Saskatchewan Research Council

Conceptual Aquifers Management Framework Study

Prepared for Prairie Provinces Water Board

By Harm Maathuis
Saskatchewan Research Council
Environment and Forestry

SRC Publication No. 12092-1C07

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TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

1. INTRODUCTION

The Prairie Provinces Water Board (PPWB) administers the Master Agreement on Apportionment that governs the apportionment of interprovincial streams that flow eastward through Alberta, Saskatchewan and Manitoba. Considering that there are a large number of transboundary aquifers, the importance of groundwater in the rural areas of the prairies and the increasing realization that surface water and groundwater should be treated as a single resource, the PPWB is exploring if there is a need to include groundwater in apportionment agreements. As a result the PPWB conducted a review of transboundary groundwater apportionments (Plaster and Grove, 2000). Based on the report by Plaster and Grove (2000) regional hydrogeological studies along the Alberta – Saskatchewan and Saskatchewan – Manitoba boundaries were conducted (Judd-Henrey *et al.*, 2004: Judd-Henrey and Simpson, 2005).

This report was prepared in response to a request for proposal (RFP) by the Prairie Provinces Water Board (PPWB) and builds on the work done by Plaster and Grove (2000), Judd-Henrey *et al.,* (2004) and Judd-Henrey and Simpson (2005).

Based on the request for proposal and the proposal prepared by the Saskatchewan Research Council (Maathuis, 2006), the objectives of the study were:

1. Review a limited set of aquifer management plans in the prairies or similar settings, including plans for which digital models were developed, evaluate their comprehensiveness and how they can be applied to improve the effectiveness of groundwater management. These should include aquifer management plans where digital models of the groundwater systems were developed, and evaluate the application, value, limitations and uncertainties of these models with regard to aquifer management plans should be evaluated;
2. Identify the important elements that should be considered for the management of transboundary aquifers, taking into account the Plaster and Grove (2000) report on transboundary groundwater apportionment;
3. Review the recent reports on aquifers along the Saskatchewan – Manitoba (Judd-Henrey *et al.*, 2004) and Saskatchewan – Alberta borders (Judd-Henrey and Simpson, 2005) with respect to identifying gaps in information needed for the development of aquifer management plans;
4. Identify possible consequences of water development decisions (e.g. drainage of wetlands, groundwater withdrawals, or sensitive area prescriptions that might limit water development);
5. Provide detailed consideration for the various kinds of information needed to allocate or apportion water in consideration of both surface and groundwater within a complete hydrological balance. The contractor is to include an estimated cost for the required data needs. Some information may require data collection in real-time or over several years. Some may require hydrograph analysis in order to have confidence in decision making; and
6. Discuss how such a transboundary aquifer management plan would be administered, what are the long-term commitment associated with the administration of such a plan, and the management issues surrounding the development of aquifer management plan.

The present study benefited from the insight and information on aquifer and watershed management plans provided by: David Toop, Alberta Environment; Kevin Parks, Alberta Geological Survey; Bob Betcher and Barry Oswald, Manitoba Water Stewardship; Jim Gerhart, Saskatchewan Watershed Authority and Ron Neufeld, Councillor, City of Winkler.

2. PREVIOUS HYDROGEOLOGICAL BOUNDARY STUDIES

The hydrostratigraphical settings along the Alberta – Saskatchewan and Saskatchewan – Manitoba boundaries were initially provided by Tokarsky (1985, 1986). The area of investigation extended up to three (3) ranges (about 30 km) from the borders (Figure 1). For each pair of NTS maps sheets along the boundaries the hydrostratigraphy was presented in the form of south - north 1:250,000 horizontal scale cross sections and a bedrock geology and topography map. The base of groundwater exploration was identified on the cross sections. The base of groundwater exploration is the depth below which it is uneconomical to drill for water either because of cost of drilling or because the quality of the water below the depth is unsuitable for the intended use. The reports provide no information on the extent of aquifer and only limited information on water quality, aquifer properties and aquifer yield. The Quaternary deposits were shown on the cross sections as an undifferentiated unit as it was not possible at the time to separate till units.

Based on existing information, Judd-Henrey *et al.*, (2004) and Judd-Henrey and Simpson (2005) mapped the Saskatchewan – Manitoba and Saskatchewan – Alberta transboundary aquifers in more detail. The studies focussed on **regional** mapping of shallow bedrock and Quaternary aquifers in the same area mapped by Tokarsky (1985, 1986). The transboundary aquifers identified are summarized in Table 1.

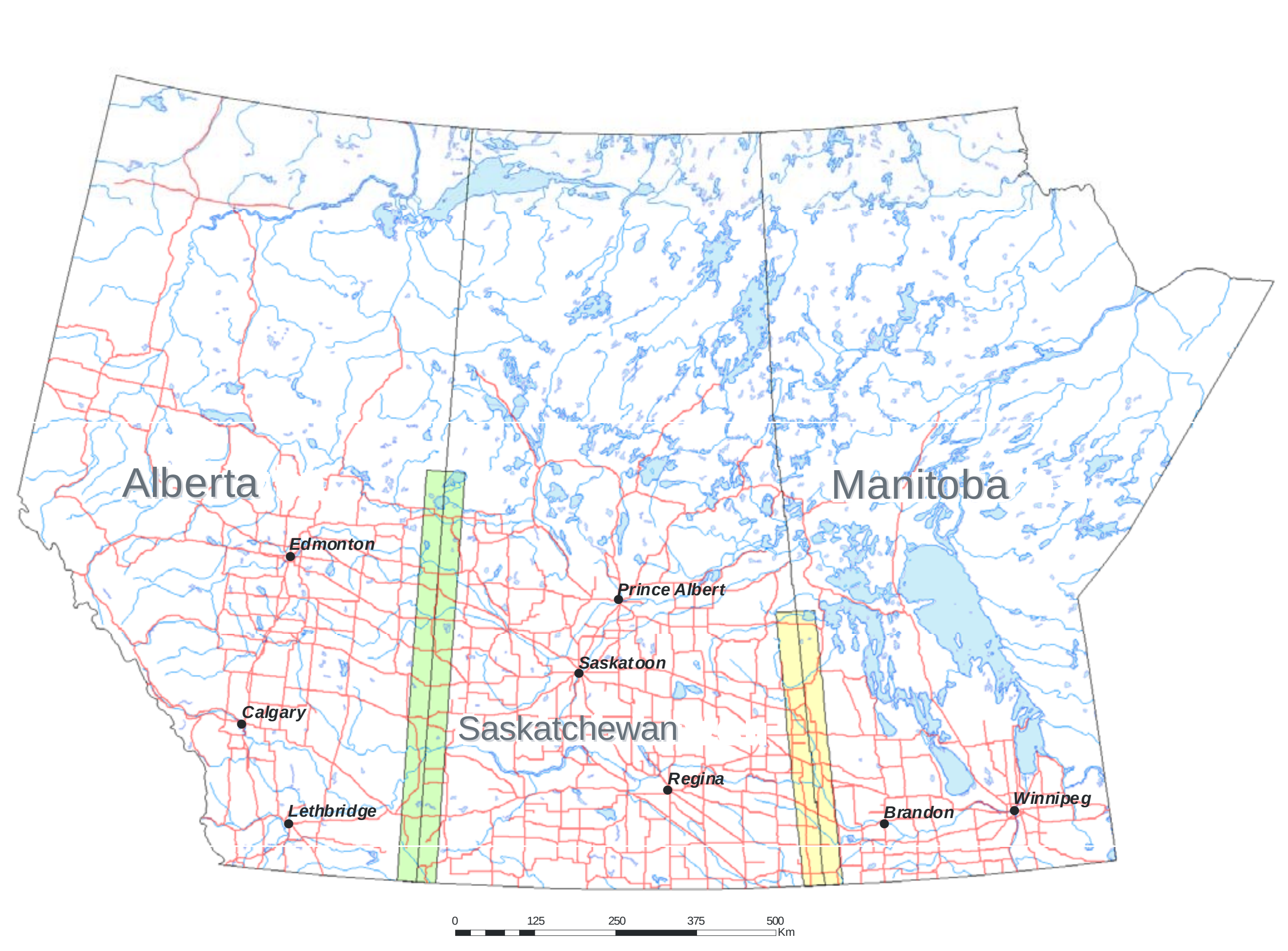

Figure 1 Extent of transboundary study areas

Table 1. Summary of shallow bedrock and Quaternary transboundary aquifers between Saskatchewan – Manitoba and Saskatchewan - Alberta

Saskatchewan - Manitoba		Saskatchewan - Alberta
Bedrock Aquifers:		**Bedrock Aquifers:**
Mannville/Swan River aquifer		Ribstone Creek aquifer
Odanah Shale aquifer		Judith River aquifer
Tertiary-Quaternary (“Bredenbury” aquifer)		Bearpaw sand aquifers
		Eastend – Ravenscrag Fm aquifer
Quaternary Aquifers:		**Quaternary Aquifers:**
Empress Group aquifers (*e.g.* Hatfield Valley aquifer)		Empress Group aquifers (*e.g.* Helina/Hatfield Valley aquifer, Wainright/Battleford Valley, Tyner Valley etc.)
Intertill aquifers (undifferentiated)		Intertill aquifers (undifferentiated)
Surficial aquifers		Surficial aquifers

The Judd-Henrey *et al.,* (2004) and Judd-Henrey and Simpson (2005) reports include maps showing the extent of the shallow bedrock and Quaternary aquifers and include a south – north cross section. The aquifers were described in general terms with respect to extent, connectivity to surface water, groundwater flow (recharge and discharge), water quality and yields. Groundwater allocations could not be assessed as allocations are difficult to relate to specific aquifers. It was noted that there are few provincial groundwater level observation wells along the borders.

As the studies by Judd-Henrey *et al.,* (2004) and Judd-Henrey and Simpson (2005) were of regional scale, detailed hydrogeological information on transboundary aquifers (*i.e.* quasi 3-D (hydro) geological models) were not developed. For the Saskatchewan – Manitoba boundary, Judd-Henrey *et al.,* (2004) recommended further study of the Odanah aquifer, the Tertiary – Quaternary aquifers, Hatfield and Rocanville aquifers and several Quaternary aquifers. Along the Saskatchewan – Alberta boundary the Helina/Hatfield Valley aquifer, the Tyner Valley aquifer and several Quaternary aquifers were highlighted as aquifers to be studied further (Judd-Henrey and Simpson, 2005). Not mentioned for further study are the aquifers formed by the Judith River Formation and Ribstone Creek Tongue along the Alberta – Saskatchewan boundary. As shown in Figure 2, these aquifers are large regional transboundary aquifers.

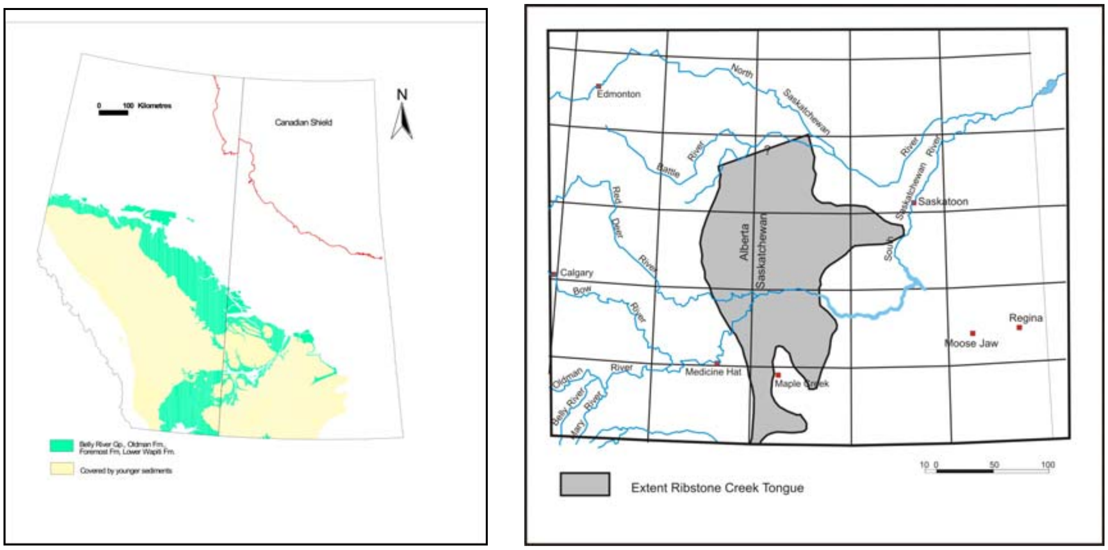

Figure 2 Extent of the aquifers formed by sediments of the Judith River/Oldman Formation (Figure 2a) and the Ribstone Creek Tongue (Figure 2b)

An integral part of aquifer management plans is protection of the groundwater resources. Mapping of the vulnerability/susceptibility of aquifers to contamination from potential sources at or near the ground surface is a first step in developing aquifer protection plans. Groundwater vulnerability maps covering an area extending 30 km away from the boundaries were prepared by Grove and Androsoff (1994, 1995). The mapping was based on the Aquifer Vulnerability Index (AVI) method developed by Van Stempvoort *et al.,* (1992, 1993). The method as applied doesn't discriminate between the various aquifers that might be present at a particular location as it only considers the shallowest aquifer below the ground surface at that location. Therefore, the maps presented by Grove and Androsoff (1994, 1995) are not vulnerability maps for a particular transboundary aquifer.

3. AQUIFER MANAGEMENT PLANS IN THE PRAIRIES

3.1 Introduction

Aquifer management plans are not new and there is a generally accepted approach to establishing an aquifer management plan. The technical components of an aquifer management plan typically are (*e.g.* Banga *et al.*, 1994):

- establishment of comprehensive geological and hydrogeological databases
- establishment of the geological and hydrogeological settings
- comprehensive evaluation of the groundwater resources and surface water – groundwater interactions
- evaluation of past groundwater use and prediction of future use
- development of a groundwater allocation plan
- development of a groundwater protection plan
- development of water quality and water level monitoring programs
- development of an education plan

The development of an aquifer management plan is based on consensus building. Typically, a working committee is established which guides the development of an aquifer plan. Working committees commonly are chaired by a representative of the governmental department in charge of groundwater management or planning. A stakeholder group is an important component of the working committee. It may include area residents, the various water users and providers, and representatives of cities and towns and rural municipalities/counties. For the technical/scientific aspects the working committee is supported by, and in part provides guidance to, a technical support group.

Although more and more driven by governmental policies, in particular those related to source water protection and sustainability of groundwater supplies, there are other reasons for starting aquifer management plans. Other reasons include concerns about the potential impact of a proposed major groundwater development, the cumulative impact of small withdrawals in areas of rapid growth, observed depletion of groundwater resources, observed deterioration of groundwater quality and observed impact on ecosystems.

3.2 Saskatchewan

3.2.1 Regina Aquifer Management Plan

The development of an aquifer management plan for the Regina area in Saskatchewan was started in the mid 1980s. At that time groundwater, obtained from several well fields, constituted 30% of the total municipal water supply for the City of Regina, but no Water Rights Licenses were issued for the production wells. The well fields were in operation for decades but little was known about the aquifers in which the production wells were completed and their long-term yield. With respect to the groundwater resources, a comprehensive evaluation was conducted (Maathuis and van der Kamp, 1988). This study showed that the well fields were operating at near the maximum sustainable pumping rates (van der Kamp *et al.*, 2007). Under the direction of the Regina Groundwater Technical Committee numerous hydrogeological studies were conducted. Draft groundwater allocation, groundwater quality protection and land use management plans were developed but these plans were never formally adopted and implemented. However, the City of Regina incorporated the results of an aquifer sensitivity study in a zoning bylaw. The Saskatchewan Watershed Authority (SWA) adopted a policy of restricting new groundwater allocations from the aquifer system. As a result of increased pipeline capacity from a surface water source (Buffalo Pound Lake) currently less than 1% of the City's municipal water supply is derived from groundwater. Groundwater is only used occasionally to meet peak demands.

3.2.2 Saskatchewan Southeast Aquifer Management Plan

The Saskatchewan Southeast aquifer management plan was initiated by the government in the late 1980s in response to a plan to withdraw large amounts of water from the Estevan Valley and the Tableland aquifer systems in southeastern Saskatchewan. At that time little was know about the water resources in these aquifers and about the potential impact of the proposed withdrawals on these aquifers, adjacent and overlying aquifers and surface waters. A comprehensive evaluation of the groundwater resources was conducted (Van Stempvoort and Simpson, 1994) but a formal aquifer management plan was never developed.

3.2.3 Yorkton Area Aquifer Management Plan

The City of Yorkton is totally dependent on groundwater for its municipal water supply which is obtained from several aquifer systems. As was the case for the City of Regina, the absence of Water Rights licences for the City of Yorkton production wells formed the impetus for starting the development of an aquifer management plan. After an initial evaluation of the groundwater resources in the Yorkton area (Maathuis, 1991), numerous additional groundwater studies were conducted under the direction of the Yorkton Aquifer Technical Committee but no numerical groundwater models were developed. An updated characterization of the groundwater resources was provided by Maathuis and Simpson (2006). This report formed the basis for the development of a source water protection plan for the Yorkton aquifers (SWA, 2006a).

3.3 Alberta

3.3.1 Town of Edson

The Town of Edson, Alberta, and its surrounding area, depends on groundwater for its water supply. Continuous development of the town and area and concerns about the sustainability of these groundwater resources formed the impetus for a detailed hydrogeological study which could support the development of an aquifer management plan (Komex International Ltd., 2001). Although monitoring of the groundwater resources continues, there are no formal plans to develop an aquifer management plan (personal communication Mr. A. Masend, Town of Edson). An alternative water supply from a nearby river is available, if needed.

3.3.2 Milk River Aquifer Reclamation and Conservation Plan

The Milk River aquifer in southern Alberta aquifer is an important regional aquifer which has been used since the early 1900s as a water supply source. Over time, numerous wells were drilled and later a significant number of these wells were abandoned. A survey identified 1,027 wells of which 442 were inactive (43%) and 41 of the inactive wells were flowing. A reclamation and conservation plan was implemented as water quantity and protection of the water quality were major concerns. A total of 101 wells, 22 of which were flowing, were plugged by cementing (Printz, 2004). Monitoring data are being collected but the impact of the well decommissioning on the aquifer has not yet been assessed.

3.3.3 Grimshaw Aquifer

Community-based concerns regarding the wise use of groundwater and the protection of these resources led to the preparation of a document outlining the various components needed to develop management strategies for the Grimshaw aquifer (Agriculture and Agri-Food Canada, 1998). A formal aquifer management plan was never developed but the need for protection of the aquifer was included in municipal bylaws. A Grimshaw Gravels Aquifer Management Advisory Association exists but its activities are limited to annual meetings.

3.4 Manitoba

In Manitoba, aquifer management plans have been developed for a number of aquifers, including the Winkler aquifer (Winkler Aquifer Management Plan Round Table, 1997), Oak Lake aquifer (Oak Lake Aquifer Management Plan Round Table, 2000) and Assiniboine Delta Aquifer (Assiniboine Delta Aquifer Management Plan Round Table, 2005). The aquifer plans were developed in response to local concerns regarding sustainability of groundwater supplies and economic development.

The aquifer plan for the Winkler aquifer is a typical example of the planning process in Manitoba. The Winkler aquifer is a narrow (1 to 5 km wide) elongated (27 km long), up to 60 m thick aquifer which except for its northern portion is confined by tills and clays. In the northern portion, the aquifer outcrops at the ground surface and is unconfined. This is the main recharge area. The upper part of the aquifer contains freshwater whereas the lower portion yields saline water (Render, 1990). Withdrawals by the Town of Winkler started in 1963 and increased over time. In addition to the withdrawals by the town, groundwater is withdrawn by farm wells, for an irrigation project and by other rural municipal wells. As the total amount of withdrawals significantly exceeds the recharge to the aquifer, continued pumping from the aquifer was not sustainable and also would result in a deterioration of the quality of the water over time (Render, 1990). The aquifer management plan developed included a water use, aquifer protection, recharge enhancement, monitoring and education plan. The implementation of the plan is under the guidance of the Winkler Aquifer Management Advisory Board. The Winkler Aquifer Management Advisory Board is a voluntary board to which members are appointed. Although the Board can develop plans and can make recommendations, it has no powers to enforce these recommendations. To date, implementation of the water use plan had resulted in a significant reduction in the volume withdrawn from the aquifer. This was achieved by a reduction in groundwater allocations and obtaining an alternate source of water from a piped distribution system. The reduction in water use from the aquifer was implemented by the Province by not renewing water rights licences. A groundwater level and groundwater quality monitoring plan is in place as is a recharge enhancement plan (snow entrapment through planting trees). The groundwater level and quality monitoring programs are conducted by the Province. As a result of the implementation of the aquifer management plan, groundwater levels have recovered but water quality issues remain a concern (Phipps and Betcher, 2007).

4. WATERSHED-BASED WATER RESOURCE MANAGEMENT PLANS

Throughout the world water resources managers have come to the realization that surface water and groundwater should be managed as an integrated resource rather than as separate resources (*e.g.* Winter *et al.*, 1998). Typically, the process used in developing a watershed management plan is similar to what has been used for the development of an aquifer management plan and includes a stakeholder group and a technical support group.

4.1 Saskatchewan

In Saskatchewan, watershed-based source water protection plans have been completed for the Assiniboine River watershed (SWA, 2006b), the Lower Souris River watershed (SWA, 2006c), the Moose Jaw River watershed (SWA, 2006d) and for the Yorkton Area Aquifers (SWA, 2006a). A draft of the South Saskatchewan River watershed plan is currently under review (SWA, 2006e) and plans are nearing completion for the North Saskatchewan River and Upper Qu'Appelle River watersheds. Figure 3 shows the locations of the watersheds.

Consistent with Saskatchewan's *Safe Drinking Water Strategy* (Saskatchewan, 2003), the primary focus of the watershed planning process is to protect and secure source water to ensure present and future availability of safe drinking. The plans are focused on beneficial management practices for ground and surface water but detailed hydrogeological frameworks for the watersheds were not developed.

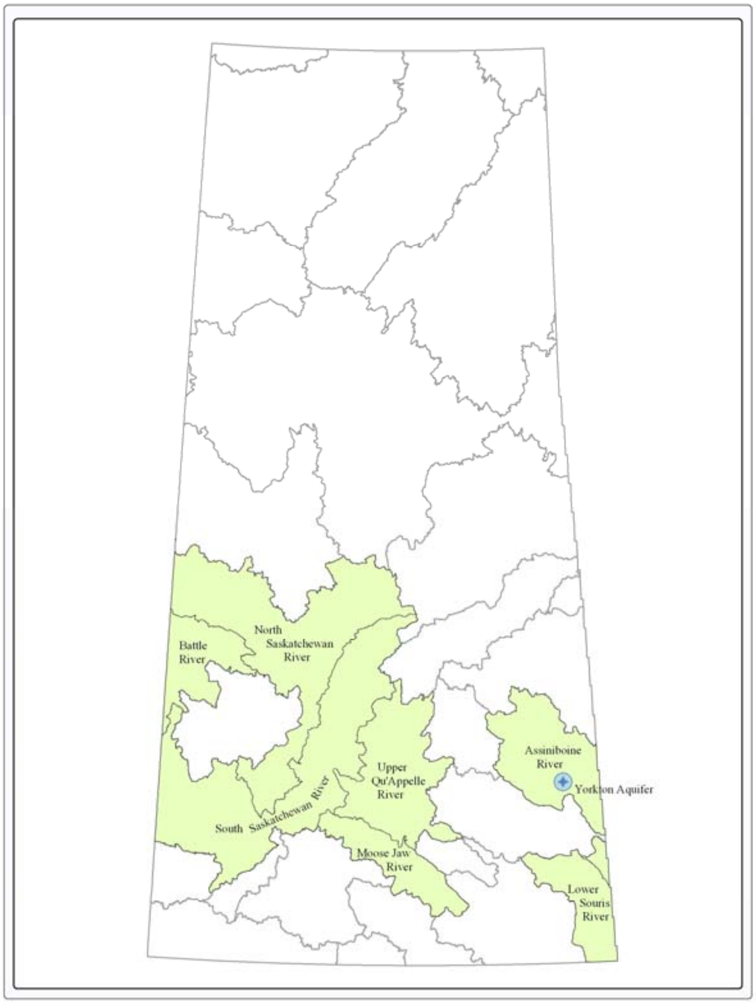

Figure 3 Watershed-based source water protection plans in Saskatchewan

With respect to groundwater, these plans typically include implementation of projects related to well head protection of municipal wells, proper decommissioning of abandoned and improperly decommissioned wells. In addition, the plans call for the development of a groundwater level and quality monitoring system. However, the plans do not include the development of a groundwater allocation plan and not all address issues such as sustainability of the groundwater resources and groundwater – surface water interactions.

4.2 Alberta

The development of a water management plan in Alberta requires that approval is obtained at two stages of the planning process (Alberta Environment, undated). Approval by the Lieutenant Governor in Council or the authorized minister is required for the Terms of Reference for the plan. Once a plan has been developed, it must be submitted for approval and, if approved, a Water Management Plan becomes an Approved Water Management Plan. To date, an Approved Management Plan only exists for the South Saskatchewan River basin. Currently Watershed Management Plans for the Cold Lake – Beaver River basin, Lesser Slave basin, Athabasca River and Battle River basin are being developed.

4.2.1 South Saskatchewan River Basin

The approved water management plan for the South Saskatchewan River basin in Alberta (Figure 4) focussed on surface water (Alberta Environment, 2006a).

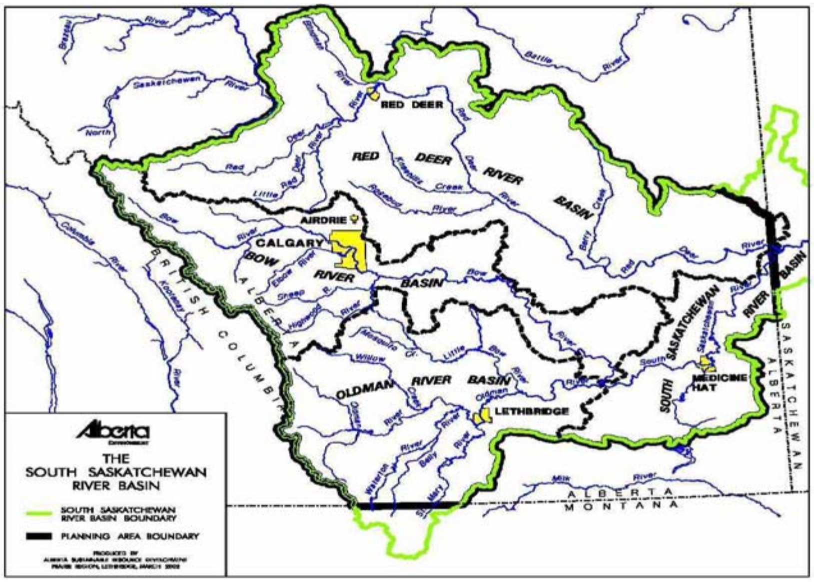

Figure 4 South Saskatchewan River basin and sub-basins in Alberta

As a result of the water management plan, Alberta Environment will no longer accept new surface water licence applications for the Bow, Oldman, and South Saskatchewan sub-basins. However, surface water allocation transfers may be approved. It is in the context of the transfer approval process that, amongst other issues, groundwater – surface water linkages need to be considered (Alberta Environment, 2006a, Table 1).

4.2.2 Cold Lake – Beaver River Water Management Plan

Since the early 1980s numerous groundwater studies have been conducted in Alberta in the Cold Lake – Beaver River area (Figure 5). These studies were conducted to determine the impact of groundwater withdrawals by the oil industry for enhanced oil recovery and the sustainability of the groundwater resources. A long-term water management plan, applying to both groundwater and surface water, was developed in 1985 (Alberta Environment, 1985). The plan mainly focused primarily on water allocations and set target limits for surface water and groundwater withdrawals for the basin. Based on the information available at the time, the Prairie Provinces Water Board (PPWB, 1996) concluded that there was no reason to include groundwater in the Cold Lake apportionment agreement. This conclusion was based on the fact that there was no physical evidence that groundwater withdrawals in Alberta had impacted groundwater inflow into Cold Lake. Because of an increase in industrial development, population growth and years of below-normal precipitation, the need existed for an update of the 1985 plan. An updated Cold Lake – Beaver River Water Management Plan was recently prepared (Alberta Environment, 2006b).

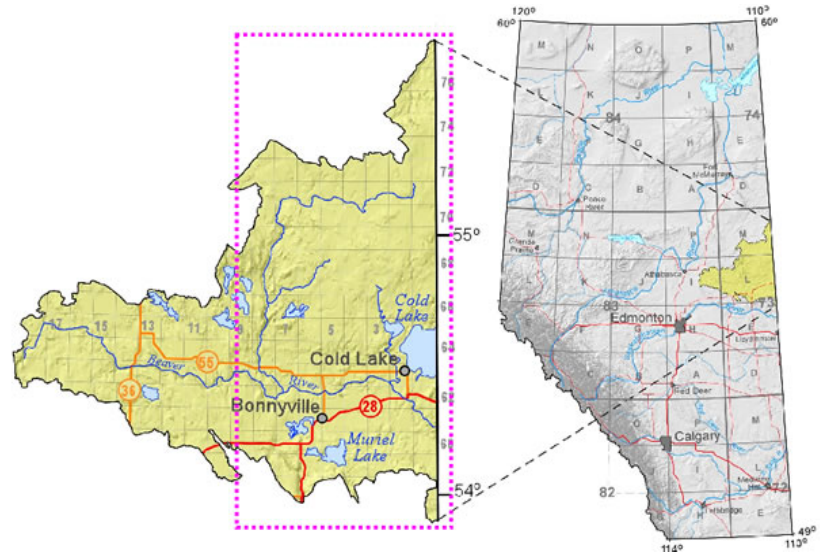

Figure 5 Cold Lake – Beaver River water management plan area

In the development of the updated plan, groundwater flow modeling played an important role (Parks *et al.*, 2005) as did a detailed review of the regional groundwater quality (Lemay *et al.*, 2005). The updated plan is watershed-based and treats surface water and groundwater as a single resource. It recognizes the complexities of watershed water resources management with respect to surface water groundwater interactions, water quality protection, the need to protect aquatic resources, the recreational values of lakes and wetlands and impact of climate change/variability.

4.2.3 Battle River Watershed

The Battle River watershed (Figure 6) is of interest because it crosses the Alberta – Saskatchewan boundary. The watershed covers about 30,000 km^2: 83 % of this area is in Alberta. The watershed is underlain by a major bedrock aquifer formed by sediments of the Judith River (Oldman) Formation.

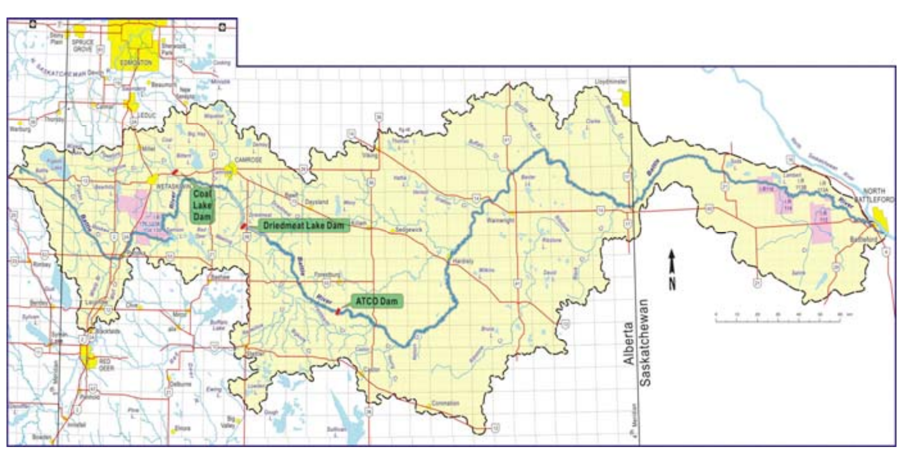

Figure 6 The Battle River watershed in Alberta and Saskatchewan

A water management plan is currently under development but only covers the Alberta portion of the watershed. Although the importance of groundwater and groundwater – surface water interactions is recognized, the plan under development will be focused on surface water. A preliminary assessment of the hydrogeological framework of the Battle River basin in Alberta was conducted by Parks (2006).

4.3 Manitoba

Manitoba's *Water Protection Act* (http://web2.gov.mb.ca/laws/statutes/2005/c02605e.php) calls for the establishment of watershed-based integrated watershed management plans. In these plans, there is an emphasis on source water protection. Groundwater and surface water are treated equally and planning includes both water and related resources (*e.g.* land use planning). To date, the development of plans have started for seven (7) watersheds (Figure 7).

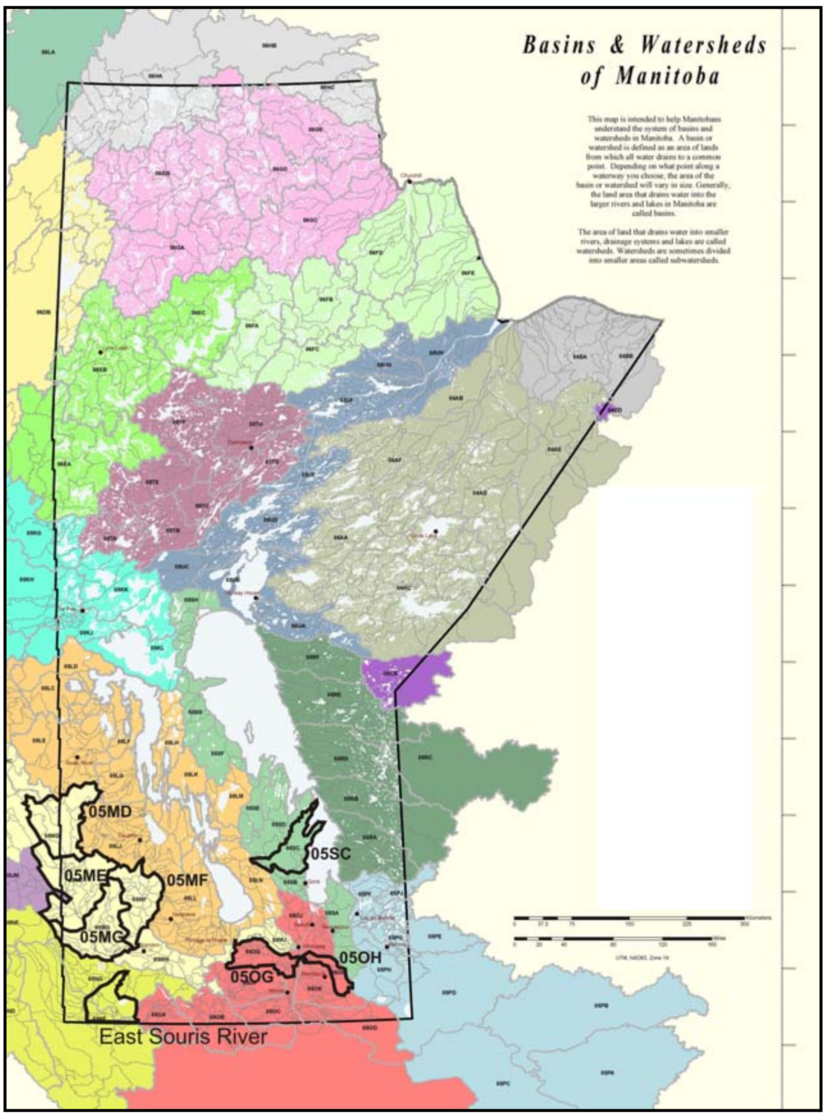

Figure 7 Locations of watersheds in Manitoba for which integrated watershed management plans are being developed

The watersheds for which plans are in development are: Icelandic River/Washow Bay Creek (05SC), Sienne River (05OH), La Salle River (05OG), Little Saskatchewan River (05MF), Arrow/Oak River

(05MG), Birdtail/Assiniboine West (05ME) and Shell River (05MD). The development of the plans is lead by Conservation Districts, being the "local water planning authority". In the implementation of a plan, the local authority will have to work within existing legislation, policy and regulations and therefore, the legal responsibilities will still reside with the Province.

The East Souris River watershed management plan was developed prior to the introduction of the *Water Protection Act*. This plan is currently under review for approval.

5. GROUNDWATER MODELS

5.1 Introduction

There are several types of models: physical models (*i.e.* sand tank model) and mathematical models. Mathematical models are physical-based models that simulate groundwater flow by means of solving governing equations that represent the physical processes that occur in a system. Mathematical models can be solved either analytically or numerically.

5.2 Analytical Models

For most aquifer settings analytical methods are available for the analysis of pumping tests (*e.g.* Kruseman and de Ridder, 1990). The analytical models are based on (very) simplified aquifer settings and typically assume that (*e.g.* Kruseman and de Ridder, 1990):

1. the aquifer is infinite in extent
2. the aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by the pumping
3. the aquifer is pumped at a constant pumping rate
4. the pump well has an infinitesimal diameter (*i.e.* negligible storage in the well)
5. the well penetrated the entire thickness of the aquifer
6. water is released instantaneously with the decline of head in the aquifer
7. the aquifer is confined by a uniform aquitard with a uniform hydraulic conductivity

Analytical models can be used to predict the extent of drawdown. Various commercial computer packages are available which allow both the analysis of pumping test data as well as the prediction of the extent of pumping for assumed aquifer and aquitard properties (*e.g.* AQTESOLV from HydroSolve Inc., and Aquifertest (pro) from Waterloo Hydrogeologic Inc.).

In Figure 8, the distance – drawdown curves are shown for an unconfined, semi-confined and confined aquifer after 20 years of pumping. The curves were calculated using AQTESOLV and are based on the assumptions shown in Figure 8.

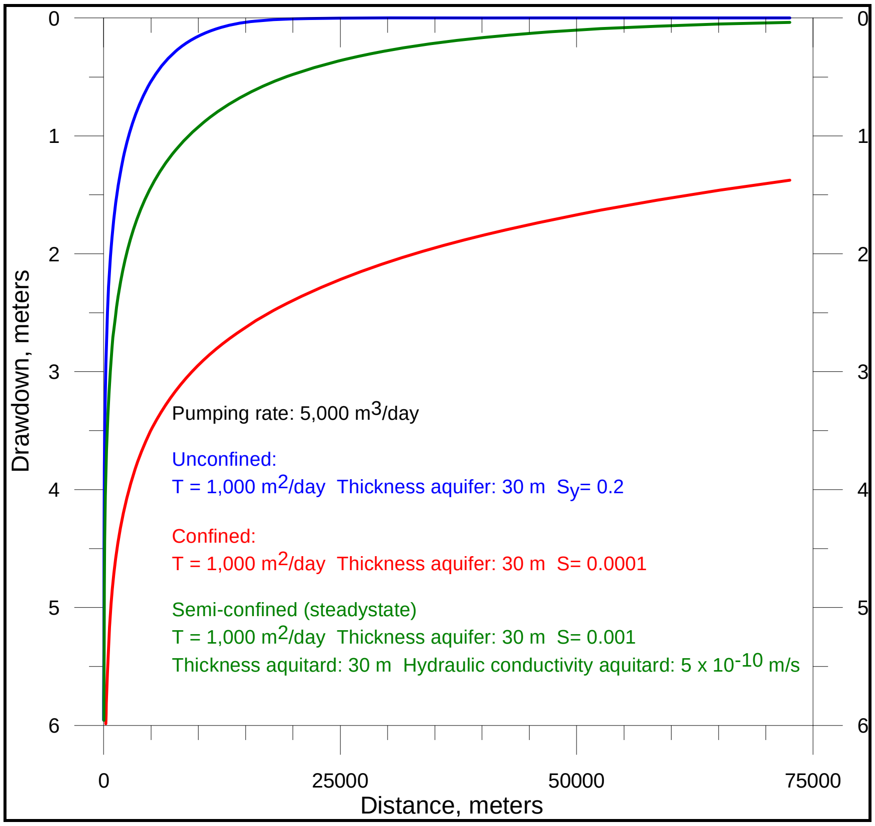

Figure 8 Distance drawdown curves for an unconfined, semi-confined and confined aquifer after 20 year of pumping

Figure 8 shows that unless there is significant pumping from a surficial aquifer near (within a few kilometers) of the boundary, there is little need for developing an aquifer management plan to resolve transboundary apportionment issues as the drawdown in unconfined aquifers extends to relatively short distances. However, in the case of semi-confined aquifers drawdowns may extend over very large distances and therefore, apportionment issues may arise.

The leakage length (L) is a useful parameter in estimating the impact of pumping from, or injection into, an infinite semi-confined aquifer. It is defined as (*e.g.* Kruseman and de Ridder, 1990):

$$L = \sqrt{KD\frac{b'}{K_v^{'}}} = \sqrt{Tc} \qquad [1]$$

where: L = leakage length (m), K= hydraulic conductivity of aquifer (m/day), D = thickness of aquifer (m), b' = thickness of overlying aquitard (m), $K_v^{'}$ = vertical hydraulic conductivity of overlying aquitard (m/day), $c = \frac{b'}{K'_v}$ = vertical hydraulic resistance (days), T = transmissivity of aquifer (m^2/day).

For radial flow in an infinite semi-confined aquifer the major drawdown occurs within a radius L from the production well and that at a distance r=3L the impact is negligible. In typical prairie settings the leakage factor L may range in value from a few hundred meters to hundreds of kilometers.

Maathuis and van der Kamp (2006) introduced the R_{20} concept which is also based on analytical models. R_{20} is defined as the distance from a pumping well where the drawdown after 20 years of pumping at the requested rate equals some given limit, which might typically be set as about equal to the natural fluctuation of the water level in the aquifer, say 0.5 m for prairie aquifers.

Buried valley aquifers are a particular type of semi-confined aquifers with a unique response to pumping stress. These types of aquifers are long and narrow and bounded on all sides. Equations for calculation the drawdown in such aquifers were provided by Maathuis and van der Kamp (2006, Appendix B, section B.6). Withdrawals from such aquifers result in drawdowns tens of kilometers away from the pumping centre (Maathuis and van der Kamp, 1998; van der Kamp and Maathuis, 2002; Maathuis, 2005).

Both in general as well as with respect to transboundary aquifers, the application of analytical models allows for a quick evaluation of the extent and potential impact of withdrawals. If the extent of the drawdown is large, and there are numerous small withdrawals from individual wells or large withdrawals from a few wells, then there is a need for the development of an aquifer management plan.

The simple analytical models will become inadequate if the hydrogeological setting is complex and/or there are many boundary conditions (*i.e.* streams, lakes, wetlands) and/or there is significant pumping from various sites (*i.e.* well interference). In those cases a numerical model will be needed.

5.3 Numerical Groundwater Models

Within the Prairies Provinces groundwater flow models have not played a significant role in the development of aquifer or watershed-based water resource management plans, except for the recent groundwater model prepared for the Cold Lake – Beaver River area (see section 4.2.2). Because of the limited use of groundwater flow models in the development of aquifer management plans this section provides a generic review of the steps and information needed to develop groundwater flow models.

A numerical model is more than a computer code as it includes the conceptual hydrogeological framework, a definition of the geometry and structures, assumptions and limitations, governing equations, boundary conditions, stresses and solution method (*e.g.* Anderson and Woessner, 1992; CCME, 1994).

To develop a site-specific groundwater flow model some basic steps will have to be taken (*e.g.* Anderson and Woessner, 1992):

- Definition of the conceptual model
- Discretization of the flow domain
- Assigning hydraulic properties
- Definition of boundary conditions and stresses
- Calibration of the model
- Verification of the models and adjustment

5.3.1 Defining Conceptual Geological and Hydrogeological Frameworks

The development of a model starts with the compilation of the geological and hydrogeological data available. The geological information is used to construct a framework of the geological setting. At all times the geological framework will be conceptual. The level of confidence in the geological framework is a function of the complexity of the geological setting and the availability of testhole information. Based on the geological framework a conceptual groundwater flow can be developed by including features which may influence groundwater flow such as the locations of production/injection wells, rivers and lakes and wetlands.

Once the hydrogeological framework has been established, the model is discretized into grid or finite element blocks. Further simplifications of the conceptual model might be needed because of computational limits. The hydraulic properties within each block are constant but variations in properties between blocks/elements allow simulating (hydro)geological variability.

5.3.2 Hydraulic Properties

The typical hydraulic property data needed for the model are the hydraulic conductivities of aquifers and aquitards and specific storage coefficient (for transient simulations). The hydraulic property data are obtained from pumping test results. However, generally only short-term pumping test have been conducted and the selection of values for the hydraulic parameters often depends on the judgement of the hydrogeologist.

5.3.3 Boundary Conditions

The next step in the modelling process is assigning boundary conditions. There are various types of boundary conditions such as no flow boundaries (*i.e.* impermeable boundaries), constant head boundaries (*e.g.* lakes, wetlands) and specified flux boundaries (*i.e.* flow into model domain).

5.3.4 Stresses

Withdrawal/injections from/into wells are the main stresses on groundwater flow systems. Maathuis and van der Kamp (2006) provided a review of the groundwater allocation process in the Prairie Provinces.

In Alberta, household users (up to 1,250 m^3/a, 3,425 L/day) and traditional agricultural users (up to 6,250 m^3/a, 17,100 L/day) have a statutory right to withdraw groundwater and require no prior authorization. For short-term withdrawals approval is needed (*e.g.* dewatering) and for withdrawals lasting less than 1 year a temporary licence is required. For longer-term withdrawals a licence is needed. Wells have been assigned a priority number (date). The priority date follows the doctrine of “first-in time, first-in right”, which assigns available water to the most senior license holders first, in the event of a drought or other water shortage. Conditions attached to most large-scale groundwater licenses require annual reporting to Alberta Environment. Small-scale operations usually do not have any information collection or reporting requirements. A registration program was conducted to assign priority dates to traditional agricultural operations. It is because of this program that the number of licensed wells on the Alberta side of the Alberta – Saskatchewan boundary is so much higher than on the Saskatchewan side (Judd-Henrey and Simpson, 2005, Figure B1).

Saskatchewan requires a license to withdraw groundwater for all uses except for domestic purposes. It does not recognize the “first-in time, first-in right”, principle, but in granting a license existing users are taken into account. Monitoring requirements (*e.g.* water level, water quality and actual volumes pumped) are generally attached to a license.

In Manitoba, no groundwater licence is required if the water is used for domestic, agricultural and irrigation purposes as long as the withdrawal does not exceed 25,000 L/day. In all other cases a licence is required. Records of water use need to be kept and submitted. The licence may be required to report water levels in either the pumping well or in a nearby observation well on a periodic basis. The "first-in time, first-in right" principle is used in Manitoba.

It is a well known fact that the volumes of allocated groundwater withdrawals are an estimate only of the actual volumes used. Unfortunately, the collection and processing of actual withdrawal data in the Prairie Provinces is highly variable. Actual groundwater withdrawal data for domestic and traditional farm use are not available.

5.3.5 Calibration and Verification

Calibration of the model involves running the model and altering parameters (boundary conditions and cell parameters) until a close agreement is reached between observed and model calculated values. Commonly, a groundwater flow model is considered successfully calibrated if observed water levels closely match model calculated values. Nowadays, many models have sophisticated routines that assist the modeller in the calibration process.

A model is considered verified if the calibrated model matches observations which were not used in the initial calibration process. If necessary, changes to the model will have to be made.

5.4 Surface water – Groundwater Models

The groundwater flow model used by Parks *et al.,* (2005) for the Cold Lake – Beaver River area was the well known and widely used U.S. Geological Survey finite-difference groundwater flow model MODFLOW. Since its introduction in 1988 (McDonald and Harbaugh, 1988), improvements have been made (Hill *et al.*, 2000: Harbaugh, 2005). The MODFLOW-2000 model was used by Parks *et al.,* (2005) in their groundwater flow modelling of the Cold Lake – Beaver River area. The model has very limited surface water modeling capability except for a routine allowing for determination of flow from/into rivers.

There are a large number of coupled surface water – groundwater models available. A detailed review of these models was provided by Gordon *et al.*(2005). The capabilities of these models varies from being able to simulate surface water runoff but having a limited groundwater modeling component, to very sophisticated models in which a surface runoff model is coupled to 3D unsaturated – saturated groundwater flow models. In addition to the data requirements for groundwater flow models, the surface water – groundwater flow models require data on climate (precipitation, estimates of potential evaporation, temperature, wind, and solar radiation), stream flow data, and information on land use and vegetation.

5.5 Limitations of Groundwater Flow Models

Any geological model, by definition, is a conceptual model as it is based on the availability, quality and distribution of testhole information and on assumed geological processes. Therefore, although a numerical model can provide a highly precise solution to a given mathematical problem, it cannot predict the future behaviour of a hydrogeologic system in a precise and definite way (CCME, 1994). The main value of models is that it allows for evaluation of the impact of various groundwater management options/scenarios.

5.6 Recharge and Wetland Drainage

Throughout the Prairie Provinces, there are competing interests between draining wetlands for agricultural purposes and preserving wetlands for ecological and wildlife reasons.

The term recharge refers solely to water that originates directly from precipitation, or surface water bodies, which infiltrates into the ground surface and moves downward to become part of the saturated groundwater system, represented by the water table. Confusingly, the term recharge is also used with respect to flow into semi-confined aquifers. In the semi-arid Prairies, recharge to the water table and replenishment of shallow semi-confined aquifers is limited by the amount of precipitation. The low hydraulic conductivity of thick aquitards is the factor limiting replenishment of deep semi-confined aquifers (Maathuis and van der Kamp, 1986; van der Kamp and Maathuis, 1991).

In the Prairie Provinces, recharge to the water table is distributed both in time and spatially. Recharge takes place during/after the snow melt and during the early spring when precipitation is the highest. It may also occur as a result of intense summer storms and may also happen during wet falls. Within the landscape, recharge varies from place to place. It is well documented that wetlands (sloughs, potholes) play an important role in groundwater recharge in the prairies (*e.g.* van der Kamp and Hayashi, 1998). The complexity of the recharge process was demonstrated by Hayashi *et al.,* (2003).

Van der Kamp and Hayashi (1998, 2007) conclude that drainage of wetlands may have a significant impact on shallow groundwater and vegetation in the vicinity of wetlands (*i.e.* lowering of the water table and stress on vegetation around wetlands) but may have little impact on water levels in underlying regional aquifers. The lowering of the water levels in such regional aquifers would be very small and difficult to identify in water level records. Drainage of wetlands in areas where aquifers are at shallow depth and the water table in the overlying aquitard is deep may have a significant impact on the recharge to such semi-confined aquifers. It is noted that as drainage of wetlands will not be "instantaneous", there always will be some recharge as small depressions may not be drained. Furthermore, the drainage channels themselves could become areas of recharge.

6. SUSTAINABLE WELL AND AQUIFER YIELD

Important aspects of aquifer management, and watershed water resources management, are sustainable well yields and sustainable aquifer yield. These issues were discussed in more detail by Maathuis and van der Kamp (2006).

The sustainable well yield deals with the long-term yield of a groundwater development, either an individual well or well field. Such a development is considered sustainable if it has no unacceptable consequences for the foreseeable future. Unacceptable consequences refer to constraints that must be satisfied such as that the drawdown in the well or well field should not exceed 70% of the available drawdown, that wetlands are not negatively impacted and that baseflow to nearby streams remains sufficient so that during droughts the instream flow needs are satisfied. The concept of sustainable aquifer yield applies to an aquifer system in its entirety and thus includes the cumulative impact of all groundwater withdrawals within the system. In recent years, the concept of sustainable yields has evolved to a concept of sustainability. The sustainability of groundwater development is linked to the biosphere, bio-diversity of ecosystems, human activities and welfare (*e.g.* Alley *et al.*, 1999; Alley and Leake, 2004; Devlin and Sophocleous, 2005). As pointed out by Sophocleous (1997) and Devlin and Sophocleous (2005), because of the broad definition of sustainability, groundwater developments might be "safe" from a pure groundwater dynamics point of view but may not be sustainable. Sustainable well and aquifer yields are not fixed values as parameters may change over time (*e.g.* land use changes, climate change and climate variability) (Alley and Leake, 2004; Sophocleous, 2004). Furthermore, the way society views and values water and the environment are subject to change over time.

7. TRANSBOUNDARY AQUIFER MANAGEMNT, WATERSHED SURFACE WATER MANAGEMENT AND INTEGRATED WATERSHED WATER RESOURCES MANAGEMENT

It is a well established fact that in the Prairie Provinces aquifer and watershed boundaries do not coincide. This raises the questions whether or not groundwater and surface waters should be managed separately or as a single resource.

A recent report (Rosenberg International Forum on Water Policy, 2007) suggests that, because watershed and aquifer boundaries do not coincide, aquifers should perhaps be managed separately from surface waters. However, the argument can be made that this view is simplistic.

Whether to develop a separate aquifer management, watershed-based surface water management or an integrated watershed-based water resources management plan depends on the type of aquifers, the size of the watershed, and groundwater – surface water interactions.

If the watershed is small compared to the extent of a regional aquifer, and withdrawals from the aquifer extend over large distances, the development of separate management plans may be warranted. A typical case would be a small watershed overlying an extensive regional aquifer confined by a thick aquitard with a low vertical hydraulic conductivity. Withdrawals from such an aquifer have little to no impact on surface waters. However, major withdrawals from such an aquifer, either from a few high volume production wells or a large number of smaller volume producing wells, would result in drawdowns extending over tens of kilometres (see section 5.2). With respect to transboundary aquifers in the Prairie Provinces, typical examples would be the aquifers formed by sediments of the Judith River/Oldman, the Ribstone Creek Tongue and a number of buried valley aquifers (for example, the Hatfield Valley aquifer).

If the size of a watershed is large compared to the extent of the aquifers and there are no significant groundwater – surface water interactions, the development of separate plans may also be warranted.

However, as was identified as an issue by Plaster and Grove (2000), if a watershed crosses a provincial boundary, groundwater development on one side of the border may reduce baseflow to a river on that side of the boundary. In turn, this would impact the amount of flow in the river as it crosses the border. In such cases, groundwater and surface water must be treated as a single resource.

8. DEVELOPMENT AND ADMINISTRATION OF TRANSBOUNDARY WATER RESOURCES MANAGEMENT PLAN

The process of developing an aquifer, surface water or integrated water resources management plan is the same throughout the Prairie Provinces and involves a "working" group composed of representatives of governmental departments and a stakeholders group. Technical support typically is provided by governmental departments. The process of developing a plan is based on consensus building. The development of a transboundary water resources management plan is expected to follow the same process but it is more complicated. Under "*The Constitution Act, 1867*", the Provinces are designated as the owner of both groundwater and surface waters. The provinces have the responsibility for the development, management and protection of these resources. Each province has enacted legislations and regulations for this purpose. The role of the Federal Government with respect to interprovincial surface waters (water courses crossing provincial boundaries) is clearly laid out in the 1969 Master Agreement on Apportionment (http://www.mb.ec.gc.ca/water/fb01/fb00s05.en.html) which is being administered by the Prairie Provinces Water Board. The Master Agreement was amended in 1992 to include a section (section 6.1) on groundwater. This section states that "*the parties mutually agree to consider groundwater matters that have implications affecting transboundary surface and groundwater, to refer such matter to* *the Board, and to consider recommendations of the Board theron*". In contrast to surface waters, the Master Agreement doesn't provide any rules regarding groundwater apportionment. Groundwater apportionment was considered for the Cold Lake Basin but it was concluded at the time that there was no technical basis for inclusion of groundwater in the apportionment calculations (PPWB, 1996).

There are no simple rules or methods to arrive at a groundwater apportionment for a particular aquifer or aquifers within a watershed. Hydrogeological settings and groundwater – surface water interactions are complex and may vary from place to place. As waters are not confined by political boundaries, the provinces will have to agree on a framework of basic principles before starting the development of transboundary water resources management plans.

Plaster and Grove (2000) consider the principles of equitable and reasonable use of shared waters as the most essential principles to agree on. To develop such principles the Provinces (Alberta – Saskatchewan and Saskatchewan – Manitoba), for example, will have to come to an agreement on how to determine current and future groundwater use. This issue arises from the fact that rules for when a licence is required are different in the provinces. In addition, Alberta has assigned an allocation to traditional agricultural users whereas this has not been done in Saskatchewan and Manitoba. The collection and sharing of data (*e.g.* water level, actual withdrawal and stream flow data) is also an issue requiring agreement. A critical issue will be coming to an agreement on a definition of sustainability of the groundwater and surface water resources. Finally, agreement between provinces needs to be reached on issues related to the resolution of groundwater disputes/conflicts and the appeal process.

There is little experience within the Prairie Provinces with the process of implementing developed plans. Typically, a watershed board/authority would play a significant role in the implementation of a plan but its legal status will be limited. Consequently, watershed boards/authorities will have to work within existing legislation, policy and regulations. The legal responsibilities will remain with the Province(s). Watershed boards/authorities for transboundary aquifer/watersheds would have to work within the agreed upon framework of principles and rules regarding equitable and reasonable use and dispute/conflict resolution. A typical task of boards/authorities would be the preparation of annual aquifer/watershed reports. These reports would have to be reviewed by provincial regulatory agencies or perhaps by the Committee on Groundwater and Committee on Hydrology of the Prairie Provinces Water Board, if there are implications affecting transboundary surface and groundwater.

9. GAPS IN CURRENT INFORMATION LIMITING THE DEVELOPMENT OF TRANSBOUNDARY WATER REOURCE MANAGEMENT PLANS

Although the names, locations and extents of transboundary aquifers between Alberta – Saskatchewan and Saskatchewan – Manitoba are known (Plaster and Grove, 2000; Judd-Henrey *et al.*, 2004 and Judd-Henrey and Simpson, 2005), the (hydro)geological frameworks needed for the development of water resource management plans have not been established.

It is essential for groundwater management that long-term monitoring of the response of aquifer systems to pumping is conducted (van der Kamp and Maathuis, 2006). Such monitoring should include pumping rates, water levels and groundwater discharge to surface waters (springs, base flow of streams).

There are no provincial groundwater observation wells along the Saskatchewan – Manitoba border zone (Judd-Henrey *et al.*, 2004). Along the Saskatchewan – Alberta border there are 20 observation wells (Judd-Henrey and Simpson, 2005). The locations of these wells are shown in Figure 9. Wells are located away from the boundary and monitoring of the water levels in the major regional aquifers (Judith River and Ribstone Creek) is very limited. With the exception of the buried channel aquifers in the Cold Lake area, monitoring of the water levels in these types of aquifers is also limited.

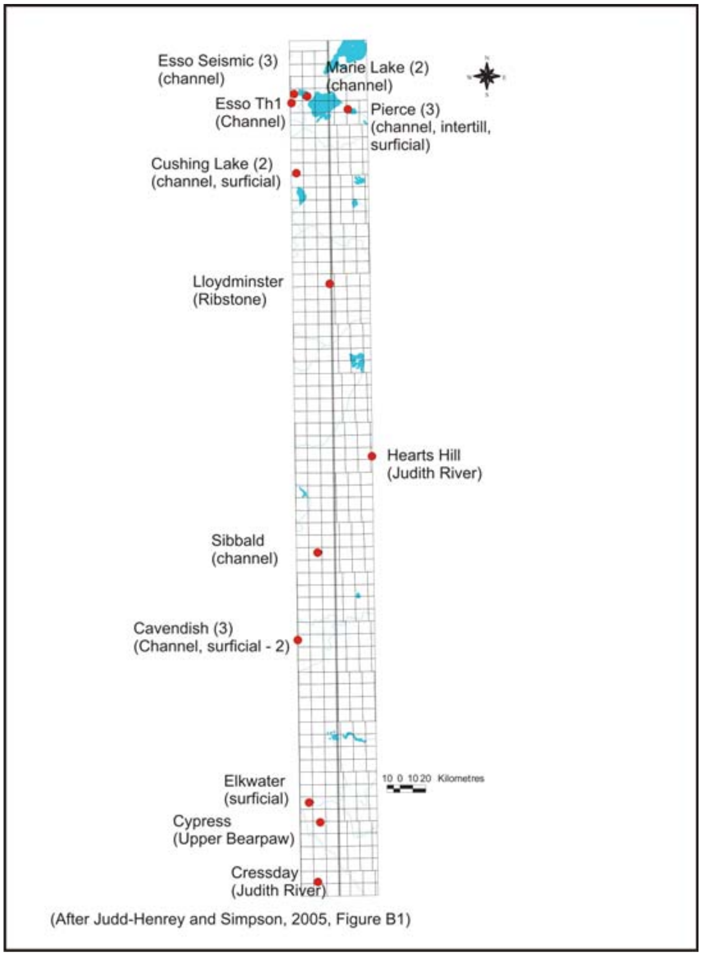

Figure 9 Provincial groundwater level observation wells along the Saskatchewan – Alberta border

Judd-Henrey *et al.,* (2004) and Judd-Henrey and Simpson (2005) presented maps with locations of groundwater allocations but did not relate withdrawals to aquifers and/or watersheds. Relating allocations to specific aquifers was beyond the objectives of their studies.

Judd-Henrey *et al.,* (2004) and Judd-Henrey and Simpson (2005) identified a number of aquifers in the boundary zones with potential groundwater – surface interactions. However, these aquifers were not related to specific watersheds. Further investigation of the groundwater – surface water interactions of these aquifers was recommended.

10. CONCLUSIONS

- **Aquifer Management Plans**
  Within in Prairie Provinces, Manitoba has developed aquifer management plans for a number of aquifers. In Saskatchewan, draft management plans for the Regina aquifer were developed but not formally adopted. However, the draft allocation plan has been adopted in policy by the Saskatchewan Watershed Authority. No aquifer management plans have been developed in Alberta but groundwater played an important role in developing the Cold Lake – Beaver River Water Management Plan.

- **Current Water Resources Management Emphasis**
  The current emphasis within the Prairie Provinces is on watershed-based management of surface waters and on source water protection. The source water protection plans may have a groundwater quality protection component but do not address issues related to allocations, groundwater – surface water interactions and sustainability. Manitoba has started the development of watershed-based integrated water management plans in which surface water and groundwater are treated equally.

- **Groundwater Flow Models**
  Groundwater flow models have not played a role in the development of aquifer management plans in the Prairie Provinces, except for a groundwater flow model developed for the Cold Lake – Beaver River area in Alberta. This model was an essential part of the development of a water management plan for that area. Groundwater flow models may play a role in the development of watershed-based integrated watershed management plans currently underway in Manitoba.

  The current knowledge about transboundary aquifers is essentially limited to information on the extent of the aquifers. It will take considerable effort and cost to develop the hydrogeologic frameworks needed for the development of groundwater flow models which could be used to support of the development of transboundary aquifer/watershed plans.

- **Extent of Planning Areas**
  Although watersheds and aquifers extend beyond borders, planning areas tend to stop at provincial boundaries. As any water "activity" in one province may affect the neighbouring province, plans should cover the entire basin from the onset and should include both surface water and groundwater.

- **Development of Groundwater and Surface Water Management Plans**
  The development of both groundwater and surface water management plans is based on consensus building. The process is commonly lead by a governmental agency and a stakeholders group which is a critical component of the process. Scientific support is provided by a technical committee/group.

  Development of transboundary plans will be similar but should not be done without establishing a framework of principles. Boards/authorities will play a major role in implementing plans but the legal responsibilities for management of water resources will rest with the provinces.

- **Deficiencies**
  This study identified the two major deficiencies in the current knowledge about transboundary aquifers:
  - the withdrawals from individual transboundary aquifers are not known as licensed withdrawals have not been related to specific aquifers
  - there are limited long-term water level records for major transboundary aquifers

11. SUGGESTIONS FOR FURTHER WORK AND COST

- As cost will be prohibitively high to develop aquifer management plans for all the Alberta – Saskatchewan and Saskatchewan – Manitoba transboundary aquifers, a systematic and phased approach is required to determine for which aquifers/watersheds, if any at all, the development of a transboundary aquifer/watershed management plan is warranted at the present time.

  This study identified the two major deficiencies in the current knowledge about transboundary aquifers:
  - the withdrawals from individual transboundary aquifers are not known as licensed withdrawals have not been related to specific aquifers
  - there are limited long-term water level records for major transboundary aquifers

  Based on these deficiencies the following suggestions are made:

  - Priority should be given to a study relating licensed groundwater withdrawals to specific transboundary aquifers, on a watershed basis. The Provinces, in cooperation with the PPWB, should define the transboundary (sub) watersheds to be considered.

    An analysis of aquifer specific water level data, if available, should be part of this study. The suggested study will provide an indication of the pumping stresses on the transboundary aquifers and will aid in deciding which aquifer/watershed, if any, may require the development of an aquifer/watershed water management plan. The estimated cost of this study is in the order of $ 25,000.

  - A second project would involve the establishment of a groundwater level observation well network along the provincial borders. The project should initially focus on establishing observations wells in the major semi-confined transboundary aquifers (*e.g.* aquifers formed by the Judith River/Oldman Formation and Ribstone Creek Tongue along the Alberta – Saskatchewan boundary and the Hatfield Valley aquifer crossing the Saskatchewan – Manitoba border). The reason for initially focusing on these regional semi-confined aquifers is that major withdrawals from these aquifers may result in drawdowns extending over tens of kilometers. Construction of observation wells in other aquifers should be considered if the study of withdrawal data indicates significant stress on these aquifers. The proposed observation wells can be either wells specifically constructed for that purpose or use can be made of existing wells which can be converted into observation wells. The observation wells should become part of the provincial networks of groundwater level observation wells.

    Without information on the location and depth of the proposed wells, realistic costs for the construction of observation wells can not be provided. Construction of a 100 m deep observation well likely would be in the $ 25,000 to $ 50,000 range. Converting existing wells into observation wells will be cheaper but finding suitable wells might be a challenge.

- The Battle River watershed can be considered as an ideal "test case" for the development of an integrated, transboundary, watershed-based water management plan management. The watershed includes a regional extensive transboundary aquifer (Judith River aquifer) which extends beyond the watershed boundaries as well as smaller aquifers within it and a river which crosses the Alberta – Saskatchewan boundary. Groundwater - surface water interactions are known to exist within the watershed. An initial hydrogeological framework for the Alberta part of the watershed already has been developed (Parks, 2006). The cost of extending this framework into Saskatchewan is estimated to be in the $ 25,000 to $ 50,000 range. Once completed, it is likely that further studies are needed to refine the framework.

12. REFERENCES

Agriculture and Agri-Food Canada, 1998. Proposed community-focused management strategy for the Grimshaw gravels aquifer. Agriculture and Agri-Food Canada, PFRA, online report, (http://www.agr.gc.ca/pfra/water/grimrpt2.htm#1)

Alberta Environment. 1985. Cold Lake – Beaver River long term water management plan. Alberta Environment, 11 p. (http://www3.gov.ab.ca/env/water/Management/clbr/pdf/1985plan.pdf)

Alberta Environment. 2006a. Approved water management plan for the South Saskatchewan River (Alberta). Alberta Environment, 45 p. (http://www3.gov.ab.ca/env/water/regions/ssrb/pdf/SSRB_Plan_Phase2.pdf)

Alberta Environment. 2006b. Cold Lake – Beaver River basin water management plan (2006). Alberta Environment, August 2006, 64 p.

Alberta Environment. (undated) Framework for water management planning. Alberta Environment, 37 p. (http://environment.gov.ab.ca/info/library/6367.pdf)

Alley, W.M., Reilly, T.E., O.L Franke. 1999. Sustainability of ground-water resources. U.S. Geological Survey, Circular 1186, 79 p.

Alley, W.M., and S.A. Leaky. 2004. The journey from safe yield to sustainability. Ground Water, Volume 42, No. 1, pp 12-16

Anderson, M.P., and Woessner, W.W. 1992. Applied groundwater modelling. Simulation of flow and advective transport. Academic Press, 381 p.

Assiniboine Delta Aquifer Management Plan Round Table. 2005. Assiniboine Delta aquifer management plan. Planning for the future of the Assiniboine Delta Aquifer. Assiniboine Delta Aquifer Management Plan Round Table, 31 p. (http://www.gov.mb.ca/waterstewardship/reports/acquifer/assiniboine_delta_aquifer-mgmt_plan.pdf

Banga, A.B., Shaheen, N.J., and Maathuis, H. 1994. Aquifer management plans – A Saskatchewan experience. In Proceedings 47th Canadian Water Resources Association Conference, Winnipeg, June 14-17, pp. 273 – 282.

Canadian Council of Ministers of the Environment (CCME). 1994. Subsurface assessment handbook for contaminated sites. Minister of Supply and services, Report CCME EPC-NCSRP-48E, 293 p.

Devlin, J.F., and Sophocleous, M. 2005. The persistence of the water budget myth and its relationship to sustainability. Hydrogeology Journal, Volume 13, pp. 549 – 554.

Gordon, S., Jones, J.P. and Jacksteit, R. 2005. Review of groundwater and surface water interaction – knowledge and modelling approaches for stream flow prediction in Alberta. Unpublished report prepared for Alberta Environment, 71 p.

Grove, G., and Androsoff, M. 1994. Groundwater vulnerability mapping along the Alberta-Saskatchewan boundary. PPWB Report No. 137, 45 p.

Grove, G., and Androsoff, M. 1995. Groundwater vulnerability mapping along the Manitoba - Saskatchewan boundary. PPWB Report No. 137, 45 p.

Harbaugh, A.W. 2005, MODFLOW-2005, the U.S. Geological Survey modular ground-water model -- the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16, variously p. (http://pubs.usgs.gov/tm/2005/tm6A16/PDF/TM6A16.pdf)

Hayashi, M. van der Kamp, G. and Schmidt, R. 2003. Focused infiltration of snowmelt water in partially frozen soil under small depressions. Journal of Hydrology, Volume 270, pp. 214 – 229.

Hill, M.C., Banta, E.R., Harbaugh, A.W., and Anderman, E.R., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- User guide to the Observation, Sensitivity, and Parameter-Estimation Processes and three post-processing programs: U.S. Geological Survey Open-File Report 00-184, 210 p. (http://water.usgs.gov/nrp/gwsoftware/modflow2000/ofr00-184.pdf)

Judd-Henrey, I, Simpson, M., and Maathuis, H. 2004. Transboundary aquifer mapping and assessment: Saskatchewan – Manitoba. Saskatchewan Research Council, Publication 11738-1E04, 54 p.

Judd-Henrey, I., and Simpson, M. 2005. Transboundary aquifer mapping and assessment: Saskatchewan – Alberta. Saskatchewan Research Council, Publication 11895-1E05, 51p.

Komex International Ltd., 2001. Aquifer management planning study for Edson and surrounding areas. Komex International Ltd., Calgary, 88 p.

Kruseman, G.P., and de Ridder, N.A. 1990. Analysis and evaluation of pumping test data. ILRI Publication 47 (2nd edition), Wageningen, The Netherlands, 377 p.

Lemay, T., Parks, K., Andriashek, L.D., Michael, K., Jean, G., Kempin, E., and Stewart, S. 2005. Regional groundwater quality appraisal, Cold Lake – Beaver River drainage basin, Alberta. Alberta Energy and Utilities Board, Alberta Geological Survey, EUB/AGS Special Report 74, 161 p. (http://www.ags.gov.ab.ca/publications/SPE/PDF/SPE_073.pdf)

Maathuis, H. 1991. Evaluation of groundwater resources in the Yorkton area. Interim report. Saskatchewan Research Council, SRC Technical Report No. 227, 165 p.

Maathuis, H. 2005. Review of pumping and recovery data for the Tyner Valley aquifer and impact of pumping on the Tessier aquifer. Saskatchewan research Council, Publication 10417-2-E05, 31 p.

Maathuis, H. 2006. Proposal and cost estimate. Conceptual aquifers management framework study KA511-05-0992. Saskatchewan Research Council, Publication 11222-3F06, 4 p. Confidential proposal and cost estimate prepared for Environment Canada

Maathuis, H., and van der Kamp, G. 1986. Groundwater observation well network in Saskatchewan, Canada. Proceedings of Canadian Hydrology Symposium No. 16, National Research Council Canada, NRCC No. 25514, pp. 565-581.

Maathuis, H., and van der Kamp, G. 1988. Comprehensive evaluation of groundwater resources in the Regina area. Saskatchewan Research Council, Technical Report No. 209, 151 p.

Maathuis, H. and van der Kamp, G. 1998. Evaluation of pumping and recovery data for the Estevan and Tableland aquifers. Saskatchewan Research Council, Publication No. 10421-1C98, 28 p.

Maathuis, H. and van der Kamp. G. 2006. The Q_{20} concept: sustainable well yield and sustainable aquifer yield. Saskatchewan Research Council, Publication 10417-4E06, 55 p.

Maathuis, H. and Simpson, M. 2006. Groundwater resources in the Yorkton area aquifer management plan: final report. Saskatchewan research Council, Publication 10419-1-E06, 51 p.

McDonald, M.G., and Harbaugh, A.W. 1988. A modular three- dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p. (http://pubs.usgs.gov/twri/twri6a1/pdf/TWRI_6-A1.pdf)

Oak Lake Aquifer Management Plan Round Table. 2000. Oak Lake aquifer management plan. Planning for the future of the Oak Lake aquifer. Oak Lake Aquifer Management Plan Round Table, 23 p. (http://www.gov.mb.ca/waterstewardship/reports/planning_development/oak_lake.pdf)

Parks, K. (2006) Hydrogeological framework of the Battle River basin, Alberta – progress report 2005-06. Alberta Energy and Utilities Board, Alberta Geological Survey, unpublished draft report, 32 p.

Parks, K., Andriashek, L.D., Michael, K., Lemay, T., Stewart. T., Jean, G. and Kempin, E. 2005. Regional groundwater resource appraisal, Cold Lake – Beaver River drainage basin, Alberta. Alberta Energy and Utilities Board, Alberta Geological Survey, EUB/AGS Special report 74, 157 p. (http://www.ags.gov.ab.ca/publications/SPE/PDF/SPE_074.pdf)

Phipps, G.C. and Betcher, R.N. 2007 Long-term water level and water quality response to pumping: the Winkler aquifer in Manitoba. Accepted for presentation at the 60th Canadian Geotechnical Society Conference and 8th Joint CGS-IAH/CNC Groundwater Conference, October 2007, Ottawa.

Plaster, K. and Grove, G. 2000. A review of transboundary groundwater apportionment. Prairie Province Water Board, Report 155, 71 p.

Prairie Provinces Water Board (PPWB). 1996. Groundwater apportionment in the Cold Lake basin. Prairie Provinces Water Board, Committee on Groundwater, PPWB Report No. 142, 10 p.

Printz, J. 2004 Milk River aquifer reclamation and conservation program. 1999-2004 Summary report. Agriculture and Agri-Food Canada, PFRA, online report, (http://www.agr.gc.ca/pfra/water/reports/aquifer_e.pdf)

Render, F.W. 1990. The water supply capacity of the Winkler aquifer. Presentation at the Annual Conference of the International Coalition for Land/Water Stewardship in the Red River Basin, November 15 and 16, Winnipeg, Manitoba, 13 p.

Rosenberg International Forum on Water Policy, 2007. Report on the Rosenberg international forum on water policy to the minister of Environment, province of Alberta. Rosenberg International Forum on Water Policy, University of California, Berkeley, USA, 26 p.

Sophocleous, M. 1997. Managing water resources systems; why "safe" yield is not sustainable. Ground Water, Vol. 35, No.4, p. 561.

Sophocleous, M. 2004. Climate change: why should water professionals care? Ground Water, Volume 42, No. 5, p. 637.

Saskatchewan. 2003. Saskatchewan's safe drinking water strategy. Government of Saskatchewan, 6 p. (http://www.se.gov.sk.ca/environment/protection/water/Water_report_April_2003.pdf)

Saskatchewan Watershed Authority (SWA). 2006a. Yorkton area aquifers. Source water protection plan. Saskatchewan Watershed Authority, 27 p. (http://www.swa.ca/publications/documents/YorktonAreaAquifersSourceWaterProtectionPlan.pdf)

Saskatchewan Watershed Authority (SWA). 2006b. Assiniboine River watershed source water protection plan. Saskatchewan Watershed Authority, 54 p. (http://www.swa.ca/publications/documents/AssiniboineRiverWatershedSourceWaterProtectionPlan.pdf)

Saskatchewan Watershed Authority (SWA). 2006c. Lower Souris River watershed source water protection plan. Saskatchewan Watershed Authority, 54 p. (http://www.swa.ca/publications/documents/LowerSourisRiverWatershedSourceWaterProtectionPlan.pdf)

Saskatchewan Watershed Authority (SWA). 2006d. Moose Jaw River watershed source water protection plan. Saskatchewan Watershed Authority, 60 p. (http://www.swa.ca/publications/documents/MooseJawRiverWatershedSourceWaterProtectionPlan.pdf)

Saskatchewan Watershed Authority (SWA). 2006e. South Saskatchewan River watershed. Draft source water protection plan. Saskatchewan Watershed Authority, 26 p. (http://www.swa.ca/Publications/Documents/DRAFTSouthSaskatchewanRiverWatershedSourceWaterProtectionPlan.pdf)

Tokarsky, O. 1985. Hydrogeologic profile Alberta – Saskatchewan boundary. Prairie Provinces Water Board, 63 p.

Tokarsky, O. 1986. Hydrogeologic profile Saskatchewan – Manitoba boundary Prairie Provinces Water Board, PPWB report No. 79, 44 p.

van der Kamp, G., and Maathuis, H. 1991. Annual fluctuations of groundwater levels as a result of loading by surface moisture. Journal of Hydrology, Volume 127, Nos. 1-4, pp. 137 - 152.

van der Kamp, G. and Maathuis, H. 2002. The peculiar groundwater hydraulics of buried-channel aquifers. ***In*** Stolle, D., Piggott, A.R., and Crowder, Proceedings of the 55th Canadian Geotechnical and 3rd Joint IAH-CNC groundwater Speciality Conference, Niagara Falls. Southern Section of the Canadian geotechnical Society, pp.695 – 698.

van der Kamp, G., and Maathuis, H. 2006. Groundwater sustainability in the prairies – some examples. Proceedings (CD) of the 59th Canadian Geotechnical and 7th Joint CGS/IAH-CNC Groundwater Specialty Conference, Vancouver, October 1 – 4, pp. 1288 – 1293.

van der Kamp, G., and M. Hayashi. 1998. The groundwater recharge function of small wetlands in the semi-arid northern prairies. Great Plains Research 8, pp. 39 -56.

van der Kamp, G., and Hayashi, M. 2007. Drainage of prairie wetlands and groundwater recharge: a question of integrated water management. Abstract submitted for oral presentation at the 60th Annual National Conference of the Canadian Water Resources Association, Special Session on integrated management of groundwater and surface water, June 25-28, 2007, Saskatoon SK.

van der Kamp, G., Maathuis, H., and Shaheen, N. 2007. Groundwater supply for the City of Regina – a century of sustainable groundwater use. Accepted for presentation at the 60th Canadian Geotechnical Society Conference and 8th Joint CGS-IAH/CNC Groundwater Conference, October 2007, Ottawa.

Van Stempvoort, D., Ewert, L., and Wassenaar, L. 1992 AVI: a method for groundwater protection mapping in the Prairie Provinces of Canada. PPWB Report No. 114, 18 p.

Van Stempvoort, D., Ewert, L., and Wassenaar, L. 1993 Aquifer vulnerability index; a GIS-compatible method for groundwater vulnerability mapping. Canadian Water Resources Journal, Volume 18, No. 1, pp. 25-37.

Van Stempvoort, D.R., and Simpson, M. 1994. Hydrogeology of the southeast aquifer management plan. Volume I; text. Saskatchewan Research Council, Publication R1220-9-E-94, 223 p. (revised 1995)

Winkler Aquifer Management Plan Round Table. 1997. Winkler Aquifer management plan. Planning for the future of the Winkler Aquifer. Winkler Aquifer Management Plan Round Table, 22 p. http://www.gov.mb.ca/waterstewardship/reports/planning_development/winkler_aquifer_mp.pdf

Winter, T.C., Harvey, J.W., Franke, O.L. and Alley, W.M. 1998. Groundwater and surface water. A single resources. U.S. Geological Survey, Circular 1139, 79 p. (http://pubs.usgs.gov/circ/circ1186/pdf/circ1186.pdf)