Water Supply Investigation for the City of Enderlin, Enderlin Aquifer, Ransom and Cass Counties, North Dakota

By
Andrew Nygren
North Dakota State Water Commission

North Dakota Ground Water Studies No. 118
North Dakota State Water Commission
2012

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WATER SUPPLY INVESTIGATION FOR THE CITY OF ENDERLIN, ENDERLIN AQUIFER, RANSOM AND CASS COUNTIES, NORTH DAKOTA

INTRODUCTION

The City of Enderlin currently obtains its municipal supply from 5 production wells located in the City of Enderlin. Within the City of Enderlin there is a large grain elevator and associated rail yard that facilitates the grain elevator. The ADM sunflower processing plant is located a mile east of the City of Enderlin (Figure 1). The City of Enderlin has three municipal water permits for a total annual allocation of 850 acre-feet. In 2010 the City of Enderlin reported using 1,118.7 acre-feet. Their use incorporates the municipal use of the city and the ADM sunflower processing plant. Concern over contamination (or potential contamination) to the Enderlin Aquifer within the city limits as a result of spills at the rail yard, and their need to apply for additional water, prompted the City of Enderlin to consider a well field outside the city limits. The City of Enderlin entered into a cooperative agreement with the North Dakota State Water Commission (SWC) in the fall of 2009 to investigate a sustainable city groundwater supply outside of the city limits of Enderlin.

PURPOSE

The purpose of the investigation is to locate new areas for the City of Enderlin's municipal well field(s) that will provide acceptable well yields, have no significant water quality limitations, and will be economically feasible to develop.

OBJECTIVES

The objectives of the investigation are as follows:

1) Further define the geometry of the Enderlin Aquifer.
2) Investigate and evaluate mechanisms of recharge and discharge to the Enderlin Aquifer.
3) Determine the location of more productive areas of the Enderlin Aquifer.
4) Investigate and evaluate the water quality of the Enderlin Aquifer.
5) Recommend the location(s) of viable groundwater resources for the City of Enderlin.

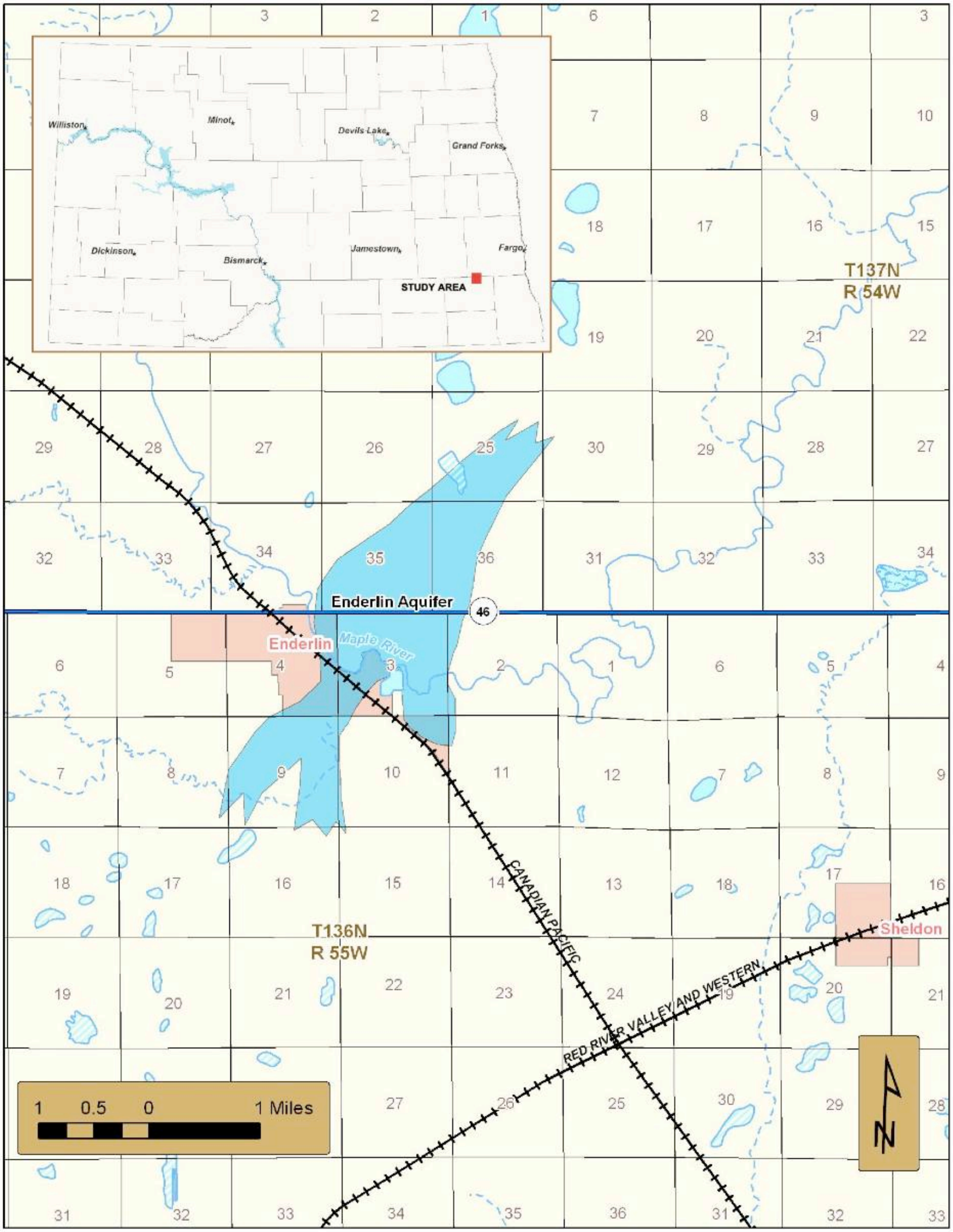

Figure 1. Location of study area.

Acknowledgements

This project involved contributions from many SWC personnel including Terry Olson, Neil Martwick, Roger Nelson, Merlin Skaley, Albert Lachenmeier, Dan Sauter, and Dan McDonald. The City of Enderlin Superintendent of Public Works, Rick Gillund also contributed to this project. Jon Patch, Alan Wanek, and Robert Shaver critically reviewed the report.

Location and Numbering System

Locations are numbered according to the public land classification for the United States Bureau of Land Management (Figure 2). The first numeral denotes the township north of the Base Line, the second numeral denotes a range west of the 5th Principal Meridian, and the third numeral denotes the section. For North Dakota, the intersection of the Base Line and 5th Principal Meridian is in east-central Arkansas. Letters A, B, C, and D designate, respectively, the northeast, northwest, southwest, and southeast sub dividing of a section of land into the quarter section, quarter-quarter section, and quarter-quarter-quarter section (10-acre tract). Consecutive terminal numerals are added if more than one well or test hole is located in a 10-acre tract. For example, well 13605509ABC is a test hole or observation well located in the SW¼ NW¼ NE¼ Section 09, Township 136 North, Range 055 West (Figure 2).

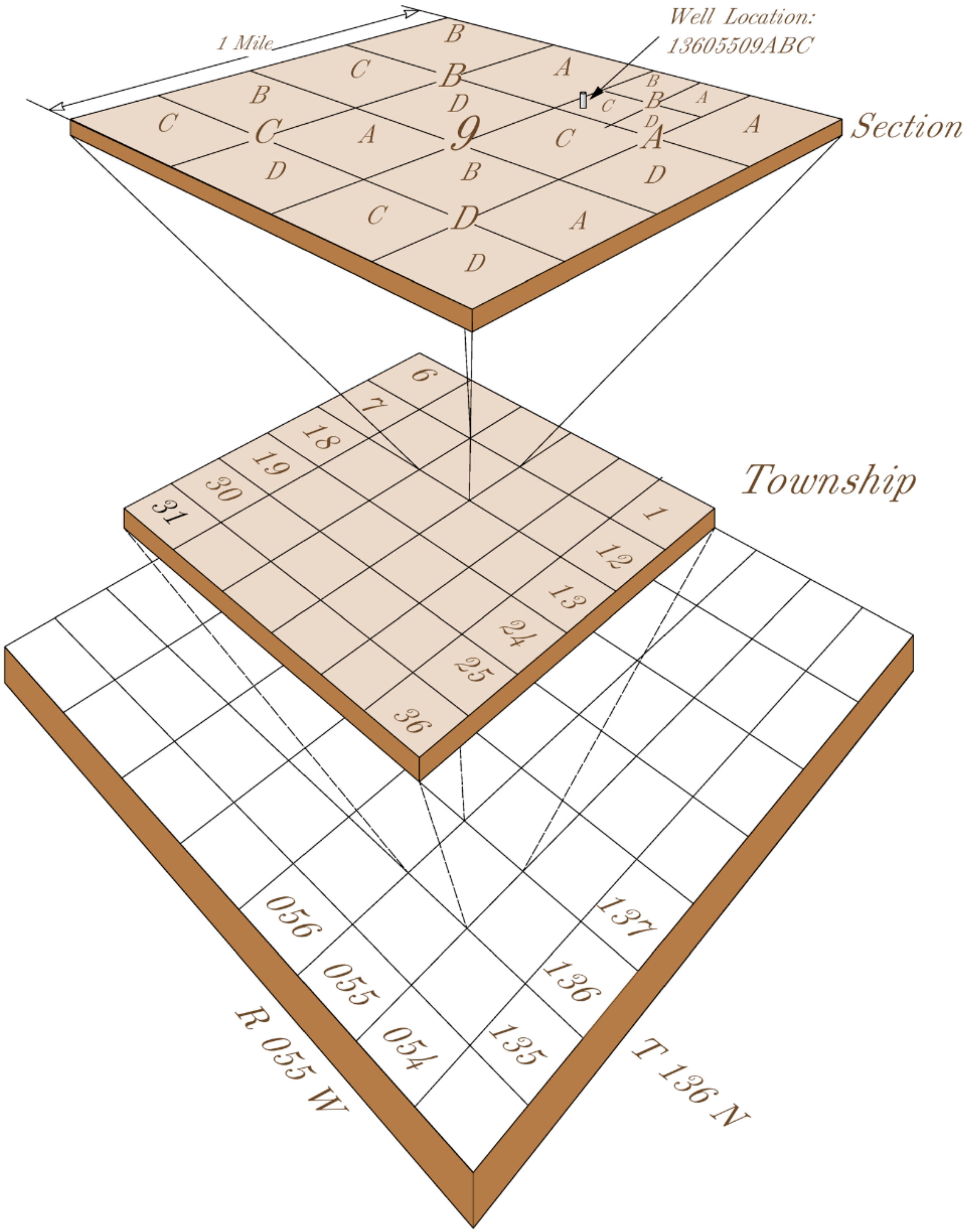

Figure 2. Well location system.

Summary of Work

- **Evaluation and Analysis of Existing Data for Enderlin Aquifer**

Existing data in the Enderlin area was gathered from test hole drilling and observation wells installed for the Cass County (Klausing, 1968) and Ransom County (Armstrong, 1982) Groundwater Studies conducted in the mid 1960s (Cass County) and late 1970s (Ransom & Sargent Counties). Subsequent test hole drilling and observation well installation was conducted in the Enderlin area during November and December 1979 by the SWC. LTP Enterprises conducted test hole drilling south and west of Enderlin along the South Branch of the Maple River in September 2006. Water levels in observation wells completed in the Enderlin area as part of the county groundwater studies and SWC drilling program have been periodically monitored since their installation. Additional test hole drilling for this project was initiated based on a preliminary conceptual model of the Enderlin Aquifer developed from pre-existing hydrogeologic data.

- **Test Drilling and Observation Well Installation**

A total of 26 test holes were drilled totaling 5,340 feet in September and October 2009. Test hole drilling was completed with a forward mud-rotary drill rig. Samples of the drill cuttings were analyzed and described by the project hydrogeologist. If significant saturated aquifer material was encountered, the test hole was completed as an observation well using 2-inch diameter polyvinyl chloride (PVC) screen and casing (Figure 3).

A total of 17 observation wells were installed, 6 of which were replacement wells for wells that no longer pumped sufficient quantities of water. Three observation wells were subsequently plugged in spring 2010. The 5-foot screened intervals of the observation wells ranged from 40 feet to as much as 280 feet below land surface (bls). In deeper wells, silica sand was placed in the annular space around the well screen to a height of about two feet above the top of the well screen (Figure 3). All other wells were completed by collapsing the formation around the well screen and annular space. The annular space above the sand pack or collapsed formation was filled to land surface with high-solids bentonite grout or bentonite chips.

Wells were developed by air-lift pumping for many hours to ensure the well screens were not plugged and transmitted sufficient quantities of water. Each observation well was secured at land surface with a 4-inch diameter protective plastic casing set in concrete (Figure 3). The bottom of the protective casing was set to a depth approximately 2 feet below land surface and the top of the casing was set slightly above the top of the 2-inch observation well casing, which extends 2.5 to 3 feet above land surface. Screw-on plastic caps on top of the 4-inch protective casing secured access to the well.

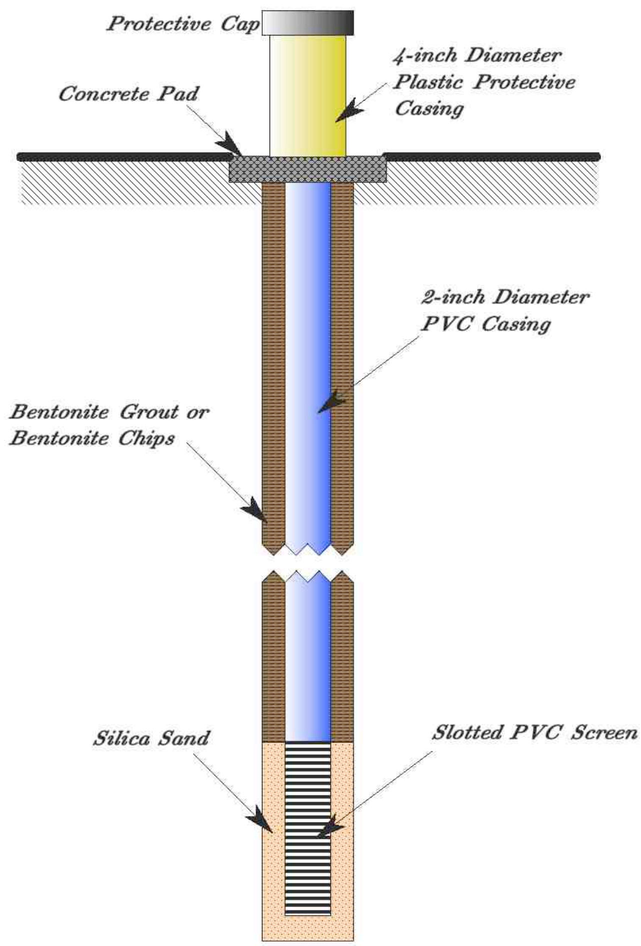

Figure 3. Well construction diagram.

- **Surveying**

Elevations were determined for the top of each observation well, protective casing, and land surface. The elevation of the top of the observation well is the reference for groundwater elevation measurements. SWC personnel surveyed elevations to 3rd order accuracy.

- **Water-Level Monitoring**

Water levels in each observation well were periodically measured using electric monitoring tape. Four observation wells had hourly water-level recorders installed to better understand water level fluctuations under current aquifer conditions. Water levels were recorded after measurement, verified, stored in the SWC relational database, and are available to the public through the SWC website.

- **Water Quality Analysis**

Water samples for chemical analysis were collected from all observation wells using a bailer, bladder pump, or centrifugal pump. Samples were transported to the ND Department of Health Division of Laboratory Services, and analyzed for major cations, anions, and selected trace metals. A summary of the water quality analysis is in this report. Complete sampling results are available to the public through the SWC website.

Description of Study Area

The Enderlin area is located near the boundary of the Lake Agassiz Plain and Drift Prairie of North Dakota in southwestern Cass County and north central Ransom County. Specifically the area of interest is located in the north part of T136N R055W in Ransom County and the south part of T137N R055W located in Cass County (Figure 1). The area of interest is transected by the Maple River, which forms the eastern boundary of the City of Enderlin. The population of Enderlin has varied from 636 according to the 1900 census to as high as 1,919 in the 1920 census. The 2010 census reported a population of 886 for the City of Enderlin.

- **Climate**

Recorded precipitation from the Enderlin area is presented in Figure 4. Data was gathered from the National Climatic Data Center (NCDC) station at Enderlin from 1951 to present. Data prior to 1951 and data missing from the Enderlin station was taken from the Lisbon station approximately 12 miles south-southwest of Enderlin or from an Atmospheric Resources Board (ARB) station located at 13705402, 9-miles northwest of Enderlin. In some rare instances data was missing from the Enderlin, Lisbon, and ARB stations. In these cases data was taken from the NCDC McLeod station approximately 21 miles southeast of Enderlin. Figure 4 presents the climate record for the Enderlin area in terms of Water Year (October through September), Winter (October to March), and Summer (April to September). Five-year backward weighted moving averages in Figure 4 show the long term climatic fluctuations of wetter periods, such as the 1940s, early 1960s, and 1990s along with drier periods such as the 1930s, 1950s, and late 1980s. Long-term averages for the Water Year, Summer, and Winter are 20.02 ± 4.63 inches, 15.32 ± 4.23 inches, and 4.69 ± 1.87 inches respectively. The majority of the precipitation, and variation in precipitation, is in summer months as opposed to winter months. Summer precipitation is characterized by local thunderstorms whereas winter precipitation is characterized by regional snowstorms.

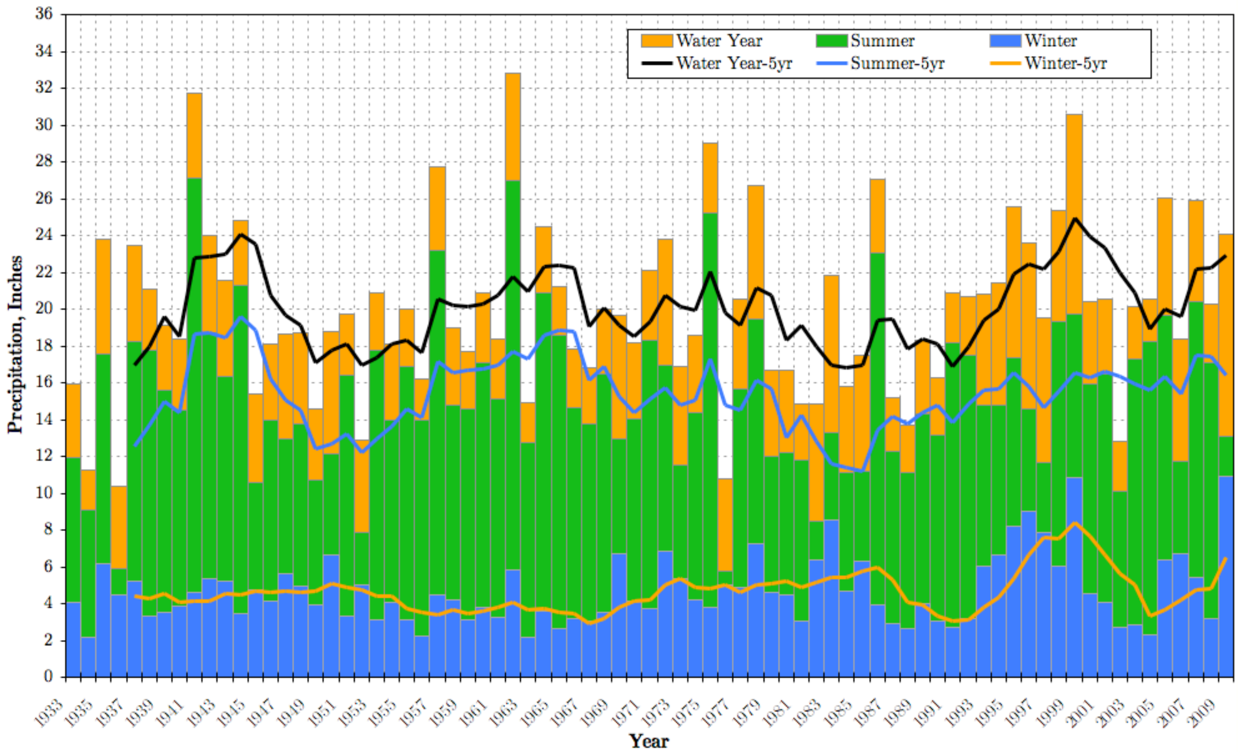

Figure 4. Composite climate record of Enderlin Area.

- **Geology of Enderlin Area**

The geology of the Enderlin area as it relates to the Enderlin Aquifer is comprised of unconsolidated sediments deposited by continental glaciation. The glacial sediments overlie the Cretaceous age Carlile Shale. The Enderlin area has three distinct depositional facies that overlie the Carlile Shale:

1. ***Till 1*** - *An unsorted mixture of sand-sized to boulder-sized material composed of metamorphic, igneous, and carbonate rocks (from the Canadian Shield), and shales and lignites (from underlying bedrock layers) contained in a silty clay matrix. Till is deposited directly by glacial ice.*

2. ***Fluvial*** - *The fluvial (water deposited) sediments composed of fine sands to coarse gravels with interlayering of thin to thick sequences of silts to silty clays.*

3. ***Till 2*** - *In areas outside the Maple River Valley, the land surface is underlain by surficial till. The surficial till is distinctly siltier than the underlying till (Till 1).*

The underlying geologic structure of the Enderlin area is illustrated in Figures 5-9, which are geohydrologic sections that have been constructed based on test hole drilling conducted in the Enderlin area (Figure 5). The three distinct depositional facies are apparent in each of the geohydrologic sections.

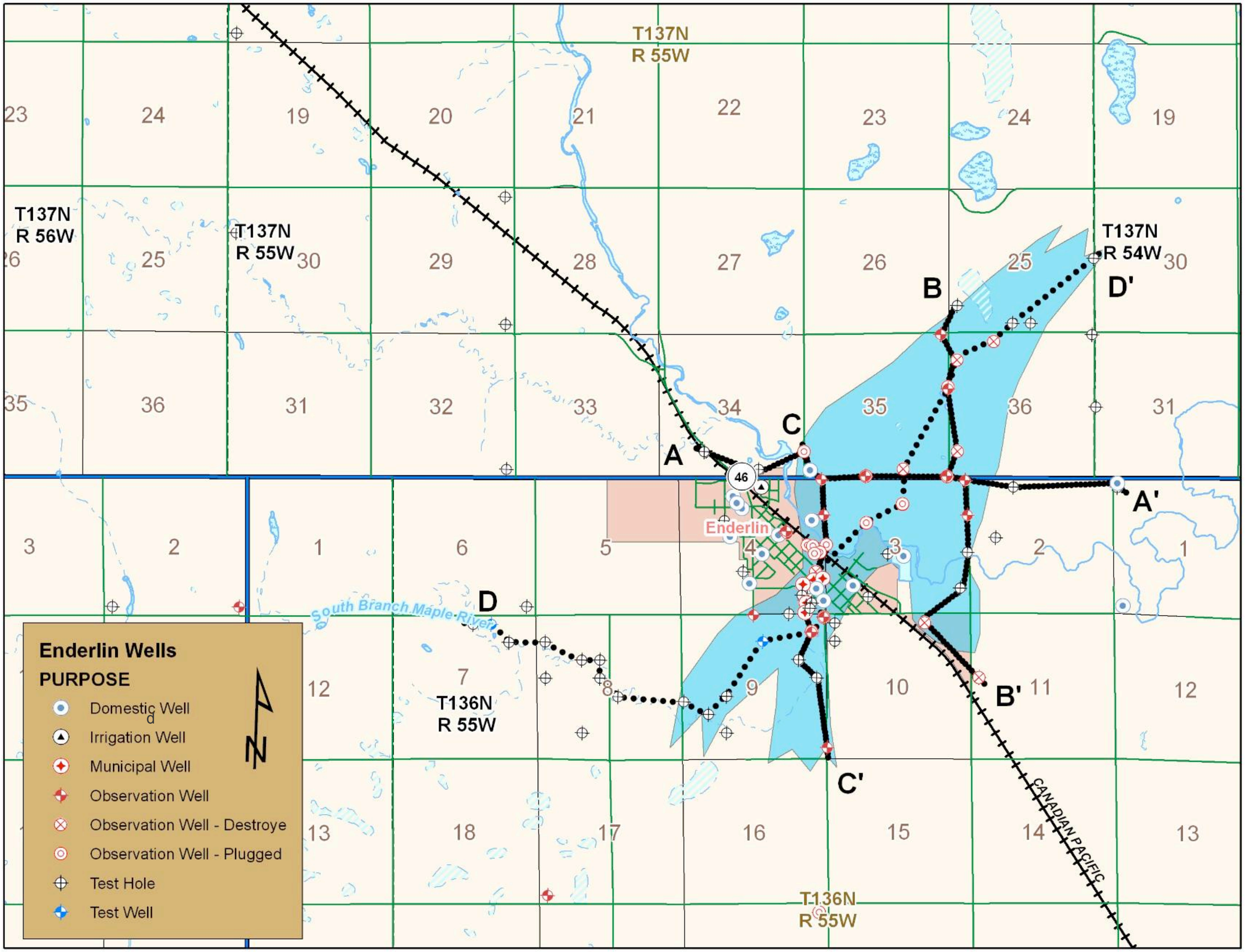

Figure 5. Location of test holes, wells, and geohydrologic section traces in Enderlin Aquifer area.

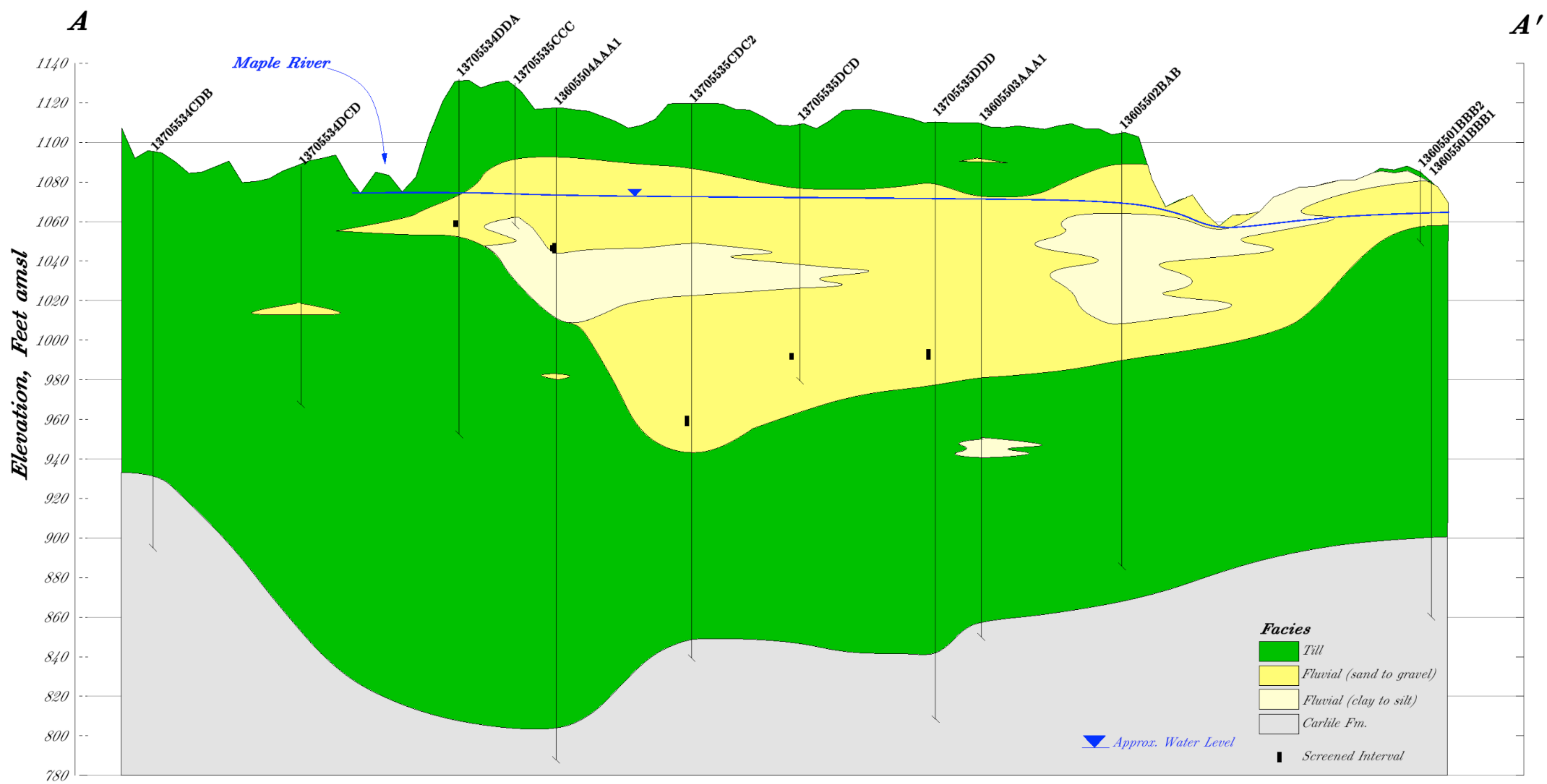

Figure 6. Geohydrologic section A-A'.

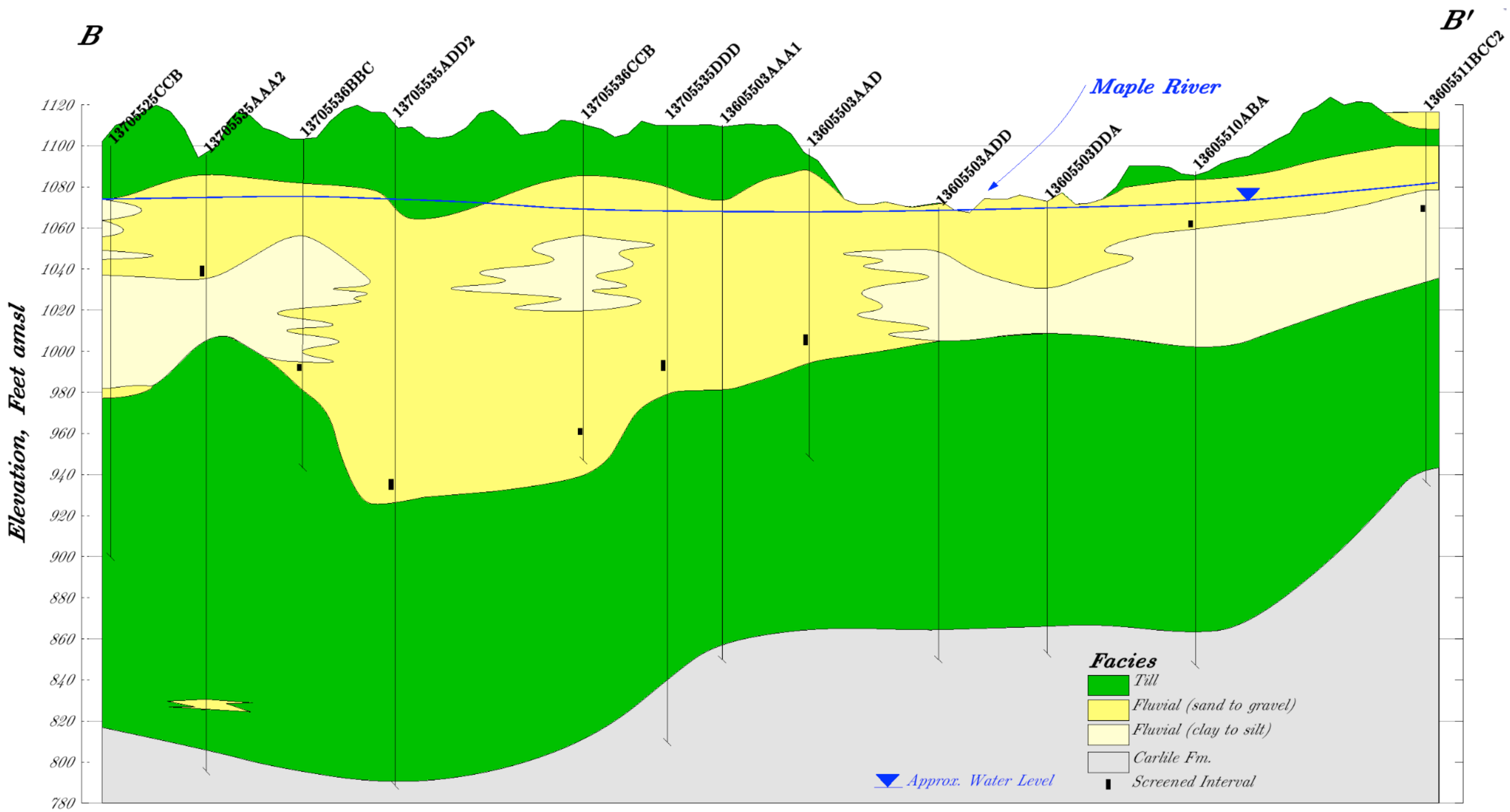

Figure 7. Geohydrologic section B-B'.

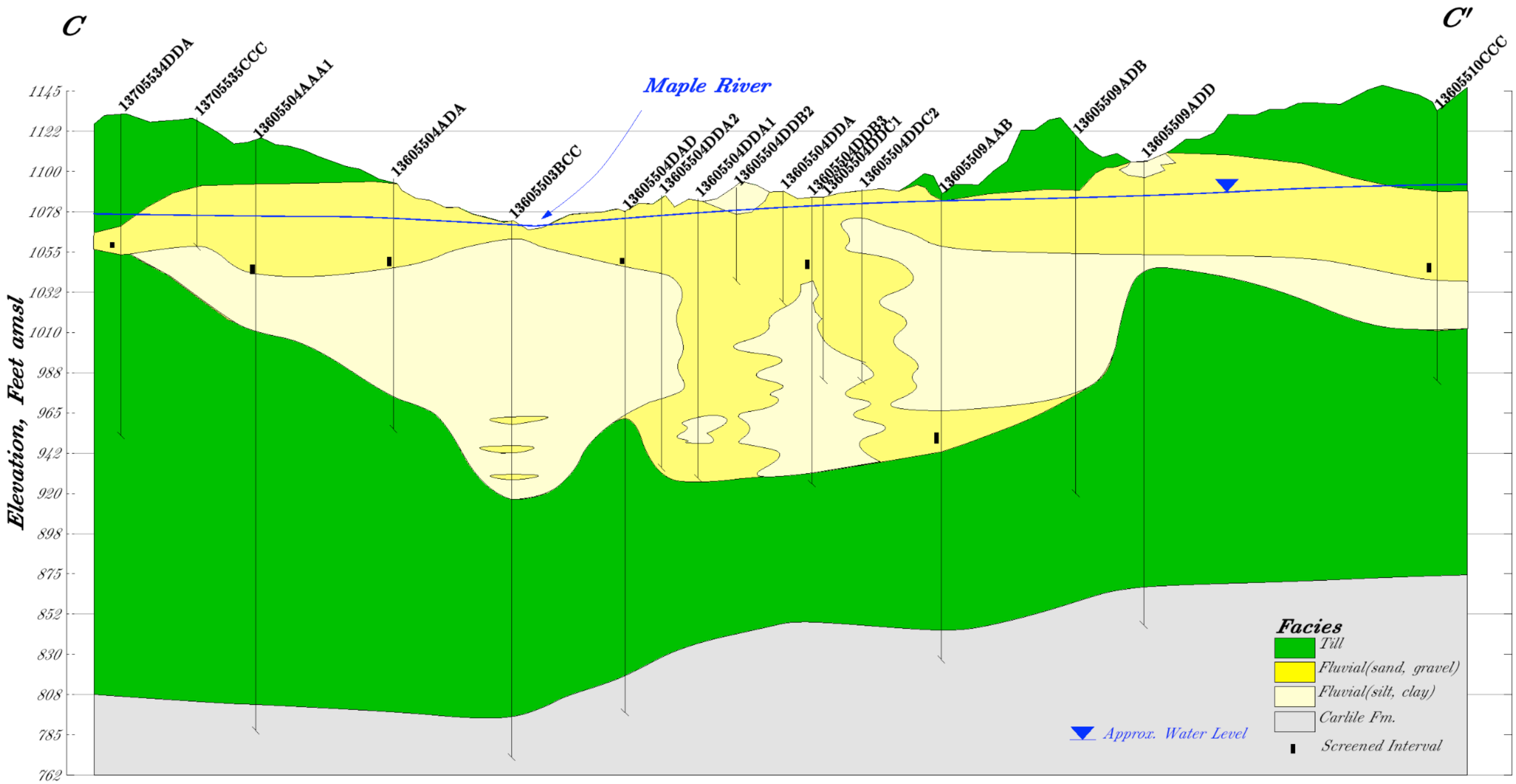

Figure 8. Geohydrologic section C-C'.

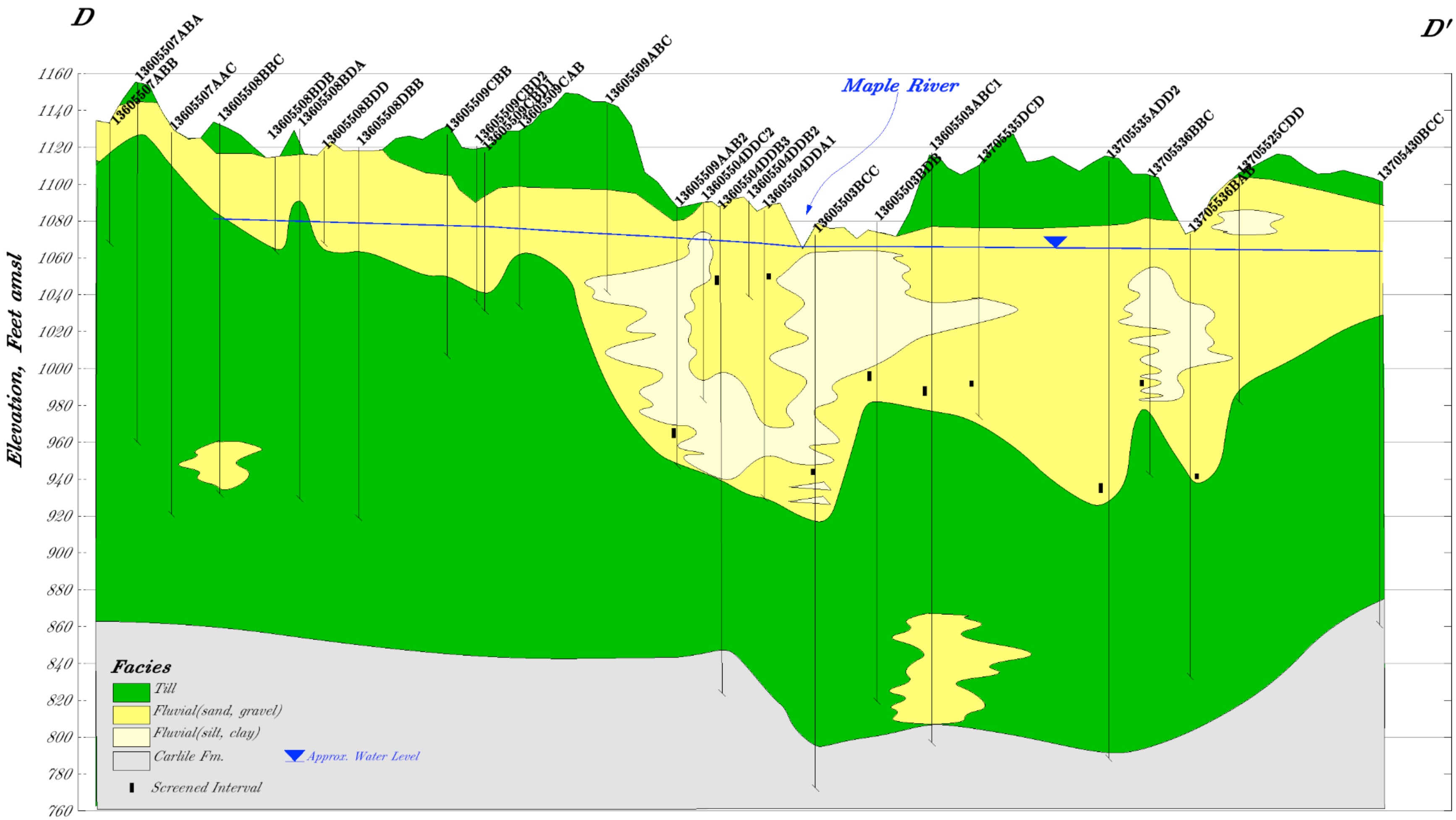

Figure 9. Geohydrologic section D-D'.

The sequence of sediments suggests that early glacial advances, which deposited *Till 1*, covered the preglacial bedrock surface. A glacial retreat and the resulting melt water deposited the *Fluvial* sediments over *Till 1*. The thicker sequences of the *Fluvial* sediments shown in the geohydrologic sections are indicative of more active fluvial events. A final glacial advance deposited a veneer of till (*Till 2*) over the *Fluvial* sediments. The final glacial recession resulted in the surficial geology of the Enderlin area.

The surficial features in the Enderlin area are shown in Figure 10, which are a result of processes associated with, and subsequent to the last glacial advance in the area. The surficial deposits in Figure 10 area are described as follows:

Abbreviation	***Description***
Qod	*Windblown sand*
QTou	*Windblown sand (including older, Tertiary sand)*
Qcdc	*Collapsed/draped transition sediments*
Qccg	*Collapsed glacial sediment, gentle undulated topography*
Qccu	*Collapsed glacial sediment, undulating topography*
Qcew	*Water eroded glacial sediment*
Qcs	*Shoreline sediment*
Qcoh	*Ice walled lake sediment or collapsed supra-glacial lake sediment*
Qcrf	*Un-collapsed river sediment*
Qor	*River sediment*

From Figure 10 it is possible to construct a synopsis of the processes that shaped the landscape features. Initially the area was covered with glacial ice, as the glacial ice receded, it would periodically stall resulting in the formation of ridges shown in Figure 10. During this last glacial retreat melt water was flowing ice marginally likely forming the river channels shown in Figure 10. This melt water was discharging into glacial Lake Agassiz to the east of the area. As glacial ice continued to recede and Lake Agassiz continued to fill, the ice marginal rivers and Lake Agassiz eventually coalesced, as evident by the abrupt change in direction of the Maple river from south (glacial influenced drainage) to the northeast (pre-glacial drainage). Beach ridges from Lake Agassiz are shown in Figure 10. As Lake Agassiz retreated, the beach sand was transported by aeolian processes resulting in the windblown sand deposits. With continued retreat of Lake Agassiz the present day path of the Maple River into the Lake Agassiz Plain, or Red River Valley was created.

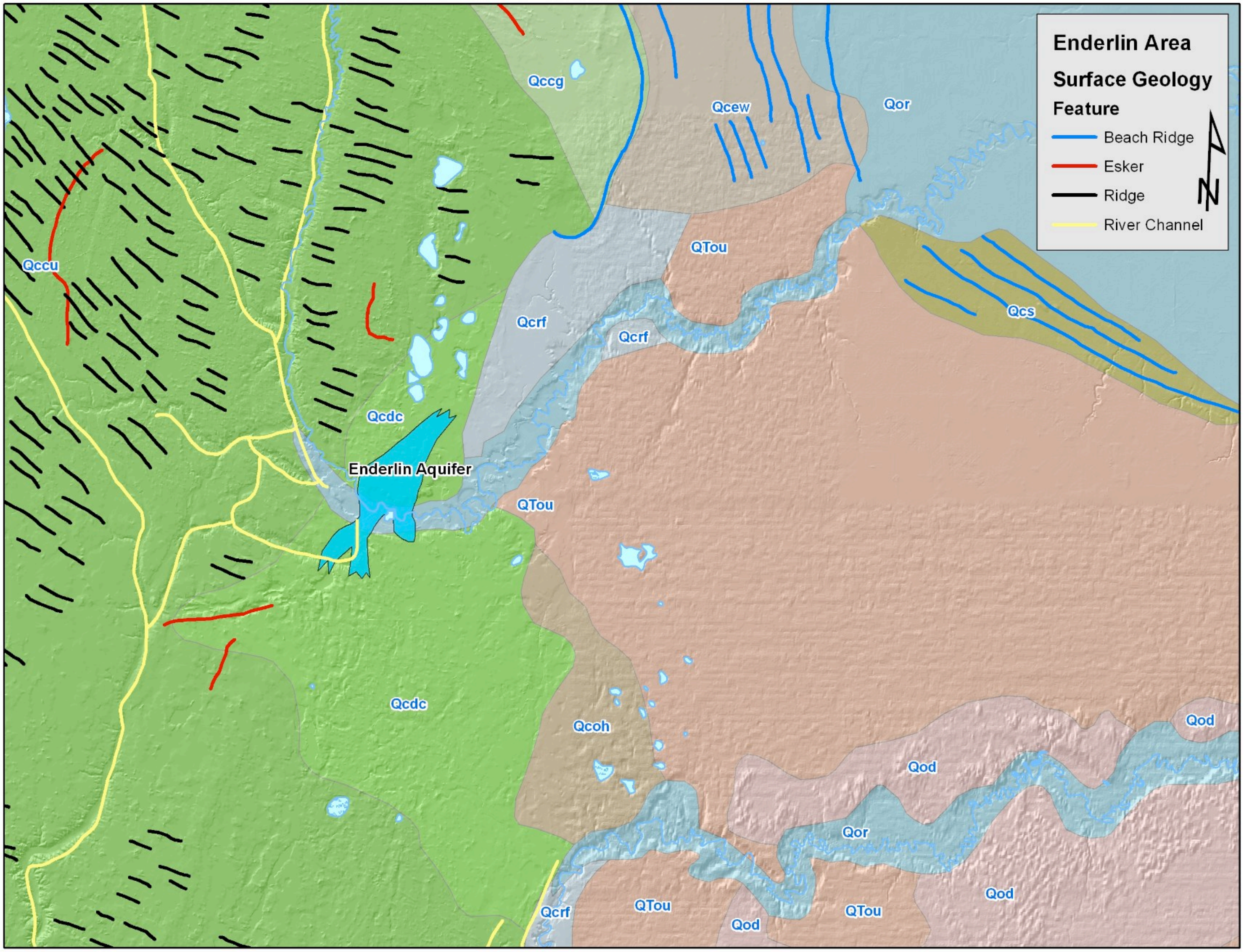

Figure 10. Surficial geology of Enderlin Area.

- **Aquifer Description**

The Enderlin Aquifer is the saturated coarse-grained glaciofluvial sediment that underlies the Enderlin area. The approximate extent of the Enderlin Aquifer, as shown in Figure 5, is representative of the thicker areas of the coarse grained fluvial sediments. As shown in the geohydrologic sections, however, over its areal extent the thickness of the sand and gravel sediments is highly variable. Thicknesses can range from a couple of feet to over 100 feet of saturated sand and gravel. Areas of thick gravel intervals can be located very near areas of little or no saturated sand and gravel. For example, test hole 13605509AAA encountered 120 feet of saturated sand and gravel, whereas test holes 13605509AAB and 13605510BBB respectively encountered 11 feet and 19 feet. The most productive areas of the aquifer are located in areas of the SE1/4 of Section 4, T136N, R055W extending to the northeast through the western and central areas of Section 3, T136N, R055W.

- **Enderlin City Water Supply and Use**

Enderlin currently uses 5 municipal wells, all located in 13605504D, as shown in Figure 11. LTP Enterprises drilled City Well 1 in April 1976. The well driller's report described the following lithology:

Formation	**From, feet**	**To, feet**
Clay, sandy, brown	0	15
Sand with hard shale, colored (took water)	15	25
Sand & gravel, colored, with hard shale (took water)	25	37
Sand, fine, blue	37	52

The 12-inch diameter well was screened from 27 feet to 37 feet below land surface (bls) with a stainless steel 40-slot size well screen that was sandpacked with Red Flint 10-20. The static water level was measured at 13.3 feet bls. LTP Enterprises conducted an aquifer test on City Well 1, which will be discussed in a later section.

City Well 3 was drilled in January 1983 by LTP Enterprises. The well driller's report described the following lithology:

Formation	**From, feet**	**To, feet**
Topsoil, black	0	1
Sand & gravel, colored	1	22
Sand, colored	22	42
Sand finer w/ black shale	42	47
Sand, coarser, 18-20 slot, colored	47	62
Sand, coarse, 25-30 slot, colored	62	69
Sand, finer, 15-18 slot, colored and black	69	84.5
Clay, sandy, silty, blue	84.5	102

The 12-inch diameter well was screened from 65 feet bls to 85 feet bls with a stainless steel 45-slot size well screen that was sandpacked with Red Flint 10-20. The static water level was reported as 8.15 feet bls. LTP Enterprises conducted an aquifer test on City Well 3, which will be discussed in a later section.

City Well 4 was drilled in January 1983 by LTP Enterprises. The well driller's report described the following lithology:

Formation	**From, feet**	**To, feet**
Sand & gravel, with shale, some clay, black	0	15
Sand with shale and clay, dirty, black	15	39
Clay, sandy, soft, black	39	44
Sand, 20-25 slot, dirty, colored	44	47
Sand, finer, 12 slot, colored	47	59
Sand, dirty, colored	59	62
Sand, looked good, drilled poor	62	67
Sand, 15-18 slot, coarsened to 25 slot with depth	67	82
Sand, finer, 15-18 slot, colored	82	88
Sand, finer, colored	88	97
Clay, sandy with fine silty sand	97	107

The 12-inch diameter well was screened from 71.5 feet bls to 91.5 feet bls with a stainless steel 45-slot size well screen that was sandpacked with Red Flint 10-20. The static water level was reported as 4.73 feet bls. LTP Enterprises conducted an aquifer test on City Well 4, which will be discussed in a later section.

City Well 5 was drilled in July 1996 by LTP Enterprises. The well driller's report described the following lithology:

Formation	**From, feet**	**To, feet**
Topsoil	0	5
Clay, sandy	5	11
Sand & gravel	11	41
Sand, fine	41	53
Sand, dirty	53	118
Sand, very fine	118	133
Sand, fine	133	156

The 12-inch diameter welded steel casing well was screened from 136 feet bls to 156 feet bls with a stainless steel 40-slot size well screen. The well was gravel packed and the annular area was filled with cement from 10 feet bls to 106 feet bls. The static water level was reported as 7 feet bls and was 66 feet bls after 1 day of pumping at 390 gpm indicating a specific capacity of 6.61 gpm/foot drawdown.

City Well 6 was drilled in July 1996 by LTP Enterprises. The well driller's report described the following lithology:

Formation	From, feet	To, feet
Topsoil	0	8
Sand	8	13
Sand & gravel	13	37
Sand, light gravel	37	43
Sand, very fine	43	113
Sand, fine	113	152

The 12-inch diameter welded steel casing well was screened from 132 feet bls to 152 feet bls with a stainless steel 40-slot size well screen. The well was gravel packed and the annular area was filled with cement from 10 feet bls to 102 feet bls. The static water level was reported as 7 feet bls and was 43 feet bls after 1 day of pumping at 350 gpm indicating a specific capacity of 9.72 gpm/foot drawdown.

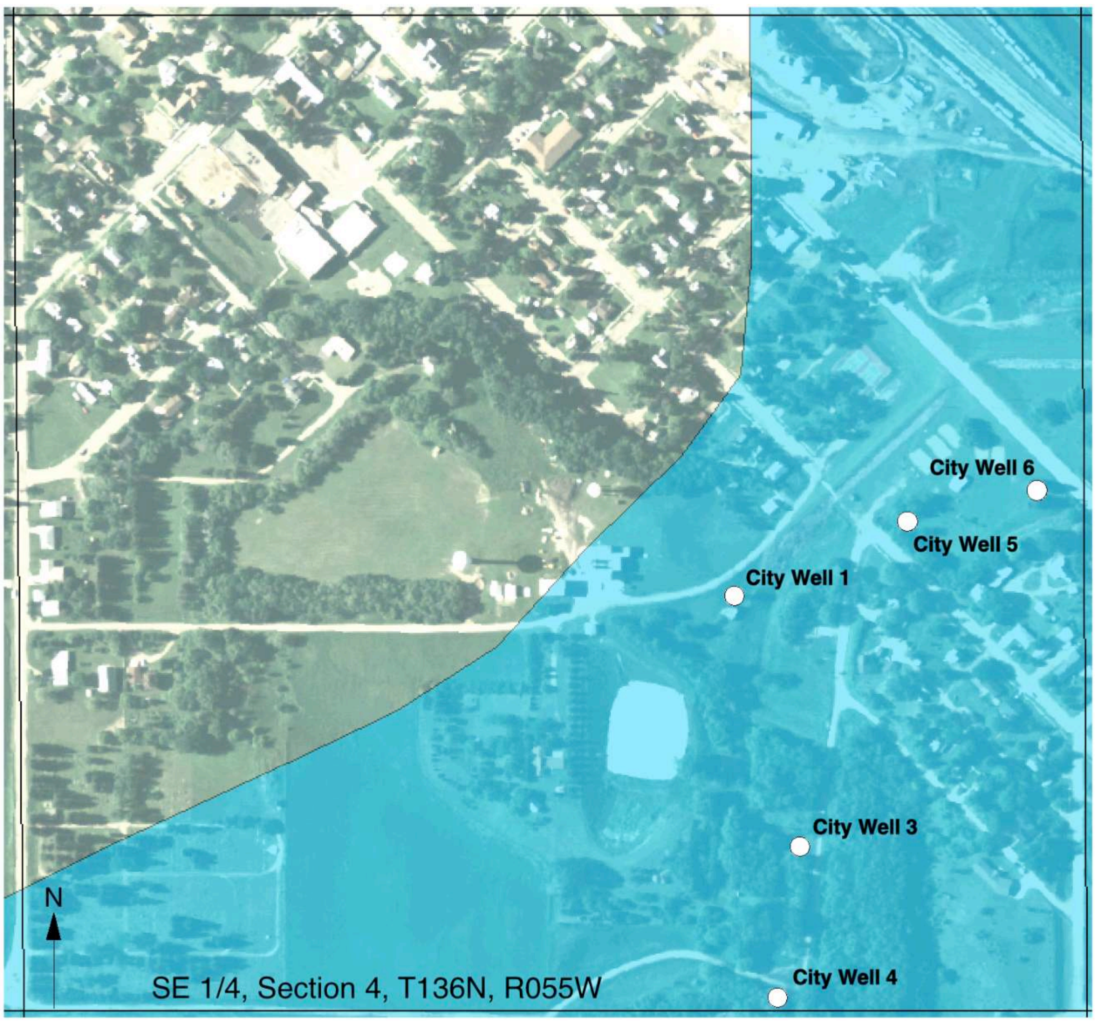

Figure 11. Enderlin municipal water wells.

The municipal water supply for the City of Enderlin supplements the domestic needs for the city as well as providing water for the ADM sunflower processing plant located on the east side of town. The municipal water supply is permitted under the following three perfected water permits:

Permit No.	Permit Holder	Priority Date	Approved Acre-Feet	Approved Rate, GPM	Point of Diversion
734	ENDERLIN, CITY OF	6/19/57	300	350	13605504A 13605504D
3594	ENDERLIN, CITY OF	12/2/82	350	753	13605504D
4962	ENDERLIN, CITY OF	12/6/95	200	375	13605504D

The City of Enderlin is permitted a total of 850 acre-feet at a rate of no more than 1,478 gpm annually. The reported water use from the City of Enderlin is summarized in Figure 12, which has ranged from a little over 100 acre-feet in 1976 to over 1,100 acre-feet in 2010. The principal user of the City of Enderlin's water supply is the sunflower plant, with municipal use likely ranging from approximately 200 to 300 acre-feet annually.

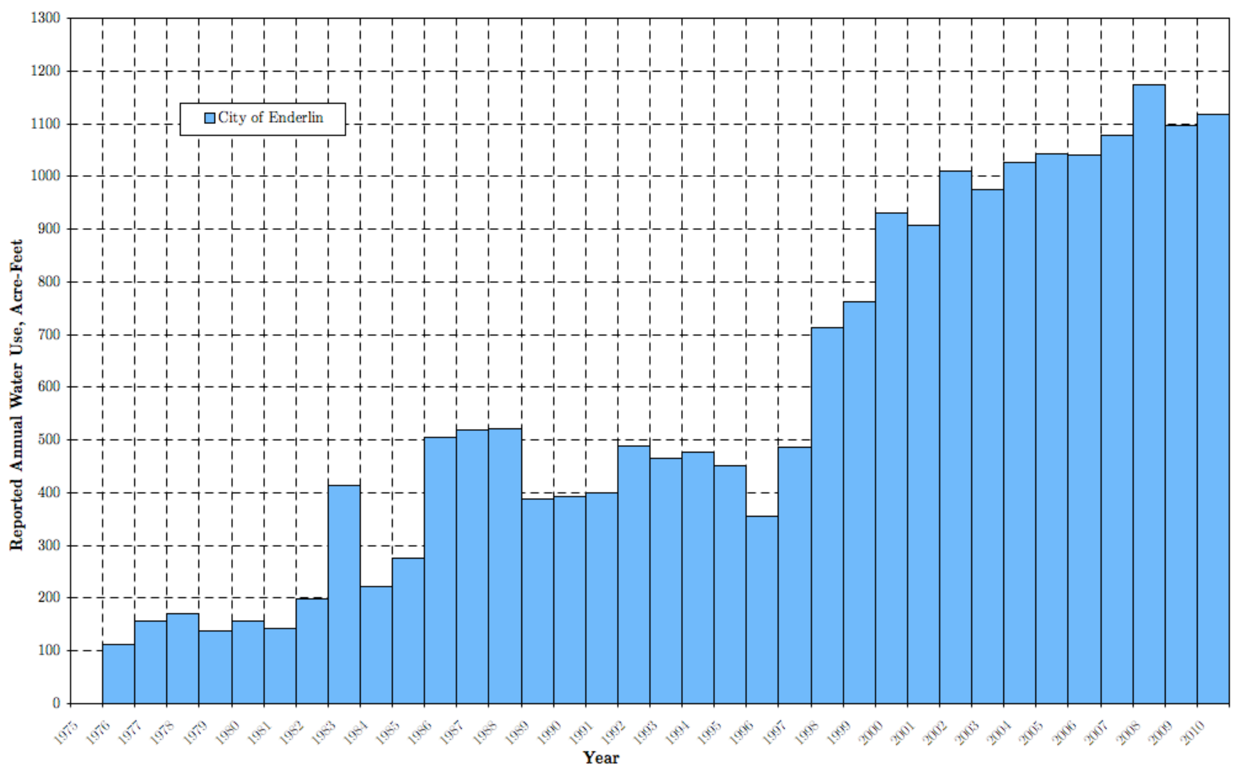

Figure 12. Reported water use from the City of Enderlin.

Hydrogeologic Setting

- **Groundwater Movement, Recharge, and Discharge**

In general, groundwater moves under the influence of gravity from areas of aquifer net recharge to aquifer net discharge. Groundwater flow in the Enderlin Aquifer is predominantly towards the Maple River (Figure 13). Water levels in Figure 13 are from June 2010 (in NGVD 29) except for water levels rounded to the nearest foot, which are estimated water levels from wells that have been plugged or destroyed. The water level elevation of 1063 feet amsl (NGVD 29) is representative of the Maple River stage in June 2010 as recorded at the USGS gaging station. As illustrated in Figure 13, the Maple River is likely the main discharge area for the Enderlin Aquifer. Additional discharge occurs in riparian areas by evapotranspiration. Recharge to the aquifer occurs predominantly by infiltration of meteoric water either directly in areas where the surficial till has been eroded away or indirectly by leakage through the overlying till. Additional discharge from the aquifer occurs by pumping of wells, most notably the Enderlin municipal wells. During periods when the stage of the Maple River is higher than the adjacent aquifer, water will discharge from the Maple River to the Enderlin Aquifer. This would likely only occur during notable rises in the Maple River stage such as following spring snowmelt or from runoff after a large precipitation event.

- **Aquifer Properties**

The transmissivity and storativity are aquifer properties of interest in characterizing hydrogeologic units in aquifer systems. The transmissivity (T) quantifies the ease with which water moves through the aquifer, similar to hydraulic conductivity (K), which quantifies the ease with which water moves through a unit aquifer segment. The aquifer transmissivity is the product of the aquifer thickness and hydraulic conductivity. Materials such as well-sorted gravels have very high hydraulic conductivity values whereas clays have very low hydraulic conductivity values. The storativity (S) quantifies the amount of water released from the aquifer under a change in aquifer water level, similar to specific storage (S_S) which quantifies the volume of water released from a unit volume of aquifer sediment under a unit change in head. Aquifer storativity is the product of the aquifer thickness and specific storage. For aquifers under water table conditions, such as most of the Enderlin Aquifer, the amount of water released under a unit change in aquifer water level is approximately equal to the drainable porosity or specific yield (S_Y), which is the amount of water that would drain from a unit aquifer volume under the influence of gravity.

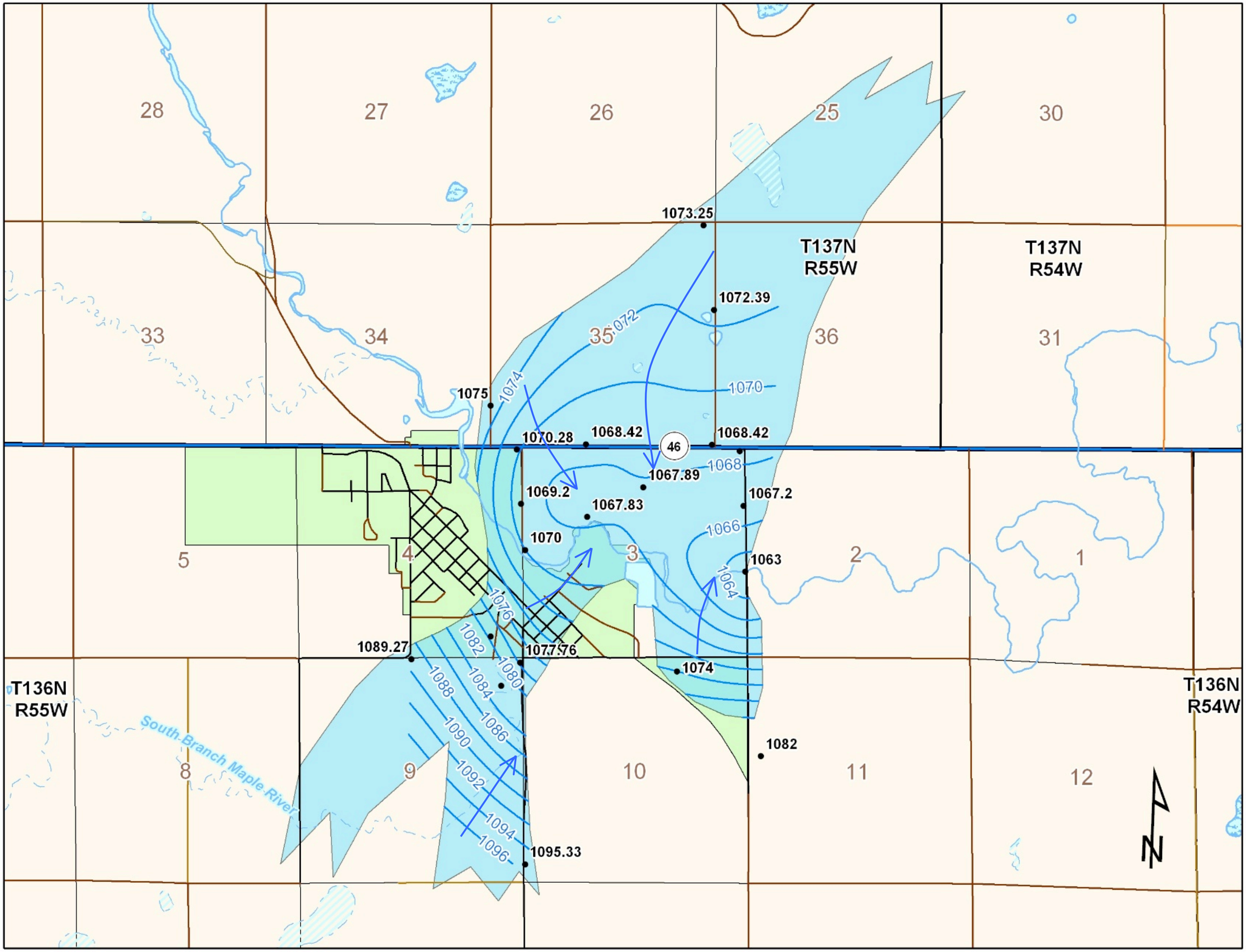

Figure 13. Potentiometric surface and direction of groundwater flow in Enderlin Aquifer from water levels (in NGVD 29) measured in June 2010.

Aquifer tests are typically conducted to determine aquifer properties. A well is pumped at a known pumping rate, Q, and the changes in aquifer water levels, or drawdown, are monitored throughout the period of pumping. The drawdown is typically measured at the pumping well and observation wells completed at various distances from the pumping well. The recorded drawdown is fitted to analytic mathematical solutions describing changes in aquifer water levels in the presence of a pumping well under various hydrogeologic settings. The Enderlin Aquifer has been described as an unconfined aquifer that, in some areas is locally overlain by or interbedded with silt to silty clays. Therefore the mathematical model describing the effects of a pumping well on aquifer water levels in a leaky aquifer overlain by a water table aquitard will be used. The mathematical model (Figure 14) is derived and described in Appendix A and was first studied by Case and Cooley (1973). This model allows for estimation of the aquifer radial hydraulic conductivity (K_r), or the ease with which water moves through the aquifer material towards the pumping well, the vertical aquitard hydraulic conductivity (K_z'), or the parameter that describes the ease with which water can move from the overlying aquitard to the aquifer, the aquifer and aquitard specific storage (S_S and S_S'), which describes the amount of water that is released from a given unit of aquifer or aquitard material, and the specific yield of the aquitard (S_Y'), which is the amount of water that drains under the influence of gravity from a given unit of the aquitard. The thicknesses of the aquifer and aquitard were derived from the well logs. Pumping rates, Q, and drawdown data were reported on the aquifer test field sheets completed by LTP Enterprises.

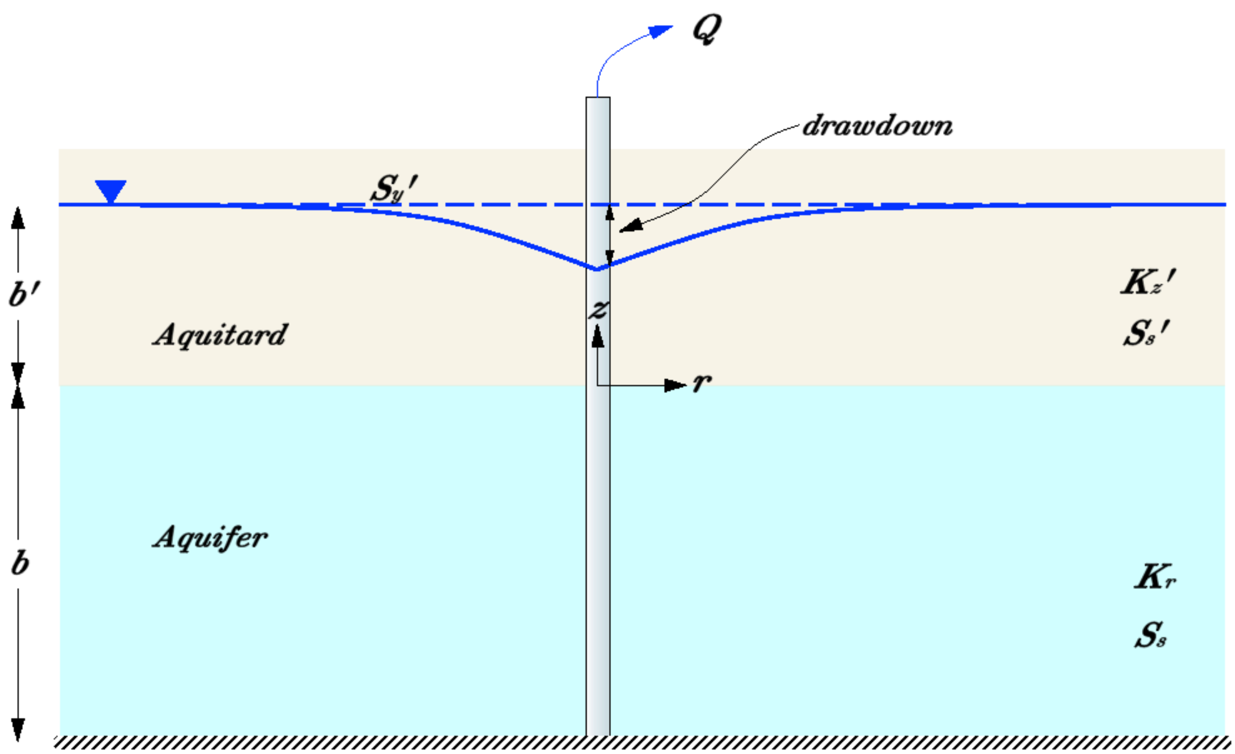

Figure 14. Aquifer and aquitard properties and parameters used or estimated using mathematical model.

LTP Enterprises conducted aquifer tests on City Well 1 in May 1976 and City Wells 3 and 4 in June 1983. The observed drawdown in each of the pumping wells served as the only usable data for aquifer test analysis. The observed and simulated drawdowns are shown in Figure 15 for City Wells 1, 3, and 4. The aquifer parameters and properties used for each well is summarized as follows:

	Unit	City Well 1	City Well 3	City Well 4
Q	gpm	411	400	400
b	feet	22	38	53
b'	feet	2	39	39
K_r	feet/day	305	155	180
K_z'	feet/day	6	12	6
S_y'	-	0.28	0.25	0.06
S_s	1/feet	3E-4	7E-5	7E-5
S_s'	1/feet	3E-4	3E-5	3E-5

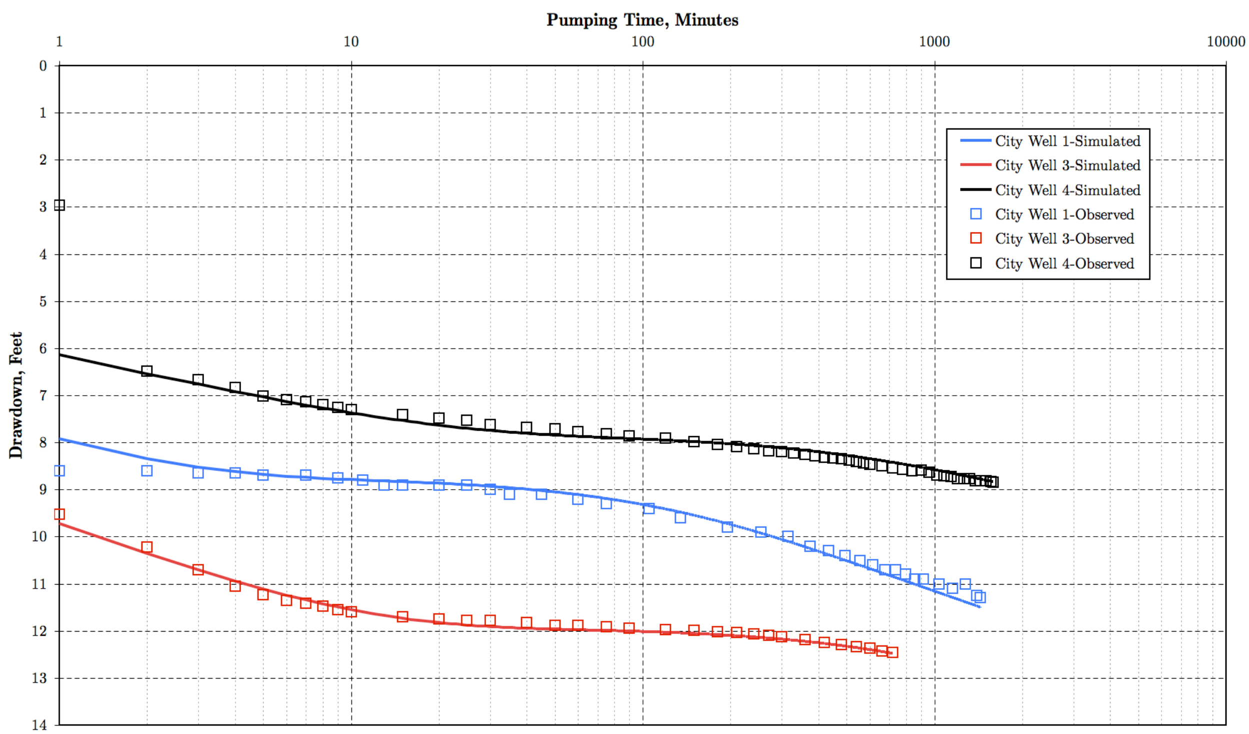

Figure 15. Observed and simulated drawdown for aquifer tests conducted on City Wells 1, 3, and 4.

City Wells 1, 3, and 4 were pumped long enough such that the drawdown became linear with respect to log time. Transmissivity and storativity could therefore be estimated using the Jacob-Cooper Method. The results are as follows:

	Unit	City Well 1	City Well 3	City Well 4
T	feet^2/day	7,400	15,650	15,570
S	-	8E-2	1E-9	5E-5

Determination of aquifer storativity from drawdown data measured in the pumping well is questionable. The aquifer storativity affects the slope of the straight-line portion of the late time drawdown data in Figure 15. Due to wellbore storage effects, the determination of aquifer storativity using early time drawdown data can overestimate storativity and underestimate transmissivity, because initially water is removed from the wellbore and not the aquifer. It is also important to realize that since drawdown data is from pumping wells, the effect of well inefficiency and partial penetration also increases drawdown. Well inefficiency will not affect transmissivity estimates, but storativity estimates will be underestimated.

- **Water levels**

Water levels in the Enderlin Aquifer have been periodically recorded since the 1970s and with more frequency since the late 1980s. All water levels are presented in NGVD 29 for continuity. Long-term aquifer water levels from observation wells completed in the Enderlin Aquifer are shown in Figure 16. Water levels have not significantly varied over the past 30 years indicating that the aquifer system is in equilibrium with the current development from the City of Enderlin. Observation well 13605509AAA shows a slight decline in water levels through the drier 1980s, followed by an increase in water levels through the wetter 1990s and the latter part of the 2000s.

In the fall of 2009 a number of observation wells were installed and existing observation wells were replaced. Recorded aquifer water levels from replacement wells were combined with replaced wells water data in Figure 16. Water level measurements from the new observation wells are shown in Figures 17 through 20. Wells at 13605503ABC and 13605503BDB were plugged in June 2010. Water levels have increased since fall of 2009 as a result of above average precipitation and spring runoff. Observation well 13605503BDB was completed very near the Maple River. The punctuated March 2010 water level measurement at well 13605503BDB illustrates the hydraulic connection to the Maple River (Figure 21). At two drilling sites in the Enderlin area two wells were constructed in order to measure water levels in different water bearing units. Hydrographs from these two nested well sites are shown in Figures 19 and 20. Site 13705535AAA indicates downward groundwater movement from the overlying Enderlin Aquifer to the underlying unnamed unit. Site 13605503ABC indicates upward groundwater movement from the underlying unnamed unit to the overlying Enderlin Aquifer.

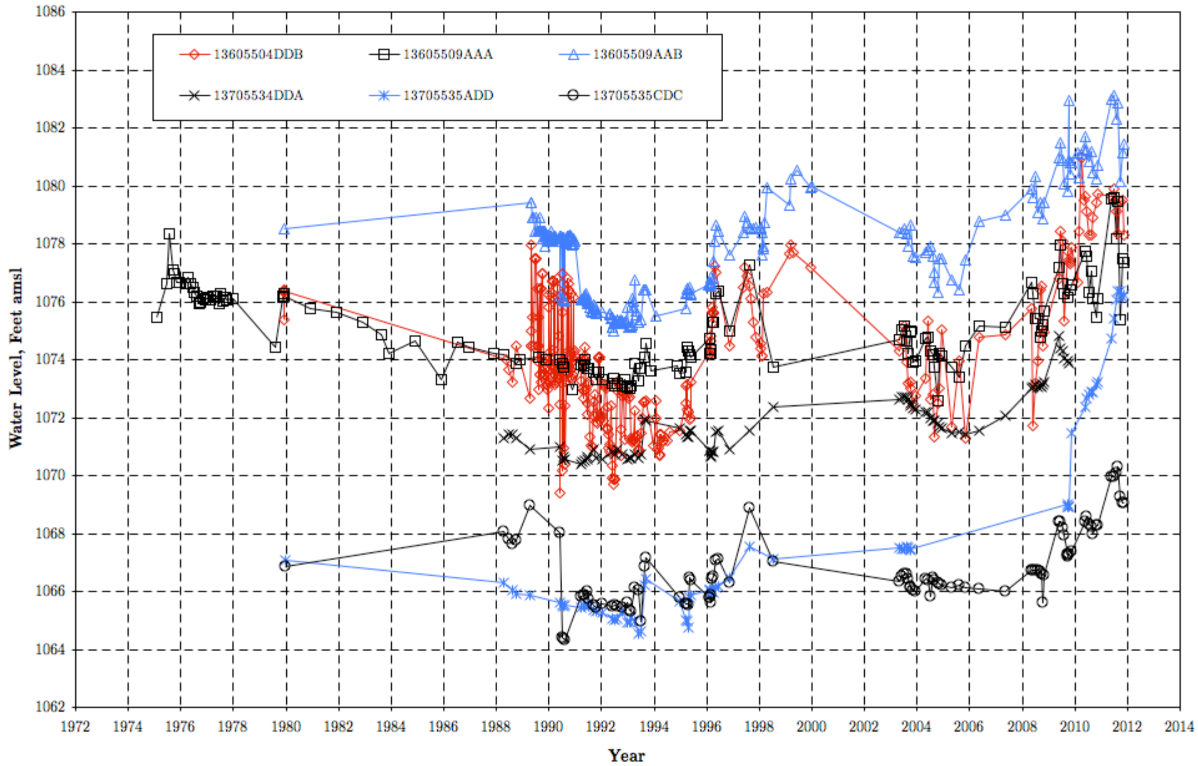

Figure 16. Recorded aquifer water levels from long-term observation wells in Enderlin Aquifer.

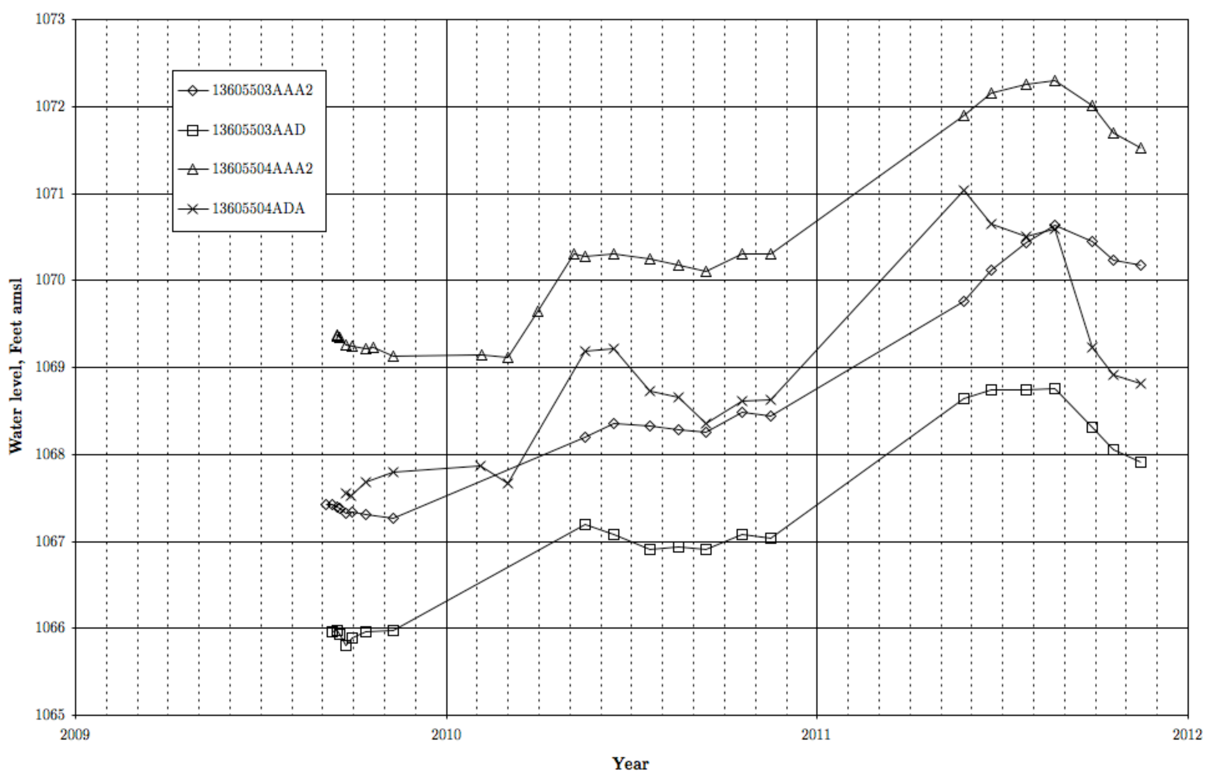

Figure 17. Recorded aquifer water levels from observation wells 13605503AAA2, 13605503AAD, 13605504AAA2, and 13605504ADA installed in fall 2009.

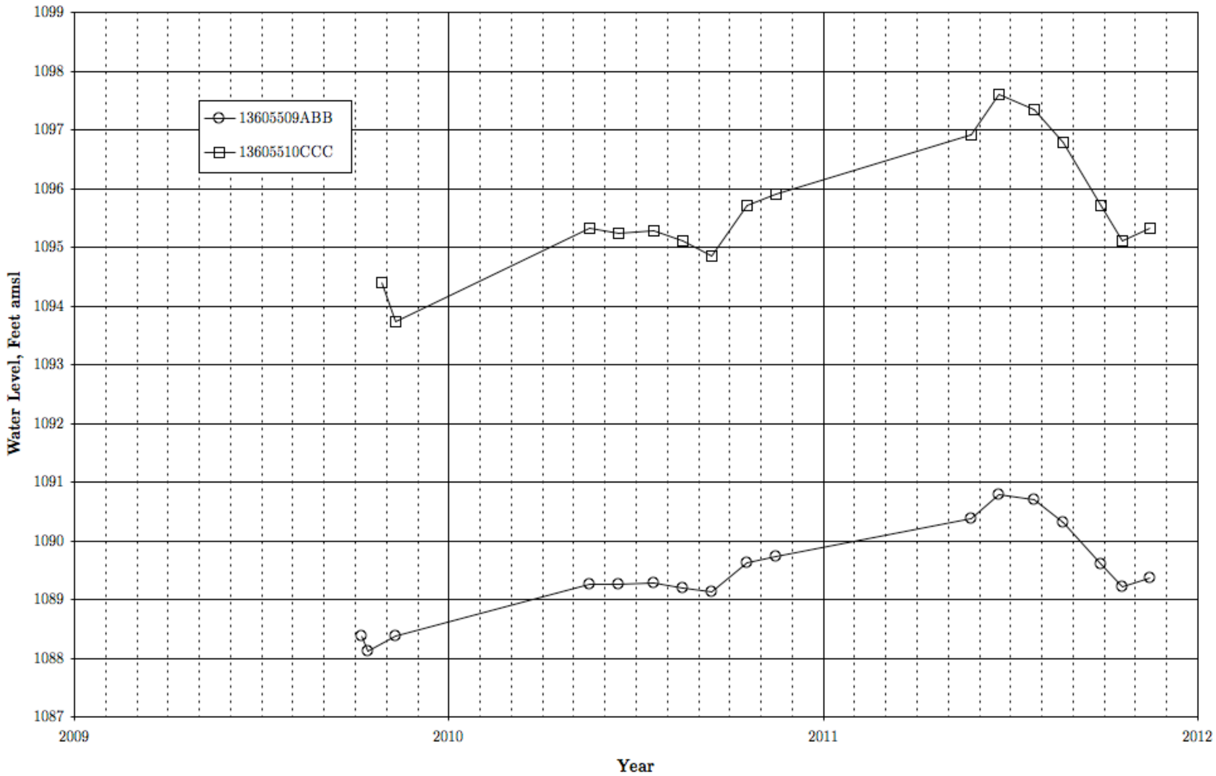

Figure 18. Recorded aquifer water levels from observation wells 13605509ABB and 13605510CCC installed in fall 2009.

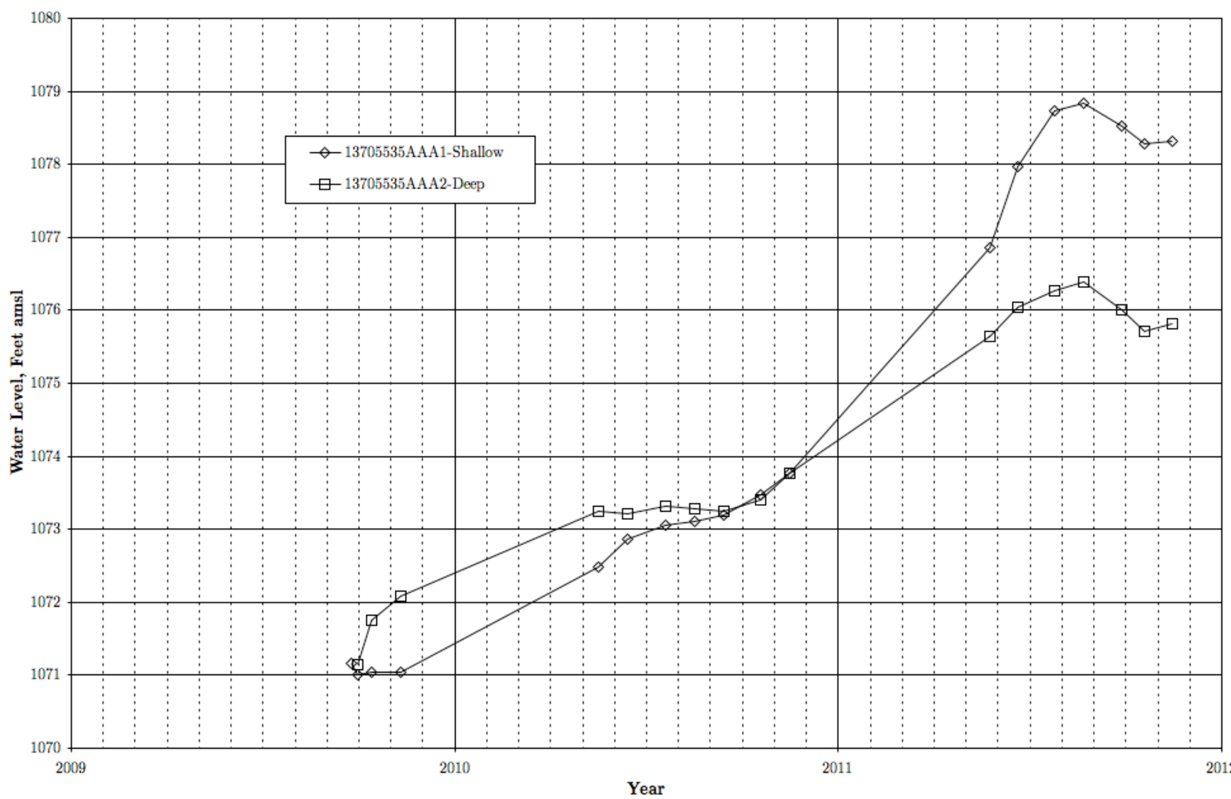

Figure 19. Recorded aquifer water levels from nested observation wells at 13705535AAA.

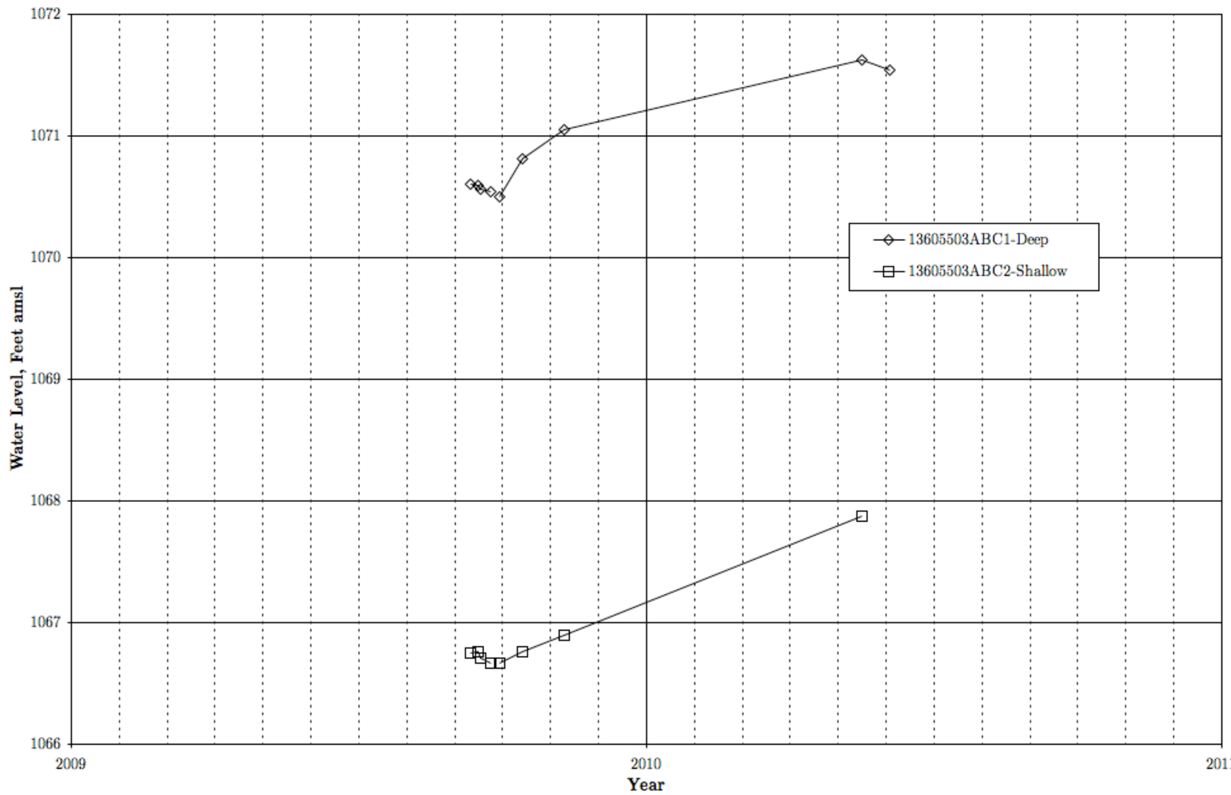

Figure 20. Recorded aquifer water levels from nested plugged observation wells at 13705503ABC.

- **Recorder Wells**

Automated hourly water level recorders were installed in a number of wells from fall 2009 to spring 2010. The recorded aquifer water levels are shown in Figures 21. Equipment problems during the winter months resulted in incomplete water level measurements for all wells except 13605509AAB2. All the wells, with the exception of 13605504AAA2, show a punctuated water level increase that correlates well with the increased stage of the Maple River as recorded at the USGS Maple River gaging station east of Enderlin. This indicates hydraulic connection between the Enderlin Aquifer and the Maple River. Well 13605504AAA2 had a slower more subdued response that lagged by 2 weeks or so.

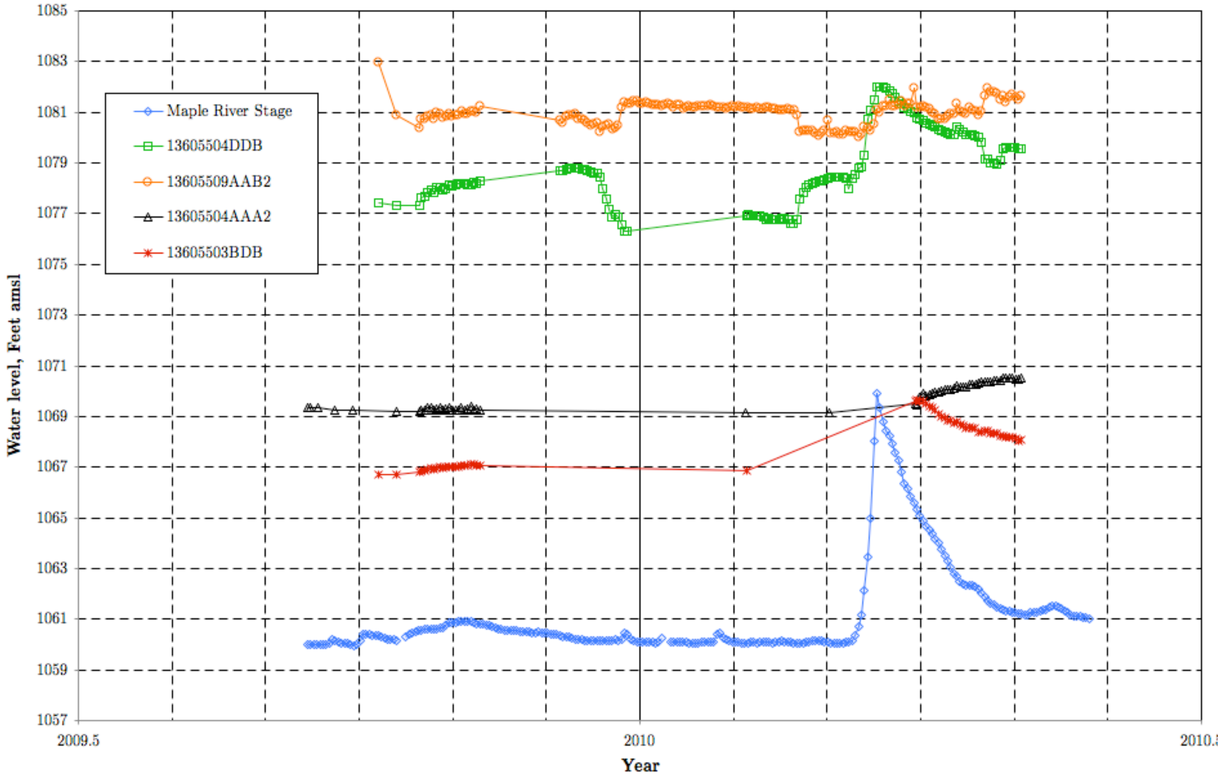

Figure 21. Automated recorded aquifer water levels and Maple River stage from September 2009 to May 2010.

- **Maple River Gaging Station at Enderlin, ND**

The Enderlin Aquifer system is transected by the Maple River, which serves as the major natural discharge area for the aquifer system. The Maple River flows south to southeast into the City of Enderlin where it changes direction, flowing east and then northeast before flowing into the Sheyenne River north of West Fargo, ND. The USGS Maple River gaging station at Enderlin is located just north of the sunflower processing plant, and has a period of record dating back to 1956. A summary of the monthly mean daily minimum flows, median flows, and maximum flows at the USGS Maple River gaging station for the period of record is shown in Figure 22. Monthly minimum flows range from 1 to 2 cfs, while monthly maximum flows have ranged from under 10 cfs in January to approximately 3000 cfs in April. Monthly median flows have ranged from just over 2 cfs in January and February to almost 100 cfs in April.

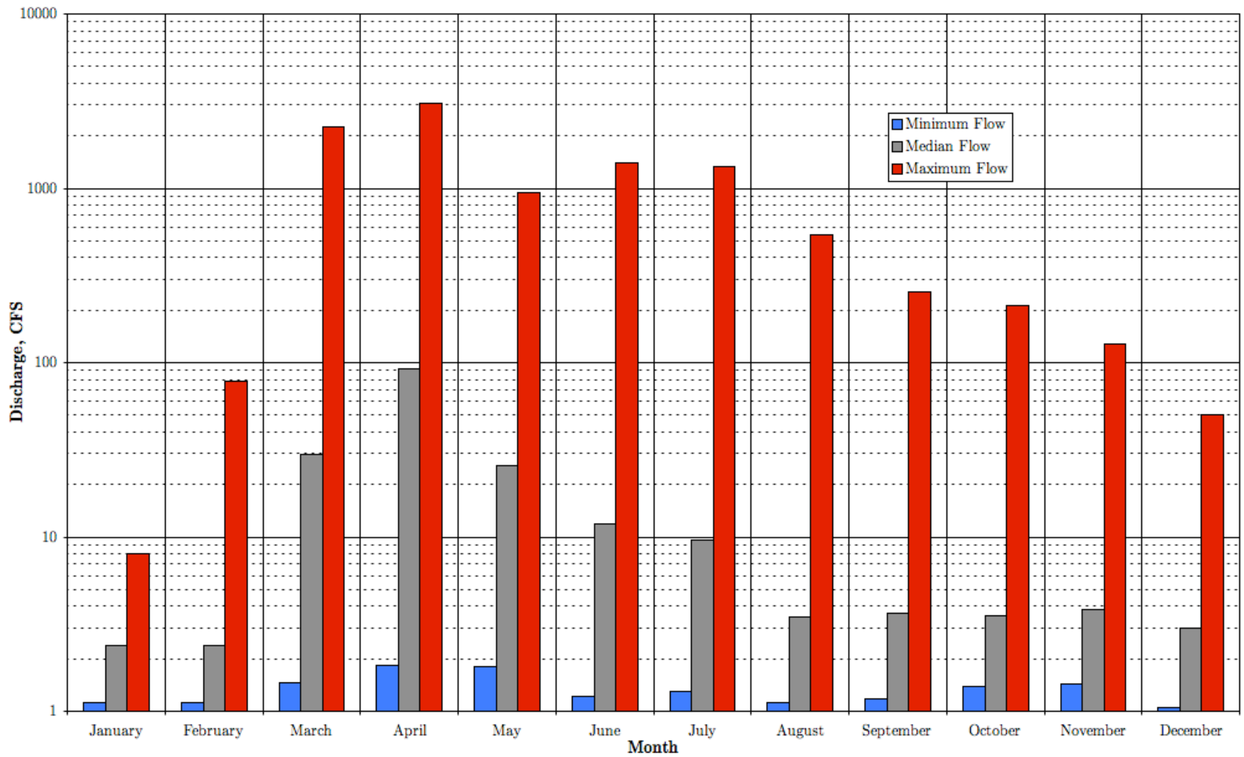

Figure 22. Minimum, median, and maximum flows of daily flows averaged for each month at Maple River gaging station.

- **Maple River-Enderlin Aquifer Hydraulic Connection**

Based on the automated recorded aquifer water levels and the Maple River stage data shown in Figure 21, it appears that the river and aquifer are hydraulically connected, the degree of which can be quantified by use of an analytic model from Barlow and Moench (1998). The analytic model is derived and described in Appendix B. The model considers the changes to a leaky water table aquifer system hydraulically connected to a constant head boundary through a membrane boundary condition.

The analysis will consider water levels from 3/3/2010 to 5/3/2010 during the spring rise in the Maple River. Since aquifer water levels are at elevations beyond the river stage, the water levels will first be expressed relative to the 3/3/2010 water level measurement. These relative water levels will then be divided by the maximum water level (both simulated and measured) such that this normalized relative water level will be less than or equal to 1 and for the most part greater than zero. Relative changes in aquifer water levels caused by the changes in the Maple River will be simulated and compared for calibration purposes. The results from the 4 recorder wells shown in Figure 21 are shown in Figures 23-26. The response of the wells to changes in the Maple River appeared in large part, to be a function of the distance from the river source and the streambed conductance. This is because the aquifer has a high diffusivity facilitating rapid propagation of stresses through the aquifer such that the main controls on transmittance of hydrologic stress would be streambed conductance and distance from stress. The following parameters were used in Figures 23 though 26:

Well	**x_{obs}, feet**	***L*, feet**	***d*, 1/feet**
13605504DDB3	500	5000	6.45E-4
13605509AAB2	500	5000	9.68E-5
13605503DBD	150	10000	3.23E-4
13605504AAA	9500	15000	6.45E-4

Other values for model input were $K_x = K_z = 155$ feet/day, $S_s = 7E\text{-}5$ 1/feet, $b = 38$ feet, S_y'=0.0005, S_s' = 3E-5 1/feet, and b' = 1 foot. These parameters simulated a hydrologic response in a confined aquifer to changes in river stage, because there was a rapid response of aquifer water levels to changes in river stage implying high transmissivity and low storativity (a confined response). Wells 13605504DDB3 and 13605509AAB2 appear to respond to changes in the stage of the nearby South Branch of the Maple River in addition to the Maple River. As expected, well 13605503DBD quickly responded to the changes to the Maple River stage due to its location very near the river. It is interesting to note that well 13605504AAA, although being only a ¼ mile from the river, responded like a well simulated at over 1.75 miles from the river. This suggests the hydraulic connection between the river and aquifer west of the well (in northern Enderlin) is rather indirect, and a more direct connection exists between the aquifer and river to the east of Enderlin.

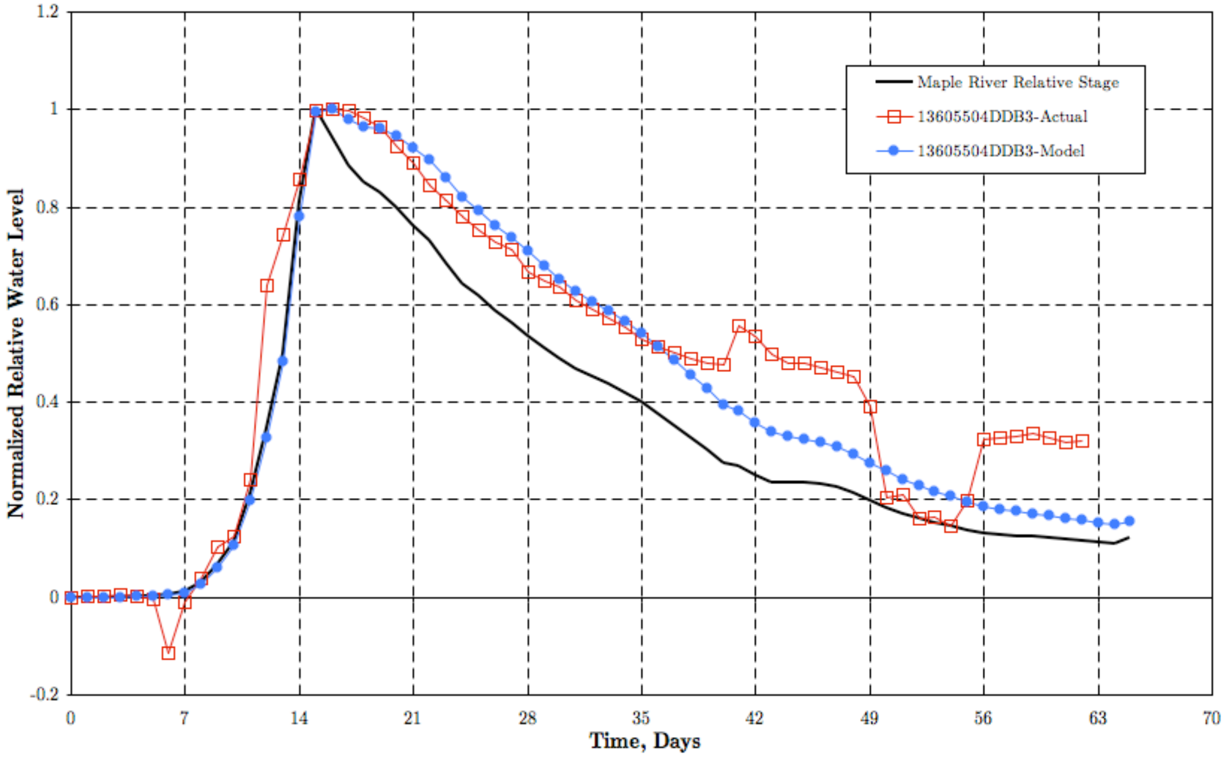

Figure 23. Actual and simulated aquifer normalized relative water levels at well 13605504DDB3.

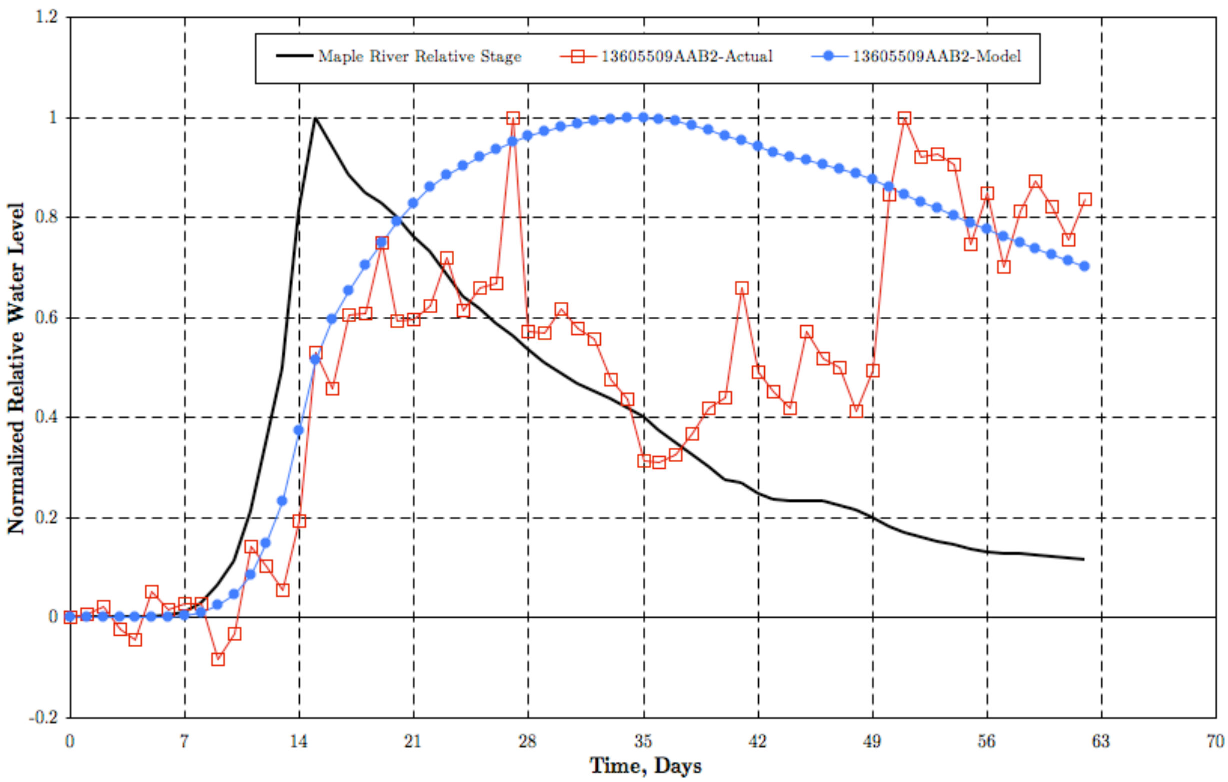

Figure 24. Actual and simulated aquifer normalized relative water levels at well 13605509AAB2.

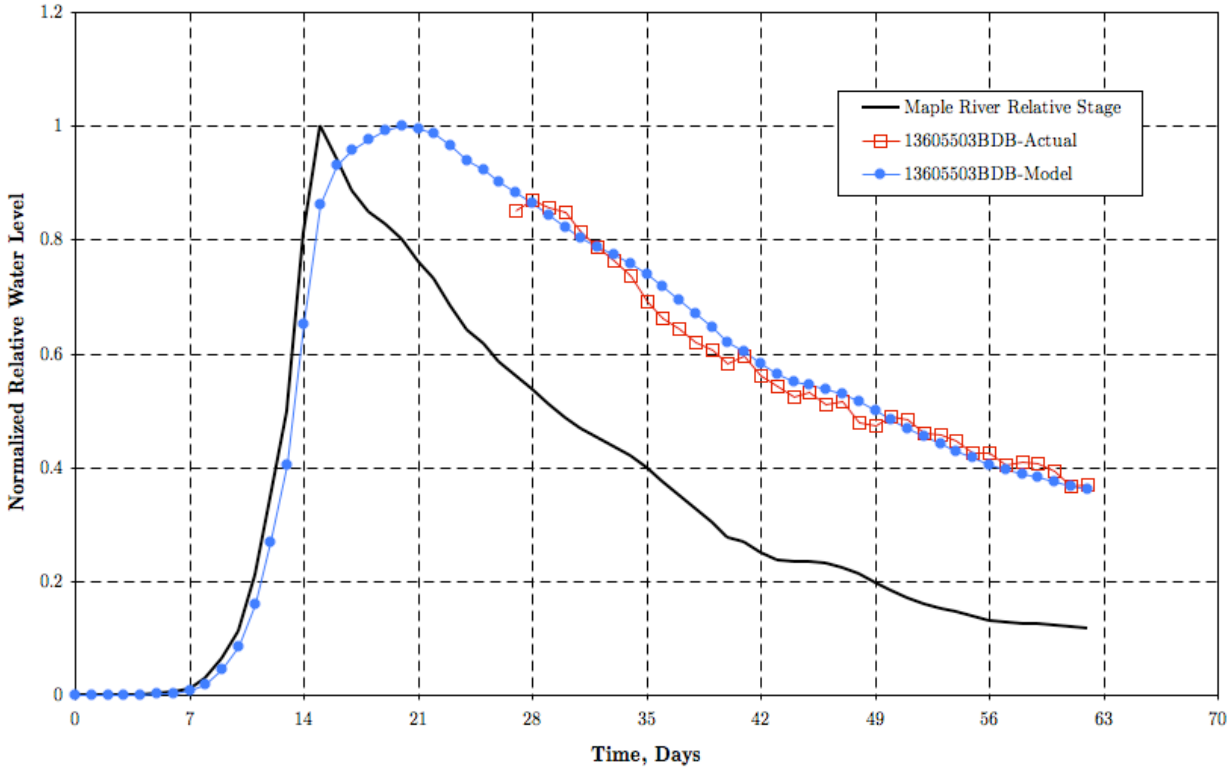

Figure 25. Actual and simulated aquifer normalized relative water levels at well 13605503BDB.

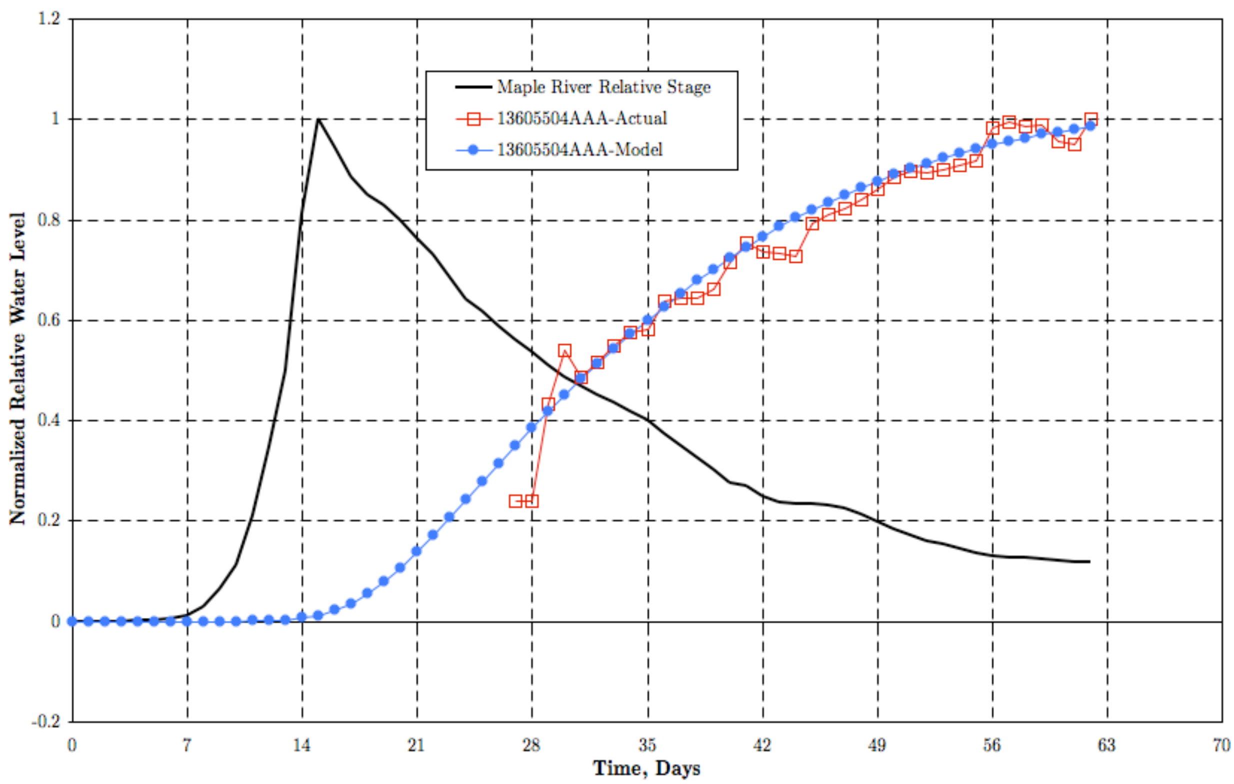

Figure 26. Actual and simulated aquifer normalized relative water levels at well 13605504AAA.

- **Water Quality Sampling**

Historically, wells in the Enderlin Aquifer have been periodically sampled for chemical analysis. Wells installed for this study were also sampled for trace chemical constituents subsequent to installation. A summary of the results is given in Table 1.

Table 1. Summary of water quality analysis on all sampled water in Enderlin Aquifer [SD-sample date, C-conductivity in µmhos, DS-dissolved solids in ppm, H-hardness. Maximum values are shown in red and minimum values are shown in blue].

Location	SD	C	pH	Ca	Mg	K	Na	F	HCO_3	SO_4	Cl	DS	H
13605503AAA2	9/23/09	1620	6.94	222	61.7	10.4	74.3	0.154	441	449	58.2	1000	809
13605503AAD	9/23/09	1440	6.95	172	53.4	10.6	79	0.169	436	397	21	893	650
13605503ABC1	9/23/09	1700	7.09	69.1	22.1	13	272	0.484	350	331	145	1050	264
13605503ABC2	9/23/09	1720	6.81	220	67.3	9.87	92.1	0.155	418	539	51.2	1070	827
13605503BDB	10/7/09	1560	7.49	192	59.3	10	79.2	0.177	436	475	43.5	967	724
13605504AAA2	9/23/09	2150	6.94	288	115	10.2	78.6	0.096	340	878	56.7	1330	1190
13605504ADA	9/24/09	2040	7.55	81.4	39.8	15.6	364	0.138	423	566	93.9	1260	367
13605504DDA1	7/29/98	1460	7.32	180	51	9.5	86	0.2	454	450	34	1040	660
13605504DDA1	10/6/03	1510	7.23	184	53.1	9.2	84.1	0.185	433	474	46.4	1070	679
13605504DDA2	7/29/98	1550	7.37	200	60	8.6	77	0.2	476	510	25	1120	750
13605504DDA2	10/6/03	1520	7.24	200	61.5	8.7	72.5	0.185	452	496	30.2	1090	753
13605504DDB3	10/7/09	1580	7.23	213	69.5	9.28	68.2	0.184	424	507	42	980	818
13605509AAA2	10/28/09	1620	7.48	254	69.4	10.2	67.5	0.198	493	534	20.2	1000	921
13605509AAB	12/5/79	1400	7.6	190	65	7.5	55	0.2	432	440	24	1030	740
13605509AAB	6/9/99	1490	7.96	210	61	7.7	59	0.2	477	480	33	1090	780
13605509AAB	8/23/04	1490	7.73	196	57.9	8.6	58.3	0.202	457	480	28.8	1060	728
13605509AAB2	10/7/09	1490	7.45	216	56.7	11.4	52.2	0.18	433	452	32.5	924	773
13605509AAC	5/30/90	1490	7.35	200	60	9.6	55	0.2	459	480	31	1090	750
13605509ABB	10/7/09	1700	7.38	243	82.8	9.25	68.6	0.137	424	603	36.4	1050	948
13605510ABAB	12/6/79	1370	7.7	200	63	7.9	38	0.2	514	420	10	1020	760
13605510CCC	10/27/09	2060	7.09	255	86.4	13.2	88.6	0.149	535	773	14.8	1280	993
13605511BCC2	12/6/79	1610	7.4	240	68	8.7	50	0.2	376	630	29	1240	
13605512BBB	7/1/76	991	7.4	130	45	6.2	22	0.1	420	210	4.9	661	510
13705535AAA1	9/23/09	2120	7.34	297	89.6	11.4	91.3	0.24	480	807	47.1	1310	1110
13705535AAA2	9/23/09	3660	7.71	29.4	14.2	21.5	760	2.59	642	376	627	2270	
13705535ADD	12/19/79	1300	7.6	160	37	11	93	0.2	436	360	20	924	
13705535ADD	5/30/90	1190	7.13	150	48	13	56	0.1	428	320	15	834	570
13705535ADD2	9/23/09	1600	7.04	209	54.1	13.3	81.2	0.132	516	428	25.8	992	745
13705535CDC	12/18/79	1750	8	260	78	8.6	56	0.2	509	660	13	1360	970
13705535CDC	5/29/90	1590	7.46	230	65	11	51	0.1	442	600	17	1220	840
13705535CDC	7/13/98	1690	7.69	250	77	9.3	51	0.1	488	580	47	1260	940
13705535CDC	10/6/03	1300	7.69	128	65	8.3	48.6	0.053	260	460	55.3	896	587
13705535CDC2	9/23/09	2000	6.88	279	83.8	9.64	76.1	0.163	548	651	57.2	1240	1040
13705535DCD	12/5/79	1300	7.6	160	54	7.5	69	0.2	312	430	42	948	620
13705535DDD	8/16/64	1440	7.9	112	110	8.7	66	0.4	362	473	46	1020	700
13705535DDD2	10/7/09	1680	7.21	211	69.6	9.47	72.1	0.131	502	472	60.7	1040	814
13705536BAB	12/19/79	4630	7.6	450	210	38	420	0.1	528	2000	370	3780	2000
13705536BBC	12/20/79	1710	7.4	270	79	7.8	40	0.1	551	610	11	1320	1000
13705536CCB	12/19/79	1850	7.5	260	76	8.6	57	0.1	505	490	140	1310	960

- **Geochemical Characterization**

The concentrations of dissolved minerals in the Enderlin area groundwater, as presented in Table 1, is in large part determined by the geologic materials through which percolating waters must pass. Lithologies in glacial settings are highly variable including silicates and carbonates transported from the Canadian Shield by glaciers, along with detrital shale and lignites from the underlying bedrock surfaces in North Dakota, which were reworked and assimilated into the drift. The solution of ions into groundwater in North Dakota may be largely attributed to the following mechanisms and reactions (e.g. Moran et al., 1978):

1) Infiltration of water through the organic-rich soil horizon, where water reacts with carbon dioxide:

$$H_2O + CO_2 \rightarrow H^+ + HCO_3^- \qquad (1)$$

The acidity and bicarbonate concentration is increased.

2) Oxidation of pyrite in mineral rich soil horizon by dissolved oxygen in the infiltrating water:

$$4FeS_2 + 15O_2 + 14H_2O \rightarrow 4Fe(OH)_3 + 16H^+ + 8SO_4^{2-} \qquad (2)$$

The acidity and sulfate concentration is increased.

3) Dissolution of calcite or dolomite (resulting in increased calcium, magnesium, and bicarbonate) and gypsum (resulting in increase sulfate and calcium) in mineral rich soil horizon

$$\begin{aligned} &CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^- \\ &CaMg(CO_3)_2 + 2H^+ \rightarrow Ca^{2+} + Mg^{2+} + 2HCO_3^- \qquad (3a,b,c) \\ &CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \end{aligned}$$

The calcium, magnesium, bicarbonate, and sulfate concentrations are increased, and the acidity is decreased.

4) Cation exchange of Ca^{2+} and Na^+ in montmorillonitic clays, which will decrease the calcium concentration and increase the sodium concentration.

Mechanisms 1 through 3 occur as water moves through the soil horizon, and mechanism 4 can be attributed to water that has moved or is moving through an aquitard. Therefore as water percolates from land surface through the unsaturated zone to the water table it will increase in calcium, magnesium, bicarbonate, and sulfate. This is illustrated in Figures 27 and 28 showing the relationships between major cations and anions with increasing concentrations of dissolved solids. Figure 28 shows that bicarbonate concentrations increase no more than approximately 1000 ppm at which point it is presumed that water is saturated with respect to calcite or dolomite. However increases in calcium and magnesium beyond 1000 ppm (or about 10 epm) suggest the continued dissolution of gypsum as evident by the increase in sulfate. The two water samples from the deeply buried units of sand and gravel are very evident in Figure 27 due to the increased sodium as a result of what is probably cation exchange associated with groundwater movement through the overlying clay layers.

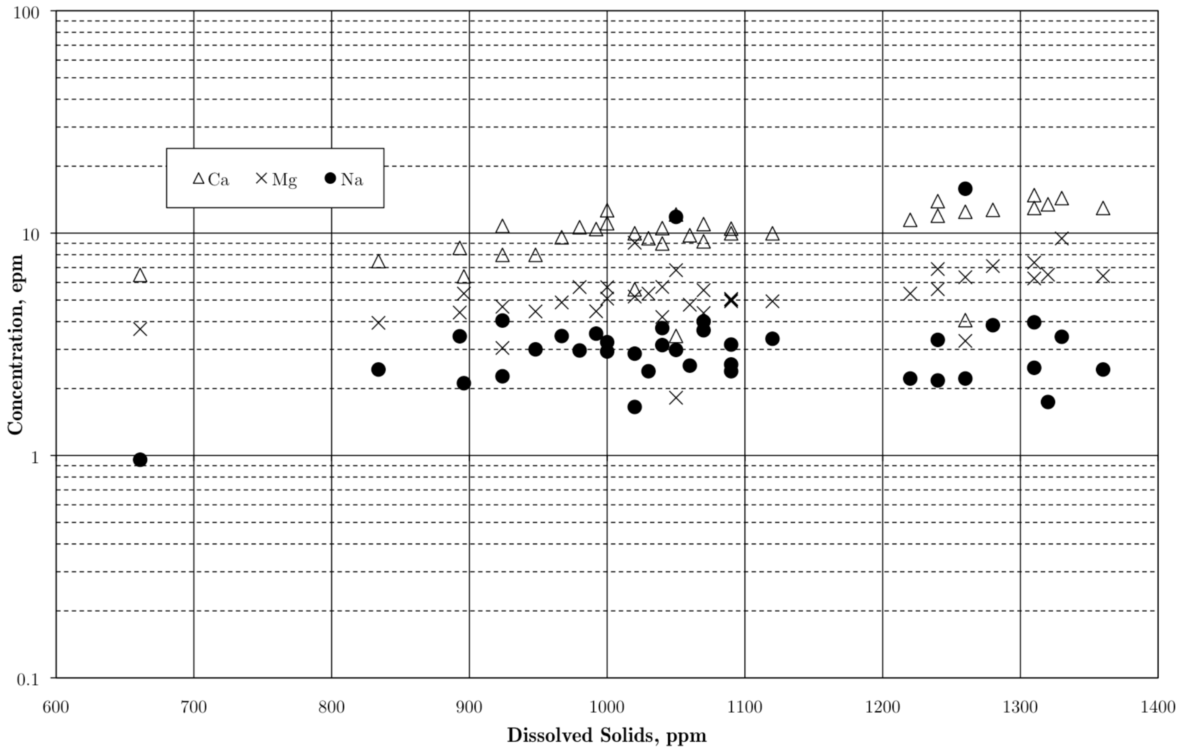

Figure 27. Distribution of major cations with respect to dissolved solids.

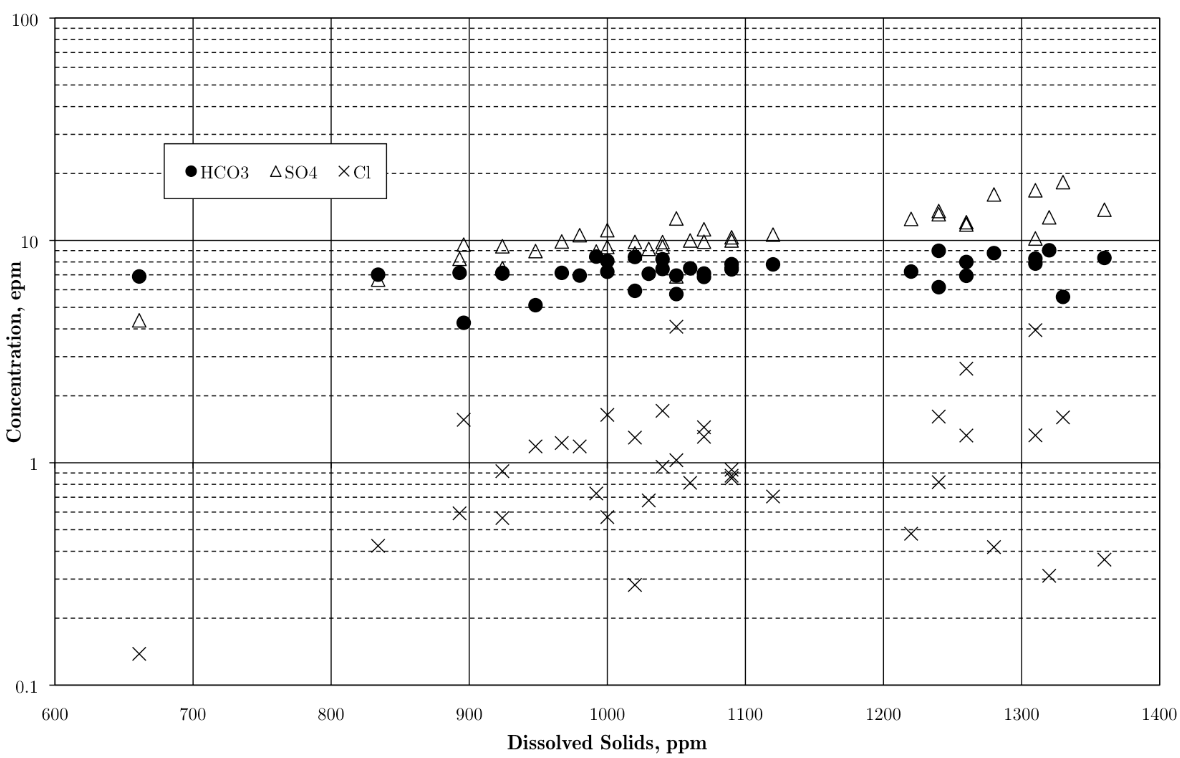

Figure 28. Distribution of major anions with respect to dissolved solids.

A Piper diagram showing the relative distribution of major ions in the Enderlin Aquifer is presented in Figure 29 illustrating that water in the Enderlin Aquifer is calcium-sulfate type. The two outlying samples that are dominant in sodium, as opposed to calcium, are from lower units of sand and gravel which immediately overly the Carlile shale. Water in these units likely migrated through the adjacent clay layers where cation exchange likely increased the sodium concentration.

Figure 30 is a contour map showing the areal distribution of the concentrations of dissolved solids (in ppm) for wells sampled in the Enderlin Aquifer. The depth of the screened interval is represented in Figure 30 by the size of the location marker, however the sample depth appears to be independent of the dissolved solids. There is a correlation between the distance of the sampled well from the Maple River and dissolved solids. Water near the Maple River had less dissolved solids than water sampled with greater distance. During the spring rise in the Maple River, when water levels in the river are greater than in the aquifer, water from the Maple River will move into the aquifer thereby freshening the aquifer.

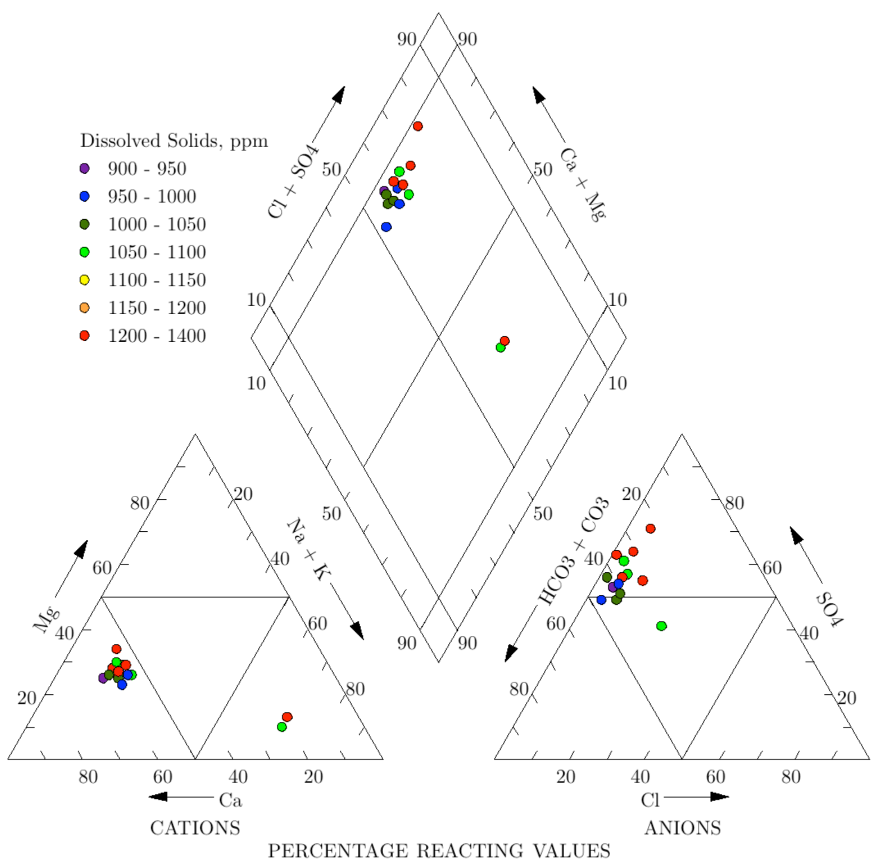

Figure 29. Piper Diagram showing the relative distribution of major ions in the Enderlin Aquifer (samples from 2009).

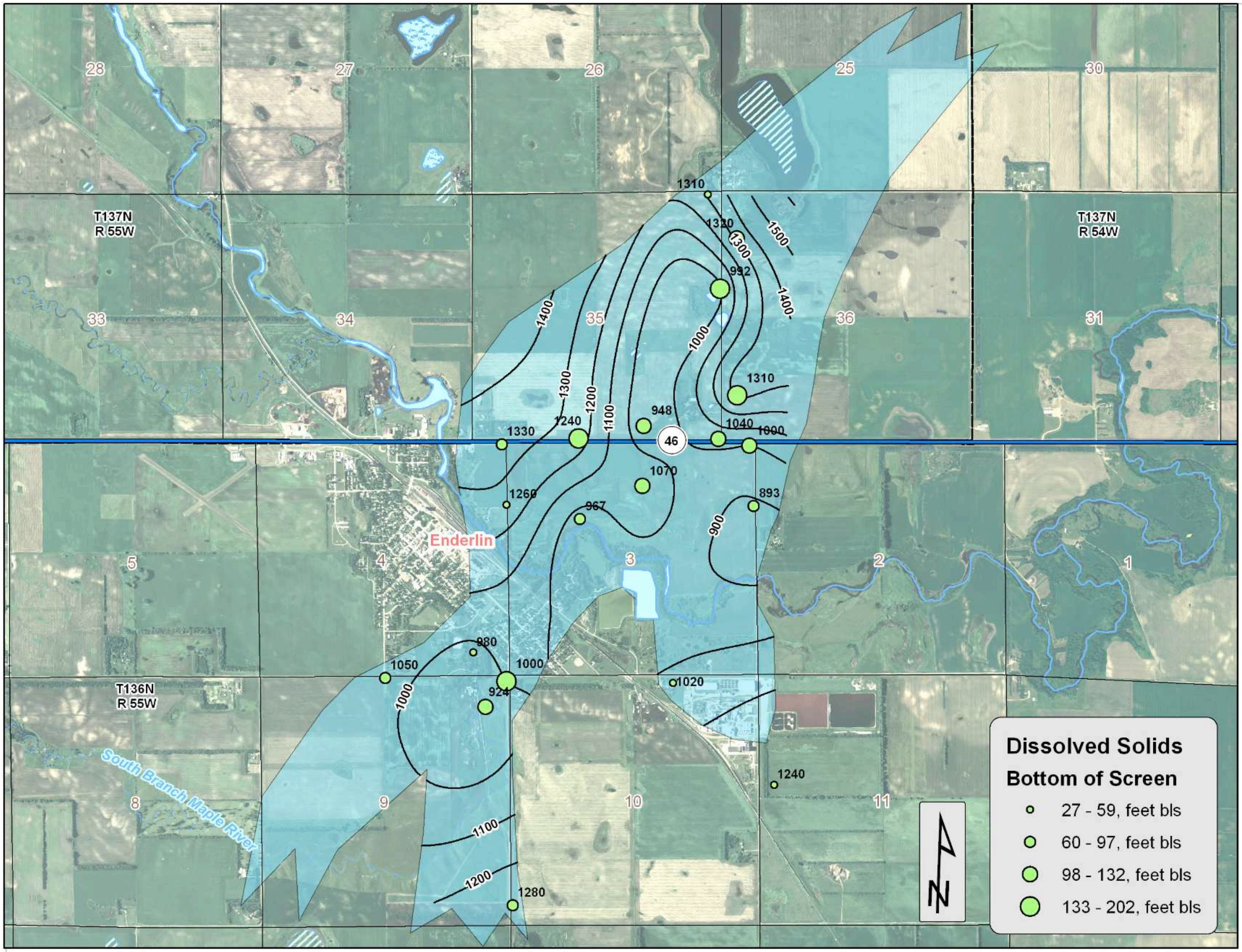

Figure 30. Contour map showing the areal distribution of dissolved solids (in ppm) of observation wells completed in Enderlin Aquifer.

Water Budget and Selection of Municipal Well Site

As previously described, aquifer water levels in the Enderlin Aquifer system respond to changes in recharge and discharge. When the natural recharge to the aquifer system is equal to the natural discharge from the aquifer system, the water levels in the aquifer system remain invariant. Therefore the following can be written:

$$\text{RECHARGE} - \text{DISCHARGE} = 0 \qquad (4)$$

Based upon the hydrogeologic characterization of dominant recharge and discharge mechanisms the above equation can be written as (Figure 31a):

$$Q_{INF}(t) - \left[Q_{ET}(t) + Q_{RIV}(t)\right] = 0 \qquad (5)$$

where Q_{INF} is the amount of water entering the Enderlin Aquifer through infiltration of precipitation or snowmelt, Q_{ET} is the volume of water leaving the system by evaporation and transpiration, and Q_{RIV} is the amount of water discharging from the aquifer to the river. As indicated above all of these rates are functions of time. Disequilibrium between recharge and discharge cause changes in the amount of water stored in the aquifer. This is manifested as either increases in aquifer water levels (increases in storage with respect to time) or decreases in aquifer water levels (decreases in storage with respect to time), or:

$$Q_{INF}(t) - \left[Q_{ET}(t) + Q_{RIV}(t)\right] + \Delta Q_{INF}(t) + \Delta Q_{ET}(t) + \Delta Q_{RIV}(t) = S\frac{\partial h}{\partial t} \qquad (6)$$

where h is the aquifer water level and S is the storage coefficient indicating the amount of water released for a unit change in aquifer water level, and the Δ denotes the changes in recharge or discharge for the respective mechanism. Combining (5) and (6) the following can be written:

$$\Delta Q_{INF}(t) + \Delta Q_{ET}(t) + \Delta Q_{RIV}(t) = S\frac{\partial h}{\partial t} \qquad (7)$$

Eqn. (7) illustrates that the natural changes in observed aquifer water levels are independent of the background average recharge or discharge and dependent only upon the changes that can occur to these mechanisms with respect to time. Natural disequilibrium occurs for example during the spring when aquifer water levels rise from increased infiltration from snowmelt and also increases in river stage resulting in water moving from the river to the aquifer. Aquifer water levels typically decline during summer months as lower river levels cause increased aquifer discharge to the river, and warmer temperatures and more plant growth result in increased evapotranspiration in areas where the aquifer water level is close to land surface. However, averaged out over decades of time, these seasonal fluctuations result in little or no long-term change in aquifer water levels indicating an equilibrium state in which recharge is equal to discharge (Eqn. 5).

The addition of wells to an aquifer system results in an additional discharge mechanism. Immediately after the initiation of pumping, Eqn. (5) will be modified as:

$$Q_{INF}(t) - \left[Q_{ET}(t) + Q_{RIV}(t)\right] - Q_{WELL}(t) = S\frac{\partial h}{\partial t} \tag{8}$$

Based upon Eqn. (5), Eqn. (8) can be simplified as follows:

$$-Q_{WELL}(t) = S\frac{\partial h}{\partial t} \tag{9}$$

Eqn. (9) shows that initially all water pumped from the aquifer using wells will result in the removal of water from storage. If the natural recharge and discharge to the aquifer remains constant, the pumped water will continually be derived from aquifer storage resulting in water level declines indefinitely. However, this is not typically the case and the addition of wells result in less discharge by natural mechanisms (Figure 31b). Therefore, by combining (7) and (9) after a period of time in which water is no long being removed from aquifer storage the following can be written:

$$\Delta Q_{INF}(t) + \Delta Q_{ET}(t) + \Delta Q_{RIV}(t) = -Q_{WELL}(t) \tag{10}$$

Assuming that there are no discernable changes to the infiltration into the system, Eqn. (10) can be simplified as (Figure 31c):

$$\Delta Q_{ET}(t) + \Delta Q_{RIV}(t) = -Q_{WELL}(t) \tag{11}$$

It can be surmised that during the initial stages of pumping, the aquifer system will respond as shown in (9) where water is taken solely from aquifer storage resulting in aquifer water level declines. However with continued pumping the reduction in aquifer water levels will propagate away from the pumping well (cone of depression) resulting in less water being discharged by evapotranspiration (due to the decline in water levels further below land surface) and less water discharging to the river (due to the changed relative water level in the aquifer and river). This is shown in Eqn. (11). Additionally, if the amount of pumping exceeds what was naturally discharging to the river in the cone of depression, then water will begin to recharge the aquifer from the river to offset the discharge caused by pumping.

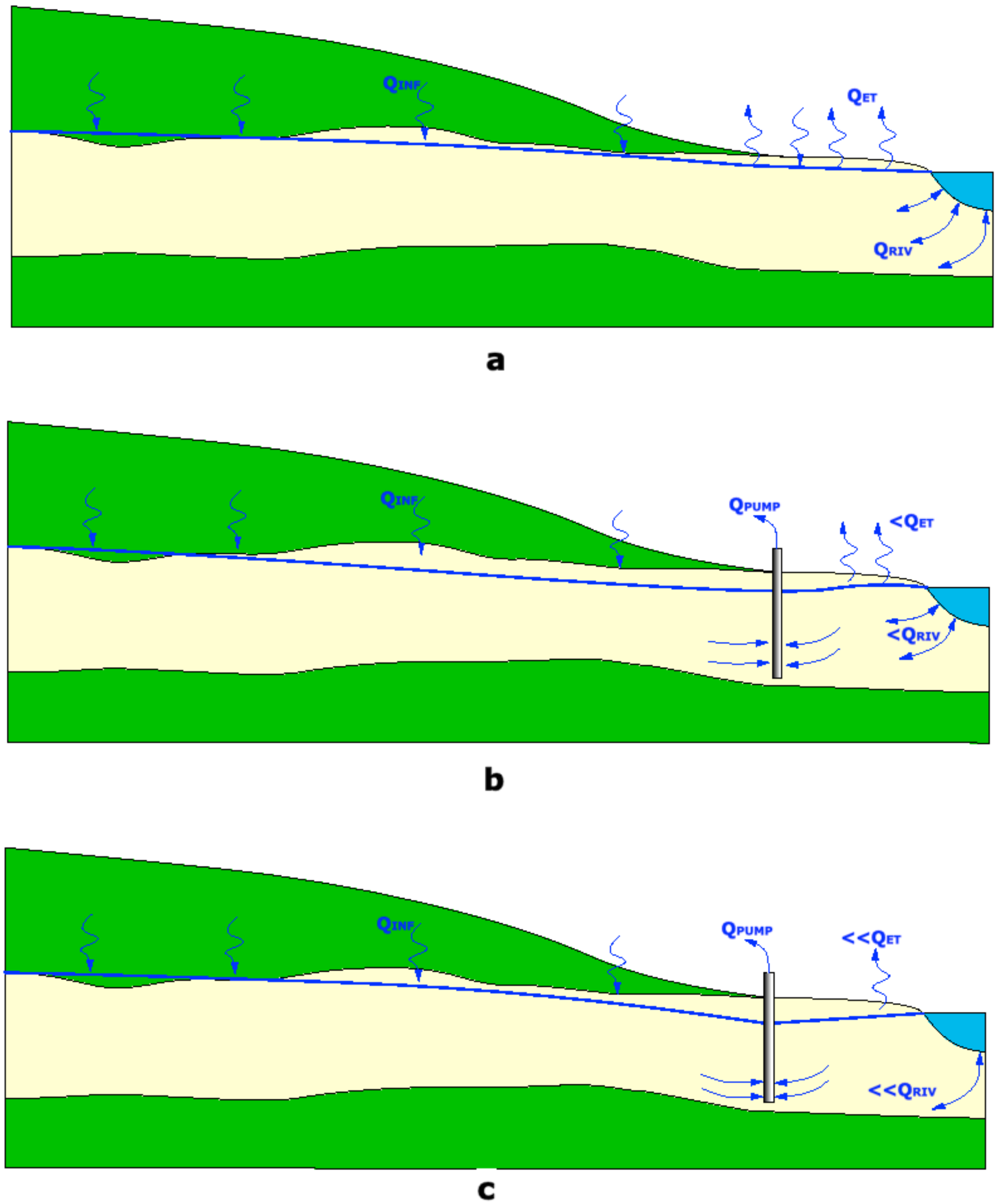

Figure 31. a) Natural equilibrium conditions in Enderlin Aquifer, b) Developmental decline in Enderlin Aquifer, and c) New equilibrium in Enderlin Aquifer.

A better understanding of the placement of wells with respect to the discharge area of a well can be understood by considering the following simple example (Figure 32). Consider an aquifer discharging to a constant head boundary (a lake or river for example). To investigate the developmental decline associated with the pumping well, consider a well pumping at a constant rate some distance from the constant head boundary. The zone of influence can be depicted using hydraulic head due to pumping and also in terms of the stream function, which describes the path lines that groundwater follows as a result of groundwater pumping. The mathematical development of the functions describing flow for the system in Figure 32 is described in Appendix C and are presented as follows:

$$h_D(x_D, y_D) = -\frac{Q_D}{2}\ln\left(\frac{(x_D+1)^2 + y_D^2}{(x_D-1)^2 + y_D^2}\right) + x_D + h_{DO} \quad (12)$$

$$\psi_D(x_D, y_D) = y_D + Q_D\left[\tan^{-1}\left(\frac{y_D}{x_D+1}\right) - \tan^{-1}\left(\frac{y_D}{x_D-1}\right)\right] \quad (13)$$

with $h_D = \frac{h}{id}$, $x_D = \frac{x}{d}$, $y_D = \frac{y}{d}$, $h_{DO} = \frac{h_O}{id}$, $Q_D = \frac{Q}{2\pi d q_O}$. The problem presented in Figure 32 is an elementary problem that can be found in many hydrogeology or well hydraulics textbooks (e.g. Strack, 1989). Eqn. (12) and (13) show that the changes in the head and streamlines are solely based on the parameter Q_D, which shows the inverse relationship between pumping rate and distance of well from the constant head boundary. The hyperbolic (i.e. inverse) relationship between pumping rate and well distance shows that great well distances from the constant head boundary will significantly decrease pumping rates at a given Q_D and conversely very small well distances can greatly increase well yield while having the same Q_D. Figure 33 shows the head and stream fields for Q_D = ¼, ½, and 1 showing how increases in Q_D cause increases in the zone of influence on aquifer. It also shows the effect on the stream, showing only reduced discharge to stream at Q_D = ¼, no discharge to stream at Q_D = ½, and, recharge to the aquifer at Q_D = 1. The conclusion from this exercise relevant to the City of Enderlin is that the most efficient well system in mitigating developmental decline to the Enderlin Aquifer is to minimize Q_D, which can most easily be done my limiting the distance of wells from the Maple River.

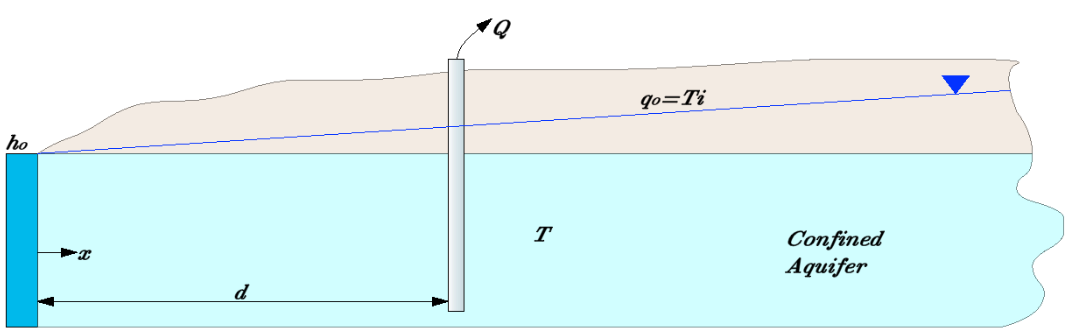

Figure 32. Well pumping from nearby constant head source in presence of sloping water table.

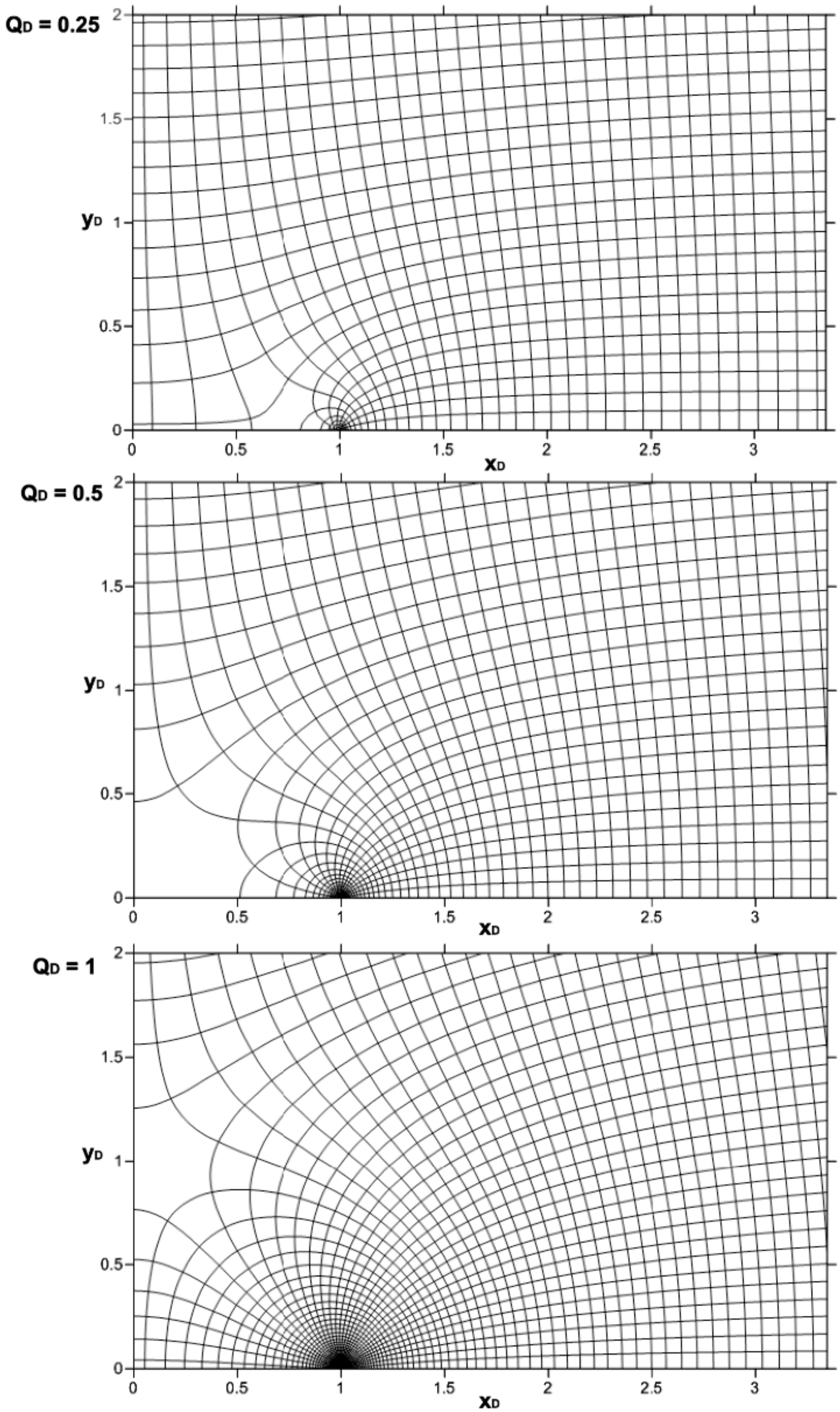

Figure 33. Head and stream field (flow lines) for various Q_D values showing increased zone of influence.

From the discussion of the water budget, the effects of aquifer development on the water budget, and the discussion of well location in relation to aquifer discharge areas, the optimal places for the City of Enderlin to site wells can be discussed. Since Eqn. (11) is an inevitability of aquifer development, mitigating these effects on the aquifer system must be paramount. Placement of wells near the Maple River would result in the least amount of changes in aquifer storage from development. The City of Enderlin had also indicated that a future water supply system should be located in an area that would mitigate potential contamination from spills that may occur at the railroad yard on the east side of town. Given this constraint, the best alternative to the current location of the city's wells would be in the riparian areas of Section 3 to the east and north of the river (Figure 34). Furthermore, test hole drilling and water quality sampling in the area outlined in Figure 34 has suggested ample saturated thicknesses of coarse aquifer material and good quality of water. This would suggest the aquifer area outlined in Figure 34 has high transmissivity values, which would be capable of high individual well yields. The nearby location of the river would also assuage excessive drawdown, and foster capture of higher quality water.

It should be noted that the existing Enderlin city wells are in excellent locations. These well locations are within the riparian area of the South Branch of the Maple River allowing for well discharge to be readily offset by reduction in evapotranspiration and discharge to the Maple River. The railroad yard, where the city had expressed concerns over chemical spills, is downgradient from the wells and likely outside the capture area of the existing municipal wells.

Other locations beyond the current well field and the suggested alternative well field location north of the Maple River would have to be either north or south of the Maple River Valley. These locations are less desirable most notably because of the increased distance from the natural discharge area of the Enderlin Aquifer. As a result an increased volume of water would have to be permanently removed from storage in order create a large enough gradient to capture natural discharge to evapotranspiration and to the Maple River (Eqns. 9 and 11, and Figure 31).

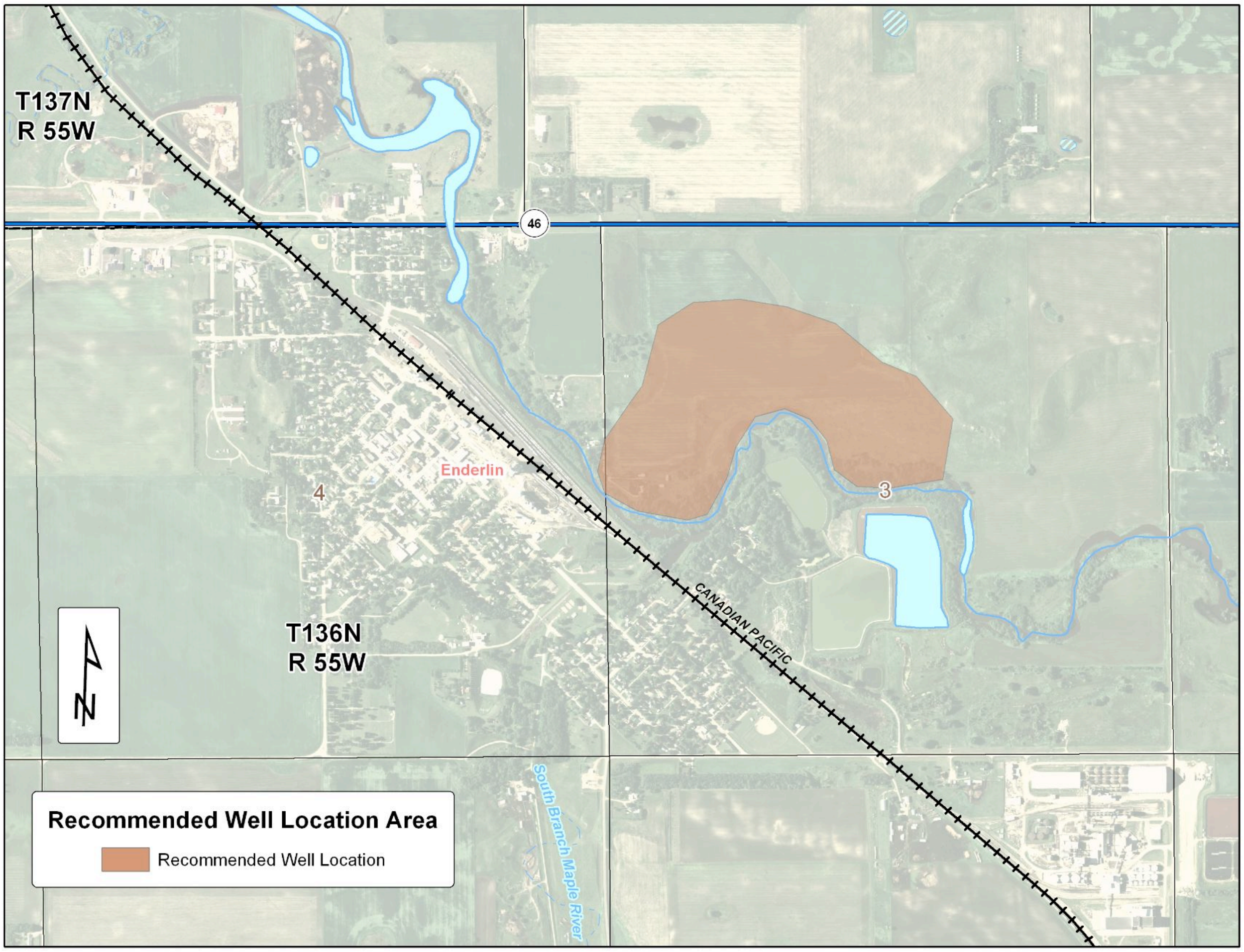

Figure 34. Recommended location of alternative well sites for the City of Enderlin.

Summary, Conclusions, and Recommendations

The hydrogeologic setting of the Enderlin Aquifer system was discussed including the geologic origin, geometry, direction of groundwater flow, recharge and discharge mechanisms, hydraulic connection with the Maple River, aquifer properties derived from pumping tests on Enderlin municipal wells, presentation of water quality, discussion of water budget, and effects of well locations on the Enderlin Aquifer system. The discussion of the hydrogeologic setting indicates the Enderlin Aquifer system is an aquifer of glaciofluvial origin composed of a highly variable complex of fluvial material ranging from clay to gravel. The flow of groundwater is towards the Maple River, from areas of recharge to discharge. The Enderlin Aquifer is recharged from infiltration of precipitation, and at times from the Maple River during periods of rapid increases in river stage. Discharge from the aquifer is to the Maple River, to evapotranspiration, and to wells. Analysis of aquifer and river levels during the spring of 2010 indicated that the aquifer is hydraulically connected to the Maple River. The greatest degree of hydraulic connection is along the reach of the river that runs west to east including and downstream from the City of Enderlin. A rather indirect hydraulic connection was indicated by wells completed near the river just south of the highway on the north side of the City of Enderlin. Investigation of the drawdown response of the municipal wells to pumping showed the Enderlin Aquifer responds to pumping as an aquifer overlain by a water table aquitard. The overlying fine-grained sediment and silty layers are major constraints affecting the aquifer drawdown response. Water levels in the aquifer suggest the aquifer is in equilibrium with the discharge from the municipal wells. Analysis of water quality indicates the water is a calcium sulfate type suggesting dissolution of calcite and gypsum in the soil horizon and only minor cation exchange with underlying clay as suggested by the relatively low sodium levels. Based on the water budget analysis, it is concluded that the best alternative or supplement to the current municipal well field is to install wells on the north side of the river just north and east of the City of Enderlin. Other locations would increase the distance from the Maple River resulting in increased declines to aquifer storage in response to pumping. The aquifer properties in this area would also allow for large individual wells yields and wells would capture good quality water from the nearby Maple River. Existing municipal wells for the City of Enderlin are up gradient from the railyard and near the Maple River suggesting that the current well locations are in an excellent area for continued sustained use from the aquifer and freshening from Maple River. Should the current well field become compromised by contamination, the best alternative for new municipal wells is along the north side of the river in the riparian areas north and east of the City of Enderlin in Section 3 of T136N R055W.

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Appendix A: Response of Aquifer Underlying Water Table Aquitard to Pumping

- **Mathematical Model**

The problem under consideration is illustrated in Figure 14 of the main report. Expressing the problem in terms of drawdown, i.e. $h_D = h_o - h(r,z,t)$,where h_o is the ambient water level in the aquifer, we arrive at:

$$\frac{\partial^2 h_D(r,0,t)}{\partial r^2} + \frac{1}{r}\frac{\partial h_D(r,0,t)}{\partial r} + \frac{v_z}{bK_r} = \frac{S_s}{K_r}\frac{\partial h_D(r,0,t)}{\partial t} \tag{A.1}$$

$$\frac{\partial^2 h_D(r,z,t)}{\partial z^2} = \frac{S_s'}{K_z'}\frac{\partial h_D(r,z,t)}{\partial t} \tag{A.2}$$

where r is the radial distance from the well, and z is the vertical distance above the aquitard/aquifer interface, and K_r , S_s and K_z', S_s' are the respective hydraulic conductivity and specific storage of the aquifer and aquitard, and v_z is the leakance velocity. Eqn (A.1) is the unsteady groundwater flow equation for radial flow in a leaky aquifer in a homogeneous aquifer, and (A.2) is the unsteady groundwater flow equation for movement of water in the aquitard assuming groundwater movement is only in the vertical or z-direction. The boundary conditions are:

$$\lim_{r \to 0} \frac{\partial h_D(r,0,t)}{\partial r} = \frac{-Q}{2\pi K_r b} \tag{A.3}$$

$$h_D(\infty,0,t) = 0 \tag{A.4}$$

$$h_D(r,0,t) = h_D(r,z,t)\Big|_{z=0} \tag{A.5}$$

$$\frac{\partial h_D(r,b',t)}{\partial z} = -\frac{S_y'}{K_z'}\frac{\partial h_D(r,b',t)}{\partial t} \tag{A.6}$$

$$v_z = K_z' \frac{\partial h_D(r,z,t)}{\partial z}\Bigg|_{z=0} \tag{A.7}$$

where S_y' is the aquitard specific yield, b is the aquifer thickness, and b' is the aquitard thickness. Eqn. (A.3) is a specified flux boundary at the origin that assumes a fully penetrating well and negligible wellbore storage, (A.4) assumes no drawdown at infinity, (A.5) is a continuity condition at boundary of the aquifer and aquitard, (A.6) describes the assumed instantaneous drainage at the water table, and (A.7) assumes that leakage from the aquitard to the aquifer is Darcy-type flow. The appropriate initial condition is given as

$$h_D(r,z,0) = 0 \tag{A.8}$$

In order to solve the above problem we apply the Laplace transform to the time variable, which will transform the problem into a quasi two-dimensional problem independent of the time variable. Eqn. (A.1)-(A.7) become

$$\frac{\partial^2 \eta_D(r,0,s)}{\partial r^2} + \frac{1}{r}\frac{\partial \eta_D(r,0,s)}{\partial r} + \frac{v_z(r,0,s)}{bK_r} = \frac{s}{c_r}\eta_D(r,0,s) \tag{A.9}$$

$$\frac{\partial^2 \eta_D(r,z,s)}{\partial z^2} - \frac{s}{c_z}\eta_D(r,z,s) = 0 \tag{A.10}$$

$$\lim_{r\to 0}\frac{\partial \eta_D(r,0,s)}{\partial r} = \frac{-Q}{2\pi K_r bs} \tag{A.11}$$

$$\eta_D(\infty,0,s) = 0 \tag{A.12}$$

$$\eta_D(r,0,s) = \eta_D(r,z,s)\Big|_{z=0} \tag{A.13}$$

$$\frac{\partial \eta_D(r,b',s)}{\partial z} = -\frac{s}{c_y}\eta_D(r,b',s) \tag{A.14}$$

$$v_z(r,0,s) = K_z \frac{\partial \eta_D(r,z,s)}{\partial z}\Bigg|_{z=0} \tag{A.15}$$

where $\eta_D(r,z,s)$ is the Laplace transform function of the function $h_D(r,z,t)$, $c_r = K_r/S_s$, $c_z = K_z'/S_s'$, $c_y = K_z'/S_y'$, and s is the Laplace transform parameter. Note use of the Laplace transform incorporates (A.8) into the transformed problem. The quasi two-dimensional nature of the problem allows for the aquitard problem to be solved first. The result is then substituted into (A.9) to solve for the aquifer problem.

- **Solution**

The solution to (A.10) subject to (A.13) and (A.14) is

$$\eta_D(r,z,s) = \eta_D(r,0,s)\left[(1+\gamma)\exp\left(-z\sqrt{\frac{s}{c_z}}\right) - \gamma\exp\left(z\sqrt{\frac{s}{c_z}}\right)\right] \tag{A.16}$$

with $\gamma = \frac{A}{A+B}$ and $A = \sqrt{\frac{c_y}{c_z}} + \sqrt{\frac{s}{c_y}}$, $B = \left(\sqrt{\frac{c_y}{c_z}} - \sqrt{\frac{s}{c_y}}\right)\exp\left(-2b'\sqrt{\frac{s}{c_z}}\right)$. Substituting (A.16) into (A.15), using the result in (A.9), and applying (A.11) and (A.12) gives the final solution as:

$$\eta_D(\xi,z,s) = \left(\frac{Q}{2\pi K_r b}\right)\frac{K_0(\xi)}{s}\left[(1+\gamma)\exp\left(-z\sqrt{\frac{s}{c_z}}\right) - \gamma\exp\left(z\sqrt{\frac{s}{c_z}}\right)\right] \tag{A.17}$$

where K_0 is the zero order modified Bessel Function of the second kind and $\xi^2 = r^2 \frac{s}{c_r}\left[1-(1-2\gamma)\frac{\sqrt{K'_z S'_s}}{\sqrt{sbS_s}}\right]$. A computer program is applied to evaluate (A.17). The Bessel function is evaluated using polynomial approximations given in Abramowitz and Stegun (1972) and numerical inversion from the Laplace domain to the time domain is accomplished by use of the Stehfast inversion (Stehfast, 1970).

- **Long-Term Solution**

The behavior of the long-term solution can be examined by allowing s to approach 0 in (A.17). As s approaches zero γ will approach ½ and the exponential terms become 1. Therefore, the bracketed function on the right-hand side of (A.17) becomes 1. The bracketed term in ξ also becomes 1. The final result is the Theis solution in the Laplace domain:

$$\eta_D(r,s) = \left(\frac{Q}{2\pi K_r bs}\right) K_0\left(r\sqrt{\frac{s}{c_r}}\right) \tag{A.18}$$

Appendix B: Hydraulic Interaction of River-Leaky Water Table Aquifer

- **Mathematical Model**

The problem under consideration is illustrated in Figure B.1. Expressing the problem in Figure B.1 in terms of relative head change, i.e. $h_D = \dfrac{h_i - h(x,z,t)}{h_i - h_o}$ we arrive at:

$$\frac{\partial^2 h_D(x,0,t)}{\partial x^2} - \frac{K_z'}{bK_x}\frac{\partial h_D(x,0,t)}{\partial z}\bigg|_{z=0} = \frac{1}{c_x}\frac{\partial h_D(x,0,t)}{\partial t} \tag{B.1}$$

$$\frac{\partial^2 h_D(x,z,t)}{\partial z^2} = \frac{1}{c_z}\frac{\partial h_D(x,z,t)}{\partial t} \tag{B.2}$$

with $c_x = K_x / S_s$, $c_z = K_z' / S_s'$, where K_x, S_s and K_z', S_s' are the respective hydraulic conductivity and specific storage of the aquifer and aquitard, and $v_z = -K_z' \dfrac{\partial h}{\partial z}\bigg|_{z=0}$ is the leakance velocity. Eqn (B.1) is the unsteady groundwater flow equation for one-dimensional flow in a leaky homogeneous aquifer, and (B.2) is the unsteady groundwater flow equation for movement of water in the aquitard assuming groundwater movement is only in the vertical or *z*-direction. The problem under consideration is quasi two-dimensional meaning that first (B.2) is solved and the result is substituted into (B.1). The aquitard and aquifer problems are linked by the leakage boundary condition appearing as the second term on the left-hand side of (B.1). Utilizing this approach essentially allows (B.1) to be a boundary condition at $x = 0$ for (B.2) and requires that flow in the z-direction of the aquifer is negligible.

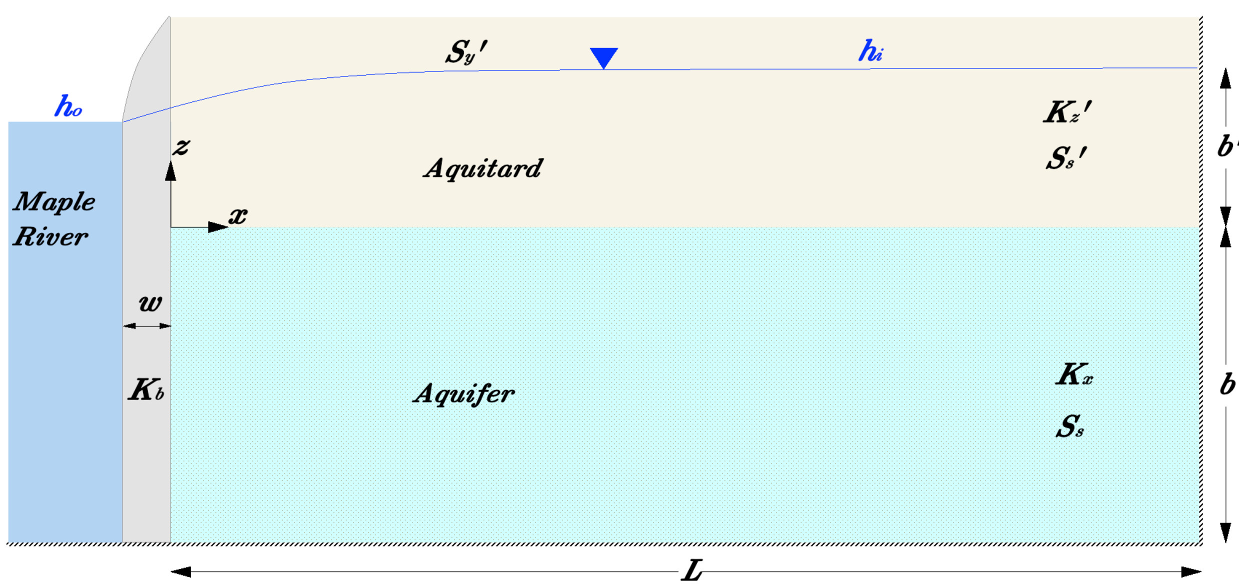

Figure B.1. Mathematical model of river-aquifer interaction.

The initial and boundary conditions from Figure B.1 are:

$$h_D(x,z,0) = 0 \quad \text{(B.3)}$$

$$\frac{\partial h_D(0,0,t)}{\partial x} = d\left[h_D(0,0,t) - 1\right] \quad \text{(B.4)}$$

$$\frac{\partial h_D(L,0,t)}{\partial z} = 0 \quad \text{(B.5)}$$

$$\frac{\partial h_D(x,b',t)}{\partial z} = -\frac{1}{c_y}\frac{\partial h_D(x,b',t)}{\partial t} \quad \text{(B.6)}$$

$$h_D(x,0,t) = h_D(x,z,t)\Big|_{z=0} \quad \text{(B.7)}$$

where $d = \frac{K_b}{wK_x}$, $c_y = \frac{K_z'}{S_y'}$, S_y' is the aquitard specific yield, K_b is the riverbed hydraulic conductivity, and w is the river bed thickness. Eqn. (B.3) is the initial condition, (B.4) is the membrane boundary condition linking the river to the aquifer through a streambed of negligible storage, (B.5) is a no flow boundary limiting the aquifer lateral extent, (B.6) is a boundary condition describing the drainage at the water table as instantaneous, (B.7) is a continuity condition at the aquitard-aquifer interface.

In order to solve the above problem we apply the Laplace transform to the time variable, which will transform the problem into a quasi two-dimensional problem independent of the time variable. The governing equations and boundary conditions become:

$$\frac{\partial^2 \eta_D(x,0,s)}{\partial x^2} - \frac{K_z'}{bK_x}\frac{\partial \eta_D(x,0,s)}{\partial z}\bigg|_{z=0} = \frac{s}{c_x}\eta_D(x,0,s) \quad \text{(B.8)}$$

$$\frac{\partial^2 \eta_D(x,z,s)}{\partial z^2} - \frac{s}{c_z}\eta_D(x,z,s) = 0 \quad \text{(B.9)}$$

$$\frac{\partial \eta_D(0,0,s)}{\partial x} = \frac{K_b}{wK_x}\left[\eta_D(0,0,s) - \frac{1}{s}\right] \quad \text{(B.10)}$$

$$\frac{\partial \eta_D(L,0,s)}{\partial x} = 0 \quad \text{(B.11)}$$

$$\frac{\partial \eta_D(x,b',s)}{\partial z} = -\frac{s}{c_y}\eta_D \quad \text{(B.12)}$$

$$\eta_D(x,0,s) = \eta_D(x,z,s)\Big|_{z=0} \quad \text{(B.13)}$$

where $\eta_D(x,z,s)$ is the Laplace transform function of the function $h_D(x,z,t)$, and s is the Laplace transform parameter. Note use of the Laplace transform incorporates (B.3) into the transformed problem.

- **Solution**

The solution to (B.9) subject to (B.12) and (B.13) is

$$\eta_D(x,z,s) = \frac{\eta_D(x,0,s)}{1-\beta_z}\left[\exp\left(z\sqrt{\frac{s}{c_z}}\right) - \beta_z \exp\left(-z\sqrt{\frac{s}{c_z}}\right)\right] \tag{B.14}$$

with $\beta_z = \exp\left(2b'\sqrt{s/c_z}\right)\left(\frac{\sqrt{sc_z} - c_y}{\sqrt{sc_z} + c_y}\right)$. Substituting (B.14) into (B.8), and applying (B.10) and (B.11) gives the solution in the aquifer as:

$$\eta_D(x,0,s) = \alpha\left[\exp\left(x\sqrt{\xi}\right) + \gamma_L \exp\left(-x\sqrt{\xi}\right)\right] \tag{B.15}$$

where $\alpha = \frac{d}{s\left[\sqrt{\xi}(\gamma_L - 1) + d(1+\gamma_L)\right]}$, $\gamma_L = \exp\left(2L\sqrt{\xi}\right)$, $\xi = \sqrt{\frac{s}{c_z}\frac{K_z'(1+\beta_z)}{bK_x(1-\beta_z)}} + \frac{s}{c_x}$. Numerical inversion from the Laplace domain to the time domain is accomplished by use of the Stehfast inversion (Stehfast, 1970).

- **Superposition of Solution**

The solution in (B.15) reflects the response to an instantaneous step change in a hydraulically connected river. To determine the change in aquifer water levels to continuous changes in river stage, Duhamel's principle of superposition is applied:

$$h(x,z,t) = h_i + \int_0^t \frac{dH(\tau)}{d\tau} h_D(x,z,t-\tau)d\tau \tag{B.16}$$

where $H(t)$ is the recorded river stage, h_D is the numerically inverted solution of (B.14), t is total time, and t is time at each change in river stage. The integral in (B.15) cannot be analytically evaluated typically; therefore it is evaluated numerically in discrete form:

$$h(x,z,t_j) = h_i + \sum_{n=2}^{j}\left[H(t_n) - H(t_{n-1})\right]h_D(x,z,t_j - t_n + 1) \tag{B.17}$$

A computer program was written to evaluate (B.17).

Appendix C: Potential and Stream Functions for Pumping Well in Uniform Flow near Constant Head Boundary

The problem under consideration is illustrated in Figure 32 of the main report. The head field for a pumping well at a distance, d, from a constant head source is written as:

$$h_W(x,y) = \frac{Q}{2\pi T} \ln\left(\frac{\sqrt{(x+d)^2 + y^2}}{\sqrt{(x-d)^2 + y^2}} \right) \tag{C.1}$$

The head field for a uniform flow field of gradient, i, to a constant head boundary is:

$$h_i = ix + h_o \tag{C.2}$$

where h_o is the head of the constant head boundary. The solution to a well pumping in a uniform flow field near a constant head boundary is then found by adding the solutions of (C.1) and (C.2), which in dimensionless form in terms of the ambient flow rate $q_o = Ti$, is

$$h_D(x_D, y_D) = \frac{Q_D}{2} \ln\left(\frac{(x_D + 1)^2 + y_D^2}{(x_D - 1)^2 + y_D^2} \right) + x_D + h_{DO} \tag{C.3}$$

where $h_D = \frac{T}{q_o d} h$, $x_D = \frac{x}{d}, y_D = \frac{y}{d}$, $Q_D = \frac{Q}{2\pi q_o d}$. The stream function, ψ, is the functional representation of the path of groundwater flow which is the orthogonal trajectories of the hydraulic head function, (C.3). Dimensionless orthogonal trajectories to the dimensionless head function can be written as:

$$\frac{\partial \psi_D}{\partial y_D} = \frac{\partial h_D}{\partial x_D}, \quad \frac{\partial \psi_D}{\partial x_D} = -\frac{\partial h_D}{\partial y_D} \tag{C.4}$$

with the dimensionless stream function as $\psi_D = \frac{\psi}{q_o d}$. Similarly to (C.3) each of the stream functions can be separately analyzed. For the uniform flow field the stream function is easily found to be:

$$\psi_D = y_D \tag{C.5}$$

The stream function is solely defined for y_D, just as the hydraulic head function in (C.2) is solely defined for x_D. For flow to a single well, it is easier to derive the stream function in terms of polar coordinates or:

$$T\frac{\partial h}{\partial r} = \frac{1}{r}\frac{\partial \psi}{\partial \theta} \tag{C.6}$$

Realizing that (C.1) in radial coordinates is simplified down to the ln(r), for a single well, results in:

$$\psi = \frac{Q}{2\pi}\theta \tag{C.7}$$

and now converting to Cartesian and dimensionless coordinates gives:

$$\boldsymbol{\psi}_D = Q_D \tan^{-1}\left(\frac{y_D}{x_D}\right) \tag{C.8}$$

Combining the two stream functions, (C.6) and (C.7), results in:

$$\boldsymbol{\psi}_D(x_D, y_D) = y_D + Q_D\left[\tan^{-1}\left(\frac{y_D}{x_D + 1}\right) - \tan^{-1}\left(\frac{y_D}{x_D - 1}\right)\right] \tag{C.9}$$