Groundwater resource evaluation in southeastern Manitoba

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ABSTRACT
A large part of southeastern Manitoba is underlain by two major bedrock aquifers: the basal Winnpeg aquifer consisting of inter-layered sandstone and shale and the overlying Carbonate aquifer formed by Ordovician limestone and dolostone. Recharge is primarily associated with the eastern subcrop of the aquifers where a large glacial moraine forms a local topographic high. These aquifers are used extensively as a source of municipal, agricultural, industrial and rural residential water supply; however, with rates of withdrawal steadily increasing there is concern that the long-term sustainable rate of withdrawal is being approached. In this paper we discuss a program currently underway to evaluate the sustainability of the groundwater resource in this region of Manitoba.

RÉSUMÉ
Une grande partie du sud-est du Manitoba repose sur deux aquifères principaux du substratum rocheux : l'aquifère de fond de Winnipeg, composé de grès et de schiste argileux interstratifiés, et l'aquifère carbonaté sus-jacent, composé de calcaire et de dolomie de l'Ordovicien. L'apport d'eau aux aquifères est associé principalement au subaffleurement est des aquifères où une large moraine glaciaire forme une hauteur topographique locale. Ces aquifères servent considérablement à approvisionner en eau les villes, les exploitations agricoles, les établissements industriels et les résidences en régions rurales. Cependant, vu l'augmentation constante des taux de prélèvement d'eau, on craint que le taux de prélèvement durable à long terme ne soit bientôt atteint. Dans ce document, nous discutons d'un programme en cours dont l'objectif est d'évaluer la durabilité des ressources en eau souterraine dans la région sud-est du Manitoba.

1 INTRODUCTION

Most of southeastern Manitoba relies on groundwater sourced from Ordovician bedrock and Quaternary sand and gravel aquifers for water supply. Bedrock aquifers consist of a basal sandstone/shale sequence known as the Winnipeg aquifer and the overlying Carbonate aquifer, formed by Ordovician limestone and dolostone. Significant groundwater development began around the end of the 19th century. Since then, development pressures on the aquifers in this area have been steadily increasing. Regional groundwater level declines have been documented in the Carbonate aquifer (Charron, 1965) and there is evidence of local to regional declines in groundwater levels in the Winnipeg aquifer (Betcher and Ferguson, 2003).

In response to increasing development pressures, the Province of Manitoba has launched a program of groundwater resource evaluation of these two bedrock aquifers. The program has included installation of nested monitoring wells in the aquifers along three projected groundwater flow lines to better define the regional distribution of head, groundwater flow directions and vertical hydraulic gradients; pumping tests on existing and newly installed observation wells; and building and calibration of a digital groundwater model. The model will be used as a groundwater management tool for assessing local and regional impacts from development, evaluating potential impacts on fresh water-saline water boundaries which occur in both aquifers, and supporting groundwater quality initiatives such as source water protection.

2 PHYSICAL SETTING, GEOLOGY AND CLIMATE

2.1 Location and Physical Setting

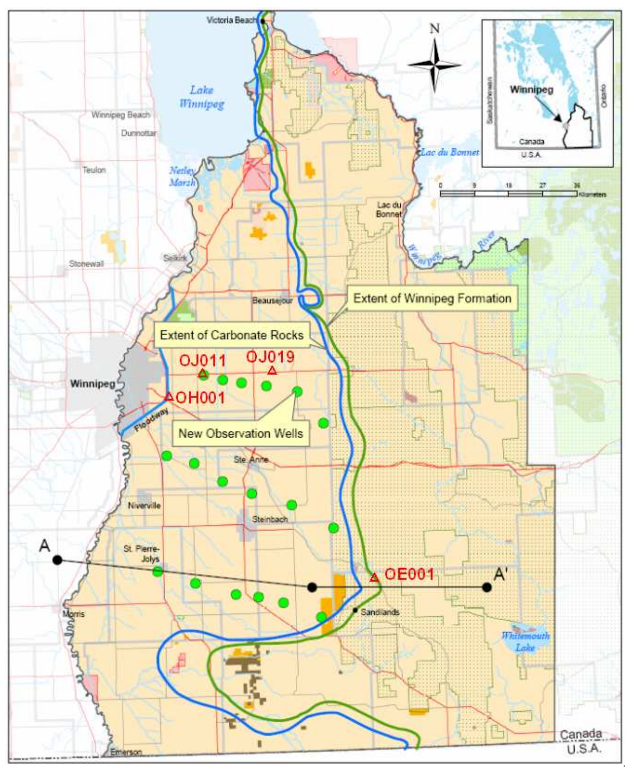

Figure 1 Location Map of Study Area and Observation Wells

The study area is located in the southeastern part of Manitoba (Figure 1). It is bounded by the Red River to the west and Lake Winnipeg and the Winnipeg River to the north. To the east the study area extends to Whitemouth Lake just west of the Ontario-Manitoba border, while to the south we have terminated the study at the international Boundary with the USA.

The topography is very flat near the Red River where thick clays deposited in the ancestral Lake Agassiz drape over glacial tills. Ground surface elevation rises to the east onto a modified glacial drift plain, dominated by a series of uplands that form the Sandilands glacial complex. A number of creeks or streams originate from Sandilands and run west or northwest toward the Red River or Lake of Winnipeg (Figure 2). The Red River forms a regional topographic low, with flow from south to north and eventually to Lake of Winnipeg which is the regional surface water discharge area.

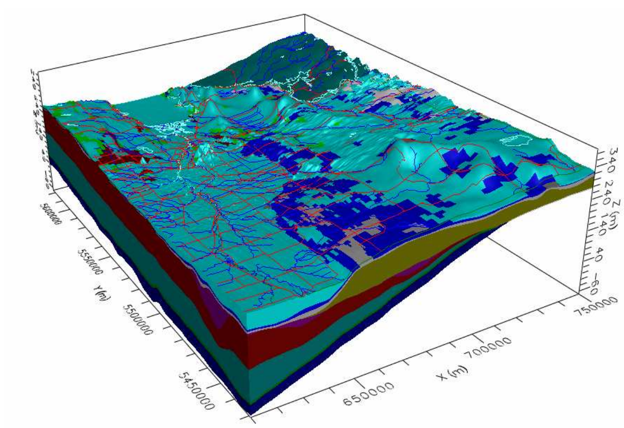

Figure 2 Geological Model for Groundwater Simulation

2.2 Climate

Meteorological data is available from the Steinbach weather station, located near the center of the study area. The 50 year (1956 to 2005) average daily temperature is 8.4 ^{o}C with an average daily temperatures ranging from low of -13 ^{o}C in January to high of 26 ^{o}C in August. The average precipitation is 540 mm/yr.

2.3 Geology

There are four major geologic units from top to bottom; that is, surficial deposits, carbonate rocks, Winnipeg formation and granitic rocks.

Surficial deposits consist of lacustrine clays overlying silt- to clay-rich tills in the Red River valley which forms the topographically lower western part of the study area. To the east, the clays disappear against the western edge of the Sandilands upland and are also absent over other local topographic highs such as the Birds Hill area just to the north-east of Winnipeg. In these upland areas, shallow surficial deposits consist of widespread coarse material including sand and gravel, and glacial till. The coarser materials are generally underlain by tills but in some areas the sand/gravel deposits may extend to the top of the underlying bedrock. The thickness of overburden material varies from 0 m in the east boundary area to over 140 m in Sandilands area.

Carbonate rocks, composed of Ordovician limestone and dolostone, underlie much of the study area but have been removed by erosion in the eastern portion of the area (Figure 1). The thickness of carbonate rocks varies from over 150 m west of the Red River to 0 m under much of the Sandilands (Figure 1, 2, 3).

The Winnipeg Formation underlies the carbonates and consists predominantly of poorly consolidated to unconsolidated very fine silica sand with siliceous to faintly calcareous shales in the upper potion. The Winnipeg Formation varies in thickness from in excess of 50 m in the west of the Red River to 0 m along the east extension limit (Figure 1, 2, 3).

Underlying the Winnipeg Formation are Precambrian-age crystalline igneous and metamorphic rocks. To the east boundary of the study area, granite rocks can appear on surface as an outcrop.

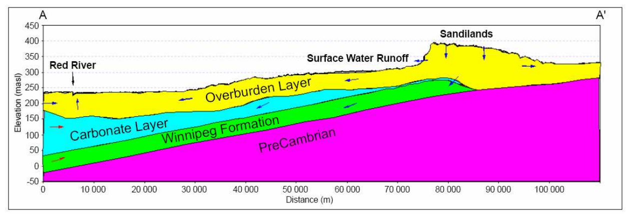

Figure 3 A – A' Geological Cross-Section (The location is shown on Fig.1)

3 HYDROGEOLOGY

There are two major bedrock aquifers which underlie most of the study area (Figure 1): the Carbonate aquifer which is overlain by overburden material and the Winnipeg aquifer which underlies the Carbonate aquifer. These two aquifers are hydraulically separated by a relatively thin shale which forms the upper part of the Winnipeg Formation. These bedrock units dip gently to the southwest (Figures 2, 3).

The Carbonate aquifer is composed of Ordovician limestone and dolostone. Although termed a single aquifer here, it is recognized that the Paleozoic carbonate sequence should more properly be referred to as an aquifer system. Fractures, joints and bedding planes form primary pathways for groundwater movement in most of the aquifer, with dissolution processes having enhanced the permeability of these fractures in some areas. In particular, the upper few meters of the bedrock surface is often found to be extensively fractured and is locally referred to as the “upper” carbonate aquifer (Render 1970).

The Winnipeg aquifer is formed by the generally poorly consolidated sandstones of the Winnipeg Formation. Shales in the upper potion act as an aquitard to separate the Winnipeg aquifer from the Carbonate aquifer.

There are also some localized surficial sand and gravel aquifers in the study area. Deposits consisting primarily of outwash sand and gravel occur in the Birds Hill area 10 miles northeast of Winnipeg. There are two sand and gravel units in Sandilands glaciofluvial deposits with a large area of extension which will potentially form important aquifers in the region. Dealing with the surficial aquifers is beyond the scope of this paper.

The Precambrian granite rocks act as an aquitard basement in the study area.

Recharge to the two bedrock aquifers is associated with a series of moraines which impose a high head on the eastern sub-crop edge of the bedrock units. Groundwater flow is to the west and northwest with discharge from the carbonate unit occurring to the Red River, the Winnipeg Floodway and perhaps to other streams and creeks. Discharge from the highly confined sandstone aquifer is likely by slow seepage through the upper confining layer near or beneath Lake of Winnipeg. Groundwaters are generally fresh throughout the eastern and central parts of the study area but transition to brackish and saline waters near the Red River. A “tongue” of saline water extends east of the Red River in the Winnipeg aquifer, east and north of Winnipeg (Betcher, 1986). More detailed discussion of groundwater quality will be provided by the paper titled “Geochemical and Isotopic Characterization of a Regional Bedrock/Surficial Aquifer System, Southeastern Manitoba” by Phipps et. al. for this meeting.

3.1 Groundwater Monitoring

Groundwater monitoring in the study area has been carried out since the early 1960’s when the Floodway was under construction. This monitoring network was initially focused on the Floodway area although observation wells to examine more regional effects were added to the system at a later time.

By 2005, a total of 135 observation wells have been installed in the study area including 83 wells in the Carbonate aquifer; 49 wells in the overburden material and only 3 wells in Winnipeg aquifer. As a component of this project an additional 18 monitoring sites have been established along three projected groundwater flow lines (Figure 1). At each site, a nest of two monitoring wells (one in the Carbonate aquifer and another in the Winnipeg aquifer) was installed.

The new nested observation well sites were installed to monitor the groundwater level and vertical gradient between the Carbonate and Winnipeg aquifers from the eastern recharge area to the western saline water boundary. Historical information indicates that the upward gradient from the Winnipeg to the Carbonate aquifer has been decreasing for the last decade or longer primarily as a result of more than 1,000 water supply wells finished as open holes through the two aquifers. Wells drilled into the Winnipeg aquifer have often been drilled to abstract the “soft” water that is found in parts of the aquifer (Betcher and Ferguson, 2003). The high pressure water in the Winnipeg Formation will recharge the Carbonate aquifer through the open holes naturally and will eventually cause the water levels in the two aquifers to equalize. Table 1 shows the water level difference at each site in the new observation well nests. In some areas the water levels in the two aquifers are already very close or the water level in Winnipeg aquifer is even lower than that in Carbonate aquifer.

Table1 Groundwater level in the new observation wells

Location	Well ID	Water Level	Water Level Difference	Formation
		masl	m	
NORTH LINE				
	G05SA013	273.10		Sandstone
1	G05SA003	272.75	0.35	Carbonate
	G05SA015	267.06		Sandstone
2	G05SA014	270.06	-3.00	Carbonate
	G05OJ175	258.02		Sandstone
3	G05OJ163	259.98	-1.96	Carbonate
	G05OJ176	246.71		Sandstone
4	G05OJ177	246.90	-0.19	Carbonate
	G05OJ178	240.34		Sandstone
5	G05OJ179	239.17	1.17	Carbonate
	G05OJ180	234.77		Sandstone
6	G05OJ011	233.73	1.04	Carbonate
CENTRAL LINE				
	G05OH020	299.50		Sandstone
1	G05OH043	294.40	5.10	Carbonate
	G05OH032	277.75		Sandstone
2	G05OH031	276.00	1.75	Carbonate
	G05OE069	254.86		Sandstone
3	G05OE049	255.60	-0.74	Carbonate
	G05OE070	242.20		Sandstone
4	G05OE050	240.88	1.32	Carbonate
	G05OE071	233.86		Sandstone
5	G05OE072	233.74	0.12	Carbonate
	G05OE073	231.20		Sandstone
6	G05OH009	229.97	1.22	Carbonate
SOUTH LINE				
1	G05OE081	302.40	N/A	Jurassic Formation
	G05OE074	285.08		Sandstone
2	G05OE044	285.91	-0.82	Carbonate
	G05OE075	282.35		Sandstone
3	G05OE076	287.92	-5.57	Carbonate
	G05OE077	276.62		Sandstone
4	G05OE037	278.78	-2.16	Carbonate
	G05OE078	257.99		Jurassic Formation
5	G05OE079	N/A	N/A	Sandstone
	G05OE080	N/A		Sandstone
6	G05OE011	238.60	N/A	Carbonate

3.2 Groundwater Level Fluctuations

Groundwater level fluctuations are mainly controlled by precipitation and development, although there are many other factors. In the Sandilands area which is also groundwater recharge area, there has historically been very little groundwater development, therefore the groundwater level fluctuations are mainly impacted by precipitation. Figure 4 illustrates the groundwater level in well OE001 (Fig.1) in the Sandilands vs. precipitation at the Steinbach Station. Precipitation was generally below the long-term average (540 mm/yr) from the 1960s to 1988, followed by a trend toward above average precipitation. Groundwater levels at this station were in a state of gradual decline from the 1960s to July 1991, then the water level starts to increase which is consistent with the trend of precipitation, although there is a time lag of about 2.5 years. The fluctuation shows a similar trend to Chen et al (2004) whose analysis indicated a possible 60 year precipitation cycle in Winnipeg area.

Groundwater levels in observation wells OJ019 and OJ011 (Fig.1) show similar long-term trends, with water levels declining from 1960s to around 1990, then starting an upward rise (Figure 5), although the actual water level fluctuations are more complicated than that of OE001, likely related to interference from nearby groundwater users. OJ019 is close to the eastern carbonate rock extend limit and on top of the carbonate rock is sandy till, so the water level can be increased very quickly after every precipitation. As for well OJ011, it is located near the center of the study area, between recharge and discharge areas where the Carbonate aquifer is overlain by clay; thus the recharge response is more muted and groundwater levels follow a relatively filtered smooth fluctuation.

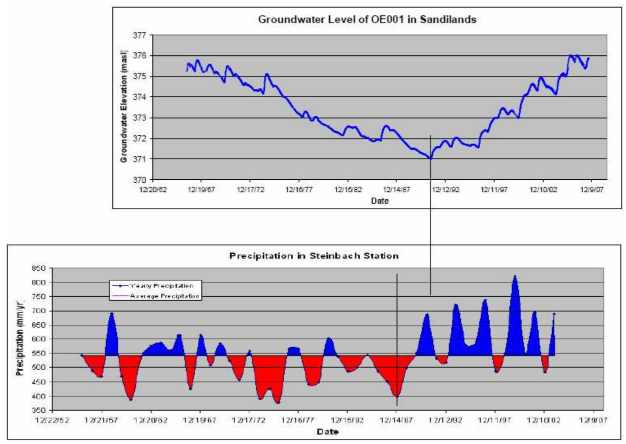

Figure 4 Groundwater level in OE001 vs. Precipitation in Steinbach Station

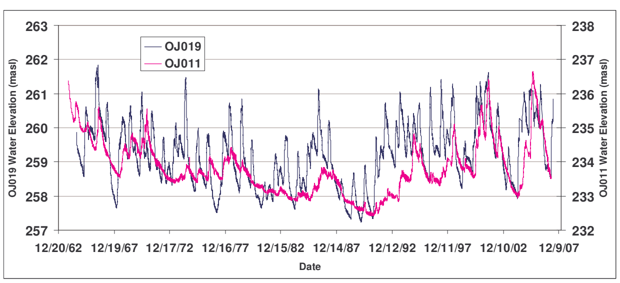

Figure 5 Groundwater Level in Observation Wells OJ019 and OJ011

OH001(Fig.1) belongs to another groundwater level change type (Figure 6). The well is located near the Winnipeg Floodway which forms a local groundwater discharge area. During the construction of the Floodway, groundwater levels dropped locally from 234 masl to about 227 masl in the 1960s and have tremained between 226 and 227 masl. When the Floodway is in use, groundwater levels rise sharply in the observation well reflecting infiltration of floodway water, a temporary cessation of discharge to the floodway or a loading effect. When diversion of water to the floodway ceases, groundwater levels rapidly decline to a level controlled by the bottom elevation of Floodway. Most of the surface water which may infiltrate during these short periods will eventually discharge back to the Floodway as hydraulic gradients re-equilibrate. The 1997 Manitoba “Flood of the Century” appears on the groundwater level in well OH001 as the highest water level after the Floodway construction. The water level drops observed in recent winters are due to dewatering for Floodway Expansion construction.

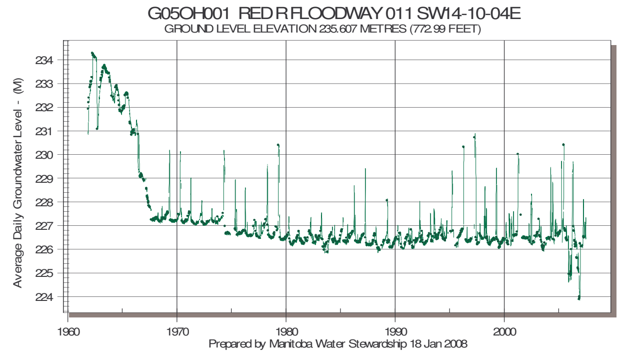

Figure 6 Groundwater Level in Observation Well OH001

Therefore, the groundwater level fluctuation types are different from recharge to discharge area; it is mainly controlled by precipitation and development. The other factors such as overburden type and the distance from recharge area etc will cause more complicate groundwater level change, BUT they can not change the long-term trend.

3.3 Hydraulic Conductivity

To do the groundwater resource evaluation, an important task is to collect good quality information on aquifer parameters. Although a few long term (24 hours to one week) pumping tests had been done in the past, most of the aquifer hydraulic conductivity information used in previous studies was obtained from specific capacity information provided on well drillers reports. Since most tests had been carried out by air lifting, the quality of this data is questionable.

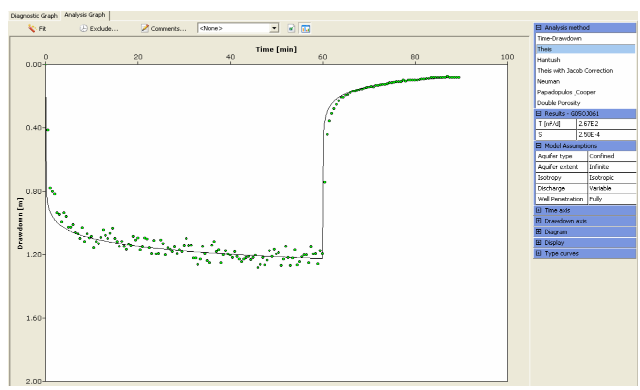

Figure 7 Single Well Pumping Test Interpretation – OJ061

For practical reason, it is impossible to do a lot of long term pumping tests in this large study area to collect representative conductivities. Instead, one hour pumping and a half hour recovery single well pumping tests were carried out on all provincial observation wells. These short-term tests need to be interpreted cautiously because many factors such as well storage and leakage will affect the results and different factors will play roles in different locations.

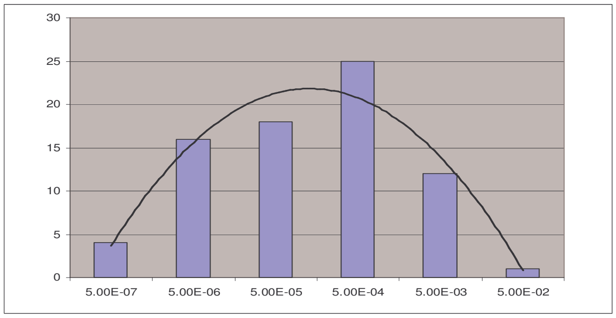

Figure 8 Histogram distribution of Conductivities in Carbonate Aquifer

Figure 7 shows a typical single well pumping test interpretation, although of course not all the pumping tests have produced such a good match. A total of 76 usable single well pumping test results were obtained from the Carbonate aquifer with an average conductivity of 8.25E-4 m/s. The conductivity also shows a normal distribution with a medium conductivity of 1E-4 m/s (Figure 8). Results are show in plan view and contoured in Figure 9. West of the Red River and east of Steinbach appear to be areas of high conductivities; there is a NE-SW direction of low conductivity between these areas (Figure 9). It is not clear why there is a NE-SW direction of low conductivity zone; the conductivity inside the zone (purple line) is less than 1E-5 m/s.

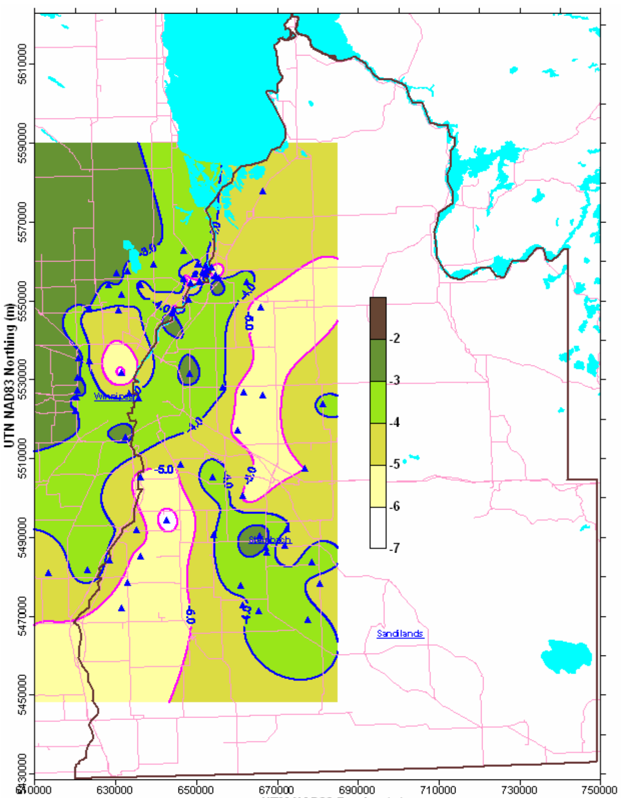

Figure 9 Log-K (m/s) Distribution in Carbonate Aquifer

Eleven pumping tests have been carried out in the Winnipeg aquifer, providing an average conductivity of 2.38E-5 m/s. It is a very uniform distribution reflecting the uniform very fine sandstone material forming this aquifer.

More field pumping tests will be done this summer and the results will be used in the modeling simulation.

3.4 Groundwater Development and Sustainable Yield

3.4.1 Groundwater Development

Under *The Water Rights Act*, it is a requirement in Manitoba to apply for a water use license if the pumping rate is greater than 25,000 L/day. There are 245 approved groundwater use licenses issued to date in the study area (Figure 10). They are mainly for withdrawal from bedrock aquifers with the larger users located around the Winnipeg and Steinbach areas.

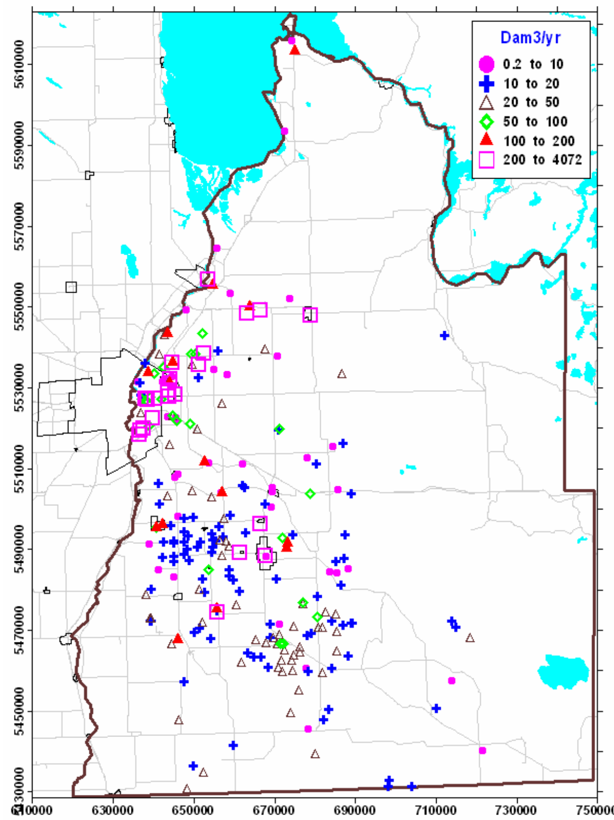

Figure 10 Groundwater License Location

The current total licensed pumping rate is 21,507,500 m^3/yr, among this, about 220 licenses only occupy 31% of the total pumping rate (Figure 11). That means 25 licenses will occupy nearly 70% of the total licenced withdrawal rate. It should be noted that the licenced rate is maximum amount of water users are allowed to withdraw – the actual withdrawal rate will be much less.

There are also approximately water well drillers logs for 22,500 private wells in the provincial groundwater database GWDrill in the study area. Most of the wells are completed in bedrock aquifers. Based on the results of water well surveys carried out in the past in Manitoba, the actual number of private wells is likely about double this amount, so the actual number of private wells will be around 45,000. If we assume the pumping rate is 0.5 m^3/d in each private well, then the total pumping rate is about 8,212,500 m^3/yr.

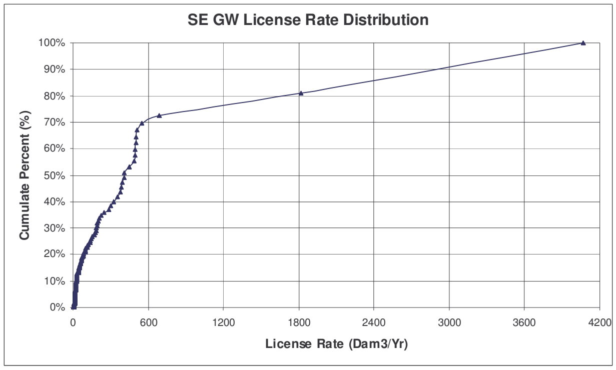

Figure 11 Groundwater License Rate Distribution

Therefore, the total groundwater usage in the study area is currently as much as 29,720,000 m^3/yr, with most withdrawal occurring from bedrock aquifers.

3.4.2 Sustainability

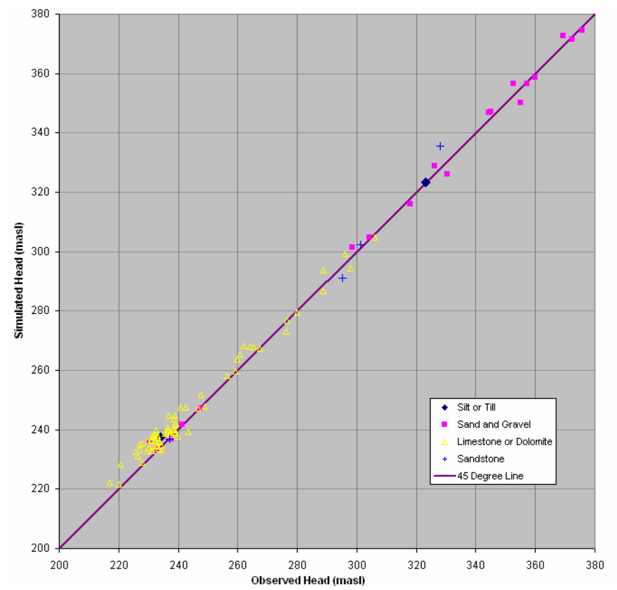

Figure 12 Steady State Calibration

Groundwater sustainability is defined as development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences (Alley et. al., 1999). A preliminary work for our study area is to check the groundwater level decline with time and the recharge rate to the aquifers to evaluate the groundwater sustainable development. A 3-D groundwater flow model including two bedrock aquifers was built, calibrated and used for the assessment.

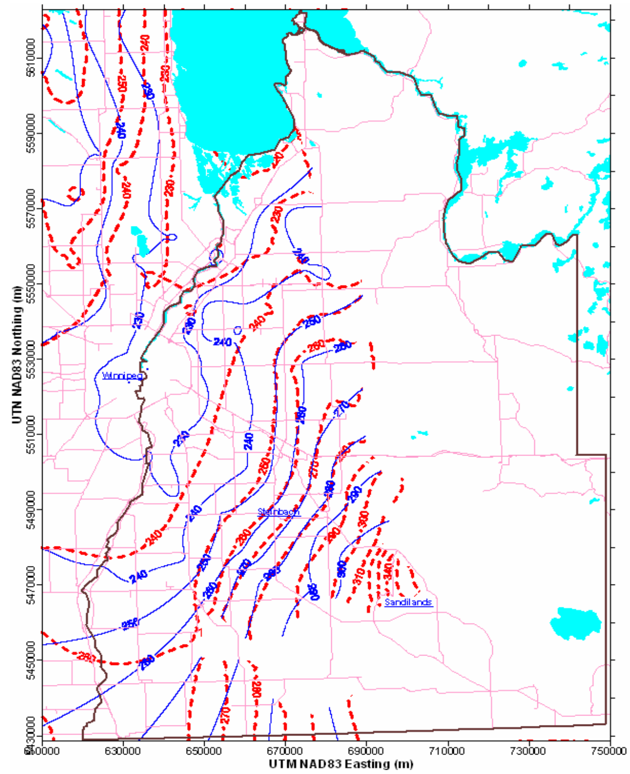

Figure 13 Groundwater Level in Carbonate Aquifer (Notes: blue contours – observed groundwater level in 2005, dashed red lines – simulated steady state groundwater level)

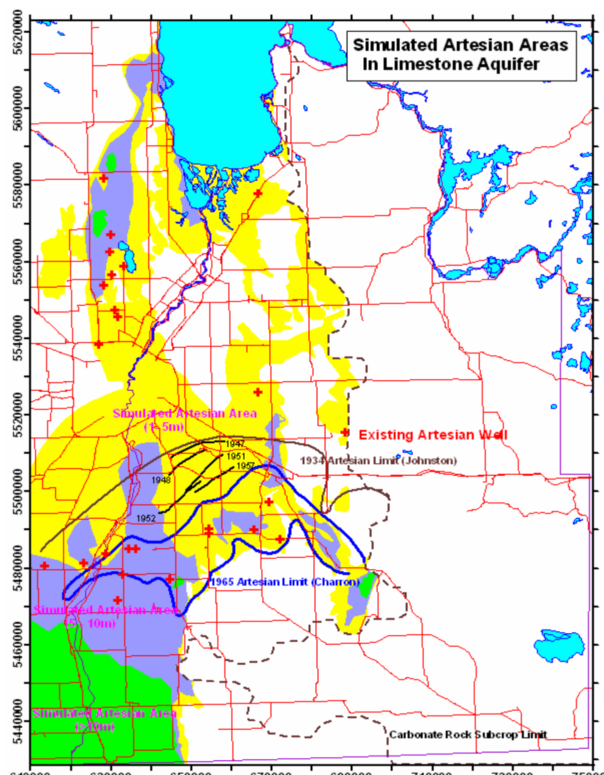

Figure 14 Simulated Artesian Areas in Limestone Aquifer

Since it's very difficult to figure out the pre-development groundwater level before 1900s, we assume 2005 groundwater level which is the highest groundwater level following the start of monitoring in 1960s is close to the pre-development state, especially in the areas of less development. And the 2005 groundwater level is used for steady state calibration.

Figure 12 shows the observed groundwater level vs. simulated groundwater level. The monitoring points have been located in 4 different units and the water level changes from 220 masl to 380 masl.

Figure 13 illustrates the observed groundwater level vs. simulated groundwater level on plan view. The contours are matched pretty well in the areas of less development or no development, such as, from Sandilands to west of Steinbach etc. The observed groundwater level is obviously lower than the simulated groundwater in Winnipeg and Red River Floodway areas because of intensive development and construction in this region.

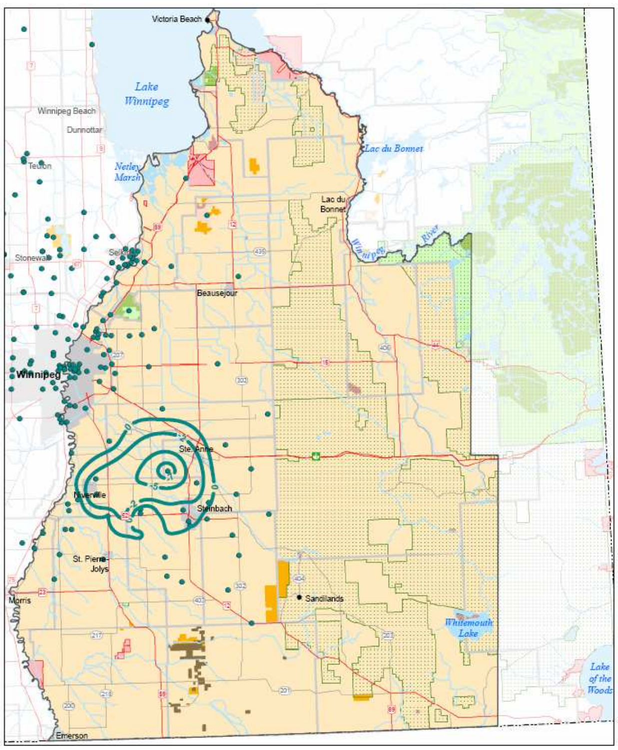

Figure 15 Negative Drawdown in Carbonate Aquifer between 2005 and 1991

Figure 14 presents simulated artesian areas in limestone aquifer. Yellow represents 0 – 5 m of artesian condition; Purple indicates 5 – 10 m of artesian area and Green represents over 10 m of artesian area. The red cross represents the existing artesian well in provincial monitoring network. The area bounded by blue lines was the artesian area surveyed by GSC (Charron, 1965) based on existing private wells. The outline of the surveyed artesian area matches well with the simulated one.

Recharge to the bedrock aquifers is composed of two parts: the lateral recharge from Sandilands highlands area flowing into the subcrop exposures of the aquifers and vertical recharge from overburden material. It is very difficult to estimate the vertical recharge component because it is related to the hydraulic conductivity of the overburden materials which has not been well characterized, the thickness and area, the head difference between surficial layer and bedrock aquifer etc. The fully calibrated groundwater model will be used to simulate the recharge rate including the vertical recharge to bedrock aquifers.

For the current discussion, the preliminary calibrated model is used to estimate the lateral recharge from Sandilands area to bedrock aquifer, because the gradient along the bedrock subcrop is nearly the same as the pre-development condition. The total lateral recharge to bedrock aquifers from Sandilands area is 1,863,000 m3/yr which is only 6.3% of current groundwater usage in the study area. If we consider the geothermal operation will return the water into aquifers and their pumping volume is not included in the total groundwater usage, the lateral recharge from Sandilands will only occupy 7.2% of the groundwater use rate.

It is generally understood that the regional recharge to bedrock aquifers is from Sandilands area (Render, 1970), but it is still a little bit surprise that the lateral recharge rate is only 7.2% of current groundwater usage based on a very preliminary estimation. Vertical recharge plays a bigger role in groundwater sustainable development.

Based on the provincial groundwater observation well network, most groundwater levels have increased following climate fluctuation cycle after 1991 (Figure 5), except in the local area to the west of Steinbach (Figure 15), where a negative drawdown is observed when 2005 peak groundwater level is subtracted by 1991 groundwater level. That means groundwater level in 2005 peak period is even lower than that in 1991, development in this localized area will need more time to reach to the new equilibrated condition. Other areas do not show stress as the west of Steinbach areas.

4 SUMMARY

Groundwater level fluctuations in southeast of Manitoba are mainly controlled by recharge and development, it follows a 60-year climate cycle. Regionally groundwater level declines from 1960s to 1990 due to deficit precipitation, and then it increases from 1990 after higher precipitation is recorded in the region.

Over 1,000 wells installed as open holes to take the "soft" water from Winnipeg Formation. This has caused the groundwater level in Winnipeg sandstone aquifer decreased; the new installed observation well network has shown the water level in Winnipeg Formation is very close to that in Carbonate aquifer, it is even lower in some localized development area.

It is normal distributed and the medium conductivity in Carbonate aquifer is 1E-4 m/s. It is not clear why there is a low NE-SW conductivity zone in the study area. More study should be done on the geological and structural reasons. The conductivity in Winnipeg sandstone aquifer is very uniform and the average conductivity is 2.38E-5 m/s.

A very preliminary estimation shows the lateral recharge from Sandilands area to bedrock aquifers only occupy 7.2% of the groundwater usage. The vertical recharge will play a bigger role on groundwater sustainable development. Most of the area shows the development is sustainable, only a small area to the west of Steinbach has shown some development pressure and the groundwater level will need more time to reach the new equilibrated condition.

5 ACKNOWLEDGEMENT

Frank Render left behind a large groundwater monitoring network and the information from the observation wells is very valuable and helpful in this study. Jeremy Mowez helped to conduct the field pumping tests and oversee the new monitoring well installation. Ryan Hewitt helped to produce some of the maps. 3 -D geologic model was provided by Gaywood Matile and Greg Keller of Manitoba Geological Survey.

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