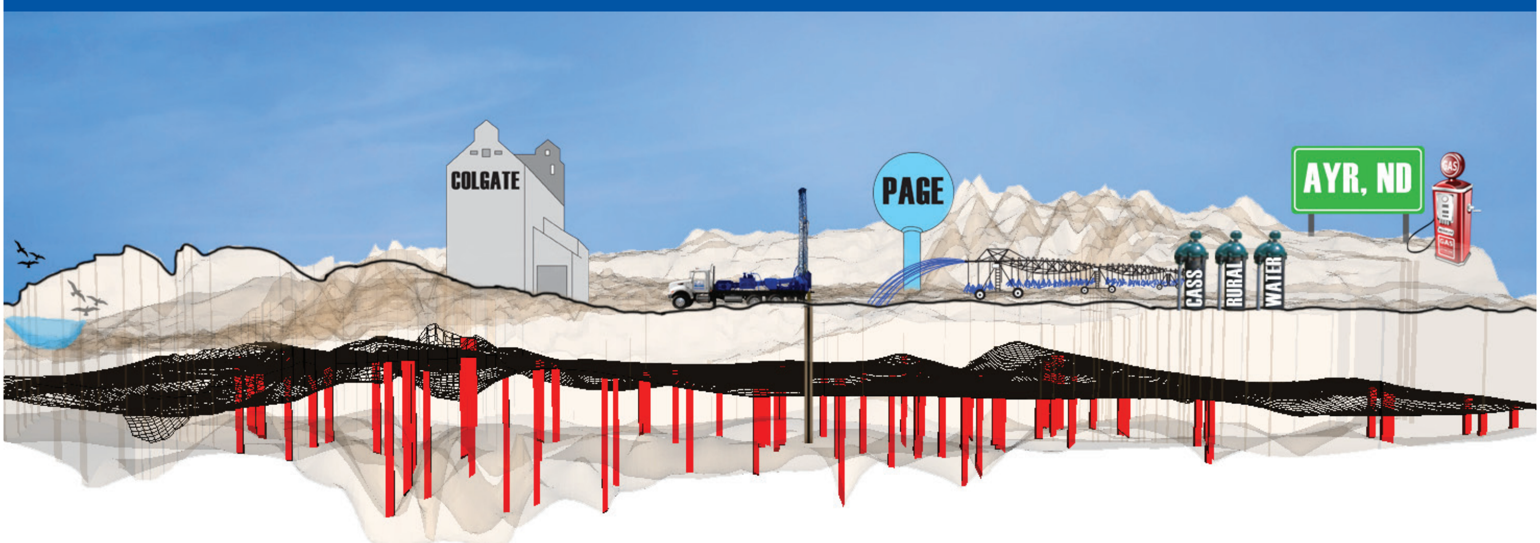
Modeling of the Page Aquifer:

An Assessment of Groundwater Availability

By Rex P. Honeyman



ND Water Resource Investigation No. 55
North Dakota State Water Commission

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Table of Contents

List of Figures

List of Tables

Introduction

Background

The Page aquifer underlies about 350 square miles located in northwestern Cass, southeastern Steele, and southwestern Trail Counties (Figure 1). The aquifer is comprised of lacustrine, deltaic, and glacio-fluvial sand and gravel deposits. The aquifer ranges from 10 feet to 150 feet in thickness. There are 14,946 acres permitted for irrigation from the aquifer under 43 perfected water permits (Figure 2).

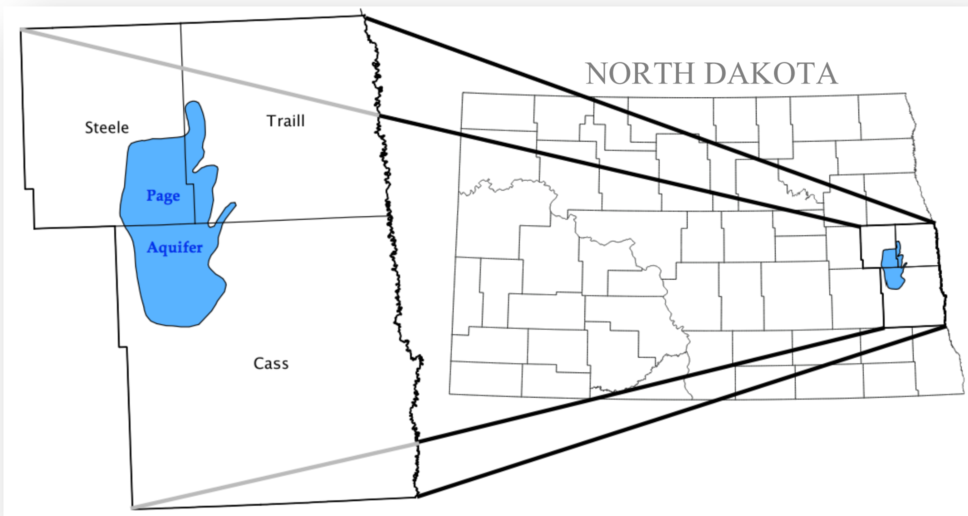

Figure 1. -- Location of the Page Aquifer (Study Area).

Historical reported annual water use for irrigation has ranged from 1.5 inches (1994) to 9.4 inches (1976) per acre with an average of 4.5 inches per acre from 1976 (when irrigation development began) to 2012. Cass Rural Water District is currently approved to divert 400 acre-feet of water for rural water purposes. Traill Rural Water District is approved to divert 1660 acre-feet of water from the aquifer for rural water purposes. Cass Rural Water District's well field is located in the southwest part of the aquifer and Traill Rural Water District's well fields are located in the northeast part of the aquifer (Figure 2). Both rural water districts provide water to rural residents and local communities in the area. In the past, the city of Page and the city of

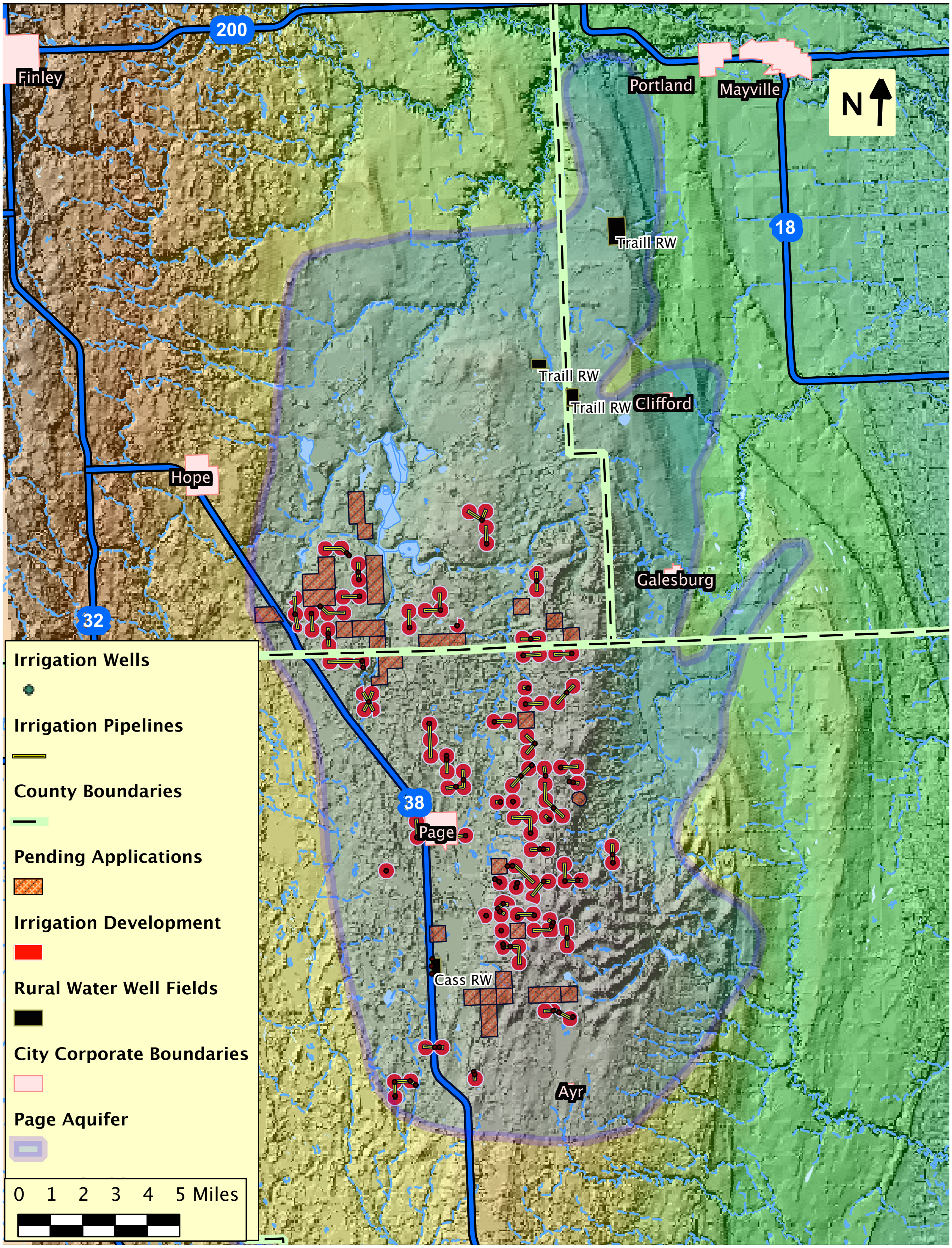

Figure 2. -- Location of irrigation and rural water development.

Hope diverted water from the aquifer for municipal use, but both are now supplied water by rural water districts.

Although domestic and municipal development occurred much earlier, the first permit approved for irrigation was in 1975. From 1975 to 1982, 34 of the 43 perfected permits were granted. The remaining irrigation permits were granted during the late 1980s through the late 1990s. Currently, there are 18 pending applications that need to be evaluated. Seventeen of these applications are for irrigation (5,810 acre-feet for 4,943.3 acres) and one is a rural water application (400 acre-feet) (Table 1, Figure 2).

The Page aquifer has reached maturity from a development standpoint. Considerable uncertainty exists with respect to growing season well interference effects and long-term aquifer sustainability, which provide the basis for allocating additional ground water appropriations from the Page aquifer. As a result a ground-water model is required to provide a basis for taking action on pending water permit applications. The ground-water model is used to determine how much additional water can be allocated without causing undue effects on prior appropriators. The U.S. Geological Survey (USGS) groundwater flow model, MODFLOW-2005 (Harbaugh, 2005), was used for this study.

Purpose and Scope

The purpose of this study is to determine the availability of ground water from the Page aquifer. Specific objectives included:

1) Evaluating growing season well interference effects caused by permitted appropriators.

2) Evaluating long-term sustainability of the Page aquifer in relation to permitted appropriators.

3) Evaluating growing season well interference effects caused by permitted appropriators and pending water permit applications.

4) Evaluating long-term sustainability of the Page aquifer in relation to permitted appropriation and pending water permit applications.

In order to accomplish the above, a conceptual model of the Page aquifer was developed. Based on the conceptual model, a finite-difference ground-water model was developed and steady-state

Priority #	Permit #	Name	POD	Permit Status	Use Type	Aquifer	Priority Date	Req Ac-Ft	Req Acres	Req Rate
1	4486	CASS RURAL WATER USERS, INC.	14205418C	Pending	Rural Water	Page	6/10/91	400	0	600
2	4488	HIAM, GARY AND CHARLENE	14405521D	Pending	Irrigation	Page	7/1/91	720	472	2850
			14405522B			Page	7/1/91			
			14405522C			Page	7/1/91			
3	4603	MEWES, JOHN E. ET. AL.	14405529S	Pending	Irrigation	Page	4/28/92	234	234	1000
4	4913	JOHNSON, STEVE B.	14305415B	Pending	Irrigation	Page	4/26/95	202.5	135	750
			14305415C			Page	4/26/95			
5	4918	NELSON, TERRY	14205416D	Pending	Irrigation	Page	10/4/95	195	130	800
			14205416C			Page	10/4/95			
			14205417A			Page	10/4/95			
6	5341	MCPHERSON, TIMOTHY L.	14405435B	Pending	Irrigation	Page	2/18/99	400	264	2000
			14405427C			Page	2/18/99			
7	5422	HIAM, GARY AND CHARLENE	14405511B	Pending	Irrigation	Page	6/12/00	324	398	1800
			14405511C			Page	6/12/00			
			14405514AW			Page	6/12/00			
			14405514BE			Page	6/12/00			
8	5423	HIAM, GARY AND CHARLENE	14405523D	Pending	Irrigation	Page	6/12/00	720	660	2700
			14405526AW			Page	6/12/00			
			14405534A			Page	6/12/00			
			14405535C			Page	6/12/00			
			14405523A			Page	6/12/00			
9	5486	MEWES, J. RAYMOND ET. AL.	14405535A	Pending	Irrigation	Page	2/26/01	243	264	2000
			14405535B			Page	2/26/01			
10	5487	MEWES, J. RAYMOND ET. AL.	14405527W	Pending	Irrigation	Page	2/26/01	243	264	2000
			14405528E			Page	2/26/01			
11	5525	THOMPSON, MARY E.	14305426E	Pending	Irrigation	Page	12/3/01	80	96.2	1000
12	5583	MUNRO, NEIL	14205404C	Pending	Irrigation	Page	7/5/02	194	129.6	800
			14205405D			Page	7/5/02			
			14205408A			Page	7/5/02			
13	5601	THOMPSON, WILLIAM & RALPH	14205427C	Pending	Irrigation	Page	11/27/02	202.5	270	800
			14205427D			Page	11/27/02			
14	5621	LANGDAHL, TERRY	14405431C	Pending	Irrigation	Page	3/5/03	639	639.4	3800
			14405431D			Page	3/5/03			
			14305502A			Page	3/5/03			
15	5815	OLSTAD, MATTHEW J.	14405435D	Pending	Irrigation	Page	3/9/06	135	135.2	800
16	6448	ANDERSON, MICHAEL	14205426C	Pending	Irrigation	Page	11/5/12	197	131.6	800
17	6455	A & A FARMS	14205428C	Pending	Irrigation	Page	11/5/12	395	263.2	1600
			14205429C				11/5/12			
18	6456	ANDERSON, WAYNE	14205428B	Pending	Irrigation	Page	11/5/12	686	457.1	3200
			14205429D				11/5/12			
			14205432A				11/5/12			
			14205432D				11/5/12			

Table 1. -- Pending applications in the Page Aquifer.

and transient simulations were run to evaluate aquifer response to pumping. Based on the results of the transient simulation the utility of the model was assessed to provide a basis for future case-by-case evaluations of pending water permit applications.

Acknowledgements

A project of this size is the result of the work of many people. The foundation of this project is built upon the reliable work of the former and current field staff during the data acquisition phase of this project. I would like to thank Gary Calheim, former Driller for the N.D. State Water Commission (NDSWC), Terry Olson, Driller for the NDSWC, Gerry Manderfeld, Driller's Assistant for the NDSWC, and all other driller's assistants for their quality work in some not so good conditions. Appreciation is expressed to the technician staff of the Water Appropriation Division of the NDSWC. I would specifically like to thank Kelvin Kunz, Albert Lachenmeier, Neal Martwick, Merlyn Skaley, and Daniel McDonald for their tireless effort in collecting quality water-level and chemistry data in a timely manner.

I would like to thank Royce Cline, Hydrologist Manager for the NDSWC for sharing his breadth of knowledge in hydrogeology and ground-water modeling. Secondly, I would like to thank Royce for his development of several scripts and programs that were vital in developing a complex transient model. Lastly, I would like to express my appreciation to Royce for his advice and support throughout this modeling project and his extensive effort in editing this report.

Appreciation is also expressed to Robert Shaver, former Director of the Water Appropriation Division of the NDSWC, for sharing his breadth of knowledge in hydrogeology. I would like to thank Robert for his advice and encouragement throughout this study and his extensive effort in editing this report.

David Ripley, former Director of the Water Appropriation Division of the NDSWC and former project manager for the Page aquifer, should be acknowledged for initiating an extensive well network in the aquifer. His work laid down the framework, which made this project possible. His innovative approach for appropriating water from the Page aquifer has proven to be vital in the further expansion of development in the aquifer.

Appreciation is also expressed to Jon Patch, Director of the Water Appropriation Division of the NDSWC and Alan Wanek, Assistant Director of the Water Appropriation of the NDSWC for their support throughout this study and for their critical review of this report.

Location-Numbering System

Wells and test holes referred to in this report are numbered according to public land classification of the United States Bureau of Land Management. The system is illustrated in Figure 3. The first numeral denotes the township of a base line, the second denotes the range west of the fifth principal meridian, and the third numeral denotes the section in which the well or test hole is located. The subsequent letters A, B, C, and D designate, the northeast, northwest, southwest, and southeast quarter-section (160-acre tract), quarter-quarter-section (40-acre tract), quarter-quarter-quarter section (10-acre tract). For example, well 14305404ADD is located in the SE1/4 of the SE1/4 of the NE1/4 of Section 4, Township 143 North, Range 054 West. Consecutive terminal numerals are added if more than one well or test hole is located within a 10-acre tract.

Previous Work

Upham (1895) describes the Pleistocene deposits of Glacial Lake Agassiz. Simpson (1929) briefly describes the geology and ground water resources of Steele and Traill Counties. Abbot (1938) assembled water-quality data from selected municipal wells throughout the state, including wells within Steele and Traill counties. Dennis and Akin (1950) completed a progress report in association with the county ground water studies in an area near the city of Portland, ND. Falcone (1983) completed a master's thesis describing the glacial stratigraphy of northwestern Cass County.

The geology and ground-water resources of Traill, Steele, and Cass Counties are described in a three-part report for each county. Part I describes the geology of the respective county (Bluemle, 1967; Bluemle, 1975; and Klausing, 1968), Part II presents the ground-water data (Jensen, 1967; Downey, 1973, and Klausing, 1966), and Part III describes the ground-water resources (Jensen and Klausing, 1971; Downey and Armstrong, 1977; and Klausing, 1968). The soils of Traill, Steele, and Cass Counties are described in the county soil survey by Prochnow (1977), Murphy and others (1997), and Prochnow and others (1985), respectively.

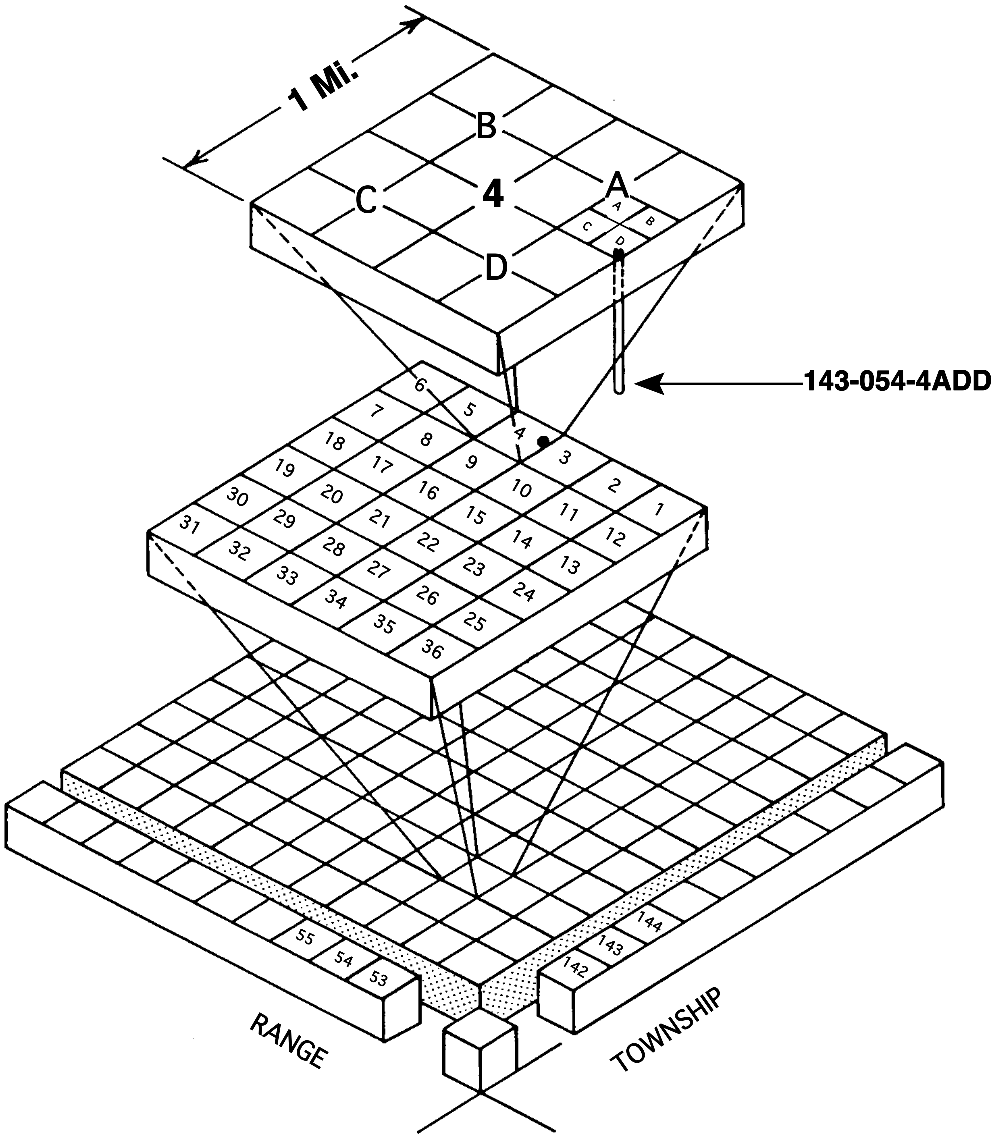

Figure 3. -- System of numbering wells, test holes, and other data points.

In 1973 and 1974, C. A. Simpson & Son Drilling completed several wells and test holes in the northeast part of the Page aquifer near the Traill Rural Water District well field. Two aquifer tests were completed in this area during the winter of 1974 using these wells. In the fall of 1978 and in the spring of 1979 four aquifer tests conducted by the Water Appropriation Division of the N.D. State Water Commission were completed in the central part of the aquifer using existing irrigation wells. Transmissivity and storativity values were calculated from these four aquifer tests. The data for the six above referenced aquifer tests are part of the N.D. State Water Commission Open-File Aquifer Test Reports.

A compilation and evaluation of existing ground-water data in the northern part of the Page aquifer was completed by Honeyman (2005). Honeyman (2006) completed an evaluation of the potential expansion of Traill Rural Water District's water supply, which included test drilling, construction of monitoring wells, water-level and water-quality monitoring, and aquifer test analysis in the northern part of the Page aquifer.

Description of the Study Area

Physiography

The extent of the study area is defined by the boundary of the Page aquifer, which is located in east-central North Dakota. The eastern one-third of the study area is within the Lake Agassiz Plain district and the western two-thirds of the study area is within the Drift Prairie district, both of the Central Lowland physiographic province (Figure 4). The study area can be divided into six landforms consisting of a lake plain, beach ridges, delta plains, till plain, supra-glacial ridge, and stream valleys. The eastern flank of the study area consists of a broad, flat, and fertile lake plain, associated with Glacial Lake Agassiz. The elevation (above mean sea level) of this plain within the study area ranges from 964 feet in the northeast to 1,073 feet in the southeast.

The western part of the lake plain consists of beach ridges. These ridges reach several feet to nearly 35 feet above the surrounding lake plain and are nearly level to gently rolling (Figure 5). They generally trend north to south and represent the former shorelines of Glacial Lake Agassiz.

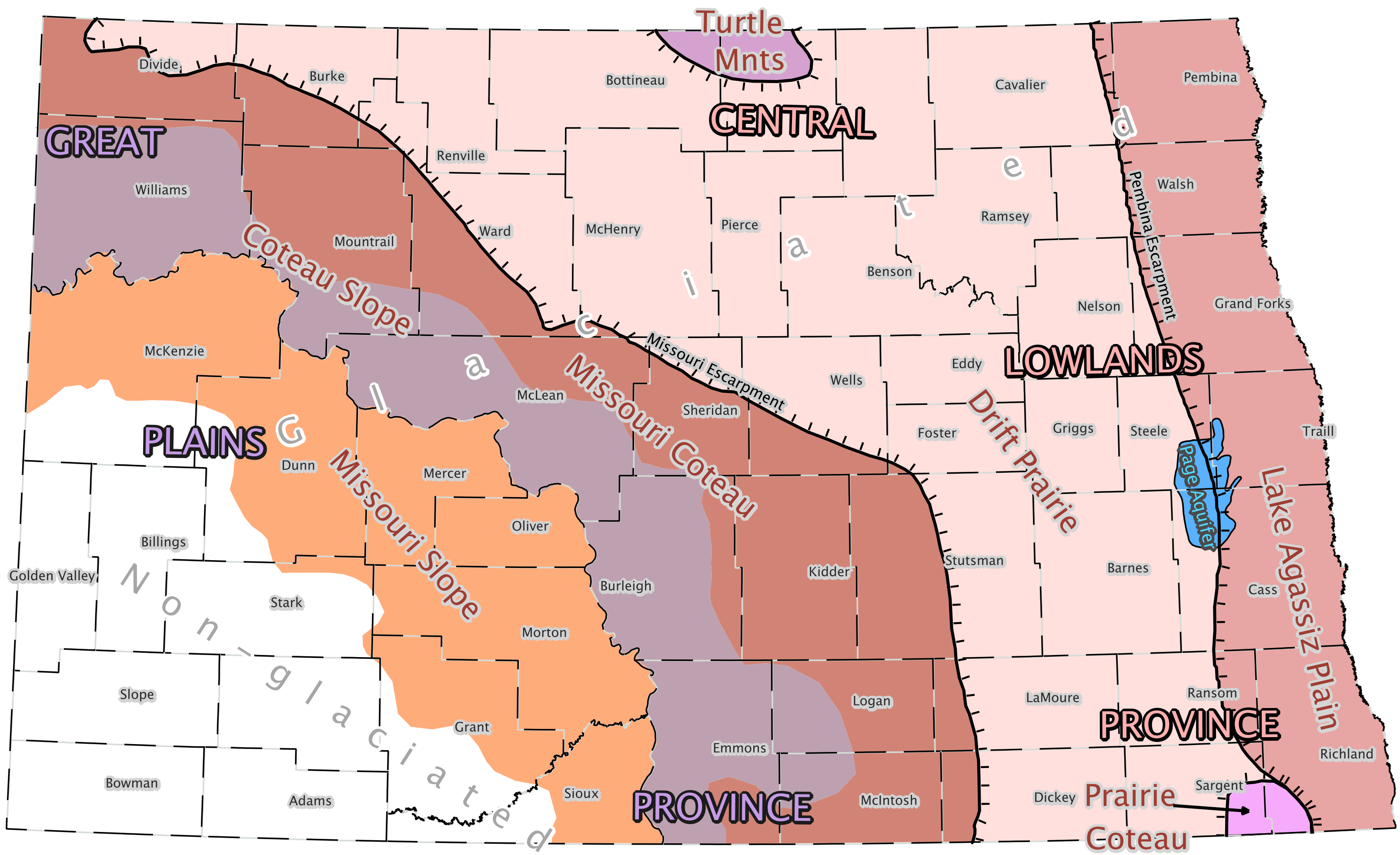

Figure 4. -- Physiographic divisions in North Dakota and location of study area (Modified from Simpson, 1929).

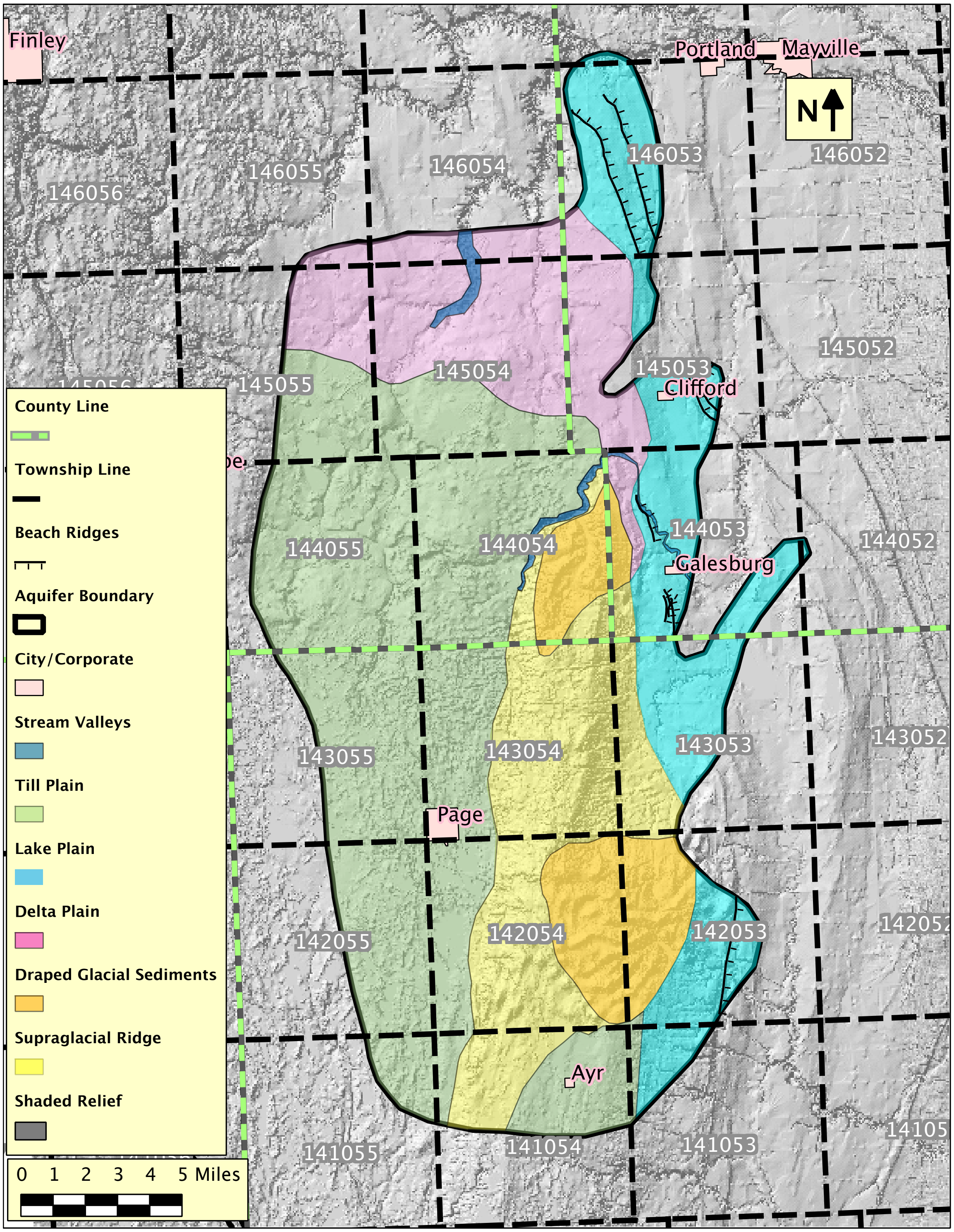

Figure 5. -– Physiographic landforms within the Study Area.

The northeastern part of the study area is comprised of a delta plain that rises approximately 30 to 100 feet above the lake plain. The delta plain is gently undulating and consists mostly of sands and silts that were deposited by rivers entering Glacial Lake Agassiz. In parts of the delta plain a thin veneer of till has covered the sands and silts. The delta plain and the northern parts of the Lake Agassiz Plain make up what has been referred to as the Galesburg Delta or Galesburg Aquifer by Bluemle (1967). The Page and the Galesburg aquifer coalesce near the Steele and Trail county lines and as a result Honeyman (2006) referred to the entire aquifer system as the Page/Galesburg aquifer. In this report, all references made to the Page and or Galesburg aquifer will be referred to as the Page aquifer.

The till plain makes up most of the study area south and west of the Steele and Trail County correction line, with exception of the supra-glacial lake ridge. The till plain consists of a nearly level to gently rolling ground moraine interspersed with lake deposits. The elevation of the till plain ranges from approximately 1130 feet to 1180 feet above mean sea level. The supra-glacial ridge separates the till plain from the lake plain and trends from the northeast to the southwest starting at the Steele and Trail County correction line and extending to the southern extent of the study area.

There are several streams within the study area. The two most prominent stream valleys are the South Branch of the Goose River and the Elm River (Figure 6). The South Branch of the Goose River bisects the till plain and the delta plain in the north central part of the study area. The Elm River bisects the till plain in the east central portion of the study area.

Climate

Climate data was collected from the following sources: Atmospheric Resource Board (ARB), North Dakota Agricultural Weather Network (NDAWN), and Hydrosphere Data Products (2011 CD containing NOAA Cooperative Observer Data (NCDC)). The ARB cooperative observer network for measuring precipitation began in 1977 and the NDAWN program for measuring climate data began in 1990. None of the stations in an around the study area have a complete climate record so composites of several stations were generated.

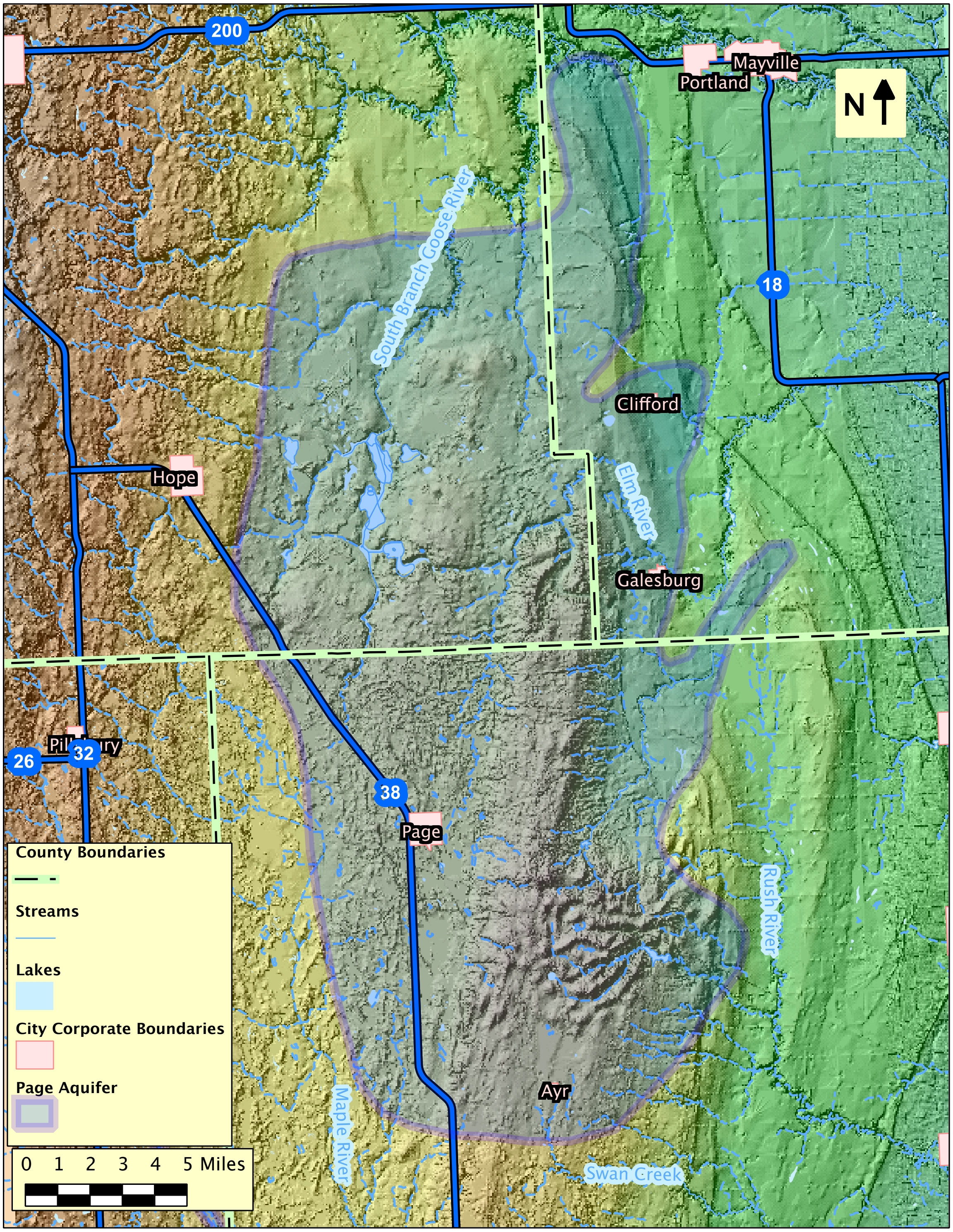

Figure 6. -- Location of surface water bodies within the study area.

The analysis of climate data and input to the soil moisture budget model used to calculate recharge and irrigation water requires continuous daily data. To facilitate the creation of these continuous daily records, the NDSWC developed the computer program hydrosphereNCDC that uses NCDC, NDAWN and ARB daily data as input. A ranked list of data files is input into the program. The first station in the list is the primary station. When precipitation or temperature data is missing at the primary station, the program searches down the list until a value is found and uses that value for the date. There are a limited number of stations with data prior to 1948, so the stations tend to be further away from the primary station and therefore the early record in the composite is less representative of the local conditions. The ARB and NDAWN stations have more recent data and are within or are close to the study area, which makes the more recent portion of the record in the composite (1978-2010) more representative of the local conditions.

Composites of several stations were used to generate a Page North and a Page South climate dataset. Figure 7 shows the location of these stations and the source of the data for the two composite datasets. To generate the datasets, a timeline of 1901 to 2010 was first determined, and then a group of stations was selected to fill in the missing data for that respective timeline.

The Page North composite climate set uses Cooperstown and Fargo data from 1901-1911, Mayville data from 1911-1948, Colgate data from 1948-1983, and local ARB Stations and Colgate data from 1983-2010 (Figure 8). The primary station selected in the Page North composite climate set is ARB site ID 777 (ARB777), which is located in the northern portion of the study area (Figure 7). Available precipitation data for this site is plotted in green and is defined by the number 1 in the plot (Figure 8). The other climate stations listed in Figure 8 were used to fill in the missing data based on their ranking. The numbers 1 through 9 define the ranking of how data from stations was in filled to make a complete climate record. The same method was used for the Page South composite climate set, which uses Fargo data from 1901-1905, Hillsboro and Fargo data from 1905-1949, Amenia data from 1949-1979, and a combination of Chaffee, Casselton, Galesburg and local ARB stations from 1979-2010 (Figure 9).

A comparison of the Page North and Page South climate sets is shown in Figure 10. The Page North is a much drier dataset with an average annual precipitation of 19.2 inches in relation

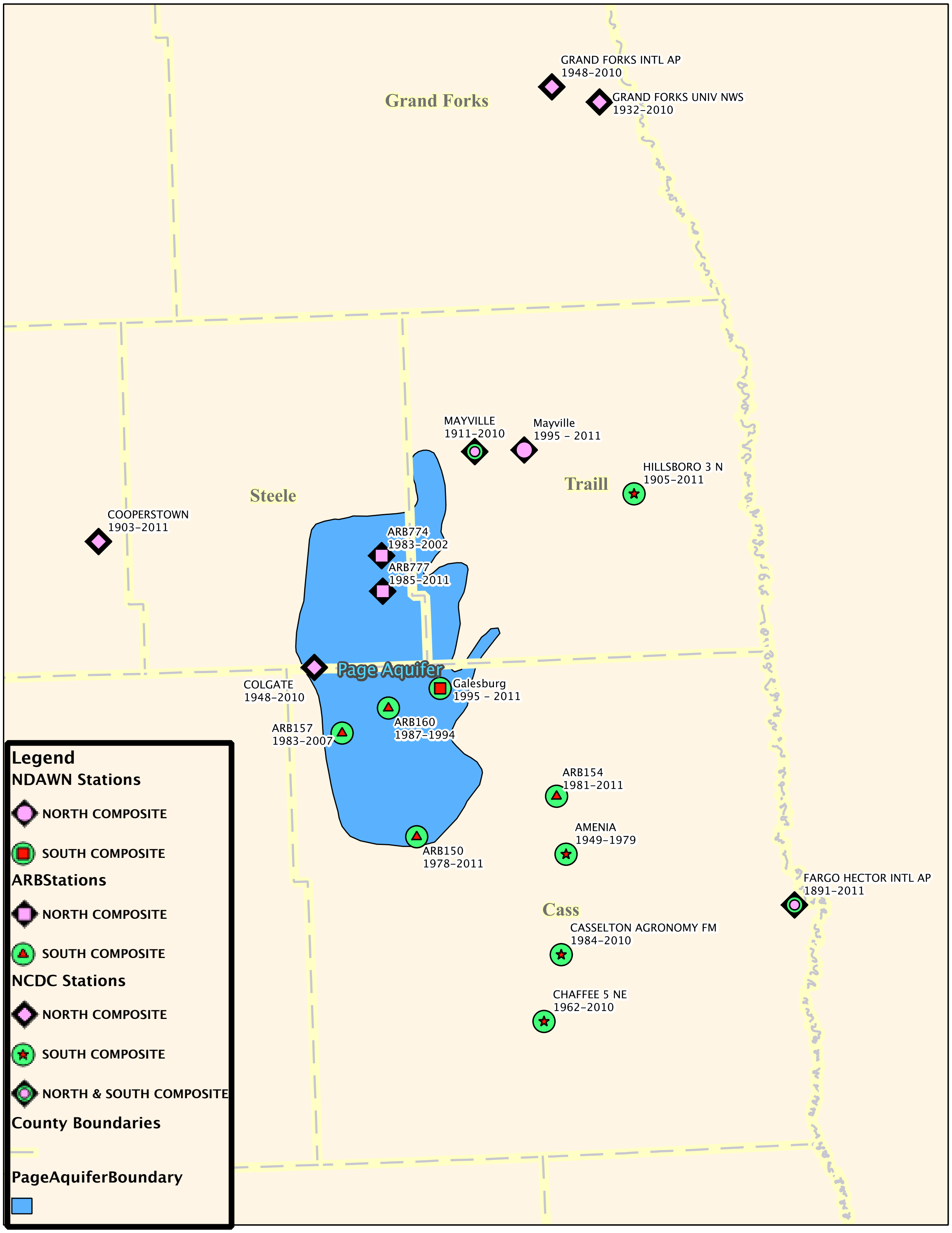

Figure 7. -- Location of climate stations used in this study.

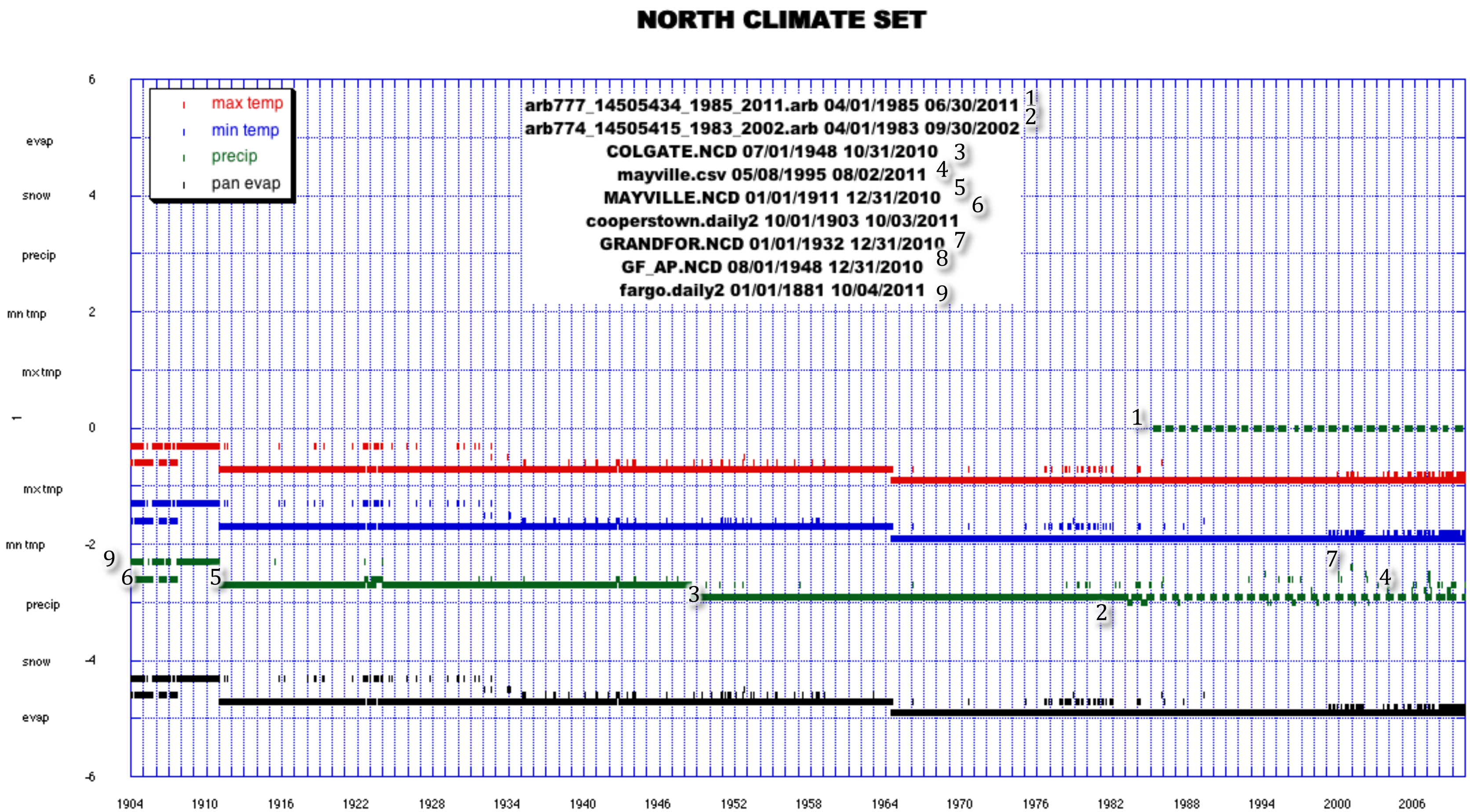

Figure 8. -- Climate stations used to construct the Page North Climate Dataset from 1901-2010. [Precipitation data is shown in green].

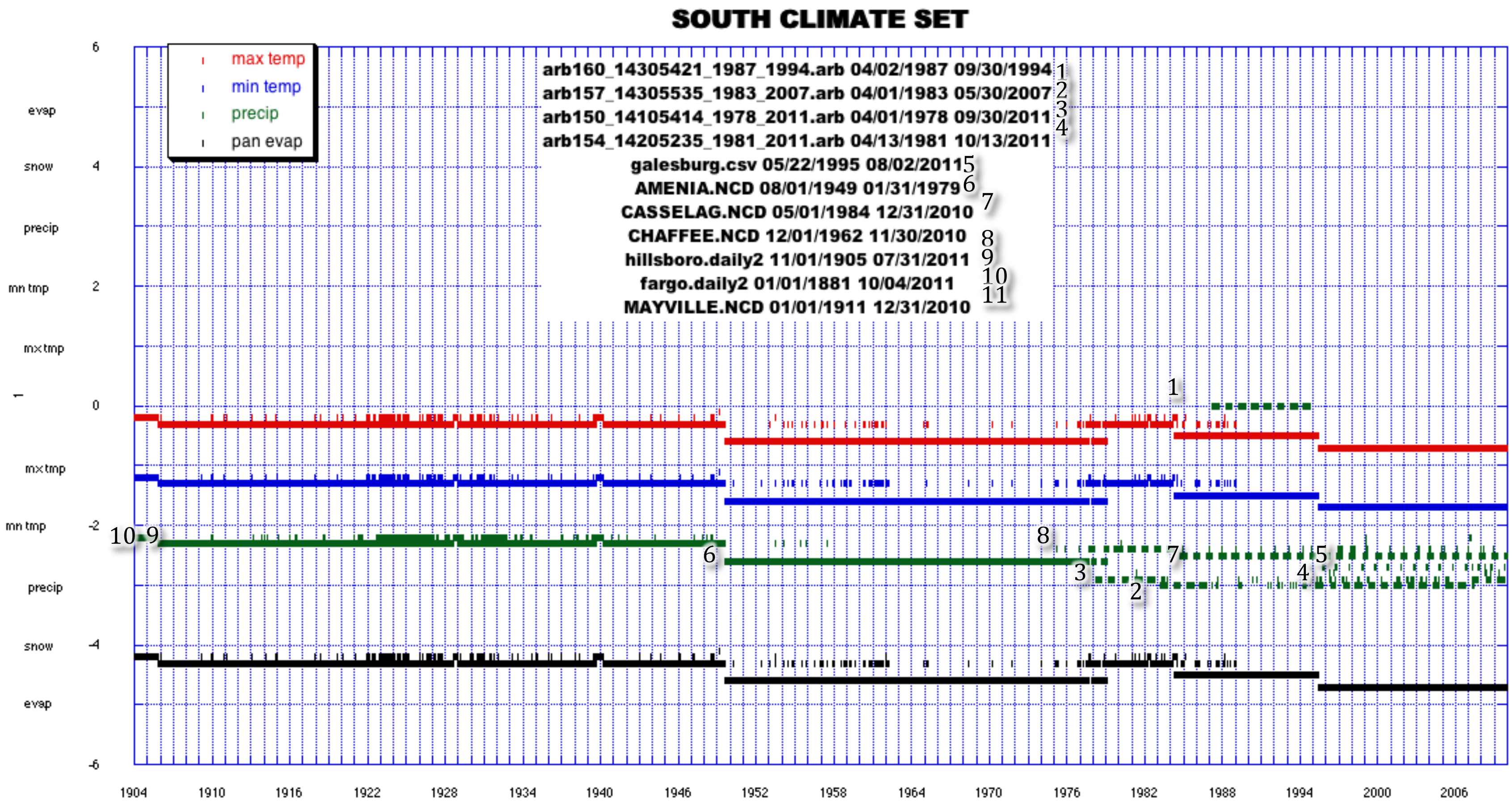

Figure 9. -- Climate stations used to construct the Page South Climate Dataset from 1901-2010. [Precipitation data is shown in green].

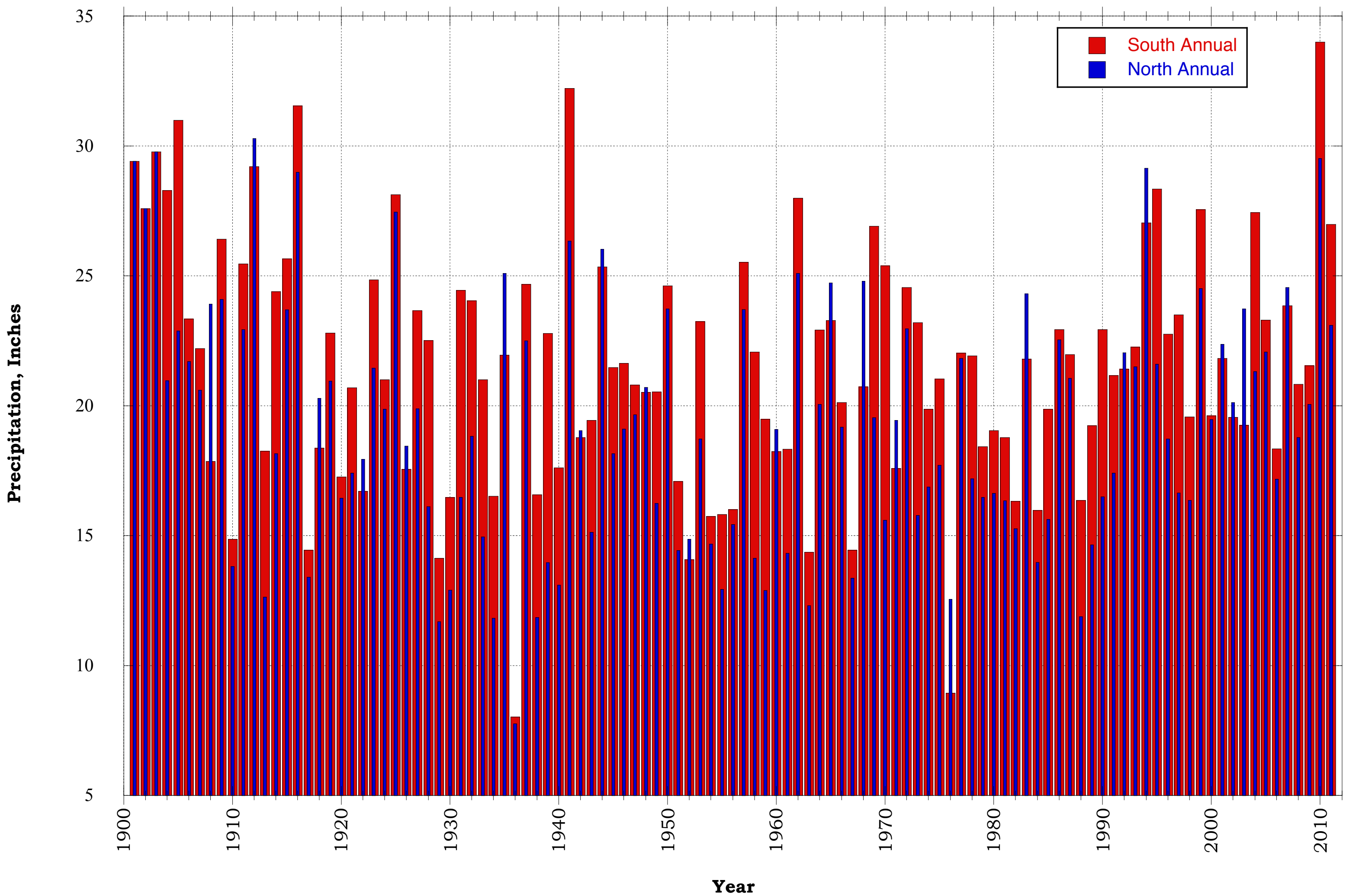

Figure 10. -- Comparison of the North and South Composite Climate Datasets.

to the Page South dataset with an average annual precipitation of 21.5 inches. The annual precipitation is highly variable between each climate set. Most of the spatial variability is due to localized high intensity rainfall events that occur in the summer primarily from convective thunderstorms. It is important to recognize this spatial variability exists when developing ground-water models in North Dakota.

Soils

This section discusses the soil properties within the defined model area (model domain). Limited discussion of the model development will be included within this section of the report. A more thorough discussion of the model can be found in the "Model Development" section of this report. Soil properties are imperative in estimating recharge, discharge, and crop water use during model development. The most prominent soil within the model domain is the Barnes soil series. According to the Soil Series Name Search provided by National Resource Conservation Service (NRCS) of the United States Department of Agriculture (USDA), the Barnes series is defined as a very deep, well-drained soil that formed in loamy till. These soils occur on till plains and moraines and have slopes ranging from 0 to 25 percent. The Heimdal soil series is the second most prominent soil within the model domain. According to the Soil Series Name Search, the Heimdal series consists of very deep, well drained, moderately permeable soils that formed in calcareous till. These soils occur on till plains and moraines and have slopes ranging from 0 to 40 percent. The Barnes and Heimdal series have very similar descriptions and appear to be used interchangeably when comparing soils defined as a Barnes south of the Cass/Steele-Traill county line and the soils defined as Heimdal north of the Cass/Steel-Traill county line (Figure 11). Nearly all of the irrigation development within the model domain occurs on a Barnes or Heimdal soil series. Both of these soil series are well drained and have relatively large available water capacities, which average 10.5 inches for the Barnes and 10 inches for the Heimdal (Figure 12). Available water capacity is the amount of water that a soil can store that is available for use by plants. Soils with high available water capacities require less irrigation water use to meet crop demands.

The drainage classification of soils was used to determine areas of ground-water recharge and discharge (Figure 13). Areas of well-drained soils facilitate ground-water recharge and poorly drained soils hinder recharge and are areas of ground-water discharge. The soil series,

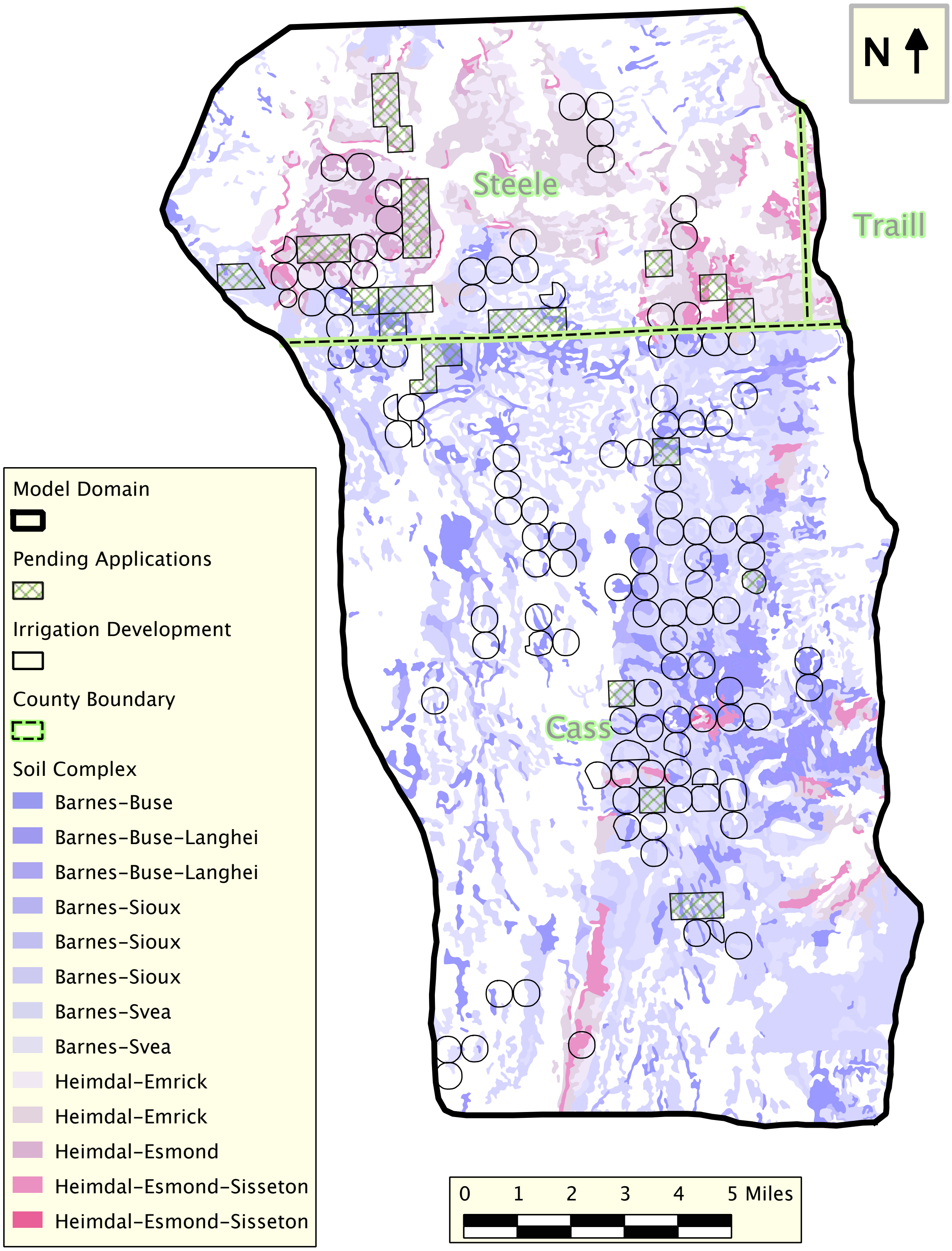

Figure 11. -- Dominant soil series (Barnes and Heimdal) within the model domain (derived from Cass, Steele, and Traill County SSurgo data).

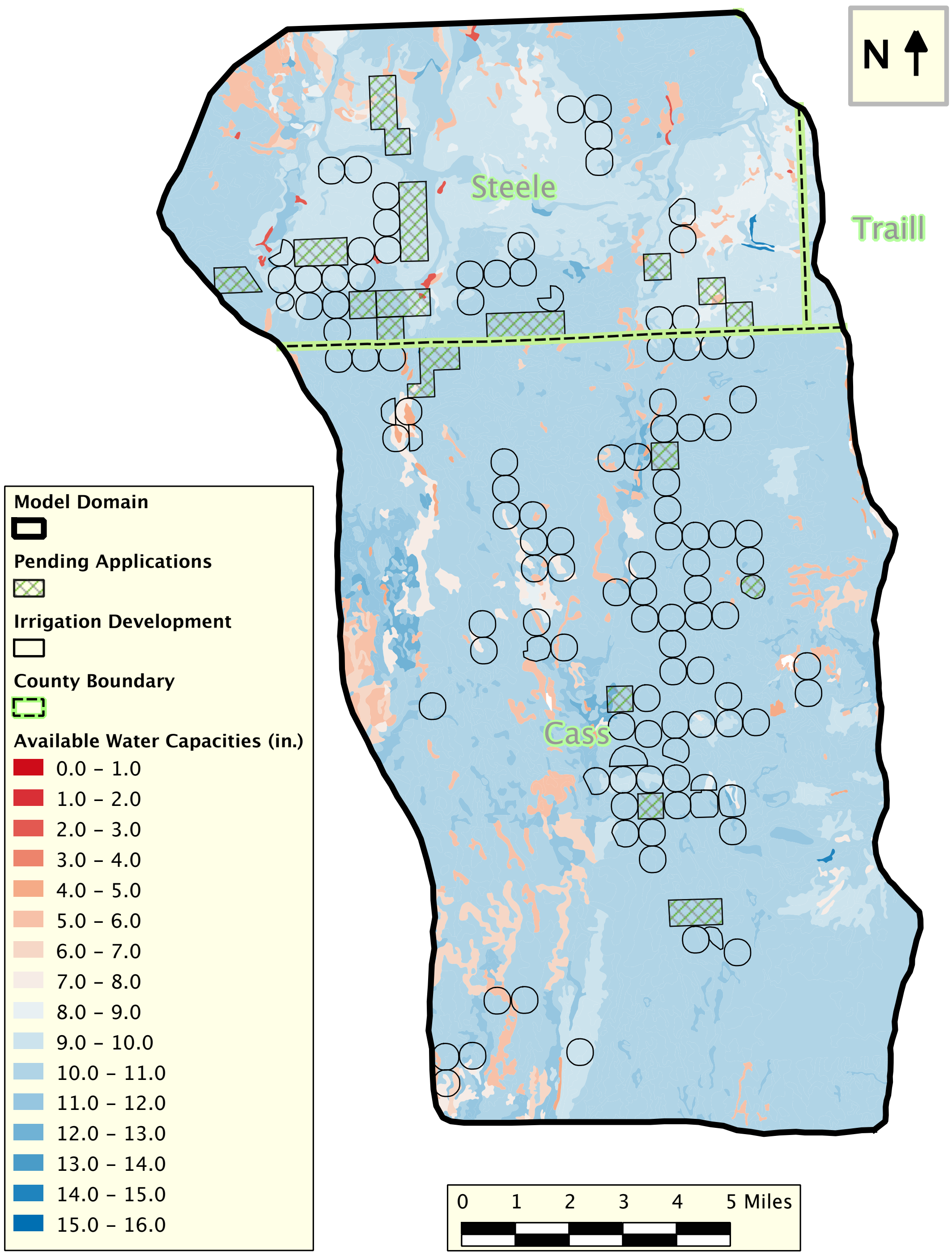

Figure 12. -- Available water capacity of soils within the model domain (derived from Cass, Steele, and Traill County SSurgo data).

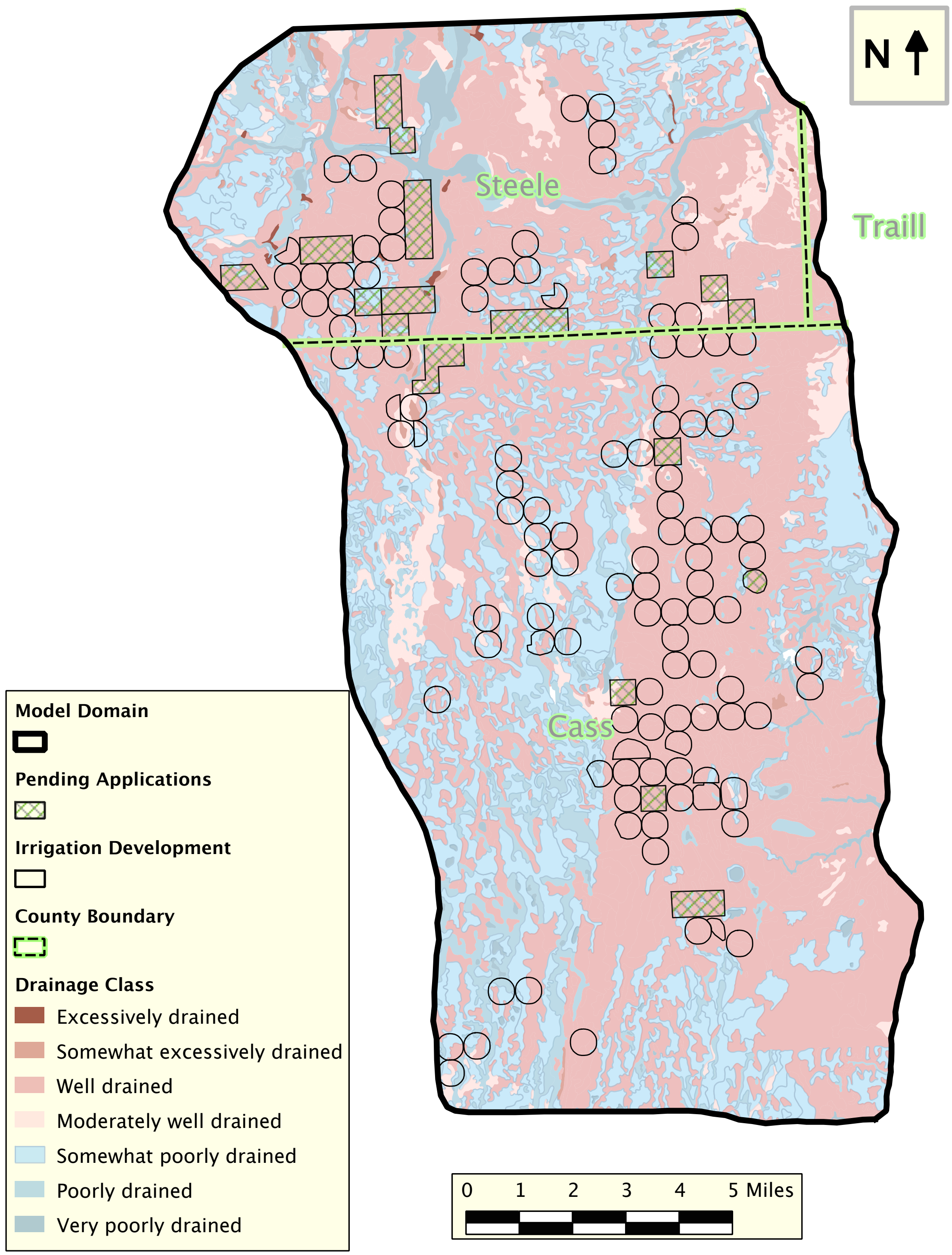

Figure 13. -- Drainage classification of soils within model domain (derived from Cass, Steele, and Traill County SSurgo data).

available water capacity, and drainage classification maps were all generated using SSURGO soils data downloaded from the USDA-NRCS Soils Mart website.

Geology

The surface geology of the study area is characterized by the Pleistocene Coleharbor Formation (Bluemle, 1975). The Coleharbor Formation is comprised of till facies, sand and gravel facies, and silt and clay facies.

The till facies are a non-stratified mixture of sand, gravel, and boulders in a silty-clay matrix. The coarser fraction of the till consists of shales, carbonates, granitics, and basal igneous rocks. The shale was derived from local bedrock formations. Carbonates were derived from a Paleozoic carbonate sequence from southern Canada and the granitics and other igneous rocks were derived from the Canadian Shield (Bluemle, 1975).

The sand and gravel facies consist primarily of deltaic and fluvial sediments deposited by glacio-fluvial processes during the Pleistocene. During early development of the Page aquifer, glaciers covering the study area were receding to the north. As they receded, sediment-laden melt water began flowing into Lake Agassiz and other proglacial lakes within the study area. As the melt-water reached the lakes, the streams slowed and dumped their sediment load near the mouth of the streams forming a series of deltas. These deltas coalesced to form a somewhat continuous mass of sand deposits, which we now refer to as the Page aquifer. The Page aquifer is primarily a deltaic fine-textured sediment consisting mostly of very fine to medium sand. However, coarser fractions of fluvial sand and gravel can be found in the northwest part of the aquifer, where the melt-water streams first moved into the area. The texture of the aquifer matrix becomes finer the further away from the melt-water source. Therefore, the south and east portion of the aquifer is comprised of finer grained sediments.

The hydrostratigraphy associated with the sand and gravel facies is a fairly continuous layer throughout the model domain with exception of the areas defined in Figure 14.
The areas of complex hydrostratigraphy comprise approximately 25% of the model domain. In these areas, extensive drilling would be required to define the highly complex geology and flow system. Figure 15 shows the trace of two hydrogeologic cross-sections I-I' and FF-FF' that cross the areas of complex hydrostratigraphy (Figure 16 & 17). Hydrogeologic section I-I' shows a

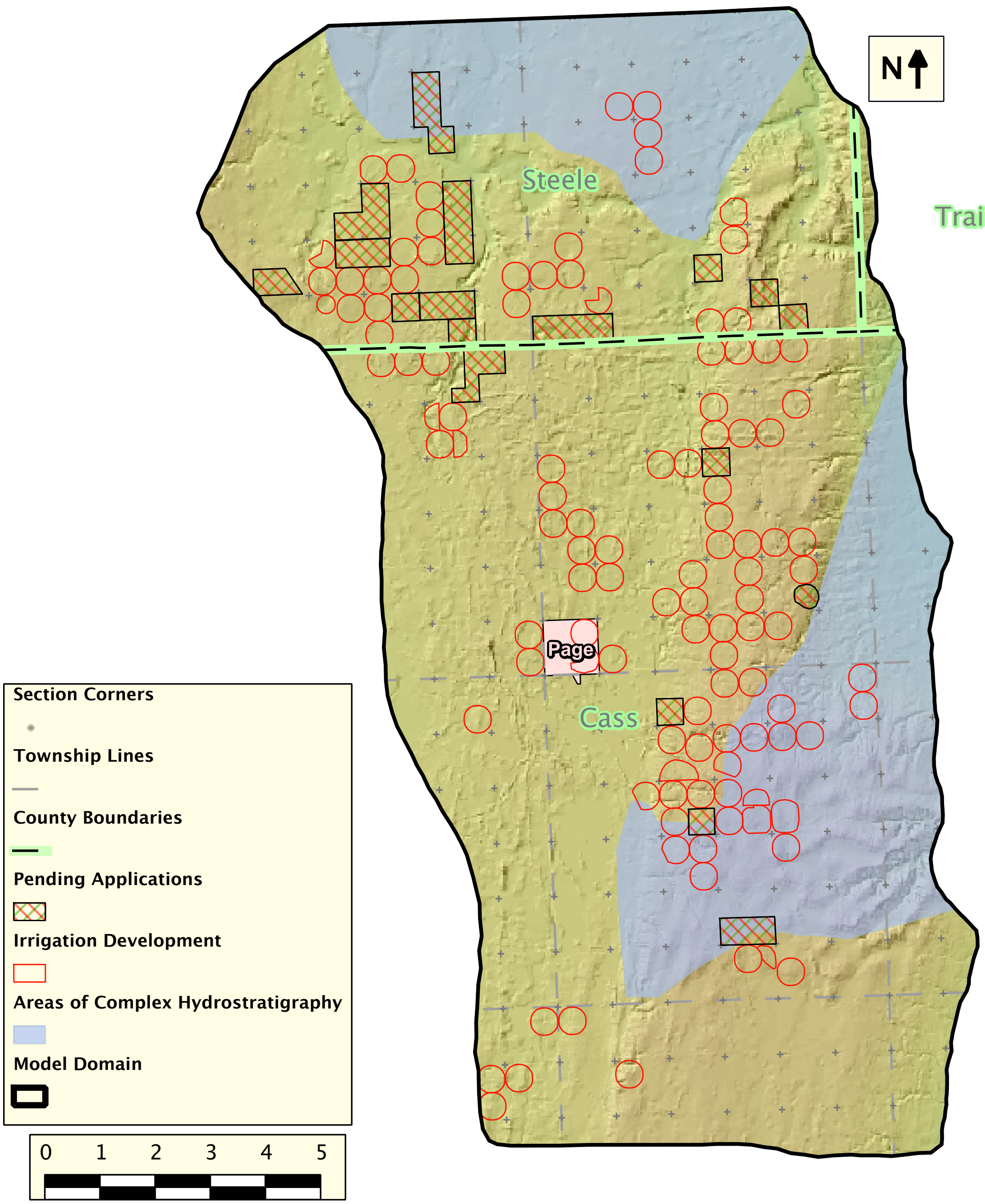

Figure 14. -- Areas defined as having complex hydrostratigraphy.

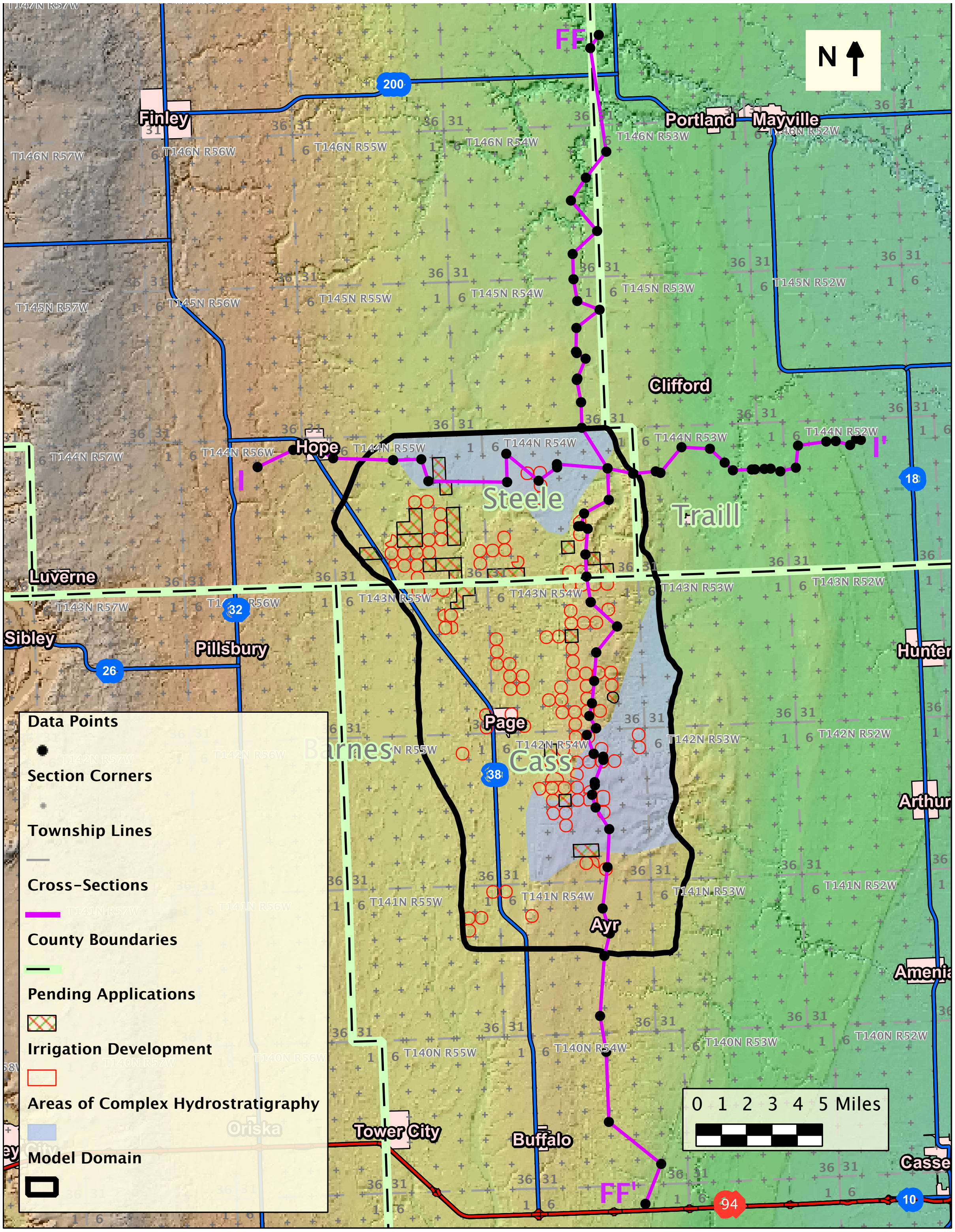

Figure 15. -- Areas defined as having complex hydrostratigraphy with traces of hydrogeologic sections I-I' and FF-FF'.

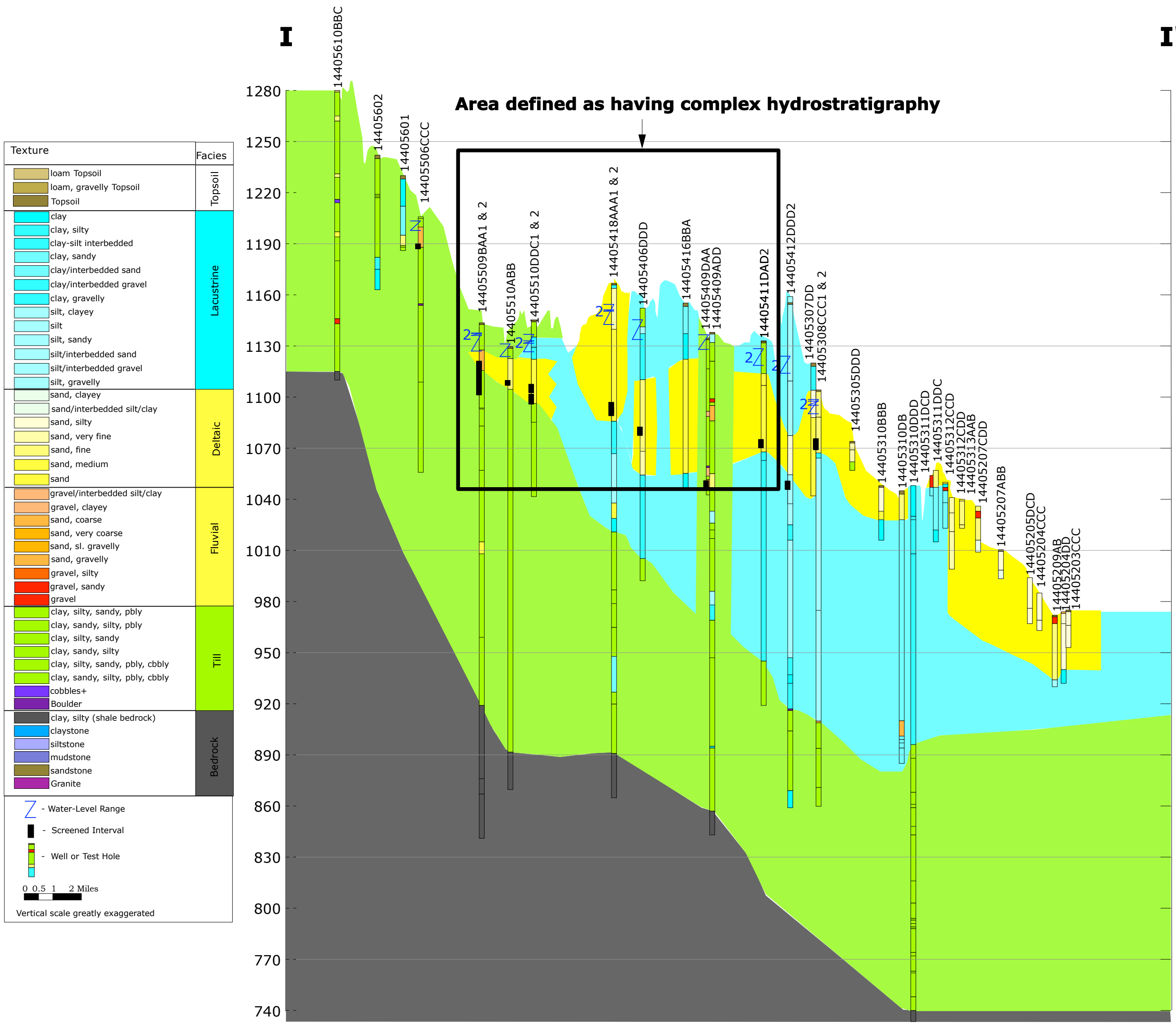

Figure 16. -- Hydrogeologic section I-I' showing area of complex hydrostratigraphy.

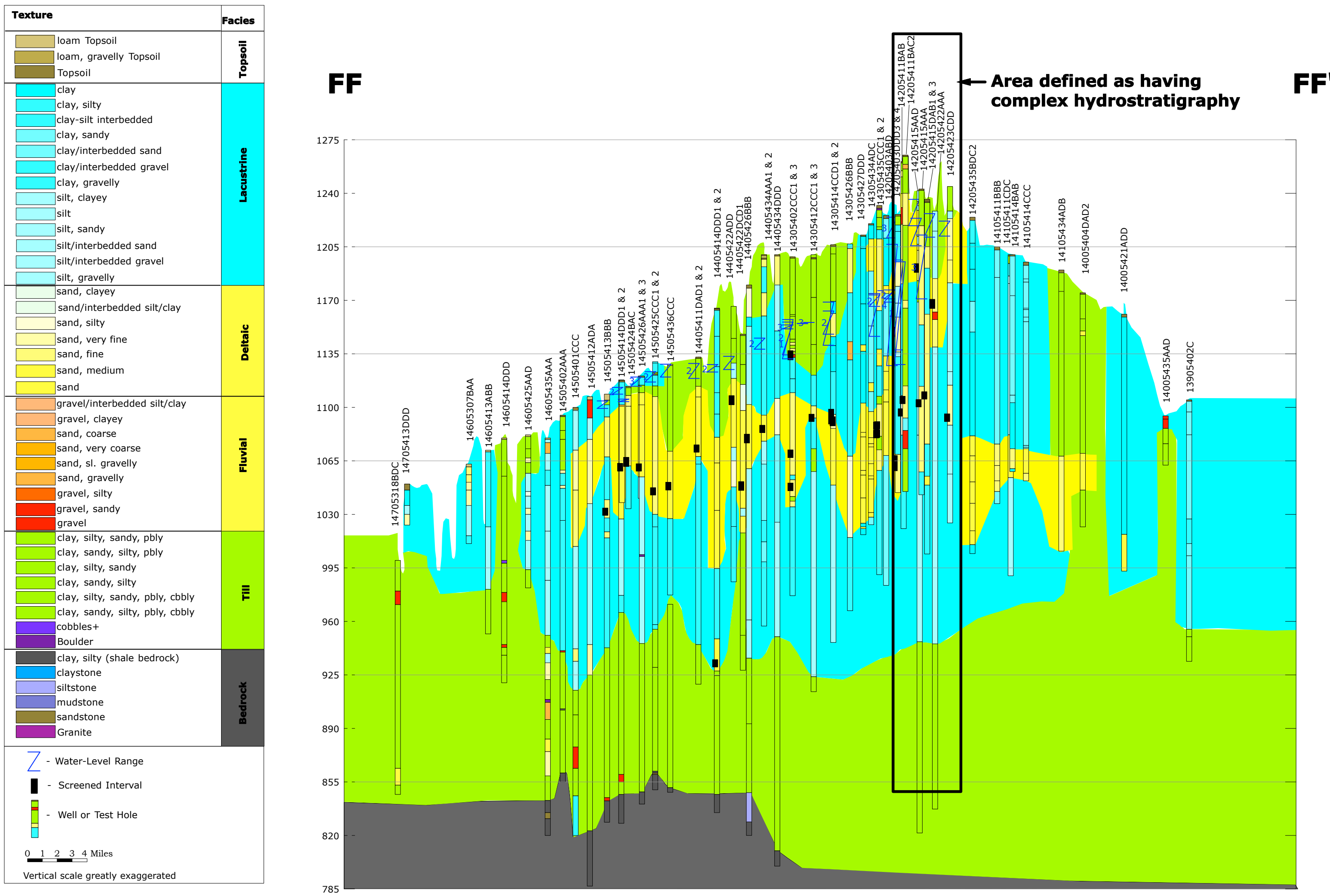

Figure 17. -- Hydrogeologic section FF-FF' showing area of complex hydrostratigraphy.

transverse section through discontinuous sand facies in the northern part of the aquifer and hydrogeologic section FF-FF' shows a longitudinal section through discontinuous sand facies in the southeastern part of the aquifer. Both hydrogeologic sections show significant water-level discontinuities in the areas defined as having complex hydrostratigraphy.

Areas outside the shaded regions in Figure 18 represent areas with more continuous hydrostratigraphy. Hydrogeologic sections M-M' and BB-BB' show fairly continuous sand and gravel facies and similar water levels within the model domain (Figures 19 & 20). Silty-clay and clayey-silt facies of the Coleharbor Formation occur throughout the study area. These finer sediments were deposited by proglacial lakes. In the study area, the Coleharbor Formation is unconformably underlain by the Greenhorn Formation. The Greenhorn Formation consists of marine shale deposited during the Cretaceous Period. The bedrock in eastern North Dakota makes up the eastern edge of the Williston Basin and the northwest flank of the Transcontinental arch. All the bedrock formations have a westerly dip and become thicker westward (Bluemle, 1967).

Hydrologic Setting

Recharge

Recharge to the Page aquifer occurs primarily during the spring in response to increased precipitation and snow melt (Figure 21). The peaks on the 1970 to 1980 hydrograph within Figure 21 represent recharge events. Recharge, for the most part, is significantly less during the summer months because potential evapotranspiration exceeds precipitation. At times, summer precipitation events of sufficient intensity and duration can overcome soil-moisture deficits and generate recharge, particularly in local depression areas. During the fall, potential evapotranspiration decreases significantly and precipitation events can be large enough to generate recharge. Even when recharge does not occur during the fall, soil-moisture deficits can be reduced significantly, affecting an increase in the magnitude of the following spring recharge event(s) (Cline, 2011). Steady water-level increases throughout the summer and fall of 1993, 1994, and 2004 reflect relatively large recharge events (Figure 21).

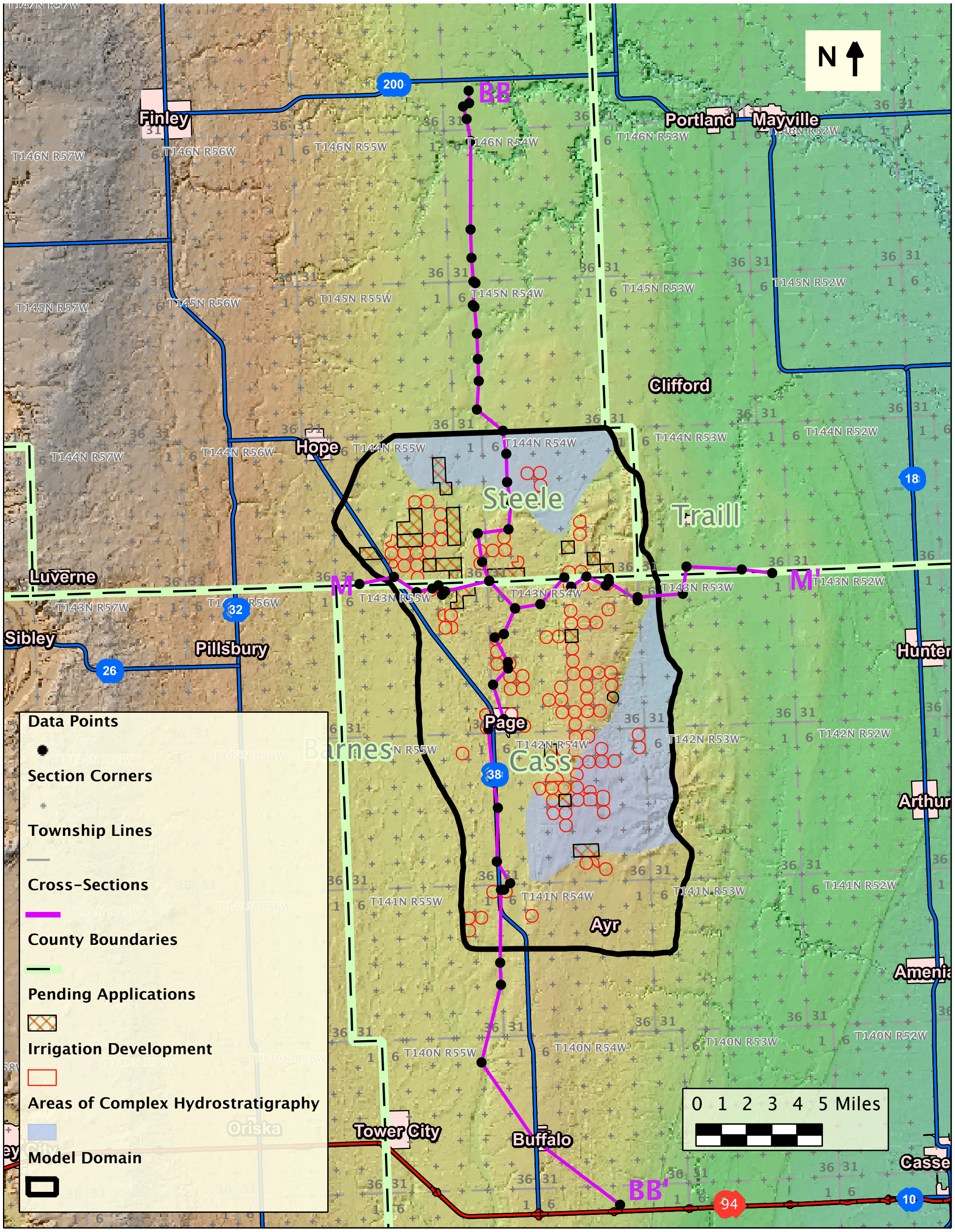

Figure 18. -- Areas defined as having complex hydrostratigraphy (gray) with traces of hydrogeologic sections M-M' and BB-BB' through areas of continuous hydrostratigraphy.

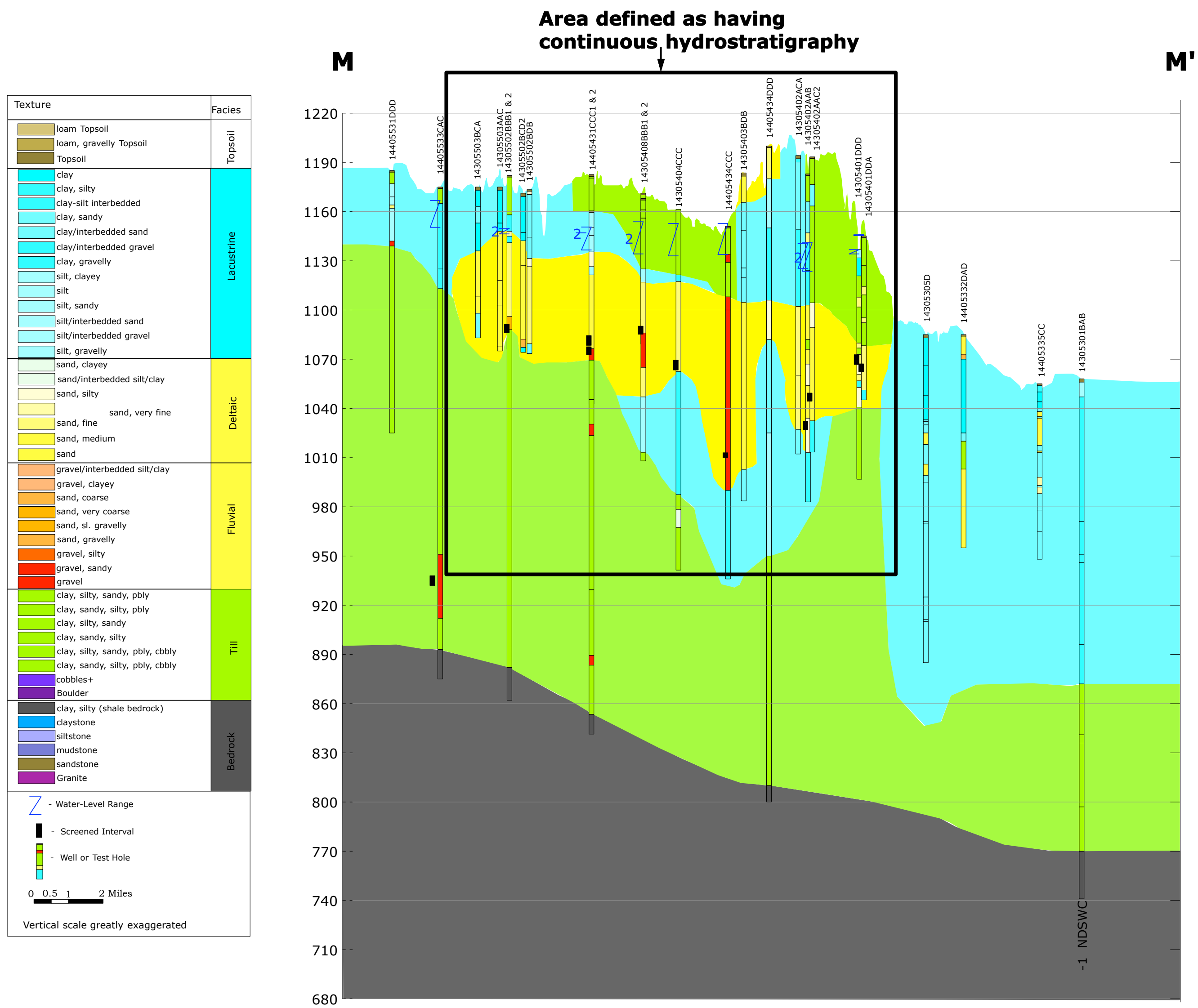

Figure 19. -- Hydrogeologic section M-M' showing area defined as having continuous hydrostratigraphy.

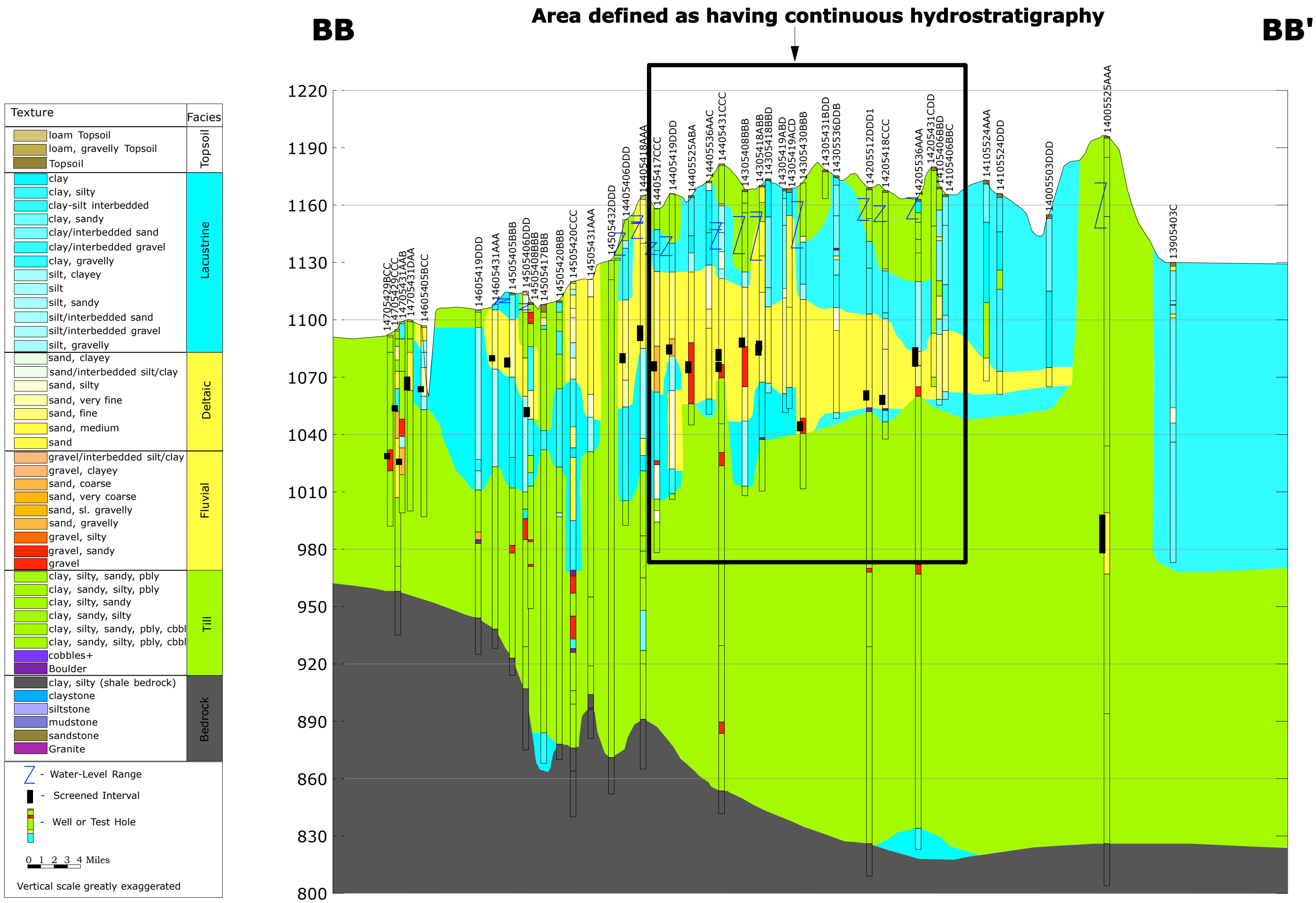

Figure 20. -- Hydrogeologic section BB-BB' showing area defined as having continuous hydrostratigraphy.

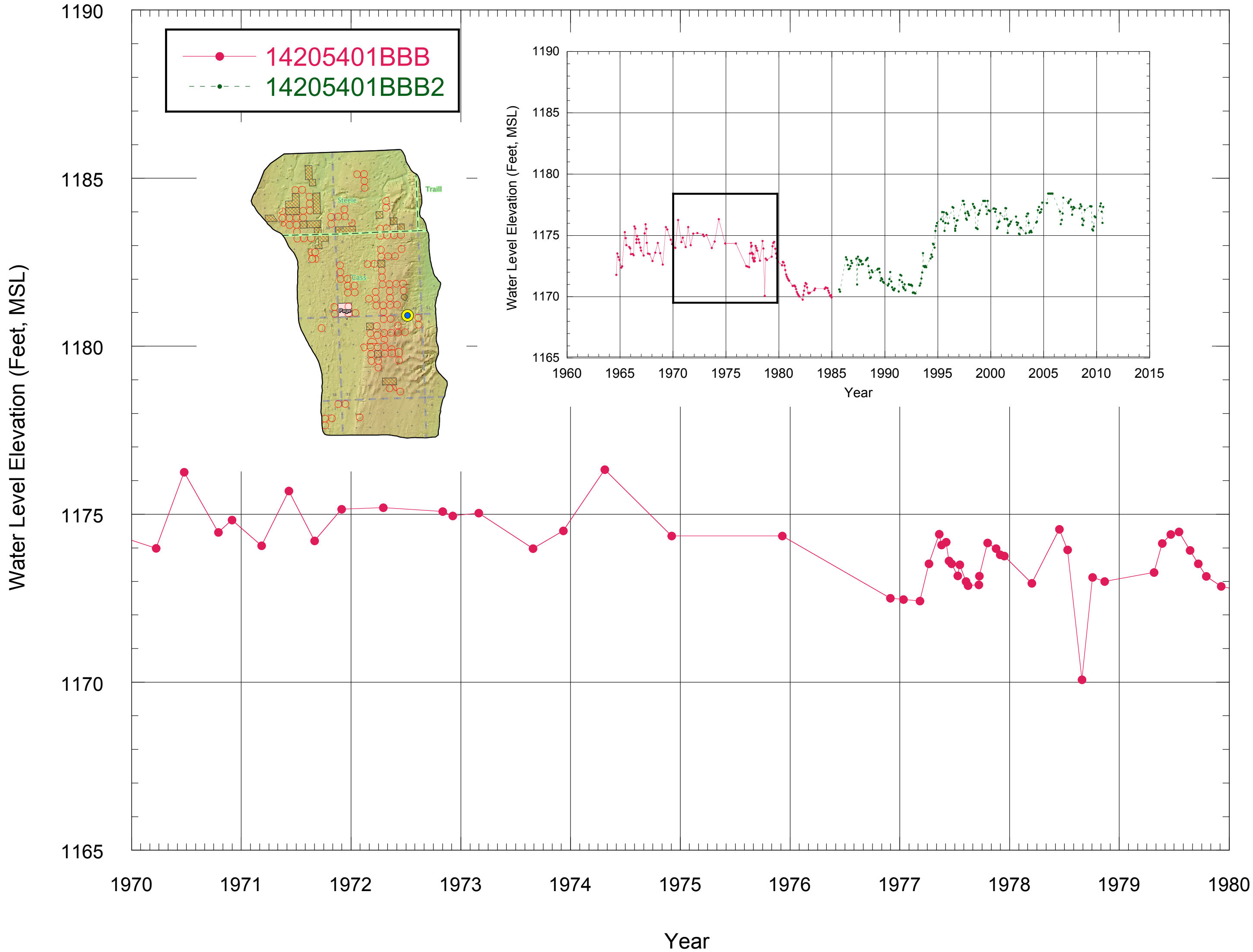

Figure 21. -– Hydrograph of observation well 14205401BBB1 & 2 showing water levels before and during irrigation development.

Discharge

Ground water moves under the influence of gravity from areas of recharge to areas of discharge. In low relief areas discharge occurs as springs and seeps. In closed basins, these springs and seeps develop into small wetlands (Figure 22). However, where possible most wetlands have been drained into county drains or local streambeds to improve productivity of agricultural lands. In well-drained areas these springs and seeps become the headwaters for streams. The south branch of the Goose River, Elm River, Rush River, and Swan River all derive some proportion of flow from Page aquifer discharge (Figure 6).

Discharge from the aquifer also occurs by evapotranspiration and discharge from stock, domestic, municipal, rural water, and irrigation wells. Areas of evapotranspiration can be determined using the National Wetland Inventory Data provided by the United States Fish and Wildlife Service (2013) and soil drainage classification data provided by the USDA (2013) (Figures 13 & 22). The National Wetland Inventory maps define the extent of temporary, seasonal, semi-permanent, and permanent wetlands, which are good indicators of where discharge from the aquifer is occurring. In addition, soils defined as poorly drained from the soil drainage classification maps are also indicators of local discharge areas.

Figure 21 shows recharge and discharge by respective peaks and valleys in the hydrograph from 1970 to 1980. Irrigation and rural water use in the Page Aquifer began in 1976 and 1979, respectively. All discharge from the aquifer before this time was by natural processes of evapotranspiration and discharge to seeps and springs, with exception to a few municipal wells and many low yielding domestic and stock wells. The hydrograph in Figure 21, shows minimal water-level declines from 1970 to 1980, with exception to the extensive water-level decline observed in 1978. The water-level decline in 1978 was primarily due to the pumping effects of nearby irrigation wells.

Of the total water allocated from the Page aquifer, 90 percent of the water is diverted for irrigation purposes. The first irrigation permit from the Page Aquifer was granted in October 1975. Figure 23 shows the historical water use from irrigation permits from 1976-2012. The maximum reported water use for irrigation was in 2006 when 7,378 acre-feet of water were applied to the land. The largest annual irrigation application rate, excluding 1976 (when only 270 acres were irrigated) occurred in 1980 when over 8 inches of water per acre was applied.

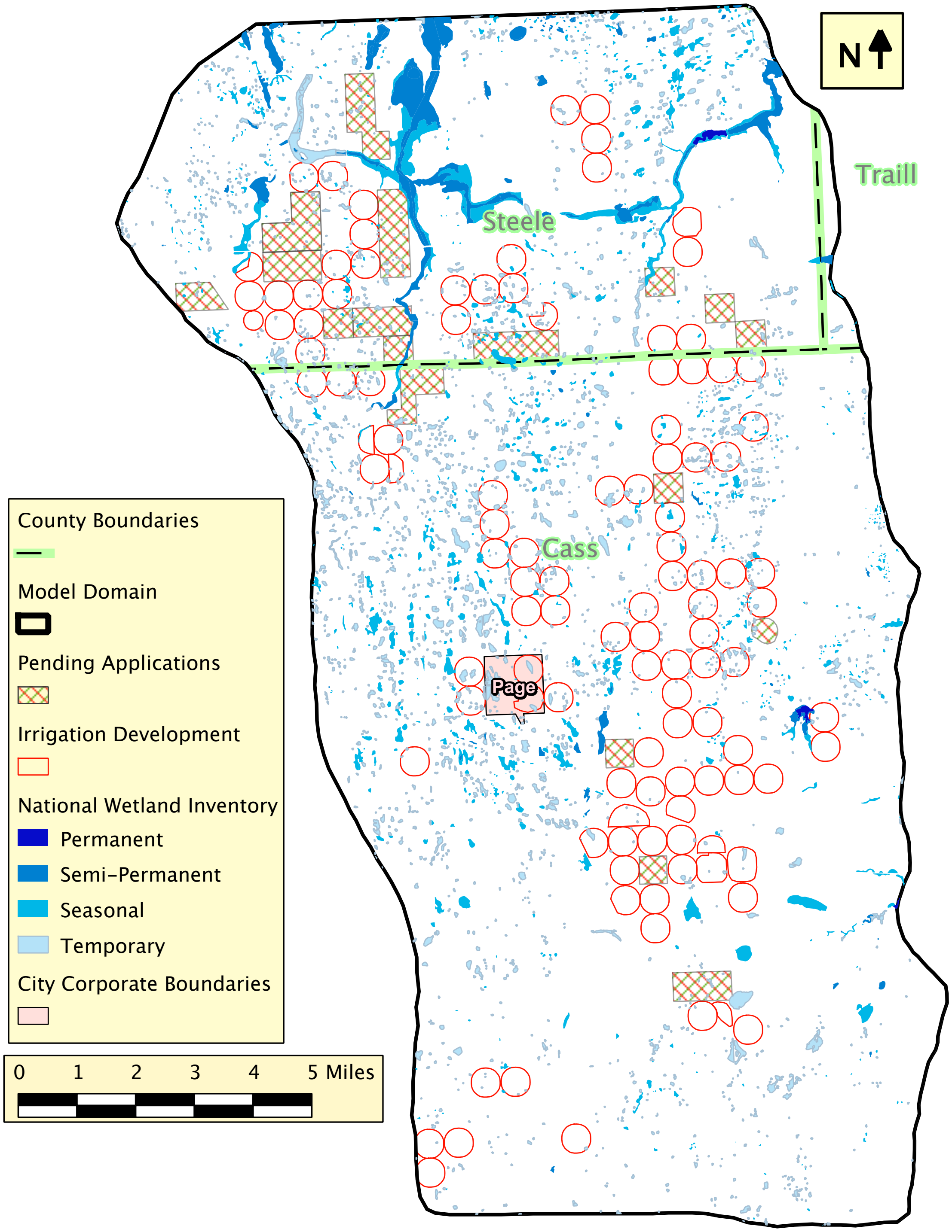

Figure 22. -- Location of wetlands within the National Wetland Inventory database.

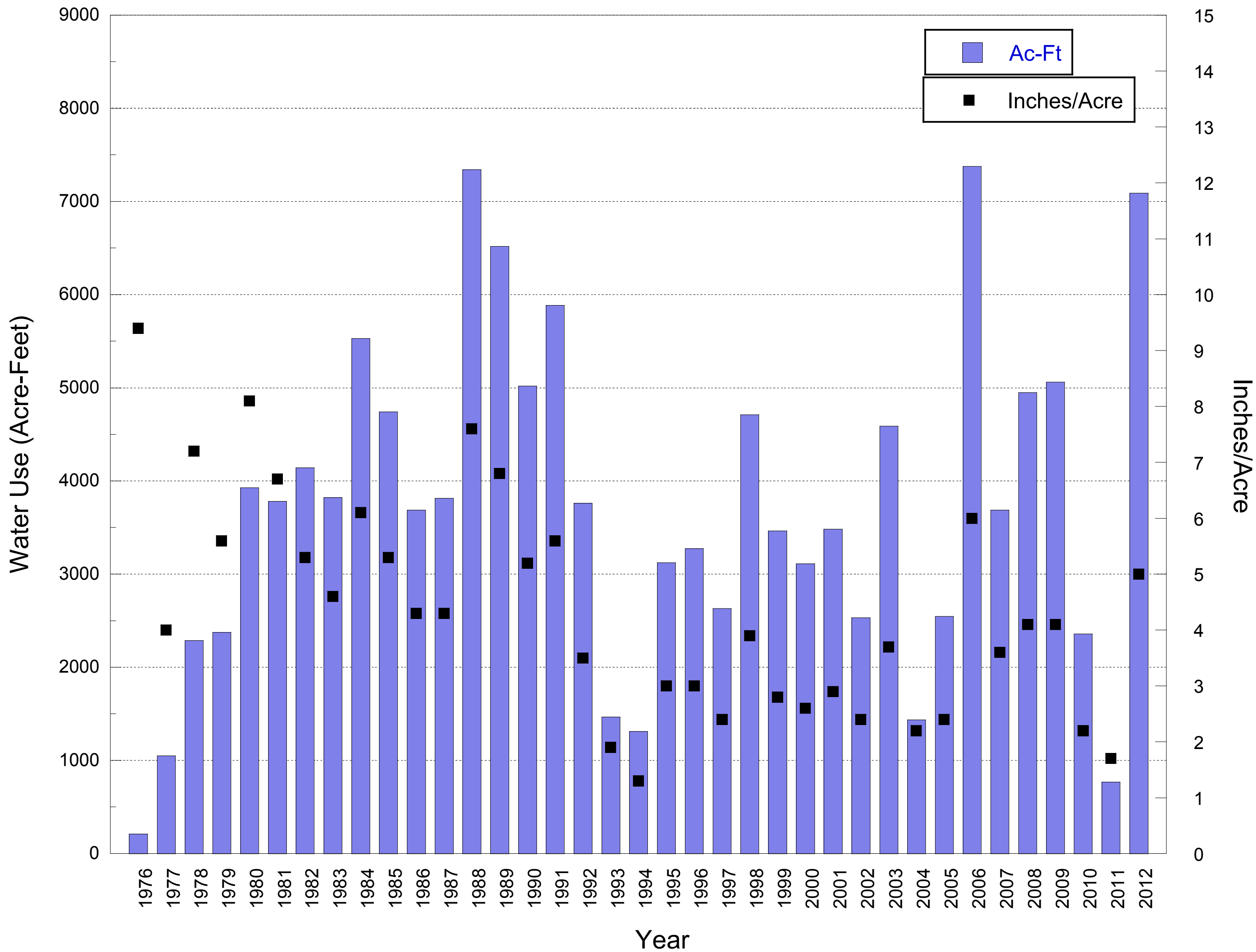

Figure 23. -- Average historical irrigation water use from 1976-2012.

Movement of Ground Water

The ground-water potentiometric surface in the Page aquifer is a subdued replica of the land surface (Figure 24). There is a water-level mound in the southeast portion of the aquifer, in the area where the aquifer is characterized by complex hydrostratigraphy. Ground-water flow from this area radiates outward in all directions while the regional flow is to the north and east toward the Lake Agassiz plain.

Figures 25 through 30 show representative hydrographs from the Page aquifer. The location of the observation wells associated with these hydrographs is shown as Figure 24. The hydrograph for observation wells 14205408DDD and 14205408DDD2 show small water-level fluctuations prior to 1977, when there was no significant irrigation development (Figure 25). Seasonal drawdown effects due to irrigation development are evident from the early 1980s through 2012 for several of the hydrographs (Figure 25-29). Observation wells 14405418AAA and 14405418AAA2 are located in an isolated part of the aquifer, where they are not affected by growing season drawdown effects from irrigation pumping (Figure 30). The general trend of the hydrographs can be correlated to the amount of precipitation received. The drought from 1988 through 1992 is defined by a decline in water levels, and the extremely wet period in the mid-1990s is defined by large increases in water levels. Additional observation well hydrographs are provided in Appendix A.

Water Permits

There are 14,946 acres permitted for irrigation from the Page aquifer under 43 perfected water permits (Figure 2). In addition to the 43 irrigation permits there are 3 rural water permits and 2 municipal permits. Cass Rural Water District holds one rural water permit in the southwest part of the aquifer and Traill Rural Water District holds three rural water permits in the northeast part of the aquifer. The municipal permits for the city of Page and the city of Hope are currently inactive because both communities are being supplied water from rural water systems. Currently, there are 18 pending water permit applications that need to be evaluated. Seventeen of these applications are for irrigation and one is a rural water application. The pending applications for irrigation total 4,091 acres. These applications have not been granted because of the uncertainty associated with the effects of pumping (both intra-seasonal and long-term) on prior appropriators.

Figure 24. -- Water-level contour map of the Page aquifer based on observed water levels from November 2010.

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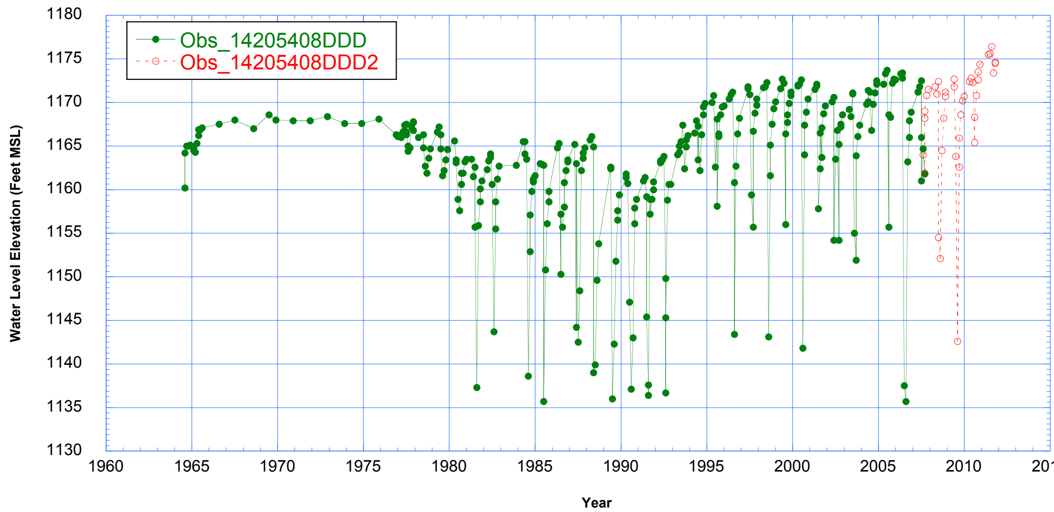

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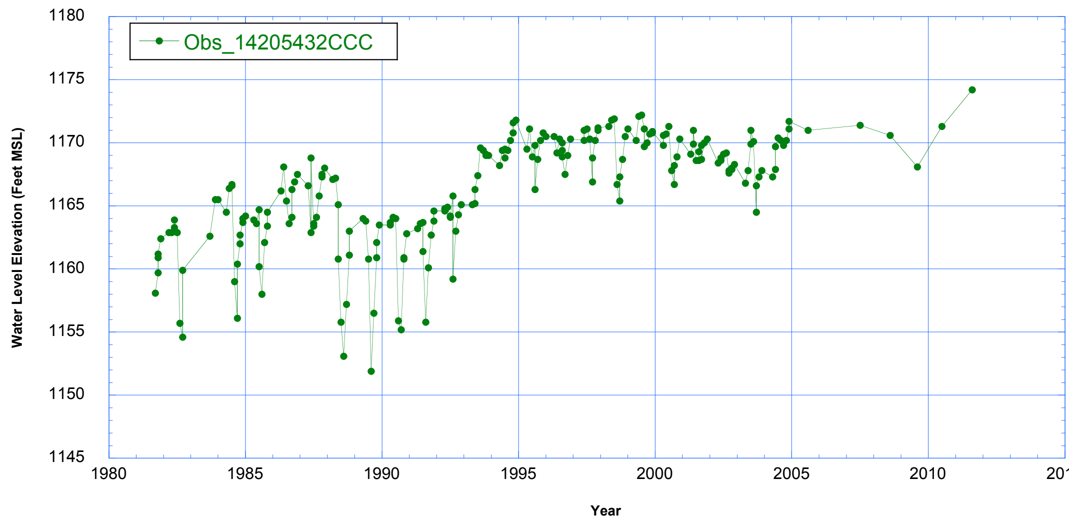

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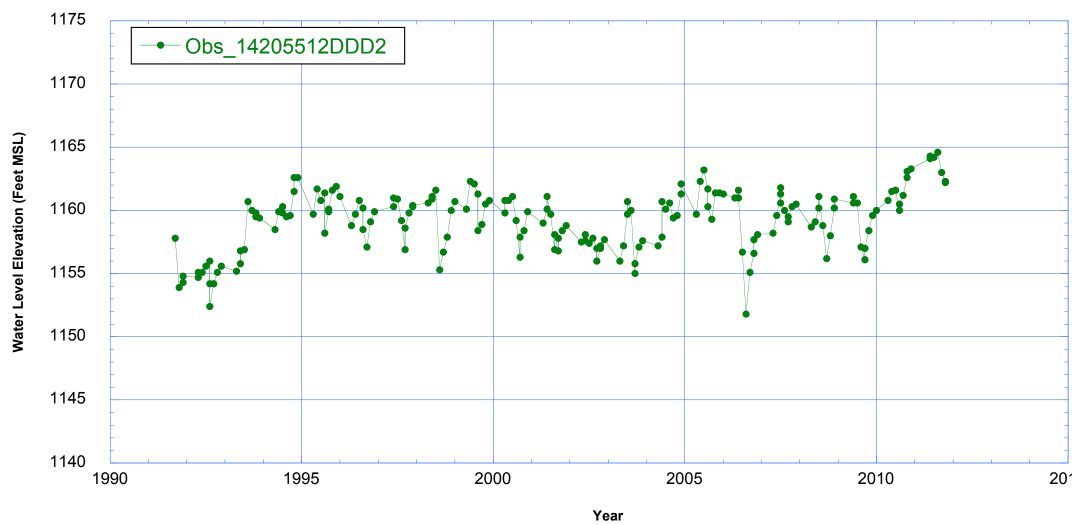
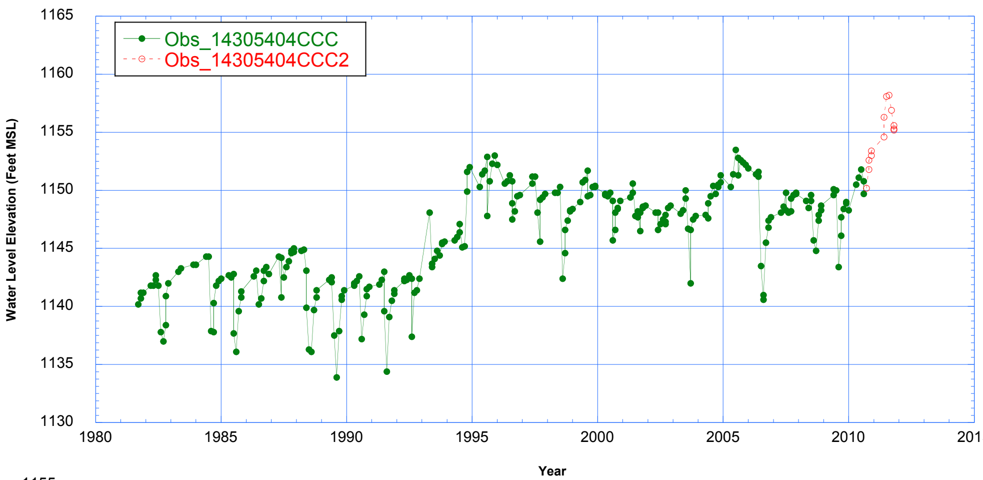


Figure 25, 26, & 27. -- Hydrographs of observation wells 14205408DDD & 14205408DDD2(25), 14205432CCC(26), & 14205512DDD2(27)

28)



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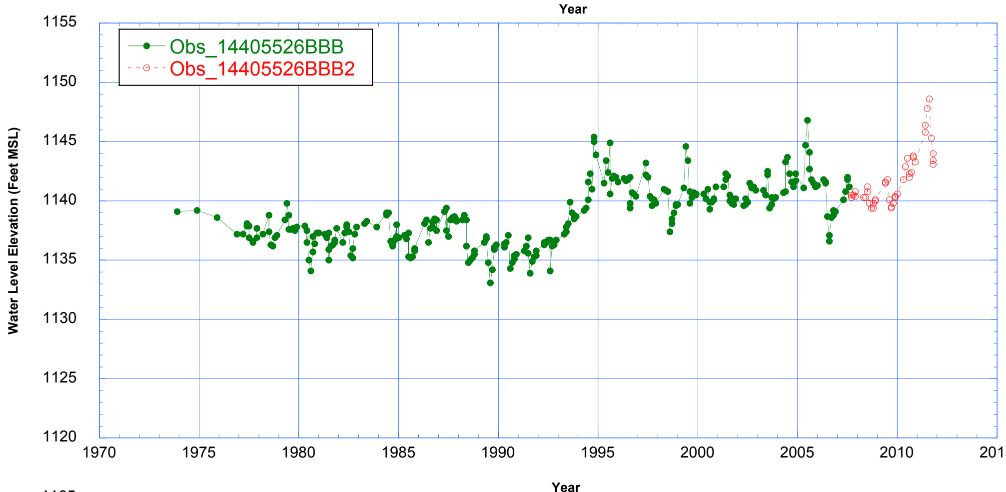

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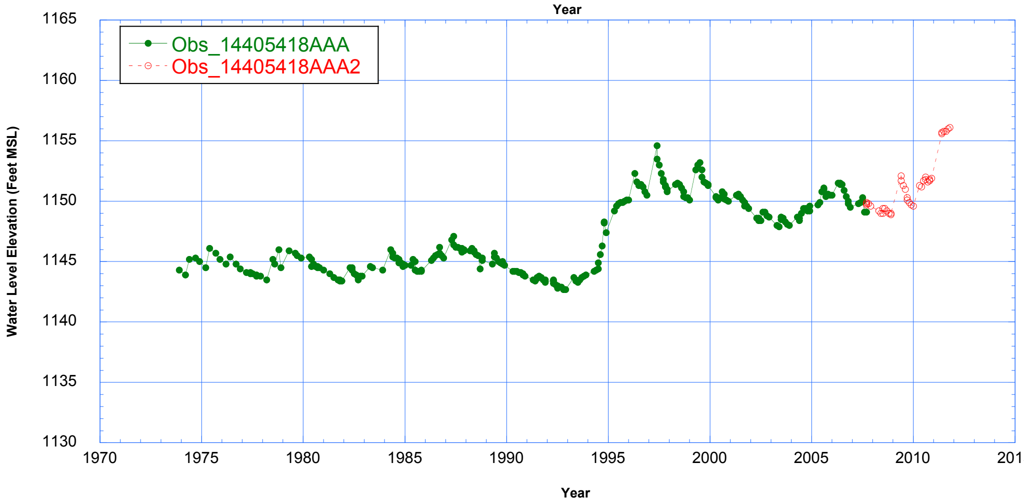


Figure 28, 29, & 30. -- Hydrographs of observation wells 14305404CCC & 2 (28), 144205526BBB & 2(29), 14405418AAA & 2(30).

Considerations in Allocating Ground Water for Irrigation

As previously stated, the land overlying the Page aquifer consists of moderately to well drained soils with large moisture holding capacities. Because of the large moisture holding capacity soils, the Office of the State Engineer has used a unique management approach to allocate ground water when compared to other aquifers in the state. When evaluating each irrigation permit from the Page aquifer, the Office of the State Engineer completed a detailed analysis of the soil types, climate, and the potential crop types in order to estimate maximum water use needs. This method was used to better manage the resource and to allow more water to be put to beneficial use.

In general, most ground water permits for irrigation in North Dakota are approved for an annual allocation of 18 inches per acre and a pumping rate ranging from 6 to 7 gpm per acre. This is done to allow the irrigator adequate water in drought years, though it is expected that average use will be significantly less than this even on gravelly soils. The Page aquifer annual allocation ranges from 7 inches per acre to 18 inches per acre with an average of 10.5 inches per acre (Figure 31). In addition, the approved pumping rates were set proportional to the annual allocations. The average approved pumping rate from the Page aquifer is 3.7 gpm per acre. The lower pumping rates insure that the irrigator cannot exceed their annual appropriation.

Conventional irrigation capture systems in other parts of the state generally consist of 1 to 3 wells to provide 800 gpm per quarter-section pivot system (133 acres). In the Page aquifer, which is overlain by large moisture holding capacity soils, it is not uncommon for irrigation capture systems to be comprised of a 500 gpm well providing water to two quarter-section pivot systems or two 400 gpm wells, providing water to 3 quarter-section pivot systems (Figure 32). Even though the Page Aquifer has been constrained to more conservative annual allocations, irrigation application rates have been adequate during the first 36 years of development. However, under extreme drought conditions more severe than has been experienced in the last 36 years, the allocation and/or well capture systems may not provide adequate irrigation application rates.

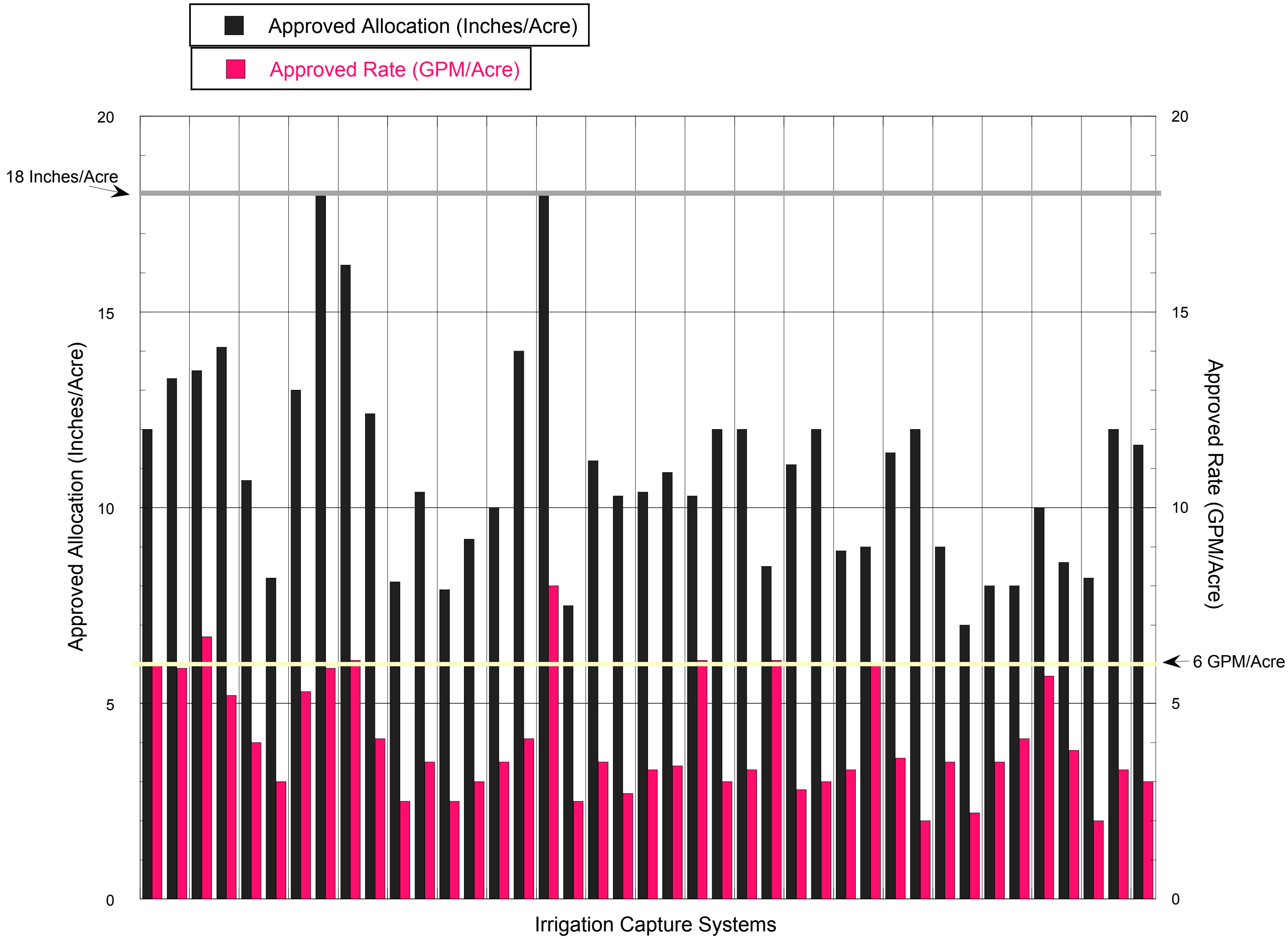


Figure 31. -- Comparison of the approved allocation (inches of water per acre) and the approved rate (gallons per minute per acre) for 41 irrigation capture systems in the Page aquifer.

Aquifer Hydraulic Properties

Prior to model development, review of four aquifer tests conducted by the Water Appropriation Division of the N.D. State Water Commission was completed to help in determining aquifer hydraulic properties (Figure 33). The hydraulic properties from the aquifer tests are shown in Table 2. Transmissivities and associated hydraulic conductivities are highly variable across the aquifer, due to varying sediment textures, which range from a very fine sand to coarse gravel.

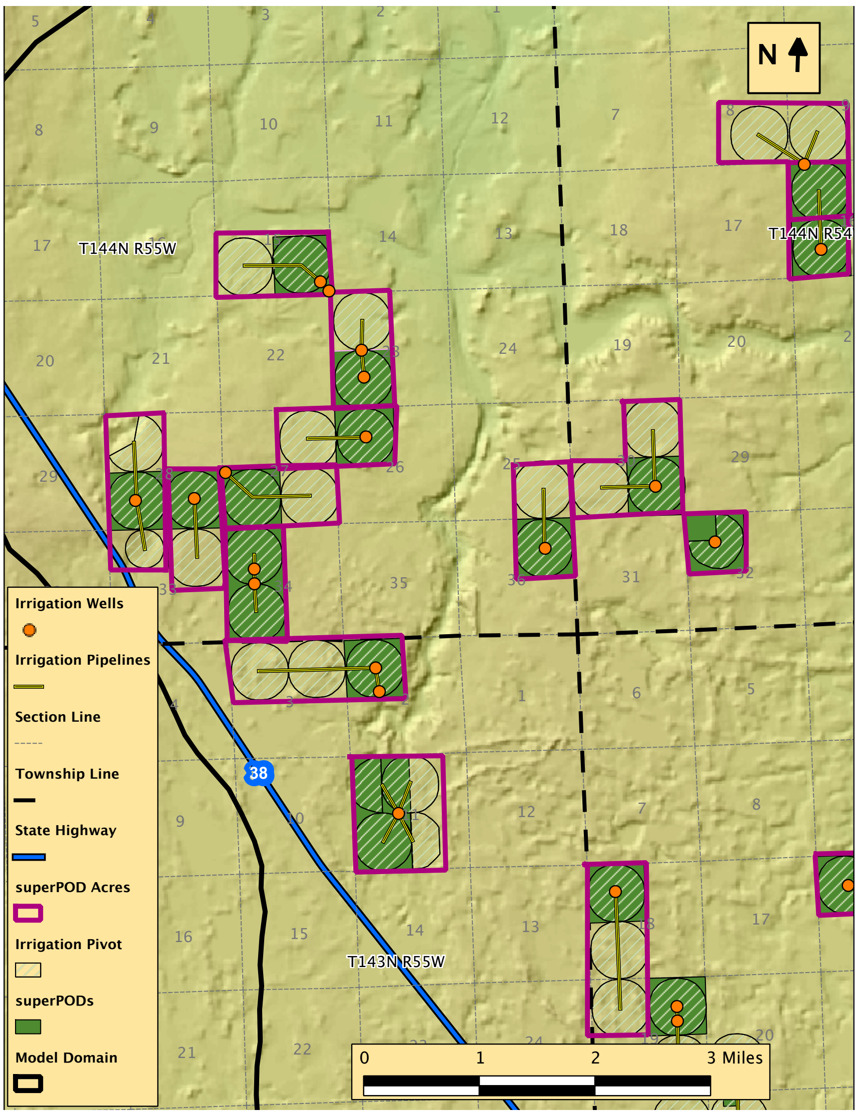


Figure 32. -- Examples of irrigation well capture systems within the Page Aquifer.

Water Quality

Based on chemical analysis of 900 ground-water samples collected from 289 wells completed in the Page aquifer, the groundwater is predominantly a calcium-bicarbonate to calcium-sulfate type (Figure 34). The samples were collected and analyzed over the period from 1964 through 2012. The water quality is considered good for irrigation applications with an average total dissolved solids (TDS) concentration of 623 mg/L and with 98 percent

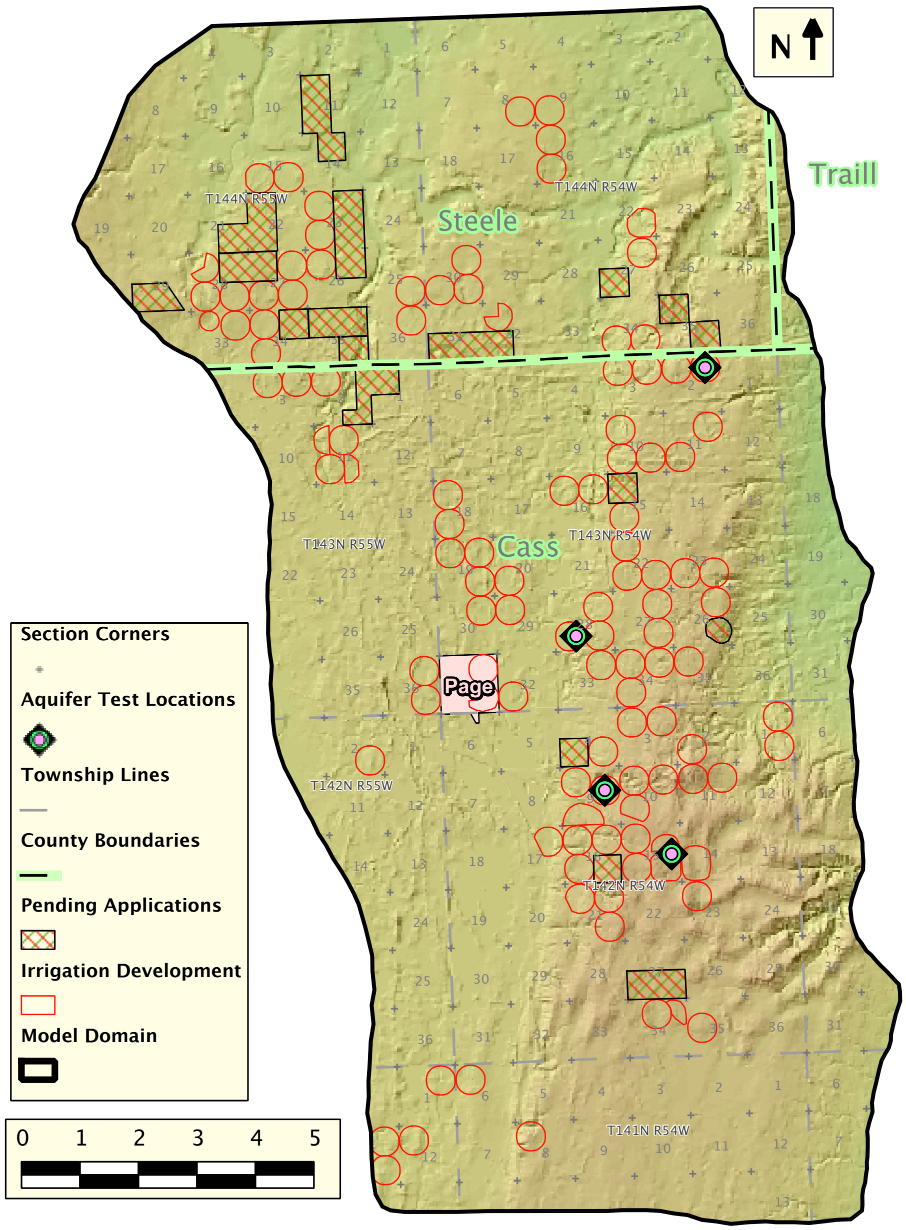


Figure 33. -- Location of N.D. State Water Commission run aquifer tests within the model domain.

Aquifer Test	Date	T (ft^2/day)	K (ft/day)	S	Specific Capacity (gpm/ft)
14305428C	Oct-78	3700	36	$4.0x10^{-4}$	9.75
14205415D	Jun-79	2005	25	$3.6x10^{-4}$	N/A
14305402A	Jun-79	5220	70	$5.6x10^{-4}$	N/A
14205409A	Jun-79	1941	N/A	$4.1x10^{-4}$	N/A

Table 2. -– Page aquifer hydraulic properties determined from aquifer tests conducted by the Water Appropriation Division of the N.D. State Water Commission.

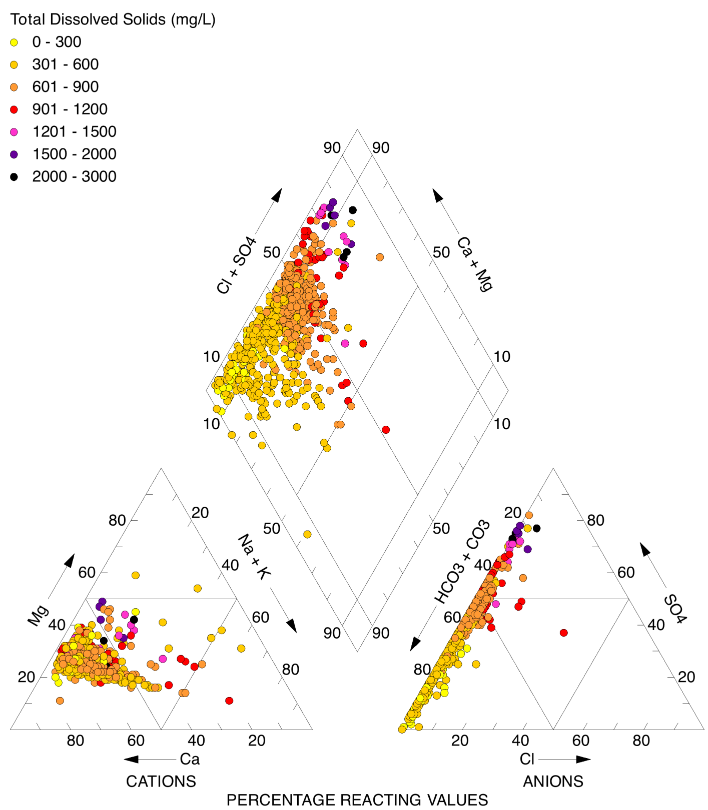


Figure 34. -- Relative distribution of major ions in wells completed in the Page aquifer.

of the samples having a TDS less than 1200 mg/L. In addition, the average sodium adsorption ratio (SAR) is less than 1 with all the samples having a SAR less than 6. Generally, an SAR less than 6 and TDS less than 1200 mg/L are considered suitable for irrigation applications.

Trace element analysis was completed on 73 of the 900 samples collected. The trace element of most concern is arsenic. Arsenic is a naturally occurring element and it is commonly found in glacial drift aquifers of North Dakota. Arsenic can impact human health through the ingestion of water. Elevated levels of arsenic can cause skin damage or problems with circulatory systems, and has been linked to numerous types of cancer. The updated USEPA maximum contaminant level (MCL) standard for arsenic became effective on January 23, 2006, when the MCL was lowered from 50 µg/L to 10 µg/L. Water suppliers are required to provide water that meets the MCL standards. Arsenic levels exceeded the MCL in 49 of the 73 samples collected from the Page aquifer. Four samples collected exceed the arsenic MCL by 10 times.

Mean values of selected ions, dissolved solids, hardness, selenium, arsenic, USEPA MCL, and USEPA secondary maximum contaminant levels (SMCL) for aquifer water samples are shown in Table 3. The SMCLs are non-enforceable recommended standards. Values exceeding SMCL are not considered a health hazard. Ground water in the Page aquifer commonly exceeds SMCL for iron, manganese, and total dissolved solids. Although there is no federal limit for the SMCL for hardness, ground water in the Page aquifer would be considered very hard (Table 3).

	Selenium (mean µg/L)	Arsenic (mean µg/L)	TDS (mean mg/L)	Hardness as CaCo3 (mean mg/L)	Sulfate (mean mg/L)	Chloride (mean mg/L)	Iron (mean mg/L)	Manganese (mean mg/L)	Fluoride (mean mg/L)
MCL	50	10	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SMCL	N/A	N/A	500	N/A	250	250	0.3	0.05	2
Page Aquifer	5.7	28.5	623	471	223	5.7	0.9	1	0.3

Table 3. -- Mean concentrations of TDS, major ions, hardness, selenium, and arsenic.

Model Development

Introduction

The Page aquifer has reached a level of maturity from a development standpoint and as a result a 3-dimensional ground-water model was developed to provide the basis for taking action on 18 pending water permit applications. The process of modeling the aquifer included developing a conceptual model, steady-state model calibration, transient model calibration, and predictions of growing season drawdown effects and long-term sustainability of ground-water withdrawals associated with permitted allocations and pending water permit applications.

Model Grid

In a finite-difference model, the aquifer is divided into rectangular blocks. The center of a block is referred to as a node. The Page model uses a grid spacing of 462 feet (east/west) by 495 feet (north/south). The model consists of 251 rows, 170 columns, and 2 layers. The active nodes are shown in Figure 35. The model simulates two layers, which represent the sediments between land surface and the bottom of the aquifer. Although the study area for this project is defined as the entire Page aquifer, the model domain does not encompass the entire aquifer (Figure 36). The model domain was defined based on aquifer geometry, existing irrigation development and pending water-permit applications.

Hydraulic Properties

In order to better understand the depositional environments and the hydrostratigraphy, a series of hydrogeologic cross-sections and lithofacies maps were generated. All cross-sections and lithofacies maps completed for this study are provided in Appendix B and Appendix C, respectively. Hydrogeologic section M-M', bisects the middle of the aquifer along the Steele and Cass county line (Figure 18 & 19). The hydrostratigraphy in this area is fairly continuous unlike other parts of the aquifer (Figures 15, 16, & 17). The aquifer is overlain by both till and lacustrine deposits, which are represented by layer 1 and the aquifer is represented by layer 2 in the model. The hydrogeologic cross-sections show each bore has several texture classes. Each bore was assigned an average aquifer property for hydraulic conductivity, specific yield, and specific storage for model layer 1 and 2 based on the texture class (Table 4). Thiessen polygons

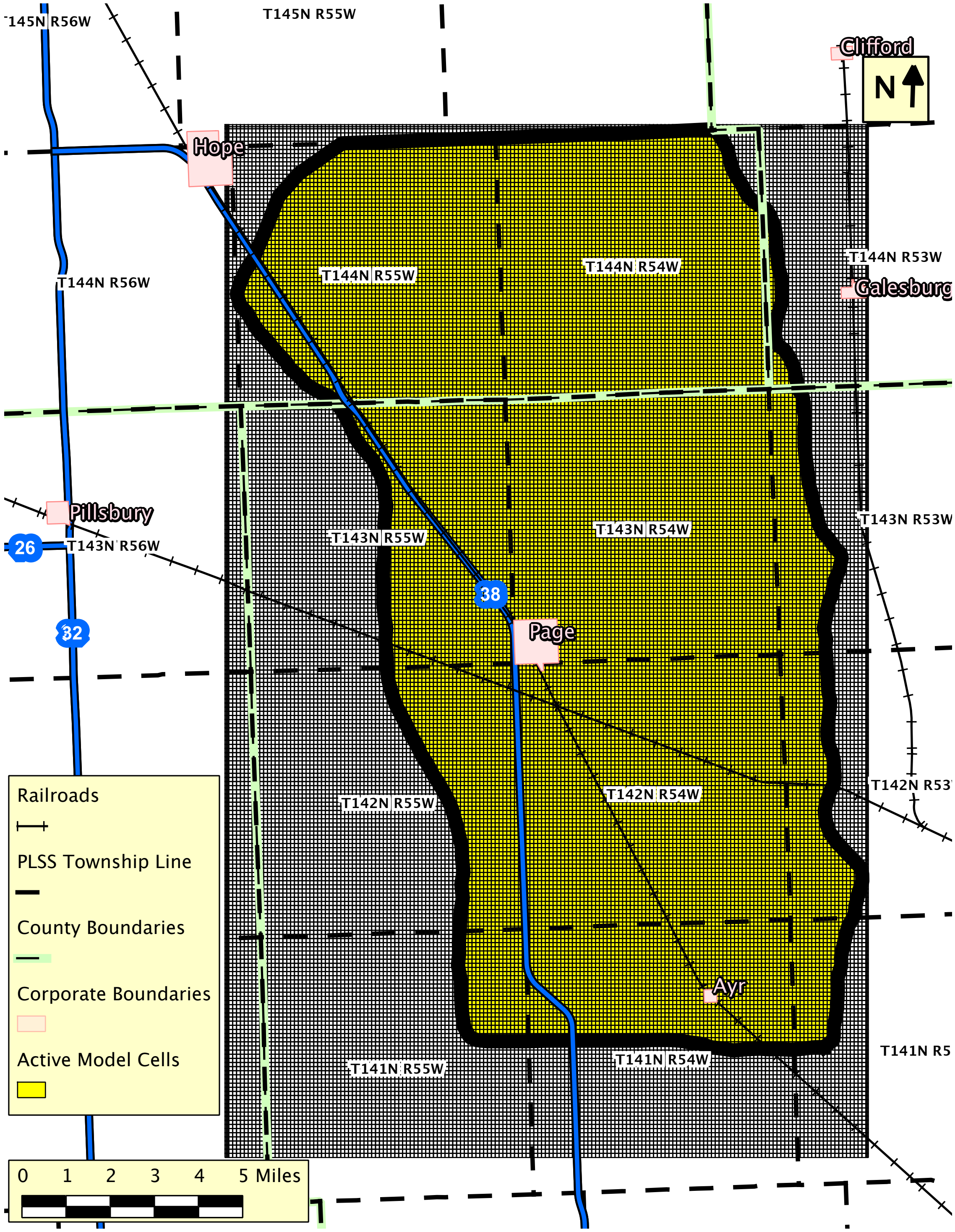


Figure 35. -- Active cells within the model grid.

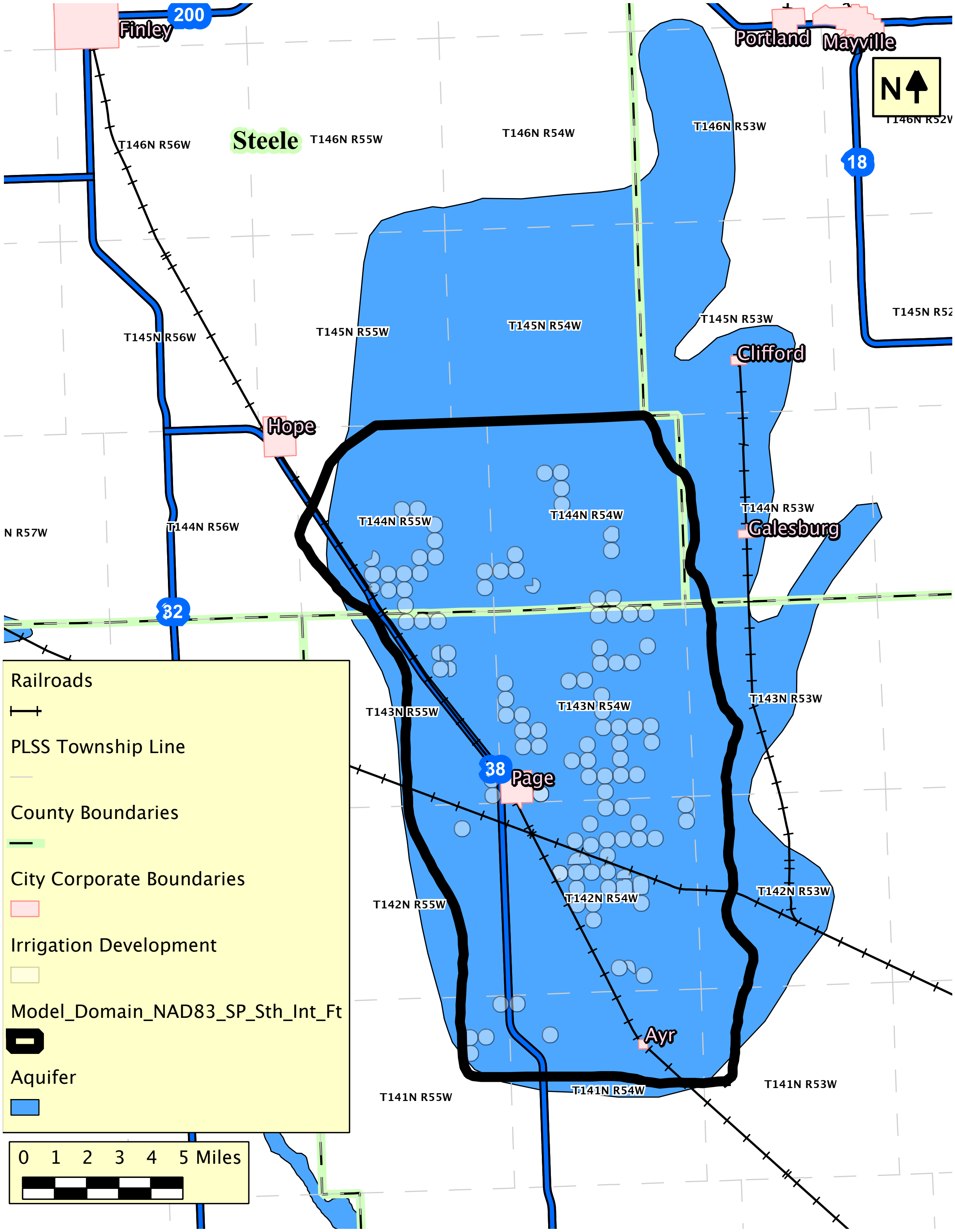


Figure 36. – Model domain in relation to the Page aquifer boundary.

Texture	Hydraulic Conductivity (ft/day)	Specific Yield	Specific Storage (ft^{-1})
clay	3.00E-04	0.03	1.00E-04
clay, silty	3.00E-03	0.03	1.00E-04
clay, sandy	3.00E-02	0.04	1.00E-04
silt	1.00E+00	0.08	1.00E-05
silt, clayey	5.00E-01	0.07	1.00E-05
silt, sandy	5.00E+00	0.1	1.00E-05
sand	5.50E+01	0.22	8.00E-06
sand, clayey	4.00E+00	0.18	8.00E-06
sand, silty	1.30E+01	0.2	8.00E-06
sand, gravelly	1.33E+02	0.22	8.00E-06
gravel	4.70E+02	0.23	8.00E-06
gravel, clayey	1.50E+01	0.2	8.00E-06
gravel, silty	3.00E+01	0.21	8.00E-06
gravel, sandy	2.67E+02	0.22	8.00E-06
cobbles+	5.00E+02	0.22	8.00E-06
loam	5.00E+00	0.1	1.00E-05
loam, gravelly	1.00E+01	0.18	1.00E-05
clay-silt interbedded	3.00E-03	0.03	1.00E-04
clay/interbedded sand	3.00E-02	0.04	1.00E-04
silt/interbedded sand	5.00E+00	0.1	1.00E-05
sand/interbedded silt/clay	1.30E+01	0.2	8.00E-06
claystone	2.00E-06	0.03	1.00E-06
siltstone	2.00E-04	0.08	1.00E-06
mudstone	2.00E-04	0.1	1.00E-06
sandstone	2.00E-02	0.17	1.00E-06
gravel/interbedded silt/clay	2.00E+01	0.2	8.00E-06
sand, sl. gravelly	1.00E+02	0.22	8.00E-06
clay/interbedded gravel	1.00E+01	0.15	1.00E-04
silt/interbedded gravel	2.00E+01	0.18	1.00E-05
silt, gravelly	1.50E+01	0.18	1.00E-05
clay, gravelly	1.00E+01	0.15	1.00E-04
sand, very fine	1.50E+01	0.22	8.00E-06
sand, fine	6.00E+01	0.22	8.00E-06
sand, medium	9.30E+01	0.22	8.00E-06
sand, coarse	1.33E+02	0.22	8.00E-06
sand, very coarse	1.90E+02	0.22	8.00E-06
clay, silty, sandy, pbly	3.00E-03	0.07	2.00E-04
clay, sandy, silty, pbly	3.00E-02	0.07	2.00E-04
clay, silty, sandy	3.00E-03	0.07	2.00E-04
clay, sandy, silty	3.00E-02	0.07	2.00E-04
clay, silty, sandy, pbly, cbbly	3.00E-03	0.07	2.00E-04
clay, sandy, silty, pbly, cbbly	3.00E-02	0.07	2.00E-04

Table 4. -- Default hydraulic properties assigned to each texture class.

were created for each bore dividing the model area initially into over 200 discrete aquifer property zones (Figure 37).

For computer interpolation routines (gridding) to accurately represent a narrow channel, the spacing of bores across the feature must be approximately one-third the size of the feature. Where the deep channel is less than 0.5 miles wide, a grid of bores less than 900 feet apart is needed. If bores forming a cross-section of the channel are far apart, the interpolation routine will represent the channel as a chain of unconnected holes. An approach to represent narrow channels included insertion of synthetic bores (Cline, 2011).

The synthetic bores were created by copying existing bores to new locations. Tops and bottoms of lithologic units were adjusted as needed to interpolate between bores. Texture classes may also be changed. As part of this procedure, deep bores were often used to extend the depth of shallow bores. The synthetic bores and associated aquifer property zones for layer 1 and layer 2 are shown in Figures 38 and 39. The lines show the parent bore from which the synthetic bore was derived. As synthetic bores were used to better define channels in the model, a more rudimentary method of creating features to represent areas of complex hydrostratigraphy was used in defining some aquifer property zones (non-polygon features in Figure 38 & 39). Average hydraulic conductivities were assigned to each synthetic and real bore for both layers in the model. The resulting transmissivities are shown in Figures 40 and 41. The channels defined by the synthetic bores for layer 2 are readily visible in Figure 41. Extensive effort was expended adjusting the aquifer properties before accepting the model.

The vertical hydraulic conductivities calculated in layer 1 for the southeast part of the model, are not representative of the actual conductivities, due to the way they were calculated. In this area, there is a fair amount of sand in the upper part of the Page aquifer along with the silts and clays. In calculating the average vertical conductance of these sediments, the conductivities are dominated by the coarser sands when actually the silts and clays should dominate the vertical conductance. One way to make this area more representative of the natural setting is to add more layers to the model, so the vertical flow is slowed in the aquitard strata.

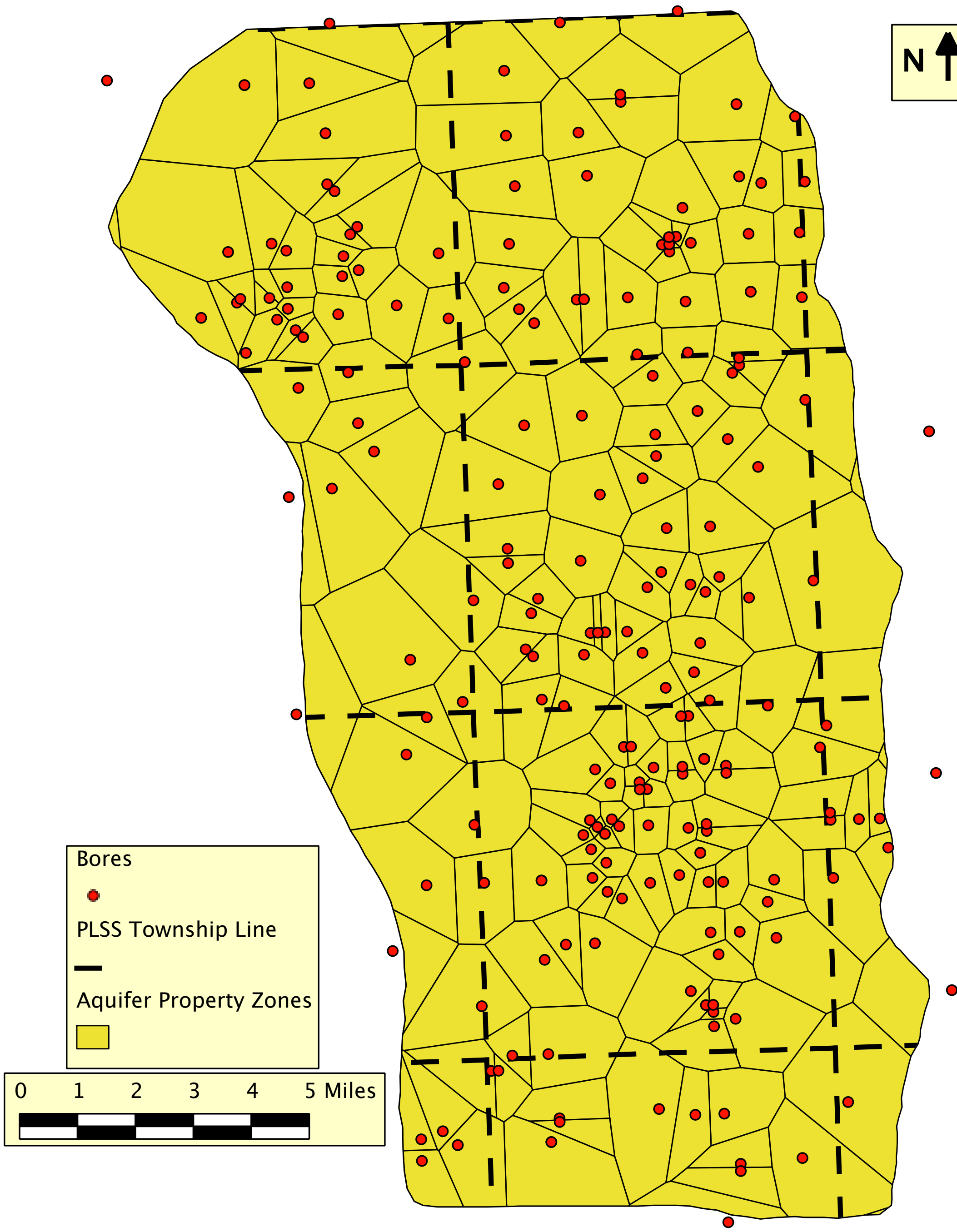


Figure 37. -- Aquifer property zones based on existing data points.

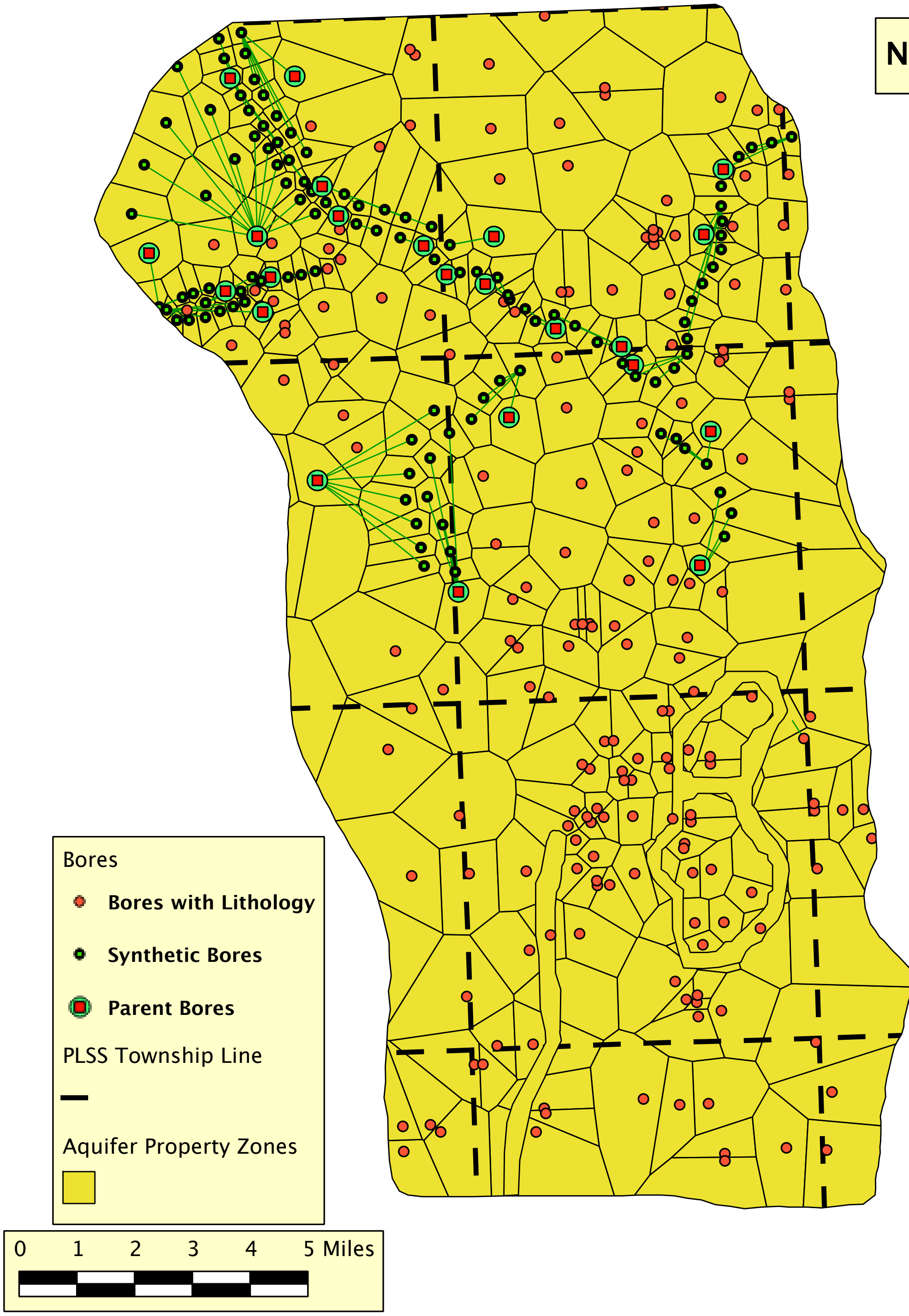


Figure 38. -- Location of synthetic bores and additional aquifer property zones for Layer 1.

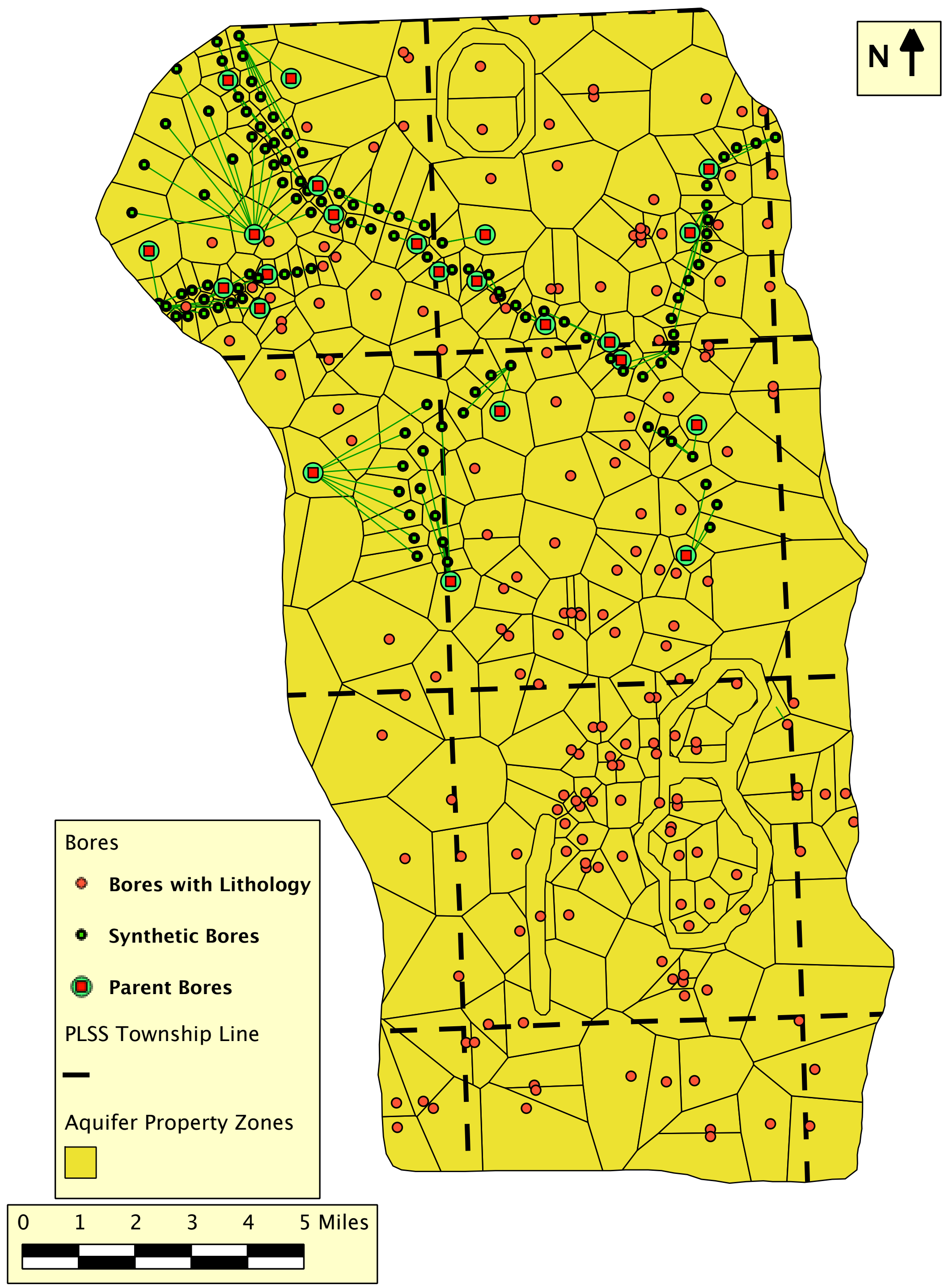


Figure 39. -- Location of synthetic bores and additional aquifer property zones for Layer 2.

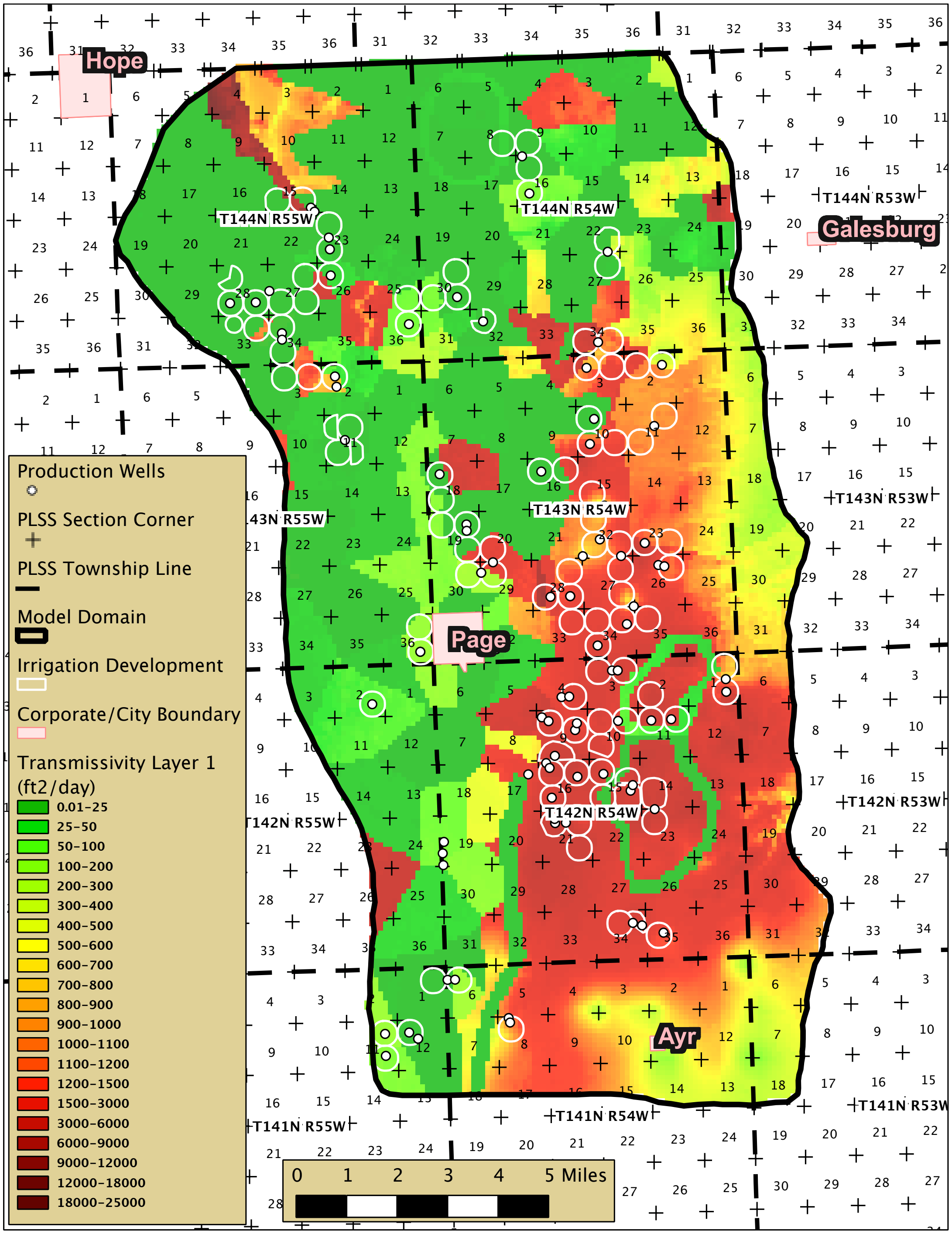


Figure 40. -- Distribution of transmissivity in Layer 1 of the model.

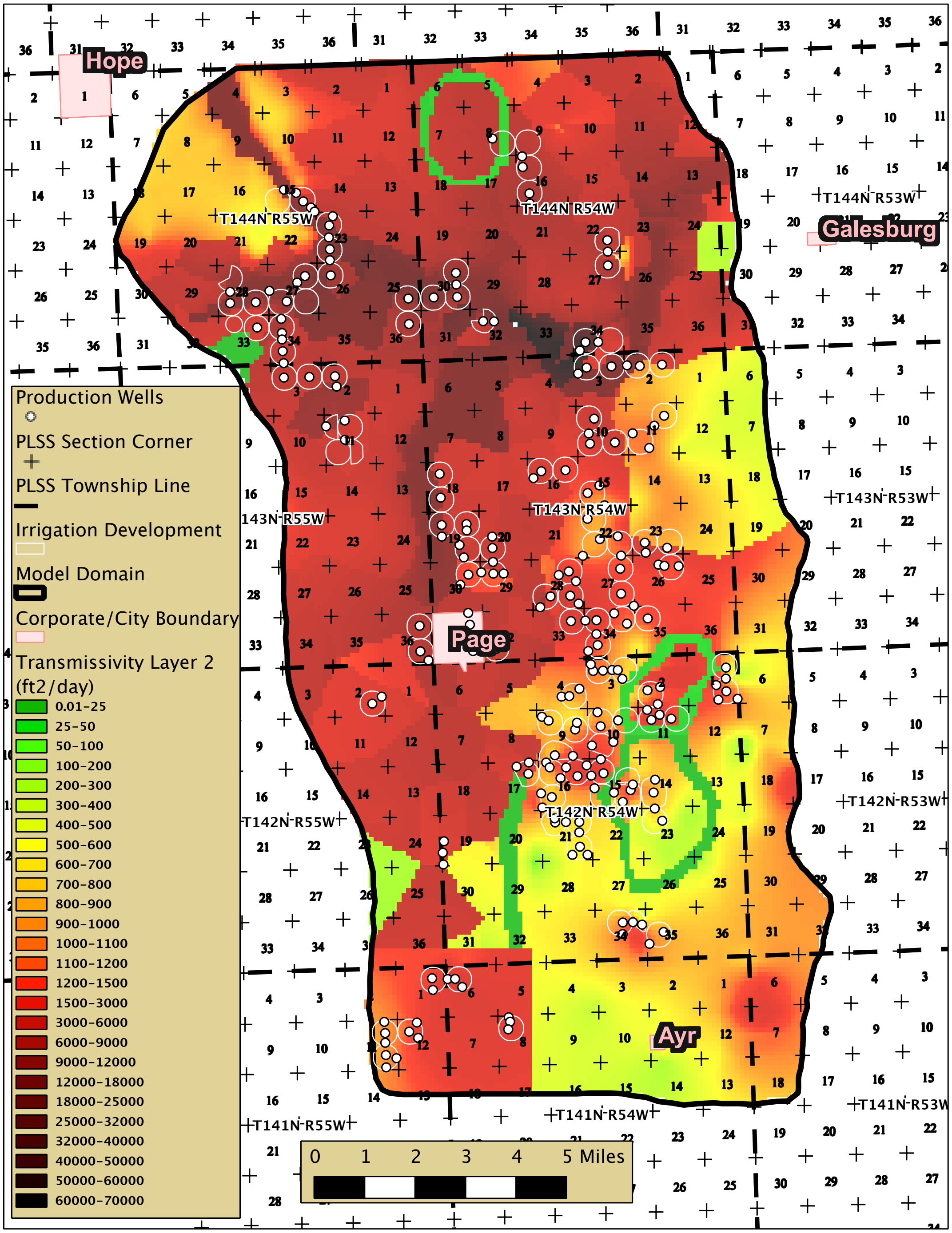


Figure 41. -- Distribution of transmissivity in Layer 2 of the model.

Recharge, ET, and Irrigation Use

The average annual precipitation based on the Page North and Page South climate datasets equals 20.4 inches from 1901-2011. The Page North composite climate dataset uses Cooperstown and Fargo data from 1901-1911, Mayville data from 1911-1948, Colgate data from 1948-1983, and local ARB Stations and Colgate data from 1983-2010 (Figure 8). The Page South composite climate dataset uses Fargo data from 1901-1905, Hillsboro and Fargo data from 1905-1949, Amenia data from 1949-1979, and a combination of Chaffee, Casselton, Galesburg and local ARB stations from 1979-2010 (Figure 9).

Through calibration of the steady-state model, recharge was estimated to be two inches of recharge per year, which equals 10 percent of the annual precipitation. In addition, an evapotranspiration (ET) rate of 19 inches was selected with an extinction depth of 8 feet. One recharge zone was applied to the entire model, because the soils throughout the model area have similar properties. The Versatile Soil Moisture Budget Model (VB 2000) was used to calculate recharge and evapotranspiration from groundwater (ET_{gw}) (Baier and others, 2000; and Dyer and Mack, 1984). The VB2000 model was run separately from the MODFLOW model. Output from the VB2000 model was used to generate input for the MODFLOW model. Input to VB2000 was daily climate data consisting of precipitation, maximum and minimum temperatures, and soil hydraulic properties. Barnes soil was considered representative of the area overlying the Page aquifer. The crop type was assumed to be corn.

For all of the simulations, Potential Evapotranspiration (PET) was input to the VB2000 model and was calculated using the Penman-Monteith method (Penman, 1948 and Monteith, 1965). Precipitation and PET data were used as input to the VB2000 model for the Page South climate dataset, and are shown in Figure 42 and 43, respectively. Actual evapotranspiration (AET) is calculated by the VB2000 model (Figure 44). In a sub-humid climate like eastern North Dakota the PET and AET have an inverse relationship, because as the PET increases the soil moisture continues to decrease, thus leaving less available water to evaporate. An example of this is shown in Figures 43 and 44, using the Page South climate dataset. In a very humid climate, AET will equal PET, as available energy is the limiting factor in evaporation and not available water (Cline, 2011). PET from groundwater (ET_{gw}) (Figure 45) was not determined

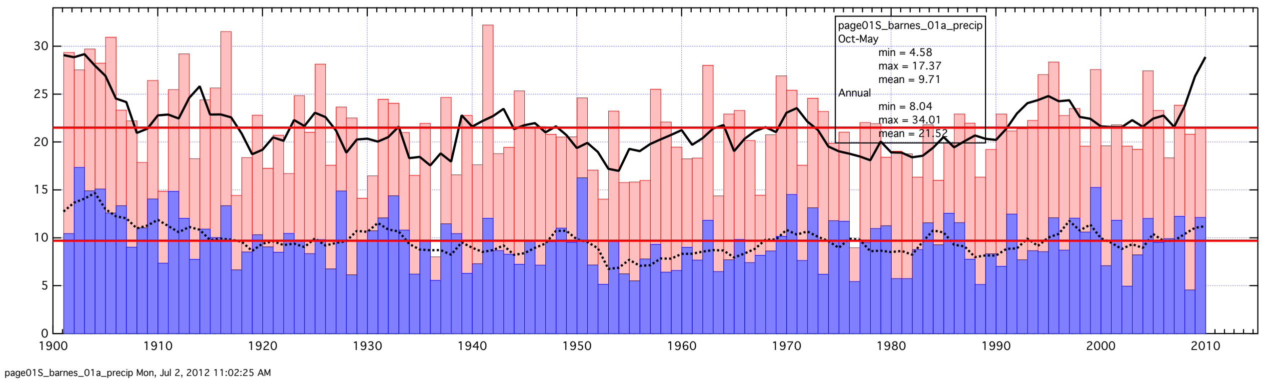


Figure 42. -- Annual water year and winter precipitation (inches) 1901 through 2010 from VB2000 Page South dataset (page01S_barnes_01a). The black solid and dashed lines show the five-year moving average respectively.

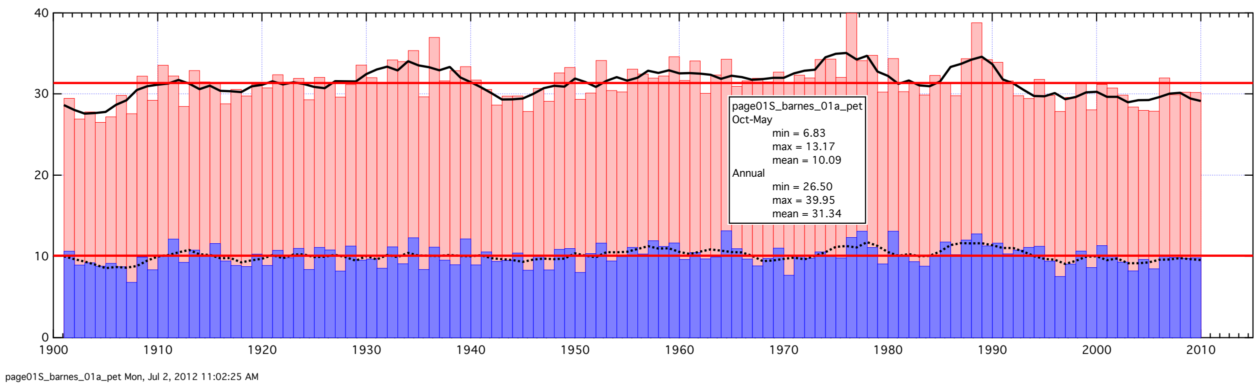


Figure 43. -- Annual water year and winter PET (inches) 1901 through 2010 from VB2000 Page South dataset (page01S_barnes_01a). The black solid and dashed lines show the five-year moving average respectively.

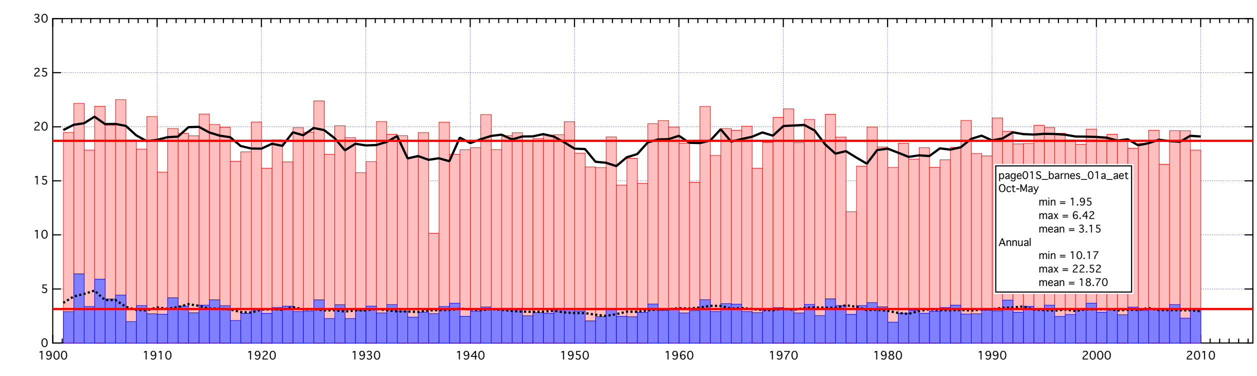


Figure 44. -- Annual water year and winter actual evapotranspiration (AET) (inches) 1901 through 2010 from VB2000 Page South dataset (page01S_barnes_01a). The black solid and dashed lines show the five-year moving average respectively.

by the VB2000 model, but rather was calculated by the following relationship: ET_{gw} = PET - precipitation + recharge. The precipitation that does not run off or is groundwater recharge must be subtracted from the PET as this water is evaporated from the unsaturated zone and not from the water table. When the water table is at land surface, ET_{gw} = PET - precipitation, therefore the recharge added to the groundwater must be added to ET_{gw} for the water budget to balance. Recharge is the water that flows through the bottom of the soil zone in the VB2000 model (Figure 46). Irrigation water use (Figure 47) was calculated from VB2000 output data using PET, AET, and soil water content (Cline, 2011). Precipitation, PET, AET, and ET from groundwater plots for the Page North climate dataset is provided in Appendix D.

Conceptual Model

Based on all the information discussed in the previous sections a conceptual model was developed. The conceptual model reflects our best understanding of the hydrology of the aquifer. Ground-water flow maps were generated and general assumptions of recharge and discharge from the aquifer were formulated. A series of hydrogeologic cross-sections and lithofacies maps were developed using available drilling data to help visualize the aquifer geometry and are included as Appendix B and Appendix C, respectively. Figure 48 shows the traces of three modified hydrogeologic cross-sections located in areas of complex hydrostratigraphy and low conductance zones. The modified hydrogeologic cross-sections I-I', M-M', and S-S' define the layer extents as well as the low conductance zones of the model (Figures 49, 50, & 51). As discussed in the "Hydraulic Properties" section of this report, synthetic bores were used to define aquifer channels and rudimentary methods of creating low conductance zones were used to define flow barriers in the model. An example of how synthetic bores were used is shown in hydrogeologic section M-M', where a synthetic bore was generated from the parent bore 14405434CCC (Figure 50). Notice the bottom of layer 2 extends below what is defined as aquifer sediments in this cross-section. The synthetic bores were used to move water out of areas of the model characterized by higher than expected water levels and where deeper channels likely occur.

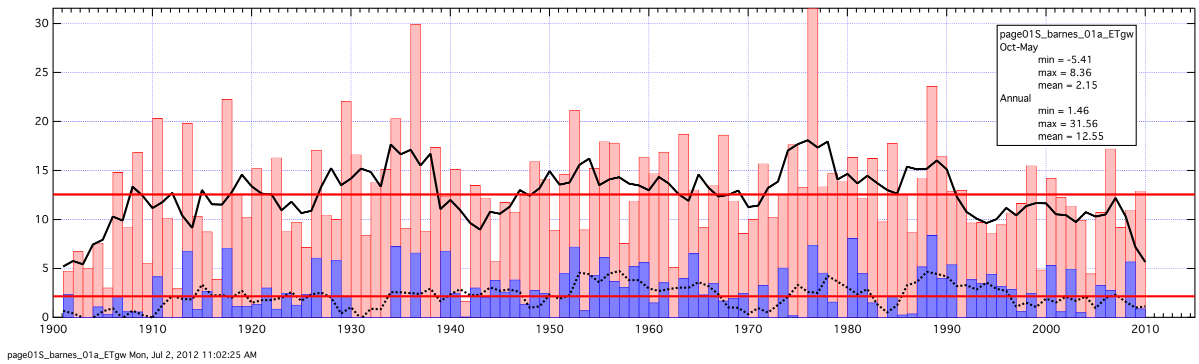


Figure 45. -- Annual water year and winter ET from groundwater (inches) 1901 through 2010 from VB2000 Page South dataset (page01S_barnes_01a). This is PET - precipitation + recharge. The black solid and dashed lines show the five-year moving average respectively.

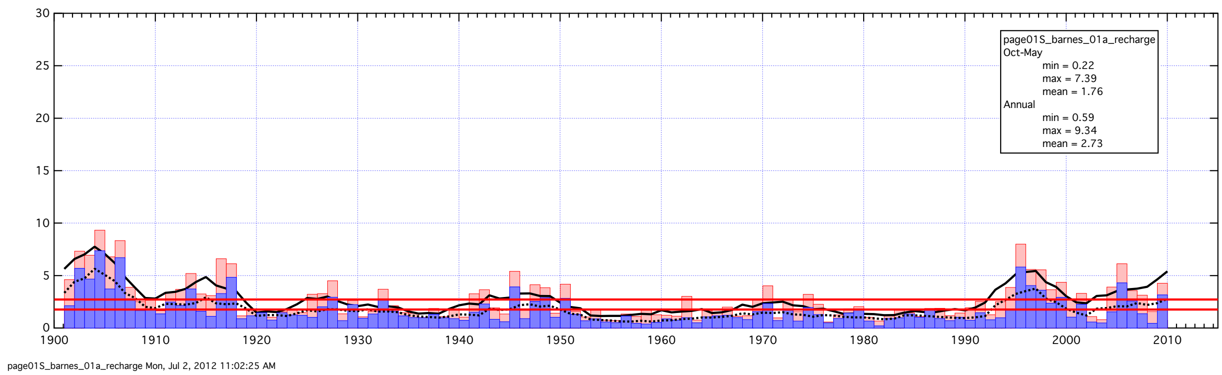


Figure 46. -- Annual water year and winter Recharge (inches) 1901 through 2010 from VB2000 Page South dataset (page01S_barnes_01a). The black solid and dashed lines show the five-year moving average respectively.

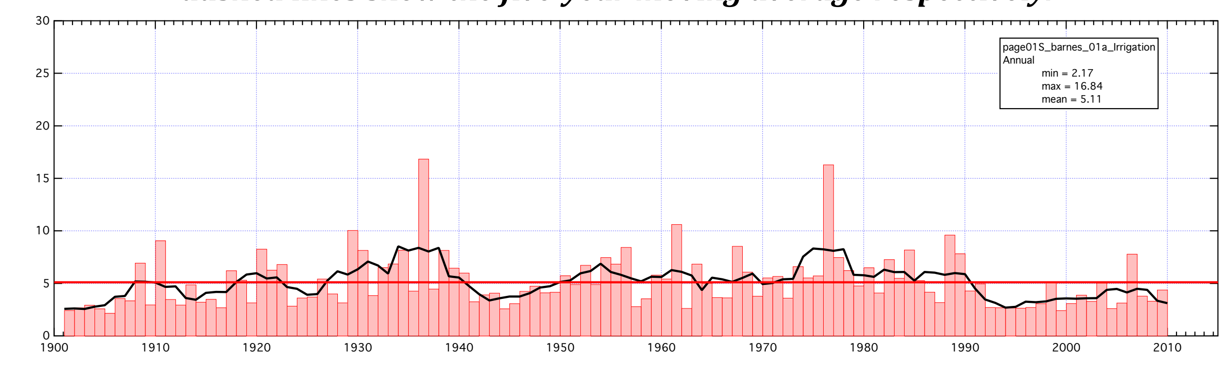


Figure 47. -- Annual irrigation (inches) 1901 through 2010 from VB2000 Page South dataset (page01S_barnes_01a). The black solid line shows the five-year moving average.

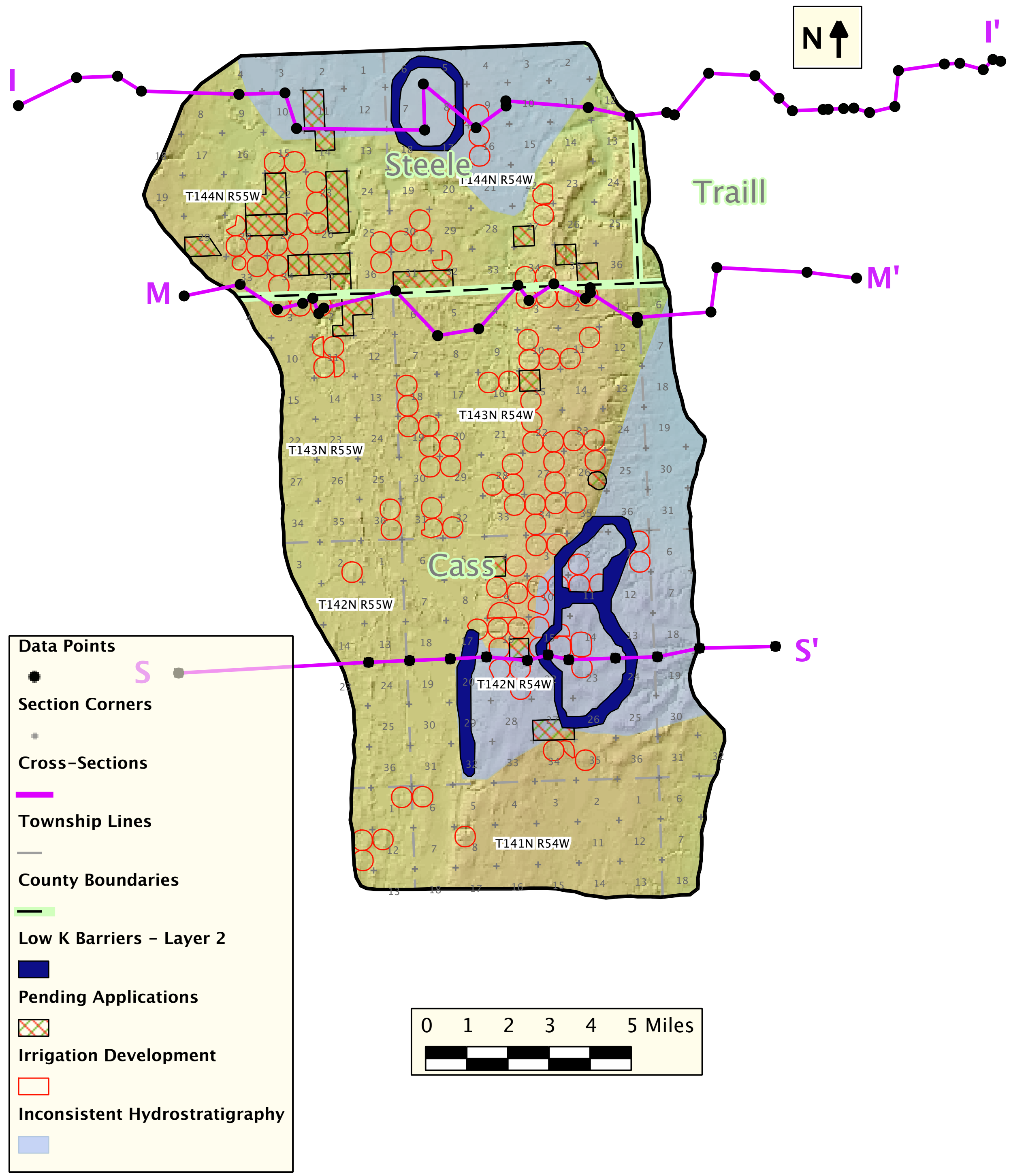


Figure 48. -- Traces of hydrogeologic sections I-I', M-M', and S-S'.

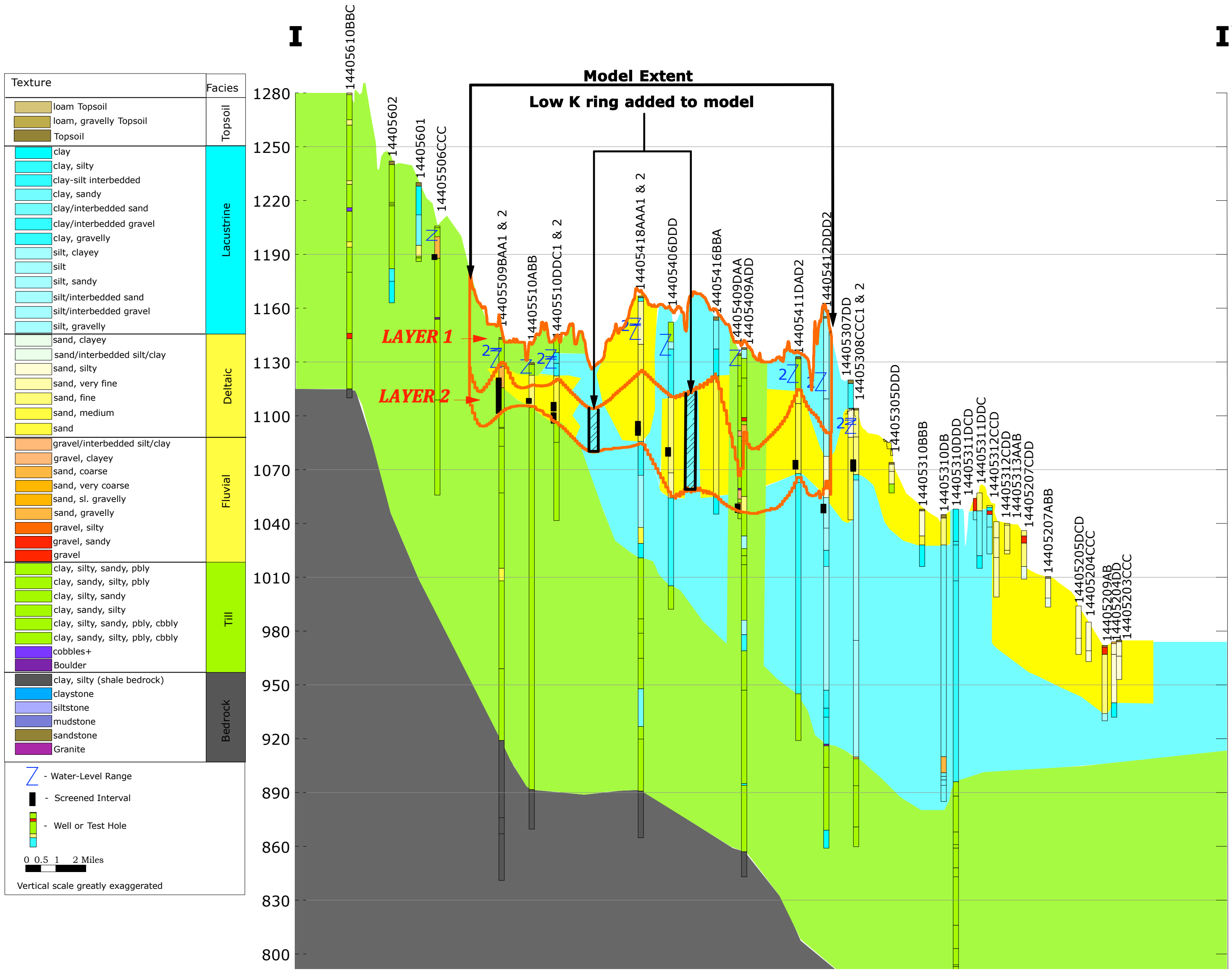


Figure 49. -- Modified hydrogeologic section I-I' with low K barriers, layer bottoms and model extent defined.

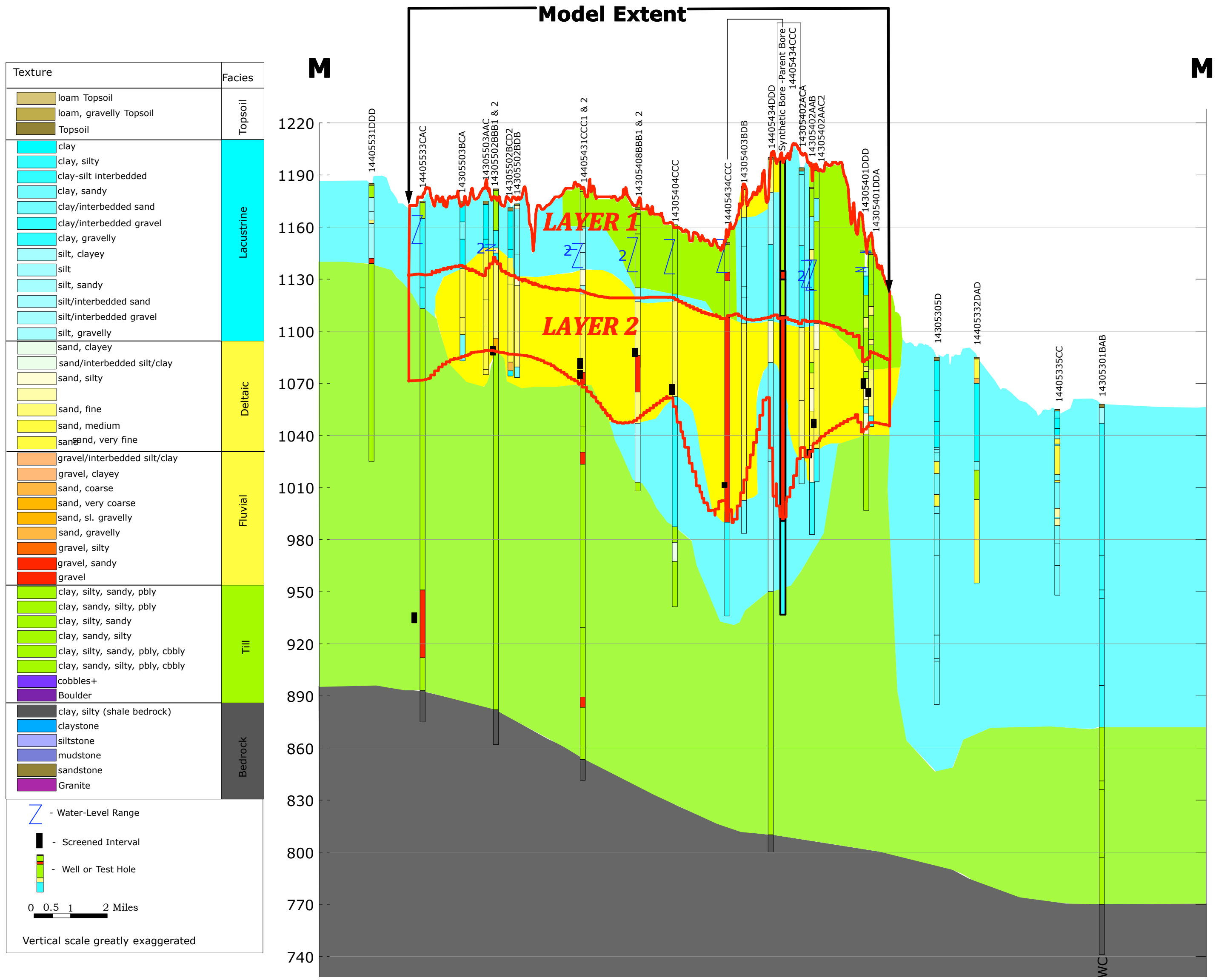


Figure 50. -- Modified hydrogeologic section M-M' with a synthetic bore, layer bottoms, and model extent defined.

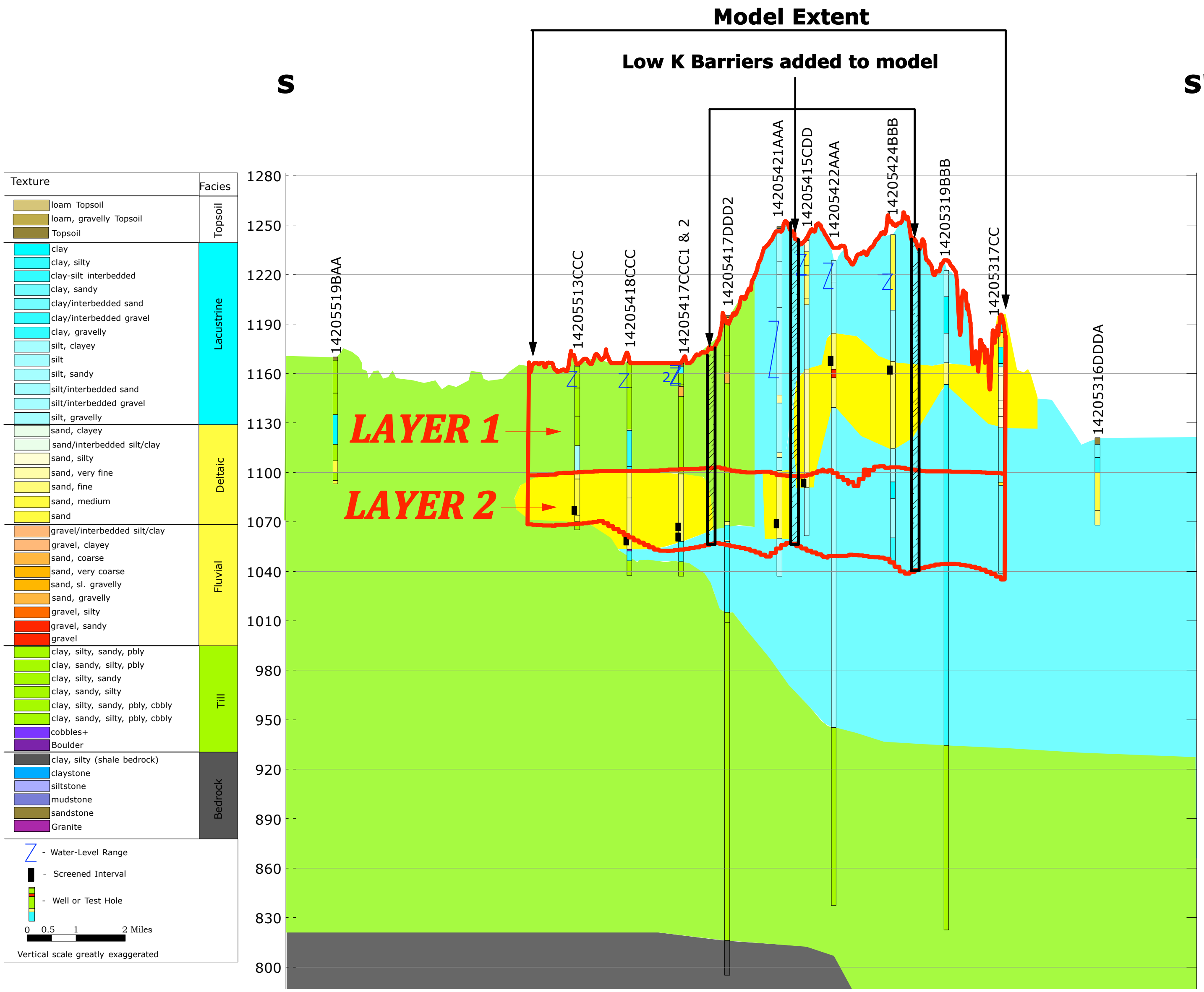


Figure 51. -- Modified hydrogeologic section I-I' with low K barriers, layer bottoms, and model extent defined.

Hydrogeologic sections I-I' and S-S' show the complexity of the aquifer in the southeast and the need for low conductance zones to slow the movement of water out of areas where water levels in the model are lower than expected (Figure 49 & 51). These areas of geologically unrealistic parameters make the model work by simulating large water-level discontinuities that are similar to the observed discontinuities. One limitation of using a layer approach when modeling is that it makes it more difficult to build complex stratigraphy into the model.

General-head boundaries were assigned to portions of the north border and south border of the model domain, where the aquifer extends beyond the model domain (Figure 52). The general-head boundary package is used to simulate head-dependent flux boundaries. A reference head and a conductance term are specified and the flux in the general-head boundary is proportional to the difference in head. The drain package was assigned to areas of the model defined as major discharge areas consisting of springs and seeps. The drain package simulates head-dependent flux boundaries. In the drain package, if the head in the cell falls below a certain threshold, the flux from the drain cell drops to zero. As the water level rises above this threshold, discharge in the cell is proportional to this distance and the drain conductance. Numerous adjustments were made to the head and conductance terms within the general head and drain packages before accepting the current packages. Since the aquifer does not extend beyond the western border of the model domain, a no flow boundary was assigned to this area (Figure 52).

Each water permit has a designated point(s) of diversion (POD), which is the legal tract of land from which water can be diverted. An irrigation tract (point of use) associated with a point(s) of diversion may consist of a one quarter-section tract to several quarter-section tracts and may involve more than one water permit. To facilitate the analysis of the water use data and in assigning pumping rates within the ground-water model, these tracts were aggregated into what is referred to as a superPOD. Each superPOD irrigates a specified number of acres with one or more irrigation well(s) (Figure 32).

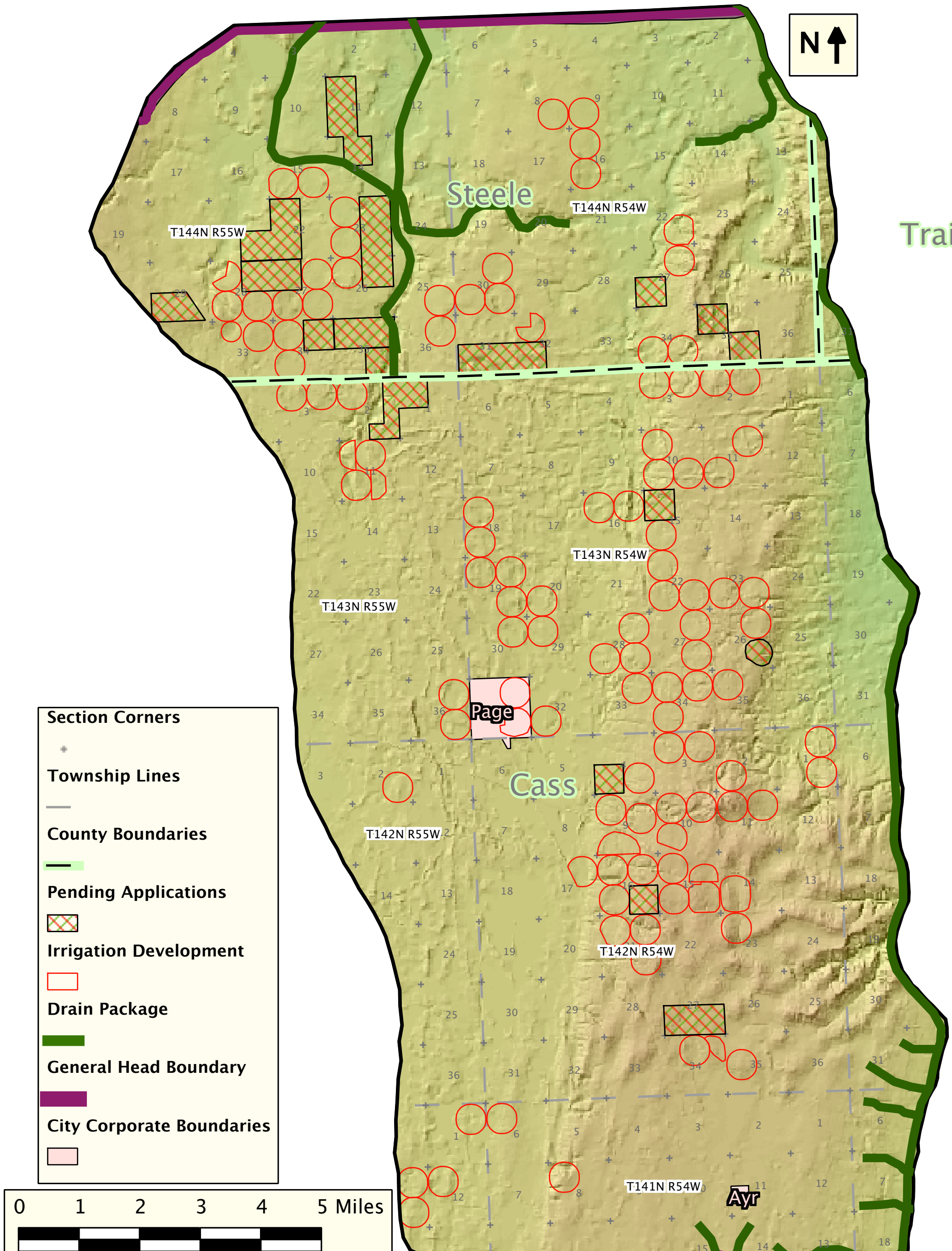


Figure 52. -- General head and drain packages.

Steady-State Model

A steady-state model was developed using the USGS finite-difference model, MODFLOW-2005. MODFLOW is the USGS Modular Three-Dimensional Groundwater Flow Model (Harbaugh, 2005). The steady-state model was calibrated to reproduce water levels for December 1983 (Figure 53). This date was selected, because of the large number of observations and because the water levels this late in the year should have recovered from pumping during the previous growing season. The steady-state model was used to evaluate recharge rates, hydraulic properties, boundary conditions, and the flow budget.

Calibration of the steady-state model involved matching simulated water levels with observed water levels. Water-level differences between observed and simulated are generally within four feet (Figures 54 and 55). The accepted steady-state model reproduces the December 1983 water levels and overall flow patterns reasonably well (Figure 56). The areas with large differences between the observed water-level contours and the simulated water-level contours may represent the model's inability to replicate the complex geology in these areas. However, in areas with limited monitoring well coverage, the simulated water-level contours may provide insight into the actual water levels in these areas.

Figure 57 shows the simulated water-level differences between layer 1 and layer 2 from the steady-state model. Brown represents areas where layer 1 water levels are higher than layer 2, and blue represents areas where the layer 1 water levels are lower than layer 2. Most of the blue areas on the eastern and northern portion of the model domain are low relief areas with spring flow. Figure 58 shows the water levels from layer 2 and the areas where ET is occurring.

As previous discussed in this report, areas of evapotranspiration can be determined using the National Wetland Inventory Data provided by the United States Fish and Wildlife Service (2013) and soil drainage classification data provided by the USDA (2013) (Figures 13 & 22). The simulated ET areas from the steady-state model in Figure 58 can be directly correlated to the actual discharge areas defined by poorly drain soils in Figure 13 and the wetlands in Figure 22.

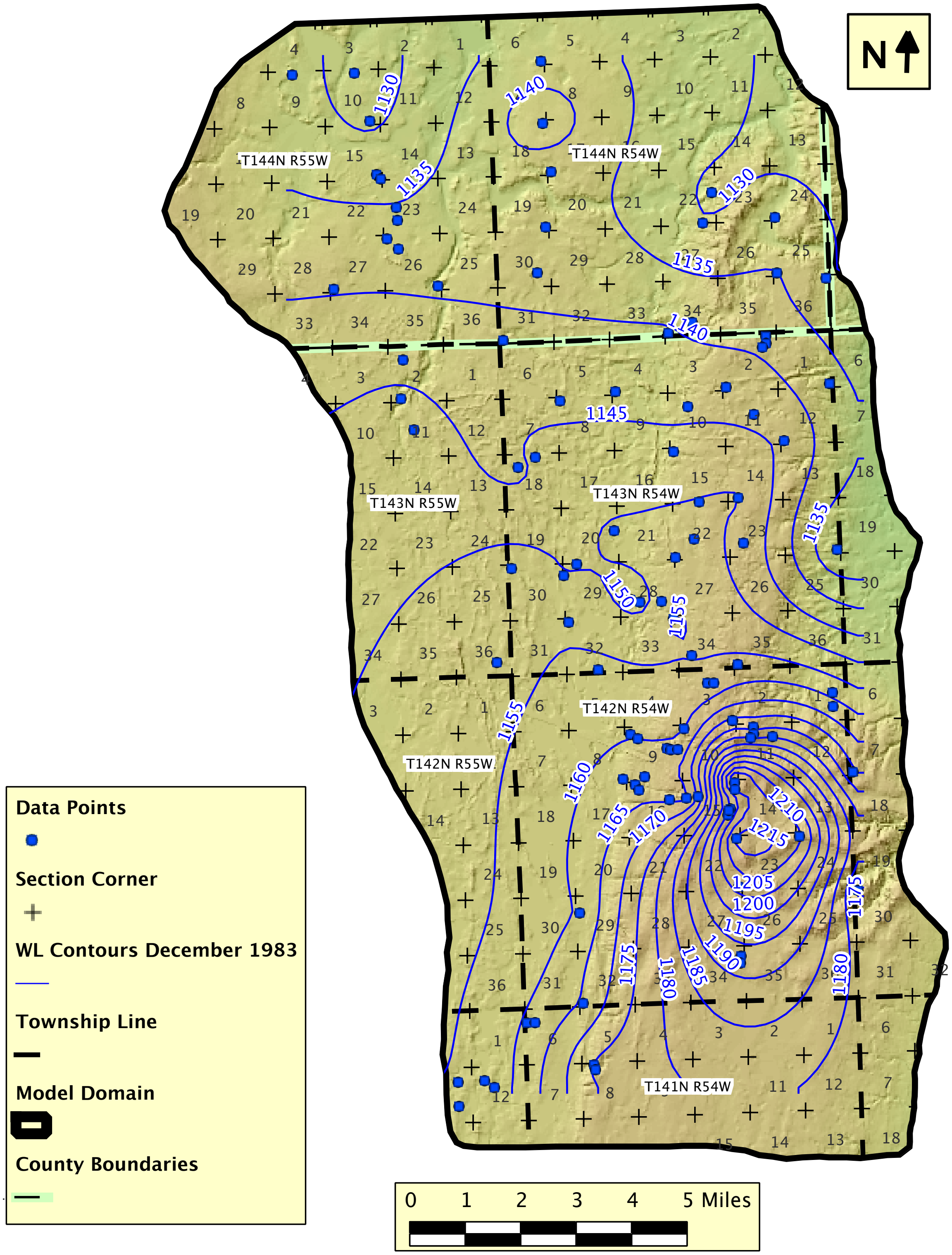


Figure 53. -- Water-level contour map based on observed water levels from December 1983.

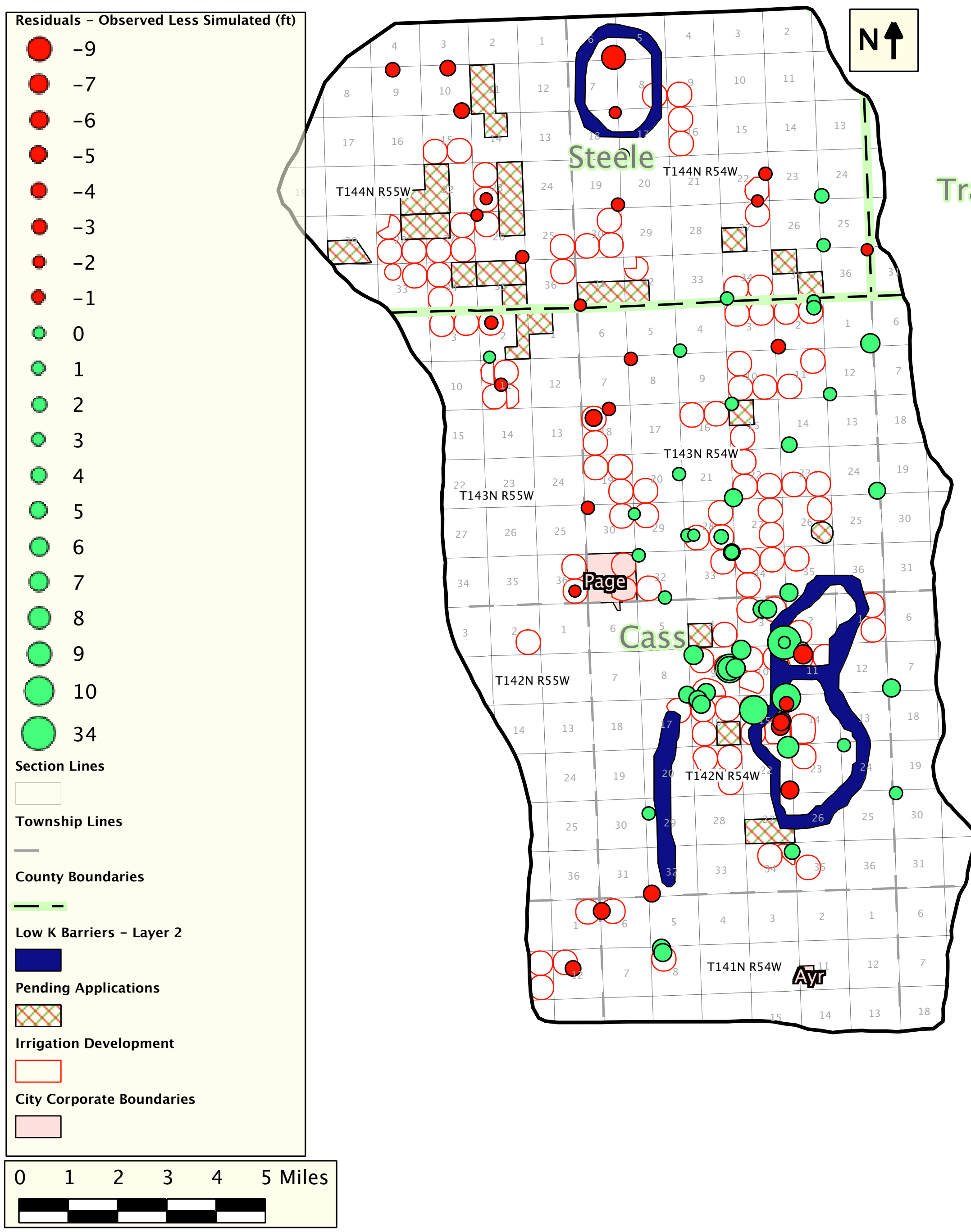


Figure 54. -- Residuals map from the accepted steady-state model.

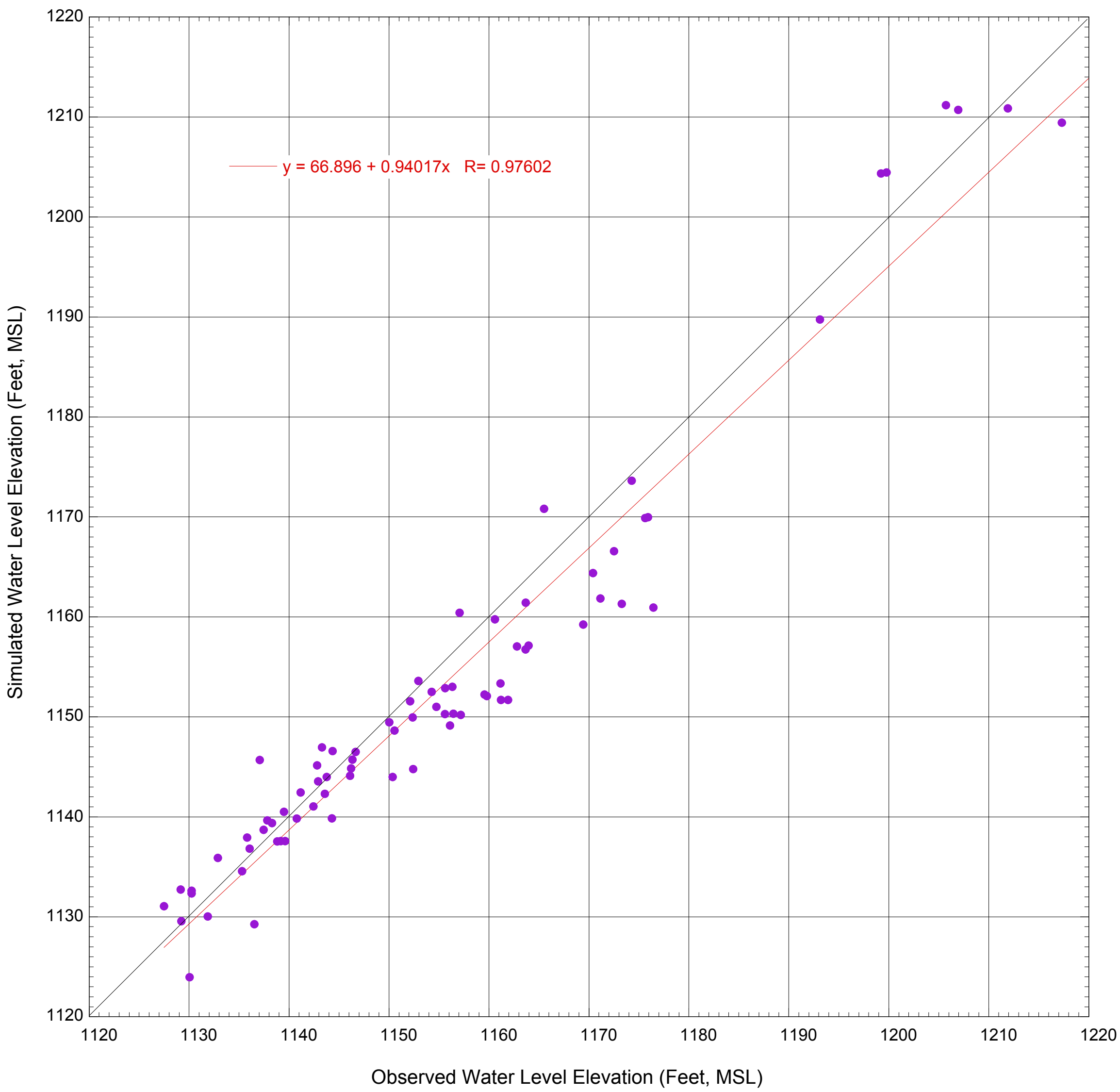


Figure 55. – Steady-state model calibration.

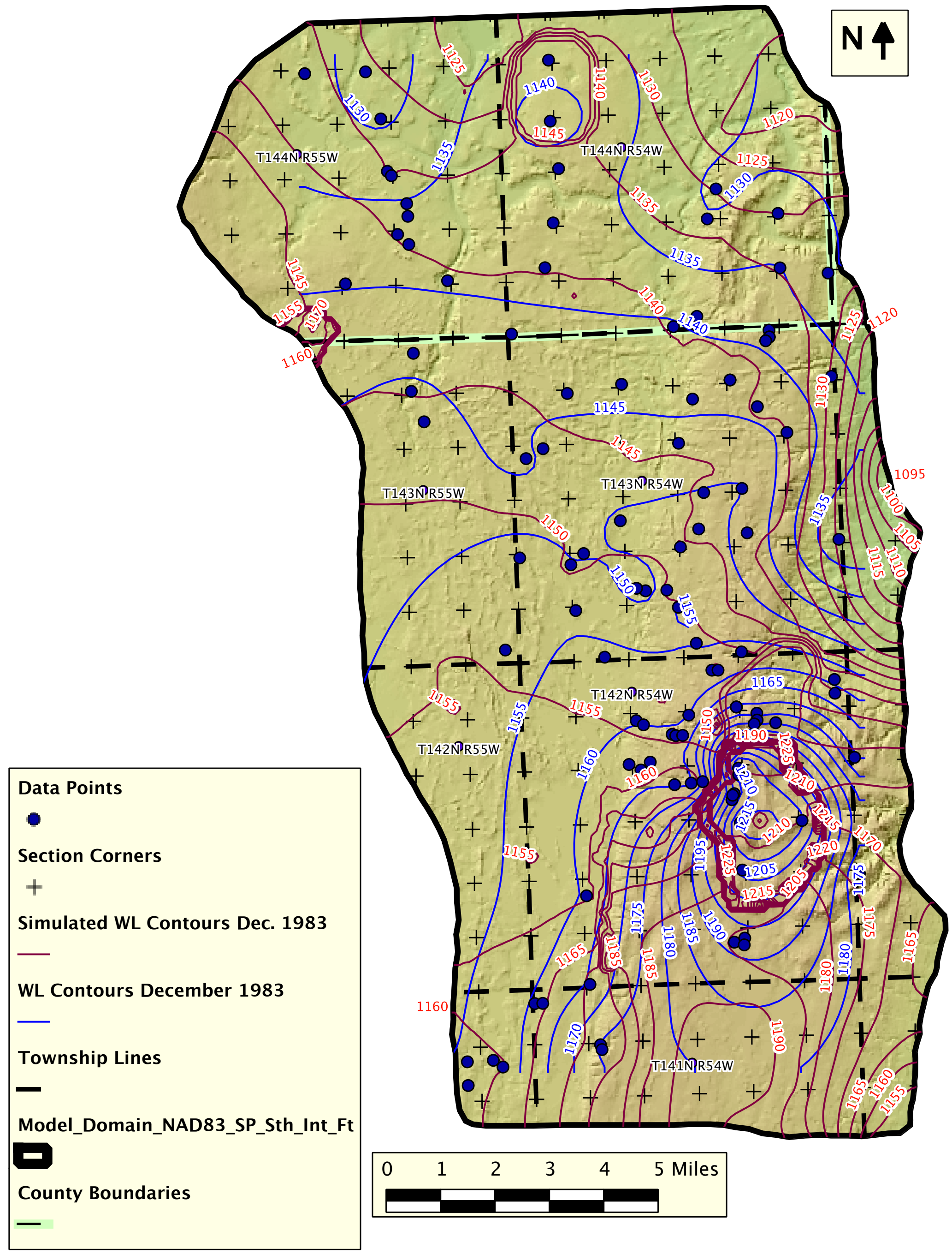


Figure 56. -- Comparison of water-level contours from December 1983 and simulated water levels from the accepted steady-state model.

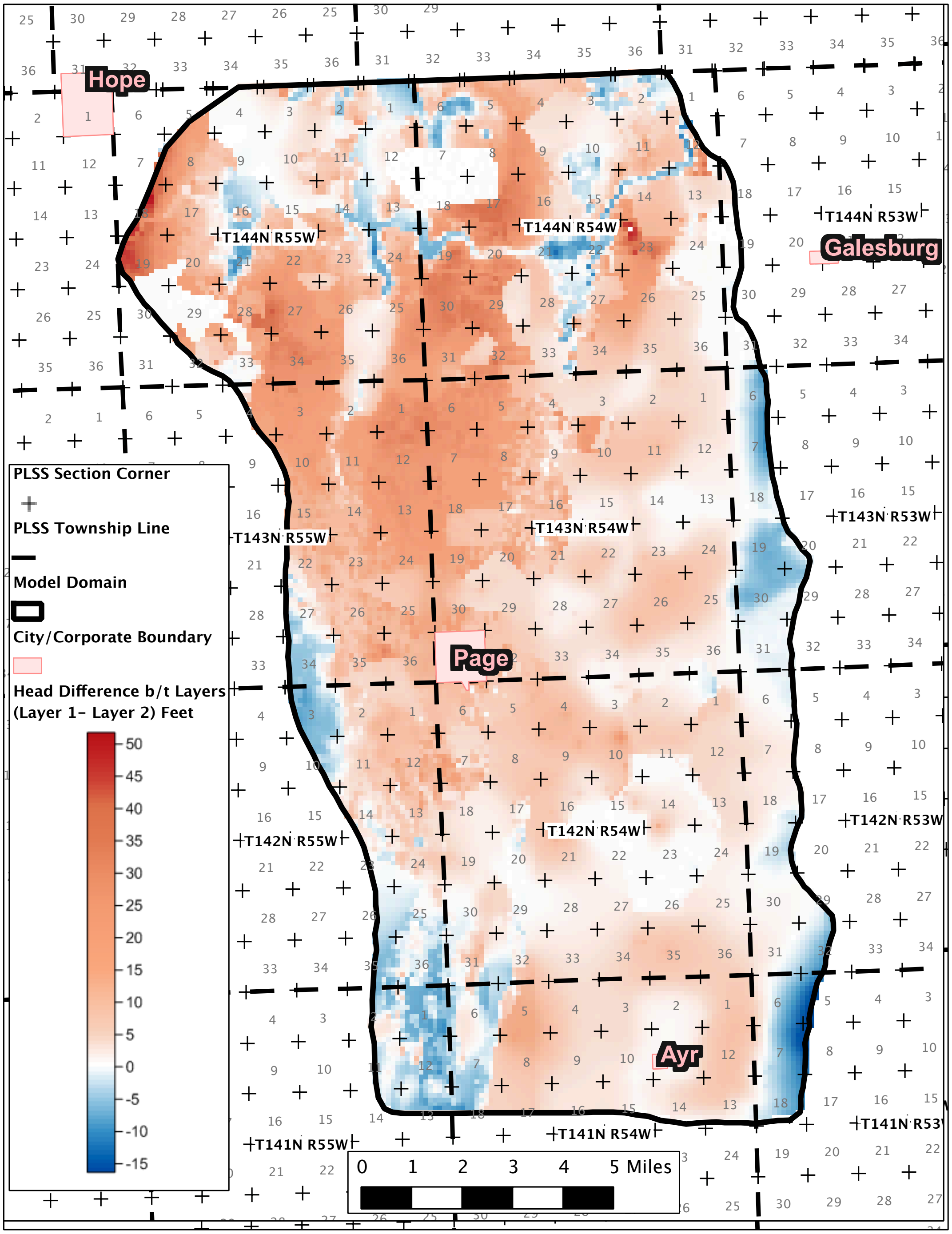


Figure 57. -- Water-level difference between layer 1 and layer 2 from the steady-state model.

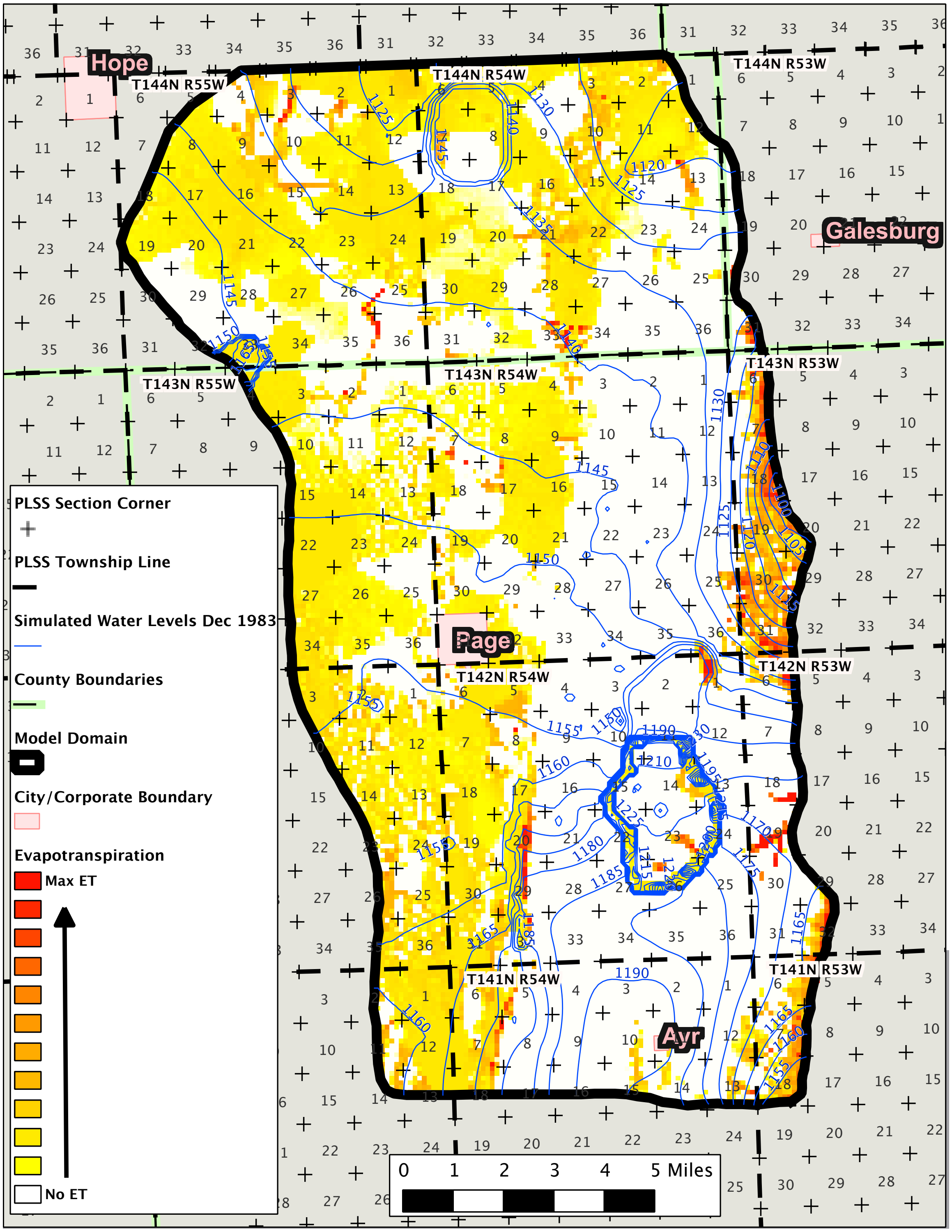


Figure 58. -- Areas where ET is occurring within the steady-state model.

When comparing Figures 57 and 58, there is a large area in Rochester Township (Township 143 North, Range 055 West) and Lake Township (Township 142 North, Range 055 West) where ET is occurring and the gradients are downward. ET in this area is dominated by local flow systems, where water infiltrates into the poorly drained till soil, but is lost to ET before it can recharge the aquifer. Additional development in this area would likely generate steeper gradients and trigger leakage from the overlying tills. This would minimize the amount of water lost to ET.

Transient Model - Calibration

Once the initial steady-state model was accepted, the next step was calibration against the historical pumping and recharge data with a transient model. Calibration for both the transient and steady-state model was an extensive iterative process. Adjustments to model parameters indicated by the transient simulation were applied to the steady-state model. Water levels from the steady-state model were then used as input to the new transient model. This cycle of steady-state model to transient model was repeated until as acceptable calibration was reached.

In conjunction with the MODFLOW model, the Versatile Soil Moisture Budget Model (VB2000) (Baier and others, 2000; and Dyer and Mack, 1984) was used to estimate aquifer recharge, ET from groundwater, and irrigation water use. The VB2000 was developed for use on the Canadian prairies to estimate available water within the root zone (See section "Recharge, ET, and Irrigation Use"). Monthly recharge and ET from ground water output from VB2000 were imported into the monthly stress periods of the transient model. The water use output from VB2000 was imported into the N.D. State Water Commission (NDSWC) developed waterUseDB program. The waterUseDB program takes water use data from the NDSWC Permit database and irrigation well information from the NDSWC Site Inventory database as well as data from other sources to aggregate and manipulate this data to generate the Well (WEL) and Multi-Node Well 2 (MNW2) (Konikow and others, 2009) packages for MODFLOW.

MNW2 was used to simulate the drawdown in the irrigation wells and the rural water wells by calculating drawdown in the node where the well is located and the Theim equation was used to estimate well drawdowns at the production well. MNW2 also has the capability to reduce the pumping rate and cease pumping at the well if water levels fall below a specified level. In addition, MNW2 allows the pumping rate to return to the specified rate as water levels recover. This eliminates the problem of having well nodes go dry and remaining inactive for the remainder of the simulation. The objective of calibration with the model is to replicate historical water levels in the Page aquifer from 1964 to 2010 (historical water-level record).

MNW2 was used to simulate the 1976 to 2010 reported irrigation water use. The Page North and the Page South climate datasets were used in VB2000 to generate model inputs (Figures 8 & 9). Figures 59 and 60 show the reported water use in comparison to the VB2000 estimated water use for the two climate sets. The Page North climate dataset severely overestimates water use. This is likely a result of the Page North climate set not being representative of the actual climate in the Page aquifer area during this time period. However, the Page South climate set provides a better estimate of the reported water use, which suggests it is more representative of the climate from 1976 to 2010. Linear regression plots of the reported water use and the simulated water use are shown as Figures 61 and 62. If the simulated water use matched exactly with the reported water use, the points would plot on a 45-degree line from the lower left to upper right.

Transient Model - Prediction

The transient model was used to determine the long-term sustainability as well as the growing season drawdown effects in the aquifer resulting from withdrawals associated with existing permitted allocations and pending irrigation applications. The use of the 1901 to 2010 climate datasets to estimate recharge, ET from ground water, and irrigation water use allow an assessment of the aquifer to a wider range of climate variability than that observed since irrigation began in 1976.

For predictive scenarios, waterUseDB takes the monthly estimated irrigation application rate (inches) and multiplies it by the number of acres irrigated in the superPOD. It is then distributed among the wells in the superPOD well field. This may be done equally among all of the wells, as a specified fraction of the total pumping, or as a specified pumping rate and the fraction is determined as part of the total rate for the well field. For the Page model, the option in waterUseDB to limit the pumping rate to the actual well pumping rate when the required rate

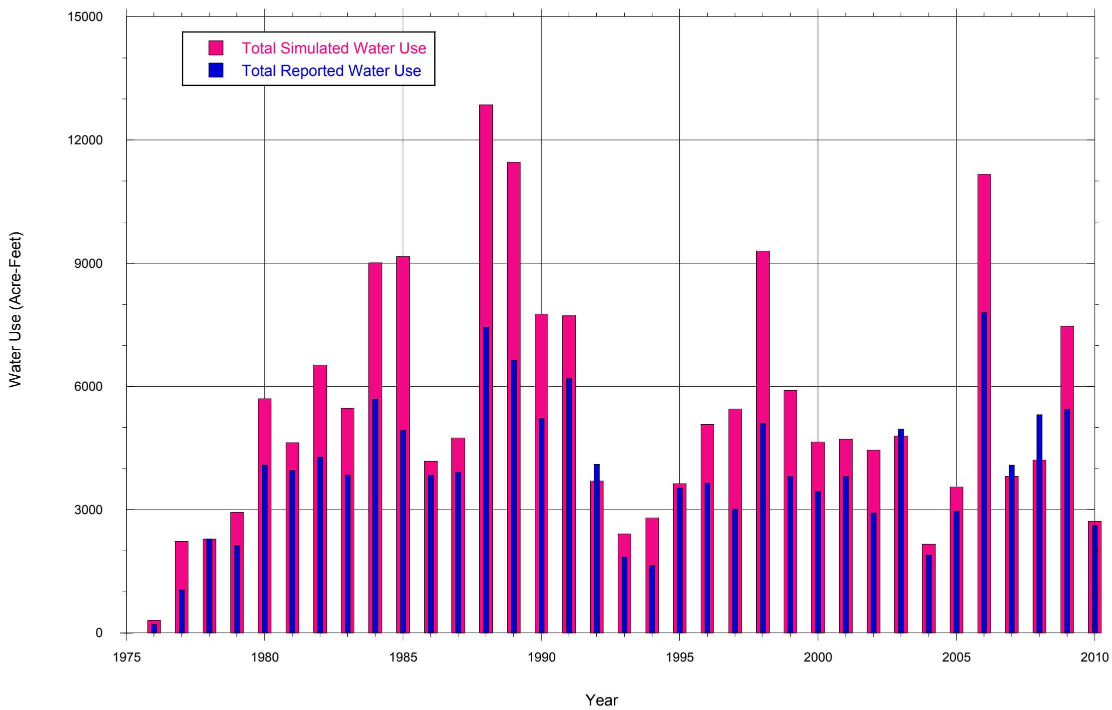


Figure 59. -- Simulated vs. reported water use from VB2000 North Climate Dataset.

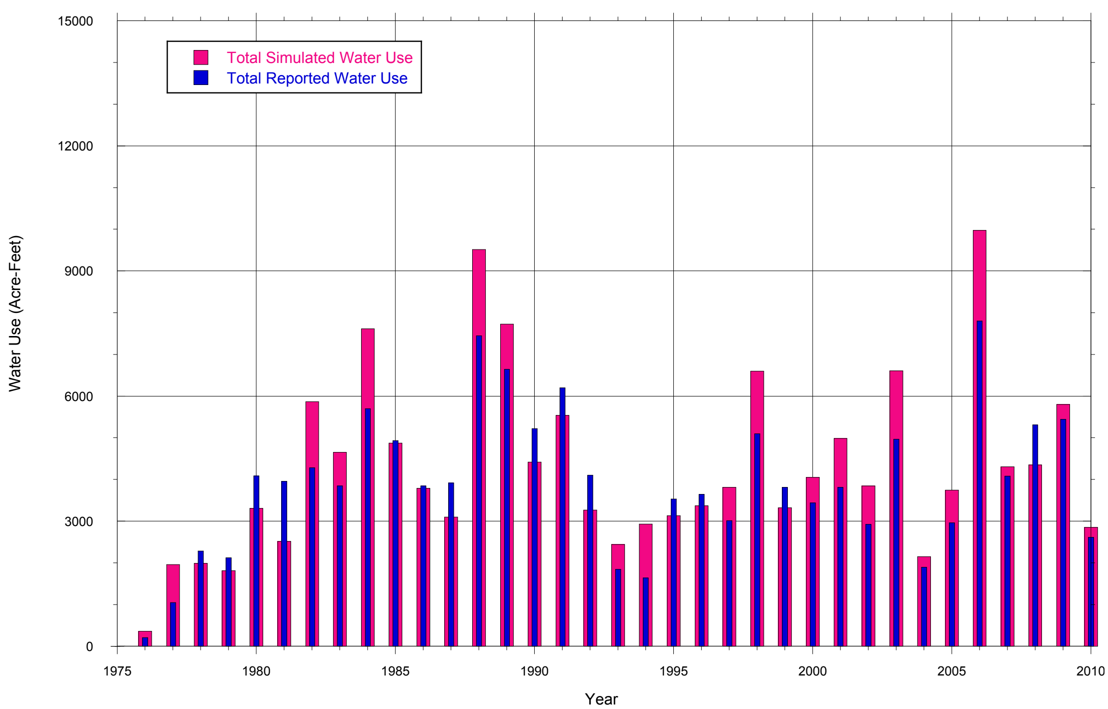


Figure 60. -- Simulated vs. reported water use from VB2000 South Climate Dataset.

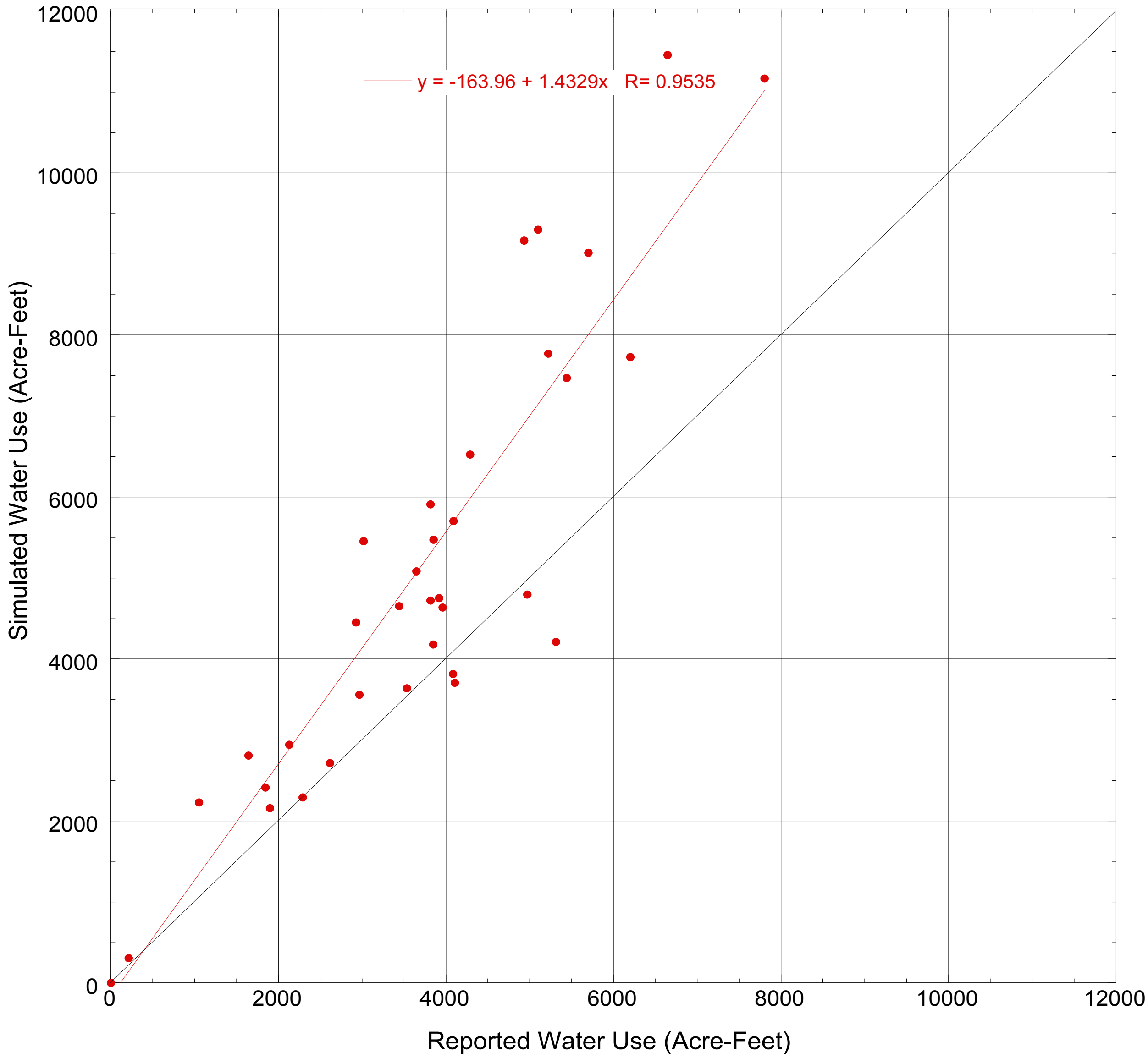


Figure 61. -- Comparison of simulated vs. reported water use from VB2000 North Climate dataset.

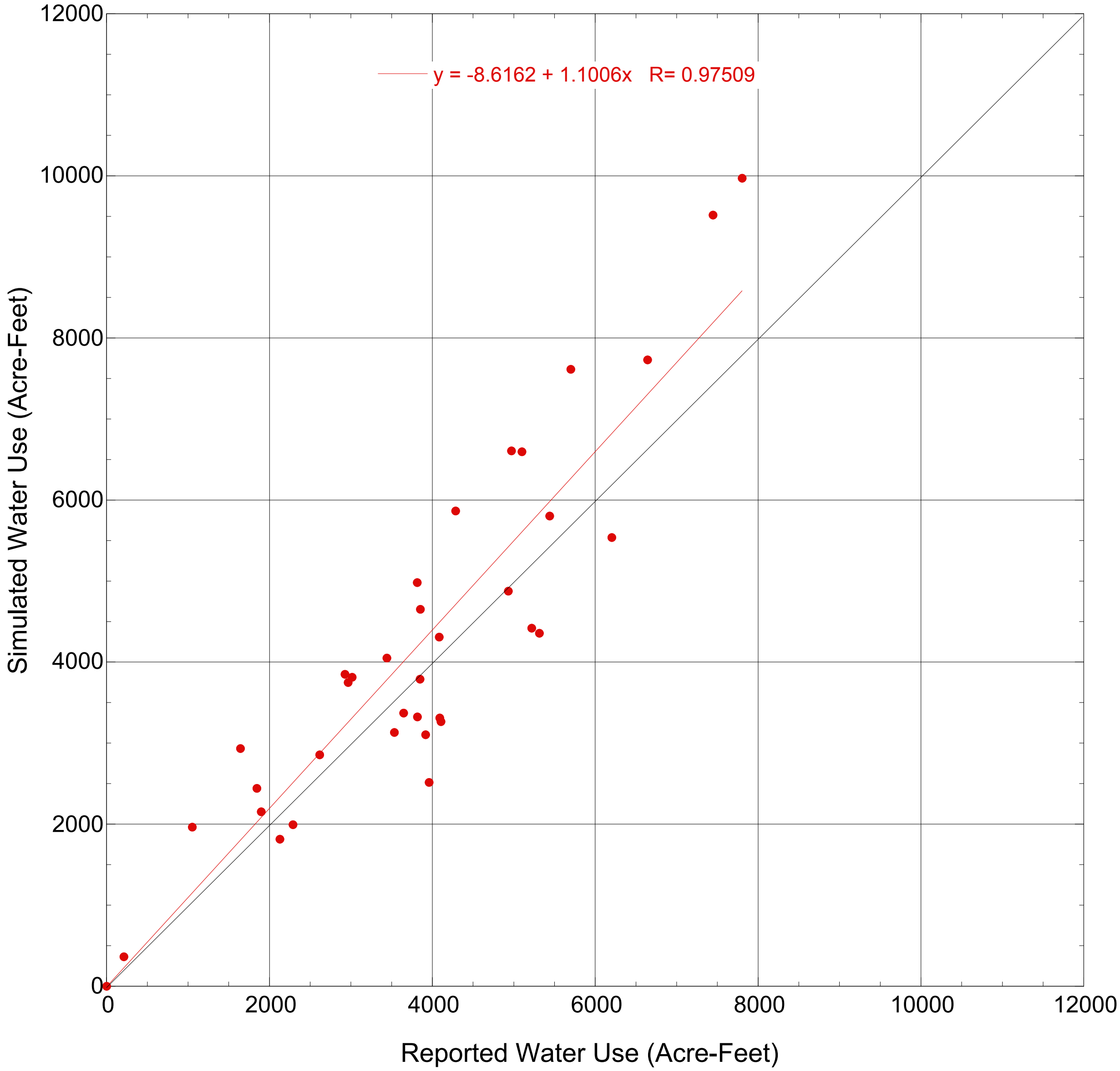
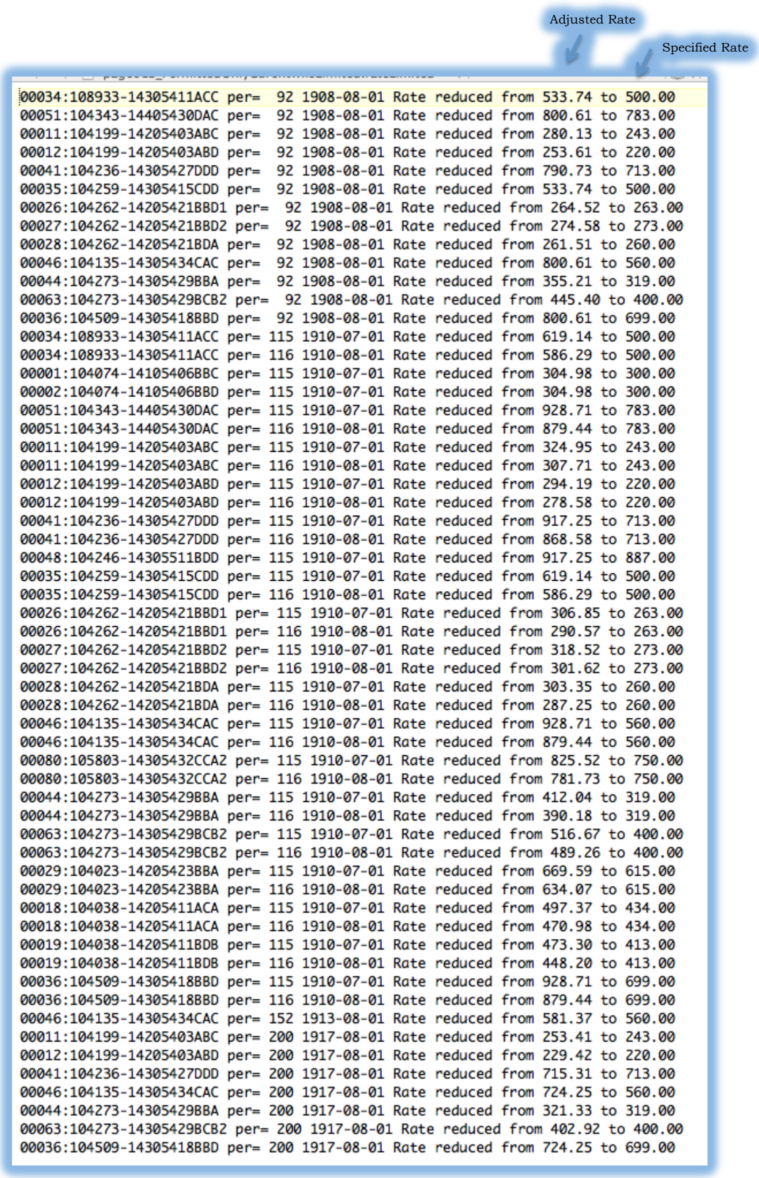


Figure 62. -- Comparison of simulated vs. reported water use from VB2000 South Climate Dataset.

exceeds that of the well was used. If the required pumping rate exceeds the specified rate, then the pumping rate in the package is set to the specified rate and a record is written to the rate limited file to show the rate should be adjusted if crop water demands are to be met (Figure 63). The specified rate is based on a measured pumping rate collected by NDSWC staff or is an estimated rate based on specific capacity and available drawdown of a well. The rate limited file is useful in defining irrigation well field designs that may not be able to provide the water needed in a period of drought.

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00018:104038-14205411ACA per= 115 1910-07-01 Rate reduced from 497.37 to 434.00
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00036:104509-14305418BBD per= 116 1910-08-01 Rate reduced from 879.44 to 699.00
00046:104135-14305434CAC per= 152 1913-08-01 Rate reduced from 581.37 to 560.00
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Figure 63. -- Example of a rate limited file generated from waterUseDB.

An annual comparison of wells requiring monthly rate adjustments using the south composite climate set from 1901-2010 was completed as Figure 64. This plot shows the number of wells within a superPOD that require monthly rate adjustments to meet crop water demands through the 110-year simulation. In addition, it also defines the specified rates, permitted rates, and number of wells in each superPOD. In some cases if the existing well field designs (specified rates) were expanded to meet the permitted rates, this would eliminate nearly half of

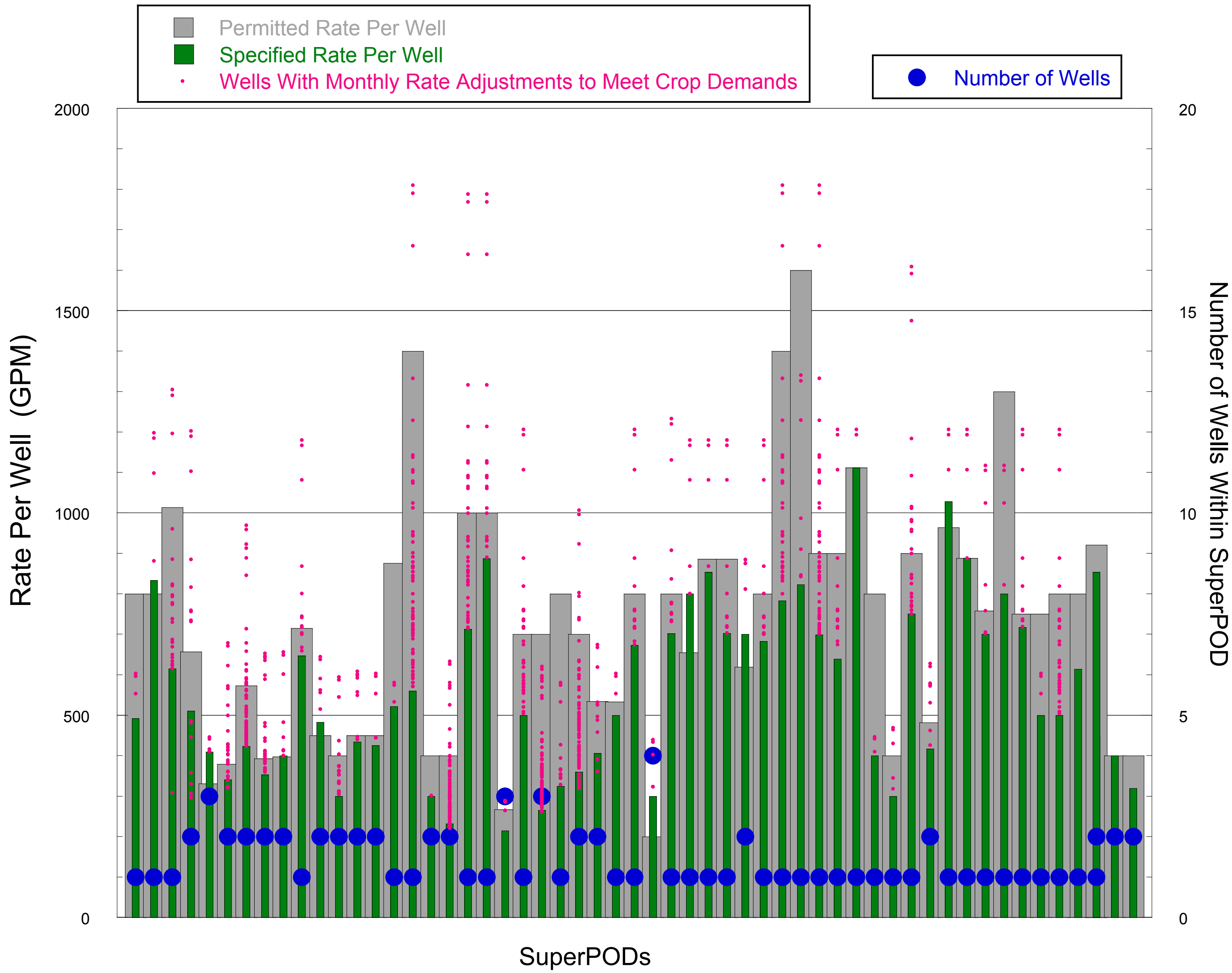

Figure 64. -- Monthly occurrences of specified rates that need adjustment to meet crop demands from 1901-2010. [Included is the specified rate per well, permitted rate per well, and the number of wells per superPOD.]

the rate adjustments required. In addition, 20 percent of the rate adjustments defined in Figure 64 happened since irrigation development began, however minimal concerns have been expressed from permit holders in regards to meeting crop water demands. This suggests the budget model is overestimating water use during drier months.

Transient - Model Results

To evaluate the sustainability of additional development in the Page aquifer, simulations of no pumping, permitted pumping, and permitted plus pending pumping were run using the 1901 through 2010 Page North and Page South climate sets. Since the Page South climate dataset more accurately estimates reported water use from 1976 to 2010, it was used to calibrate the 110-year simulations. Table 5 defines all the model runs and the codes associated with this report. In the calibration runs, estimated water use based on reported acres was used to replicate the historical aquifer conditions (Run A1 and B1). Hydrographs of observed versus simulated water levels from Run A1 and B1 are included in Figures 65-76. The starting water levels for

Code	Run Name	Period	Years
A1	MNW2NrthClimateCurrentWllsPrmitedOnlyPumping1976_2010NoLimNoSkin	1901-2010	110
B1	MNW2SthClimateCurrentWllsPrmitedOnlyPumping1976_2010NoLimNoSkin	1901-2010	110
C1	SthClimateNoPumping	1901-2010	110
D1	MNW2SthClimateCurrentWellsPermittedOnly110yrNoLimitNoSkin	1901-2010	110
E1*	MNW2SthPermittedNAllPending110YrNoLimitNoSkin	1901-2010	110
F1	MNW2SthClimateCurrentWellsPermittedOnly110yrLimNoSkin	1901-2010	110
G1*	MNW2SthPermittedNAllPending110YrLimitedNoSkin	1901-2010	110

*Model runs E1 and G1 include the pumping from pending applications with priority dates prior to 2012. The 3 pending applications (#6448, #6455 and #6456) with priority dates of November 5, 2012 from Table 1 were not included in either of these simulations or associated model results.

Table 5. -- Model Run Code Index

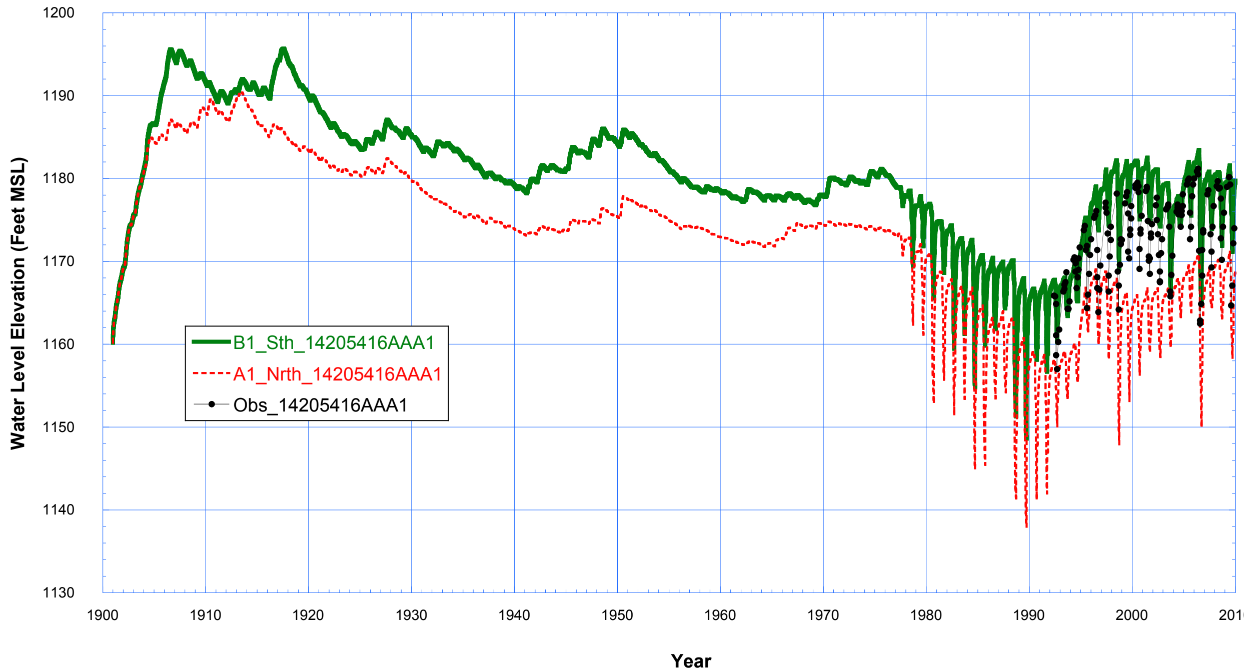

Figure 65. -- Observed vs. simulated water levels from model runs A1 (North Climate Set) and B1 (South Climate Set) for observation well 14205416AAA1.

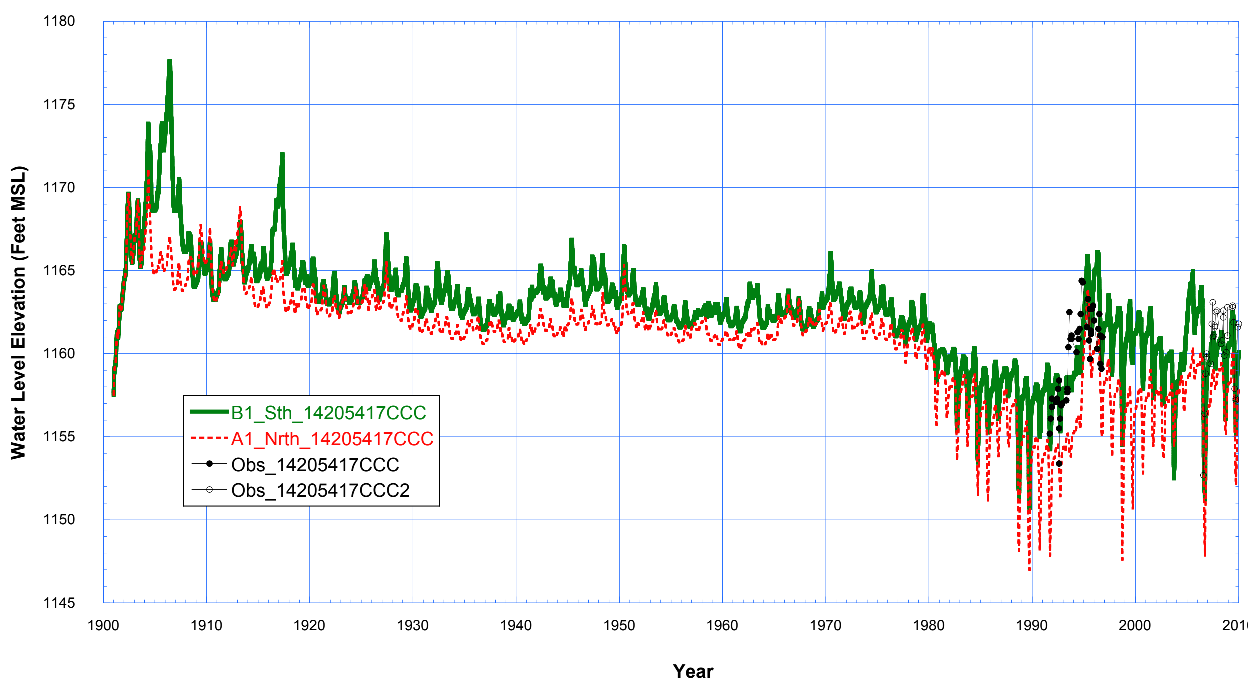

Figure 66. -- Observed vs. simulated water levels from model runs A1 (North Climate Set) and B1 (South Climate Set) for observation wells 14205417CCC1 & 2.

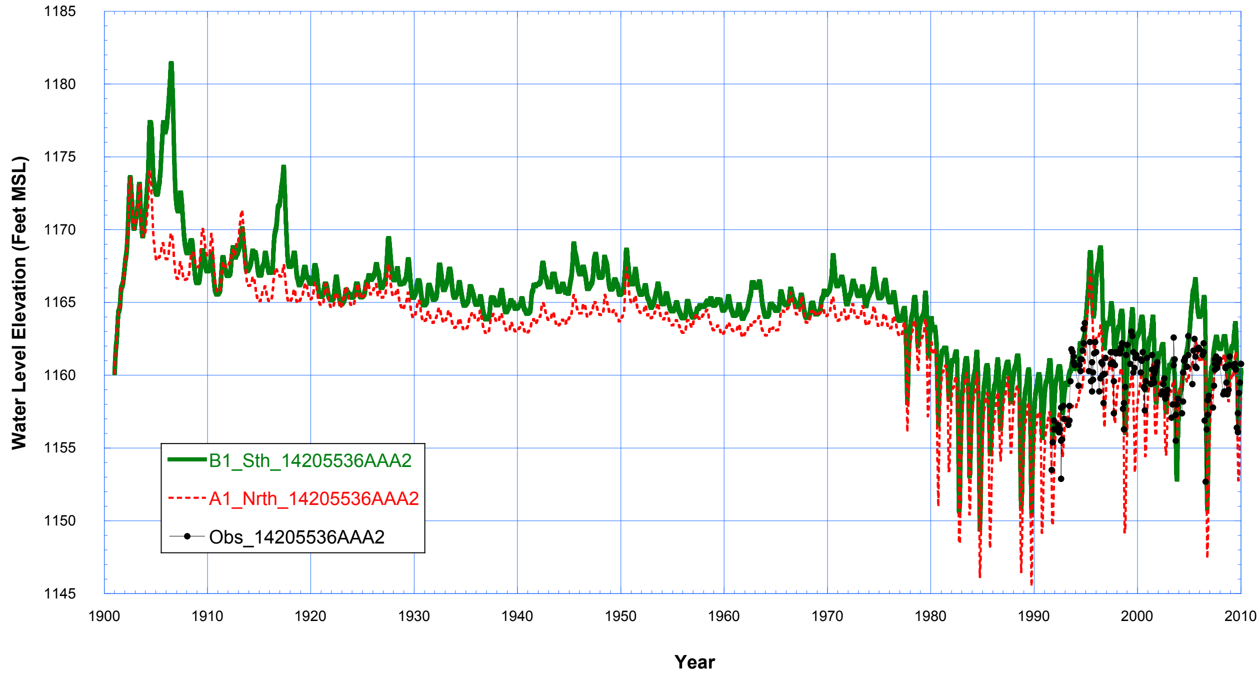

Figure 67. -- Observed vs. simulated water levels from model runs A1 (North Climate Set) and B1 (South Climate Set) for observation well 14205536AAA2.

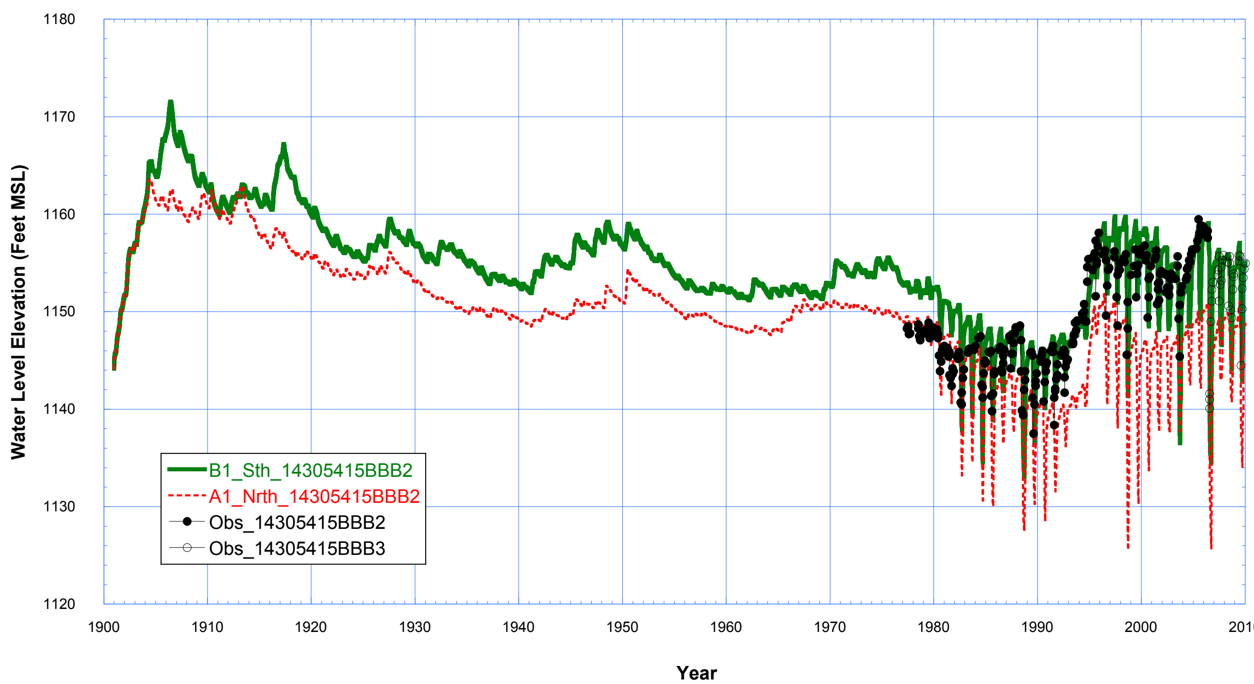

Figure 68. -- Observed vs. simulated water levels from model runs A1 (North Climate Set) and B1 (South Climate Set) for observation well 14305415BBB2.

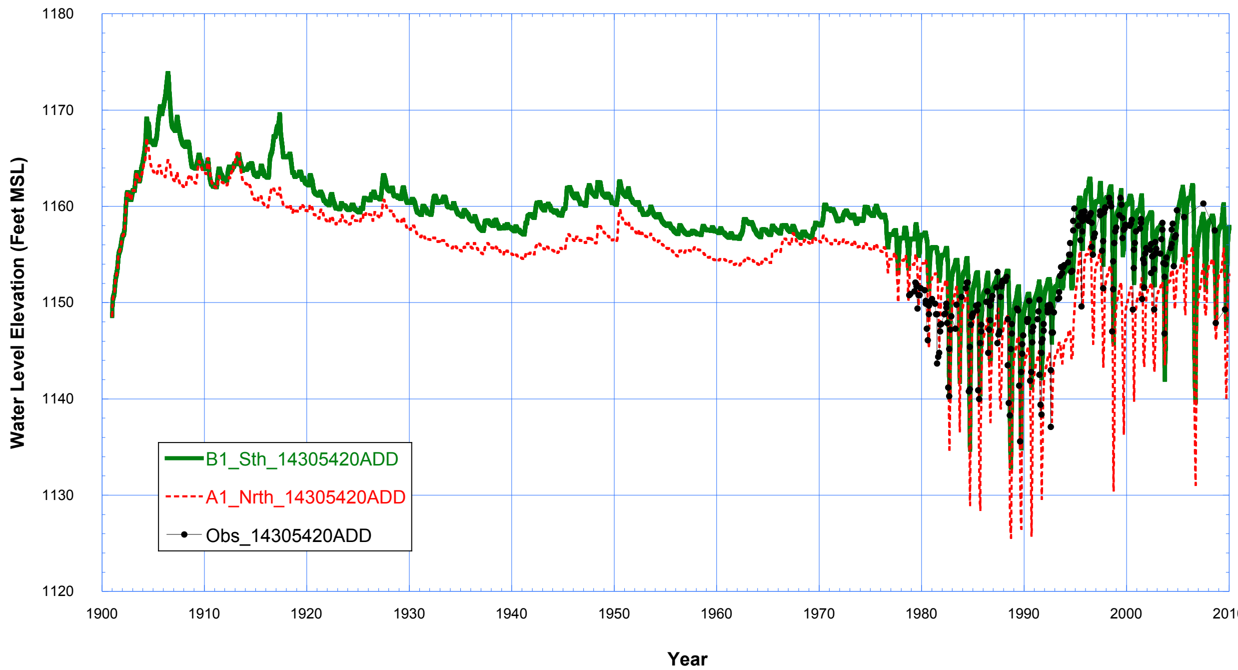

Figure 69. -- Observed vs. simulated water levels from model runs A1 (North Climate Set) and B1 (South Climate Set) for observation well 14305420ADD.

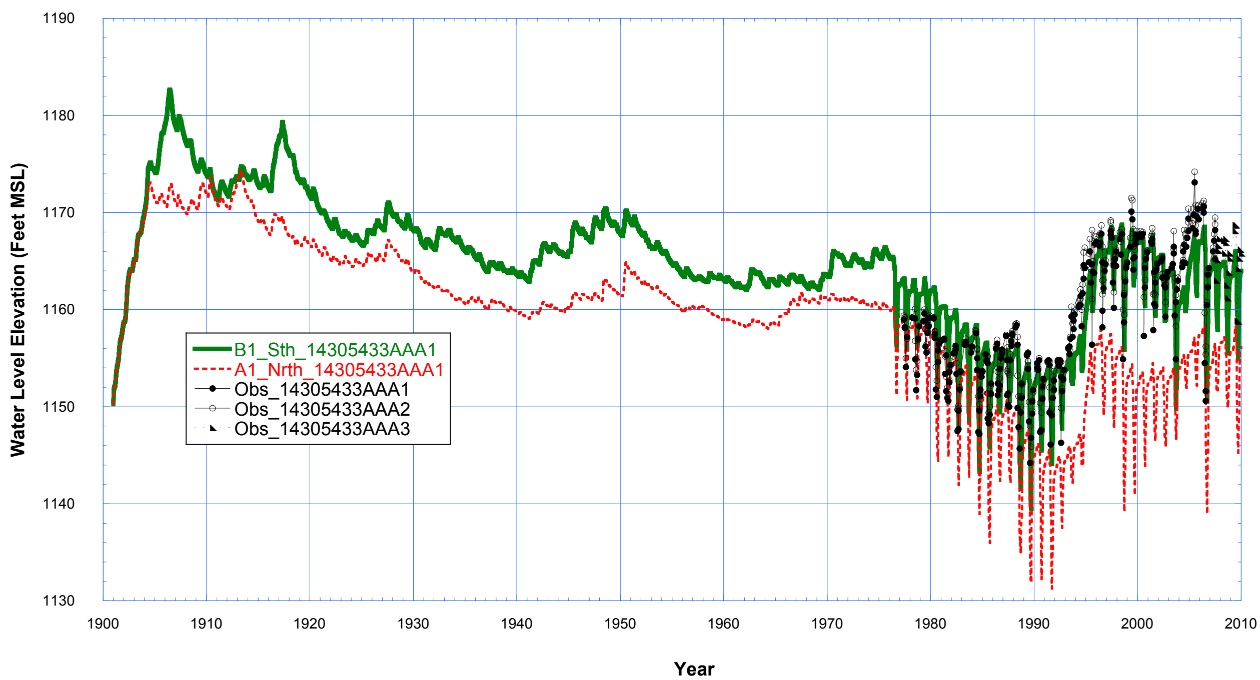

Figure 70. -- Observed vs. simulated water levels from model runs A1 (North Climate Set) and B1 (South Climate Set) for observation well 14305433AAA1,2,&3.

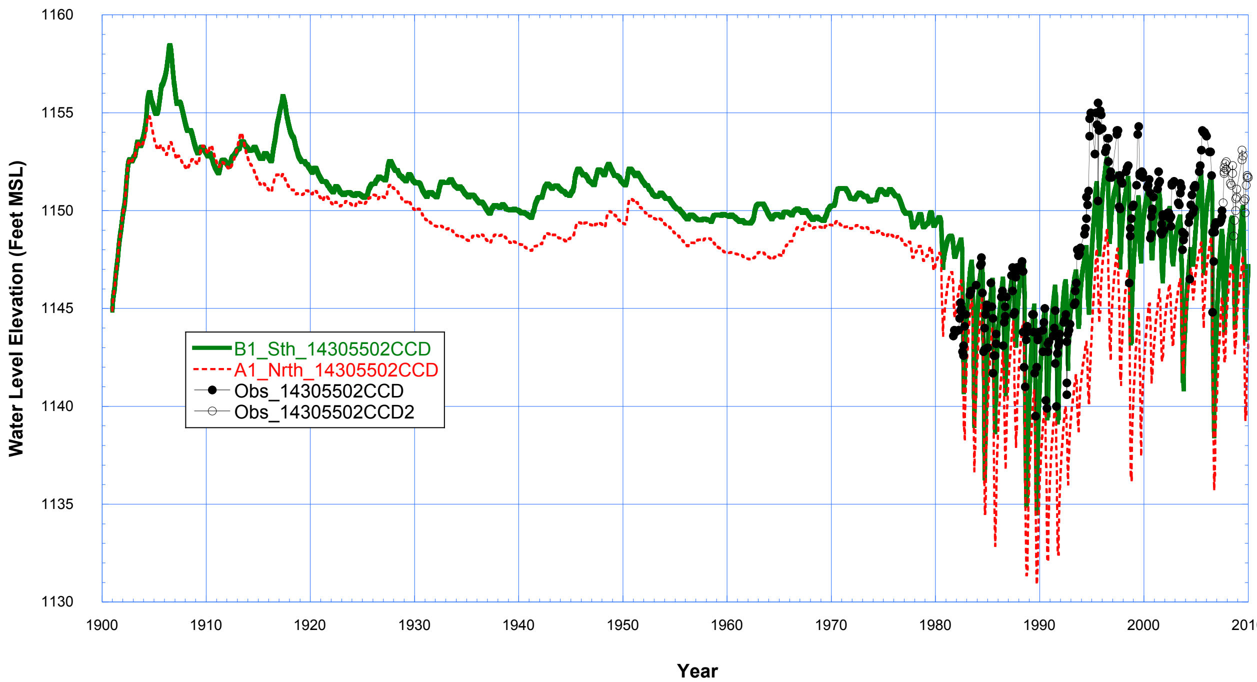

Figure 71. -- Observed vs. simulated water levels from model runs A1 (North Climate Set) and B1 (South Climate Set) for observation well 14305502CCD1 & 2.

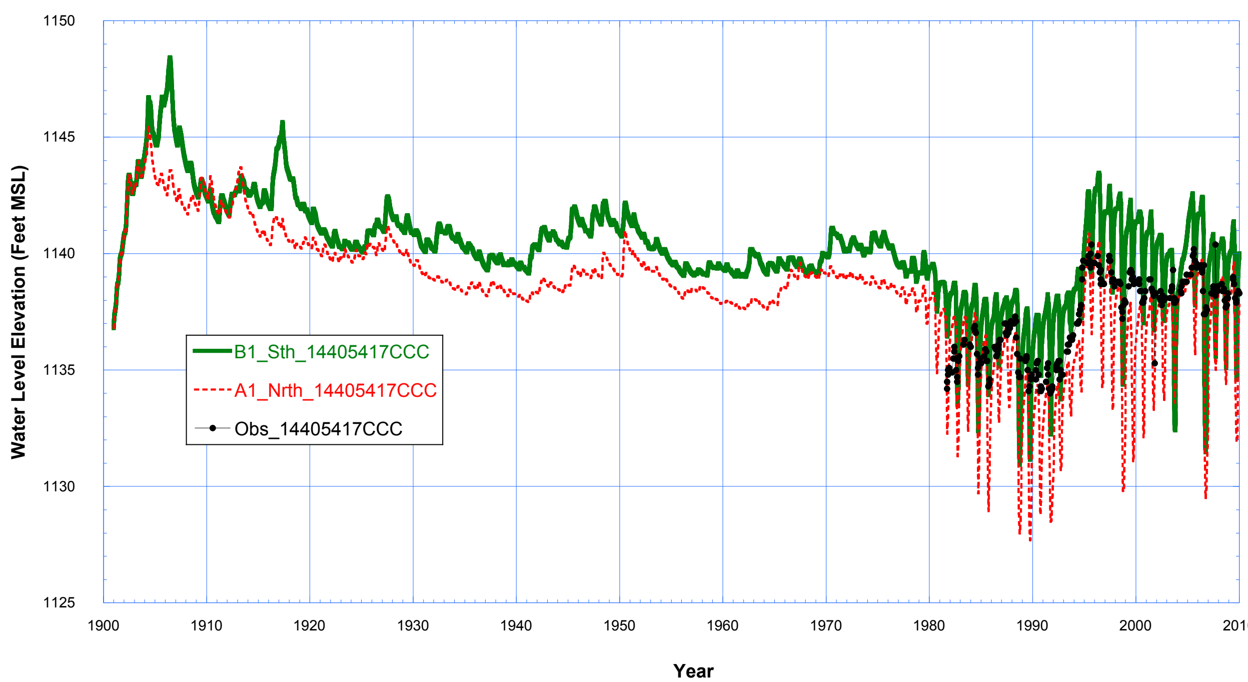

Figure 72. -- Observed vs. simulated water levels from model runs A1 (North Climate Set) and B1 (South Climate Set) for observation well 14405417CCC.

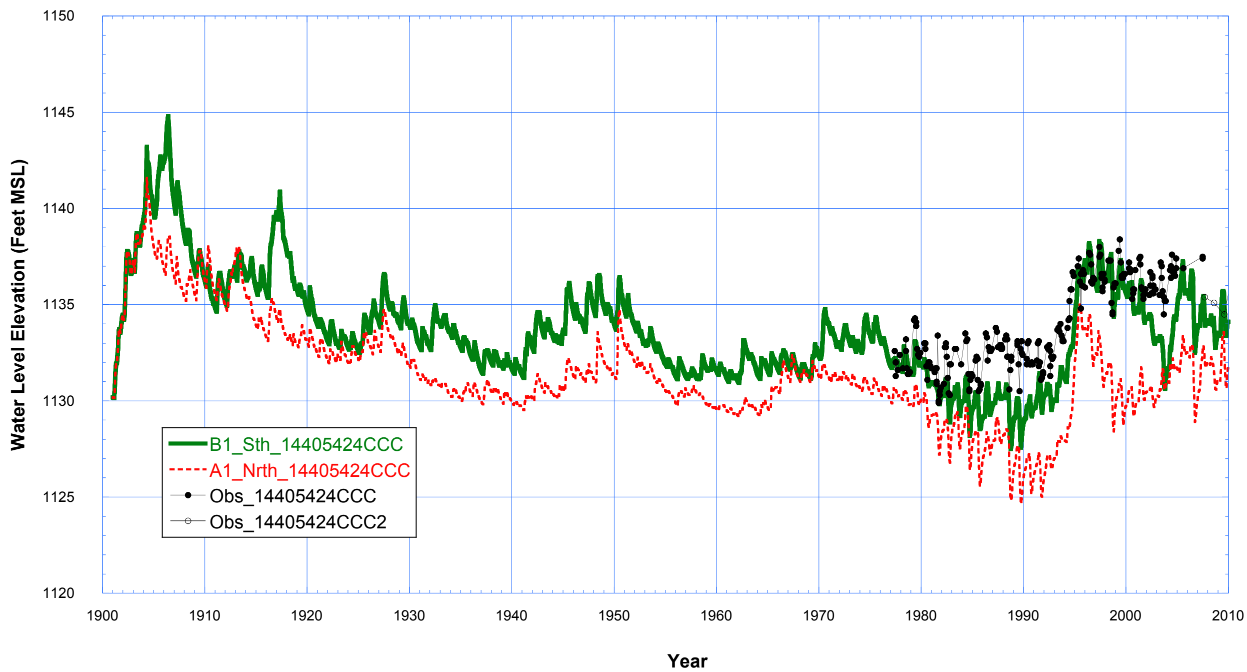

Figure 73. -- Observed vs. simulated water levels from model runs A1 (North Climate Set) and B1 (South Climate Set) for observation well 14405424CCC1 & 2.

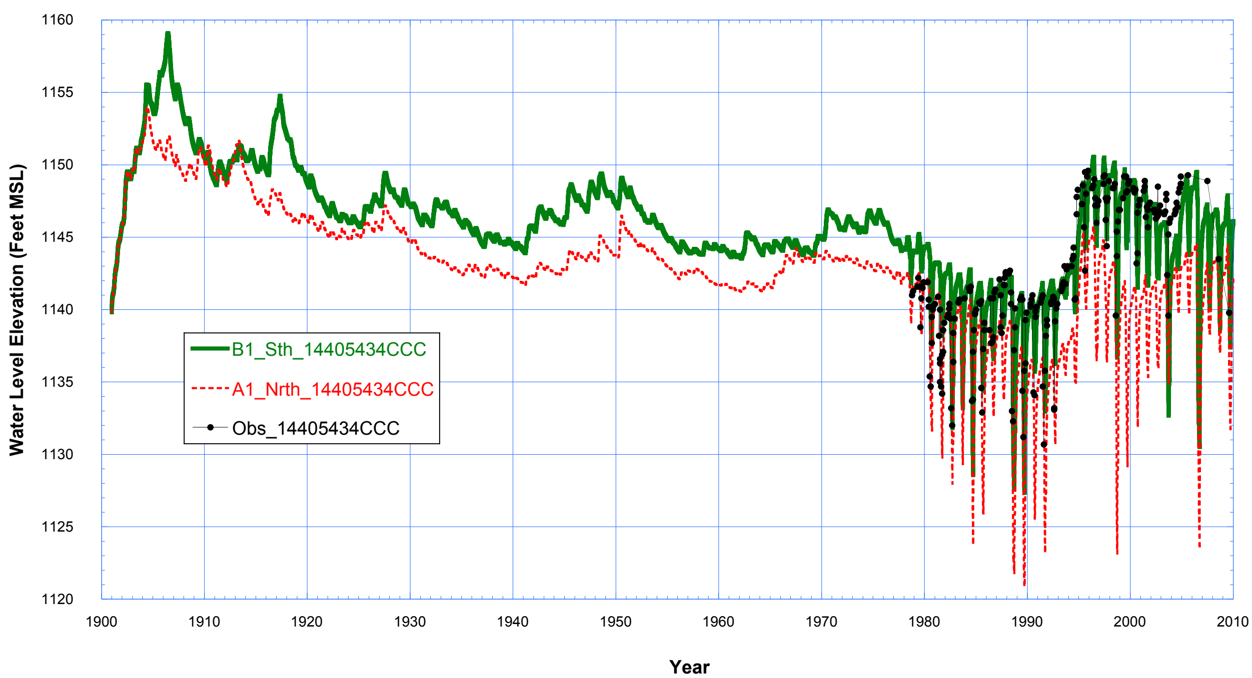

Figure 74. -- Observed vs. simulated water levels from model runs A1 (North Climate Set) and B1 (South Climate Set) for observation well 14405434CCC.

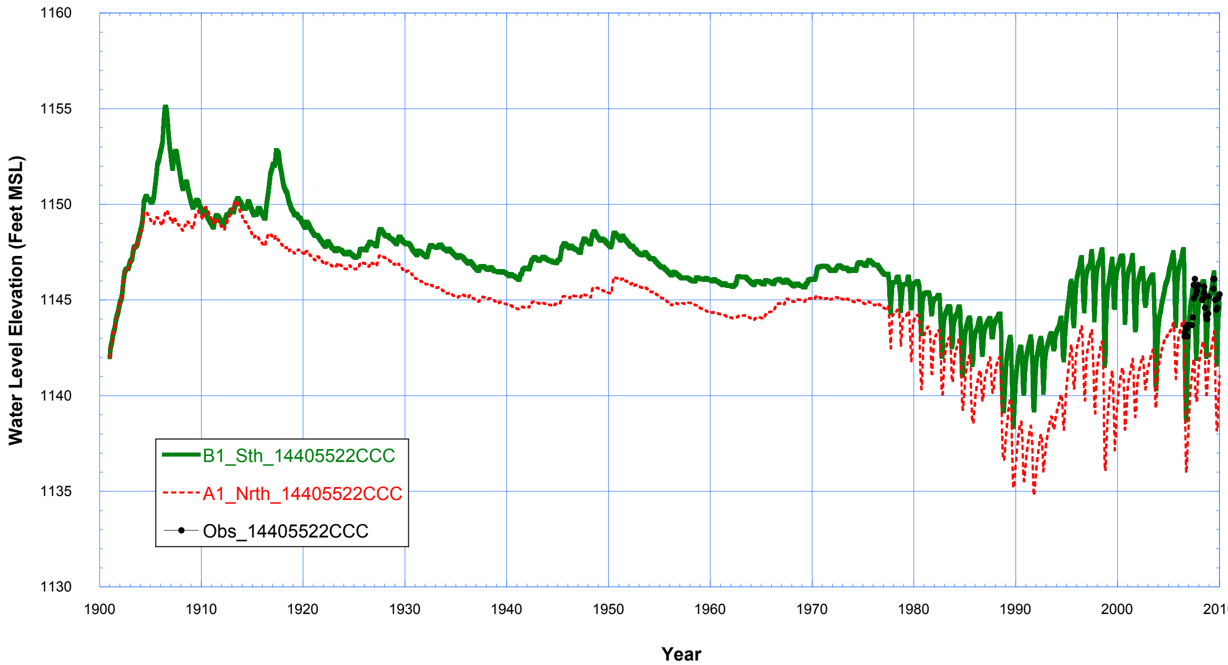

Figure 75. -- Observed vs. simulated water levels from model runs A1 (North Climate Set) and B1 (South Climate Set) for observation well 14405522CCC.

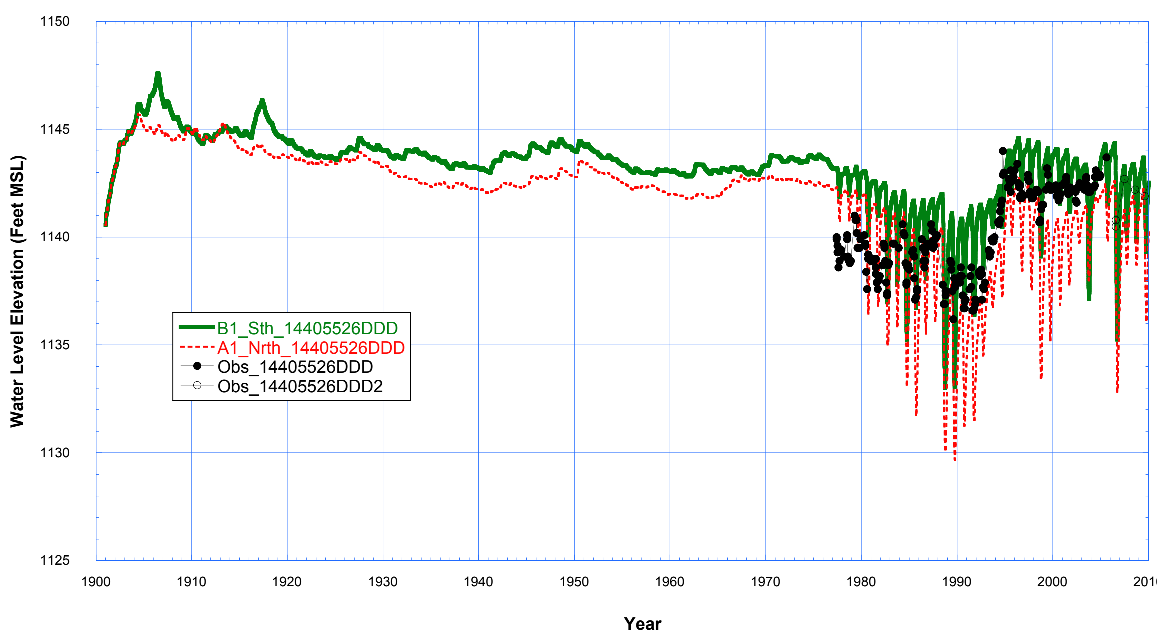

Figure 76. -- Observed vs. simulated water levels from model runs A1 (North Climate Set) and B1 (South Climate Set) for observation well 14405526DDD1 & 2.

these transient runs are based on the December 1983 steady-state condition, which included irrigation and rural water pumping in the model. In the early time data for both Run A1 and Run B1 simulations, there is a large spike in water levels. The water-level spike is due to the abundant amount of recharge put into the model associated with the wet conditions from the Fargo climate dataset used in both simulations in early time. In Run B1, the spike continues for a few years beyond what is observed in Run A1. This extended spike was initiated by a change in the source climate dataset for Run B1 from Fargo to Hillsboro in 1905, which was much wetter than the Fargo and Cooperstown datasets from Run A1 during the same time frame (Figures 8 & 9). Additional hydrographs from Run A1 and Run B1 are presented in Appendix E. Based on the hydrographs in Figures 65-76 and Appendix E, Figure 77 was generated to show the predictive capability of the transient model. In areas of continuous hydrostratigraphy the model reproduces water levels very well and in areas of complex hydrostratigraphy it does not. On the north and east edge of the domain, the model has difficulty matching water levels. This is likely attributed to the complex hydrostratigraphy and the inaccurate calculation of outflows through the drain and general head boundaries in these areas.

Model Run C1 simulates 1901-2010 water levels based on climate only, with no pumping. Run F1 expands Run B1 by estimating pumping from VB 2000 to see the growing season drawdown effects that would have occurred during the last 110 years under the current level of development (permitted pumping). Comparisons of water levels and ET between Run F1 and Run C1 are shown in Figures 78-87. These water levels and ET comparisons are made in May (before growing season drawdown effects begin) and in August (when growing season drawdown effects are at a maximum). This assemblage of head and ET comparisons was taken from the driest years in a multi-decadal selection to show impacts of the current level of development. When comparing Run F1 (permitted pumping) to Run C1 (no pumping), there are no significant changes in ET. The lack of significant changes in ET can be attributed to the leaky confined nature of the Page aquifer where pumping does not have a direct effect on water at or near the surface. During the late 1980s drought, both Run C1 and Run F1 simulations eliminate all ET from the aquifer as water levels fell below the extinction depths (Figure 85). Conversely, the 2006 comparison has much more water being harvested by ET (Figure 86 & 87).

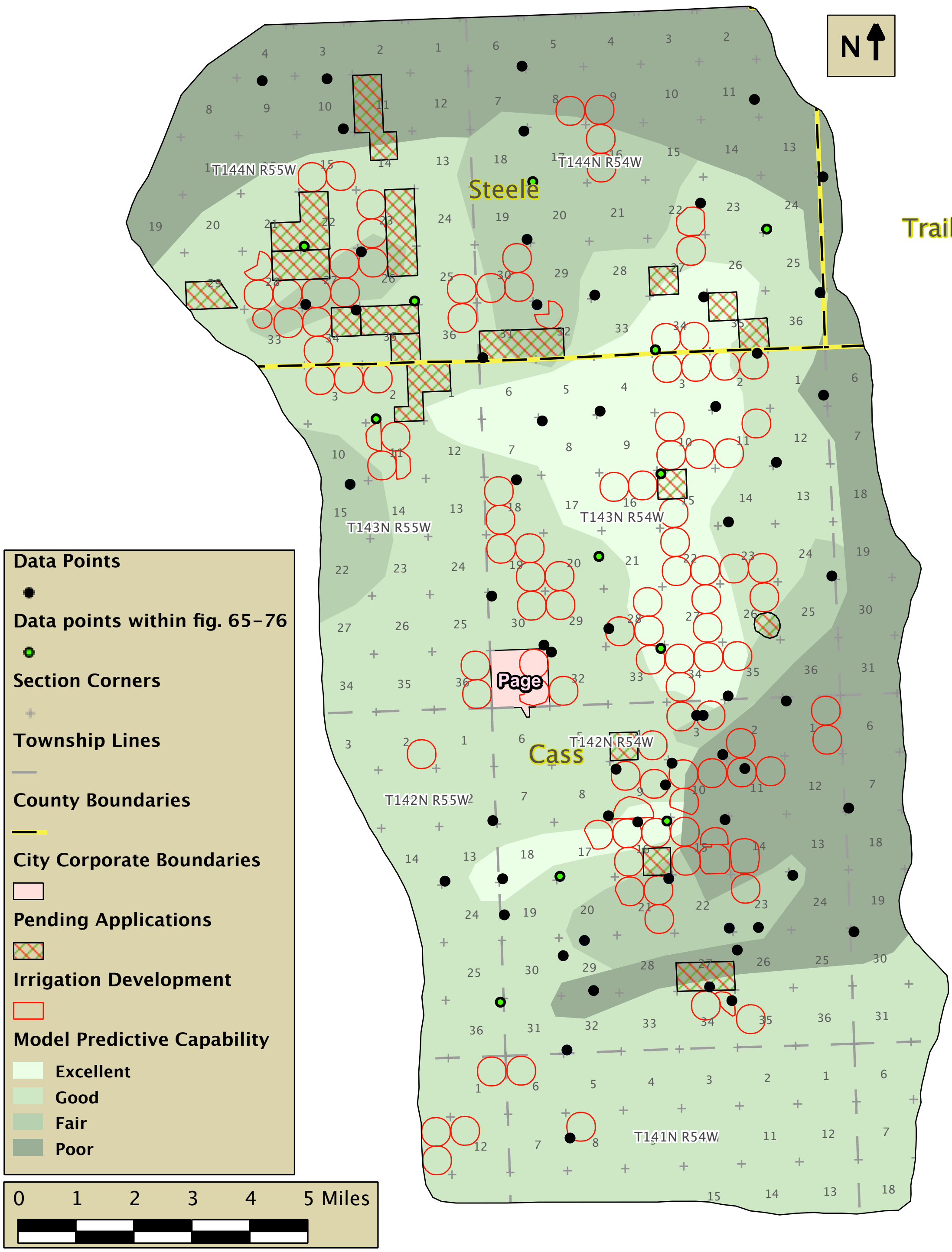

Figure 77. -- Predictive capability of the transient model based on 77 data points comparing simulated (Run A1 and Run B1) and observed water levels.

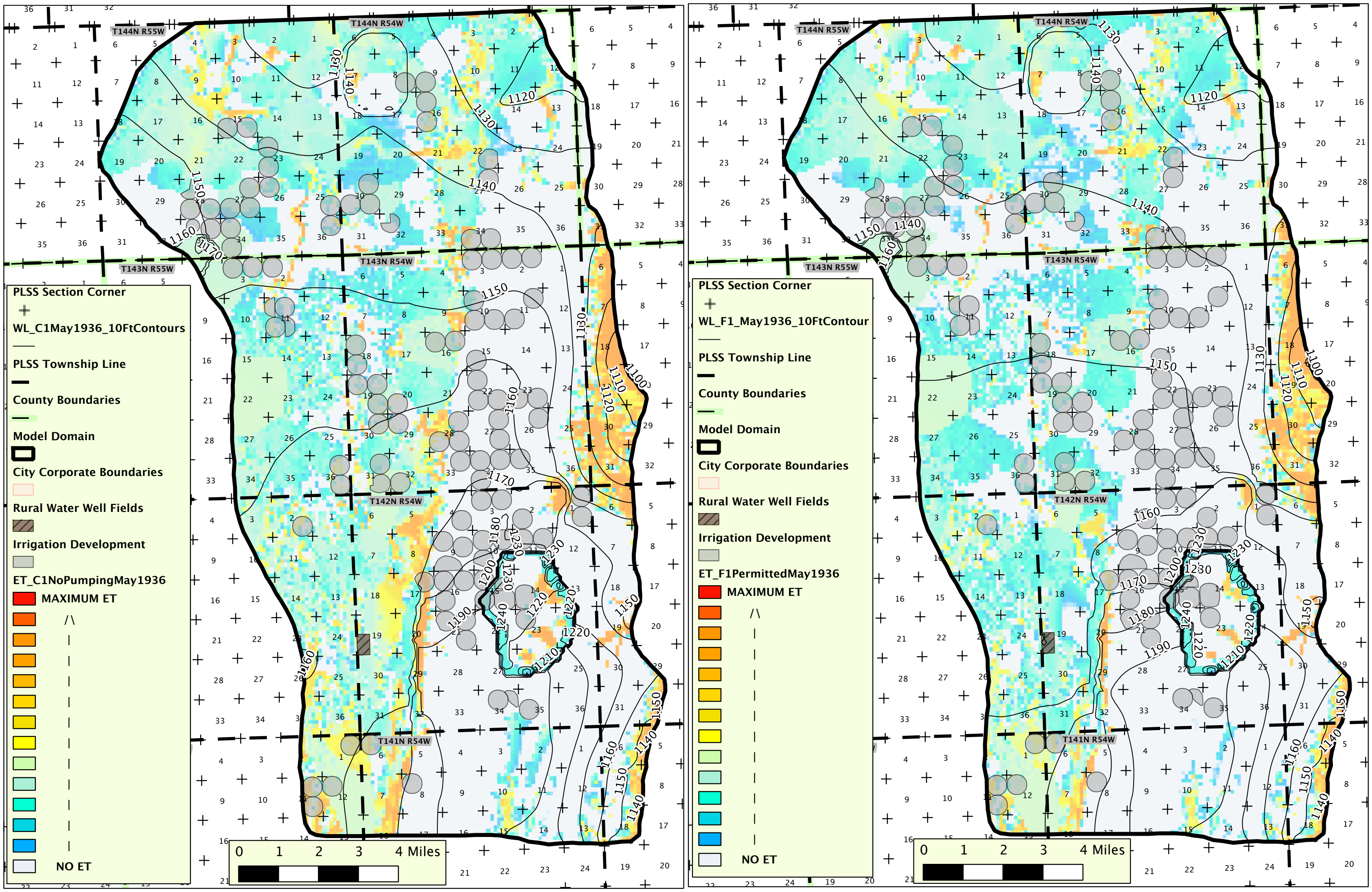

Figure 78. -- Comparison of water levels and ET from model run C1 (No Pumping) and model run F1 (Permitted Pumping) for May 1936.

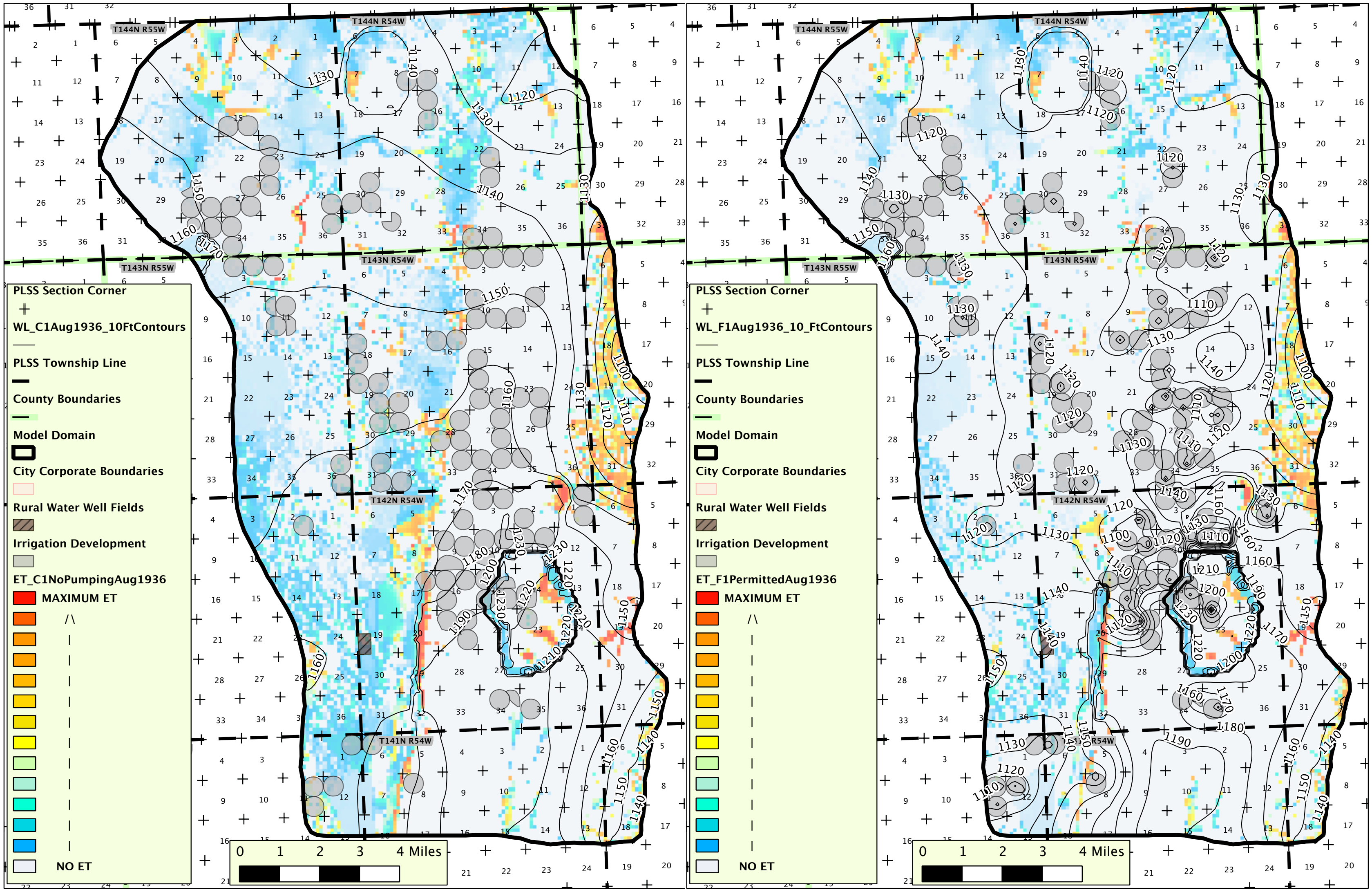

Figure 79. -- Comparison of water levels and ET from model run C1 (No Pumping) and model run F1 (Permitted Pumping) for August 1936.

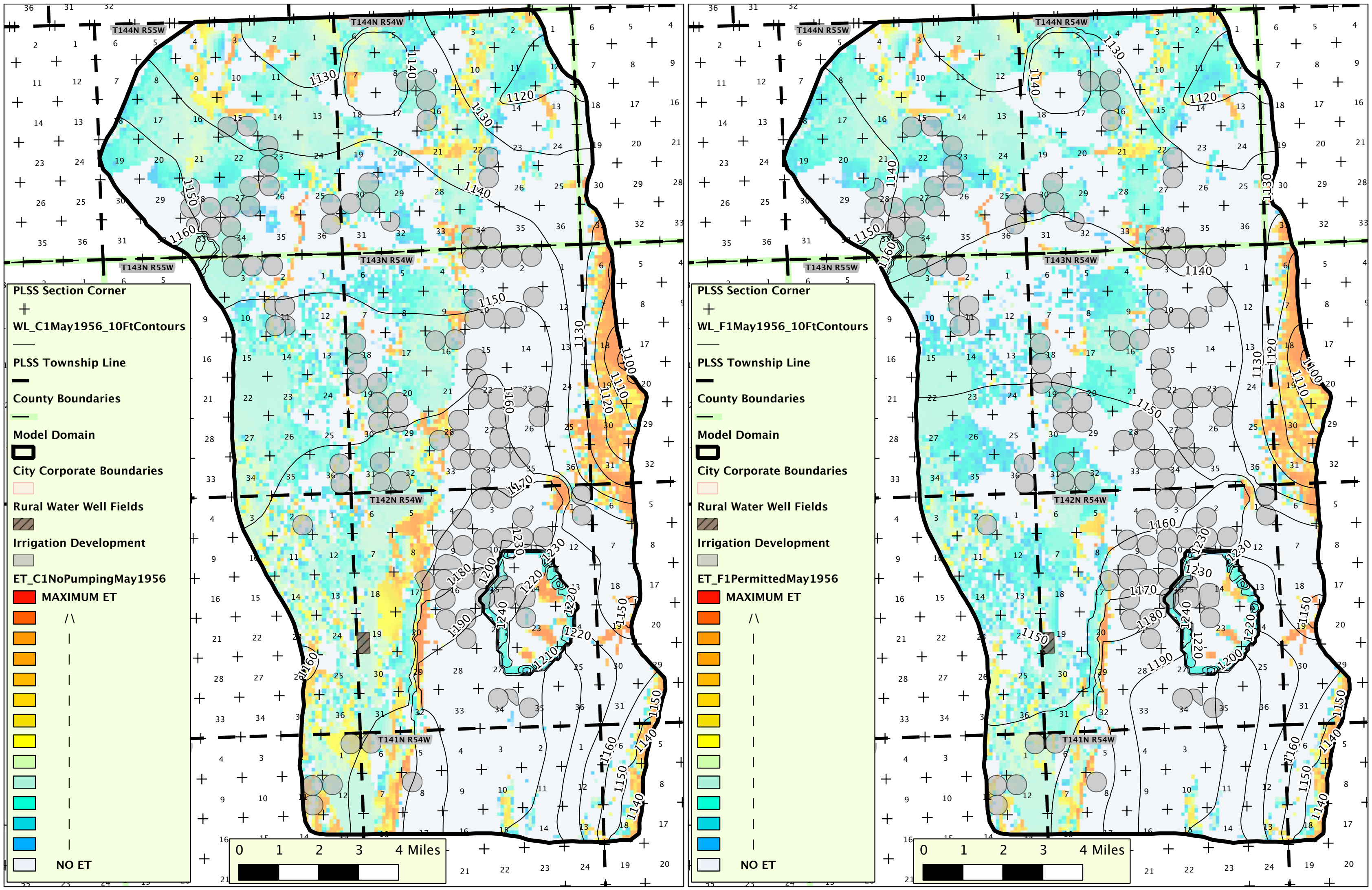

Figure 80. -- Comparison of water levels and ET from model run C1 (No Pumping) and model run F1 (Permitted Pumping) for May 1956.

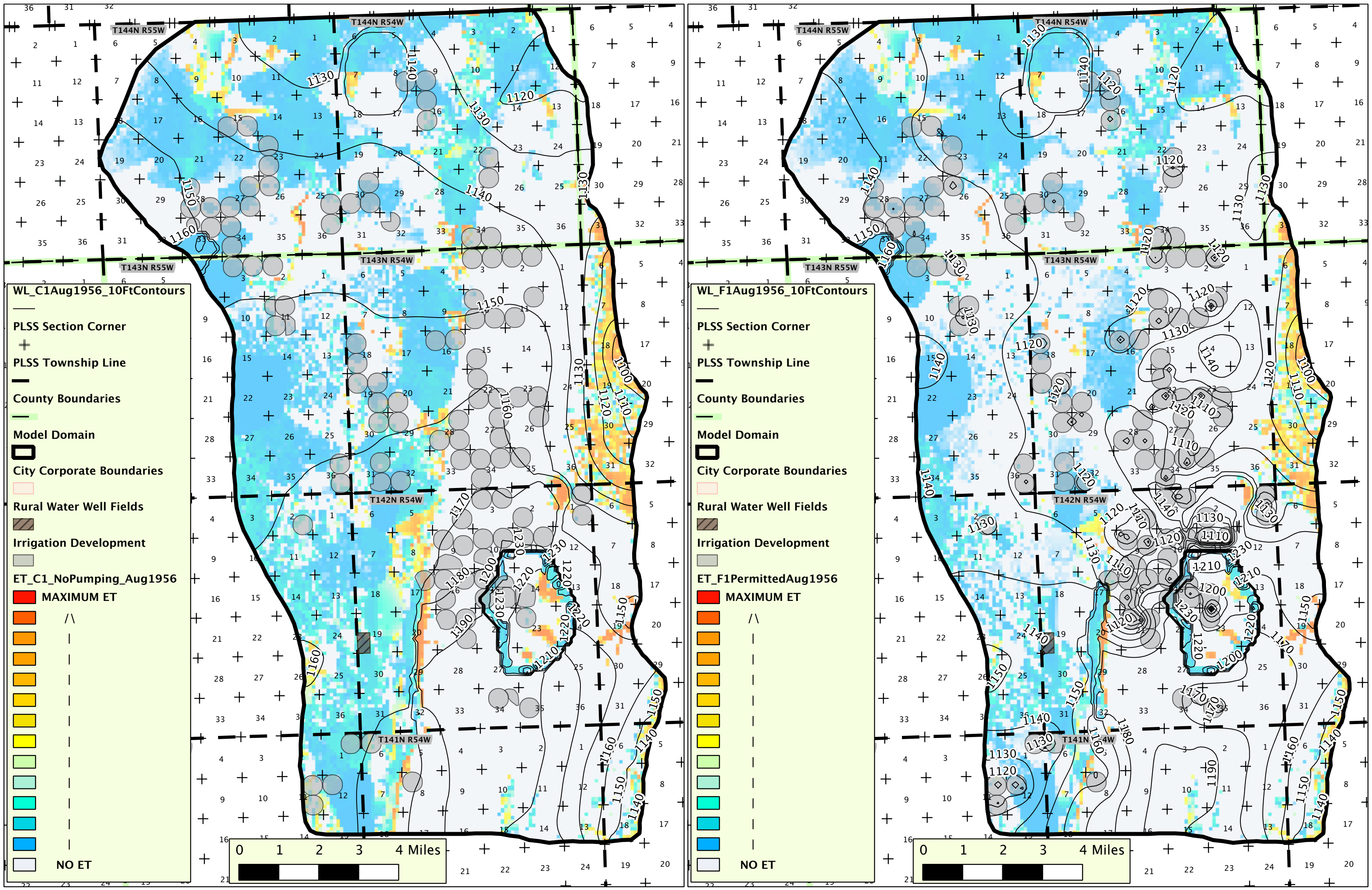

Figure 81. -- Comparison of water levels and ET from model run C1 (No Pumping) and model run F1 (Permitted Pumping) for August 1956.

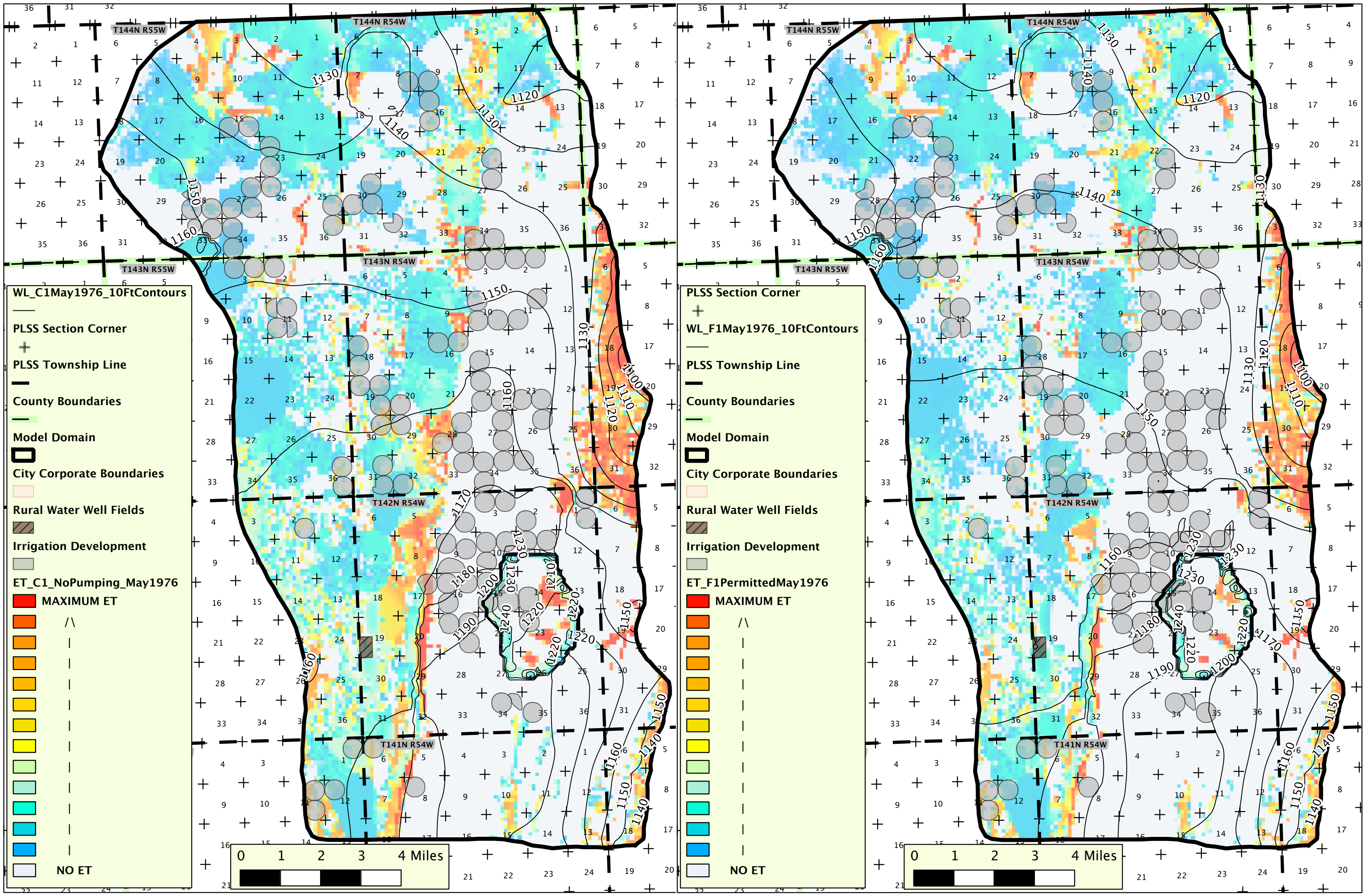

Figure 82. -- Comparison of water levels and ET from model run C1 (No Pumping) and model run F1 (Permitted Pumping) for May 1976.

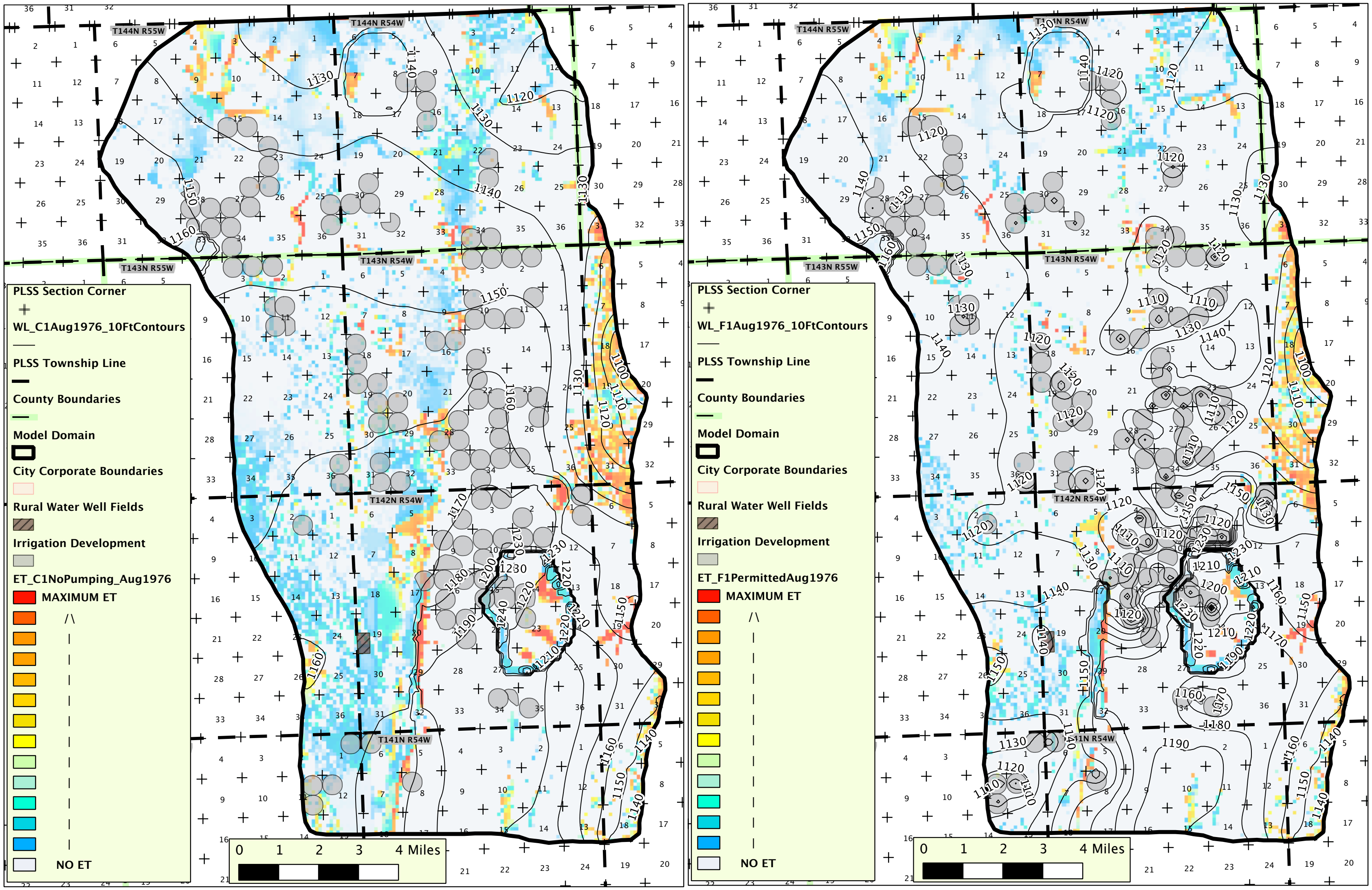

Figure 83. -- Comparison of water levels and ET from model run C1 (No Pumping) and model run F1 (Permitted Pumping) for August 1976.

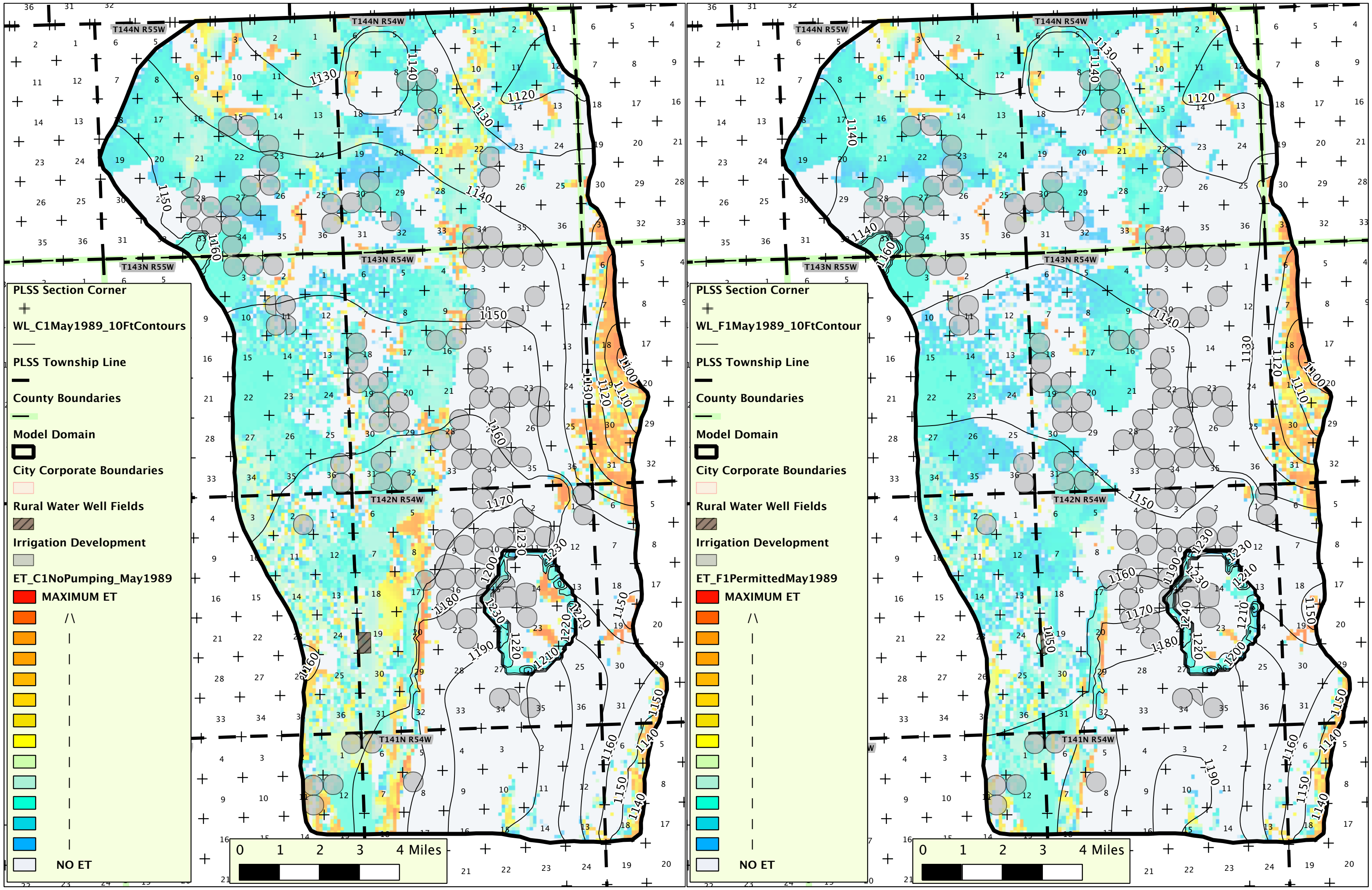

Figure 84. -- Comparison of water levels and ET from model run C1 (No Pumping) and model run F1 (Permitted Pumping) for May 1989.

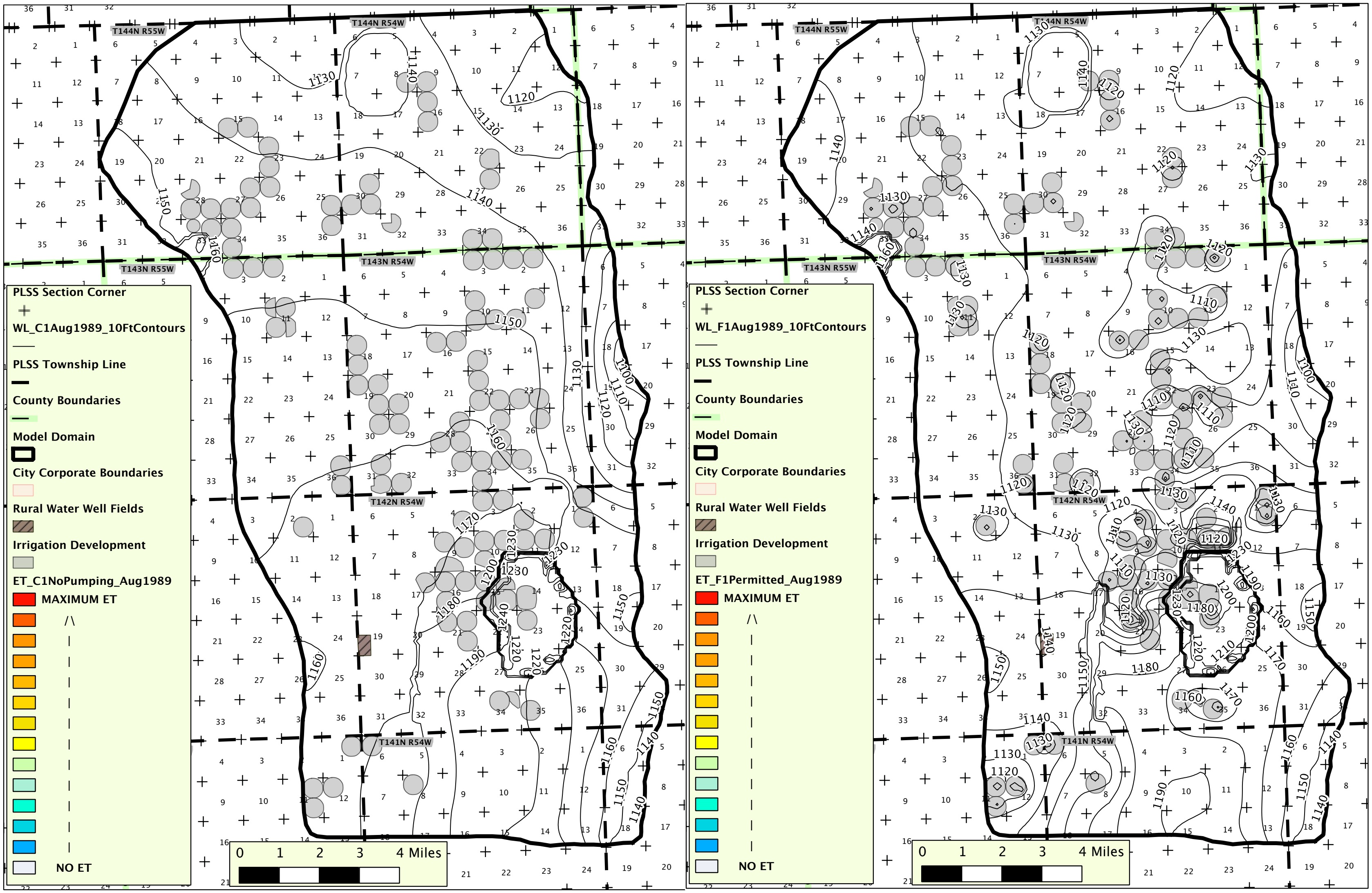

Figure 85. -- Comparison of water levels and ET from model run C1 (No Pumping) and model run F1 (Permitted Pumping) for August 1989.

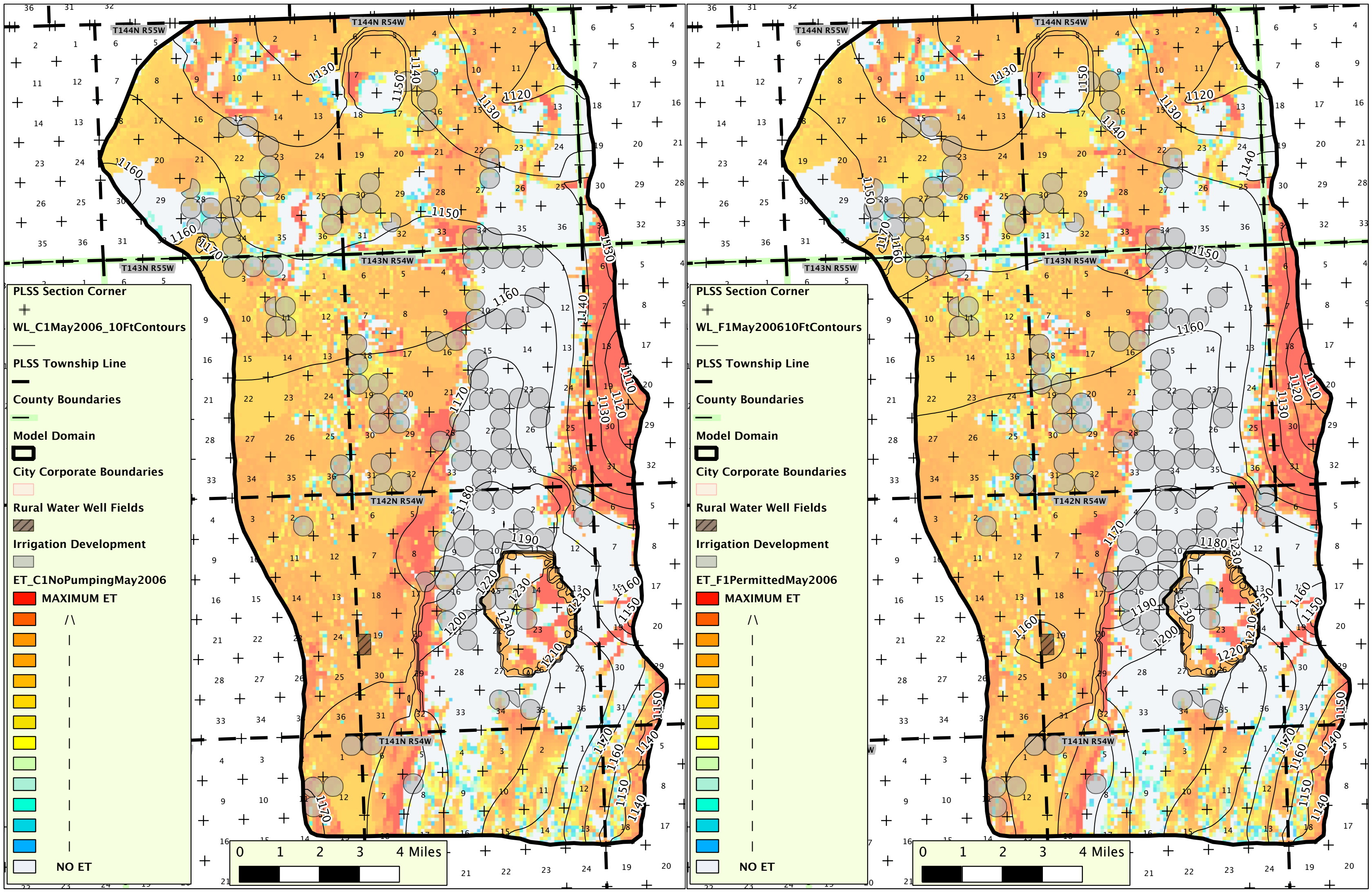

Figure 86. -- Comparison of water levels and ET from model run C1 (No Pumping) and model run F1 (Permitted Pumping) for May 2006.

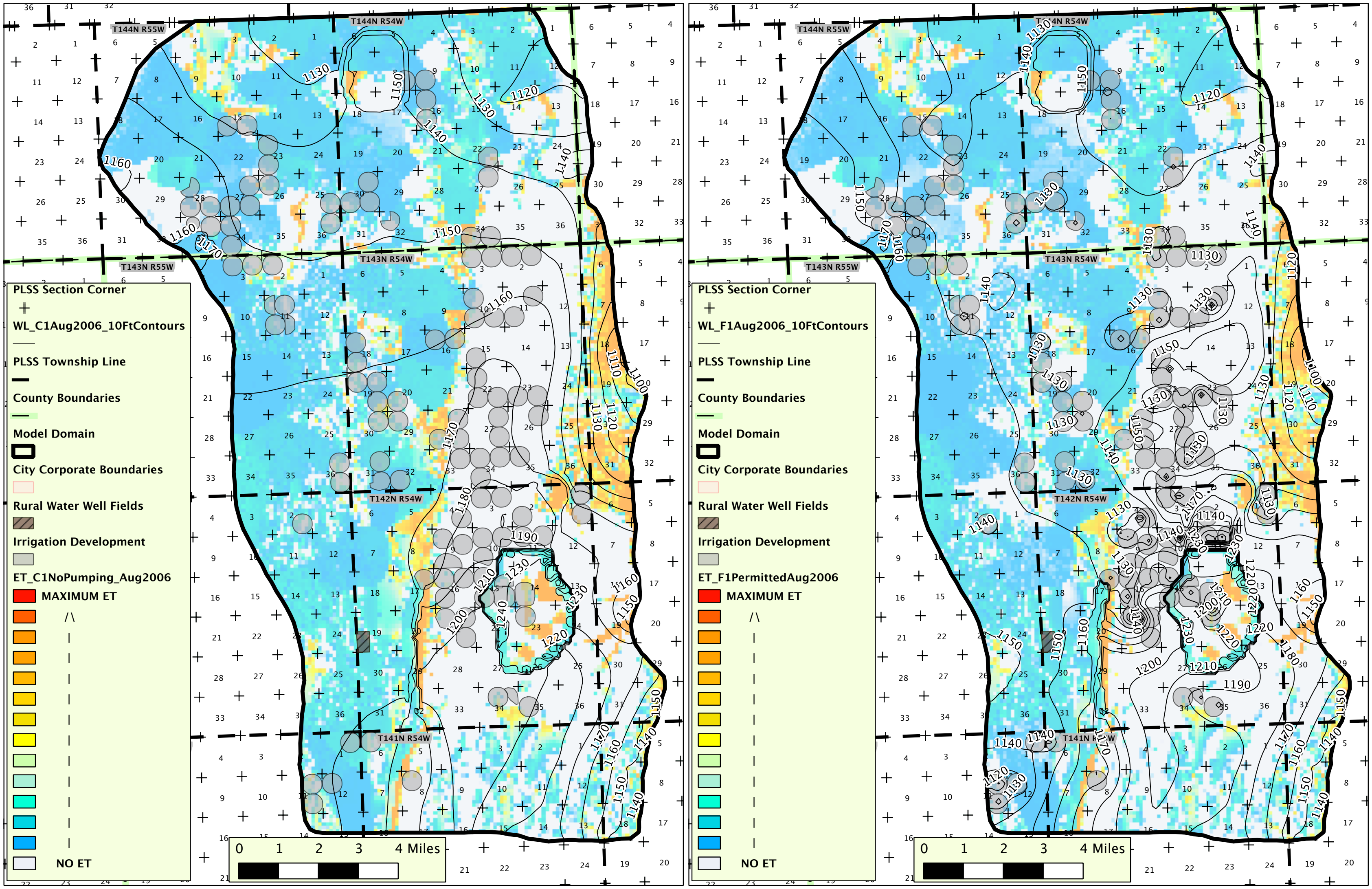

Figure 87. -- Comparison of water levels and ET from model run C1 (No Pumping) and model run F1 (Permitted Pumping) for August 2006.

Since there were wet conditions leading up to 2006, the water table was brought up to or near land surface in many areas allowing more ET to be harvested during a dry 2006.

When comparing the May water levels and ET maps for various dates in Figures 78, 80, 82, 84, and 86, there are no significant differences. This indicates there is adequate recharge to the aquifer allowing water levels to recover each spring and indicates that withdrawals from the aquifer are sustainable under the current level of development. In the comparison of water levels from Run C1 to Run F1 during the irrigation season (August), there are significant differences in water levels due to pumping (Figures 79, 81, 83, 85, & 87). Comparisons of August water levels provide insight into areas that are more susceptible to growing season drawdown effects.

Additional model runs were completed using permitted pumping plus pending pumping (Run G1). Wells were added to the model to simulate drawdown for the pending applications. Figures 88 through 92 show water-level differences between Run F1 (permitted pumping) minus Run G1 (permitted and pending pumping) for various dates.

In Figures 88 through 92 there is continuous drawdown in well 14205418CCC for both May and August, where Cass Rural Water has a pending application. Because this is a rural water application, pumping occurs year round versus irrigation pumping which occurs only during the growing season.

Historically, when irrigation wells were completed in the Page Aquifer, a fair amount of test drilling was done to find the most productive zone within the permitted area. When assigning additional wells to the pending application areas in the model, minimal consideration of placing wells in the most conductive zones were taken, because of the large local variation in the aquifer. It is likely in some cases, the hydraulic conductivities in the model cells of the added wells are underestimated and as a result the wells show excessive drawdowns during the irrigation season. An example of this may be in the August maps of Figures 88 through 92, where there is extensive drawdown in wells 14205427C and 14205427D associated with a pending application. However, if the hydraulic conductivities and associated drawdowns are realistic for this area, the pending application if approved, would require approximately 5 or more wells to support a quarter-section pivot system. Due to the complex hydrostratigraphy in

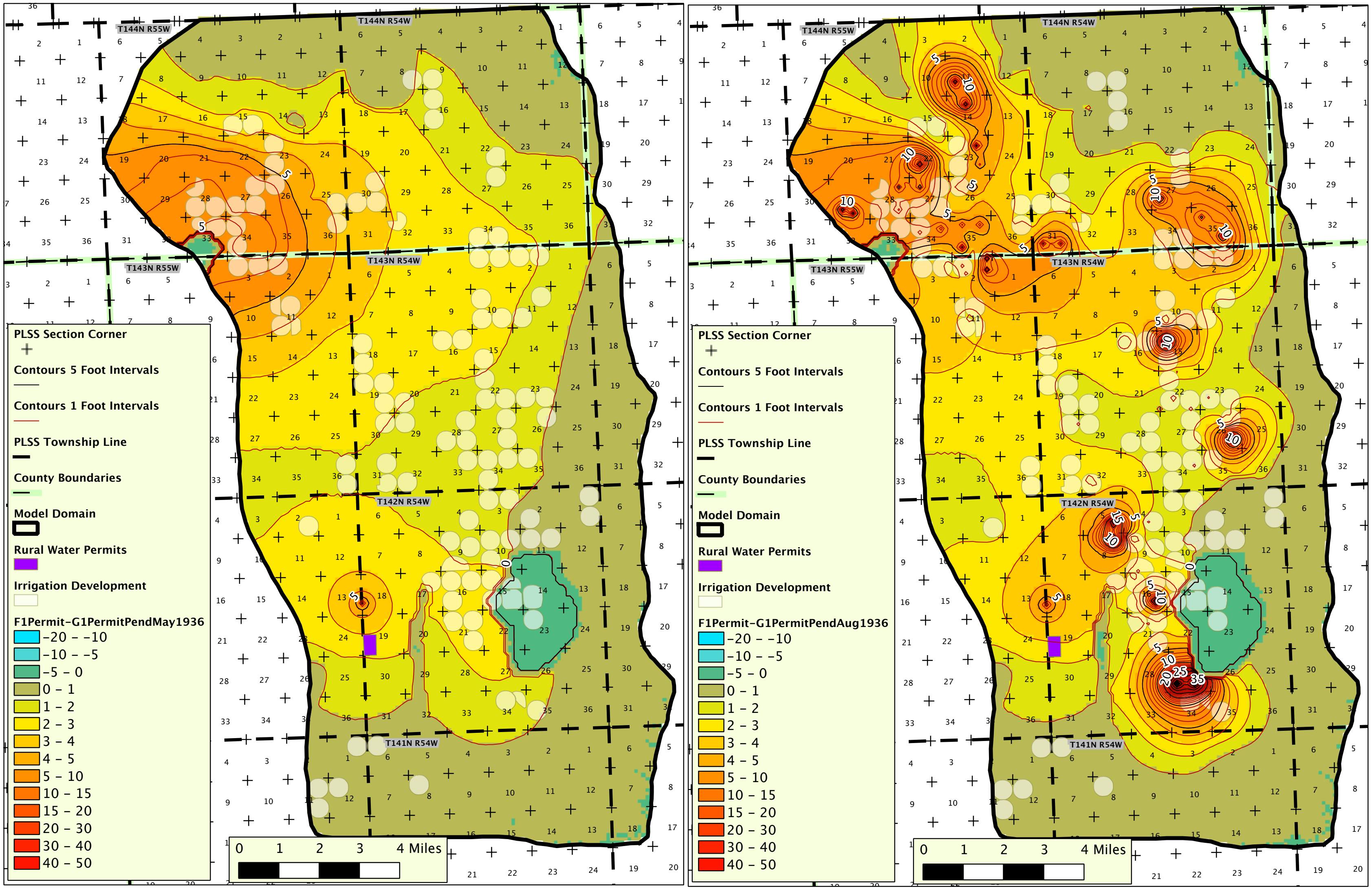

Figure 88. -- Comparison of May 1936 and August 1936 water level differences [(model run F1, Permitted Pumping) Less (model run G1, Permitted + Pending Pumping)].

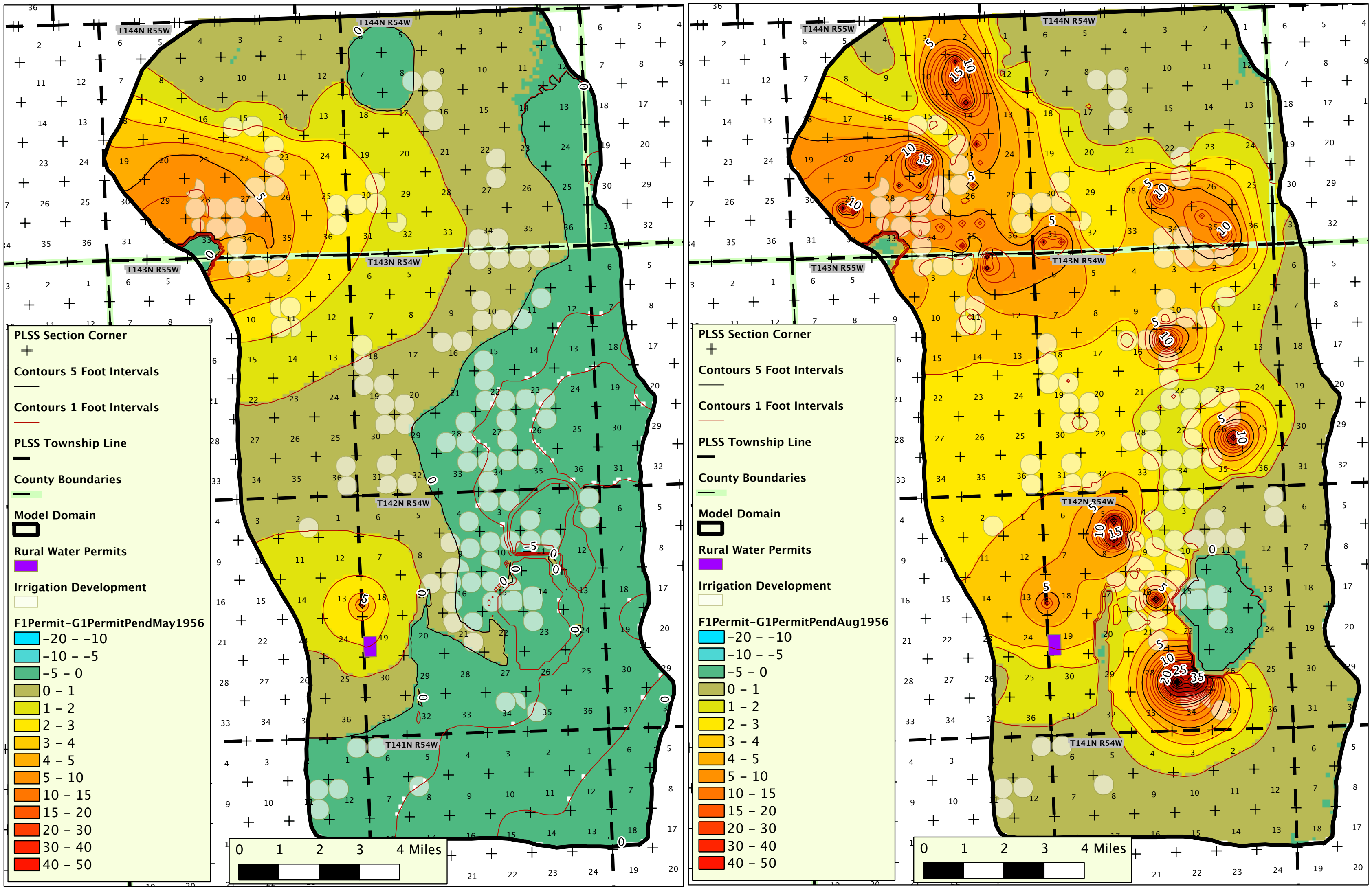

Figure 89. -- Comparison of May 1956 and August 1956 water level differences [(model run F1, Permitted Pumping) Less (model run G1, Permitted + Pending Pumping)].

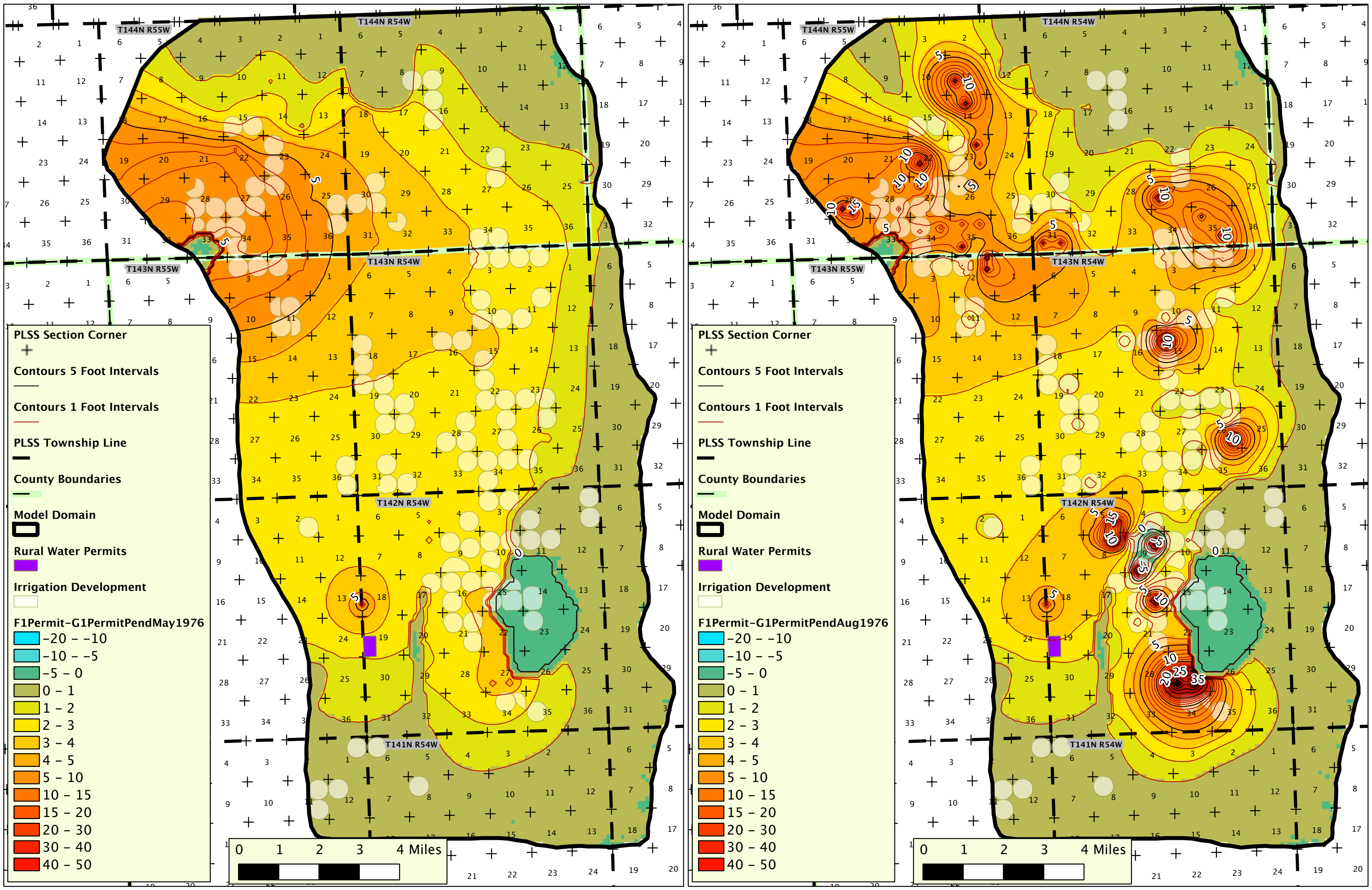

Figure 90. -- Comparison of May 1976 and August 1976 water level differences [(model run F1, Permitted Pumping) Less (model run G1, Permitted + Pending Pumping)].

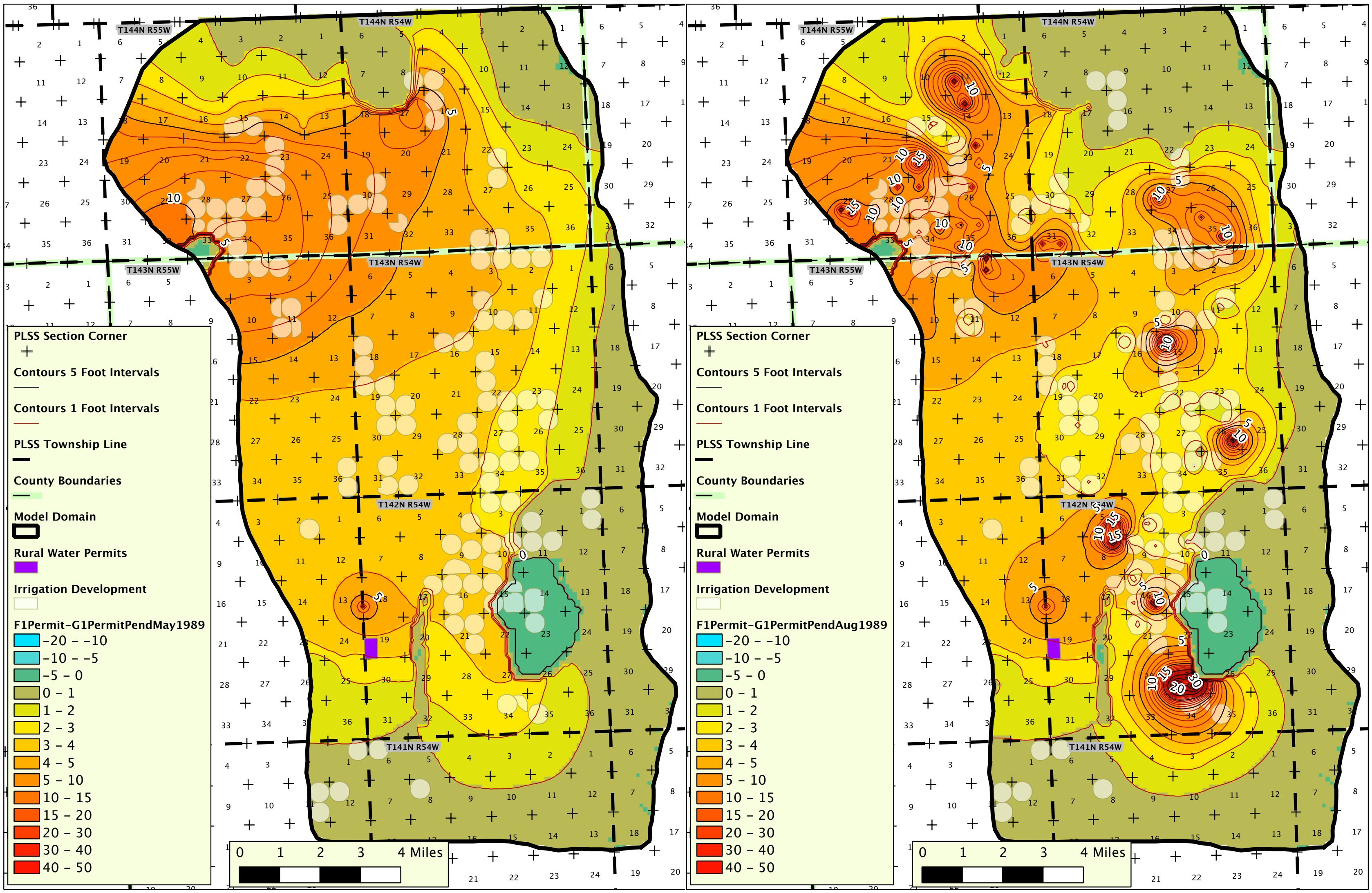

Figure 91. -- Comparison of May 1989 and August 1989 water level differences [(model run F1, Permitted Pumping) Less (model run G1, Permitted + Pending Pumping)].

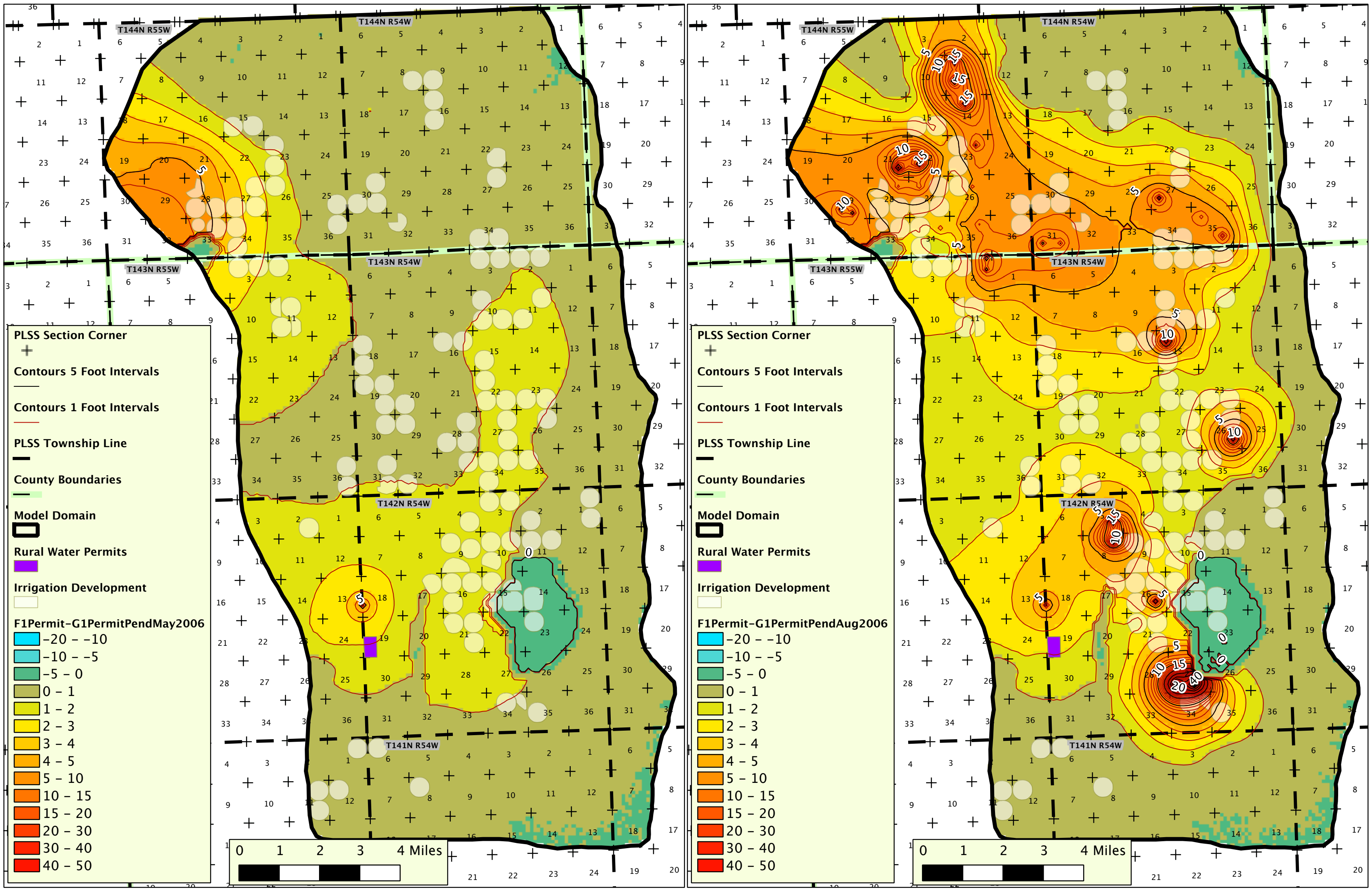

Figure 92. -- Comparison of May 2006 and August 2006 water levels differences [(model run F1, Permitted Pumping) Less (model run G1, Permitted + Pending Pumping)].

the Page aquifer, some pending applications may not have sufficient specific capacities and/or available drawdown to support irrigation. The specific capacity is used to measure the performance of a well and is determined by dividing the pumping rate, in gallons per minute, by the water level drawdown, in feet, after a specified pumping time. The available drawdown is calculated by taking the depth of the well intake less the water level in the well.

A comparison of specific capacities and minimum available drawdowns from irrigation wells is provided in Figure 93. The irrigation wells with the large specific capacities (white squares) and large minimum available drawdowns (black circles) are the higher yielding irrigation wells. Consequently, the wells with small specific capacities and small minimum available drawdowns are the lower yielding wells. These data were extrapolated from the NDSWC driller's log database and should not be used with a great amount of confidence for an individual well, but on a regional level this information provides insight into the variability of the aquifer. In many cases, specific capacities measured were based on short term (1 hour) pumping tests. More dependable specific capacity measurements could have been gathered from a longer duration pumping test of 24 hours or more. The driller's logs do not provide pump intake depths, but estimates based on the screen interval were made.

Model Strengths and Limitations

With a simple two-layer approach used in this model, complex hydrostratigraphy could not be represented properly. For example, layer 1 in the southeast portion of the model consists of multiple stratigraphic units consisting of silts, clays, and fine sands. Vertical conductance was calculated using a prorated average of the three stratigraphic units based on the thickness of each unit. In this process, the more conductive sands, rather than the tight clays dominate the vertical conductance. One approach to deal with this issue is adding more layers to the model to better represent the complex hydrostratigraphy.

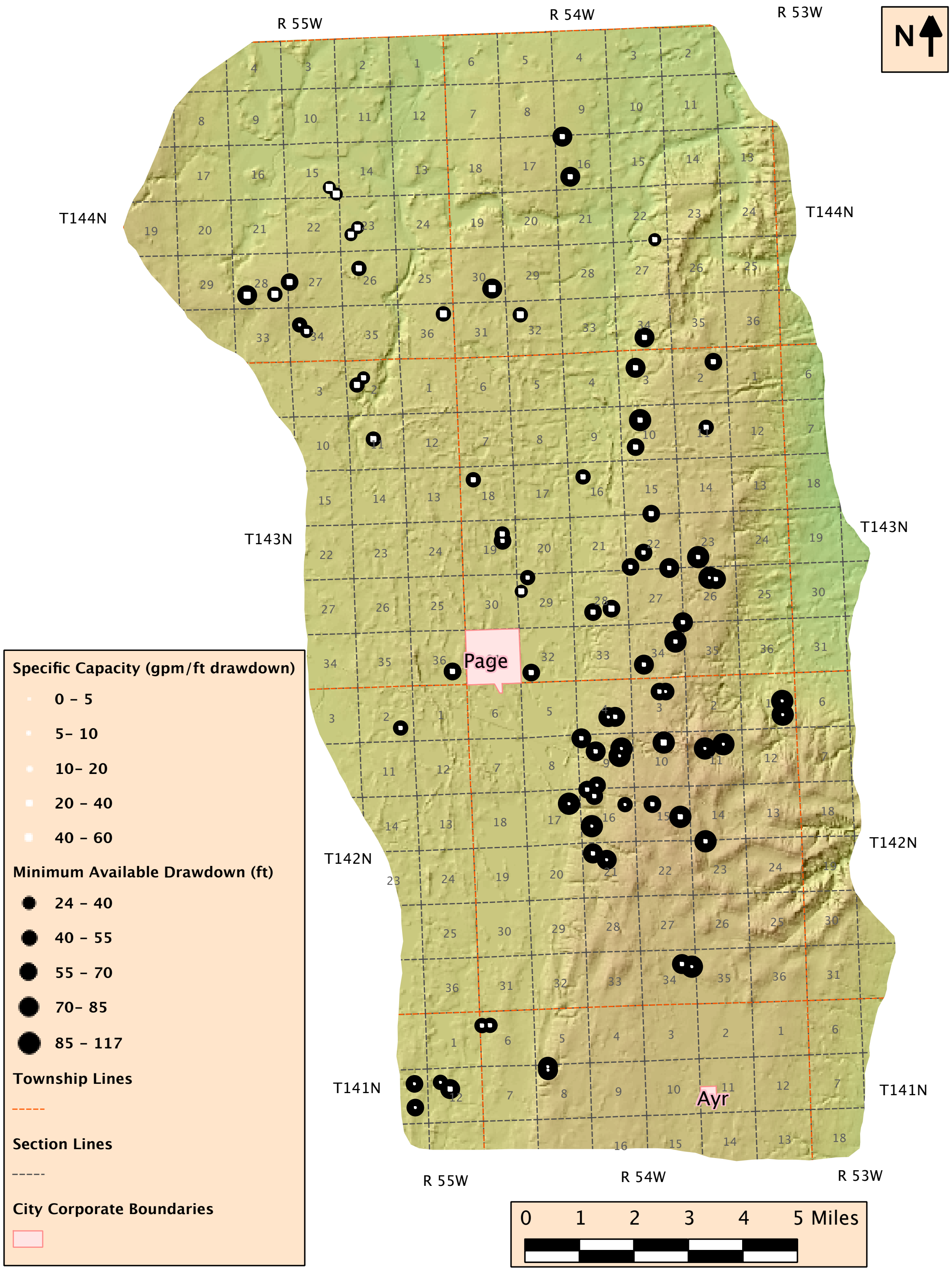

Figure 93. -- Comparison of specific capacity versus minimum available drawdown of 88 irrigation wells.

Figure 77 shows the predictive capability of the transient model. In areas of continuous hydrostratigraphy the model reproduces water levels very well and in areas of complex hydrostratigraphy it does not. In areas where the model is defined as having poor predictive capability, the model should not be used as a basis for appropriation of water.

When aquifer properties were assigned to layer 2 of the model, the drillers logs for irrigation wells were not included as data points because of the lack of detailed information in the logs. In the model, some irrigation wells were placed in areas characterized by very small hydraulic conductivity that are not representative of the actual conductivities at the well, and as a result show excessive drawdowns due to pumping. Nearby irrigation wells with more realistic hydraulic properties and associated drawdowns may be used to make estimates of potential affects due to pumping.

Summary and Conclusions

The Page aquifer has reached maturity from a development standpoint, and the basis for allocating additional ground water required development of a ground-water model. A conceptual model of ground-water flow was developed and general assumptions of recharge and discharge from the aquifer were formulated. The conceptual model provided the framework for developing the Page aquifer ground-water model. A finite-difference model using MODFLOW-2005 was developed and was used to predict water-level changes in response to pumping and changing climatic conditions. The Page aquifer model simulates two layers, which represent the sediments between land surface and the bottom of the aquifer. The modeling approach included (1) calibrating a steady-state model for a December 1983 hydrologic condition, (2) calibrating a 110-year transient model with estimated recharge, ET, and water use from the Versatile Soil Moisture Budget Model (VB2000) based on actual reported acres, and (3) using the calibrated model to predict groundwater availability by simulating permitted pumping and pending pumping for the entire 110-year simulation.

Because of large moisture holding capacity soils and higher average precipitation in the eastern part of the state, the Page aquifer has been managed with very conservative allocations in comparison to other North Dakota aquifers. The average annual allocation in the Page aquifer is

10.5 inches per acre, while the rest of the state is 18 inches per acre. Thus far, the conservative allocations from the Page aquifer have been sufficient for the last 36 years of development. The model shows that during this time frame, many permit holders should have had problems stressing crops during drought years, because of limited permit allocation and inefficient capture systems (irrigation plumbing). However, according to the reported water use, their allocations have been sufficient and there have been minimal concerns expressed in relation to stressing crops over the last 36 years. This suggests the soil moisture budget model is overestimating monthly water use in some cases. This is likely due to spatial variability of the composite climate datasets.

The calibrated model does a reasonable job of matching the water-level distribution in the aquifer. To assess the future availability of groundwater in the Page aquifer, the transient model was used to generate water levels from 1901-2010 under various pumping scenarios, including annual estimates of pumping based on permitted allocations and permitted and pending allocations. Based on the model simulations, it appears that the aquifer is not limited by long-term sustainability, therefore the aquifer has sufficient volume to sustain both the permitted and pending allocations. Although the aquifer is not limited by long-term sustainability, it is however limited by growing season interference effects of wells during severe droughts. During the peak of the irrigation season, wells screened in finer textured sediments or thinner portions of the aquifer may be competing for water due to excessive drawdown in the aquifer. Sequential model simulations based on priority date will be conducted for each pending application to determine which applications can be approved and which cannot. The approval of the pending applications will be based on the ability of prior appropriators to withdraw required amounts of water as growing season water levels decline due to increased well interference.

Under current conditions, the State Engineer views a majority of the irrigation works within the Page aquifer to have inefficient capture systems. It is not uncommon to see irrigation systems with low yielding wells, at 500 gpm capacity well, providing water to two quarter-section pivot systems or two low yielding wells, at 400 gpm capacity well, providing water to 3 quarter-section pivot systems. The addition of wells to make capture systems more efficient should in many cases diminish potential well interference effects. At this point, a majority of the permit holders have not experienced sufficient well interference effects to warrant the addition of new wells. However, increased appropriation and potential for a more severe drought, beyond what has been experienced in the last 36 years, will likely require the installation of additional wells to mitigate the increased interference effects. Some irrigation systems are already at or near their full pumping rate allocation. In these cases if additional wells are completed, the pumping rates of existing and new wells would have to be adjusted to stay within their current pumping rate allocation. For the Page aquifer system, the State Engineer considers a capture system consisting of 3 wells per quarter-section pivot system to be a reasonable effort to capture water and anything less to be an insufficient effort to capture water.

After completion of this report, the State Engineer will use the transient ground-water flow model to evaluate the 18 pending water permit applications on a case-by-case basis based on their priority date. Since the aquifer covers a large regional area, there may be cases where applications with junior priority dates will be approved ahead of some applications with senior priority dates because they are not competing applications.

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