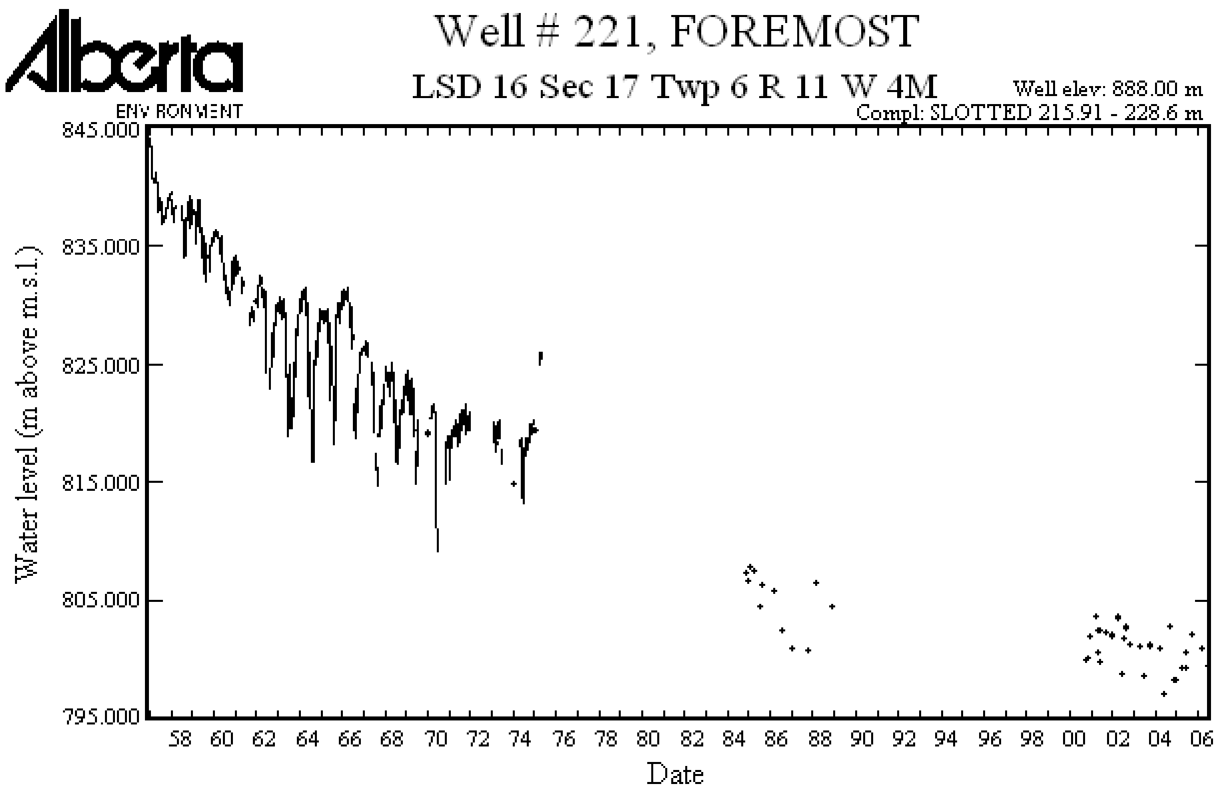
Article 18
Protection in time of armed conflict

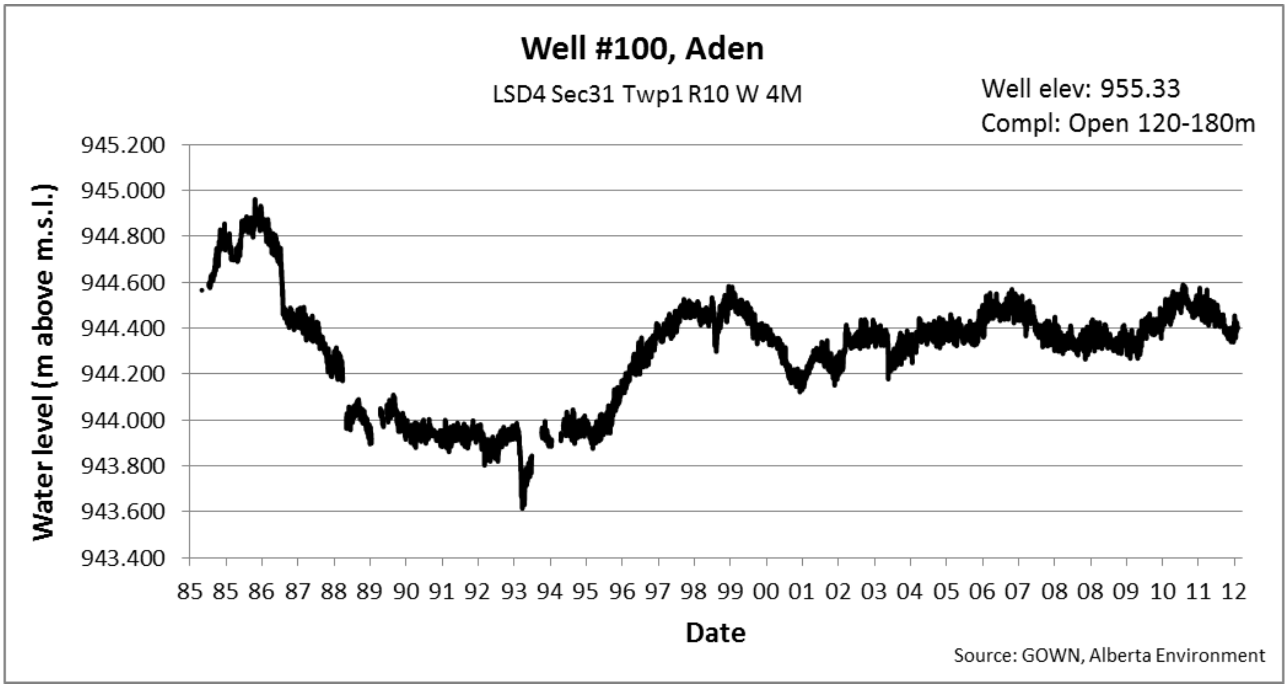
Transboundary aquifers or aquifer systems and related installations, facilities and other works shall enjoy the protection accorded by the principles and rules of international law applicable in international and non-international armed conflict and shall not be used in violation of those principles and rules.

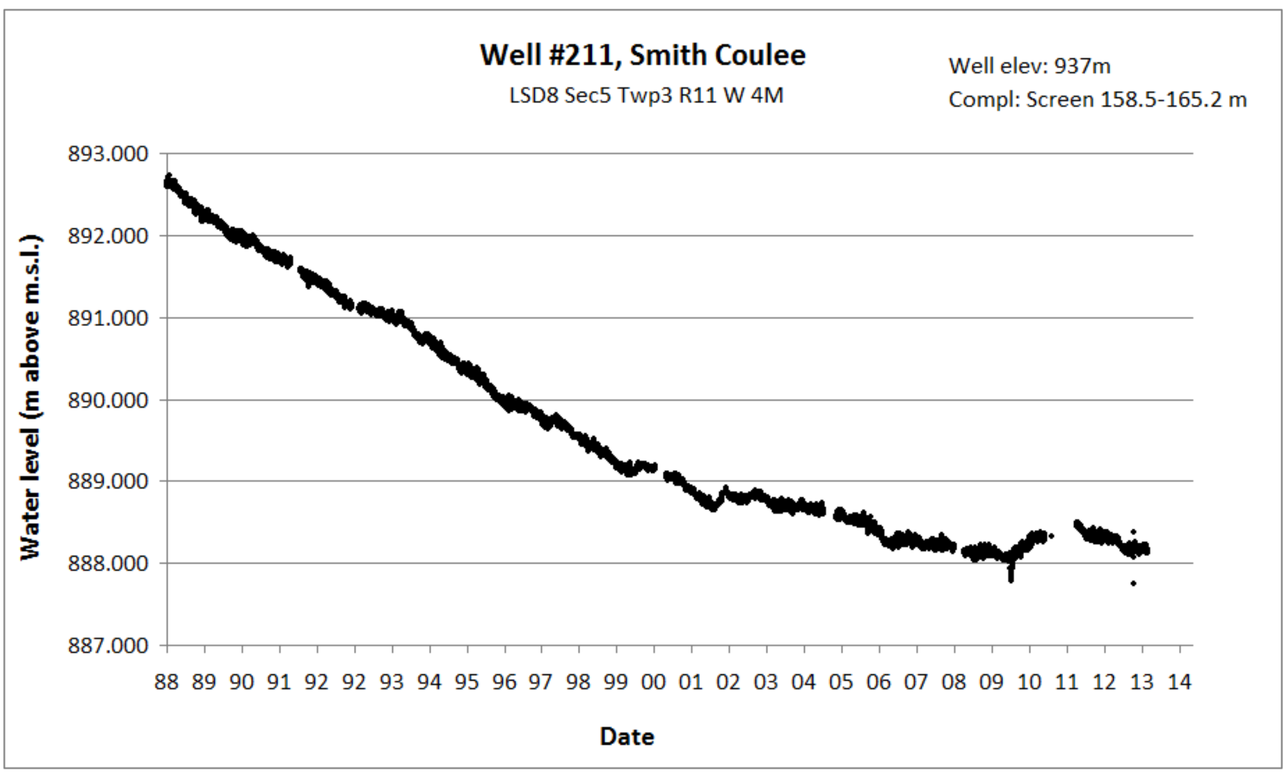
Article 19
Data and information vital to national defence or security

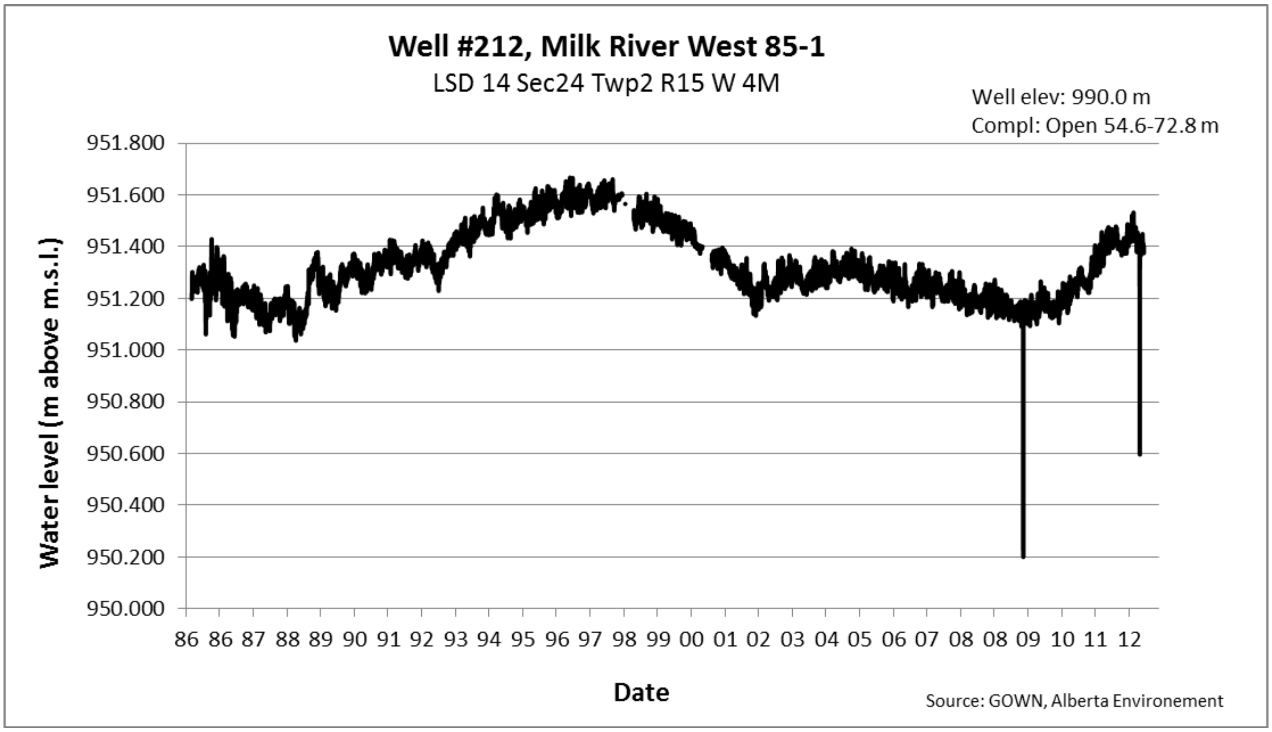
Nothing in the present articles obliges a State to provide data or information vital to its national defence or security. Nevertheless, that State shall cooperate in good faith with other States with a view to providing as much information as possible under the circumstances.

Annex B
Hydrographs of the Milk River Aquifer observation wells

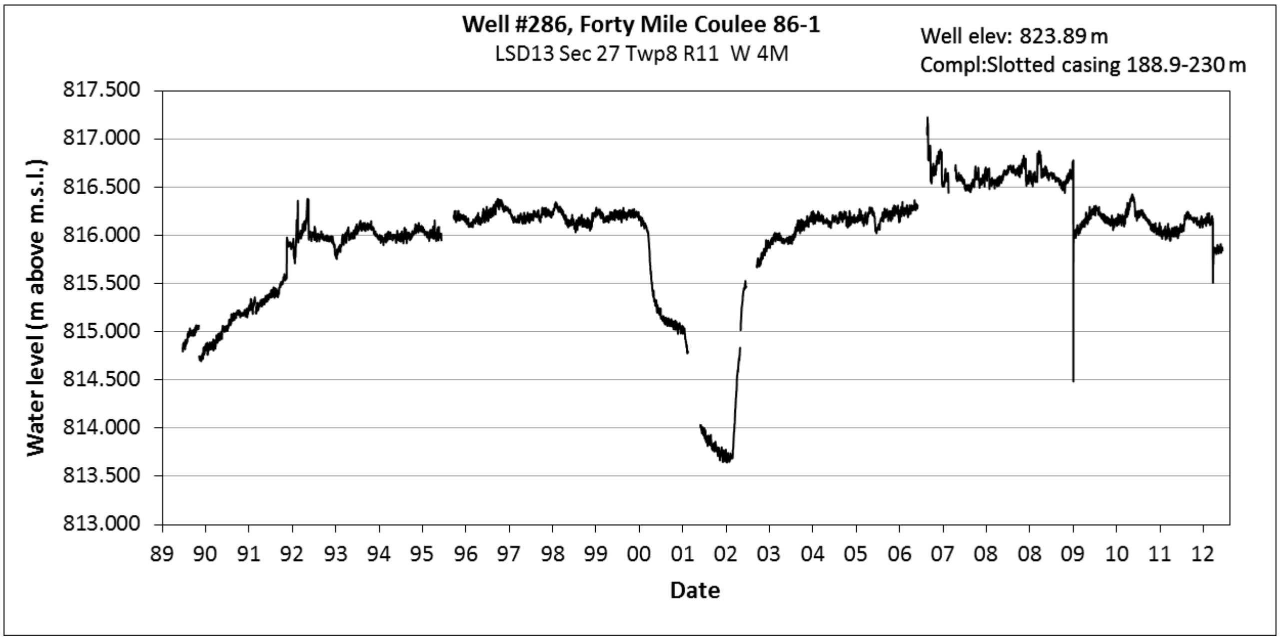


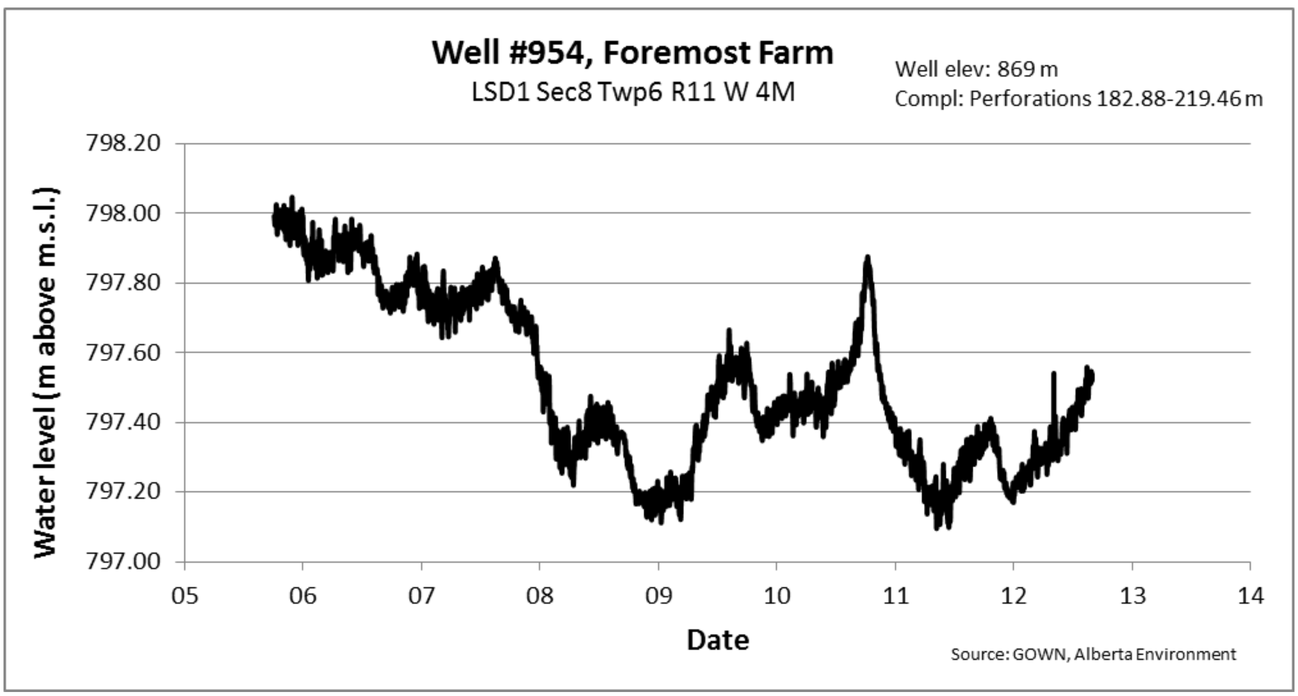

Well #100, Aden
LSD4 Sec31 Twp1 R10 W 4M
Well elev: 955.33
Compl: Open 120-180m
Water level (m above m.s.l.)
945.200
945.000
944.800
944.600
944.400
944.200
944.000
943.800
943.600
943.400
85 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 08 09 10 11 12
Date
Source: GOWN, Alberta Environment

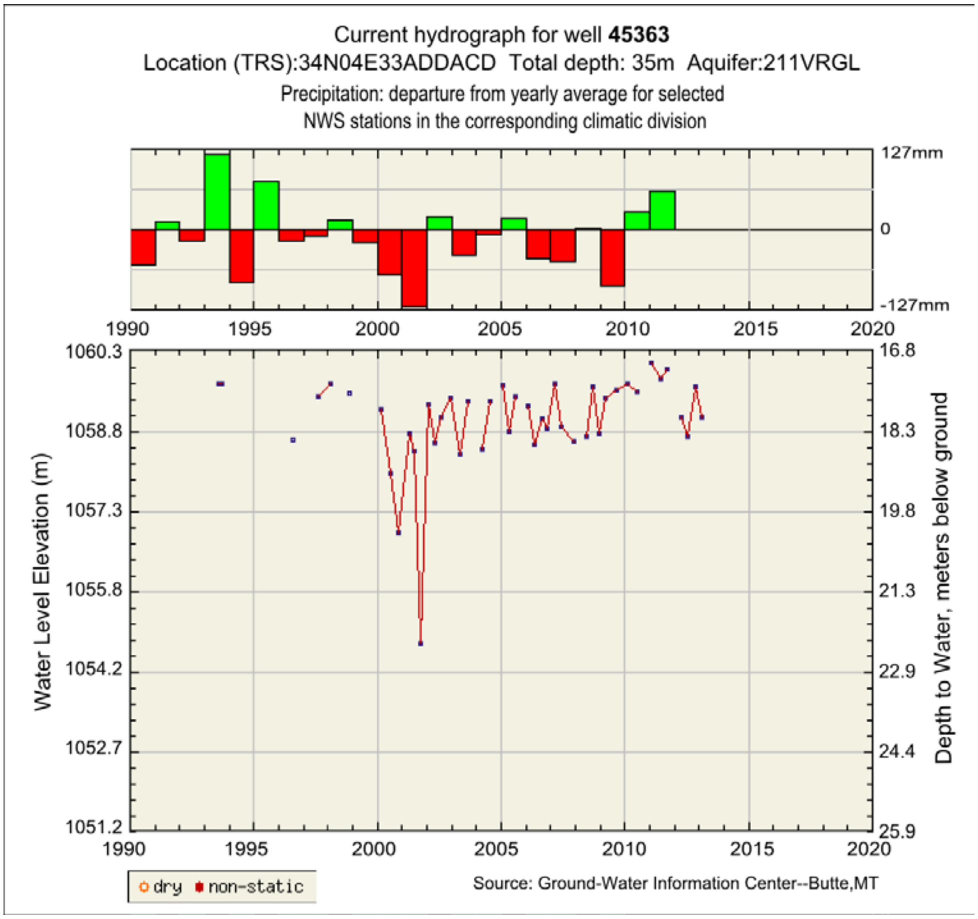

Well #211, Smith Coulee
LSD8 Sec5 Twp3 R11 W 4M
Well elev: 937m
Compl: Screen 158.5-165.2 m
Water level (m above m.s.l.)
893.000
892.000
891.000
890.000
889.000
888.000
887.000
88 89 90 91 92 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14
Date

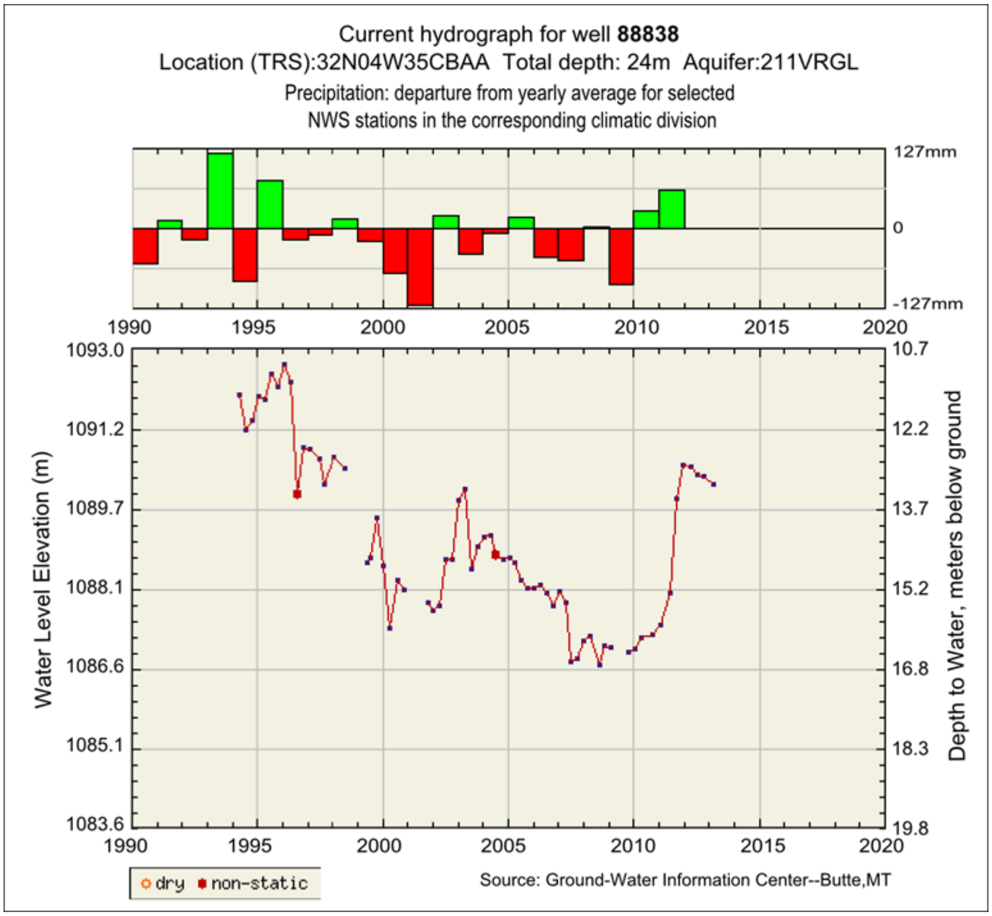


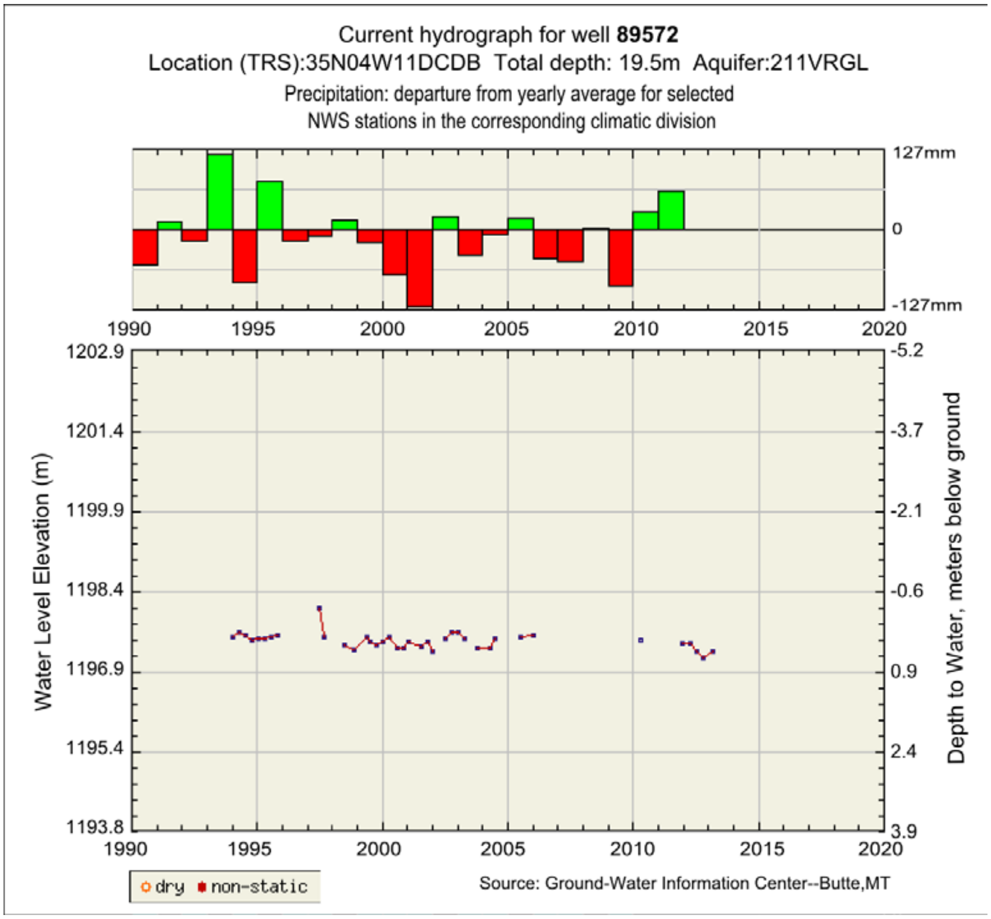
Well #212, Milk River West 85-1
LSD 14 Sec24 Twp2 R15 W 4M
Well elev: 990.0 m
Compl: Open 54.6-72.8 m
Water level (m above m.s.l.)
951.800
951.600
951.400
951.200
951.000
950.800
950.600
950.400
950.200
950.000
86 86 87 88 89 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 08 09 10 11 12
Date
Source: GOWN, Alberta Environement

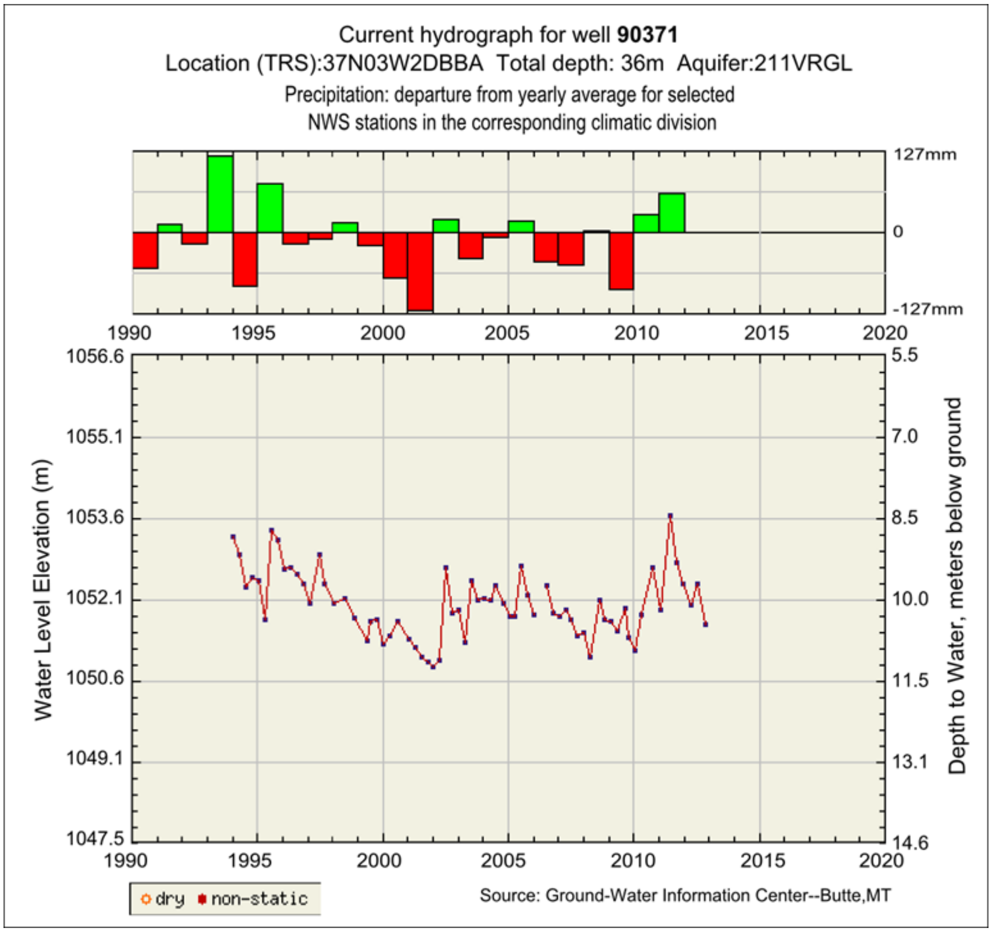

Well #286, Forty Mile Coulee 86-1
LSD13 Sec 27 Twp8 R11 W 4M
Well elev: 823.89 m
Compl:Slotted casing 188.9-230 m
817.500
817.000
816.500
816.000
815.500
815.000
814.500
814.000
813.500
813.000
Water level (m above m.s.l.)
89 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 08 09 10 11 12
Date


Well #954, Foremost Farm
LSD1 Sec8 Twp6 R11 W 4M
Well elev: 869 m
Compl: Perforations 182.88-219.46 m
798.20
798.00
797.80
797.60
797.40
797.20
797.00
Water level (m above m.s.l.)
05 06 07 08 09 10 11 12 13 14
Date
Source: GOWN, Alberta Environment


Current hydrograph for well 45363
Location (TRS):34N04E33ADDACD Total depth: 35m Aquifer:211VRGL
Precipitation: departure from yearly average for selected
NWS stations in the corresponding climatic division
127mm
0
-127mm
1990
1995
2000
2005
2010
2015
2020
1060.3
1058.8
1057.3
1055.8
1054.2
1052.7
1051.2
16.8
18.3
19.8
21.3
22.9
24.4
25.9
Water Level Elevation (m)
Depth to Water, meters below ground
dry
non-static
Source: Ground-Water Information Center--Butte,MT


Current hydrograph for well 88838
Location (TRS):32N04W35CBAA Total depth: 24m Aquifer:211VRGL
Precipitation: departure from yearly average for selected
NWS stations in the corresponding climatic division
127mm
0
-127mm
1990
1995
2000
2005
2010
2015
2020
1093.0
1091.2
1089.7
1088.1
1086.6
1085.1
1083.6
10.7
12.2
13.7
15.2
16.8
18.3
19.8
Water Level Elevation (m)
Depth to Water, meters below ground
dry
non-static
Source: Ground-Water Information Center--Butte,MT


Current hydrograph for well **89572**
Location (TRS):35N04W11DCDB Total depth: 19.5m Aquifer:211VRGL
Precipitation: departure from yearly average for selected
NWS stations in the corresponding climatic division
127mm
0
-127mm
1990
1995
2000
2005
2010
2015
2020
Water Level Elevation (m)
1202.9
1201.4
1199.9
1198.4
1196.9
1195.4
1193.8
Depth to Water, meters below ground
-5.2
-3.7
-2.1
-0.6
0.9
2.4
3.9
dry
non-static
Source: Ground-Water Information Center--Butte,MT


Current hydrograph for well 90371
Location (TRS):37N03W2DBBA Total depth: 36m Aquifer:211VRGL
Precipitation: departure from yearly average for selected
NWS stations in the corresponding climatic division
127mm
0
-127mm
1990
1995
2000
2005
2010
2015
2020
Water Level Elevation (m)
1056.6
1055.1
1053.6
1052.1
1050.6
1049.1
1047.5
Depth to Water, meters below ground
5.5
7.0
8.5
10.0
11.5
13.1
14.6
dry
non-static
Source: Ground-Water Information Center--Butte,MT