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Groundwater, Hydrogeology and Sustainability in Saskatchewan

A review of groundwater and hydrogeological issues for Saskatchewan and the development of a research strategy

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Preface

The rapid growth in the Province and increasing pressures on groundwater associated with municipal, industrial and agricultural development, made it clear that a strategic review of research needs and opportunities would be timely and helpful, for the Global Institute for Water Security (GIWS) and its provincial partners. This report was commissioned by GIWS. It is based on extensive consultations in September/October 2013 between Dr. Denis Peach and representatives of the government, industry and academic sectors in Saskatchewan, and refined following many important and helpful comments and suggestions from these individuals on a preliminary draft. We therefore believe that the report represents a broad consensus of professional opinion across these sectors. It is intended to provide a basis for further discussion and development of a collaborative framework for new research integration to address the needs and opportunities faced by the Province in the sustainable development of groundwater and protection of the subsurface environment.

Executive Summary

Importance of groundwater and the subsurface environment to Saskatchewan

Groundwater aspects of the subsurface environment are of major importance to the economic development and well-being of Saskatchewan for several reasons.

1. The groundwater resources of Saskatchewan currently provide essential water supplies to a range of users. These include:
    - Many communities outside the major cities, which rely on groundwater for domestic and municipal drinking water supplies;
    - The majority of farmers who rely on groundwater for both domestic and on-farm water supplies; and,
    - The mining and oil and gas industries who use groundwater in their extraction processes when surface waters are not readily available, for example due to distance from a main river.

2. In times of drought, when surface water supplies face increasing pressure, groundwater resources provide an important alternative water source, and are therefore a potentially-important strategic resource for the Province. We note that drought risk is likely to increase in a warmer climate, and that the palaeo-record shows more severe historical droughts than occurred in the 20th Century.
3. The pore space of geological formations beneath the Prairies is used for the disposal of waste waters from mining and oil and gas development. The Province is also home to the Weyburn-Midale carbon dioxide storage and enhanced oil recovery project and will host the world's first operational Carbon Capture and Storage project, which will also use the deep geological environment to store carbon dioxide produced in a coal fired power station.
4. Groundwater systems, including those in the Province, are vulnerable to pollution from domestic, municipal, industrial and agricultural activities. Such pollution is often long-lived, and remediation, where possible, is often costly.
5. The role of groundwater in the provision of baseflow to the main rivers is currently thought to be small, but climate change may mean that it is of growing importance.

Summary of pressures on the subsurface environment – challenges to development

Saskatchewan is currently developing at an unprecedented rate and the provincial government has placed growth at the top of its agenda in all sectors.

- Agricultural production reached 38.4 million tonnes in 2013, achieving the previously set target of increasing production by 10 million tonnes by 2020, i.e., seven years earlier than expected. However, 2013 was an exceptionally favourable year. In more normal years this target will be achieved by changes to agricultural practice, including planting drought resistant crops, increasing irrigation and other changes in land management, including precision agriculture. These measures can impact the water environment (both positively and negatively). Expansion of irrigation from surface water resources is likely, but this may put stress on surface water resources when droughts occur. Hence in some areas and under certain circumstances the importance of groundwater will grow and could become crucial.
- In the mining sector, the growth, in particular of potash production, is also unprecedented. A 90% increase is expected from expansion and extension of existing potash mines, and with one new mine due to open in the next year and several others being investigated for development over the next decade as new international mining companies invest heavily in Saskatchewan, production will grow even further. The life of a potash mine is many decades, so long-term security is needed, both of water supply and for the disposal of waste products, which is normally by injection into the deep geological formations well below the levels of mining activity. The companies also need

to understand the hydrogeological behaviour of the deposits that they are mining to avoid costly flooding inflows from deep groundwater brines, which can result in mine closure. As mines run their course and the mineral resource (e.g., uranium or potash) becomes exhausted at a particular site, mine closure plans are required so the mine, its waste and the nearby environment remains safe into the distant future. While other mining activities (e.g., base metals, gold, diamonds) also require secure water supplies, problems of water resource availability are mainly focused on developments in the south of the province where potash mining predominates.

- The oil and gas sector is also going through a boom period in Saskatchewan and this is set to continue well into the future with the further development of oil pools (often using enhanced oil recovery) and natural gas, including oil shale. The biggest expansion is in oil shale (e.g., in the Bakken formation), where development relies on hydraulic fracturing ("fracking") to extract the oil. This requires water which is often supplied from groundwater. The resultant flowback of contaminated waters requires disposal. Disposal is normally achieved by re-injection into the exploited formation, for example the Mississippian Bakken, or deeper formations. Enhanced Oil Recovery (EOR), by pressurising oil reservoirs with water or carbon dioxide, is a well-known practise in Saskatchewan and will continue for the foreseeable future.
- In parallel with the economic growth discussed above, the provincial population is increasing, resulting in increasing demand on water resources. In areas remote from surface water sources, groundwater is an important resource, and there are associated pressures for increased use of groundwater for domestic and municipal supply, for example, in the Regina East area.

Science needs to support sustainable development

The Province faces the challenges of a large land area with a complex geology, and a small population. In that context, it has made exemplary strides to develop the knowledge base, for example by a progressive programme of hydrogeological mapping. However, looking to the future, the sustainable development of the subsurface will benefit greatly from improved scientific understanding of groundwater in a number of key areas. The science challenges are summarised here. Below, we turn to the opportunities for knowledge development and mobilisation.

Although many communities rely on groundwater for their domestic water supply, the further development of groundwater supplies may be hampered by uncertainty over reliable long-term yield and storage replenishment, for example, due to a very long drought or under growing demand. As more groundwater resources are used and needed in the future, further understanding of long-term recharge, aquifer morphology and inter-connections with both surface water and other aquifers, the integrity of aquitards and cap rocks between these aquifers, and groundwater quality will be required for their safe and sustainable development. If groundwater is to be considered as a strategic resource, for instance in times of severe drought, then quantification of the storage water and its ability to be replenished will be important to bring confidence in its reliability.

Saskatchewan is heavily reliant on the South Saskatchewan River for growth and development and the current and future role of groundwater in sustaining baseflow is presently a matter for conjecture, with little study. This scientific evidence is likely to become more important with climate change and changes in weather pattern and warming winters.

It is clear that energy and mineral resource extraction and waste disposal into the deep geology are growing rapidly, but the knowledge of where these waste fluids flow in the deep geology is not clear. There are challenges for science in understanding the nature of aquifers, aquitards and cap rocks, well-bore integrity (especially of wells drilled in 1950's and 60's) and interactions between activities and between groundwaters in differing formations up and down the Saskatchewan stratigraphy. As the use of groundwater resources grows to supply the growing population and industrial requirements, a greater level of knowledge than has been necessary to date is likely to be required to ensure sustainability.

Saskatchewan has many aquifers that can be subdivided into three types:

1. deep saline aquifers currently used for waste disposal;
2. intermediate depth aquifers, beneath the Quaternary, and cross-cutting buried valley aquifers with uncertain recharge and resource capacity and variable water quality, but sometimes used for potable domestic supplies; and,
3. shallow Quaternary aquifers used in rural communities and towns, typically with uncertain geometry, inter-relationships and recharge.

These aquifers are separated or isolated from each other by aquitards, often thick clay or shale deposits. Their ability to protect, isolate and seal is also fundamental to the future management of the subsurface environment. The relationships and interactions between these different aquifers and aquitards are not well defined, so allocation and sustainability decisions are a challenge. As greater use of the subsurface is made, for mineral and energy resource development, for water supply and for waste disposal, the challenge seems likely to grow.

Investments that are currently being made in the oil and gas and mining industries are large. To make these investments, which secure the economic future of Saskatchewan and have an important positive boost for all of Canada, there is an important role for improved understanding of long-term water security, waste management and environmental risks.

The needs for Highly Qualified Personnel (HQP)

Individuals with the skills required to fill the knowledge gaps and provide informed decision-making are scarce. Although the Province has internationally-important skills and experience in many areas, with the exception of a small number of young Faculty and government scientists with related expertise, much of the hydrogeological knowledge of groundwater and hydrogeology of Saskatchewan lies in a few retired or near retiring personnel. The expertise within government is limited to a small number of individuals, and some can be found with consultant firms. However, the limited breadth of a skilled base seems likely to prove problematic in the near future.

Key Recommendations

The key recommendations made below are of a strategic nature. The role of the Global Institute for Water Security and the University of Saskatchewan has not been specified. Leadership may more appropriately fall to the Provincial government and its agencies or to industry, or may be best served by academia, or, perhaps ideally, a partnership of all three.

Our recommendations are:

1. Coordinate groundwater and hydrogeological research. Currently, the groundwater and hydrogeological science base is fragmented between multiple stakeholders including: industry (mining, oil and gas, water supply, agriculture); Saskatchewan Water Security Agency (SWSA); Saskatchewan Ministries of Economy, Environment, Agriculture and Health. Research is also uncoordinated between a variety of research organisations and institutes.
2. Conduct an audit of groundwater and hydrogeological research, data and knowledge and make the results accessible, as much as possible, via an integrated web-portal.
3. Begin a programme and seek funding from relevant stakeholders to further develop the knowledge base required for robust evidence-based decision-making. Priorities should be set by a panel comprising stakeholders and academia.
4. Develop a comprehensive Sustainable Groundwater Management Plan for the Province with input from relevant stakeholders, academia and the public at large.
5. Review the management and regulatory practices and framework to ensure that development proceeds as fast and as sustainably as possible, in light of the new knowledge being produced, the rapid growth that has occurred and increasing competition for groundwater and pore space in deep geological formations.
6. Develop training opportunities for HQP to meet the needs of government, industry and the university sector for hydrogeological and related expertise.

Conclusion

The massive development of agriculture and natural resources in Saskatchewan, set within the context of a warming climate, presents environmental challenges to science and management.

There is an important need for new research and survey to provide the basis for sound management in the face of increasing pressures. The knowledge amassed over the last few decades and the high level of skills of the managers and scientists mean that Saskatchewan is in an excellent position to meet those challenges, but action is needed now to support the development of appropriate strategies to ensure sustainable development over the next several decades.

1. Introduction – the strategic context for the review and relevant Provincial initiatives

The University of Saskatchewan (U of S) launched the Global Institute for Water Security (GIWS) on 22 March 2011 with a vision to be a driving force for research into global water security issues and their local implications. GIWS is funded through the Canada Excellence Research Chair (CERC) in Water Security initiative which received a $30 million, joint federal-provincial-university commitment over seven years beginning in 2010. The Institute's research is focused on sustainable use of water resources and protection against flood and drought hazards. Multi-disciplinary science, engineering and social science teams work with industrial and government partners to address four broad water security issues: climate change and its impacts on water resources, land use change, sustainable development of natural resources, and socio-hydrology (the human and decision-making aspects of water resource development).

GIWS seeks to improve monitoring, understanding and modelling in these areas of endeavour, and in particular, to address issues relevant to the Province of Saskatchewan. Since March 2011, efforts have concentrated on surface water quantity and quality, with less attention paid to groundwater. It is has become increasingly clear, however, the Institute's interest in carrying out research to better manage water resources in the face of societal and environmental change applies equally to groundwater and surface water, and there are significant, but uncertain, linkages between the two. Hence the GIWS commissioned a review of issues around groundwater knowledge and management with the goal to develop a future research program to address deficit areas and inform decision-making. The review was carried out by Dr. Denis Peach, recently retired Chief Scientist of the British Geological Survey and an expert in hydrogeology. The scope of service and review methodology is outlined in Appendix 1. A list of personnel and organisations consulted can be found in Appendix 2.

Growing interest in groundwater at the U of S dovetails nicely with other active or recently launched Provincial research initiatives including:

- the Petroleum Technology Research Centre (PTRC) (opened in 2000);
- the Sylvia Fedoruk Canadian Centre for Nuclear Innovation (Fedoruk Centre) (launched 2011);
- the Global Institute for Food Security (GIFS) (established December 2012); and,
- the International Minerals Innovation Institute (IMII) (launched May 2012).

Further information about these institutes can be found in Appendix 3. The PTRC managed the largest Enhanced Oil Recovery and carbon dioxide storage research project in the world ($46 million) between 2000 and 2012. The PTRC does not conduct in-house research, but commissions outside researchers from Canadian and international universities and research institutes to undertake research related to the oil and gas industry. Similarly, the Fedoruk

Centre, GIFS and IMII commission research, but do not carry it out themselves. In contrast, GIWS partners with government and industry to produce both applied and fundamental research related to water security. Given the overlapping missions and management models of the various institutes, it makes sense for one of them, in this case GIWS, to take a leadership role to promote research to ensure that there exists broad holistic coverage of society's need for groundwater and hydrogeological knowledge, including groundwater quality, quantity and links to surface water.

2. Economic, social and environmental drivers and the role of groundwater and hydrogeological science – the global context

Groundwater is under increasing pressure world-wide from over-abstraction and degradation of its quality. It is a vital source of water to many rural communities, but also for municipal, industrial and agricultural water supply. Even in places where surface water is normally plentiful, groundwater can be an important resource in times of drought. However, it is vulnerable to pollution, and due to long travel times between aquifer recharge and discharge, contaminants, once present, can persist in groundwater for decades or even centuries. It is of course, 'out of sight', and hence often 'out of mind'. While groundwater is often a cheap resource to develop, monitoring and investigation are expensive. There are thus major challenges to quantify the extent of groundwater resources and their quality, the natural recharge (and hence sustainable supply), the long-term impacts of abstractions and waste disposals, the impact of resource development (mining and oil and gas exploitation), and hence to provide the information needed for sustainable development.

There are a number of global drivers of change that are relevant to the development and protection of groundwater resources in Canada and most particularly Saskatchewan. These include increasing demand for water, from population growth and economic development, increasing need to safely and sustainably dispose of wastes to the subsurface, increasing pressures on groundwater quality, from domestic, agricultural and industrial activities, and concerns for climate variability and change, including increasing drought and flood risk.

The water-energy nexus is often discussed in the context of hydropower and surface water, but the global search for cheap and sustainable energy has direct impacts on groundwater flows and quality. Oil and gas exploitation from the natural environment clearly occurs in the subsurface where groundwater in some form is ubiquitous. The processes involved in exploitation require water and often involve the injection of fluids into the geological reservoir. For example, hydraulic fracturing or "fracking" has emerged as an important process for enhancing the recovery of oil from oil shale and shale gas, but has gained a degree of public notoriety in the United States and Europe. Both processes require water and produce volumes of contaminated water (co-produced and flowback), which are usually re-injected into the exploited or deeper geological formations. The generation of nuclear energy requires the mining of uranium and the disposal or temporary storage of mine waste in tailings ponds, which has the potential to interact with the environment, including surface water courses and groundwater. The generation of nuclear energy produces radioactive waste which must be either stored or more likely contained in a (hydro) geological environment, for many tens of thousands of years, before it can be deemed safe. Coal-based energy production similarly raises issues of groundwater protection; these include pollution from abandoned mines and the associated need for management of acid mine drainage, as well as issues of power station atmospheric emissions and 'acid rain'.

Groundwater issues associated with resource development extend well beyond the energy industries. More generally, the development of subsurface resources involves possible interactions of resource development on the groundwater environment, and issues where knowledge of groundwater flow and hydrogeochemical behaviour is essential for safe management of these activities. For example, the ten potash mines in Saskatchewan produce large volumes of brine (particularly where solution mining is practised) which is normally disposed of by injection into geological horizons much deeper that the mined formations.

Groundwater is also intimately linked to food and other agricultural production. Agriculture uses water for irrigation, livestock watering and other on-farm activities, and, globally and locally, groundwater plays a key role in providing water for some or all of these needs. In addition, agricultural land management changes the hydrological cycle and water quality, with impacts on groundwater recharge (and hence sustainability) and on groundwater quality.

In addition to its role as a key water resource in times of drought, groundwater is an important element in many other natural hazards including earthquakes, landslides and floods. In particular, groundwater is an often overlooked aspect of flooding, both in river floodplains and internal drainage basins. More generally, groundwater is important in maintaining baseflows in rivers and, as noted above, in the case of meteorological drought and limited surface water resources, groundwater storage is undoubtedly the most important global reservoir we have to draw upon in such times of water scarcity.

Notwithstanding these issues, the biggest drivers of governments and peoples are undoubtedly economics and societal culture. The "growth agenda" is firmly the aspiration of all nations as the world pulls itself slowly out of the financial instability and economic weakness of the last five years. However, it is now accepted and policy of many governments, including those of Saskatchewan and Canada, that what we do must be sustainable and represent value for money. The consequences of our actions and our decisions must be based on evidence and we need to be able to make forecasts, and if possible predict what might happen in the future, under changing circumstances and varying stresses. As our population grows and our demands for ever higher standards of living continue, the speed of change and the pressures on the water environment also increase. Given the increasing pressures on groundwater quantity and quality outlined above, there is an increasing need for improved understanding to support sustainable natural resource exploitation and the development of groundwater resources.

3. Water Demand and Use in Saskatchewan

Total Water Demand and Use

Statistics on water use by sector in Saskatchewan are scarce. Table 1, below, includes both surface and groundwaters combined and although the data are ten years old the general distribution of uses probably remains very similar today.

Table 1: Total Water Use (surface and groundwater) in Saskatchewan

Type of Use	Amount (million cubic meters)	Percentage
Agriculture	557.4	67.0
Municipal and domestic	171.2	20.6
Industry and commerce	52.8	6.3
Mining	25.8	3.1
Thermal power generation	17.1	2.1
Oil and Gas	6.7	0.8
Total	831.5	100.0

Source: Government of Saskatchewan, 2003.

By far the biggest user of water is agriculture, but with a growing population, predicted to be 1.2 million by 2020 (Government of Saskatchewan, 2012), and continued industrial and resource development, the other areas of demand will grow. A more recent study provides estimates of 2010 and predictions for 2020, 2040 and 2060, but only for eight selected catchments representing 27% of the provincial population (Kulshreshtha et al., 2012). The South and North Saskatchewan River Basins (SSRB, NSRB) (45% of the population depend on the SSRB for their daily water needs) are not included, neither is the Qu'Appelle River Basin, although similar reports on these areas are in hand. This study confirms the prediction of growing demand for industry, mining and oil and gas over the next 10 years and municipal and domestic over the period to 2060. Three scenarios are cited in the study, the baseline scenario, which assumed that trends based on past data will continue into the future, and a climate change scenario, where water demand is affected by changes in climate characteristics and by occurrences of extreme events. The project considered a further scenario which allowed for the impact of increased water conservation measures, which, if successful, would provide decreases of the same order as predicted increases due to climate change.

Summary of Total Water Demand in 8 Selected Basins for the Baseline and Climate Change Scenario from Kulshreshtha et al., 2012

The total water demand in the eight river basins for the baseline scenario is 2.5 million dam^3 of which direct anthropogenic demands made up only about 395,000 dam^3 in 2010. The largest demand is from agriculture at over 300,000 dam^3 which is expected to increase to 310,804 dam^3 by 2060. The industry/mining water demand is the next largest demand sector estimated at 59,000 dam^3 increasing to 66,171 dam^3 by 2020, but then expected to decrease by 2060 to 34,000 dam^3. This decrease is primarily a result of assuming declining oil and gas production in these basins in later decades. However, oil and gas extraction in Saskatchewan seems likely to continue at increasing rates for the next 10-20 years, as does potash mining (see Section 4).

The municipal/domestic water demand is the third largest water using sector in these basins and is predicted to increase by 17.3% over the 2010 level by 2060. This is the fastest growing sector for the eight basins combined.

Under a climate change scenario the total water demand for the eight Saskatchewan basins is expected to increase by 10.7% by 2060. Moreover, the water demand for agricultural purposes is expected to be affected most noticeably by climatic changes, increasing by 17.6% of the baseline scenario by 2060. The other sectors' water demands indicate slight increases in comparison to the baseline scenario. Indirect anthropogenic water demands (mainly evaporation) are also expected to increase under this scenario by 10%.

Irrigation

Starting in the southwest of the Province during the initial settlement, irrigation projects were developed by capturing the spring snow melt and run-off. Irrigation expansion continued with intermittent growth through the 20th Century to approach 350,000 acres. By the 1990s irrigation expansion had slowed (Clifton Associates Ltd., 2008). New irrigation infill and development projects have been identified (Clifton Associates Ltd., 2008) in all regions of Saskatchewan. In total it is estimated that there may be as much as two million acres of irrigable lands in the Province. Should development of this scale take place, then water demand would increase considerably.

Groundwater Use and Demand

Groundwater is the primary source of drinking water for over 50% of rural consumers in Saskatchewan. An adequate supply of groundwater is necessary to supply drinking water demands. It is also an important resource for industry, irrigation and agriculture (Davies and Hanley, 2010).

Obtaining accurate and current information on quantities of groundwater used and the type of use in Saskatchewan (or in Canada as a whole) is difficult, and there are many inconsistencies and inaccuracies in data (Rutherford, 2004.) This is confirmed by the Saskatchewan Watershed Authority (now the Water Security Agency) in their State of the Watershed Report for 2010 (Davies and Hanley, 2010) which characterised Groundwater Quantity indicators as follows:

Status: Quantifying groundwater is challenging due to the lack of available data. Therefore, this indicator is considered "under construction."
Trend: Trends in groundwater quantity cannot currently be assessed due to the lack of available data.

In 1996, 435,941 people were said to be reliant on groundwater in Saskatchewan i.e., 42.8% of the population of the province (Rutherford, 2004). This estimate includes rural supplies (unlicensed) and municipal supplies. The total has almost certainly decreased considerably, by well over 200,000, since this time due to the Regina (population 210,556 (Statistics Canada, 2012)) municipal supply, and that of other peri-urban communities, being changed to surface water. Nevertheless, groundwater is still the main source of water for communities surrounding the city of Regina and it seems likely that industrial uses will have increased, due to increasing mining and oil and gas development (see later). In 2004, 52.42% of groundwater use was for industrial purposes, the vast majority of which was for oil and gas recovery, cooling water and mining (Rutherford, 2004).

It seems reasonable to forecast that oil and gas development will continue to grow over the next decade or more (Government of Saskatchewan, 2013a) and will need to use groundwater because of a scarcity of surface resources in some areas, in particular in the south and southwest. In some areas where oil and gas extraction is active and likely to grow there are significant regions of internal drainage. A significant part of Saskatchewan River drainage, never enters the wider drainage system, even during extremely wet years, contributing only to small local lakes and wetlands of internal drainage basins (NRCan, 2010), so access to surface water resources can be limited.

Although very little groundwater is reportedly attributed to agricultural use (Rutherford, 2004), the farmers themselves largely rely on groundwater for their domestic supplies, and in many cases for on-farm uses, so it is essential in support of agriculture and its development in Saskatchewan.

All water used by industry not on municipal systems is reported to SWSA, whether ground or surface water. In addition, all water used by all communities on a licenced treatment system is reported by month annually. The only groundwater use not reported is by domestic users which are unlicensed, but which can be estimated and is relatively small. Information is available to the public on request.

Nevertheless, aggregated data concerning groundwater demand and use in Saskatchewan are not easily obtainable and this may be an area where further research is required or data and information integration needed to provide for more certainty in planning or highlighting research areas for the future.

4. Development in Saskatchewan

The Government of Saskatchewan has stated that growth is its primary concern and aim in its "Plan for Growth – a 2020 vision and beyond" (Government of Saskatchewan, 2012). This is seen across the agricultural sector, and those of oil and gas and minerals. The government wishes to achieve substantial growth by encouraging investment, whilst containing public expenditure and reducing government debt. The energy and mineral extraction sectors, in 2012, contributed approximately 21.8% to the provincial Gross Domestic Product (GDP) and agriculture contributed about 5% (Statistics Canada, 2013 http://www5.statcan.gc.ca/cansim/). The growth plan has a target to double the value of all of Saskatchewan's exports by 2020.

4.1 Agricultural Sector

The growth plan sets out aims to increase crop production by 10 million tonnes and to increase exports of agricultural and food products from $10 billion to $15 billion by 2020. The first of these targets was surpassed in 2013 when crop production reached 38.4 million tonnes (Government of Saskatchewan, 2014). Nevertheless, in order to maintain this as a long-term average in a sustainable way, changes are to be expected in agricultural practice. This means that either crops must be developed that produce higher yields for the same soil quality/nutrient supply and crop water intake, or the efficiency of these inputs has to be increased by some method (Council of Canadian Academies, 2013). There will be considerable efforts put into crop research and development as envisaged, for example, by the initiation of the GIFS. However, the Saskatchewan Ministry of Agriculture also plans to increase irrigated area in the province (Government of Saskatchewan, 2012), which will require more of the flows from the South Saskatchewan River to be allocated for this purpose. Currently there is a surplus of water available for irrigation, but as more of these resources are used to supply the mining industry and the growing population and in the event of long-term drought, water resource availability is likely to become a bigger issue. The Canadian Prairies are very liable to drought, mainly because of the high variability of precipitation, both spatially and temporally (Bonsal and Wheaton, 2005). The Prairies experienced multi-year droughts in the 1890s, 1910s, 1930s, 1960s and 1980s and most recently from 1999 to 2005 (Gan, 2000; Lawford, 1992; Hanesiak, et al., 2011). Recent research by Bonsal, et al. (2013) suggests that droughts in the palaeo-record from 1400 were more severe than those of the 20th century. Groundwater, currently very much a secondary resource, is now becoming a much more important consideration in long-term planning.

Farmers and their families largely rely on groundwater for their domestic supplies, for any food processing that they need to carry out and for cleaning and stock rearing purposes. It has been estimated that there are over 81,000 private wells in operation in the province (pers. com. K. Lo, Saskatchewan Water Security Agency from the Wells database). The current quality of these well waters is believed to be poor in comparison with municipal supplies derived from surface water. Between 4% and 10% of all community and farm groundwater supplies suffer from high levels of arsenic and selenium (Olkowski, 2009; pers. com. K. McCullum, Saskatchewan Ministry of Environment). This is not pollution, but results from leaching of naturally occurring minerals in the Quaternary deposits into groundwaters (Thompson, et al., 1999). However, a 2001 survey (Thompson, 2001) showed that 14.1% of the 3,425 private wells sampled in this study had concentrations of nitrate exceeding Canadian drinking water standards. While some nitrate may be present due to natural sources, the major anthropogenic sources are domestic sewage disposal, livestock operations and use of nitrate-based fertilizers (although use of the latter in Saskatchewan is much less intensive than, for example, in Europe). Thus, further work may be required to ascertain the source of this contamination. Nitrate and bacteriological contamination is suggested to occur in about 40% of wells in Saskatchewan (http://www.ppwb.ca/information/106/index.html, 2009). Currently water quality of these groundwater supplies is not regularly monitored, and unlike public water suppliers, the owners of private supplies are not required to have their water tested (Thompson, 2003).

4.2 Mineral Sector

Recently the potash mining industry has seen considerable activity with the influx of multinational mining companies who wish to open new mines. K+S Potash has set up in Canada to open a new potash mine at Legacy, and BHP Billiton (BHP) is aiming to open the first of perhaps five mines, the Jansen project, by 2020 and will initially be investing $2.6 billion. Potash exports from Saskatchewan have increased by 127% since 2007 (Government of Saskatchewan, 2012). The potash mining process both uses water and produces highly concentrated brines which must be disposed of to the environment in some way. The industry also uses water for mining and processing. Currently most water resource requirements are supplied from surface sources, much from the South Saskatchewan River system by SaskWater, which is Saskatchewan's commercial Crown water utility, but there are some groundwater allocations and other surface water sources used. Currently, planned production for the 10 operating potash mines will see a 90% increase by 2023 (Government of Saskatchewan, 2013a). New mines, including the Legacy and Jansen projects, will clearly increase production further and, if

BHP realise their current vision of five new mines over the next decade or so, production levels will increase even more, further increasing the process water and brine disposal requirements. As development reaches deeper levels in the Prairie Evaporite deposits (see Appendix 5), extraction will move more towards dissolution mining by injection of waters with relatively low total dissolved solids to dissolve the potash mineral.

The importance of water resources planning under extreme droughts was highlighted by the 1999-2005 drought (Hanesiak et al., 2011). Security of water resources is of concern to the potash industry. While the GIWS has been instrumental in modelling the South Saskatchewan River System in terms of total resource availability (although this does not include groundwater), BHP, as is their business policy to assure themselves of the risks involved, has developed their own water resources model during their assessments of the feasibility of potash mining in Saskatchewan.

Another issue that the potash mining companies take very seriously is that of water, normally brine, ingress into their mines, which can cause mine closure and considerable loss of production and income. These often catastrophic inflows occur because of mining into collapse features in the evaporate deposits which are full of water or allow water ingress from other strata. Greater understanding of how and why these occur would aid risk management by the mining companies and assist in planning mine development, thereby fostering growth and investment.

Mining of other minerals in Saskatchewan, except for uranium, is less important, from a water perspective, in comparison to that of potash, but individual, site specific problems may need research. Uranium mining is carried out in the north in the Athabasca Basin and the water resource issues associated with the activity, which include dealing with dewatering, as well as wastes, tailings ponds, mine closure and protecting fragile wetland surface water environments, have been the subject of considerable research. The industry is heavily federally and provincially regulated to ensure the protection of society and the environment. However, there is growing concern by environmental NGOs (pers. com. K. McCullum, Saskatchewan Ministry of Environment) regarding protection of the wetland habitats. Research efforts into transport of contaminants via groundwater from waste tailings and ponds to the environment and the safe closure of mines sponsored by industry and government will continue.

4.3 Oil and Gas Sector

Since 2007, Saskatchewan's crude oil exports have grown by approximately 48% (Government of Saskatchewan, 2012). In 2011, Saskatchewan exported more than $10 billion in crude oil (Government of Saskatchewan, 2012) and in 2012, crude oil production in the province reached 172.9 million barrels (from an estimated 29,600 wells), up more than 7% from the previous record of 161.0 million barrels set in 2008 (Government of Saskatchewan, 2013a, http://economy.gov.sk.ca/OilGas). The combined value of oil and gas sales for 2012 was estimated at $12.6 billion and the industry continues to be one of the largest contributors to the Saskatchewan economy ($1.4 billion in revenue (Government of Saskatchewan, 2013b)) and provides more than 34,000 direct and indirect jobs to people in the Province. Saskatchewan is the second largest oil producing province in Canada and has an estimated 1.1 billion barrels of remaining recoverable crude oil reserves.

The Province is going through an oil boom, led by the development of the Bakken play and the use of fracking and water flooding technology. The development of horizontal drilling and fracking techniques was led by industry research in Saskatchewan. Water is an increasingly important issue since it is required for reservoir flooding and fracking. Co-produced and flow-back water is of poor quality. This can, to some extent, be recycled, but some must be disposed of by injection through boreholes to the deep geological formations well below the producing levels.

There seems no doubt that the development of oil resources will continue, particularly in the south of the Province, which is a water scarce region. Crescent Point Energy Corporation (CPE) consider water security an issue they must take very seriously and they are developing a water management plan to deal with both the water scarcity issues and disposal challenges. They have conducted a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis on their water management practises and the following weaknesses and threats were identified as relevant to their operations in Saskatchewan (Delphi Group, 2013).

Weaknesses

- Data management (tracking and reporting)
- No annual water (or environmental) reporting to stakeholders (e.g., sustainability / corporate responsibility report)
- No formal water management plan
- Limited water reuse or recycling in drilling and completions operations

Threats

- Flood vulnerability in Southeast Saskatchewan
- Emerging policies (especially with respect to hydraulic fracturing)
- Increased activity in Bakken play: more demand on regional water resources
- Public perception of hydraulic fracturing (social license)
- Water license delays
- Operating in several water-short areas (Southern Alberta, Southwest Saskatchewan, potentially Southeast Saskatchewan, and Utah)

CPE have made it clear to GIWS they are interested in developing joint research programmes in the groundwater/hydrogeology area. They are often reliant on groundwater resources for the further development of their oil resources. These views were echoed by the Chief Geologist of the Saskatchewan Geological Survey (pers. com. G. Delaney). Natural gas has been developed in the Swift Current area, but remains less important, at the present time, than oil and oil shale. New oil plays are likely to be developed in the Jurassic Shaunavon Formation and the low permeability, high porosity Mississipian-Devonian Bakken. Heavy oil is likely to be further developed from the Cretaceous Manneville Group and horizontal drilling and multi-stage frac completions are resulting in a resurgence of development in the Cretaceous Viking Formation. Regarding other oil and gas developments, it is possible that oil sands might be developed on the Saskatchewan – Alberta border, most likely using in-situ recovery techniques such as steam-assisted gravity drainage. Oil sands water issues are not dealt with in this report as the province of Alberta is the main focus for current development. However, GIWS researchers are involved in oil sands research and also contributed to the Alberta Provincial Environmental Monitoring Panel (AEMP, 2011). It also seems likely under the current global “dash for gas” that shale gas prospects, which are likely to be plentiful in Saskatchewan, will be developed in the future. These are exploited with fracking similarly to oil shale, but currently these prospects are not a priority for the industry.

4.4 Other development activities which will impact on hydrogeology or groundwater resources

The widely published International Energy Agency Greenhouse Gas Weyburn-Midale Carbon Dioxide Monitoring and Storage Project was carried out at the sites of commercial scale Enhanced Oil Recovery (EOR) projects being undertaken by Cenovus Energy Inc. (Weyburn) and Apache Canada Ltd. (Midale). This world-leading research was managed by the PTRC and used the aforementioned EOR operations as a means of studying the geological storage of carbon dioxide (CO_2) on an industrial scale. The research phase of this project ended in 2012 (Hitchon, 2012). The Government of Canada has committed $240 million for the Boundary Dam Integrated Carbon Capture and Storage (CCS) Demonstration Project. This will retrofit and extend the life of Unit 3 of the Boundary Dam coal-fired electricity generating plant. SaskPower, the provincial Crown electricity utility, is contributing $1 billion. The project will capture up to one million tonnes of CO_2 per year which will be available for EOR operations. This is the largest and the first commercial scale Carbon Capture and Storage demonstration project in the world. The SaskPower CCS Global Consortium was created so that partners can gain comprehensive knowledge and explore the commercial viability of CCS (Government of Saskatchewan, 2013b).

Aquistore is an independent research and monitoring project (http://aquistore.ca/), managed by the PTRC, which aims to demonstrate that storing liquid CO_2 by injecting it into the saline

Deadwood formation (3,400m depth), rather than using it in active oil producing zones for EOR, is a safe, workable solution to reduce greenhouse gases. This will be yet another activity that uses the hydrogeology of the Western Canadian Sedimentary Basin (WCSB) to dispose of a contaminated fluid. If successful, this practise will become much more prevalent the world over, not just in Saskatchewan. Further developments using the subsurface that are or have been investigated or considered, include geothermal energy development and aquifer storage and recovery or other artificial recharge techniques using surface water during wet years.

Another development currently being considered is the geological disposal of radioactive waste in the subsurface. The Nuclear Waste Management Organisation (NWMO) of Canada is at the early stages of a process to safely dispose to the subsurface its nuclear waste under an Adaptive Phased Management Strategy (Nuclear Waste Management Organisation, 2013). So far 20 communities have expressed interest to be considered for the project. The NWMO has completed preliminary assessments on eight of these, three of which were in Saskatchewan. Of these community expressions of interest, the NWMO has determined that three, one in Saskatchewan (Creighton), have been identified for Phase 2 study. Currently this is the only site being considered for radioactive waste disposal in Saskatchewan and it is situated in the Northwest of the province on granitic rocks. Geological disposal of intermediate- and low-level radioactive waste materials is being considered at the Bruce Nuclear Power plant in Ontario. The lithologies at the level of the projected repository consist of low permeability limestones and shales overlain by thick shales (www.nwmo.ca/dgrsubmission).

A summary of development activities in Saskatchewan that are likely to have an impact on groundwater systems is given in Appendix 4.

5. Legal Frameworks for the groundwater and hydrogeological environment

The management of groundwater in Saskatchewan originated with English Common Law. Under the rule of absolute capture, a land owner was entitled to the use of groundwater that was overlain by their property with little or no consideration of impacts to the aquifer or other users. Aspects of this rule continue today, with the domestic use of groundwater, as it is narrowly defined, exempt from some regulatory requirements under current legislation.

In 1959, Saskatchewan proclaimed *The Ground Water Conservation Act,* followed in 1966 by *The Ground Water Conservation Act, Regulations.* Together the act and regulations were intended to conserve and protect groundwater resources by regulating the drilling of wells. The act also allowed for the regulation of groundwater use through a licencing process similar to what was already in place for surface water allocations. These approval processes allowed for the protection of the aquifer from exploitation and contamination, and protected the rights of existing licenced users from competing demands.

The Ground Water Conservation Act was repealed in 2005 with proclamation of *The Watershed Authority Act, 2005,* now *The Water Security Agency Act.* Under the current legislation, the allocation of surface and groundwater has been combined under a single licencing regime. *The Ground Water Conservation Act, Regulations* remain in force and continue to regulate the drilling and completion of wells.

Under the *Water Security Agency Act*, all groundwater use, except domestic, requires an Approval. Examples of works which require approval are: municipal, industrial (including groundwater de-watering), intensive livestock operations, commercial, public institutions and irrigation. The intent of the Water Security Agency's approval process for groundwater projects is to ensure the sustainable and environmentally sound development of the province's groundwater resources. The regulations require investigation to be carried out to assess the potential impact of groundwater abstraction on other users and on the resource.

Regulation of the mineral extraction and oil and gas industries falls under the Ministry of Economy, which is home to the Saskatchewan Geological Survey which provides the science expertise. This regulation covers mineral exploration boreholes, mineral waste disposal boreholes and operations, oil and gas production or injection wells and this takes place under a complex set of different legal instruments and regulations. The same is true of reporting requirements for the various mining and oil and gas operations. For example, the Potash and Salt mining activities are controlled under the Alkali Mining regulations, whereas the mining of base metals, uranium, etc. and oil and gas are controlled under a different set of regulations.

The rapid growth of the development of natural resources in Saskatchewan and the intimate relationships between these activities and the groundwater and hydrogeological environment leads to the conclusion that there is an increasing need for coordination and a streamlined approach to further encourage development. In light of the new knowledge being produced and this rapid growth, review of the management and regulatory practices and framework to ensure that development proceeds as fast and as sustainably as possible, seems a prudent course.

6. Groundwater and Hydrogeological Knowledge in Saskatchewan

There has been considerable investment by government in the mapping of the geology of Saskatchewan to support mineral and oil and gas development and to facilitate the development of groundwater supplies. The WSA and its predessessors have also developed an excellent database of hydrogeological maps which is currently being updated. Recent and current work of Natural Resources Canada, in particular on buried valley aquifers, is also important (Cummings, et al., 2012). Some studies into regional impacts of CO_2 and other fluid injections into the Basal Cambrian aquifers have been undertaken in the prairie provinces (e.g., Rebscher, et al., 2012) and further work involving the Geological Survey of Saskatchewan is current. In addition, the Saskatchewan Research Council has, over that last few dacades, carried out considerable research and data collection as have many researchers in the university and government sectors. In particular, the work of Christiansen on Quaternary stratigraphy (e.g., Christiansen and Sauer, 2002), van der Kamp on many aspects of physical hydrogeology (e.g., van der Kamp, 1989; van der Kamp and Hayashi, 1998; van der Kamp and Maathuis, 2006, 2012), Hendry on aquitards and isotope hydrogeology (e.g., Hendry, 1988; Hendry, et al., 2013), Maathuis on regional hydrogeology (e.g., Maathuis, 2005; Maathuis and Simpson, 2006; Maathuis and van der Kamp, 2011) and Hayashi on processes and other aspects (e.g., Hayashi et al., 1998a, 1998b; van der Kamp and Hayashi, 2009) is undoubtedly world class and has resulted in a firm base on which to build the future.

A brief review of the hydrogeology of Saskatchewan as pertains to the subject of this report can be found in Appendix 5. In short, there is much known about the hydrogeology of south Saskatchewan, but, as discussed below, the current and likely future pace of development will generate new challenges for the hydrogeological science base, to support both government and industry.

7. Research Challenges, Opportunities and Constraints

7.1 Research Challenges

The review of hydrogeology in Appendix 5 is accompanied by a detailed discussion of the level of scientific understanding and associated knowledge gaps. There are several issues where the level of uncertainty may prove to be too high to allow good evidence-based decisions in the coming decades. These areas need further consideration and prioritisation to allow the necessary research to be formulated and funded for the benefit of all stakeholders, and to underpin sustainable development. In summary, these include:

1. Recharge mechanisms and quantification to potentially potable aquifers.
2. The relationship between sloughs and surface water drainage systems and shallow groundwater resources and flow regimes.
3. Groundwater quality, especially pathogens and trace elements, such as arsenic and selenium, in private wells.
4. Interelationships between and morphology, groundwater quality and hydraulic parameterisation of potentially potable aquifer systems (e.g., Bear Paw, Judith River, buried valley and shallow Quaternary aquifers and aquifer systems).
5. Risks posed by waste injection into deep geological formations, including interelationships and linkages between aquifers, integrety of aquitards, linkages created by existing drillholes and fate of injected fluids and displaced brines.

Within these areas of knowledge there could be many separate research projects – generic, regional, and aquifer, aquitard and site-specific. Priorities for resourcing must be developed based on potential risks to sustainable development, environmental protection and public health.

Although there has been a considerable amount of knowledge developed and data gathered, its public availability appears to be variable. Research is sometimes not easily found, being confined to hard copy reports, or data kept confidential by companies. Data have been gathered and are held by industry, but there is considerable variation in the availability of these data and information to the public sector and to the research community. Data for groundwater and hydrogeological research purposes could be made more available with better coordination, collaboration and partnering. Government holds data in a number of Ministries and departments and agencies, including the Geological Survey of Saskatchewan, the Saskatchewan Water Security Agency, the Saskatchewan Ministries of Environment, Agriculture and Health (quality/health issues), Saskatchewan Research Council, Environment Canada, and Natural Resources Canada. It is suggested that a comprehensive audit of knowledge, data and research be undertaken and made accessible via a webportal linking the various owners of the data, information or research. The custody of such a portal would be best held by the WSA or failing that, the Ministry of Environment or perhaps the Geological Survey.

Currently, responsibility for research and development that cuts across the groundwater domain lies with a number of Ministries and agencies, including most importantly the Saskatchewan Water Security Agency. It is suggested that to encourage greater coordination across these organisations, a panel be established to agree research priorities. This would include representatives from government and agencies, industry and academia.

Detailed research requirements and recommendations are listed below. The near surface process issues have been dealt with first, as they relate to agriculture and rural groundwater supplies. Those research issues relating to industrial development and the municipal or regional water resources issues cannot be separated because of the potential interactions between groundwater systems in the deeper subsurface.

Near Surface hydrogeological processes

The understanding of near surface hydrology is incomplete, and the future impacts of irrigation, changes in farming practise, climate change and land drainage are not predictable with any useful degree of certainty at present. Farmers are often responsible for their domestic and farm-yard water supplies if they are not in close proximity to a municipal water supply network. Their livelihoods and the health of their families are very often dependent on poor quality supplies of groundwater of unknown sustainability in periods of drought. In addition, increasing urban expansion has led to housing development in areas at potential risk of flooding from near-surface groundwater. The following needs are identified:

i. Further characterisation, monitoring and modelling of small internal drainage basins, pond systems incorporating groundwater and intra/inter till domestic supply aquifers - quantity and quality.
ii. Characterisation of pilot areas to identify recharge, discharge and flow-through sloughs and relationships with aquifers, leading to development of methodologies to up-scale this characterisation to the provincial or national level, thereby highlighting sensitive or vulnerable hotspots. Use of remote sensing and ecological/vegetation typologies.
iii. Understanding and quantifying recharge mechanisms to local farm and community groundwater supplies. Understanding baseline hydrogeochemistry, nutrient balances and bacteriological quality in potable supply, aquifer evolution and future possible changes. This could take the form of exemplar catchments representing different types of hydrogeology/hydrology.
iv. Understanding the impacts of drainage and other land-use change on the hydrology/hydrogeology of Prairie pond systems and shallow aquifer systems and their sustainability under climate change.

Quaternary Aquifers, buried valley aquifers, Bearpaw and Judith River aquifers, and deeper saline aquifers their hydrogeology and their hydrochemistry

i. Assess regional aquifer characterisation and modelling of flows and pressures in the deep disposal aquifers and possible chemical interactions between saline disposal fluids and the rock. Determine regional impacts and interactions between operations (e.g., between adjacent potash mines). Regional modelling to look at vulnerabilities and weak points.
ii. The development of 3D hydrostratigraphic models would be beneficial in understanding interactions between aquifers, aquitards, surface water systems and mining or oil and gas industry operations.
iii. Quantify potable groundwater availability in the shallower (Judith River, Bear Paw, Empress buried valley) aquifers, and make estimates of its sustainability. Determination and quantification of fresh water recharge and the hydrogeological processes. Impacts on users in Saskatchewan and international boundary issues (e.g., Estevan Valley and other aquifers which cross international borders). Exemplar investigations and modelling in specific areas of high groundwater demand.
iv. Monitor the water quality of groundwater in example potable water aquifers used for rural private and municipal supplies to determine trends and processes, including biological quality, nitrate and toxic metals and metalloids (e.g., arsenic, selenium).

v. Determine groundwater inflows and collapse structures in the Prairie Evaporite deposits – origins, risks and control and development of monitoring and predictive capability.
vi. Assess and understand connectivity between both very deep saline aquifers and shallower aquifers used for industrial and potable supply, including linkage by poorly sealed wells.
vii. Determine, quantify and model interactions between the shallow groundwater systems in the Quaternary and their relationship with surface waters and recharge.
viii. Determine the integrity of the low permeability deposits under radioactive waste repository conditions and long-term containment. Assess geo-mechanical resilience of repository rocks, induced fractures and annealing processes, and bespoke laboratory experimentation.
ix. Continue research on waste tip/tailing cover and mine closure planning and re-instatement (both chemical and physical and biological). There is a long history of this and GIWS members have world-leading expertise.
x. Establish, identify and quantify, by monitoring, isotope characterisation and modelling, the groundwater contribution to baseflow in the Saskatchewan River Basin, in particular in future under climate change. Currently there is little knowledge of the role of groundwater in the upper South Saskatchewan River system. The changes due to warmer winters, glacier retreat, differing snow melt regimes, more rain and possibly more consequent infiltration and recharge may have a significant effect on the hydrological flow regime.
xi. Groundwater-Surface Water interaction and wetlands of the Athabasca Basin - radionuclide transport and impacts. This is currently an untouched area that has been flagged by the Ministry of Environment (pers. com. K. McCullum, Saskatchewan Ministry of Environment).
xii. Exploration of the potential for aquifer, storage and recovery or other methods of artificial recharge in Saskatchewan aquifer systems, to utilise excess winter and wetter season run-off.
xiii. Integrated Environmental Modelling (e.g., Moore et al., 2012; Laniak et al., 2013) to provide a whole systems approach to management of water resources and development of tools and methodologies for management of all these interlinked systems (i.e., physico-chemical, systems engineering, socio-economic).
xiv. Assess public perceptions of groundwater resources, mining, oil extraction and pollution issues including communication and policy development, where they sit currently and what the future trends are likely to be.
xv. A comparative study of regulatory practise in other jurisdictions to ensure Saskatchewan is at the leading edge of regulatory control for economic development and environmental sustainability.

7.2 Baseline Survey Needs

There are a number of baseline survey needs that would facilitate a reduction in uncertainty in the hydrogeological and hydrological knowledge base.

i. Better digital elevation information for specific areas where groundwater development is required. Because of the low relief of the Prairies, both surface and groundwater flow directions will be controlled by small variations in elevation.
ii. An airborne geophysical survey to establish the disposition, structure and morphology of the buried valley aquifers (pilot completed by Natural Resources Canada as part of a study of buried valley aquifers). There may well be many geophysical surveys completed by industry that would be useful in this context if they could be brought together and released into the public domain. The morphology and detailed distribution and linkages between these aquifers and other Quaternary or older aquifers is uncertain, but important to establish with more accuracy than can often be achieved from mapping point data (from borehole records). This information is needed to bring confidence to the sustainability of the groundwater resources held within these aquifers.
iii. Monitoring of well water quality in areas of high groundwater demand and in specific aquifers (perhaps once per year), including metals and metaloids. These data are required to establish trends, if any, and to provide indicators of improving groundwater quality due to sanitary or other measures applied by government to sustain good public health.
iv. Continued and perhaps accelerated mapping and characterisation of groundwater resources of Saskatchewan (initiative by WSA building on previous work by the Saskatchewan Research Council – currently carried out by consultants). This excellent initiative should be supported by research clustered around the mapping in specific areas where knowledge gaps become apparent.

7.3 Whole systems approaches to science and decision-making

Integrated Environmental Modelling (IEM) (e.g., Moore et al., 2013; Laniak et al., 2013) should be mentioned separately to emphasize that a whole systems approach to management, modelling and prediction in the development and use of natural resources is the only approach likely to produce publicly acceptable, reliable and sustainable results. Initiatives in this area should be pursued with vigour, but may prove challenging given the current fragmentation of data holdings.

Nevertheless, it is essential that research into integrated approaches and user- and stakeholder-led science is driven forward. The GIWS has begun this, but is some way from having a major impact. Saskatchewan could easily be a world leader in sustainable integrated and systems approaches to water resources and quality science, sustainable resource management and sustainable development.

7.4 Technology Driven Science

Technology has been a major driver of science innovation, initiative and excellence in the last couple of decades and will continue to be so in the future. Remote data collection, the use of new sensors, satellite science and isotope science all have their role.

Currently, available laboratory, field technique and remote sensing skills are scattered within the university community and the sharing of knowledge, skills and abilities appears to be uncoordinated. There is much potential future science to be done using intelligent monitoring (linked communicating motes, etc.), remote sensing (GRACE, GOCHE, etc.), tracers (isotopes in novel ways (pers. com. L. Barbour, U of S), and geophysics (ERT (ALERT) to monitor salinity, soil moisture, etc.).

It is proposed that a Water Science Technology Forum be established to raise awareness of technologies with researchers in the GIWS. This should be properly constituted and administered through GIWS so that meetings can be resourced, equipment pools organised and research and development projects proposed and funded. There is great scope here to work with the international research community and build strong international collaborations. It will be essential that collaboration and interaction with industry and government be maintained by such a forum.

7.5 Skills Availability

During the course of carrying out the research that underpins this report, there were many references to the difficulty of recruiting well-qualified staff in environmental sciences, especially those with a good mathematical background as well as geological and hydrogeological skills. There is a considerable dearth of good early career Masters/PhD qualified personnel. In government, expertise is currently scarce and this is also the case in industry and consulting. But in the case of government (e.g., the Ministries of Environment and Economy and the SWSA, the situation is acute. In the SWSA there are only two to three staff that have hydrogeological skills at a sufficient level to run investigations and carry out regulatory assessments.

But there are solutions that could be implemented including:

i. The province could grow its own hydrogeological skill base through the development of Masters courses at the GIWS (U of S) and in collaboration, where appropriate, with the University of Regina.

ii. In particular, at a PhD and postdoctoral level, skills need to be developed in applied and integrated modelling.
iii. The GIWS should work in partnership with government and industry to develop field observatories, as is the case in the Changing Cold Regions Network, which could provide training as well as scientific benefits.

In terms of skills at a higher level, at the U of S there is limited hydrogeological expertise. There are highly qualified and internationally renowned modellers, geotechnical engineers and geochemists, but no full professorial level hydrogeologist. There is considerable experience vested in older emeritus or near retirement staff in the U of S and Environment Canada. Future development cannot rest on these scientists in the longer-term, but they could perhaps be utilised in the short-term through involvement in a strategic overview team. Nevertheless, the solution to this problem is clear; young faculty and scientists must be given opportunities to develop their knowledge and expertise based on the challenges identified above. Ideally, new faculty and scientists would be brought in from elsewhere in Canada or from the international community to strengthen the resource base of skilled personnel.

8. Conclusions and Recommendations

The issues highlighted in the foregoing discussion range from knowledge gaps, research needs, staffing and skills problems to regulatory needs and concerns regarding resource scarcity in government authorities.

The groundwater and hydrogeological science base is fragmented between multiple stakeholders including; The mining industry, oil and gas industry, water industry, agricultural industry, Saskatchewan Water Security Agency, Saskatchewan Ministries of Economy, Environment, Agriculture and Health, and research is, as yet, uncoordinated between a variety of research organisations and institutes.

The question arises:
"What can and what should the GIWS and the U of S be doing about this and what future role should they have?"

Firstly, this report clearly raises important issues that should be aired with all stakeholders sooner rather than later. Secondly, the GIWS should, with its own resources, make a start at beginning to fill the knowledge gaps that have been identified, by seeking to develop its own projects in hydrogeology and groundwater modelling and integrated environmental modelling. The GIWS should build on its current strengths to promote the implementation of the report recommendations. Thirdly, there are significant opportunities for a multi-sector collaborative framework to be developed to promote the development and mobilisation of new knowledge in these areas, and these should be explored.

Recommendations for a multi-sector collaborative research programme to address, Groundwater, Hydrogeology and Sustainability in Saskatchewan

1. Coordinate groundwater and hydrogeological research. Currently, the groundwater and hydrogeological science base is fragmented between multiple stakeholders including: industry (mining, oil and gas, water supply, agriculture); Saskatchewan Water Security Agency (SWSA); Saskatchewan Ministries of Economy, Environment, Agriculture and Health. Research is also uncoordinated between a variety of research organisations and institutes.
2. Conduct an audit of groundwater and hydrogeological research, data and knowledge and make the results accessible, as much as possible, via an integrated web-portal.
3. Begin a programme and seek funding from relevant stakeholders to further develop the knowledge base required for robust evidence-based decision-making. Priorities should be set by a panel comprising stakeholders and academia.
4. Develop a comprehensive Sustainable Groundwater Management Plan for the Province with input from relevant stakeholders, academia and the public at large.
5. Review the management and regulatory practise and framework to ensure that development proceeds as fast and as sustainably as possible, in light of the new knowledge being produced, the rapid growth that has occurred and increasing competition for groundwater and pore space in deep geological formations.
6. Develop training opportunities for HQP to meet the needs of government, industry and the university sector for hydrogeological and related expertise.

Appendix 1: Scope of Service and Review methodology

Scope of Service

The University of Saskatchewan (U of S), through the Global Institute for Water Security (GIWS), is currently collaborating with the Saskatchewan Water Security Agency regarding provincial research needs with respect to water security. Working with and reporting to the Canada Excellence Research Chair (CERC) in Water Security, Dr. Denis Peach shall develop a strategic review of groundwater research needs and opportunities. This review shall address Saskatchewan's provincial needs and identify potential foci for the Global Institute for Water Security to capitalize on the available expertise at U of S. In addition, consideration shall be given to the potential for opportunities should the University invest further. This may include developments related to the work of the Sylvia Fedoruk Canadian Centre for Nuclear Innovation and the Global Institute for Food Security along with links to the International Minerals Innovation Institute. One objective will be to produce a short public position paper aimed at provincial needs. The strategic review of groundwater research needs and opportunities shall include four weeks of initial service in Saskatoon followed by a return to the UK and a subsequent one to two week visit (dates to be determined).

Review methodology

This review was carried out by Dr. Denis Peach, recently retired Chief Scientist of the British Geological Survey and expert in hydrogeology. Published research and informal reports related to groundwater science, practise and policy were reviewed. Meetings and discussions were held in Saskatchewan with researchers and representatives from government, provincial and university institutes, and industry (mining, oil and gas, consultants), over a one month period in September and October 2013. This included a review workshop where initial findings were presented and feedback sought. An initial draft report was written during the month of October and edited after consultation with the Director of GIWS in November 2013. This draft report was circulated to all discussion participants and feedback was requested by December 16th. This Final Report was produced in January 2014, benefitting from substantive feedback from the consultees.

A list of personnel and organisations with whom discussions were held is provided in Appendix 2. An overview of the hydrogeology and research opportunities in South Saskatchewan is given in Appendix 5. Appendix 6 contains the list of references and documents consulted.

Appendix 2: Individuals and organisations consulted

University of Saskatchewan

- Karen Chad, Vice-President Research
- Howard Wheater, Canada Excellence Research Chair in Water Security & Director, Global Institute for Water Security (GIWS)
- Patricia Gober, Professor, Johnson-Shoyama Graduate School of Public Policy
- Jeffrey McDonnell, Professor of Hydrology, School of Environment and Sustainability (SENS) & Associate Director, GIWS
- Lee Barbour, NSERC/Syncrude Industrial Research Chair, Civil and Geological Engineering
- Jim Hendry, NSERC/Cameco Industrial Research Chair, Geological Sciences
- Matt Lindsay, Assistant Professor, Geological Sciences
- Andrew Ireson, Assistant Professor, SENS, Civil and Geological Engineering and GIWS
- Grant Ferguson, Associate Professor, Civil and Geological Engineering
- Christopher Hawkes, Associate Professor, Civil and Geological Engineering
- Won Jae Chang, Assistant Professor, Civil and Geological Engineering

Government / Province

- Wayne Dybvig, President, Saskatchewan Water Security Agency
- Nolan Shaheen, Hydrogeologist, Saskatchewan Water Security Agency
- Kei Lo, Manager, Groundwater Services, Saskatchewan Water Security Agency
- John Fahlman, Director, Hydrology and Groundwater Services, Saskatchewan Water Security Agency
- Garth van der Kamp, Research Scientist, Environment Canada
- Kevin McCullum, Chief Engineer, Saskatchewan Ministry of the Environment
- Ginny Nisbet, Saskatchewan Ministry of the Environment
- Allana Koch, Saskatchewan Deputy Minister of Agriculture
- Scott Brown, Executive Director, Policy Branch, Saskatchewan Ministry of Agriculture
- Gary Delaney, Chief Geologist, Saskatchewan Geological Survey, Ministry of Economy
- Gavin Jensen, Senior Research Petroleum Geologist, Saskatchewan Geological Survey, Ministry of Economy.
- Michael Mitchell, Policy Division, Saskatchewan Ministry of the Economy
- Bryan Schreiner, Saskatchewan Research Council

Industry

- Engin Ozberk, International Minerals Innovation Institute
- Jens Werdelmann, K+S Potash Canada
- Alan Hocking, BHP Billiton Ltd.
- Jo Gosselin, BHP Billiton Ltd.
- Jane Howe, BHP Billiton Ltd.
- Cory Larson, Crescent Point Energy Corp.
- Neil Wildgust, CEO, Petroleum Technology Research Centre

Consultants

- Brian Ayres, O'Kane Consultants
- Malcom Reeves, SNC Lavalin Environment

Appendix 3: Other Institutes where groundwater and hydrogeology research is of interest

Petroleum Technology Research Centre (PTRC): The PTRC was set up to manage the Weyburn project in south Saskatchewan to study and monitor the use of carbon dioxide (CO_2) to pressurise the Weyburn–Midale oil reservoirs to Enhance Oil Recovery (EOR) and store the CO_2 permanently in the subsurface. It has since managed and funded a number of projects in the area of EOR and CO_2 Storage.

Sylvia Fedoruk Canadian Centre for Nuclear Innovation (Fedoruk Centre): The Fedoruk Centre has a mission to develop nuclear science and technology for medical benefits, environmental risk management and sustainable energy generation. They have recently announced funding of a number of projects including at least one in the environmental area.

Global Institute for Food Security (GIFS): The GIFS's remit covers increased crop production, by developing healthy soils, understanding hydrology and the impacts of extreme events and climate change, as well as the fostering economic benefits by developing valued added products. GIFS is a $50 million joint venture between, PotashCorp, the Government of Saskatchewan and U of S. Currently, the GIFS is funding two seed grants that are used to develop project teams who will submit full proposals in subsequent grant cycles. It has yet to fund any major research, but its first call for proposals was not aimed at environmental or water issues.

International Minerals Innovation Institute (IMII): The IMII seeks to enhance the profile and competitiveness of Saskatchewan's minerals industry, by supporting improved education and training at post-secondary education levels and supporting high quality research and development. It has issued a general call for research proposals and the IMII funding rules include that at least two mining companies must be interested in a research project and contribute to its funding. The membership is made up of six mining companies, a mineral exploration company, post secondary education institutes, other non-profit organisations and provincial government departments.

Appendix 4

Summary of development activities that, if they take place or remain ongoing, would be likely to have an impact on groundwater systems

- Municipal and private domestic use:
  a) Expansion of urban and peri-urban communities in water-scarce areas (e.g., Regina East area)
- Agriculture:
  a) Changes in agricultural practise to increase crop yields and consequent changes to the hydrological behaviour of soils, including increased use of fertilizers, chemicals, antibiotics, etc.
  b) Increased irrigation thereby stressing water resources during drought years
  c) Drainage of wetlands
- Current activities in mining and oil/gas industries in Saskatchewan that have impacts on groundwater:
  a) Groundwater abstraction for industrial purposes, geological disposal of waste water
  b) Enhanced Oil Recovery (EOR) using water or carbon dioxide
  c) Fracking for oil and gas recovery
  d) Management of tailings and solid wastes from the mining industry (largely potash and uranium, but including coal, base metals, gold and diamonds)
  e) Mine closure plans and legacy contamination
- Possible or likely future development activities which will impact groundwater
  a) Expansion of potash mining resulting in a 90% increase of production. New mine development, one new mine in the next year and at least one further mine in the next decade (mines have a life of 50-70 years)
  b) Further development of oil and gas – reservoir flooding and fracking (Bakken, Shaunavon, Viking, etc.)
  c) Carbon Dioxide Storage
  d) Radioactive waste disposal/containment (consideration of sites in Ontario and granitic site in Saskatchewan
  e) Increased fracking due to shale gas development across Western Canada Sedimentary Basin, not currently planned, but could happen the next 10-20 years
  f) Increased potash extraction using solution mining techniques
  g) Oil sands mining development in Saskatchewan
  h) Development of geothermal energy
  i) Aquifer storage and recovery projects (artificial recharge)

Appendix 5

Hydrogeology and Groundwater in Saskatchewan – a brief overview

It is beyond the scope of this report to provide a comprehensive description of the hydrogeology of Saskatchewan, but it was considered important to provide an overview so that the most important issues and knowledge gaps may be understood.

Overview of the hydrogeology of Saskatchewan

There has been considerable investment by government in the mapping of the geology of Saskatchewan to support mineral and oil and gas development and to facillitate the development of groundwater supplies. The Water Security Agency and its predessessors have also developed an excellent database of hydrogeological maps which is currently being updated. They have also presented information in their 2010 State of the Watershed Report (Davies and Hanley, 2010). Recent and current work of Natural Resources Canada, in particular on buried valley aquifers, is also important (Cummings, et al., 2012). Some studies into regional impacts of carbon dioxide and other fluid injections into the Basal Cambrian aquifers have been undertaken in the prairie provinces (e.g., Rebscher, et al., 2012) and further work involving the Geological Survey of Saskatchewan is current. In addition to these major contributions, the Saskatchewan Research Council has over that last few decades carried out considerable research and data collection, as have many researchers in the university and government sectors. In particular, the work of Christiansen on Quaternary stratigraphy (e.g., Christiansen and Sauer, 2002), van der Kamp on many aspects of physical hydrogeology (e.g., van der Kamp, 1989; van der Kamp and Hayashi, 1998; van der Kamp and Maathuis, 2006; van der Kamp and Maathuis, 2012), Hendry on aquitards and isotope hydrogeology (e.g., Hendry, 1988; Hendry, et al., 2013), Maathuis on regional hydrogeology (e.g., Maathuis, 2005; Maathuis and Simpson, 2006; Maathuis and van der Kamp, 2011) and Hayashi on processes and other aspects (e.g., Hayashi, et al., 1998, van der Kamp and Hayashi, 2009) is undoubtedly world class and has resulted in a firm base on which to build the future. In truth there is much known about the hydrogeology of south Saskatchewan, but the current and likely future pace of development will place new challenges before the hydrogeological science base, for both government and industry.

The hydrogeology of southern Saskatchewan is dominated by the Western Canada Sedimentary Basin (WCSB) and superficial deposits overlying the solid geology. Figure 1 shows the distribution of Precambrian rocks in the north and the Phanerozoic rocks of the WCSB, to the south. A summary of the major aquifers is given in the 2010 State of the Watershed Report, Appendix A (Davies and Hanley, 2010).

Figure 2 shows the WCSB, which is of primary importance to the matters discussed in this report. Figure 3 shows a simplified cross-section from southwest to northeast through the sedimentary sequence, demonstrating the way the deposits thin and wedge out towards the northeast in Saskatchewan. Table 1 lists the major formations and indicates whether their lithologies include aquifers. The subsurface extent of the major aquifers is shown on Figure 4.

For the purposes of understanding the major likely research and management issues, the succession given in Table 1 can be split into four groups.

a) The near-surface groundwater system that is often intimately connected to the prairie pond systems. This system is not fully understood and although much research into monitoring ponds, pond overflows and shallow piezometer levels close to the pond systems has been carried out, this has not been tied into the shallow aquifer systems which lie just a few metres below the base of the ponds. A description of current understanding of prairie pond hydrology and their geochemical functioning can be found in Toth, et al., 2009 and Nachshon, et al., 2013. Essentially the pond systems are separated into many hundreds of very small (often much less 1 km^2) internal drainage basins. A considerable number of these wetlands have been drained by farmers to obtain more useful farmland. The impact of this drainage on the behaviour of the hydrological system, including groundwater recharge to regional aquifers requires further work (van der Kamp and Hayashi, 1998). Understanding the roles of deep and shallow groundwater systems will improve the hydrological conceptual framework for the management of wetland ecosystems (van der Kamp and Hayashi, 2009). Much of southern Saskatchewan is largely disconnected from the main surface water river systems such as the South Saskatchewan River and other main rivers, and, although groundwater is likely to be connected to the surface water drainage systems, the role of the shallow aquifers is uncertain. Recharge processes to the uppermost aquifers, which are extensively used in rural areas for domestic supply and by farmers for livestock, yard washing and other farming activities, are largely unquantified from observation and experimentation and have not been numerically modelled with any confidence. The sustainability of these shallow aquifers and their role in sustaining pond hydrology may be rather site specific but remains uncertain.
b) Beneath this upper 5-20 metres there are many glacially-deposited aquifers of the Quaternary. These are inter-bedded with thick and very poorly permeable till deposits, where interstitial water has in some cases been shown to be many thousands of years old (Hendry, 1988; Shaw and Hendry, 1998). These aquifers tend to be discontinuous and of very variable thickness and hydraulic conductivity. Understanding flow and resource availability in these discontinuous Quaternary and Tertiary units is a major challenge. They provide water supplies to many small towns and communities, for example Yorkton

(Maathuis and Simpson, 2006). Water quality is highly variable with Total Dissolved Solids (TDS) up to 1500mg/l (Thompson, 2003). The dissolved salts are usually largely made up of sulphates derived from the surrounding tills. Water quality data from the Water Security Agency's Rural Water Quality Database indicate that as many as 10% of wells sampled have selenium levels above the Maximum Admissible Concentration (MAC) and over 4% have arsenic levels about the Interim MAC (Olkowski, 2009). It also seems that there is limited data available on the biological quality of groundwaters used for private domestic supply. The morphology of these aquifers requires more attention, their lateral heterogeneity and continuity are often unknown and their interrelationships with other aquifers not well understood. Their yields are usually low to moderate, but they are often the only sources of reasonably fresh water to be found in rural regions away from the main river basins. The areal variation in water quality is often poorly known. For example, in order to provide water supplies to the developing area to the east of Regina the Zehner and Condie aquifers (see Table 2) need to be exploited, so a good estimate of their reliable yield is essential. Although there is an estimate of reliable yield (4,800dam^3/year) from the Zehner aquifer, more refinement of the sustainable yield is required prior to further development (pers. com. K. Lo, Saskatchewan Water Security Agency). The relationships between groundwater in these aquifers and surface waters in some areas are unknown, there is an apparent hydraulic barrier within the Zehner aquifer whose extent is unknown, uncertainty in the area of recharge and lateral and vertical variations in hydraulic parameters are not well understood. The impacts of current long-term abstractions cannot be predicted reliably because of a lack of long-term monitoring. This example has been chosen to illustrate the hydrogeological knowledge gaps that emerge when sustainable development of groundwater resources is required. The regulator must allocate water resources on a sustainable basis whilst protecting the environment. Pollution of the Condie aquifer from surface leakage in the past resulted in a contaminant plume over 7 km long (van der Kamp et al., 1994), considerably restricting its use for domestic purposes. The plume was the result of leakage of effluent from a disposal reservoir used by a water softening plant.

c) As can be seen from Tables 1 and 2, the Quaternary overlies older bedrock, including aquifers of the Tertiary and Cretaceous clastic deposits. The Empress Group (see Table 2) consists of cross-cutting buried valley sands and gravels. Prairie buried-valley fills commonly function as aquifers that yield abundant groundwater. These aquifers can be many metres thick and infill valleys of a Tertiary and early Pleistocene drainage system. These deposits can form major aquifers that run longitudinally for several hundred kilometres. Examples are the Hatfield Valley aquifer, the Estevan Valley aquifer and the Swift Current Valley aquifer. They have distinct morphologies and a distinct stratigraphic setting, which imparts them with distinct hydrogeological properties. Although there has been considerable study of their geology and hydrogeology (Cummings et al., 2012), their distribution and the detail of their morphology is less well known, and the hydrogeological interactions with Quaternary aquifers or deeper aquifers like those of the Bearpaw formation or the Judith River aquifer are very uncertain. Natural Resources Canada (NRCan) have recently completed a pilot project researching these buried valley aquifers, which might be taken further in the areas where demand for groundwater is growing, see Figure 5 (Cummings et al., 2012) These buried valleys are known to cut deeply into Bearpaw and Judith River aquifers, both of which are used for supply purposes (Slawinski and Glen, 1987; Cummings et al., 2012). Little modelling of these various interactions has been carried out and the origins of recharge to these aquifers is often uncertain, as in the case of the Estevan aquifer which suffered over-pumping in the late 1980s and early 1990s (van der Kamp and Maathuis, 2012). The Estevan Valley aquifer is a buried valley, 2 – 4 km wide, up to 80 m thick and at least 70 km long. It is confined by a 60 – 80 m thick aquitard composed mainly of glacial till. From September 1988 to May 1994 it was pumped at an annual rate of 3,750,000 m^3. Long-term observation well data show that the sustainable yield of the aquifer is significantly less than 2,800 dam^3/year (Maathuis and van der Kamp, 2011) and full recovery of the groundwater level seems to be still many years away. The sustainable yield of the aquifer has been revised downwards twice in the last 20 years as recovery has taken so long.

d) There are deep saline aquifers found below the Judith River aquifer. These formations have never been used to supply potable water, but are sometimes used for oil and gas operations and as fracking water. They are extensively used for the disposal of saline brines from oil and gas extraction or potash mining and processing. The most commonly used aquifers are the deep Cambro-Ordovician Winnipeg and Deadwood aquifers. These are often used by both industries. The Ordovician, Silurian, Devonian, Carboniferous and Permian deposits are, for the most part, composed of a very thick sequence of carbonates and evaporites, within which lies the Prairie Evaporite Formation which contains the valuable Potash deposits. In Potash mines, problems of water inflow are caused by the mine galleries intersecting collapse structures in the evaporites. Sometimes these are dry, but often they are connected to groundwater flow systems which cause flooding and sometimes mine closure, and so are of great concern to the mining industry. In this respect, knowledge of connection to underlying or overlying aquifer systems is of huge importance. If, of course, the excess brine needs to be injected, then mining engineers are clearly concerned that this process should not endanger the mine or mining activity, so it is injected usually much deeper than the mining levels. Some mining takes place by solution from water injected in boreholes and shafts and pumped out having dissolved the potash minerals. This produces much more water for disposal than conventional mining. The Aquistore CO_2 storage project will inject supercritical CO_2 into the Cambro-Ordovician flow unit within the Williston Basin that is comprised of the Deadwood Formation and Black Island member of the Winnipeg Formation. These formations are also used for similar purposes by the oil and gas industry and the potash mining industry. The storage of radioactive waste would appear to be focussed on hard granitic environments in the Canadian Shield, but would clearly have to satisfy very long-term and stringent safety criteria which would include understanding the groundwater environment. The development of geothermal energy would clearly focus on the deeper deposits discussed above and would focus on high thermal gradients in the aquifers at depth. Aquifer storage and recovery was considered in the past and not taken forward, but could be in future years, for storage of excess flows for retrieval during times of drought. All of these activities that are developing the energy and mineral resources of Saskatchewan require the drilling of deep boreholes. In 2012 an estimated 29,600 wells produced 172.9 million barrels of oil. These wells all penetrate through potable aquifers and are properly sealed, but wells have been drilled since the 1950s. The sealing of these legacy wells is fundamental to the protection of one aquifer from ingress of groundwater from another, in areas where fracking is being carried out (Jackson and Desseault, 2013). These old wells may represent the weakest links between aquifers, especially since high pressures will be brought to bear on the deep aquifers as CO_2 storage become a reality.

There are some broad conclusions that can be drawn from this appreciation of the hydrogeology, its complexity and the current economic, social and science drivers outlined above.

1. Greater competition for water supplies for industrial and agricultural purposes is likely to result in a greater demand on groundwater. It is currently unknown if domestic or municipal or industrial supplies can be made available for long-term or emergency use (e.g., in the event of very severe droughts). Long-term sustainability is implemented through adaptive management of the groundwater resources so allocation and regulation requires long-term monitoring. Recharge is largely unquantified, whether directly from rainfall or indirectly from surface water. The dynamics of storage replenishment are uncertain, as demonstrated by the Estevan Valley aquifer's slow recovery, but in other aquifers the flow regimes may be quite different.
2. Greater competition will occur for the use of geological pore space, for the disposal of contaminated brines and CO_2 from a variety of sources. The long-term impacts on the subsurface and the connection to the surface and to mines and to other fresher groundwater resources are currently unknown.
3. There is a significant possibility of activities, such as adjacent mines or CO_2 storage and oil process water disposal, interacting, resulting in derogations and other unforeseen consequences. These could include pollution and contamination of resources that once contaminated would never be able to be cleaned up economically.

4. Investments that are currently being made in the oil and gas and mining industries are very large. To make these investments, which secure the economic future of Saskatchewan and have an important positive economic boost for all Canada, investors need to have confidence that the province is making sound regulatory decisions, based on the best science and evidence available.

There are some other issues not yet touched upon that are pertinent to raise at this point:

1. It is clear that although much knowledge lies with government, much also lies with industry. Both oil and gas and the potash industry will undoubtedly have much data on disposal of brines and water resources contingency planning which may not be in the public domain. Investigations into water resource availability are made for these companies to assure themselves that their investments are made with the lowest possible risk, but these are also not generally in the public domain. Many of the mining and oil and gas companies have contracted consultants to investigate and model their development and impacts of their activities to reduce their risks, and hence much relevant knowledge lies within the consultancy sector, but is not generally publicly available.
2. Provincial responsibilities for subsurface regulation and management of groundwater and groundwater quality are divided between several Ministries and Agencies. These include the Ministry of Environment, Ministry of Health, Ministry of Economy, and most importantly the Water Security Agency. This is not uncommon in other jurisdictions, but it does mean that coordination of research, data and information must be strongly pursued to produce the best results and decisions. Some of the aquifers (both supply and those used for waste disposal), cross national boundaries (Canada-USA), and therefore activities in one country may affect or impact on the groundwater environment in the other.
3. Although there is a growing cadre of excellent scientists that work in the groundwater and hydrogeological disciplines, much of the groundwater knowledge and experience for Saskatchewan lies with a few very experienced hydrogeologists who are retired or close to retirement. Once they have gone, a great deal of knowledge will be lost. Much of this knowledge is currently not in the public domain (i.e., not published but found in restricted grey literature).
4. There is no coordinated programme of scientific research across the hydrogeological/groundwater domain that seeks to fill knowledge gaps.
5. The long term impacts of current and future use of geological pore space for waste disposal are largely unknown and unpredicted. This may sometimes be simply a business risk issue, but it also poses issues of environmental protection and sustainability.

6. Long-term water security issues that may require greater use of groundwater cannot be addressed, without understanding:
   a) The interactions between the various aquifer units,
   b) The 3D morphology and structure of these units,
   c) The heterogeneity of lithology and physical parameters displayed by these aquifers,
   d) The recharge, if any, to these aquifer deposits,
   e) The integrity and vulnerability of cap rocks, and
   f) The degree of knowledge necessary will depend upon the size of the demands for resources and/or the scale of other activities in the subsurface.

Table 1 Simplified geological succession and hydrogeology of southern Saskatchewan (Maathuis and Thorleifson, 2000)

GEOLOGY			HYDROGEOLOGY	
CENOZOIC	Quaternary	Upper Clastic Unit	Upper Aquitard	Buried-valley, intra, intertill, and surficial aquifers till, silt and clay aquitards
	Tertiary			Bedrock surface Paskapoo aquifer Eastend to Ravenscrag aquifer
MESOZOIC	Cretaceous			Aquitard
				Odannah aquifer
				Aquitard
				Horseshoe Canyon aquifer
				Bearpaw sand aquifers and aquitards
				Judith River/Belly River aquifer
				Aquitard
				Ribstone Creek aquifer
				Aquitard
				Milk River aquifer
				Aquitard
			Basal aquifer/aquitard system	Mannville aquifer
	Jurasic			Triassic-Jurassic aquifer/aquitard unit
	Triassic			
PALEOZOIC	Perm	Carbonate-Evaporite Unit		Carbonate-evaporite aquifer/aquitard (undifferentiated)
	Pennsylvanian			
	Mississipian			
	Devonian			
	Silurian			
	Ordovician			
	Cambrian	Basal Clastic Unit		Winnipeg/Deadwood aquifer
Precambrian				Impermeable base

Table 2 Schematic hydrostratigraphic setting in the Regina area (Christiansen and Sauer, 2002, and SRC Publication No 10420-1004)

TIME	STRATIGRAPHIC UNITS				
	GROUP	FORMATION	UNIT AND MEMBER	DEPOSIT	AQUIFER
QUATERNARY	Saskatoon Group	Regina Clay and Surficial Stratified Deposits		Silt and sand / Clay	Surficial Aquifer
		Battleford Formation	Upper till	Till	
			Armour Member	Sand and silt Pebbly sand Gravel	Condie Aquifer
			Lower till	Till	
		Floral Formation	Upper unit	Till Sand and gravel	Upper Floral/Regina Aquifer
			Pasqua Member	Upper unit silt and sand Lower unit silt, sand, and gravel	
			Lower unit	Silt, sand, and gravel Till	Lower Floral Aquifer
	Sutherland Group	Warman Formation		Till and stratified deposits	Sutherland Group Aquifers
		Dundurn Formation	Upper Unit	Till and stratified deposits	
			Lower unit	Till and stratified deposits	
		Mennon Formation		Till	
	Empress Group			Sand and gravel	Empress Group Aquifer
TERTIARY			Tertiary sediments	Silt, sand, and gravel	
LATE CRETACEOUS	Montana Group	Bearpaw Formation	Snakebite Member	Silt and clay	
			Ardkenneth Member	Sand and Silt	Bearpaw Sand Aquifer
			Bearpaw (Undifferentiated)	Silt and clay	
		Judith River Formation		Sand and silt	Judith River Aquifer
		Lea Park Formation		Clay	

- modified after Christiansen 2002

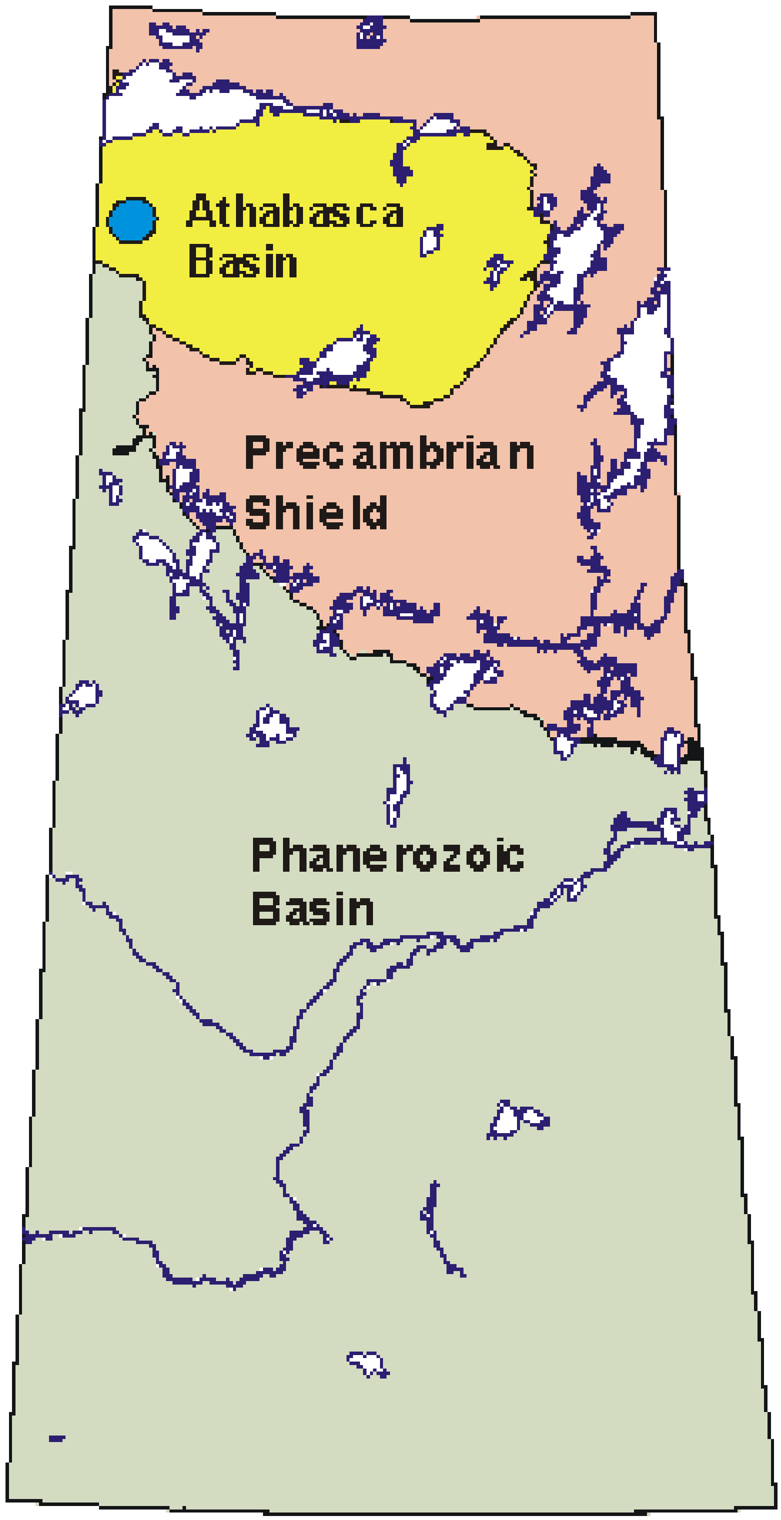

Figure 1 Simplified geological map of Saskatchewan showing the Phanerozoic or western Canada Sedimentary Basin in Saskatchewan, the Athabasca Basin and the Precambrian rocks of the Canadian Shield. The north and south Saskatchewan Rivers give an idea of location and scale.

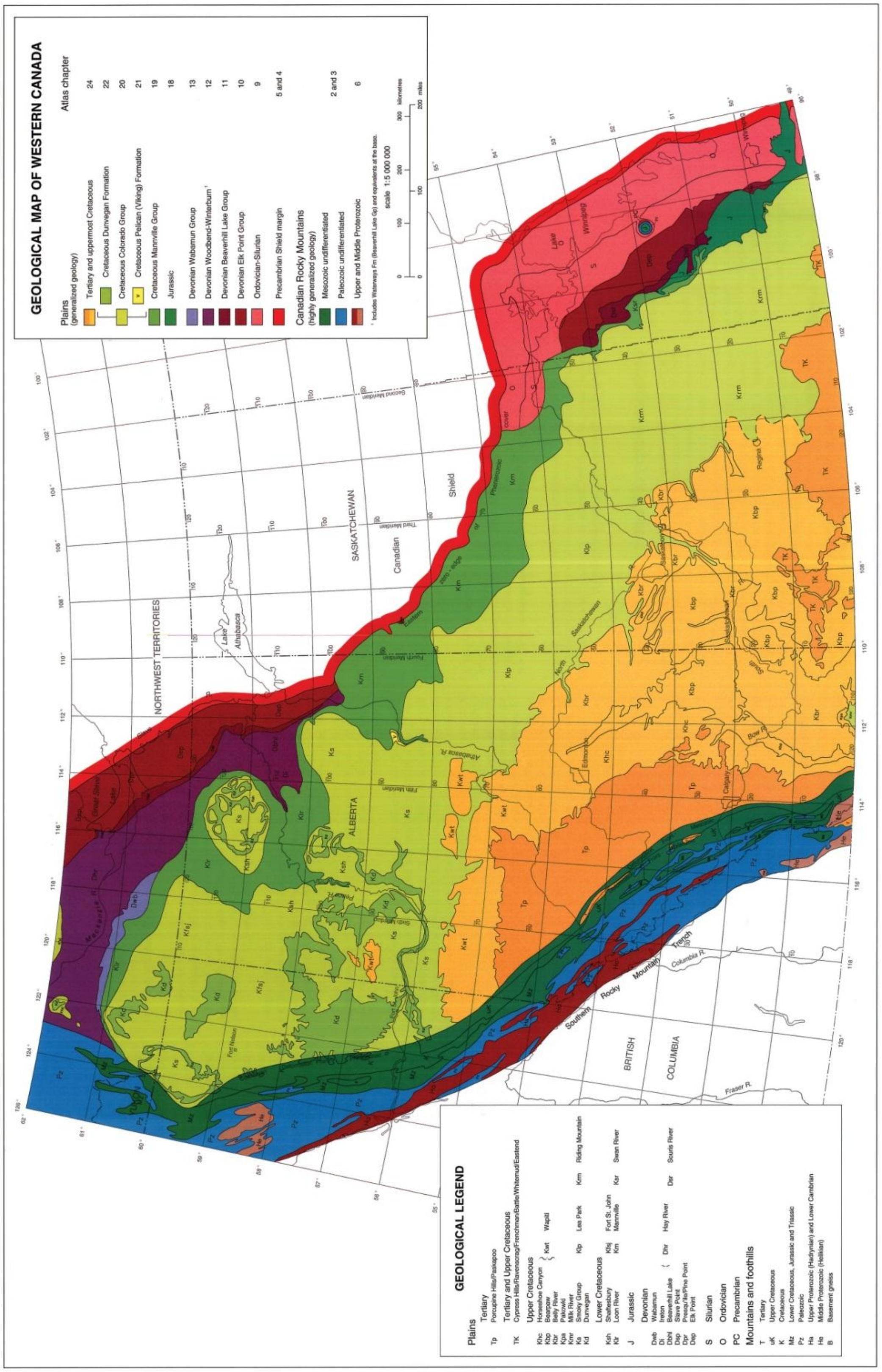

Figure 2 Simplified Geological Map of the Western Canadian Sedimentary Basin

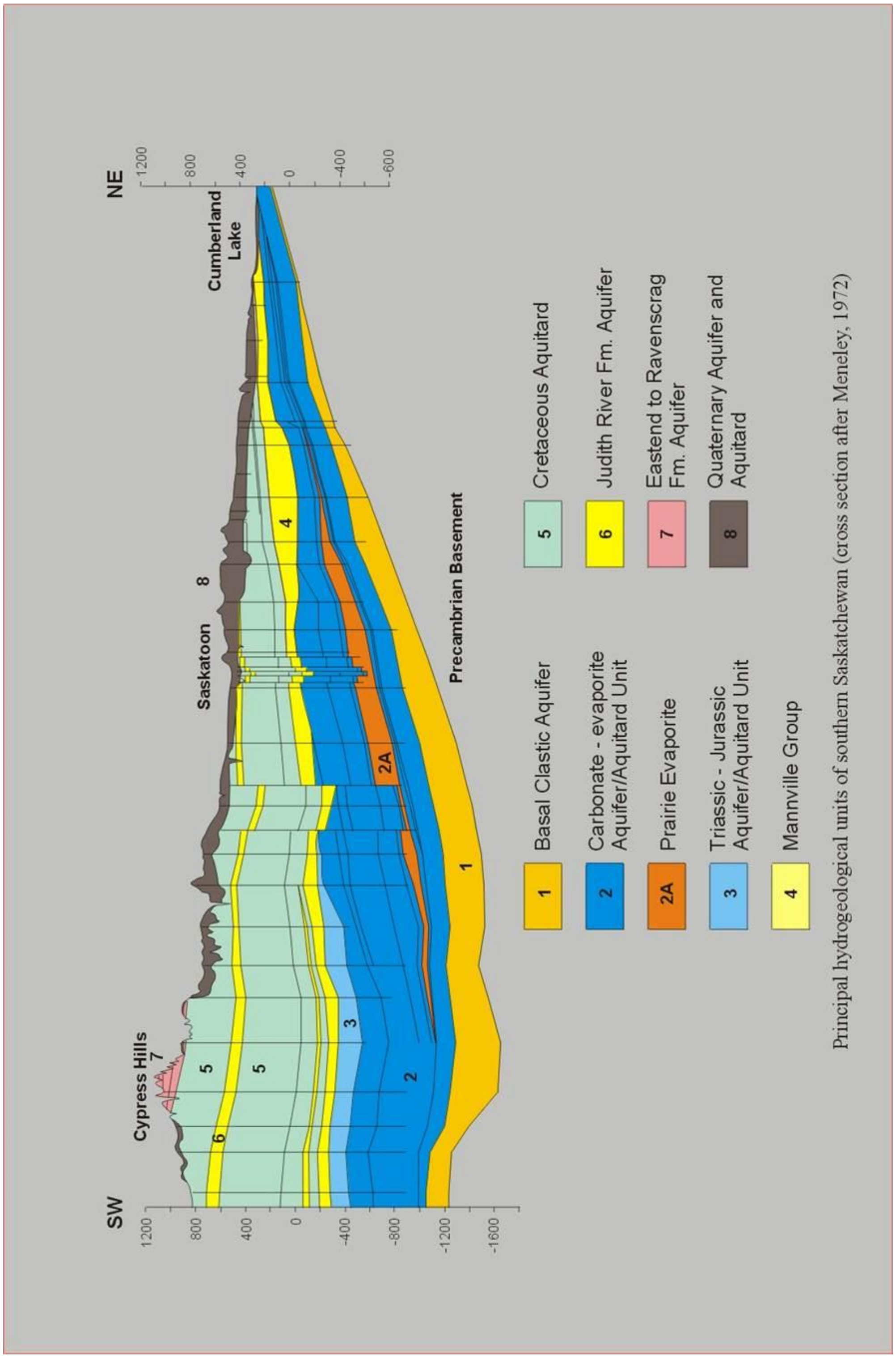

Figure 3 Principal hydrogeological units of southern Saskatchewan and the thinning of the sediments to the northeast (after Meneley, 1972)

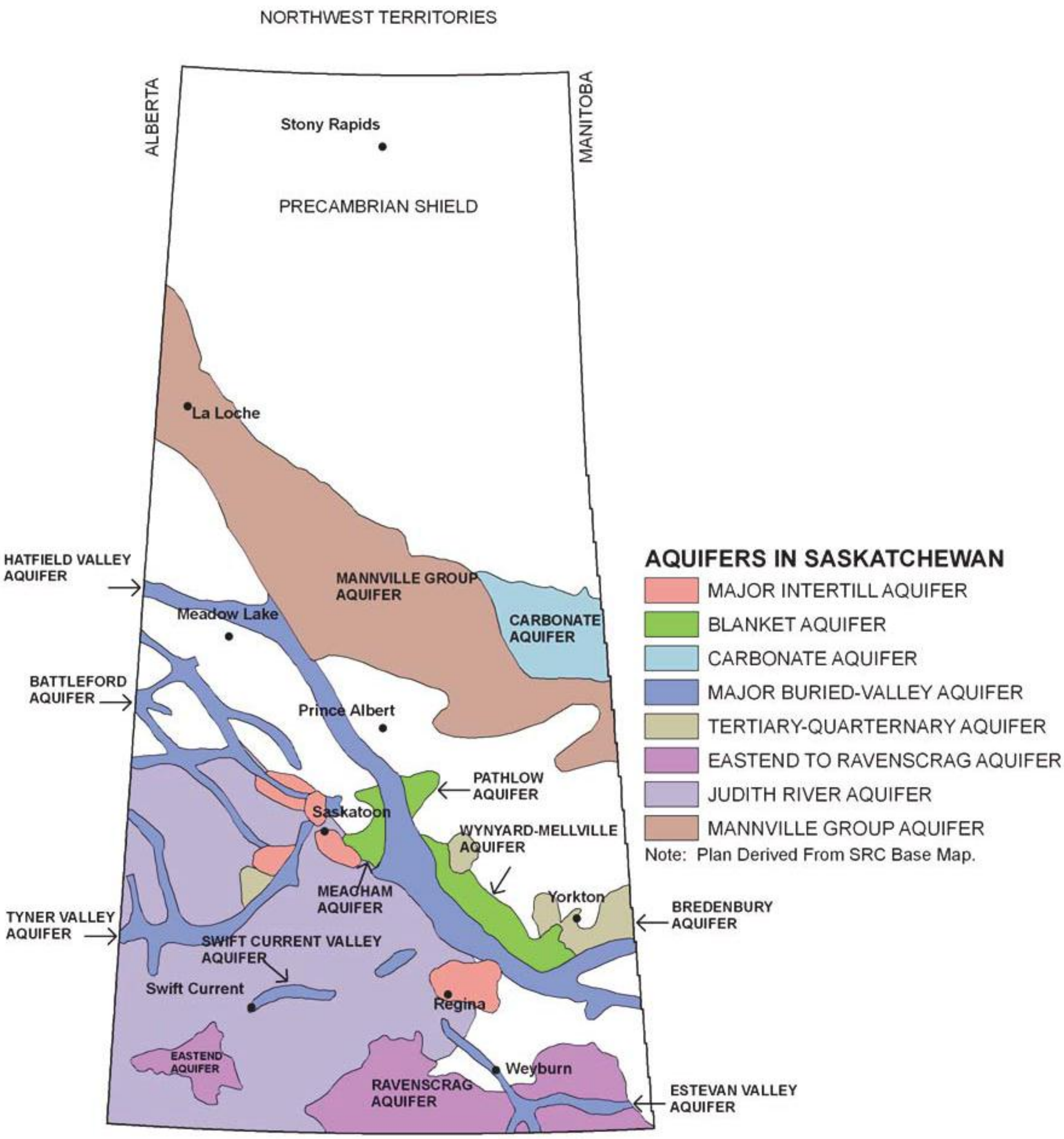

Figure 4 Distribution of aquifers used for water supply in Southern Saskatchewan (Davies and Hanley, 2010)

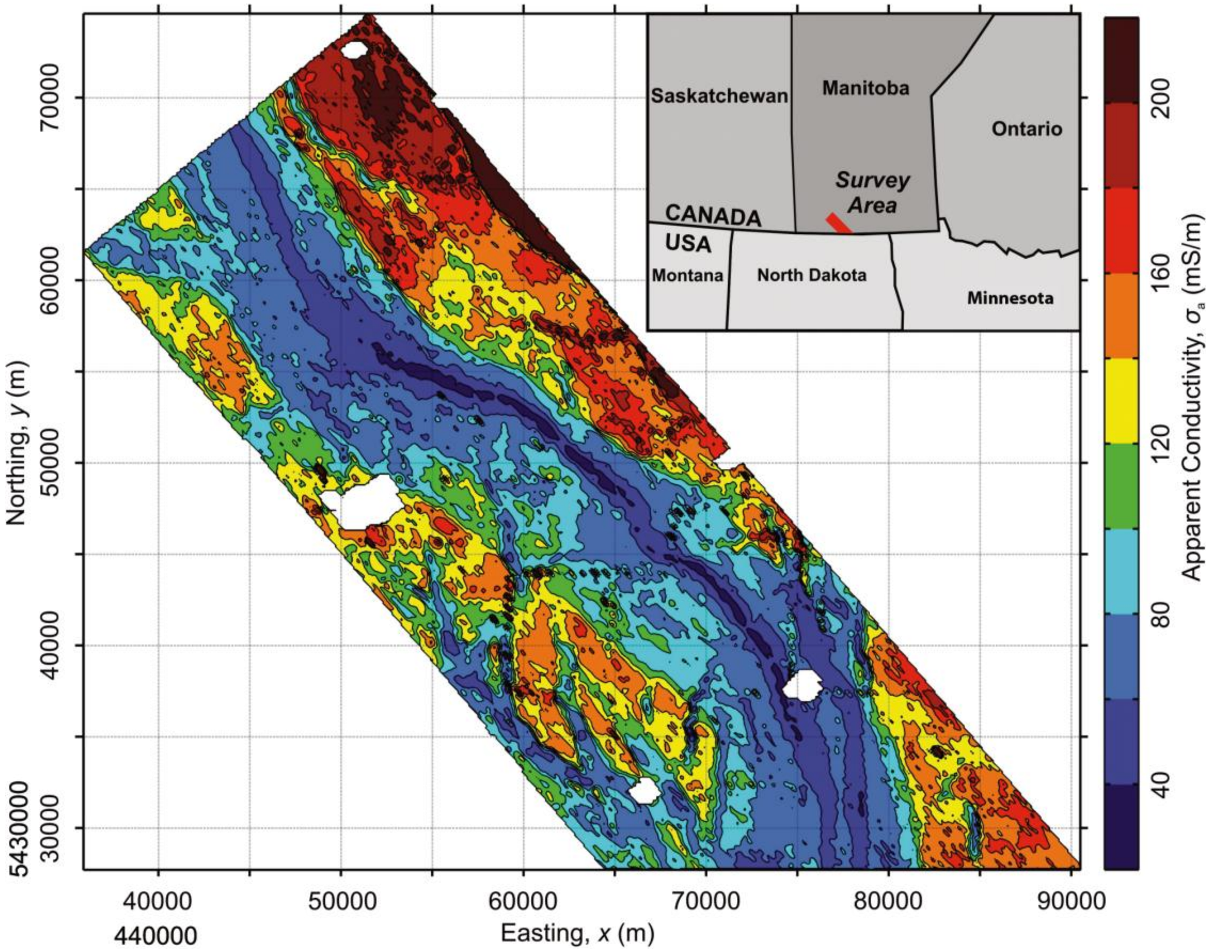

Figure 5 Helicopter-borne time-domain electromagnetic (EM) survey over the Spiritwood buried-valley aquifer in southern Manitoba, just north of the border with North Dakota (from Oldenborger et al., 2012). The geometry of the main Spiritwood buried valley (∼10 km wide) is readily apparent as a moderate conductivity feature (blue)

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